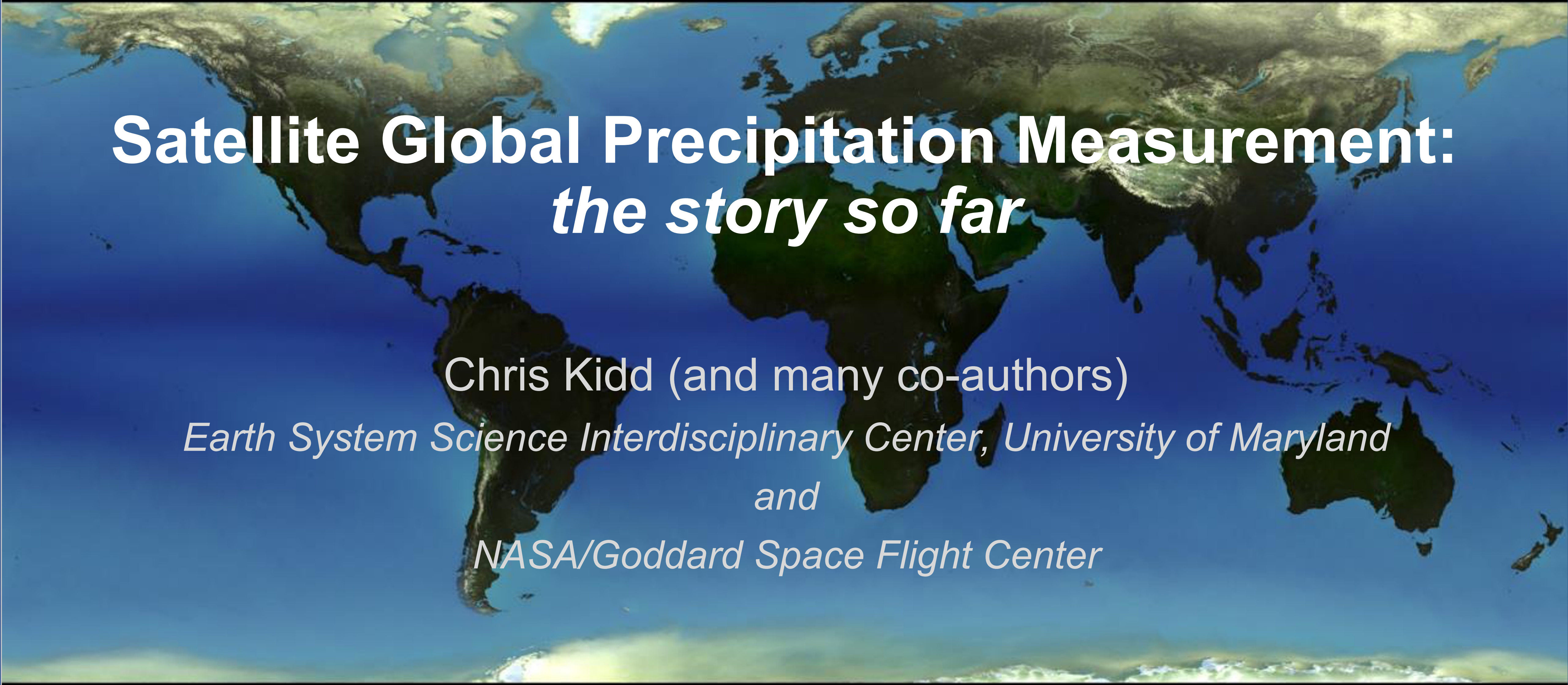

Satellite Global Precipitation Measurement: *the story so far*

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and

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Introduction

Water is

- essential to life on Earth - the only one (we know) that has abundant, usable water.
- a fundamental component of the Earth's energy and water cycle, redistributing energy through evaporation and condensation across the Earth's surface and its' atmosphere.
- critical to our social and economic well being: too much or too little can be disastrous.
- increasingly important politically: water resources transcends national boundaries.

Precipitation (rain or snow) is an essential component in all these areas

- *Precipitation is defined as the liquid or solid products of the condensation of water vapour falling from clouds or deposited from air on the ground. It includes rain, hail, snow, dew, rime, hoar frost and fog precipitation. (WMO Guide to Meteorological Instruments and Methods of Observation)*
- *Precipitation of drops of water [rain] … of ice crystals, singly or stuck together [snow], that falls from a cloud. (WMO International Cloud Atlas)*

Measuring Precipitation

How is precipitation measured?

- surface-based measurements – e.g. gauges and radar
- satellite systems – e.g. vis/IR and microwave observations

Precipitation is highly variable both spatially and temporally: all available observations must be exploited to properly represent the precipitation and, for truly global measurements, requires multiple satellite sensors.

Quantifying precipitation, accuracies and errors is extremely problematic; issues affecting and influencing the observation and measurement of precipitation include:

i. characteristics of the precipitation being observed;

ii. observational capability of the instrument;

iii. interpretation of the measurements/observations and derived parameters, and;

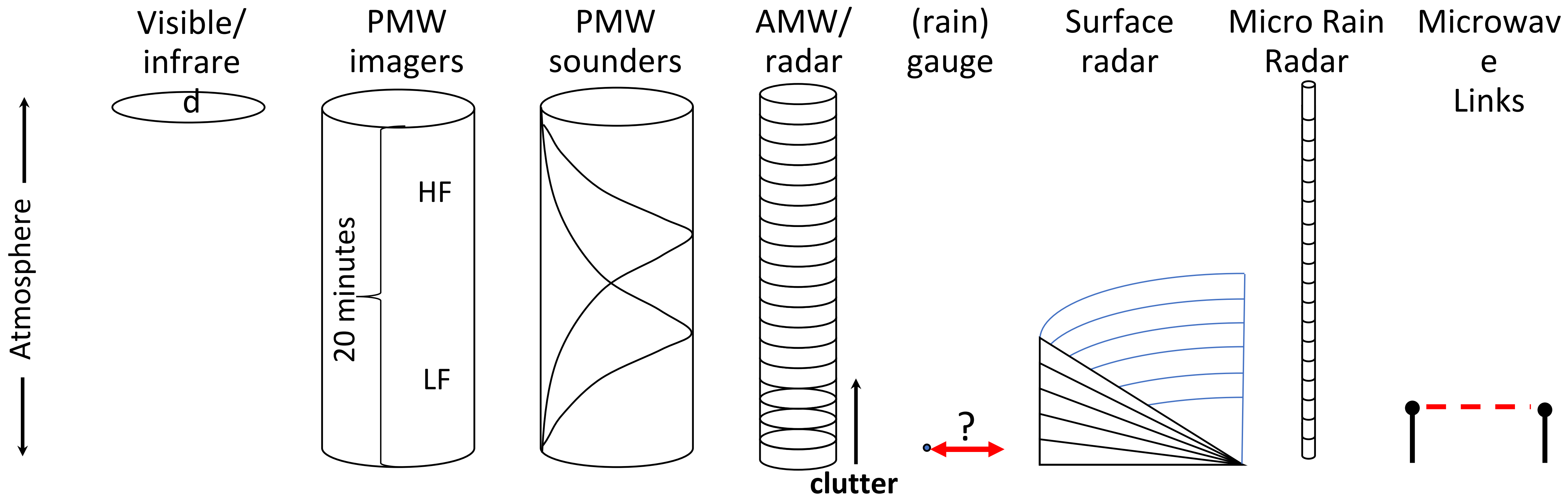
iv. perceived versus real requirements of subsequent applications.

Surface & Satellite Observing Systems

	Instrument	Temporal	Spatial	Notes
Surface	**Gauges: accumulation**	**Variable**	**Point**	**Temporal scale depends upon frequency of observation**
	Gauges: Tipping Bucket	**Quantised**	**Point**	**Quantisation of bucket (0.1, 0.2 mm or 1/100”) and data logger**
	Distrometers	Instantaneous	Point	Individual drop measurements
	Micro rain radar	Instantaneous	Point	Vertical profiles up to 256 levels/10 s sampling
	Weather radar	**Instantaneous**	**Radial**	**Radial measurements of dBZ converted to a Cartesian grid**
	Microwave links	Instantaneous	Linear	Line of sight measurements along length of link
Satellite	Visible imagery	Instantaneous	1-4 km	Intermittent (LEO) 15 min sampling (GEO)
	Infrared imagery	**Instantaneous**	**1-4 km**	**Intermittent (LEO) 15 min sampling (GEO)**
	Passive Microwave Imagers	**Column**	**5-25 km**	**Intermittent sampling (LEO) Resolution = frequency dependent**
	Passive Microwave Sounders	**Column**	**16-48 km**	**Intermittent sampling (LEO) Resolution = frequency/scan position dependent**
	Active Microwave (radar)	Instantaneous	5 km	c.80 vertical levels; Limited intermittent sampling (LEO)

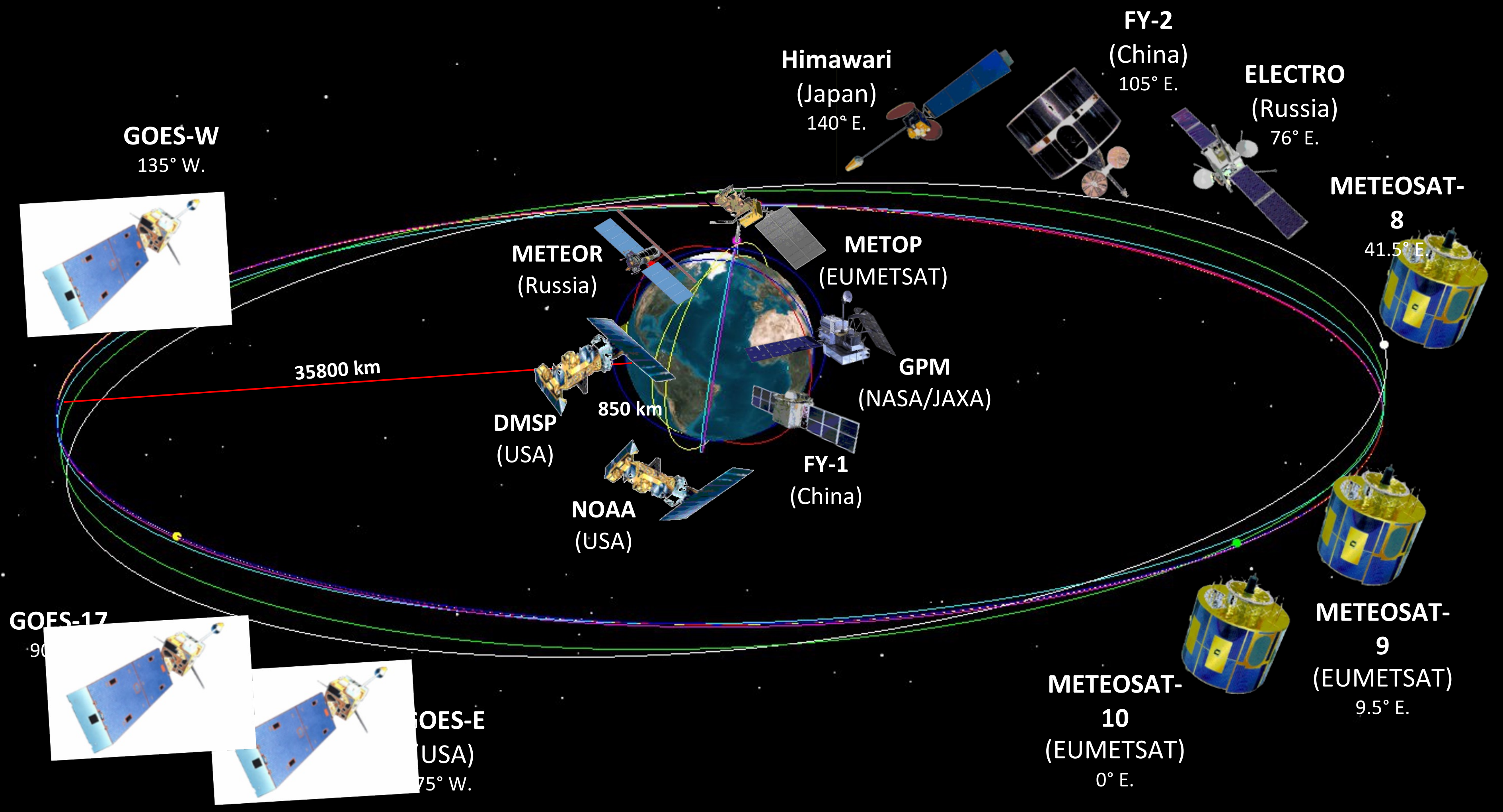
Note the different spatial and temporal sampling of each sensor.

Surface & Satellite Observing Systems



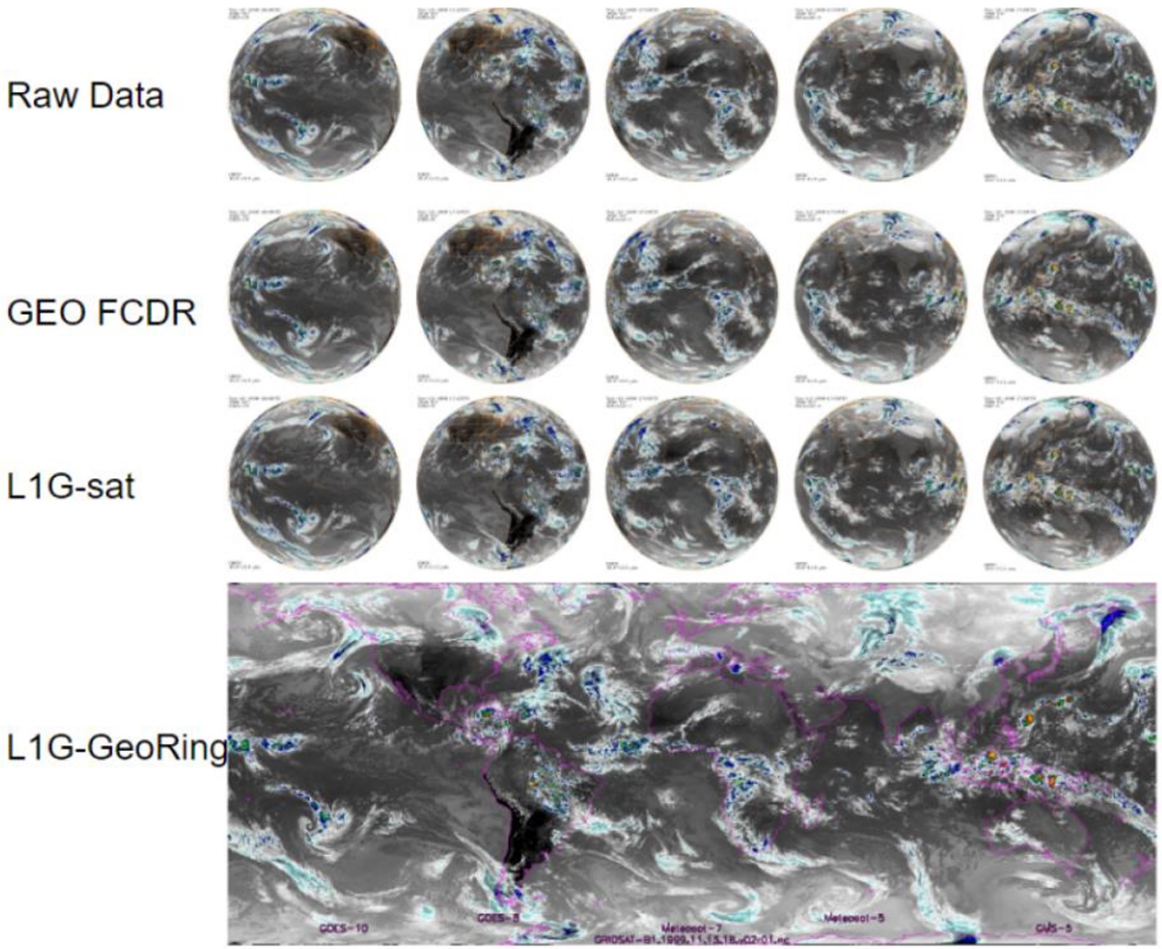
Different systems observe things differently – spatially, temporally and physically: there are good, fundamental reasons why precipitation measurements should vary.

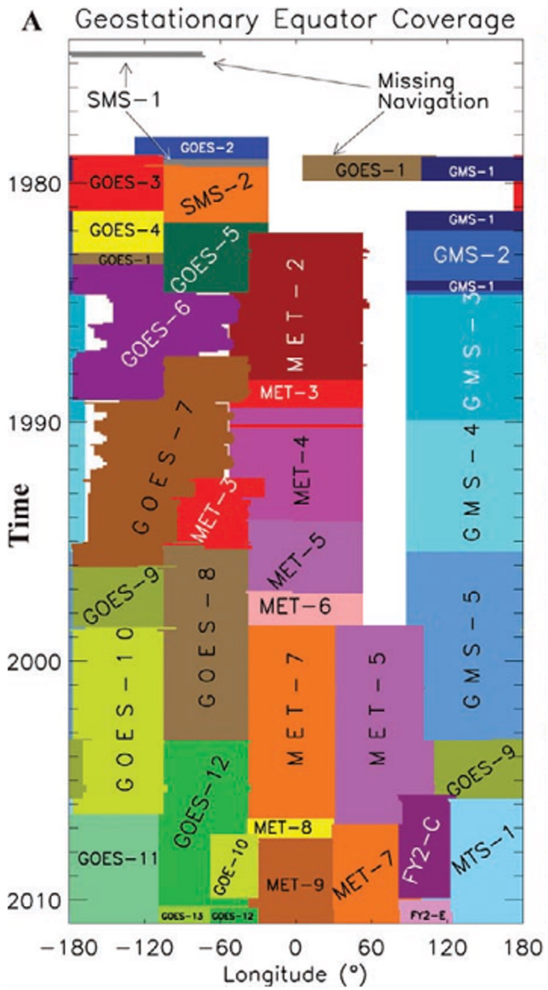
EARTH OBSERVATION SATELLITE SYSTEM (Met)



needs updating – but essentially: Low Earth Orbiting systems and Geostationary systems

Geostationary observations

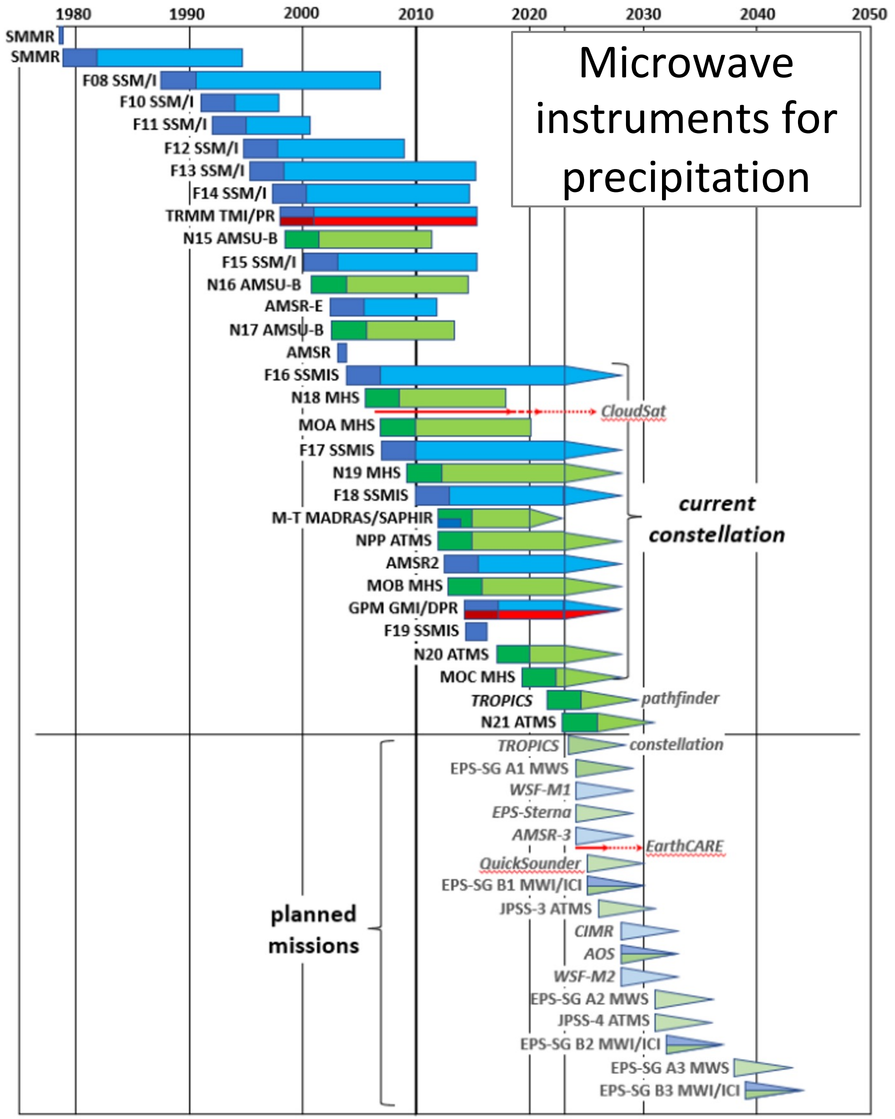




- Geostationary observations in the Vis/WV/IR available since early 1980's
- (easily) available combined products – for IR at least – from 2000 onwards (e.g. CPC Global-IR 4km)
- New effort to provide multi-spectral data through **GEO-Ring** project for whole Geo-period.

Vis/IR GEO-observations are an integral part of global precipitation measurement primarily due to their temporal sampling and good spatial resolution

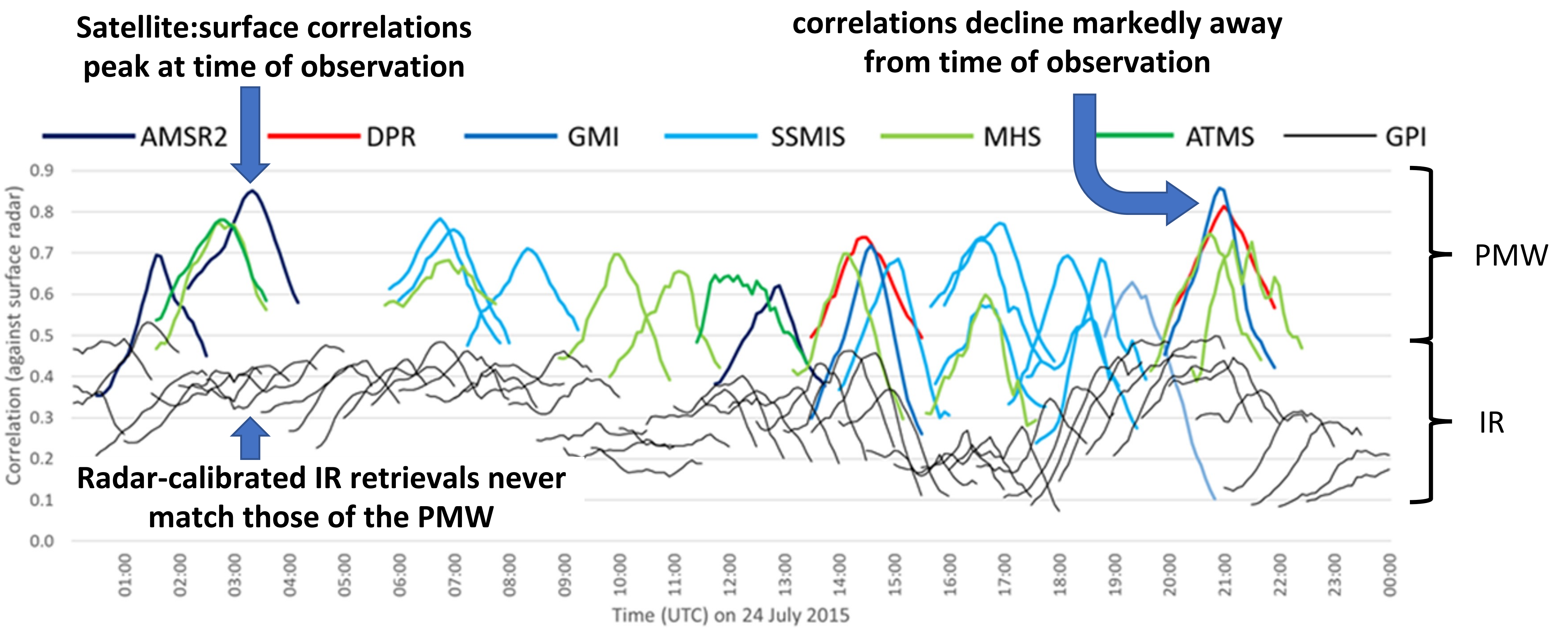
Microwave Instruments (US/Euope/Japan)



- Earliest (passive) microwave (imager) missions 1968 (Soviet), 1972 (ESMR-5) and 1975 (ESMR-6).
- SMMR (1978) initiated the start of the long-term, systematic global passive microwave imaging era.
- Only two missions, TRMM and GPM, have been precipitation-focused.

The precipitation science community has become very adept at adopting and utilizing a range of satellite observations to provide the necessary (temporal and spatial) products to meet user requirements.

Why passive microwave?



Instantaneous passive microwave retrievals are more direct than IR retrievals and are generally very good but temporal sampling greatly decreases their impact

Satellite precipitation estimation

Satellite estimates of precipitation encompass a wide range of frequencies together with auxiliary data.

Retrieval of precipitation from satellite observations is complex since the range of precipitation properties and characteristics is large (cloud, rainfall, snowfall, hail).

Requires a multi-spectral, multi-satellite, multi-sensor approach

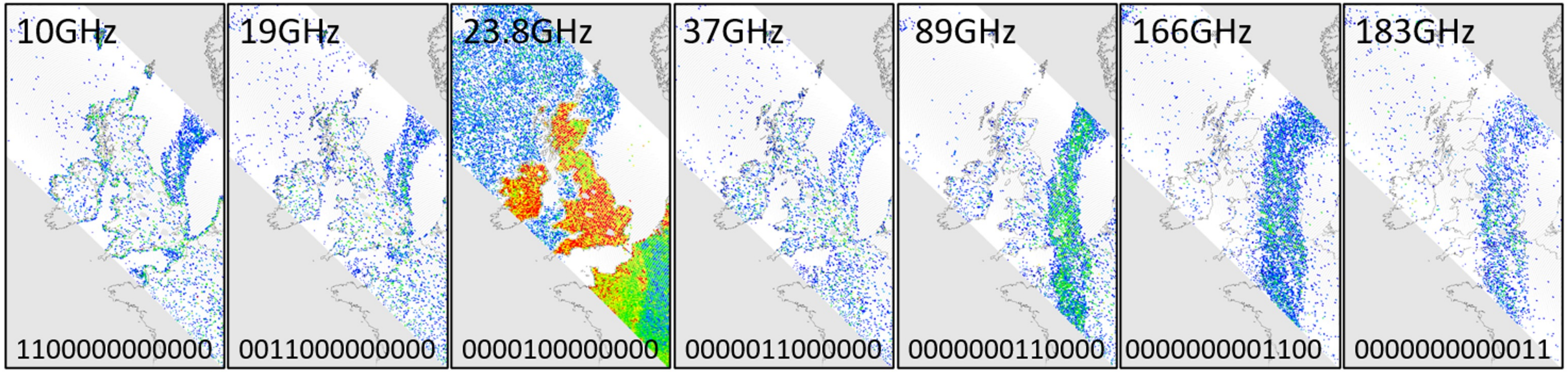
Current Passive Microwave sensors

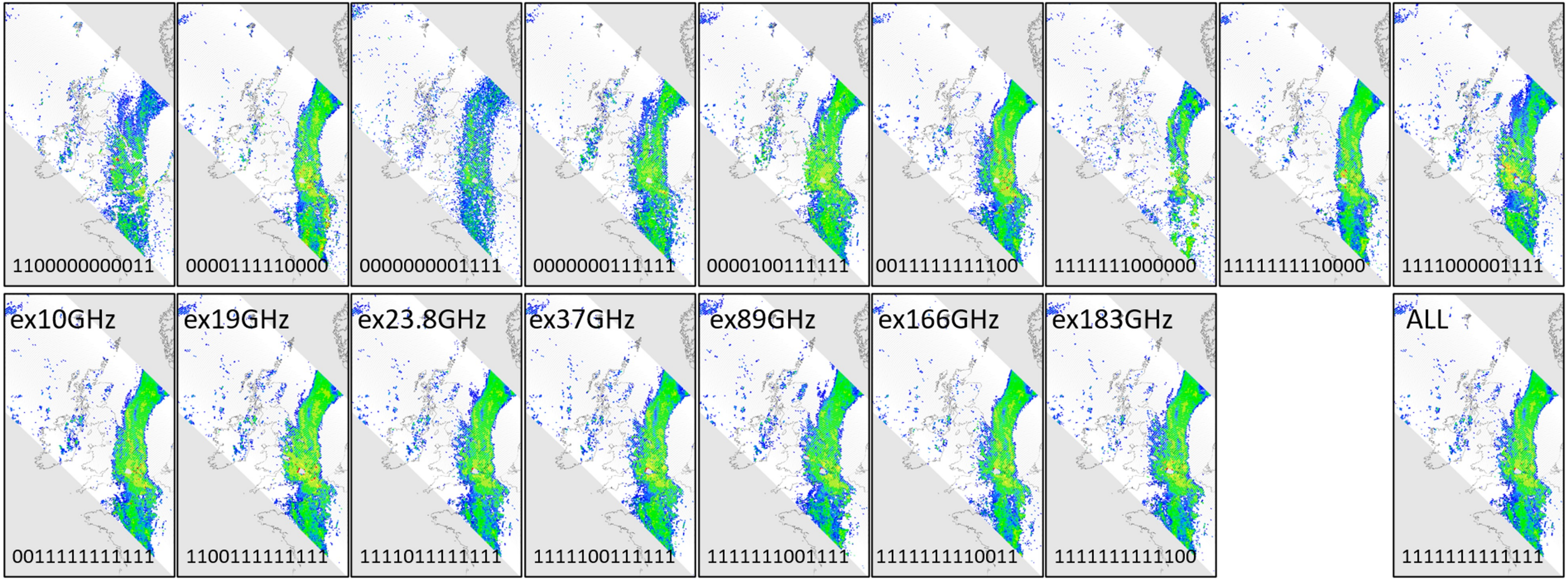
Focuses on the Global Precipitation Measurement (GPM) mission, formed of the GPM Core Observatory and constellation of international partner satellites/sensors:

- GMI/DPR (NASA/JAXA), 1xAMSR-2 (JAXA), 3xMHS (2xEUMETSAT, 1xNOAA), 3xATMS* (NOAA), 3xSSMIS (US DoD) *(*NOAA-21 in check-out)*
- Mean revisit time of 3 hours 90% of the time – *although observational gaps of 4-5 hours possible.*
- Currently, all but GPM-Core in sun synchronous orbits – *(some not necessarily providing independent observations).*
- Retrieval resolutions are sensor-dependent but generally 10-20 km.
- Merged/morphed products with Geo-IR to improve temporal/spatial sampling (e.g. IMERG/CMORPH).

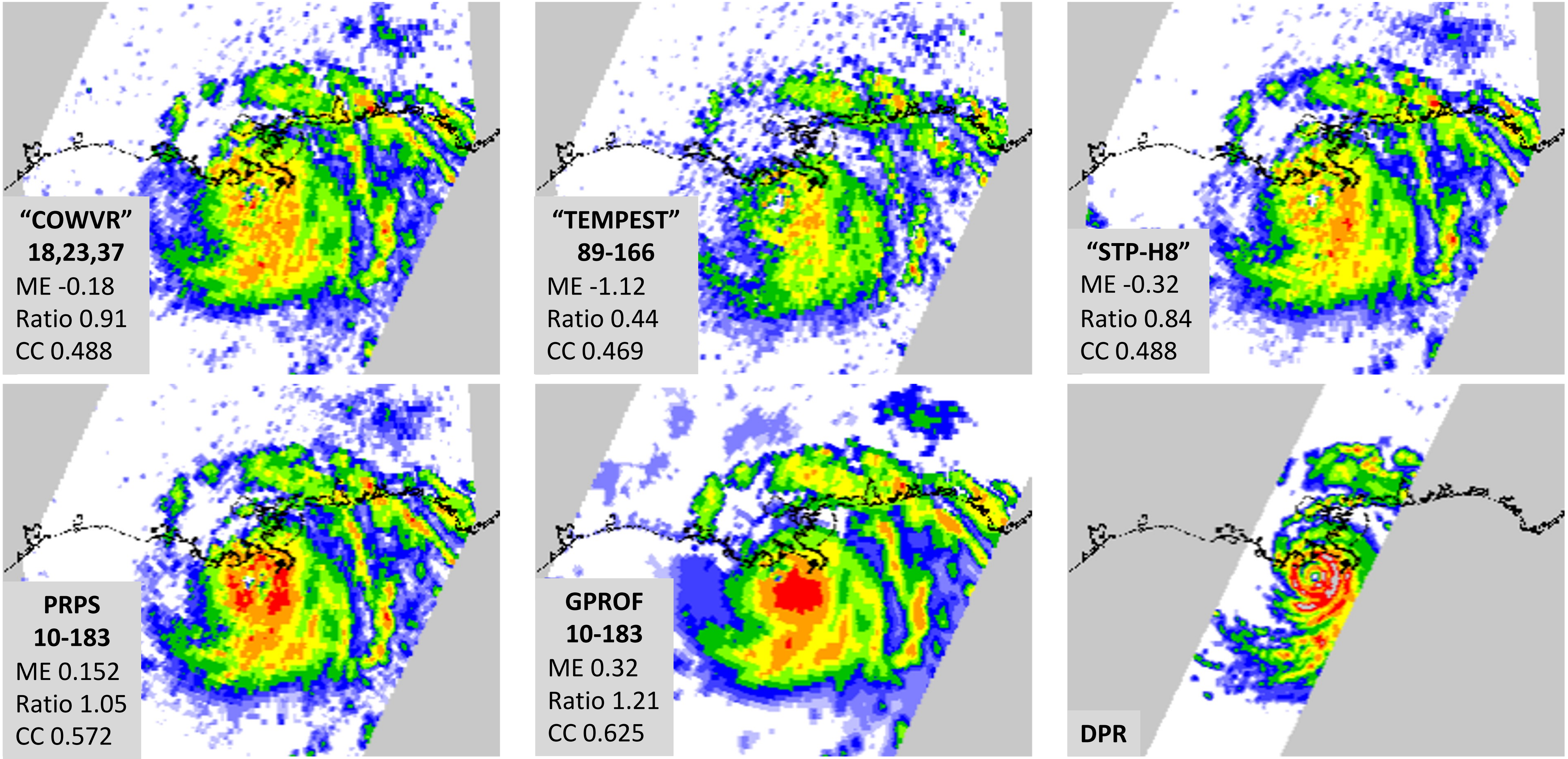
Which channels?

channel selection/ denial experiment for precipitation retrievals from GMI





Hurricane Ida (Cat.4) GMI 17:41UTC 29-Aug-2021



Planned Passive Microwave sensors

Upcoming (planned) missions include:

Imagers	Sounders *(*small/cubesats)*
JAXA: AMSR-3	NASA/MIT: TROPICS* (x4)
EUMETSAT: EPS-SG B (x3)	NOAA: JPSS-3/4
US DoD: WSF-M1/2	EUMETSAT: EPS-SG A (x3)
ESA: CIMR (x2?)	EUMETSAT: EPS-Sterna* (1+6)
	NOAA QuickSounder*
	NASA/JAXA/+ AOS (x2)

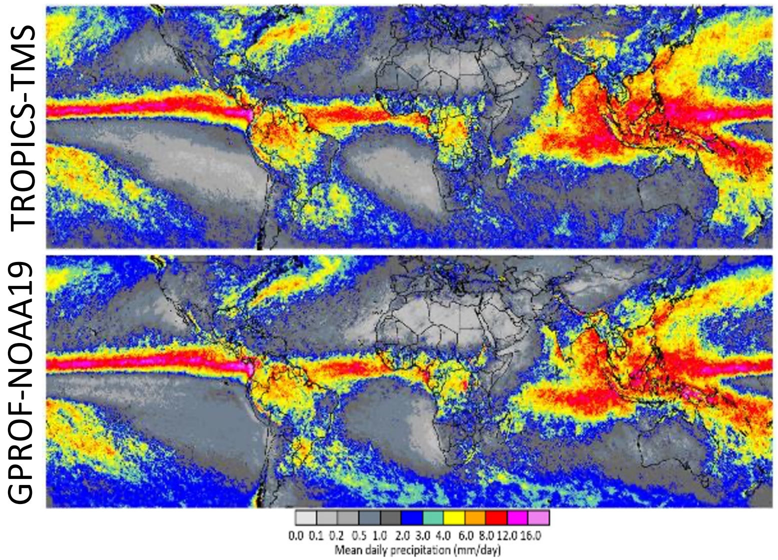
- AMSR-3, EPS-SG/B, WSF-M1/2 provide some continuity to existing capabilities, other missions provide some complementary capabilities.
- Smallsat/cubesat missions potentially good for improving temporal sampling, but generally less direct observations of precipitation *(high frequencies)* – and cross-track scanning *(variable EIA, resolution, atmospheric path length).*

The rise of the cubesat/smallsats

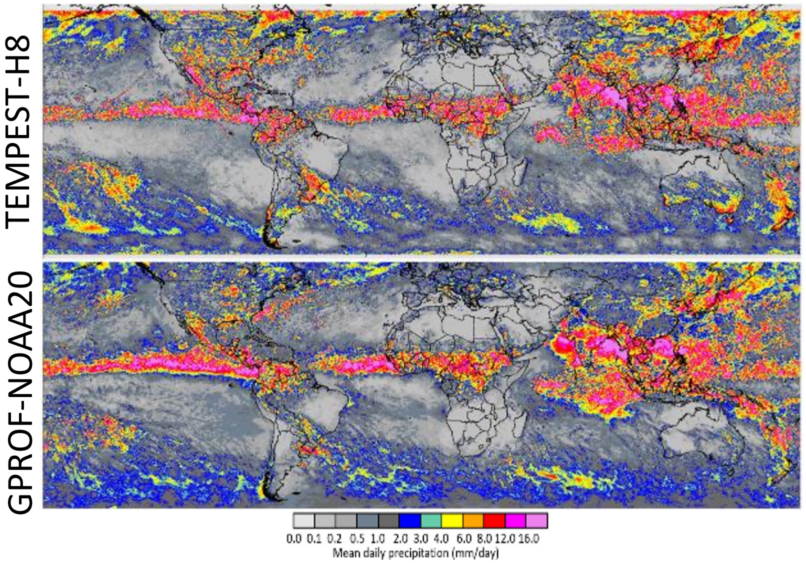
New technology has enabled smaller PMW sensors to be developed – as demonstrated by the TEMPEST and TROPICS-TMS sensors.

- Operating at frequencies from ca.89 to 183.31/204.8 GHz with resolutions similar to current PMW sounding instruments.
- Results to date are very encouraging, showing that basic retrievals are comparable with retrievals from current sensors.
- Results currently being fully evaluated (e.g. HF retrievals vs all-channel retrievals).

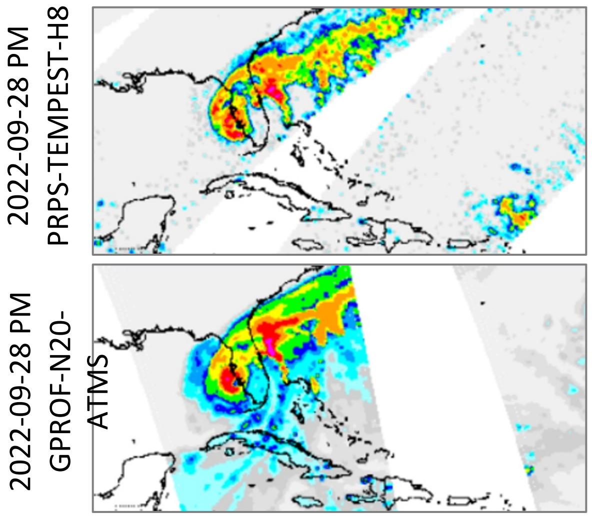
Mean annual precipitation (Aug’21-’22)



Monthly: August 2022



Hurricane Ian

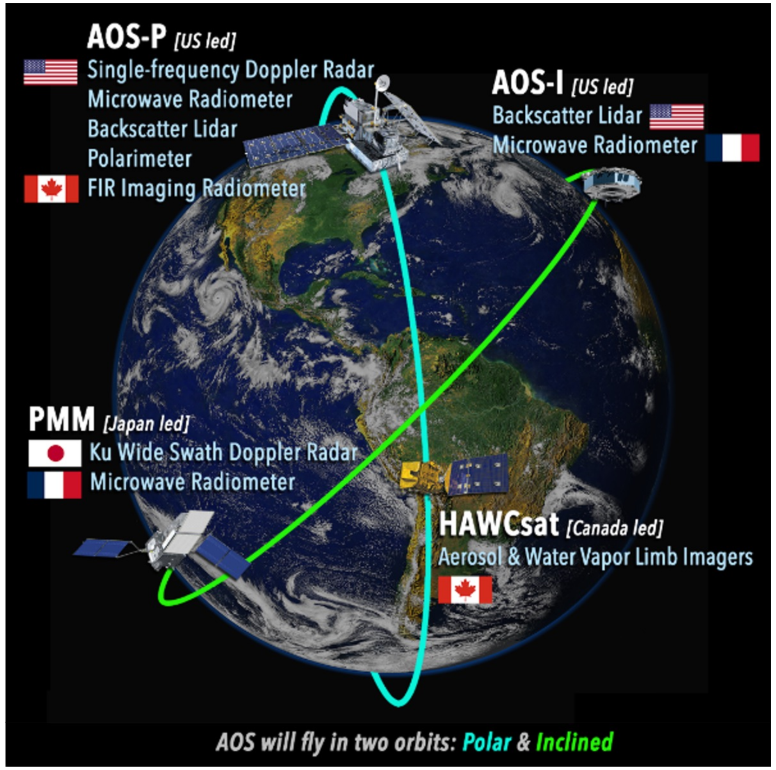


NASA's Earth System Observatory/Atmosphere Observing System

A NASA-led constellation in response to the 2017 Earth Science Decadal Survey Aerosols and Clouds, Convection, and Precipitation designated observables

Two projects, with polar component focused on global climate change-related processes, inclined component on processes over varying times of day

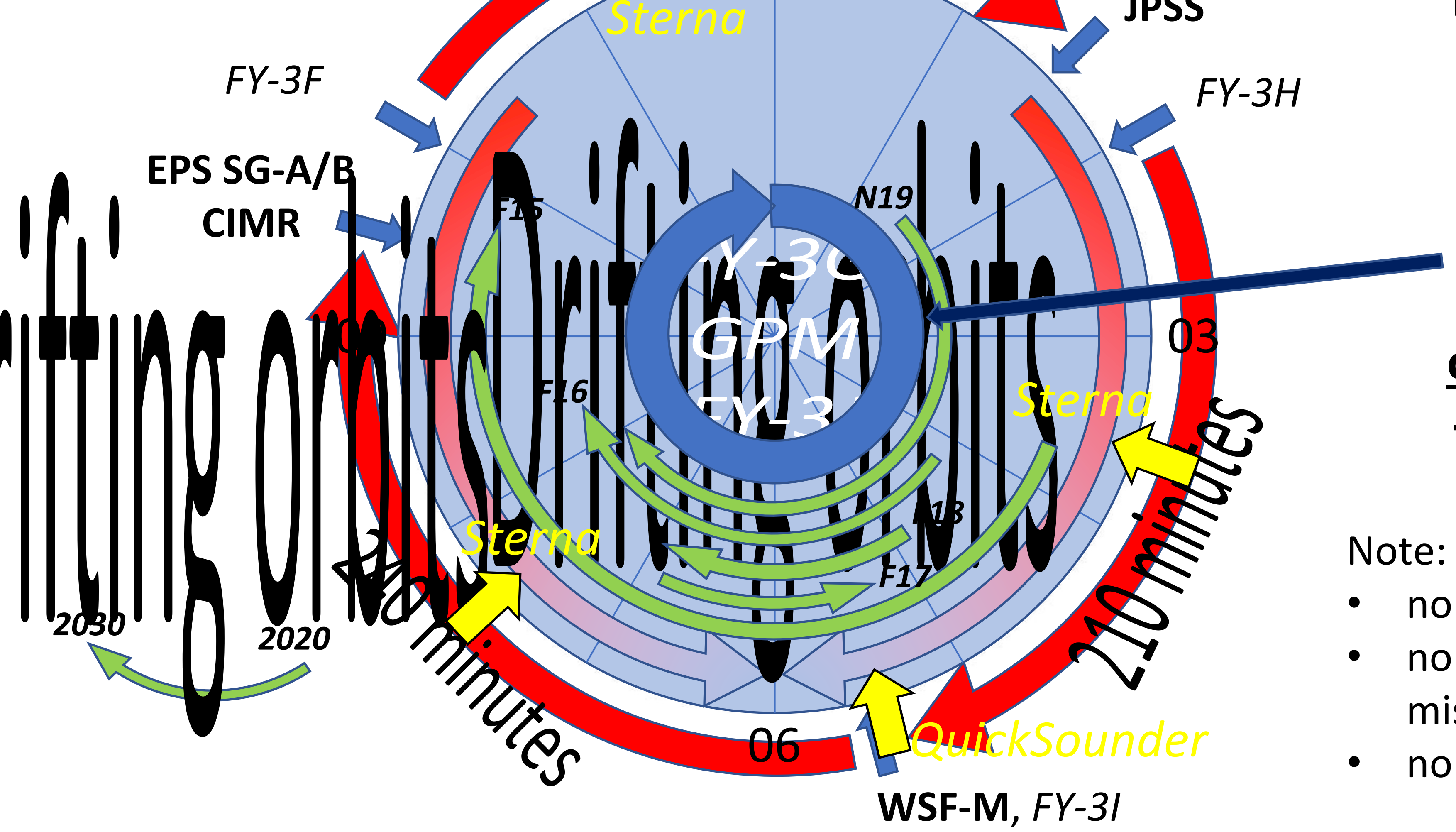
- Inclined project, AOS-I, launch no earlier than July 2028
  - JAXA PMM Ku-band radar (~5-km resolution, 255-km swath) with Doppler at nadir
  - CNES tandem passive microwave radiometers (~2-min separation; 89, 183, and 325 GHz)
  - NASA GSFC backscatter lidar (532 and 1064 nm)
- Polar project, AOS-P, launch no earlier than December 2030
  - Cloud-profiling radar (narrow swath or nadir-only) with nadir Doppler
  - Industry provided passive microwave radiometer (possible range from 89-700 GHz)
  - Industry backscatter lidar (532 nm, 1064 nm)
  - Industry provided UV-VIS multi-angle polarimeter
  - CSA far-IR spectrometer (TICFIRE) and aerosol and moisture limb sounders (ALI and SHOW, respectively)



Completed Mission Concept Review (May 2022)
Completed Key Decision Point A Review (Jan. 2023)

Future PMW radiometer constellation ca.2028-2030

Overpass clock



There are significant temporal gaps in coverage which could be filled with smallsats/cubesats.

A low-inclination 'calibrator' sensor(s) is critical for any constellation – but may not be available.

Note: this assumes:

- no orbital drift (newer missions?)
- no continuation of current missions
- no Russian Meteor series

Future challenges

Fundamental is an understanding of the properties and characteristics of what you are measuring. Precipitation (rain/snow) is highly variable in time and space, is heavily skewed towards zero intensity, with temporal/spatial scales are intrinsically linked.

- **Providing observations at scales that reflect the natural variability of precipitation** is key to improving estimates – but improving spatial resolution requires better temporal sampling.
- **Continuation of 'baseline' sensors** in the AMSR/GMI class, **augmented by smallsats/** cubesats to improve temporal sampling.
- **Provision of high-class sensor(s) in low inclination orbit(s)** to provide a calibration reference standard.

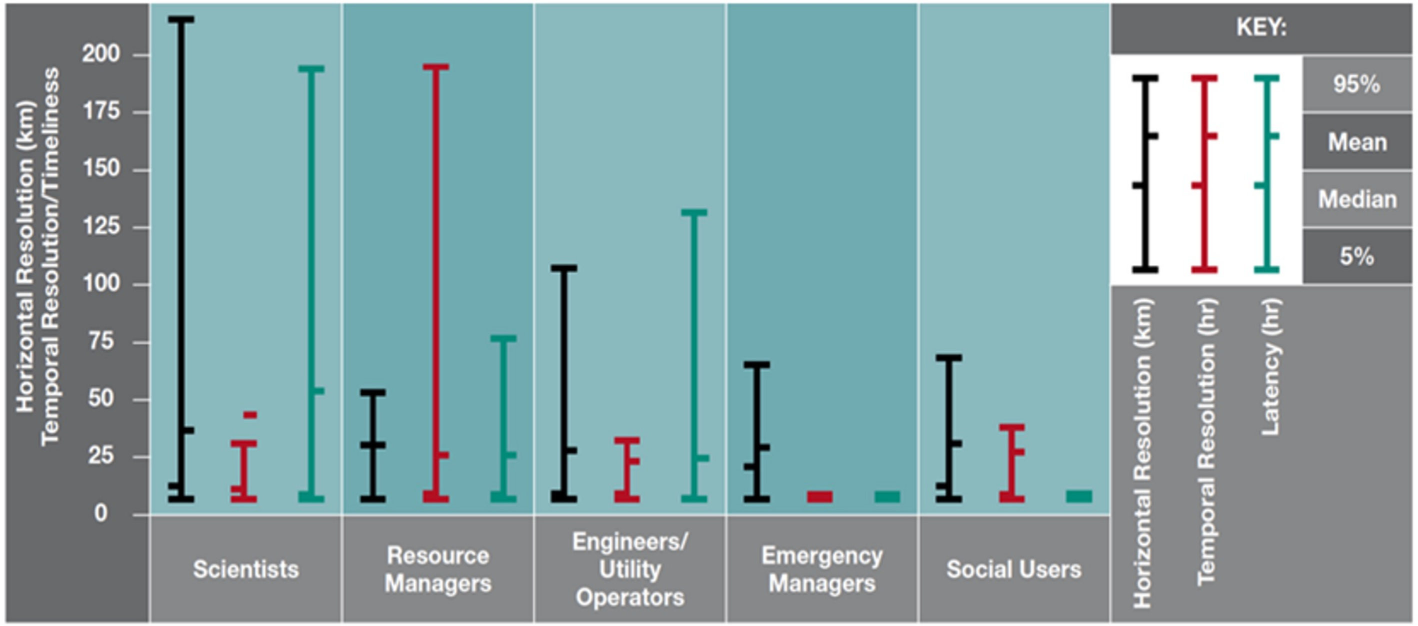
However:

- **not all observations used for retrievals are the same** - different channel availability, spatial resolution, noise/accuracy levels, etc… .
- **Integration of new, commercially-collected data** - subject to commercial pricing.

Precipitation user requirements

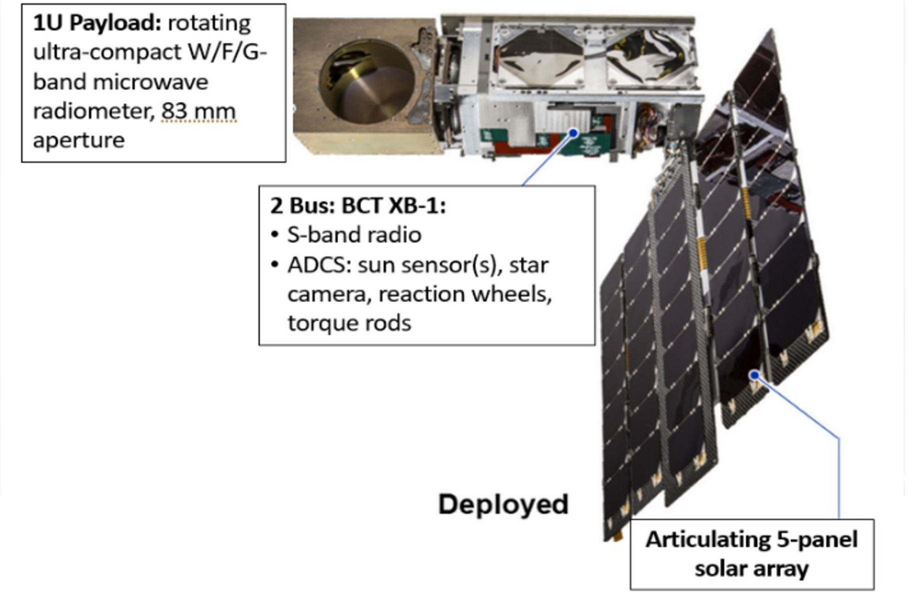
Wide range of users - wide range of requirements:

- Spatial resolutions: 300 m to 50 km;
- Temporal scales: 18 mins to 15 days;
- Latency (acquisition): 6 mins to 24 hours.



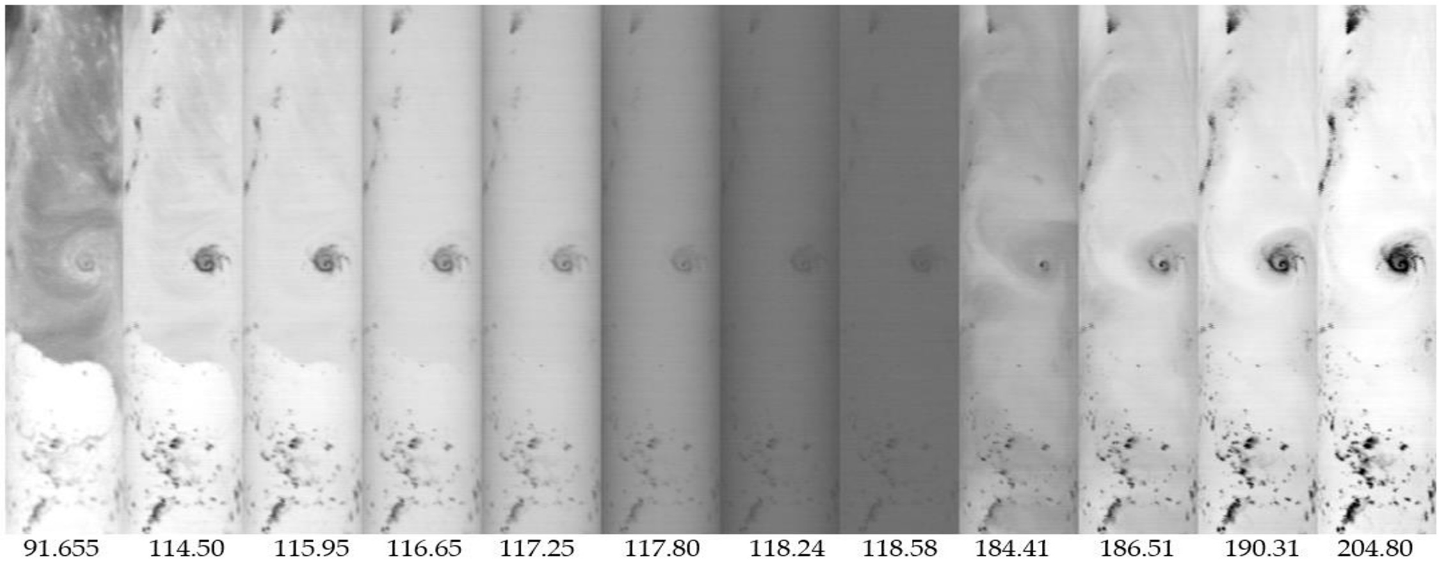
GEO (2010), Fig. 2

TROPICS & the TROPICS Millimeter-wave Sounder (TMS)



- **TROPICS pathfinder launched 30 June 2021 in near polar orbit**
- Two cubesats failed to reach orbit June 2022
- **Four cubesats set for launch May 2023+** into a low inclination orbit ca. 35N-35S.

TMS Channel	Central frequency	ATMS Channel	MHS Channel	*MWHS-2 Channel*
1	91.655±1.4 GHz	88.2 GHz	89.0 GHz	*89.0 GHz*
2	114.50 GHz	-	-	*118.75±5.0*
3	115.95 GHz	-	-	*118.75±3.0*
4	116.65 GHz	-	-	*118.75±2.5*
5	117.25 GHz	-	-	*118.75±1.1*
6	117.80 GHz	-	-	*118.75±0.8*
7	118.24 GHz	-	-	*118.75±0.3*
8	118.58 GHz	-	-	*118.75±0.2*
9	184.41 GHz	183.31±1.0	183.31±1.0	*183±1.0*
10	186.51 GHz	183.31±3.0	183.31±3.0	*183±3.0*
11	190.31 GHz	183.31±7.0	190.31	*183±7.0*
12	204.8 GHz	-	-	-



Hurricane Sam on 27th Sept 2021 as viewed by the TROPICS Pathfinder

TROPICS01.BRTT.L1B.Orbit01352.V02-03.ST20210927-170942.ET20210927-184458.CT20220208-174340

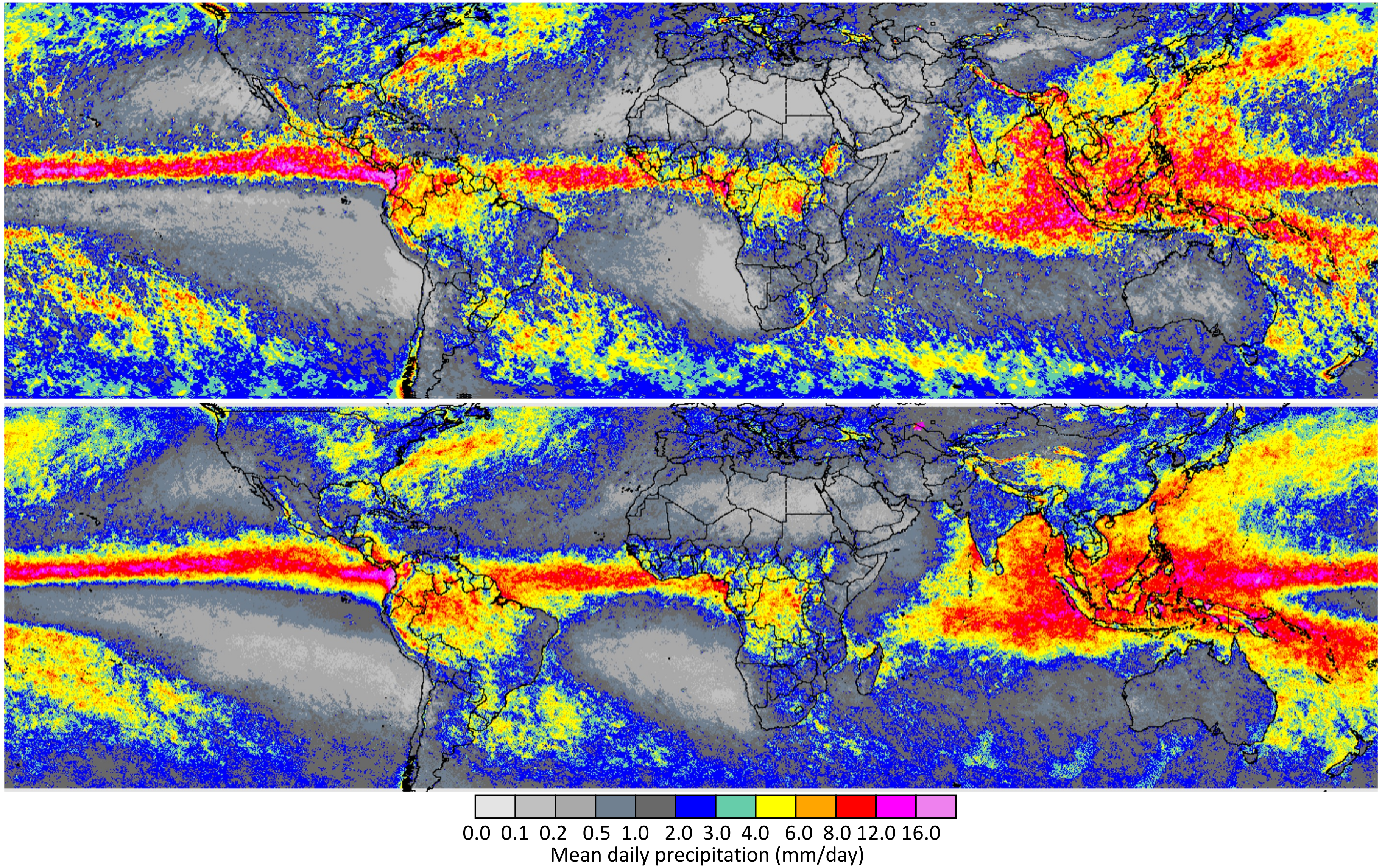
Mean annual precipitation

GPROF
GPM
GMI

2021.08.01
-
2022.07.31

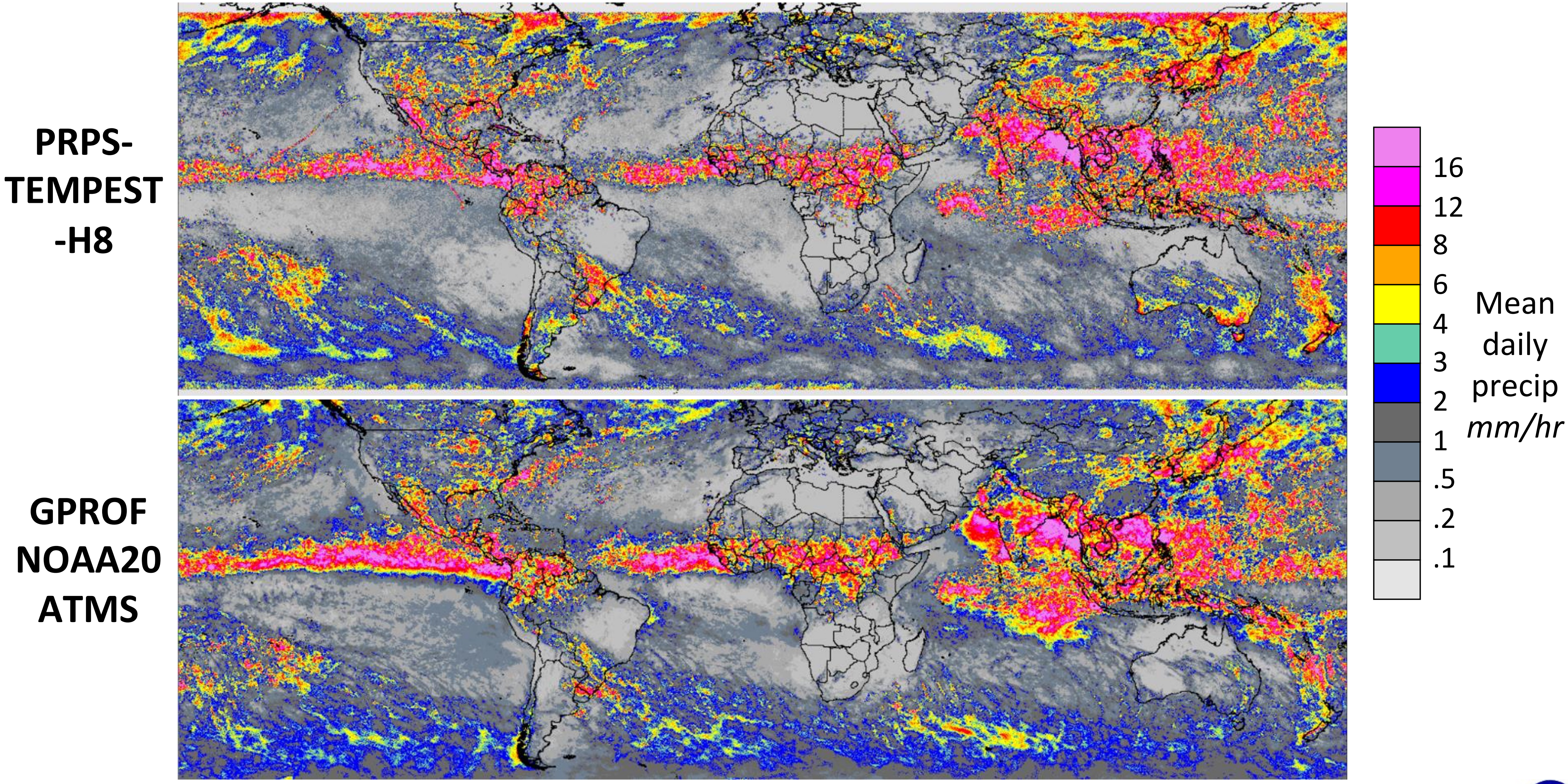
PRPS
TROPICS
TMS

2021.08.08
-
2022.07.31

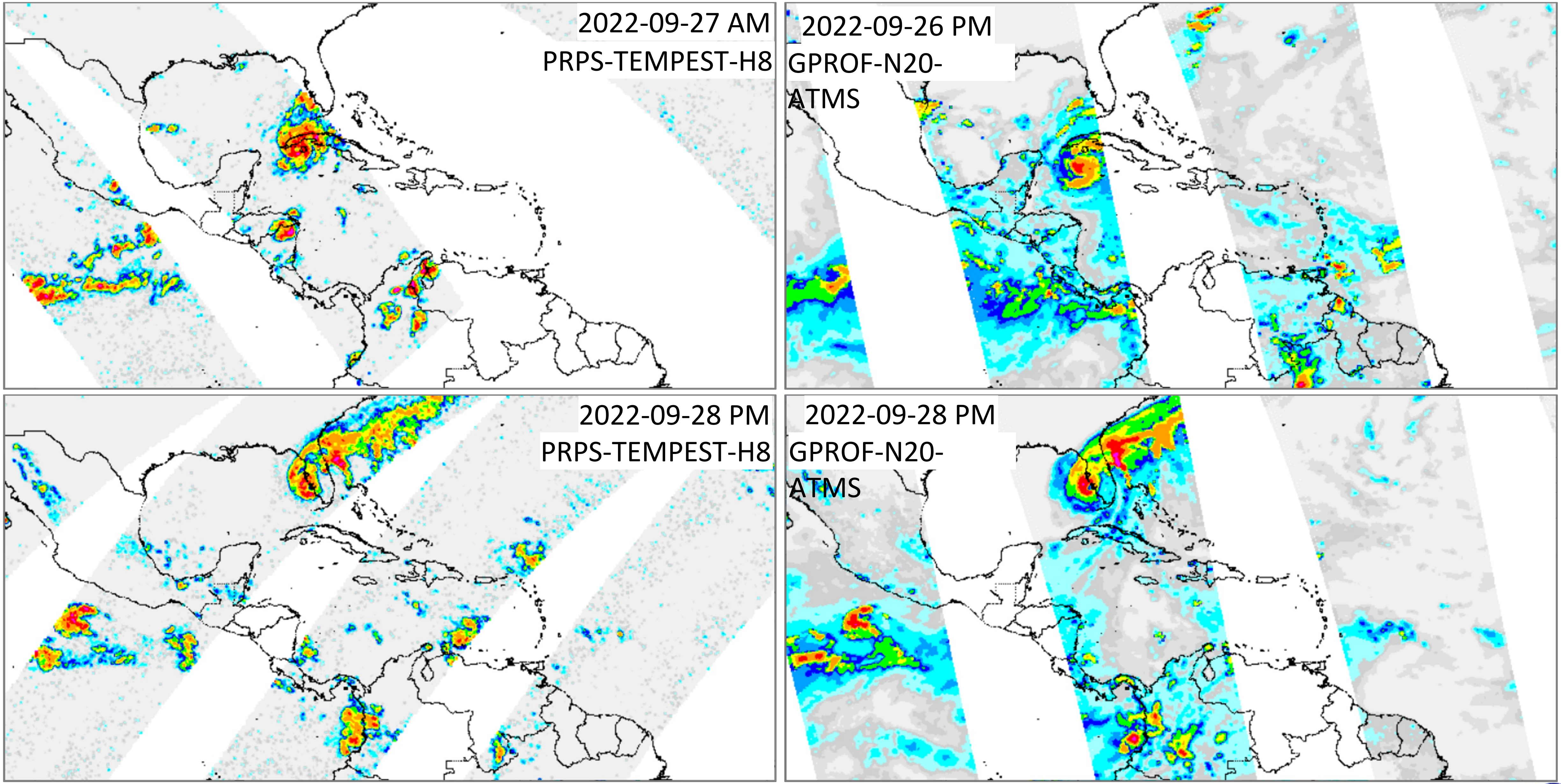


Both instantaneous and monthly PRPS-TMS in good agreement with the GPROF retrievals

PRPS-TEMPEST-H8 monthly precipitation: August 2022

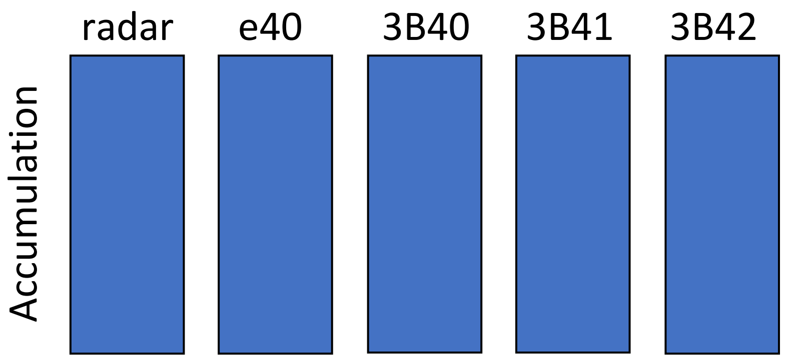


Hurricane Ian 2022

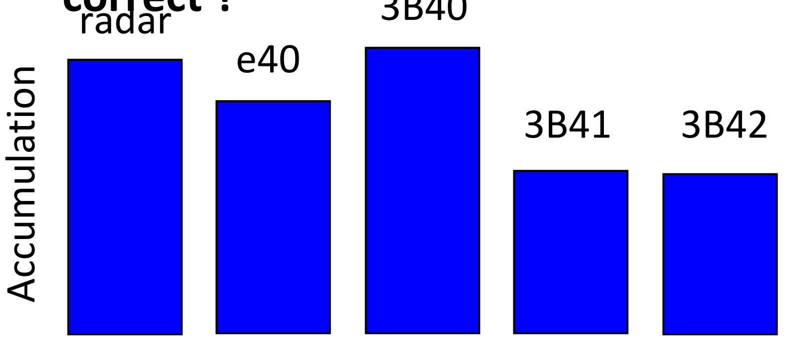


“Ideal” algorithms

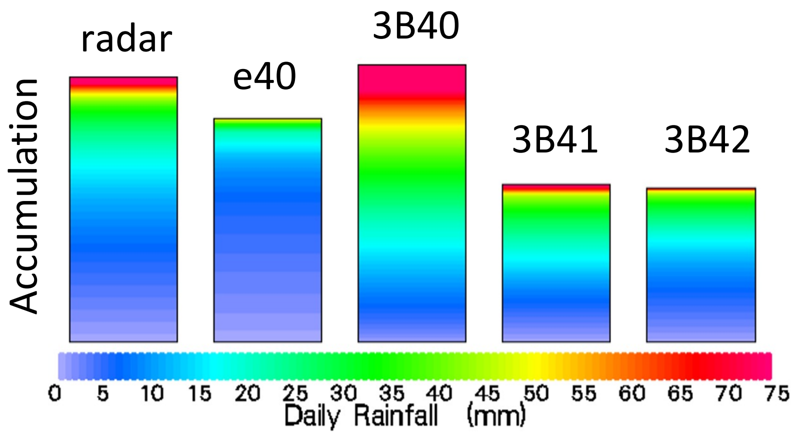
All algorithms produce identical results to any validation data set…

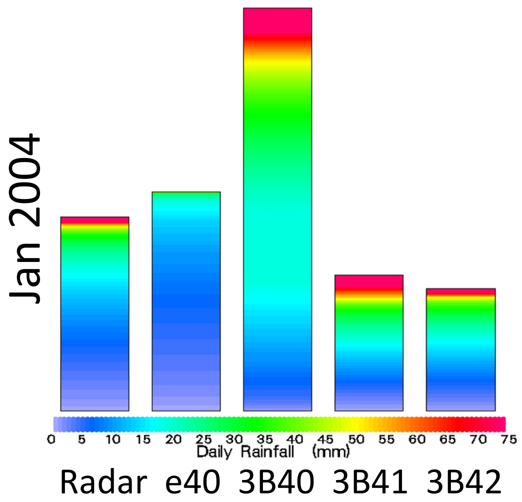


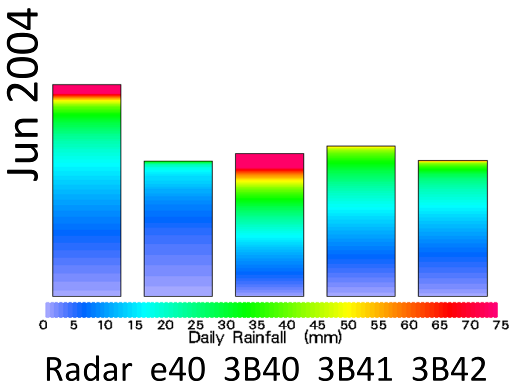
Algorithms tend to be tuned to minimise long-term biases –are they ‘correct’?

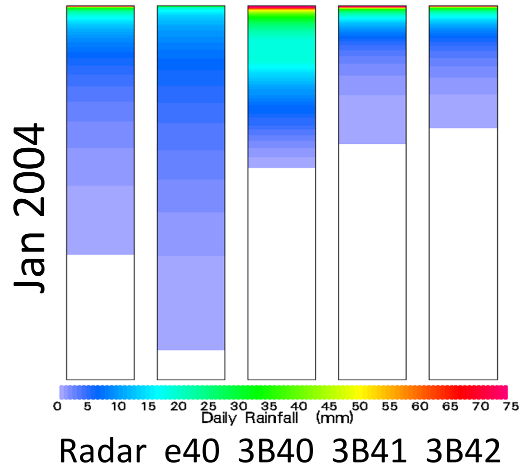


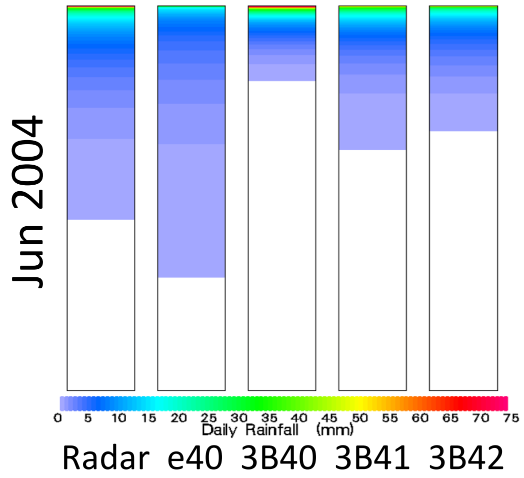
The make-up of the ‘intensities’ to the total is very important:



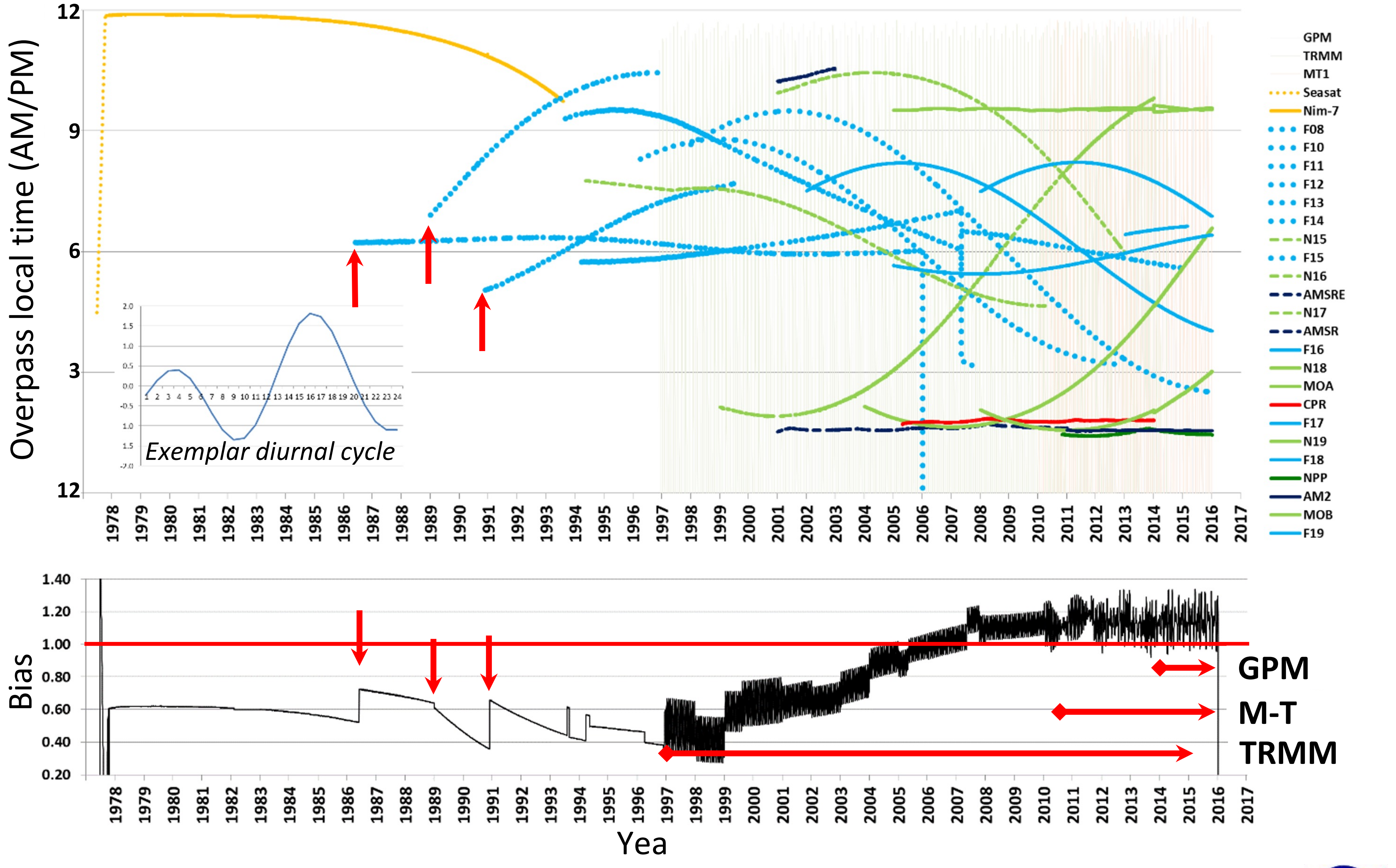








Drifting Orbits – and diurnal biases



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Channel loss/selection & Errors and Uncertainties

	Source	Quantificaiton	Verification	Status	Impact
Sensors	Channel selection	More/diverse = better (?)	scores against best available sensor	Good	Moderate
	Resolution	Commensurate with precipitation system (*high frequency channels*)	Simulations using high quality (1-km) surface radar data	Good	Moderate
	Tb precision	Measure of instrument noise – from intercalibration team	Cross-sensor and known targets	V.Good	Medium
Retrieval scheme	Channel utilisation	Channel denial simulations	Verification against high quality GV	Okay	Medium
	Retrieval scheme	Ability to capture precipitation occurrence and intensity	Validation against high quality GV and cross-sensor comparisons	Okay	Moderate
	External data	Errors and uncertainties within these data sets	Results of noise simulations within external data sets	Okay	Moderate
Products	Grid box sampling	Number of samples and distribution within each grid box	Simulations using high quality (1-km) surface radar data	Okay	Medium
	Temporal sampling	Representativeness of satellite samples re.	Comparisons with surface GV and model data sets	Okay	High
	Inherited E&Us	Additive/multiplicative E&Us	Verification against GV	Poor	High