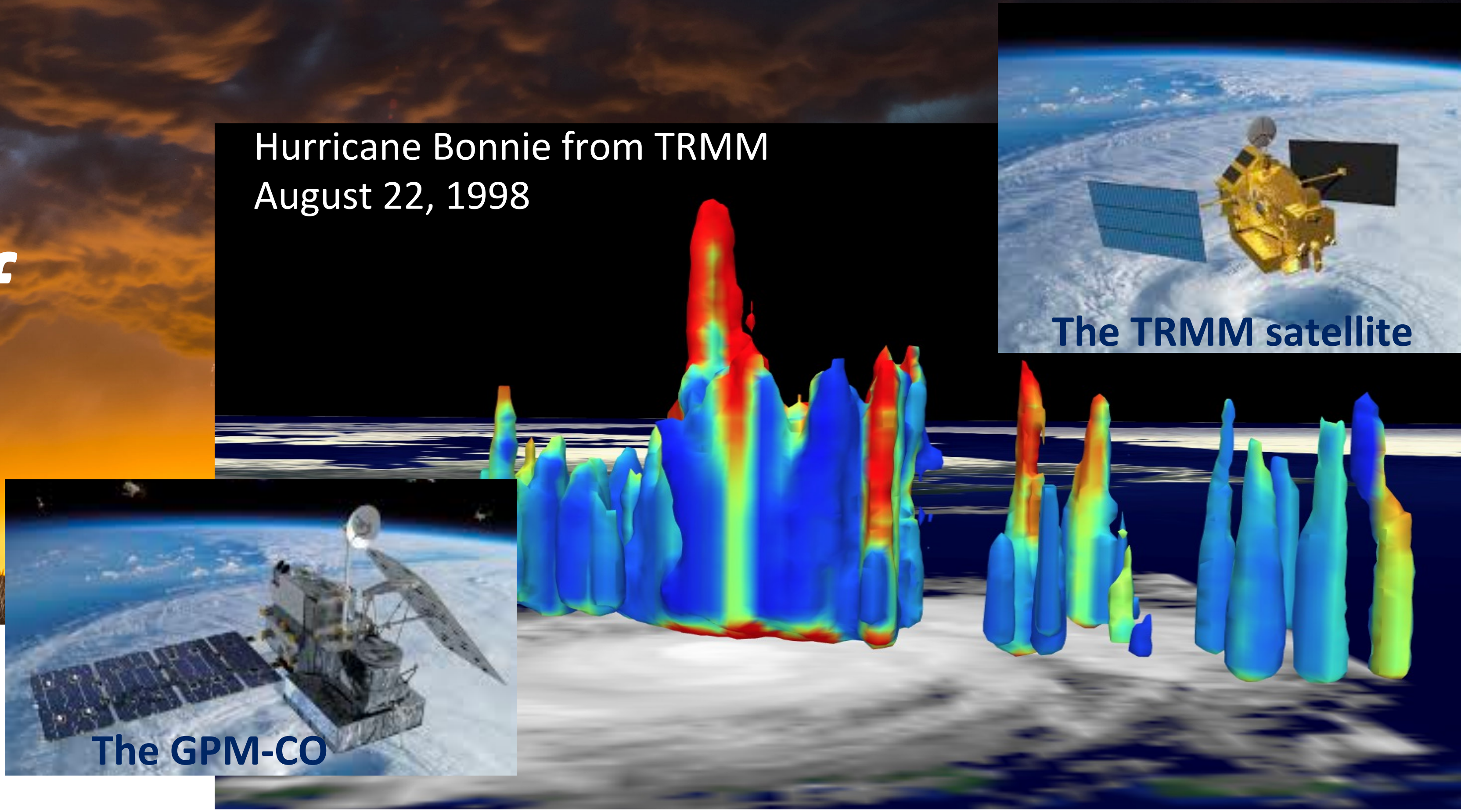
EUMETSAT H SAF

Remote Sensing of Precipitation from Space



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Outline

- Basic principles for satellite-based precipitation retrieval
- Passive microwave radiometers and retrieval history
- Precipitation retrieval techniques
- H SAF precipitation products and future perspectives

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Precipitation: an essential climate variable

- Precipitation is the key hydrologic variable linking the atmosphere with land surface processes and playing a dominant role in hydrology, weather, and climate
  - Role in Water cycle, Earth radiation budget (latent heat), weather patterns
  - Feedback mechanisms with climate change
  - Natural hazards (floods/droughts/landslides)
  - Hydrology and water management

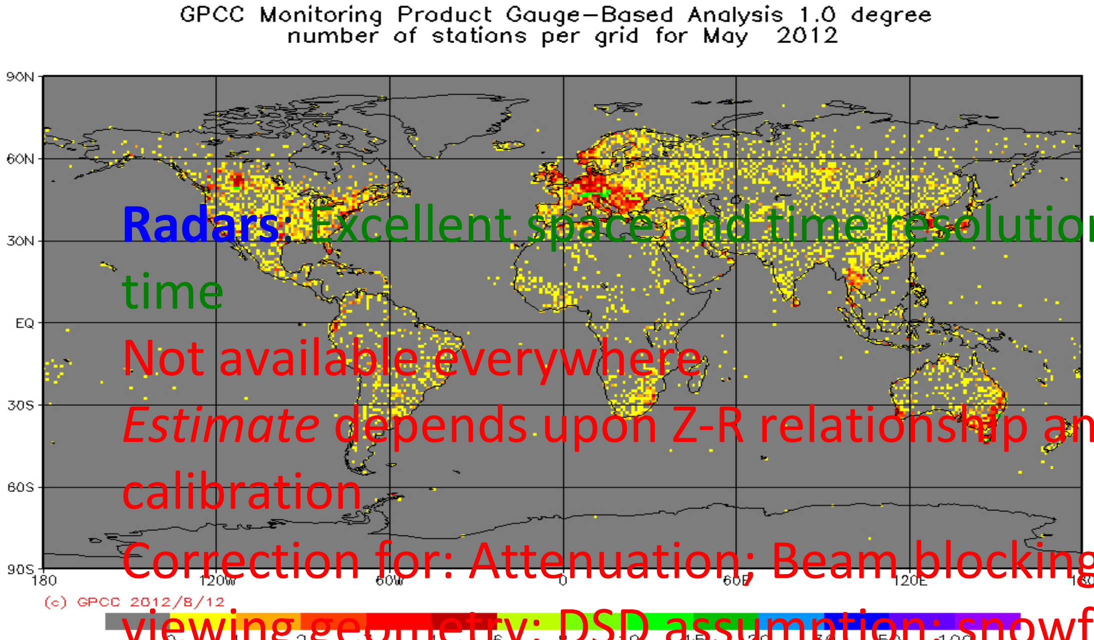
- *Accurate and continuous global* precipitation estimation is necessary for improving our understanding of climate, weather, and meteorological extremes, and their impact in hydrology

Precipitation "measurements"

Raingauges: Direct measurement of precipitation

Problem of representativeness: point measurements, in some areas they are very sparse or not available

Impact of wind/snow/floods, different networks

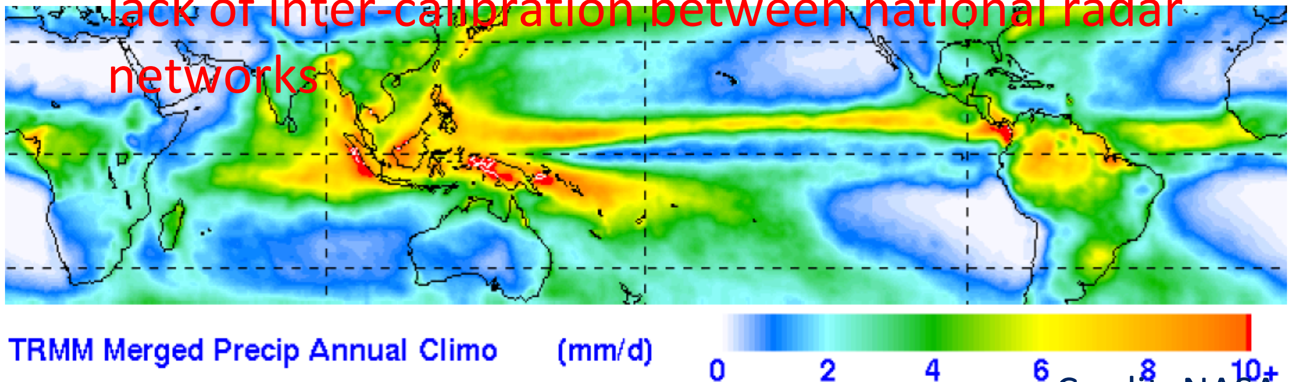


Radars: Excellent space and time resolution; real time

Not available everywhere

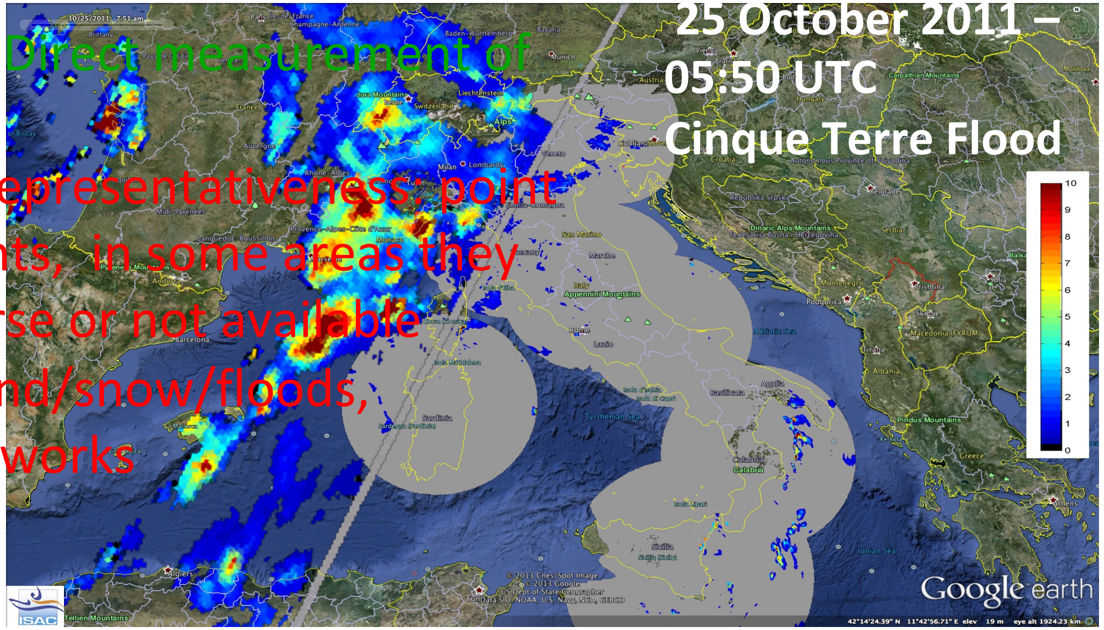
Estimate depends upon Z-R relationship and calibration

Correction for: Attenuation; Beam blocking; viewing geometry; DSD assumption; snowfall; lack of inter-calibration between national radar networks



Credit: NASA

First TRMM satellite Rainfall Global Climatology 1998-2000



Italian Radar Network Mosaic (DPC)+
Rainfall rate retrieval
SSMIS overpass at 5:50 UTC

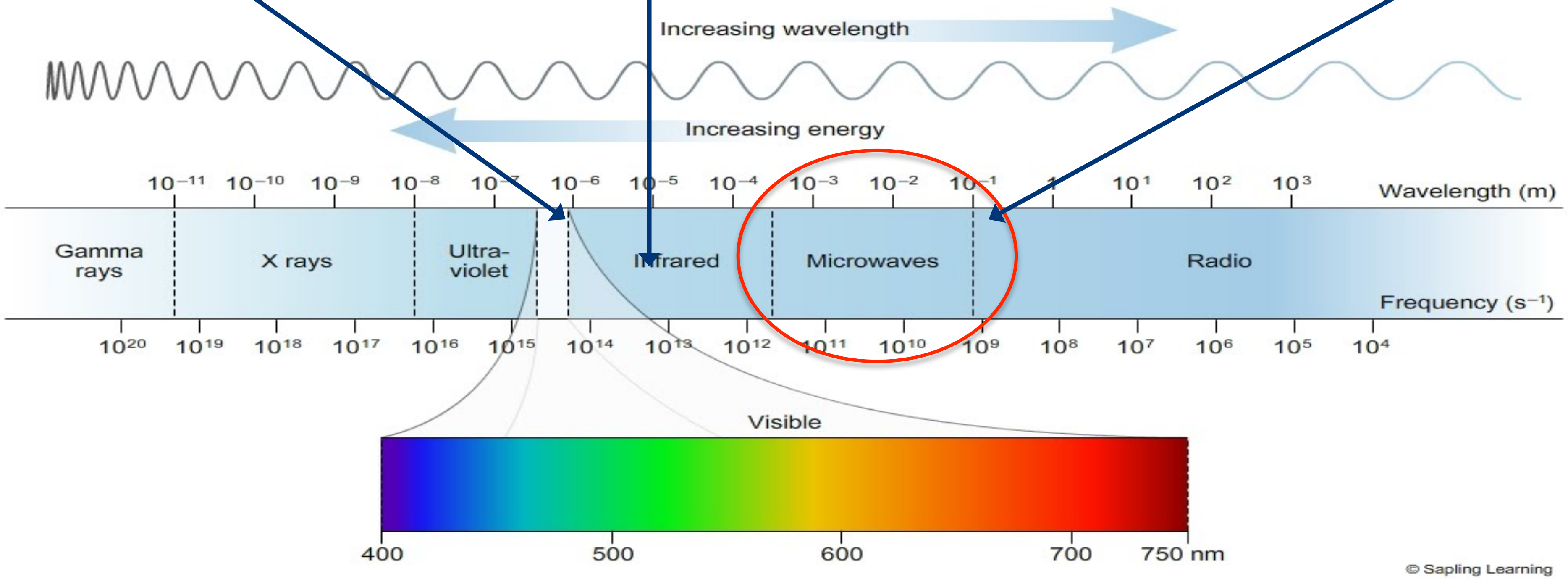
Satellite-based remote sensing of precipitation:
Global, provides precipitation at different temporal/spatial scales but…
It is a based on a very complex retrieval process

Electromagnetic Spectrum Utilized For Remote Sensing of Precipitation

VIS: Maximum emission from the sun (T=6000 K) is from 0.4-0.7 microns wavelength (Visible spectrum)

IR: Maximum thermal emission from the Earth (T=300 K) is in the infrared (IR) wavelengths near 11 microns

Passive Microwave (PMW) (10-200 GHz) emission is much weaker, but able to penetrate clouds and more directly "sense" rainfall.



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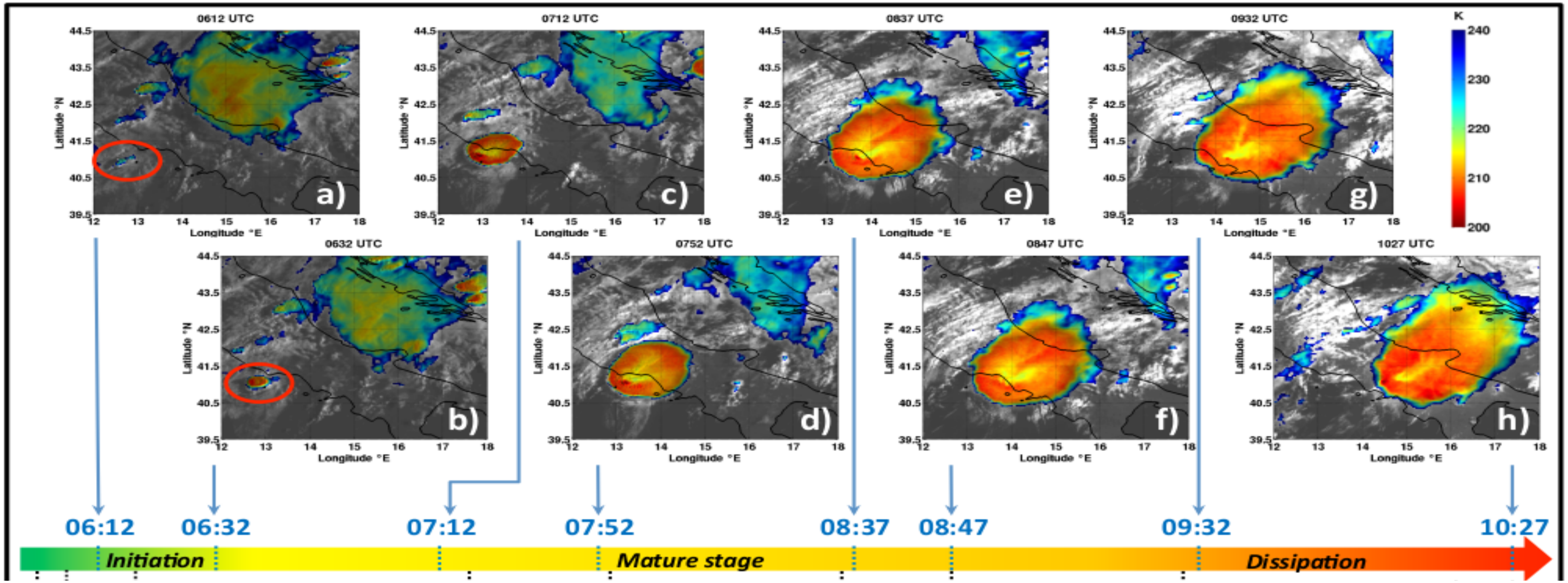
VIS/IR imagery

MSG VIS/IR composite, Naples hailstorm, 5 Sept., 2015



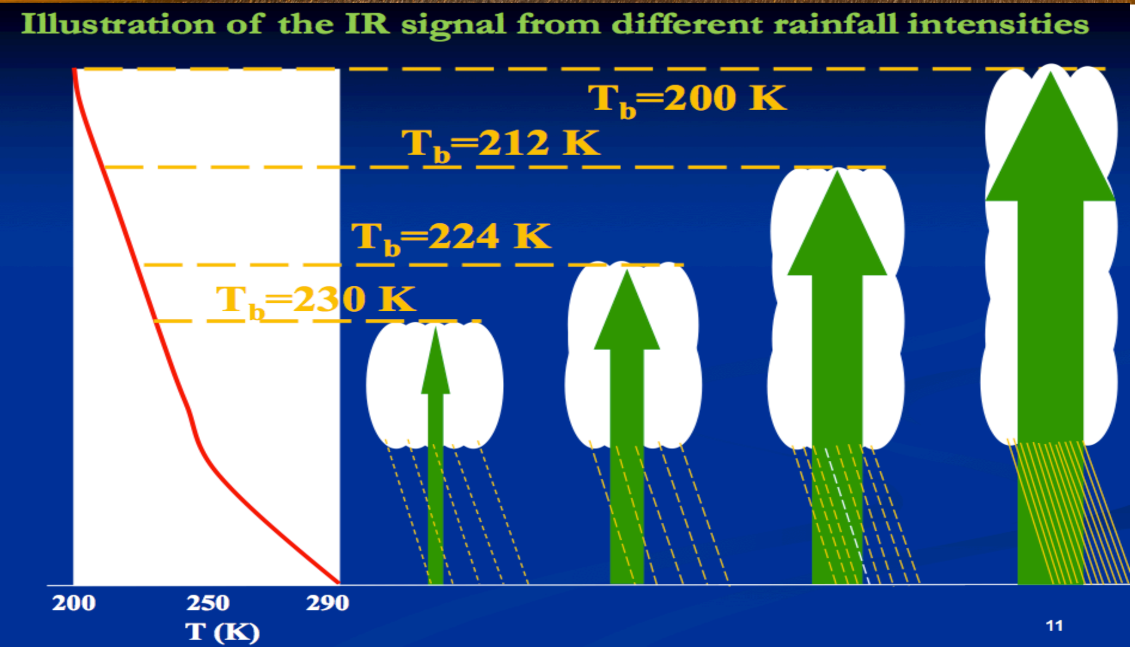
Marra et al., 2017, Atmos. Res.

Signal originates from the cloud top or a short distance below it (Rain clouds are optically thick in the VIS/IR)

IR brightness temperature *(Tb)* roughly corresponds to the cloud top T

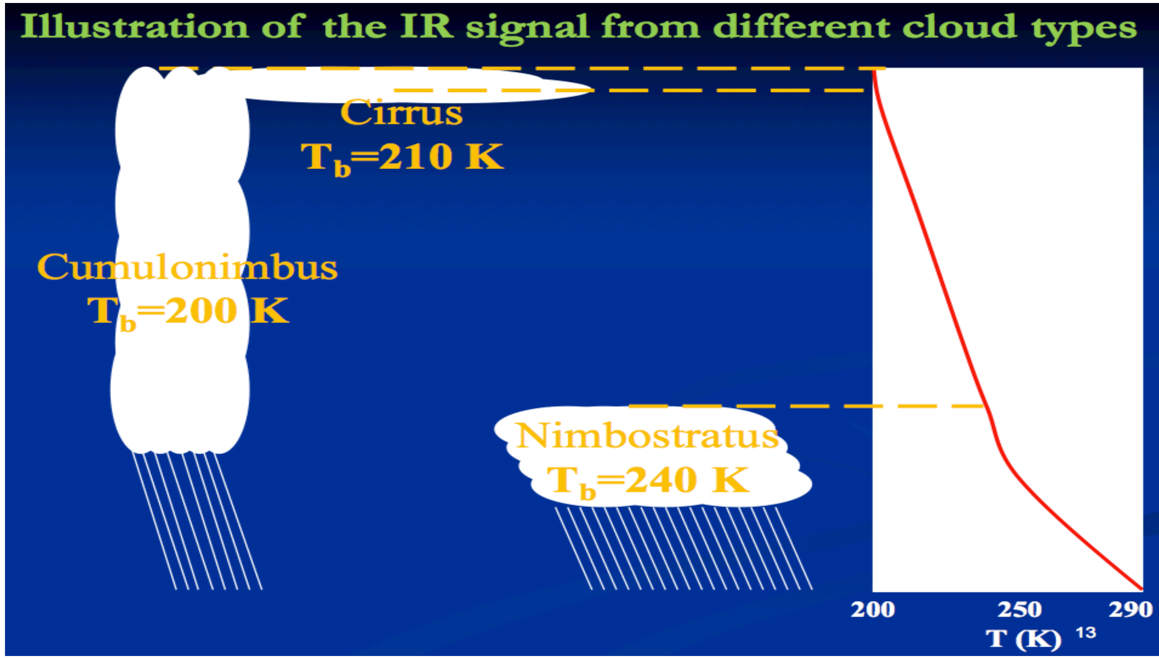
Strong signal in VIS/IR, allows to monitor from geostationary orbit (GEO) (i.e., every 5-15 min), and at very fine spatial resolution (0.5-1 km VIS, 2-5 km IR)

VIS/IR imagery and precipitation



IR Assumption:
Colder in IR (deeper) -> heavy rain

Reasonable assumption for convective clouds



Poor assumption for

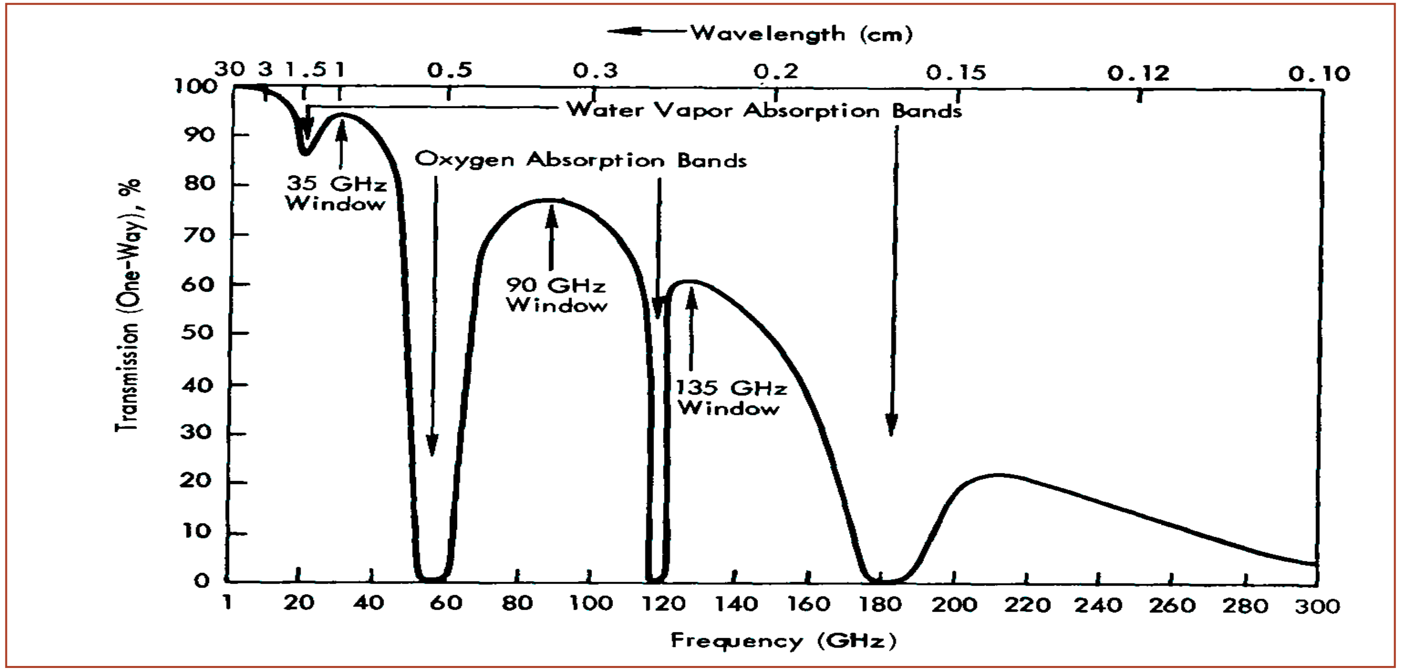
- stratiform clouds (warm, but sometimes with significant rainfall)
- cirrus clouds (cold, but rain-free)

VIS/IR cloud detection and classification is very useful to better constrain precipitation retrieval

Credit: Kuligowski 8° IPWG Workshop

MW radiometry

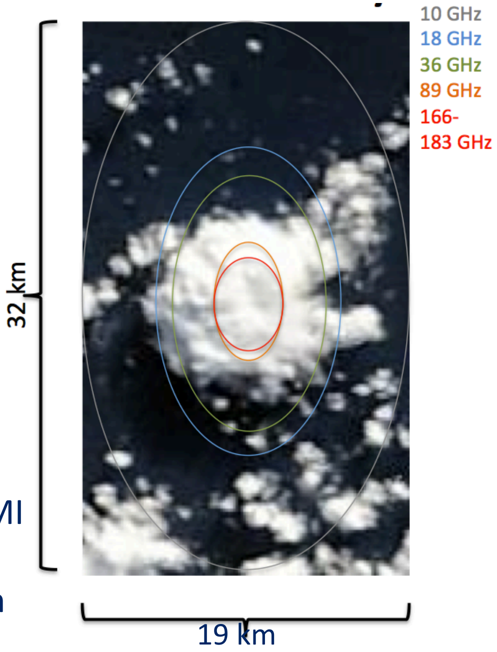
Clear-sky Zenith Microwave Transmittance



Percentage trasmission of surface emitted radiation through the Earth's atmosphere along the vertical direction, under clear-sky conditions. *[Adapted from Ulaby et al, 1981]*

Frequency range for precipitation: 10-200 GHz
Wavelength 3 - 0.1 cm
Typical precipitation sizes:
Raindrops (0.01-0.8 cm) Snowflakes (0.1-2 cm)

- Angular resolution is diffraction limited
- $\sin(\theta) = \lambda/d$ (d = antenna size)
- Low orbits allow higher spatial resolution



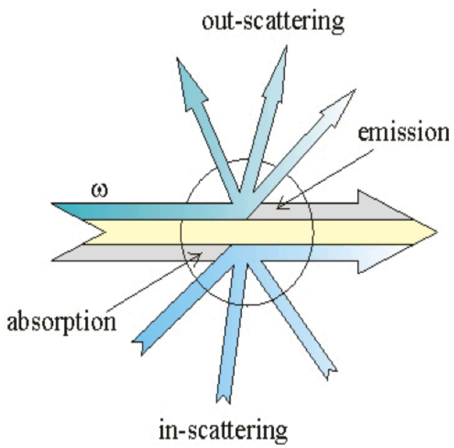
Imager IFOV: GMI
d = 1.2 m
Altitude: 407 km

Weak energy source: only on LEO satellites (low temporal sampling), low spatial resolution (5-50 km)

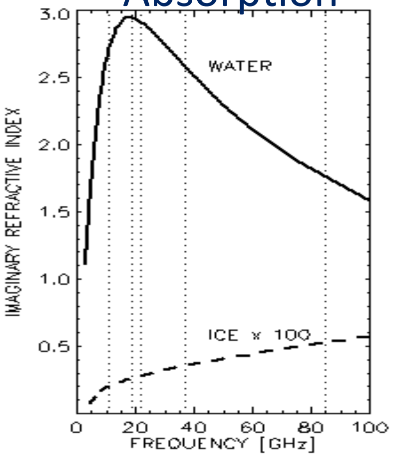
In PMW radiometry the field of view must be large to detect enough energy to record a signal.

MW radiometry and precipitation

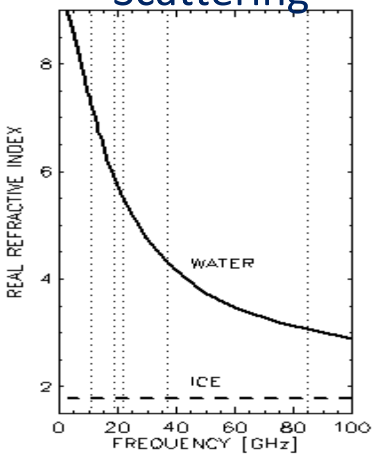
Microwave (MW) radiation emitted by the **Earth's surface** interacts with gases (oxygen and water vapour) and **liquid and solid hydrometeors** within the clouds. Interaction depends on optical properties: **scattering geometry and absorption (emission)**

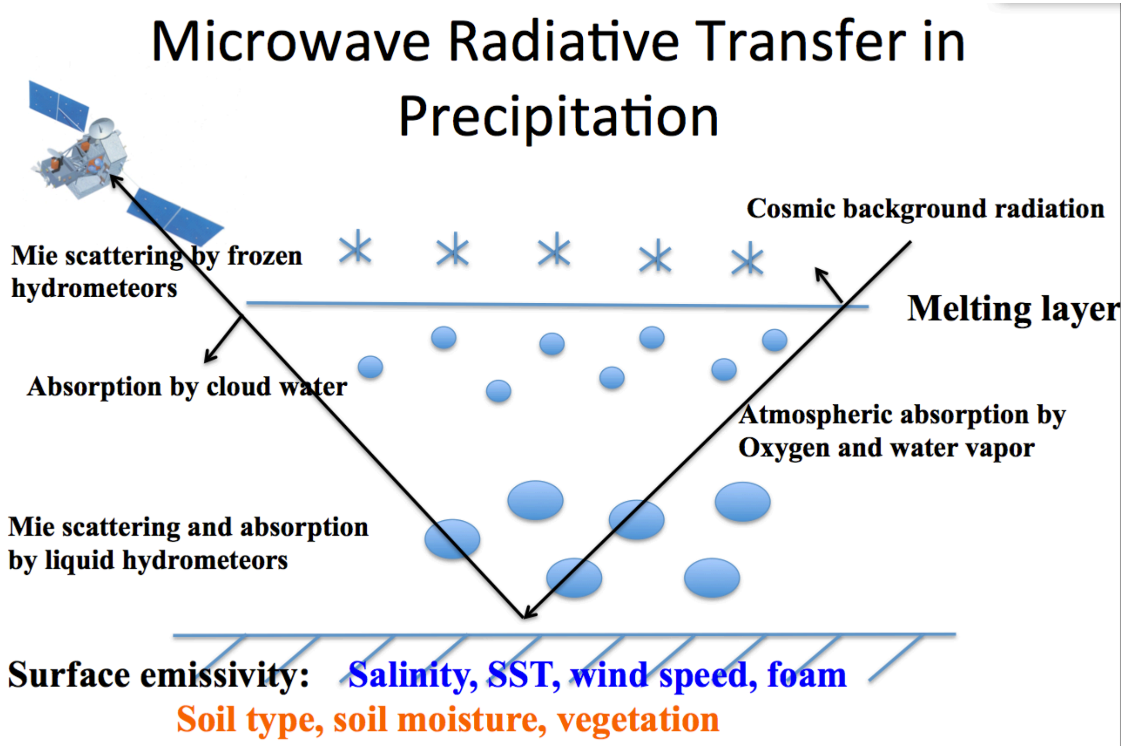


Absorption



Scattering



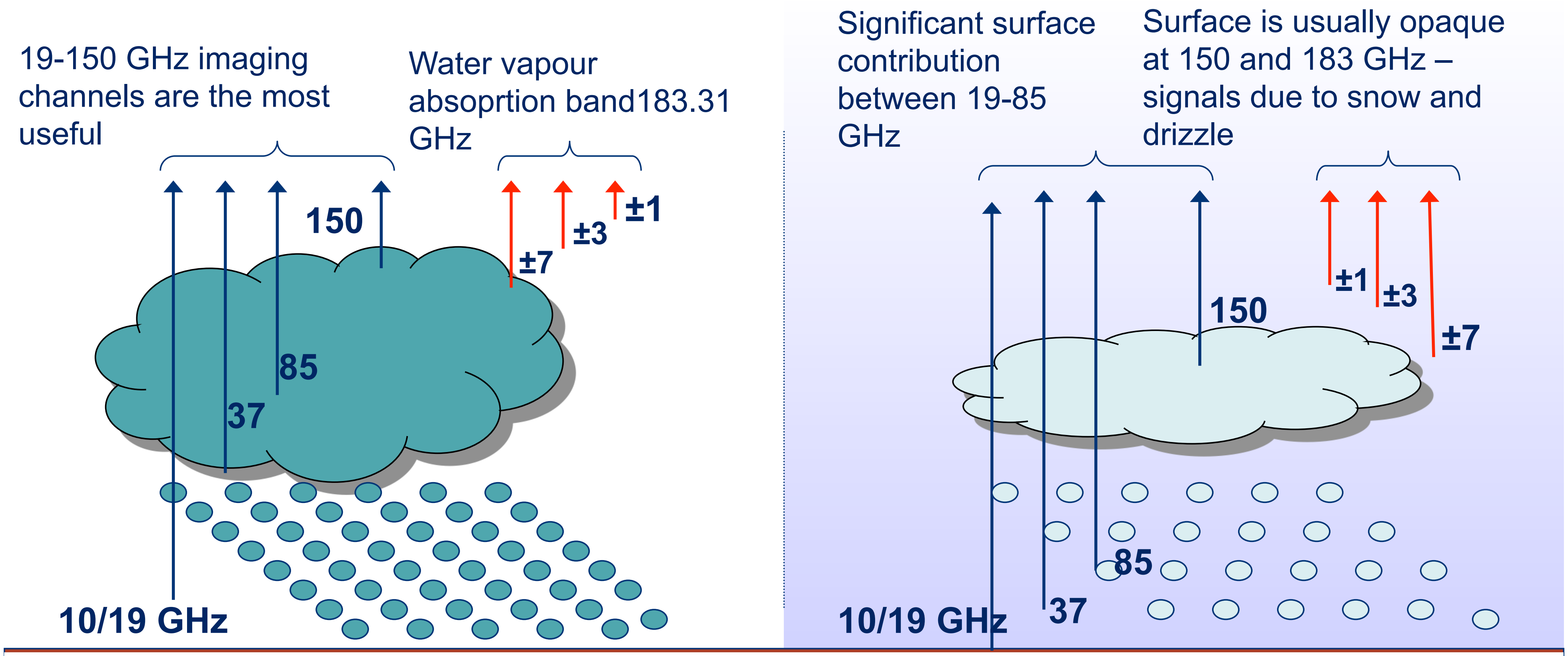


Credit: J. Munchak 8° IPWG workshop

Parameters governing optical properties:
(1) The wavelength (λ) of the incident radiation
(2) The size of the scattering particle and shape
(3) The complex index of refraction (liquid/ice fraction)

The radiation detected (or Tb) depends on several elements: surf. emissivity and T, air moisture, 3-D distribution of hydrometeors, microphysics processes (optical properties), viewing geometry and spatial resolution

MW radiometry and precipitation



Tropical Rainfall
Convective clouds with ice region above rain

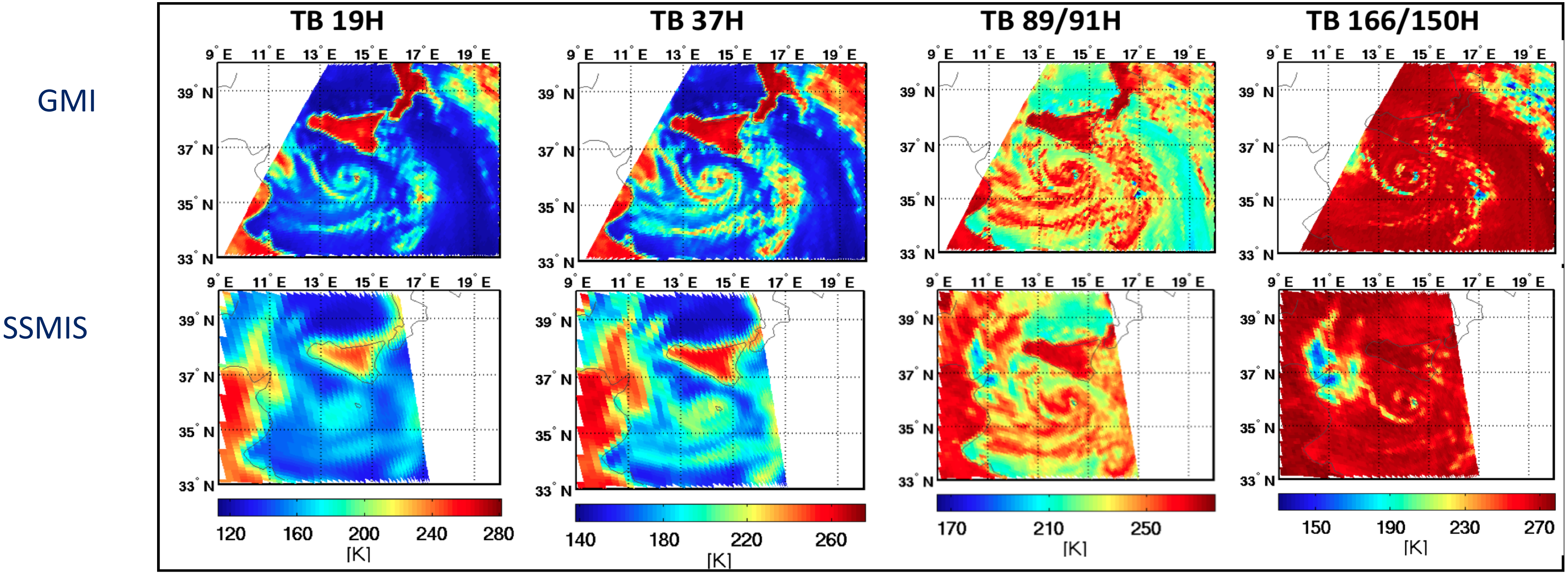
Higher Latitude Drizzle/Snowfall
Lower altitude clouds, mainly non-convective

Depending on frequency, cloud microphysical structure, and air moisture, the signal reaching the radiometer originates from different parts within the cloud.

Credit: V. Levizzani

Examples of Passive Microwave Measurements

Medicane Qendresa - GMI and SSMIS overpass – November 7, 2014 1600 UTC

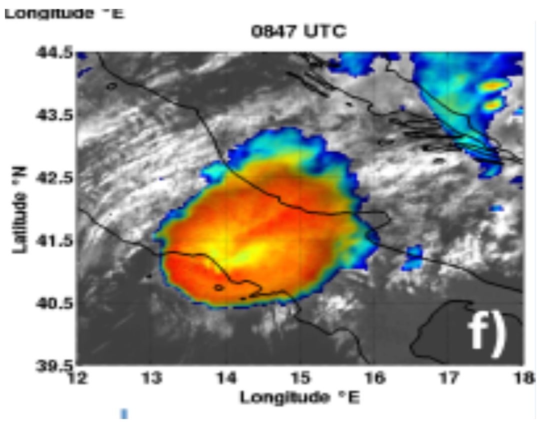


Effect of higher spatial resolution of GMI

(IFOV size 11x18 km^2 at 19 GHz, and 4x7 km^2 above 89 GHz)

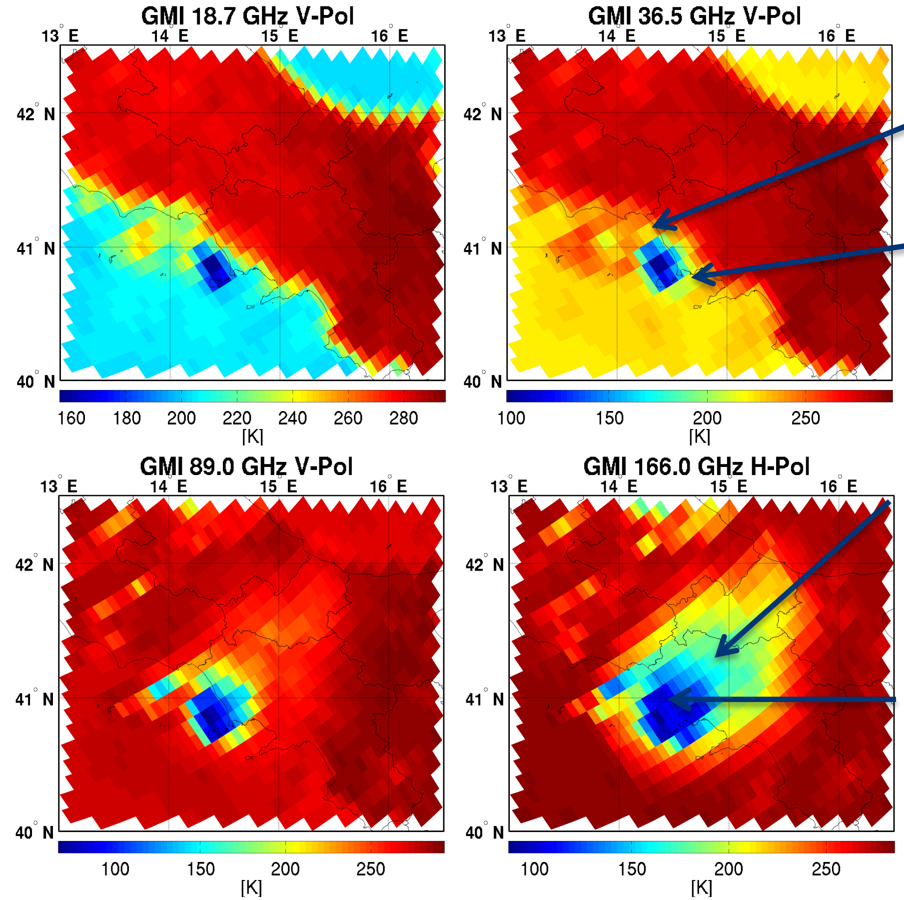
SSMIS spatial resolution is three times lower

Examples of Passive Microwave Measurements



VIS/IR
8:47 UTC

GMI overpass 5 Sept. 2015 8:47 UTC



rainfall

hail

Anvil

Convective core

Marra et al., 2017 Atmos. Res.

MW radiometers spectral signature (TBs behaviour in the different channels) allows to characterize the microphysical structure of the precipitation

Extremely intense and deep convective core appears as area of low TBs also at low frequency (scattering by large hail)

High-frequency channels are sensitive to the different ice microphysics in the core and in the anvil

PMW precipitation retrieval basic mechanisms

Emission: **liquid water (rain and cloud droplets) in clouds emits radiation (emission/absorption for ice particles is negligible). At lower frequencies (< 30 GHz) liquid precipitation appears as a radiatively warmer area (higher TBs) against a cold background (i.e. oceans)**

- **Strength**: effect visible also for clouds with little or no ice
- **Weakness**: must know terrestrial radiances without cloud beforehand; generally applicable over oceans but not over land

Scattering: **Both liquid (rain) and solid hydrometeors scatter the radiation. Scattering by ice increases with frequency; clouds scatters (warm) terrestrial radiation downward, producing cold areas in imagery**.

- **Strength**: use of high-frequency channels (higher spatial resolution), effect visible over both land and ocean
- **Weakness**: indirect relation to surface precipitation;

Low precipitation-related TB signal for:

- Orographic precipitation (with warm-topped clouds); warm rain;
- Light precipitation at high latitudes (low moisture and temperature conditions)
- Snowfall and/or with presence of snow/ice at the ground

MW or IR?

LEO MW vs. GEO VIS/IR

LEO MW

Advantages:

Samples remote (polar) regions
Consistent measurement system
More physically based, more accurate than VIS/IR estimates

Disadvantages:

- Poorer time and space resolution (~3 hr, ~5-50 km)
- Not a direct measurement of **surface** precipitation (over land)
- Different radiometers' characteristics (e.g. imagers vs. sounders)
- *Underestimates rainfall from warm-top clouds over land (i.e., orographic rain)*

GEO VIS/IR

Advantages:

Good space and time resolution
Observations in near real time
Samples oceans and remote regions
Consistent measurement system

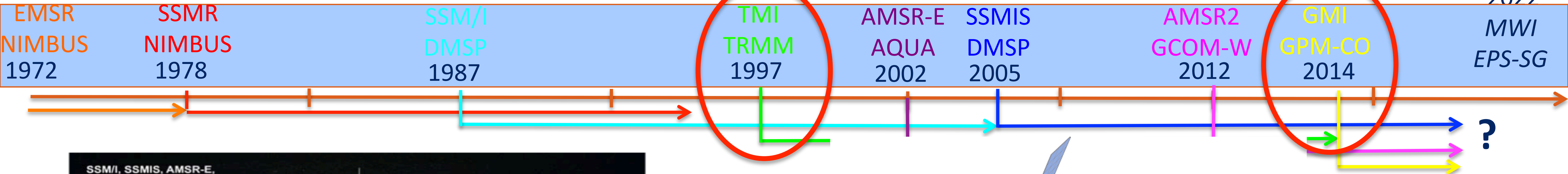
Disadvantages:

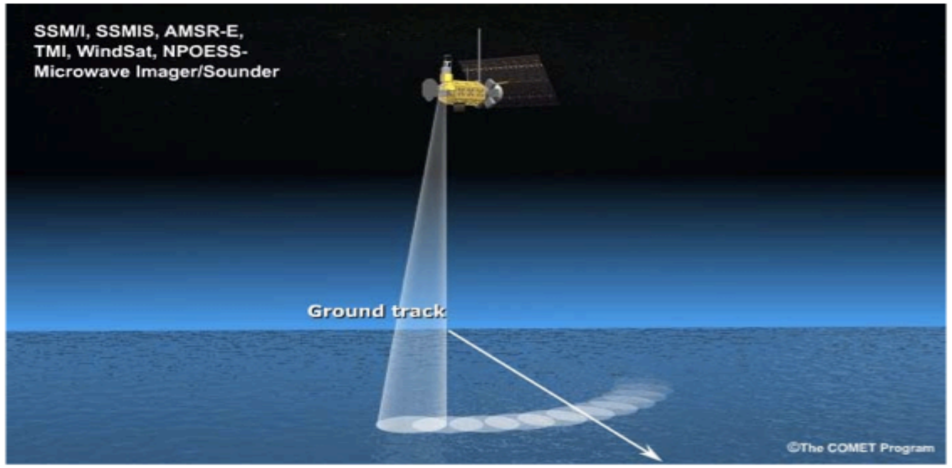
- Does not sample remote (polar) regions
- Measures cloud-top properties instead of rain
- *May mistake cirrus for rain clouds*
- *Does not capture rain from warm clouds*

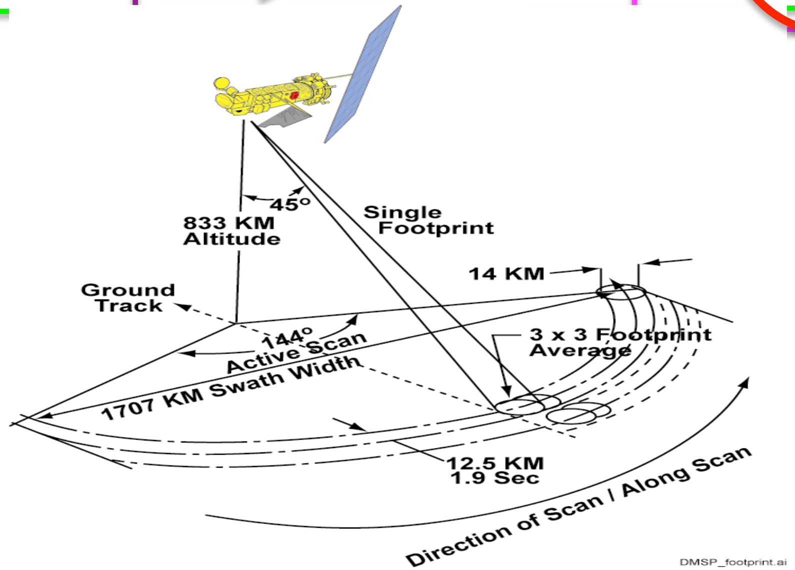
Most used approach for several applications is to combine MW-based precipitation retrievals with GEO IR osbervations, (e.g., NASA IMERG, JAXA GSMaP, NOAA CMORPH, H SAF)

MW Radiometry History- Imagers

Imagers





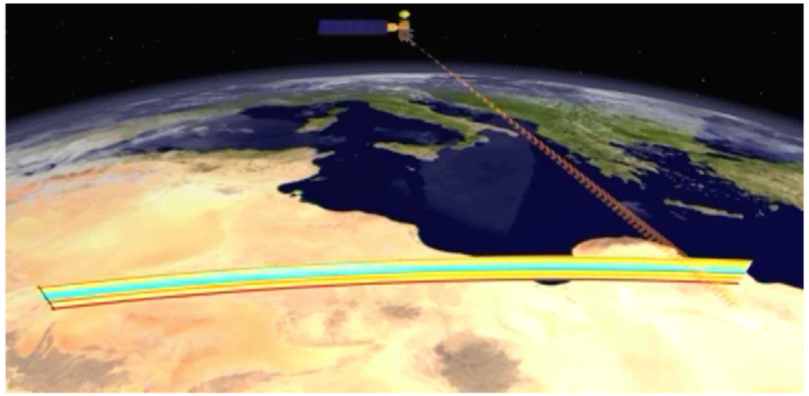


900-1800 km swath width

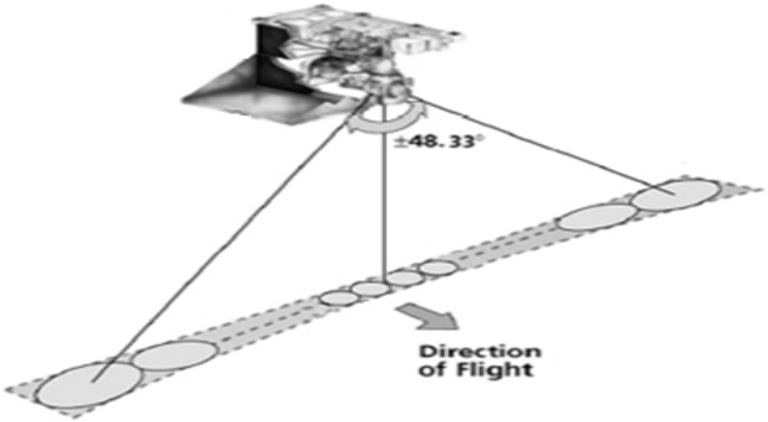
- Constant incidence angle
- Primarily window channels (low K_{abs})
- Examples: GMI, AMSR2, SSMIS
- Future: MWI, ICI

IFOV: frequency-dependent (5-50 km)
Sampling distance 5-12.5 km
Frequency range: 10-190 GHz
V and H polarization channels

MW Radiometry History - Sounders



Scan geometry



Swath width 2200-2600 km

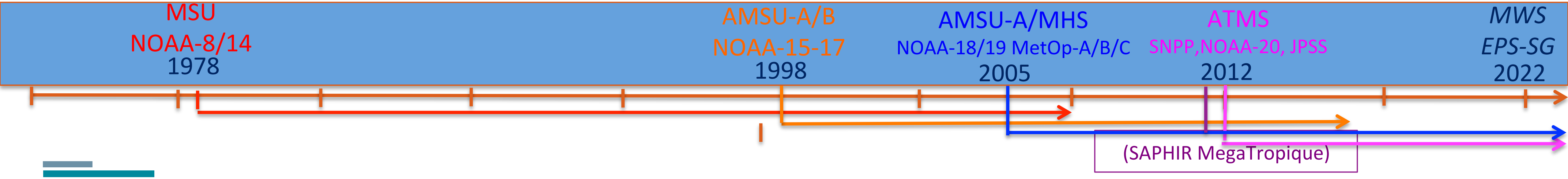
- Variable incidence angle
- Primarily sounding channels (high K_{abs})
- Examples: AMSU-A/B, MHS, ATMS, SAPHIR
- Future: MWS

IFOV: 16 km (MHS/ATMS) at nadir (decreasing towards the edge of the scan

Sampling distance 16 km

Frequency range: usually 89-190 GHz

Sounders



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PMW retrieval history

Imagers

EMSR NIMBUS 1972	SSMR NIMBUS 1978	SSM/I DMSP 1987	TMI TRMM 1997	AMSR-E AQUA 2002	SSMIS DMSP 2005	AMSR2 GCOM-W 2012	GMI GPM-CO 2014	*MWI EPS-SG* 2022

First emission-based, regression (ocean)

Emission-based, regression (ocean) development; First scattering–based approaches

Multi-channel Physcially-based approaches; SI, PCT, PCA, regression-based approaches; **CRM-based Bayesian schemes**

Advancement of all apprache; first satellite-based **observational databases** (TRMM PR)

New methods and scattering tables to exploit high frequency channels; first snowfall retrieval approaches

?

GPM constellation concept (*improved* algorithms **for *imagers and sounders***); observational databases (DPR, CPR); **ML approaches for snowfall**

Total rain/cloud water (ocean); first climatology oceanic precipitation 1978-1991

SI, regression, 1-D Optimal Estimation (OE), Bayesian, **machine learning approaches**; snowfall retrieval algorithms, exploitation of high-frequency sounding channels

Sounders

MSU NOAA-8/14 1978	AMSU-A/B NOAA-15-17 1998	AMSU-A/MHS NOAA-18/19 MetOp-A/B/C 2005	ATMS SNPP,NOAA-20, JPSS 2012	*MWS EPS-SG* 2022

(SAPHIR
R&D MegaTropique)

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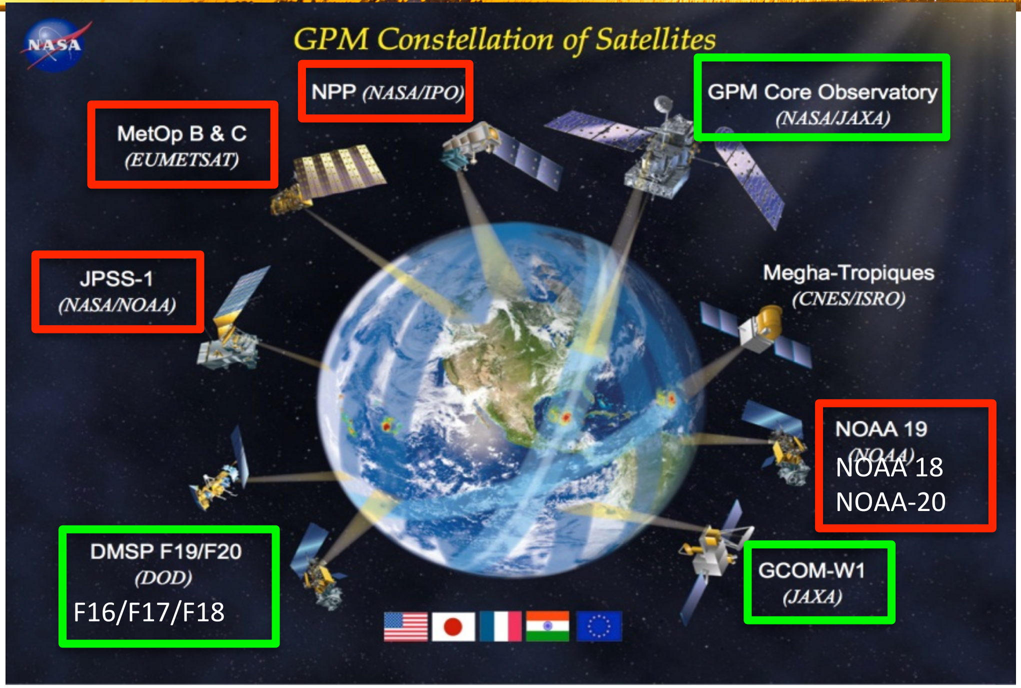
The GPM mission concept

https://pmm.nasa.gov/gpm

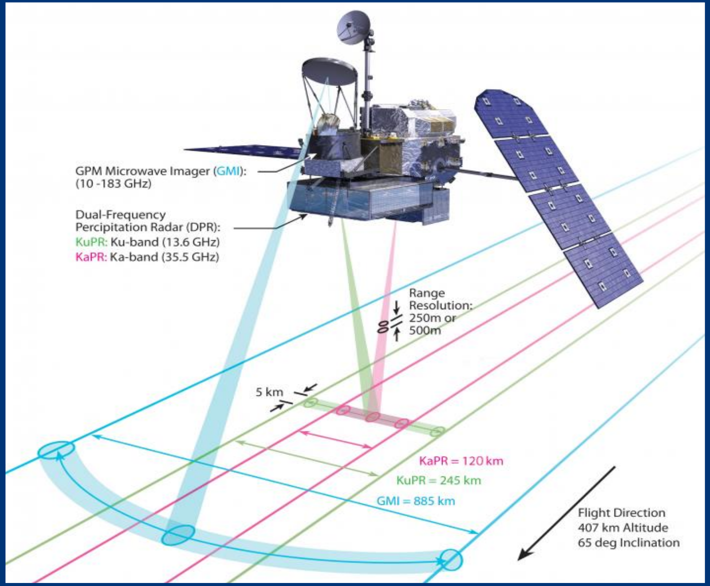


- *International effort* with 12 LEO satellites equipped with 6 different radiometers, 1 dual-frequency precipitation radar (+ CloudSat)
- 3-h global coverage (1.5-h over the Mediterranean region, on average);

THE NASA/JAXA GPM CORE OBSERVATORY

GPM Microwave Imager (GMI): 13 precipitation sensing channels (10-183 GHz) with the highest spatial resolution available (5-30 km);

Dual-frequency Precipitation Radar (DPR) (Ku and Ka band)



New opportunities for remote sensing of precipitation:

- ***Improved global* precipitation products** (rainfall and snowfall);
- **Increased use of satellite products for several applications (i.e., hydrology)**
- **Monitoring and analysis of extreme events** (3D structure of precipitation, understand processes, improve forecast)

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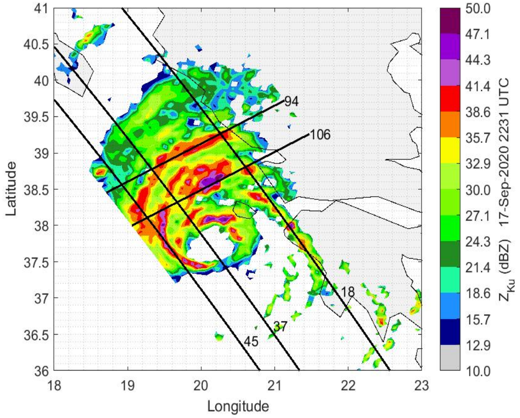
GPM DPR observations and PMW retrieval

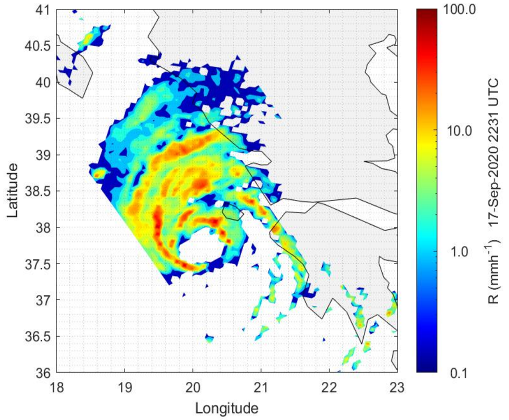
Medicane Ianos – GPM-DPR 17 November 2020 22:28 UTC

First GPM DPR overpass of a Medicane during its mature phase

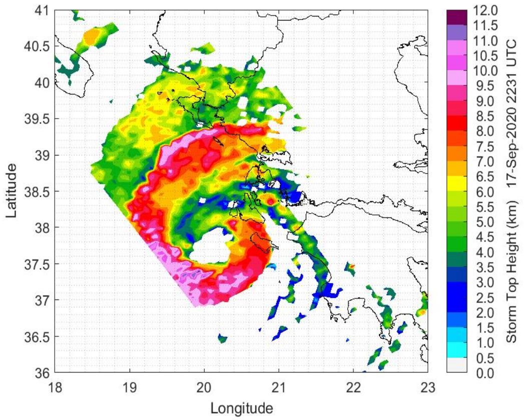
Z Ku



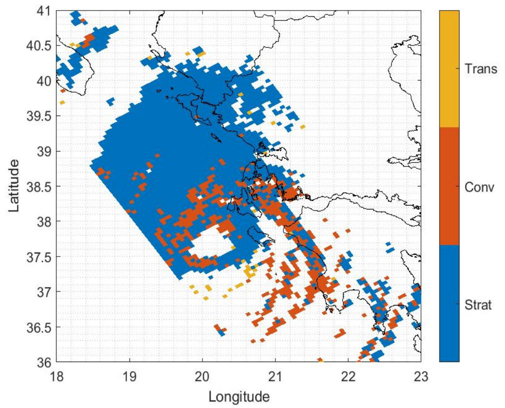
Rain Rate



Cloud Top height



Precipitation Classification

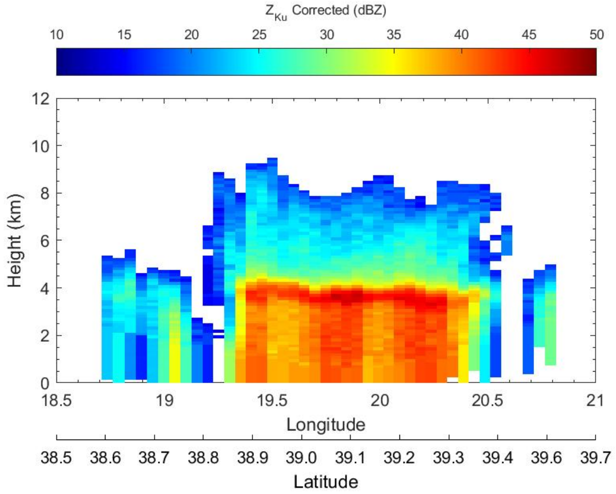


GPM DPR-based products and co-located PMW measurements allow to build near-global observational datasets to be used in PMW retrieval algorithms

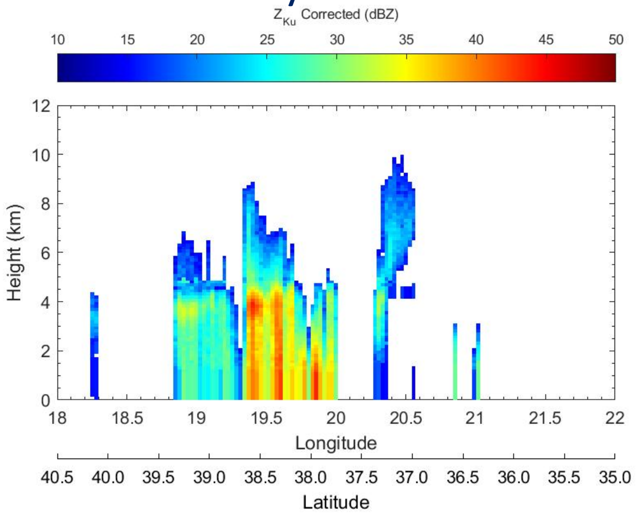
Pros: near-global coverage (65°N/S), consistency around the globe (incl. oceans)

Cons: DPR sensing capabilities (e.g., low sensitivity for very light precip. and snowfall), uncertainties of DPR-based products

Scan line 94



Ray 37



MW/IR GPM Global Products

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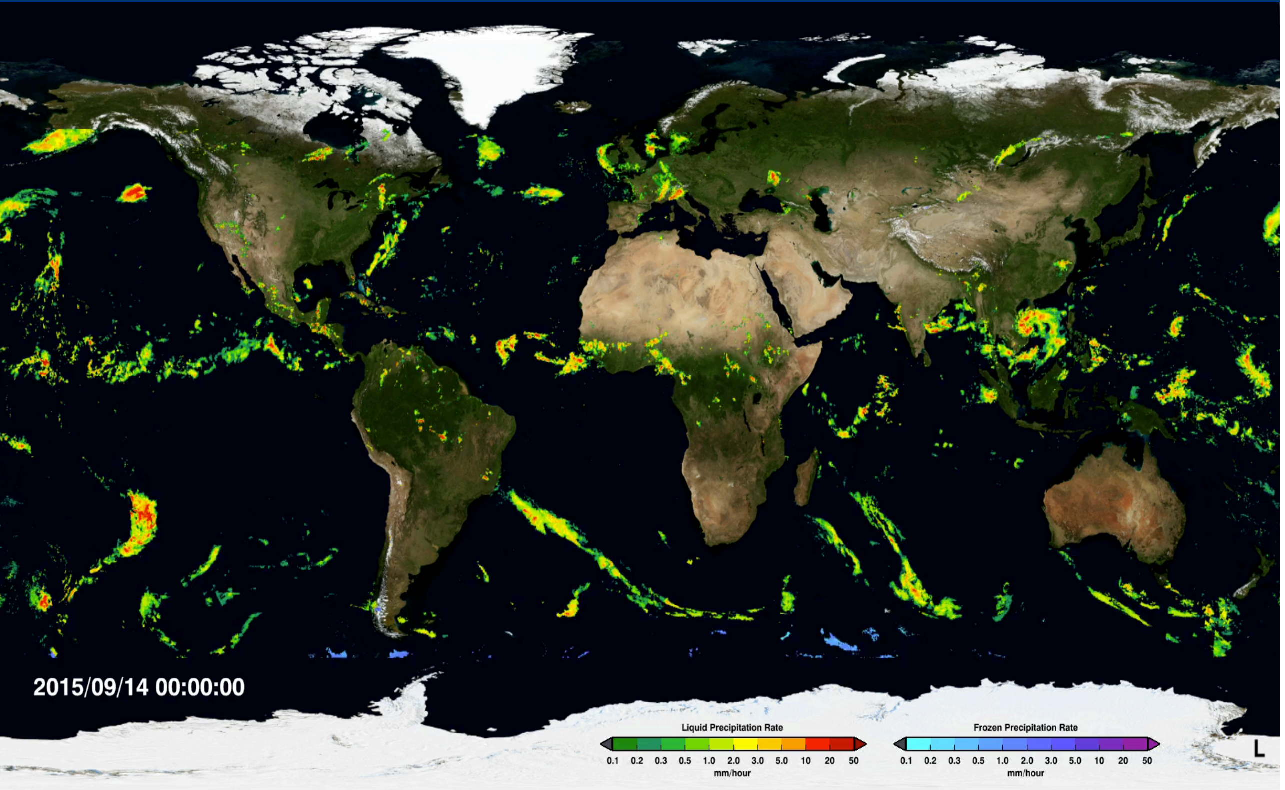
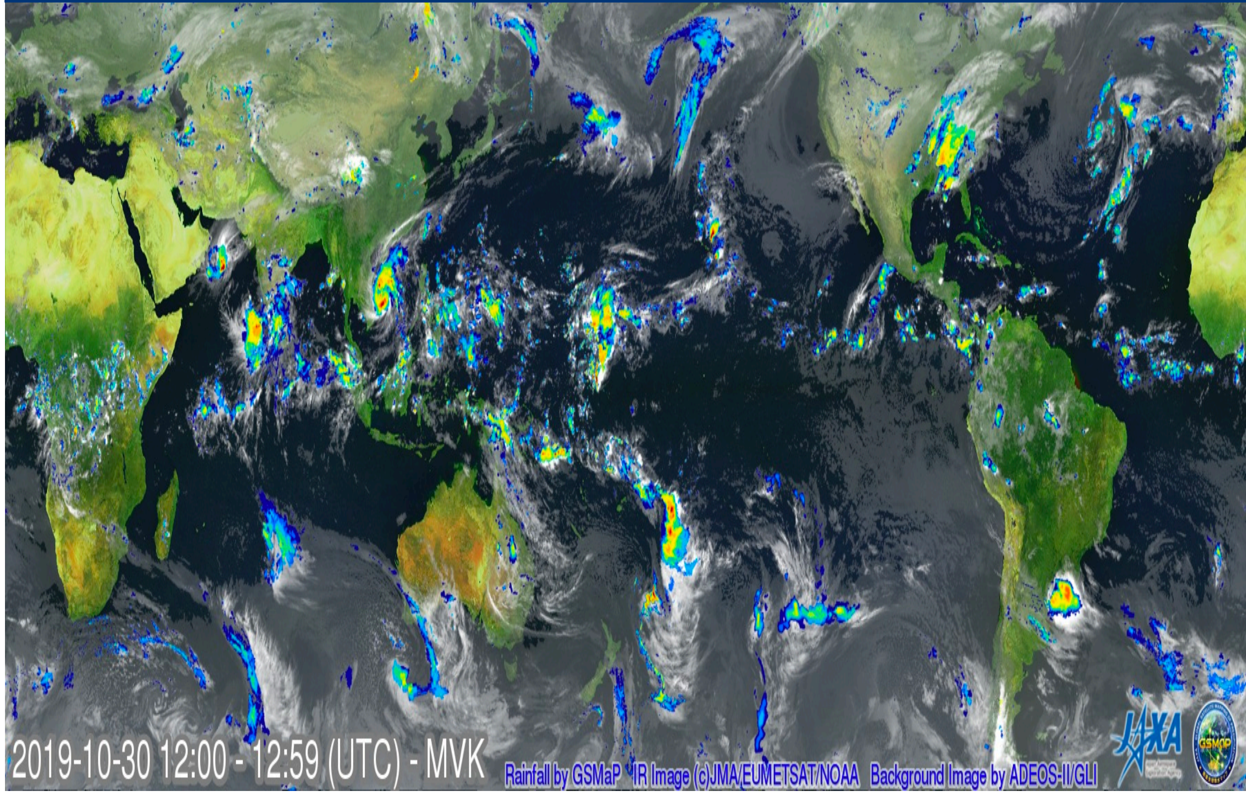
NASA GPM IMERG (https://gpm.nasa.gov/data/imerg)



Rainfall rate (mm/h) Coverage 90°N/S Grid resolution: 0.1°x0.1°
Temporal resolution 0.5 h (Credit, NASA PMM, Dr. Huffman)
Latency: Early run 4 h Final run 3-4 months

JAXA GSMaP (https://sharaku.eorc.jaxa.jp/GSMaP/guide.html)



Rainfall rate (mm/h) Coverage: 60°N/S Grid Resolution: 0.1°x0.1
Temporal resolution: 1 h Updated every 30 m
Latency 4 h

EUMETSAT H SAF and GPM

H SAF is the most important effort in Europe dedicated to provide satellite precipitation products, i.e., quantitative precipitation estimation, for operational hydrology and water management applications

The advent of GPM mission (March 2014) has offered new opportunities and challenges for H SAF PMW precipitation product development and validation

No-cost scientific collaboration proposal approved by the NASA PMM Research Program and endorsed by EUMETSAT (since 2014, ongoing)

"H-SAF and GPM: precipitation algorithm development and validation activity"

•***precipitation retrieval algorithm development***, through a fruitful interaction on several critical aspects of interest both to H SAF and GPM; ***Scientific coordinator: Giulia Panegrossi (ISAC-CNR)***

•***validation activity***, through the connection between the well established H-SAF product validation and hydrological validation programs and the Ground Validation/Calibration activity of GPM; ***Scientific Coordinator: Silvia Puca (DPC)***

H SAF Precipitation Concept

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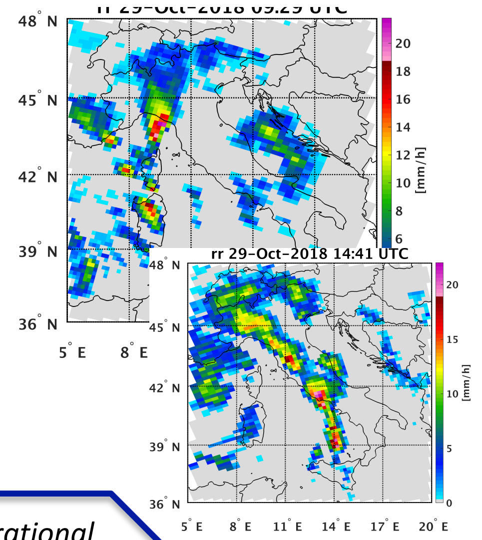
CDOP-2 H SAF Area → **CDOP-3** MSG Full Disk → **CDOP-4** Global

Exploitation of GPM constellation

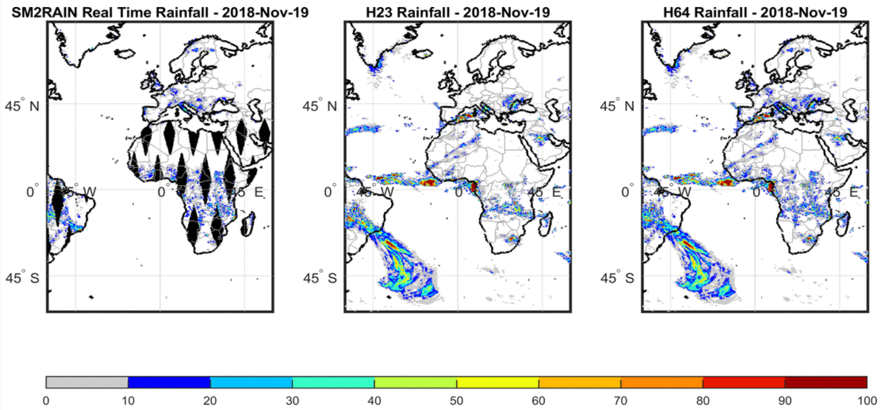
PMW Level 2 NRT **products/auxiliary modules**: Exploitation of **all current and future PMW radiometers** (conically and cross-track scanning) on board LEO satellites (Bayesian and **Machine Learning approaches)**

29 Oct 2018 P-IN-MHS (H02B)

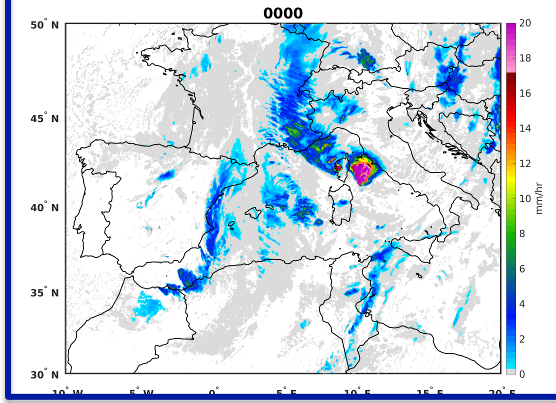


H SAF Soil Moisture-based product (SM2RAIN)

MW-based Level 3 gridded products for hydrological and water management applications (Ciabatta et al., 2017)



MW/IR NRT precipitation products for operational hydrology and precipitation monitoring (for MSG and MTG)



P-IN-SEVIRI (H03) HSAF Product:
MW/IR Rapid Update Technique

- Spatial Resolution: SEVIRI IR
- Temporal resolution: 15 min
- Available in NRT (latency 15-20 min)

H SAF PMW Level 2 Precipitation rate products: exploitation of GPM constellation

Acronym (Product ID) (Instrument)	Product Description	Algorithm	Reference	Currently available satellites	Status/ Availability
P-IN-SSMIS (H01) **(SSMIS)**	Precipitation rate at ground by MW **conical scanner SSMIS** (MSG full disk)	**Physically-based Bayesian (CDRD)** **Cloud-radiation model a priori database**	**Casella et al., 2013, IEEE TGRS** **Sanò et al., 2013 IEEE TGRS**	**DMSP F16/F17/F18**	**Operational**
P-IN-MHS (H02B) **(AMSU/MHS)**	Precipitation rate at ground by MW **cross-track scanners AMSU/MHS** (MSG full disk)	**Neural Network (PNPR)** **Cloud-radiation model training database**	**Sanò et al., 2015 AMT**	**MetOp-B/C** **NOAA-18/19**	**Operational**
P-IN-ATMS (H18) **(ATMS)**	Precipitation rate at ground by MW **cross-track scanners ATMS** (MSG full disk)	**Neural Network (PNPR)** **Cloud-radiation model training database**	**Sanò et al., 2016 AMT**	**Suomi NPP** **NOAA-20** **(JPSS series)**	**Operational**
P-IN-AMSR2 **(H-AUX-17)** **(AMSR-2)**	Precipitation rate at ground by MW **conical scanner** AMSR-2 (based on **GMI/DPR** Observational Dataset) (MSG full disk)	**Physically-based Bayesian CDRD** **GPM-based observational a priori database**	**Casella et al., 2017 IEEE JSTARS**	**GCOM W1**	**Auxiliary: Support to MW-only and MW/IR combined products**
P-IN-GMI **(H-AUX-20)** **(GMI)**	Precipitation Rate at ground by GMI – (based on **GMI/DPR** Observational Dataset) (***Global***)	**Neural Network** **GPM-based observational a priori database**	**Sanò et al., 2018, Rem. Sens.**	**GPM-CO**	**Auxiliary: Support to MW-only and MW/IR combined products**

ML techniques and future H SAF Precipitation Products

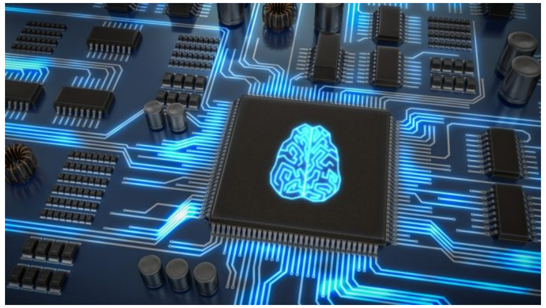
H SAF precipitation products are evolving toward massive use of *machine learning approaches* (already used since 2006, newly developed Artificial Neural Network (ANN) products since 2011)

WHY:

- Machine learning algorithms have been successfully adapted to remote sensing and rainfall applications.
- With reference to the rainfall/snowfall retrieval, this approach originates from the consideration that an exact relation between surface precipitation rate and observed multi-channel brightness temperatures is nonlinear and difficult to identify.
- Machine learning algorithms have proven to be suitable for contributing to overcome these difficulties.

WHICH ONE:

- Artificial Neural Network : used for the detection/classification/estimate of rainfall/ snow
- Convolutional Neural Network : used for the detection/classification of rainfall/snow
- Random Forest: used for the detection/classification of rainfall/snow fall
- Genetic Algorithm: used for optimization problems (i.e. the precipitation estimates)
- Gradient Boosting: used for the estimate of rainfall/snow fall
- Deep learning: is being evaluated for pattern analysis and classification



H SAF PMW precipitation Techniques

GPM-based auxiliary modules

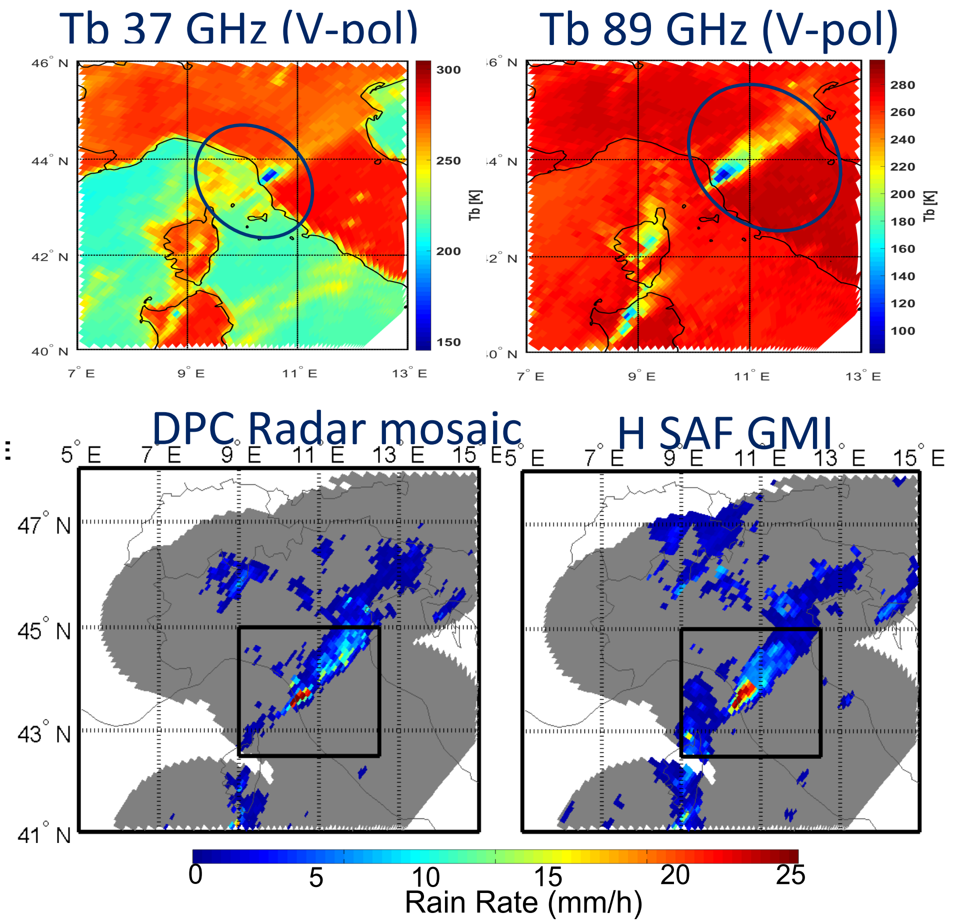
Based on PNPR Artificial Neural Network approach for the GMI conically scanning radiometer

P-IN-GMI **(auxiliary module H-AUX-20)** is based on ANN trained on an **global observational database built from GPM-CO global observations**

- DPR-based rainfall rate product is used as reference (2B-CMB product).
- Two ANN-based modules one for precip. detection and one for precip. estimation;
- New detection scheme provides different rainfall masks for different probability thresholds

A new auxiliary module for **global rainfall rate estimates from AMSR-2** will be developed during **CDOP-4**

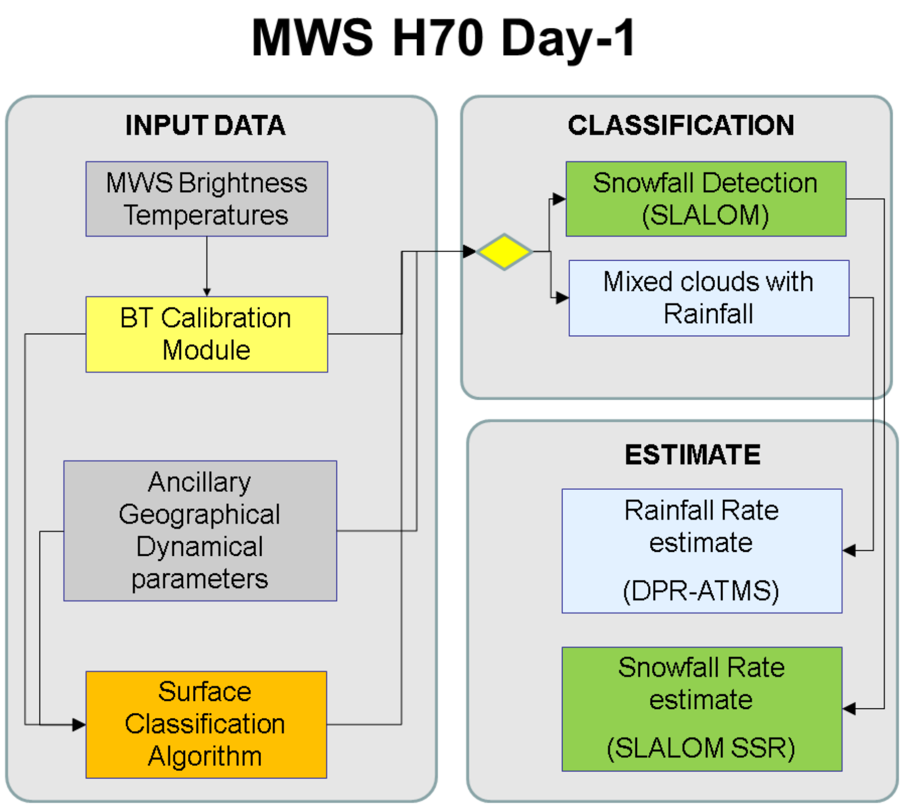
Livorno flash-flood 9-10 September 2017

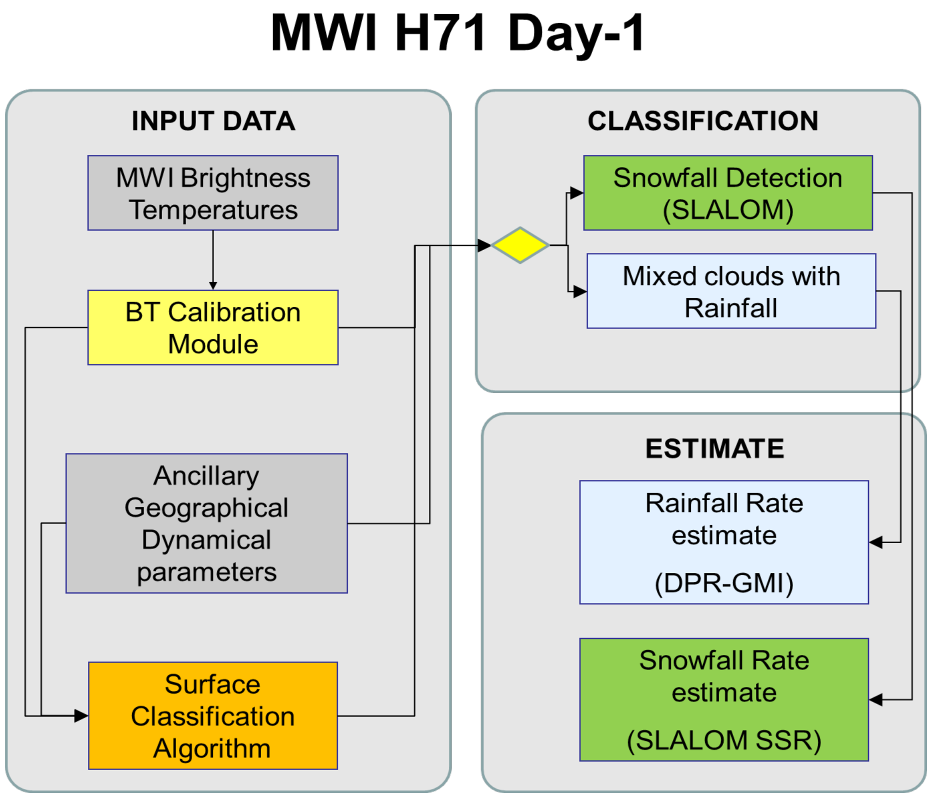


Sanò et al. 2018, Remote Sens.

EPS-SG global ML-based precipitation products

Day-1 EPS-SG Level 2 Precipitation rate products (CDOP-3**)





**** Exp. operational after EPS-SG-A/B commissioning phases, during CDOP-4**

Observational training dataset built from global coincident measurements of existing PMW radiometers (ATMS and GMI) with GPM DPR (for rainfall) and CloudSat CPR (for snowfall)

Day-2 EPS-SG products will be developed during CDOP-4 with additional ML-based dedicated modules

H SAF ML-based MW/IR product for MTG FCI

EUMETSAT H SAF

H03B – CDOP 2
- Precipitation from PMW radiometers used as calibrator
- Only IR 10.3µm channel

Rapid Update Blending Technique approach

Session 4 Wed 9 UTC

H60B/MTG day1 (H40B) – CDOP 3
- Precipitation from PMW radiometers used as calibrator
- Only IR 10.3µm channel
- NEFODINA for convective clouds

Machine Learning approach MTG Day2 product– CDOP4

Module 1
- Parallax correction
- Preliminary analysis on clouds structure
- VIS-IR channels
- Testing of different ML approaches: Deep Learning, Convolutional Neural Network, Random Forest.

Module 2

Run 1
- Precipitation rate derived from a dataset of coincidence FCI TBs-DPR/GMI RR
- Testing of different ML approaches (ML1): Gradient Boosting, Artificial Neural Network, Genetic Algorithm.

Run 2
- Calibration of Run 1 outputs with the latest PMW-based (i.e. H68) precipitation rate.
- Testing of different ML approaches (ML2): Gradient Boosting, Artificial Neural Network, Genetic Algorithm.

EUMETSAT H SAF

H SAF Precipitation Cluster

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Department of Physics and Astronomy, University of Bologna

Claudio Giorgi

Geo-K

http://hsaf.meteoam.it

(new website available soon)

Questions?

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H SAF Science Manager

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References

H SAF Products Documentation http://hsaf.meteoam.it/user-documents.php

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- Sanò P., G. Panegrossi, D. Casella, A. C. Marra, L. P. D’Adderio, J.-F. Rysman, S. Dietrich, The Passive Microwave Neural Network Precipitation Retrieval (PNPR) algorithm for the Conical Scanning GMI Radiometer, Remote Sens. 10, 1122; doi:10.3390/ rs10071122, 2018

Extra slides

Passive remote sensing: Two key terms

Brightness Temperature [K]

Tb is the temperature of a blackbody that would emit the same amount of radiation as the targeted body in a specified spectral band

$I_\lambda(T) = B_\lambda(Tb_\lambda)$

It is used to measure the Earth spectral radiance *reaching the satellite in a given direction*

Plank Function: $$B_\lambda(T) = \frac{2hc^2}{\lambda^5\left[e^{\frac{hc}{k\lambda T}} - 1\right]}$$

Rayleigh-Jeans Approximation:
hc/kλT<<1 (MW spectrum) $$B_\lambda(T) = \frac{2ckT}{\lambda^4}$$

Observed Radiance: $$I_\lambda = \varepsilon_\lambda \cdot B_\lambda(T)$$

Observed Brightness Temperature: $$Tb_\lambda \propto \varepsilon_\lambda \cdot T$$

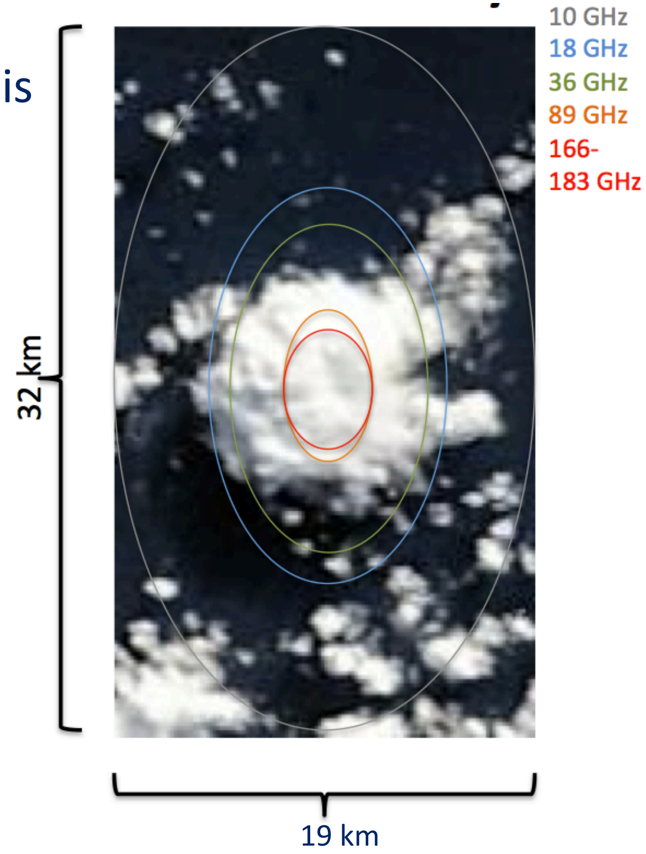
Spatial resolution

It defines the size of the smallest possible feature that can be detected (depends on IFOV)

Angular resolution is diffraction limited sin(θ) = λ/d (d = antenna size)

Low orbits allow higher spatial resolution

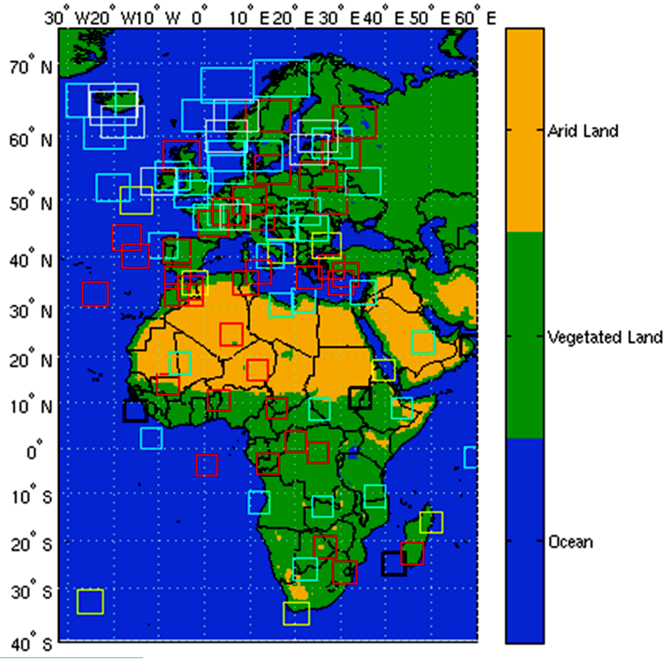
Imager IFOV: GMI
d = 1.2 m
Altitude: 407 km

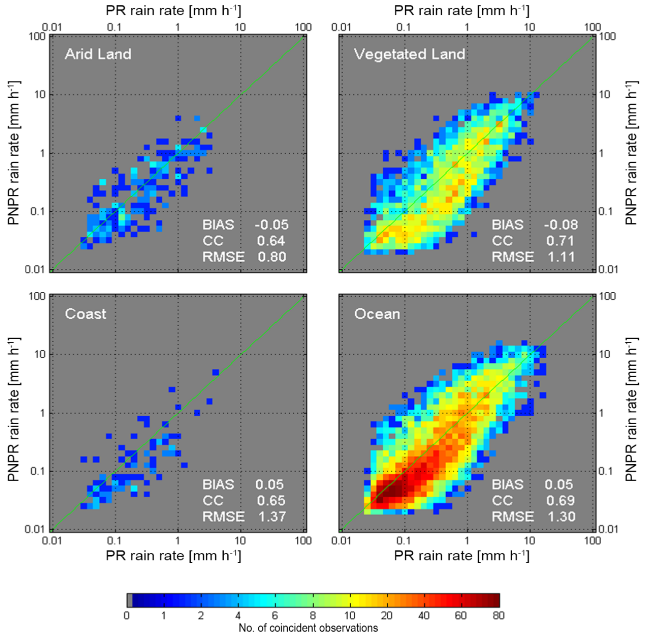


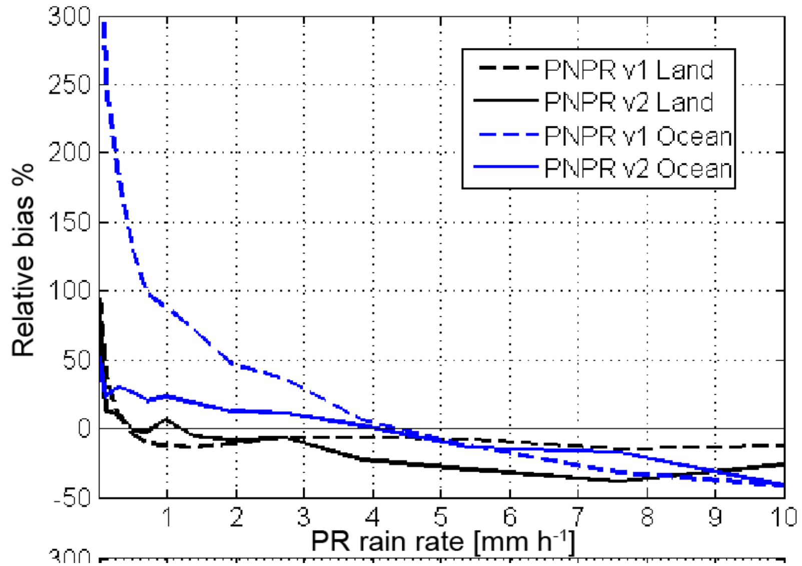
H SAF ANN-based precipitation products

Operational Products over MSG Full Disk

- **Based on PNPR Artificial Neural Network approach** used for precipitation rate retrieval algorithms for cross-track scanning radiometers
  - P-IN-MHS (H02B): PNPR algorithm for AMSU/MHS radiometers for **H SAF extended area** (60W-60°E, 60°S-75°N); it uses two ANNs (ANN-A for European Area, ANN-B for African Area) trained by the two Databases ***based on cloud-radiation model simulations***.
  - P-IN-ATMS (H18): PNPR algorithm for ATMS radiometerfor **H SAF extended area** (60W-60°E, 60°S-75°N); redesigned single ANN trained using one training database based on 94 cloud-radiation model simulations.



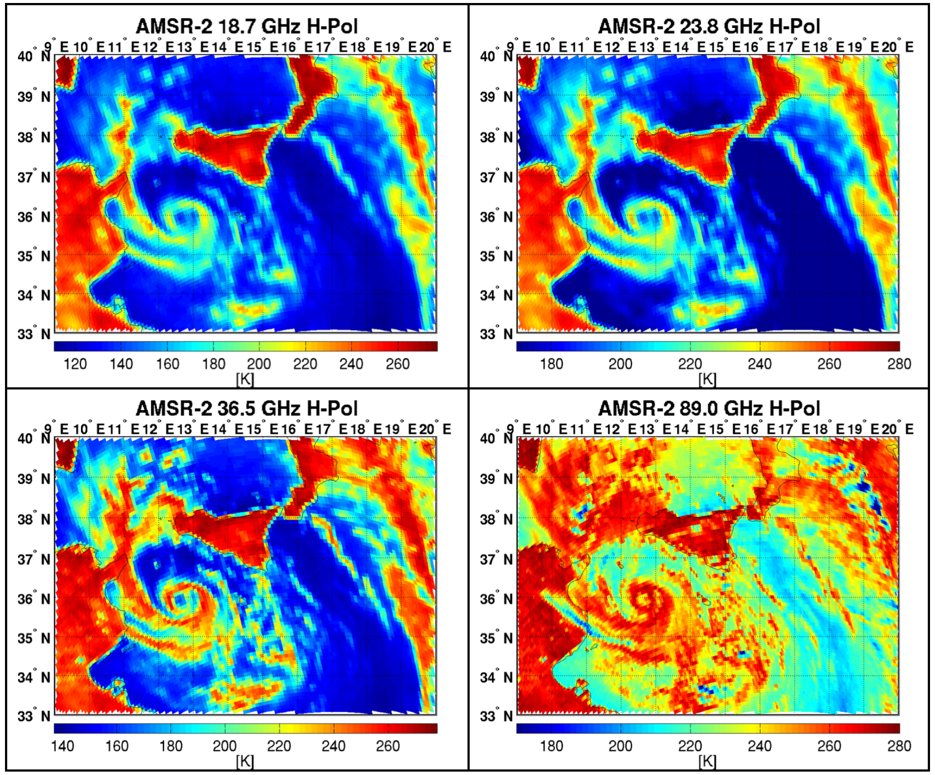




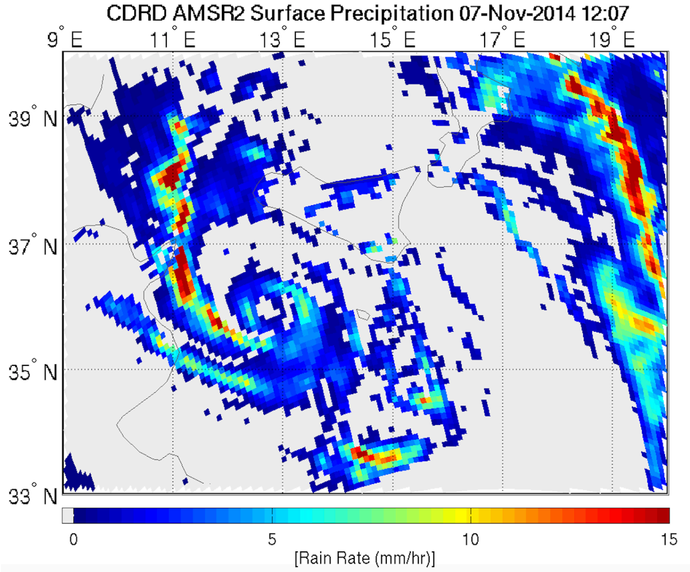
(Sanò et al., AMT, 2015, 2016)

H SAF GPM-based CDRD Bayesian scheme for AMSR-2

Medicane Qendresa 7 November 2015 - AMSR2



P-IN-AMSR2 (H-AUX-17) rainfall rate estimate

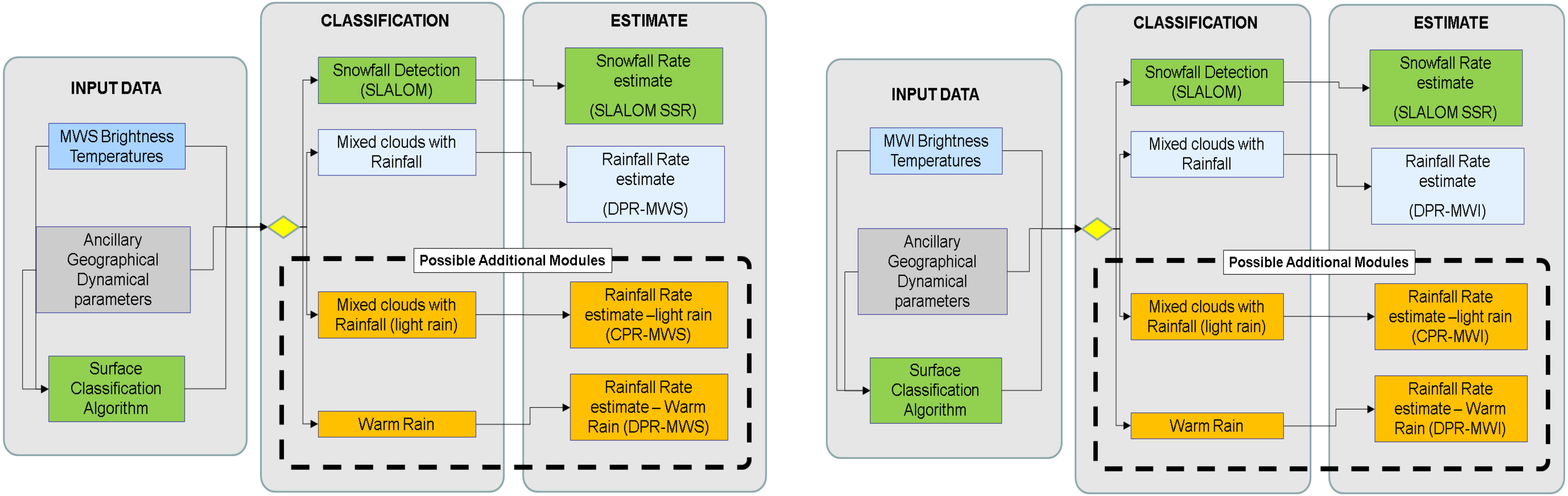


Casella et al., 2017 IEEE JSTARS

- A-priori *observational dataset* built from GPM-CO (GMI and DPR) observations;
- Calibration coefficients and error covariance matrix from AMSR-2/GMI concidence dataset;
- Space of calibrated pseudo-TBs (CCA), following Petty (2013) and Casella et al. (2015);
- Ancillary data from HRES ECMWF (0.1° x 0.1° lat/lon).
- Rain/No-rain screeening algorithm developed by Casella et al. AMT, 2015.
- ***Optimization*** to use an extremely large empirical database in NRT (timeliness reduction from 120 min to 20 min)

EPS-SG global ML-based precipitation products

Day-2 EPS-SG Level 2 Precipitation rate products (CDOP-4)



Observational training dataset built from global coincident measurements of **MWS and MWI** with GPM DPR (for rainfall) and CloudSat CPR/EarthCare (for snowfall)

Expected operational at the end of CDOP-4