Estimating surface rain rate from satellite passive microwave observations

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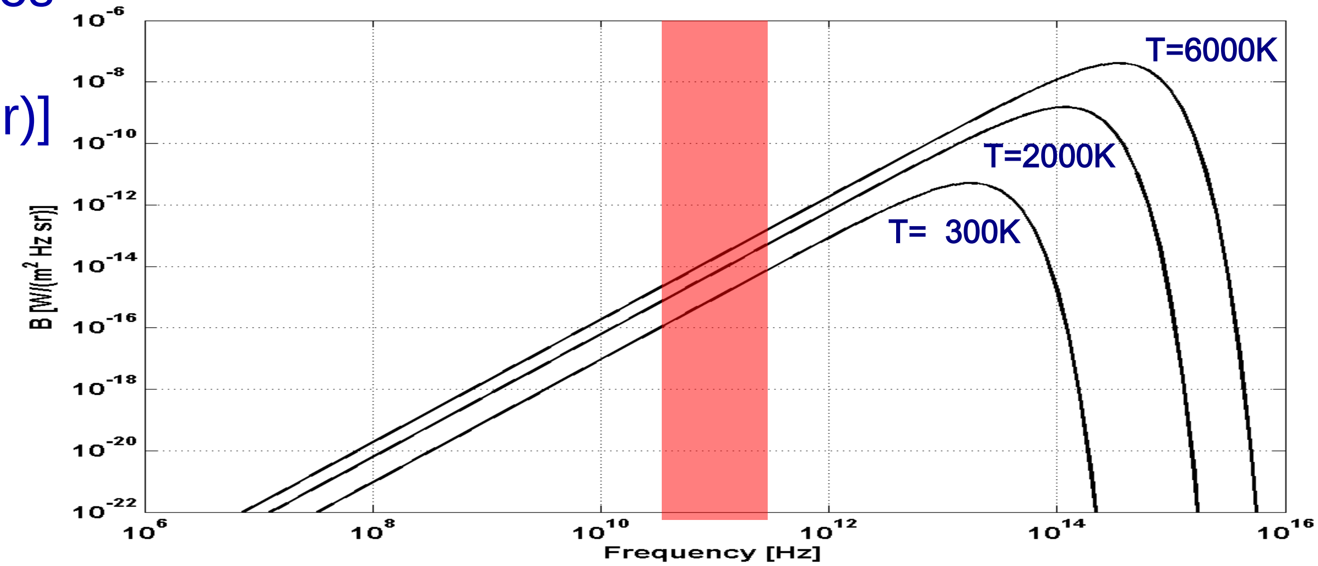
Outline

- **How does passive MW works?**
  - Passive MW in a nutshell
- **Inverse algorithm**
  - basic concepts
- **Examples**
  - Near-real-time
  - Validation

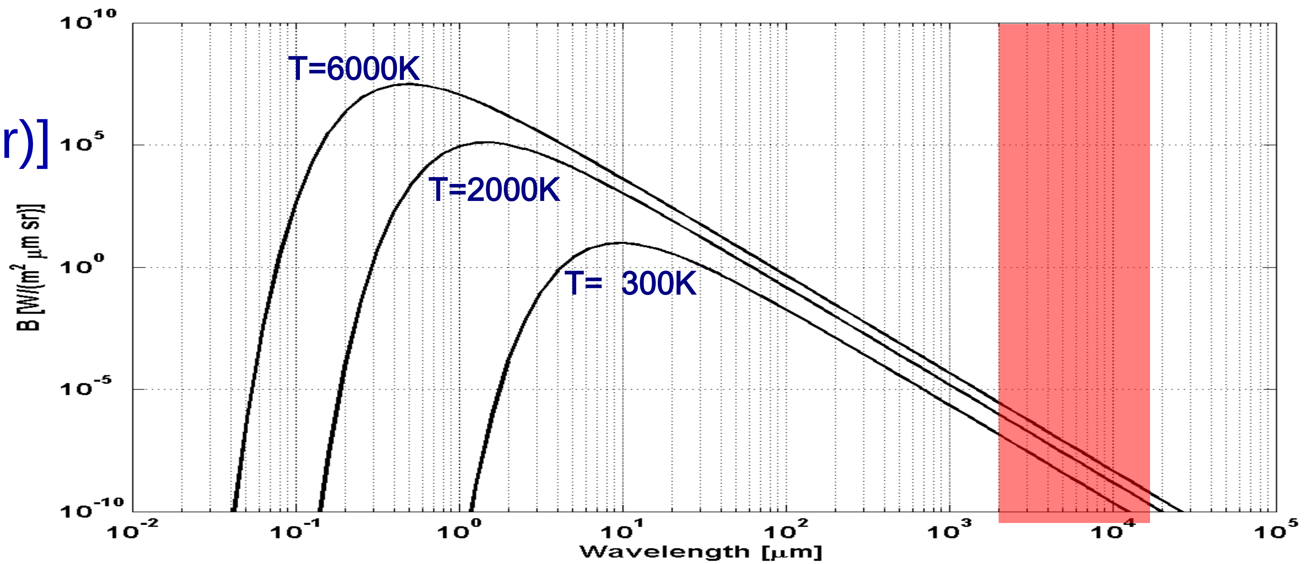
Emission of MW radiation

Planck's curves

B[W/(m² Hz sr)] vs. F[Hz]



B[W/(m² μm sr)] vs. λ[μm]



Emission of MW radiation

PLANCK FUNCTION APPROXIMATIONS

high ν (IR)

$$h\nu >> KT \Rightarrow \frac{h\nu}{KT} >> 1 \Rightarrow \frac{1}{e^{\frac{h\nu}{KT}}-1} \approx \frac{1}{e^{\frac{h\nu}{KT}}} = e^{-\frac{h\nu}{KT}} \Rightarrow B_\nu \approx \frac{2h\nu^3}{c^2} e^{-\frac{h\nu}{KT}}$$

low ν (MW)

$$h\nu << KT \Rightarrow \frac{h\nu}{KT} << 1 \Rightarrow \frac{1}{e^{\frac{h\nu}{KT}}-1} \approx \frac{1}{\frac{h\nu}{KT}} = \frac{KT}{h\nu} \Rightarrow B_\nu \approx 2KT\frac{\nu^2}{c^2} = \frac{2KT}{\lambda^2}$$

$$B_\nu = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{KT}}-1}$$

Planck function

$$B_\nu \approx \frac{2h\nu^3}{c^2} e^{-\frac{h\nu}{KT}}$$

Wien approximation (IR)

$$B_\nu \approx 2KT\frac{\nu^2}{c^2}$$

Reyleigh-Jeans approximation (MW)

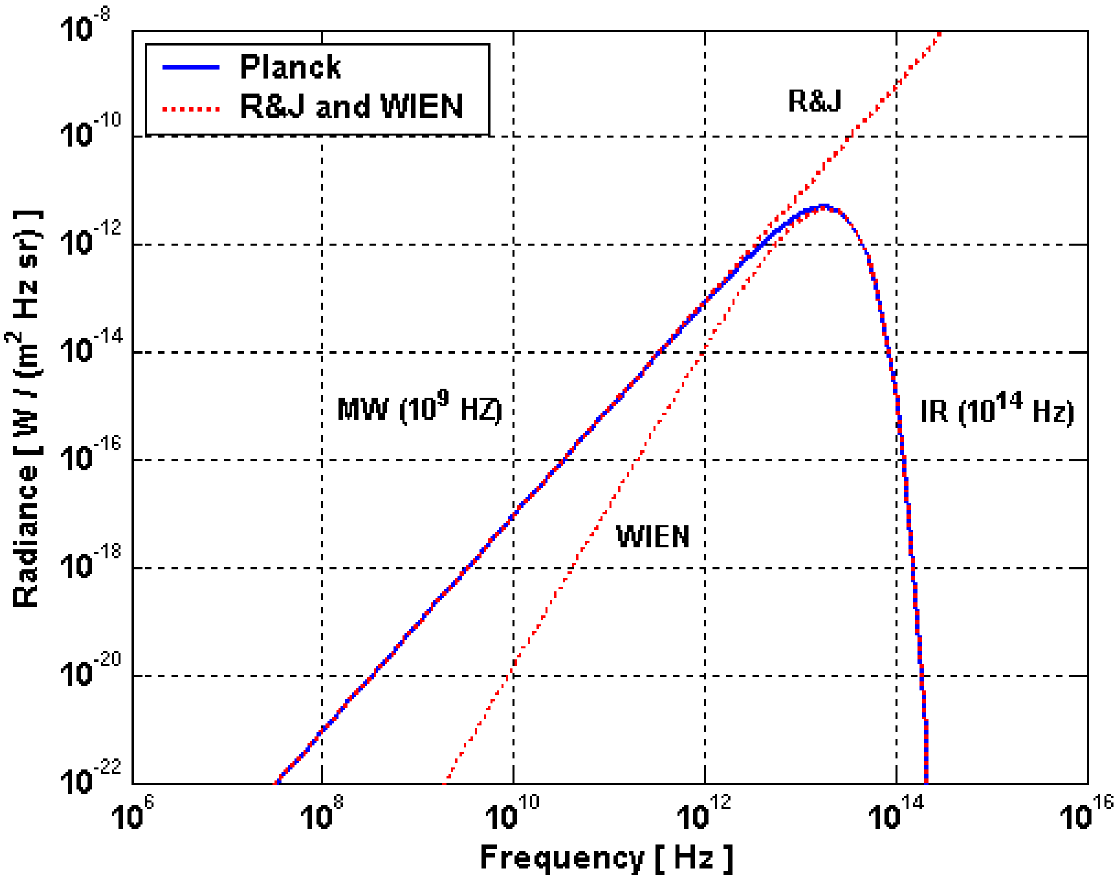
Emission of MW radiation

PLANCK FUNCTION APPROXIMATIONS

$$B_\nu = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{KT}}-1}$$

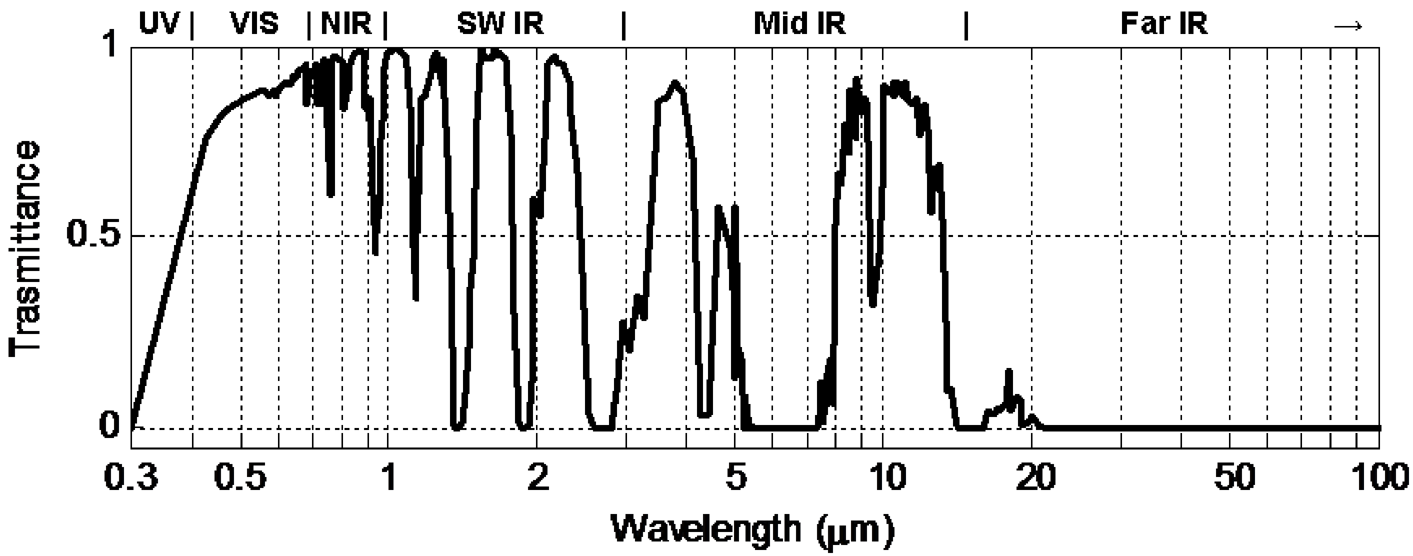
$$B_\nu \approx \frac{2h\nu^3}{c^2}e^{-\frac{h\nu}{KT}}$$

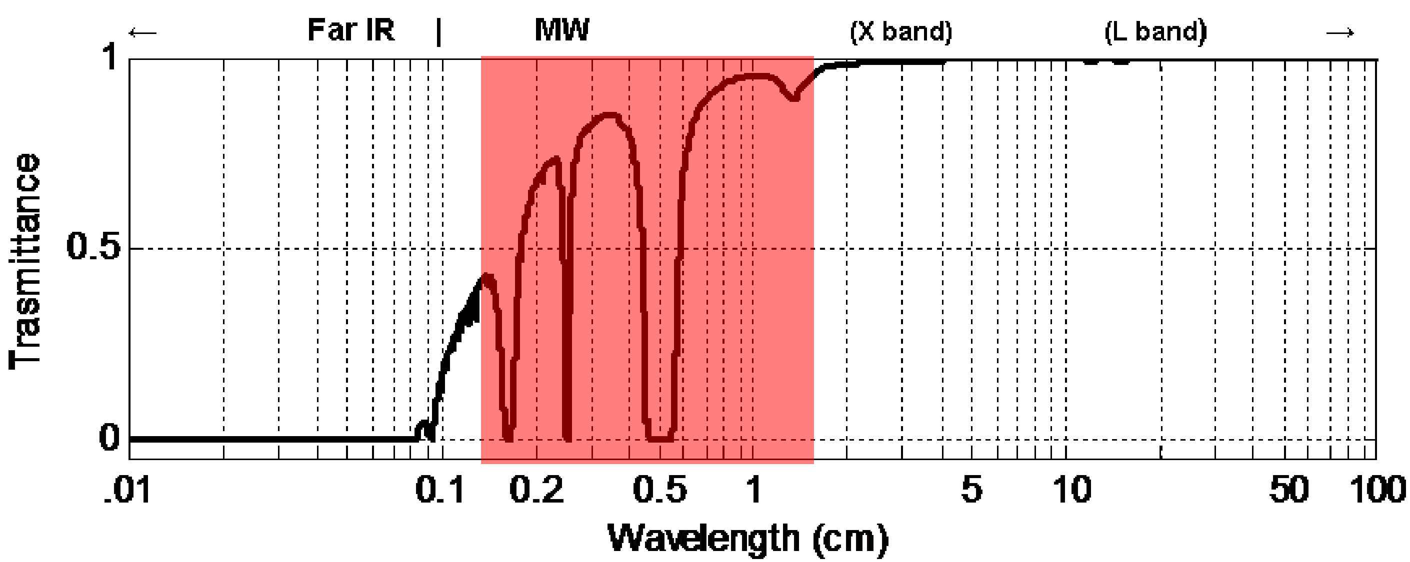
$$B_\nu \approx 2KT\frac{\nu^2}{c^2}$$



Transmission of MW radiation

- Atmospheric Transmittance (due to absorption only)





Scattering of MW radiation

- EM wave scattering happens when atmospheric particles deviate incident radiation from its original direction of propagation.

- How much scattering actually happens depends on radiation λ (or ν), molecule/particle characteristics (abundance, size, …).

- Atmospheric particle / typical size

Atmospheric particle	typical size	
Molecule:	$10^{-4} – 10^{-3}$	µm
Aerosol:	0.1 – 10	µm
Hydrometeors:	$10^{-3} – 10^{+5}$	µm
Haze:	$10^{-3} – 1$	µm
Fog:	1 – 100	µm
Cloud:	$1 – 10^{3}$	µm
Ice crystals:	$1– 5\ 10^{3}$	µm
Rain:	0.01 – 1	cm
Snow:	1 – 5	cm

Increasing size

Scattering of MW radiation

Radiation scattering depends on the ratio particle size over wavelength

Dimension parameter : $x=2\pi r/\lambda$

If	$r<<\lambda$	$x\rightarrow 0$	negligible scattering
If	$r<\sim\lambda$	$x<<1$	Rayleigh limit (simplified solution)
If	$r\sim=\lambda$	$x\sim=1$	Mie conditions (rigorous solution)
If	$r>>\lambda$	$x\rightarrow\infty$	geometric optics limit (non-selective)

Increasing x

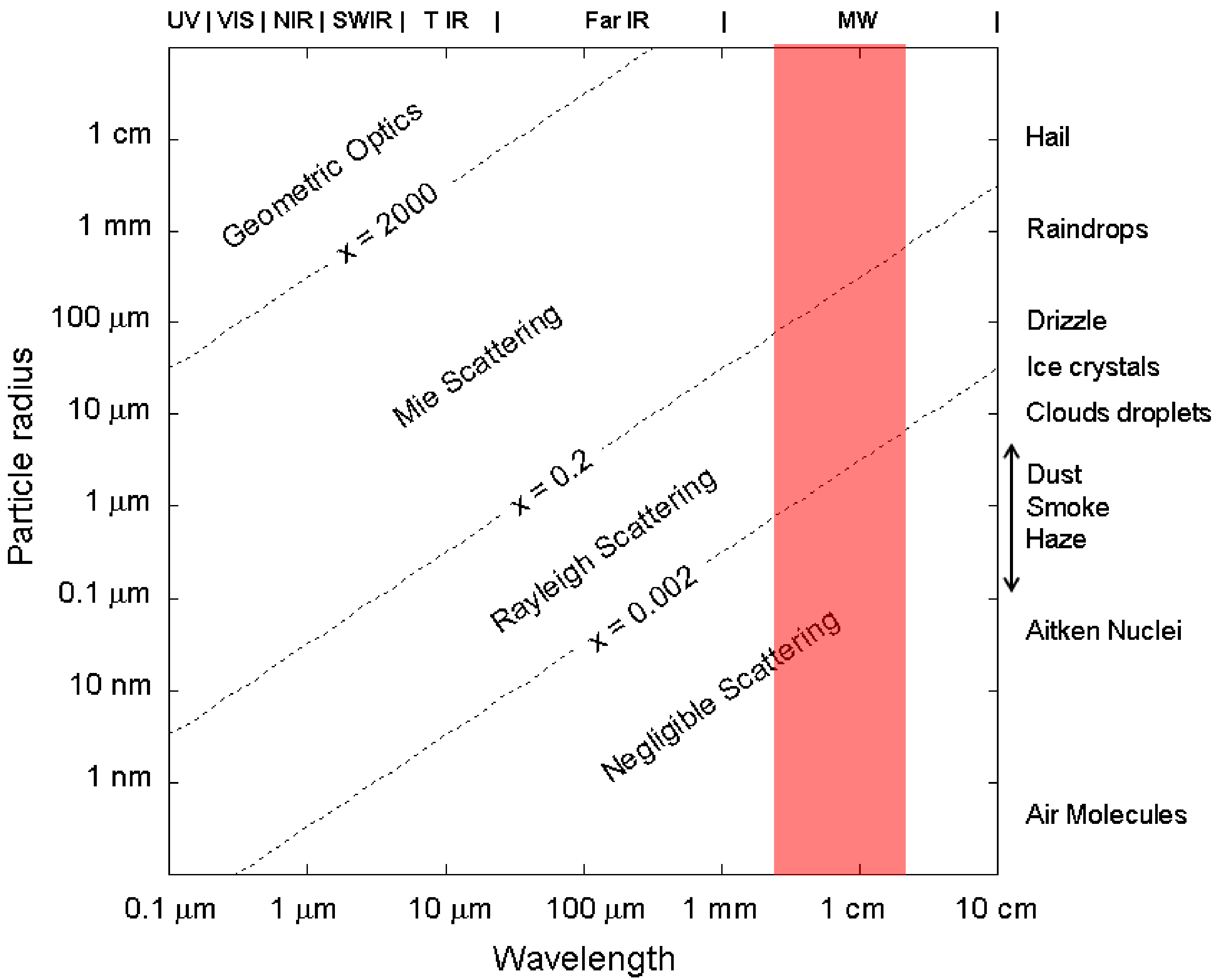
Rayleigh scattering: small particles (x<<1); molecules, fine dust,
Ex: blue sky (visible)

Mie scattering: medium particles (x~=1); dust, pollen, hydrometeors
Ex: rain (mw)

Non-selective scattering: large particles (x>>1); hydrometeors,
Ex: white clouds (visible)

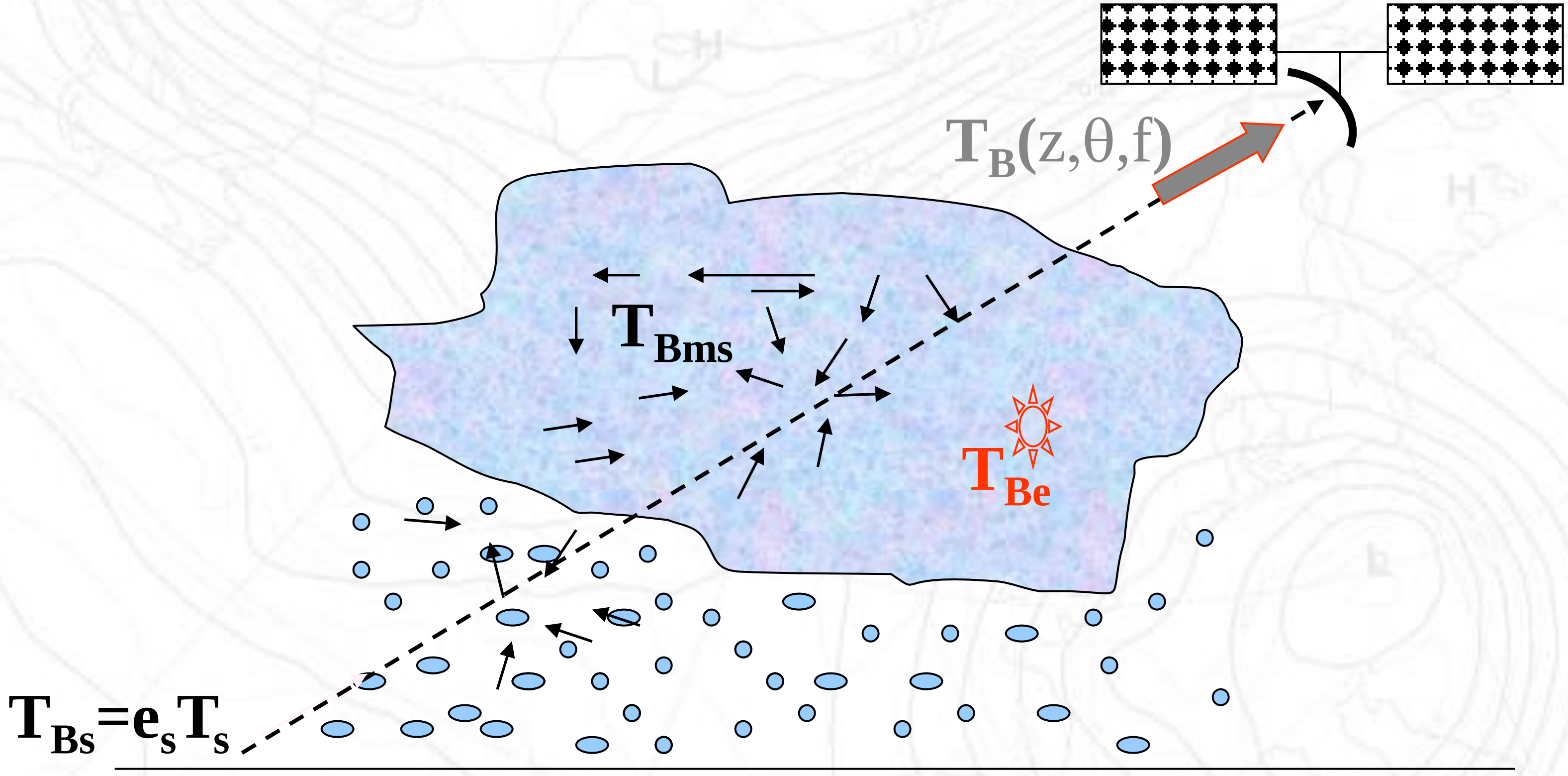
Scattering of MW radiation

- Scattering regimes



FORWARD PROBLEM
Physical basis

T_B: *brightness temperature*
f=10-160 GHz
θ=0° to 50°



e_s: surface emissivity
T_s:surface temperature

T_{Be}: emission T_B
T_{Bms}: multiple scattering T_B

FORWARD PROBLEM
Radiative transfer equation

- T_B in a plane-parallel medium: non-scattering case

$$\frac{dT_B(\tau,\Omega)}{d\tau} = \underbrace{-T_B(\tau,\Omega)}_{Extinction} + \underbrace{T(\tau)}_{Emission}$$

$\Rightarrow$**Ordinary differential equation: linearization of F**
$\Rightarrow$ **Inverse problem as a *Fredholm integral equation* (e.g., temperature retrieval)**

- TB in a plane-parallel medium: scattering case

$$\frac{dT_B(\tau,\Omega)}{d\tau} = \underbrace{-T_B(\tau,\Omega)}_{Extinction} + \underbrace{\frac{w}{4\pi}\int_{4\pi} p(\Omega,\Omega')T_B(\tau,\Omega)d\Omega'}_{Multiple\ scattering} + \underbrace{(1-w)T(\tau)}_{Emission}$$

=> **Integro-differential equation: strongly non-linear F (e.g., rainfall retrieval)**

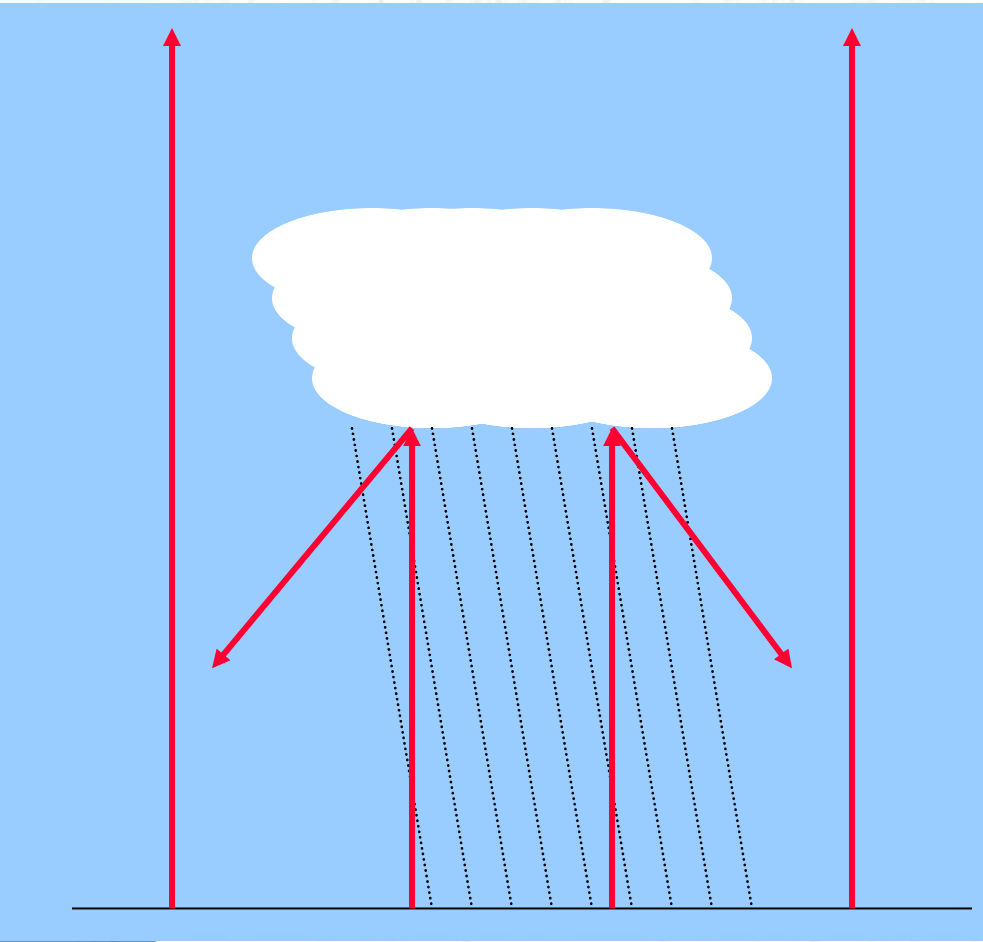
Precipitation in MW — Theory/Basis

- **Scattering signal**
  - ice in clouds scatters terrestrial radiation (cold areas over warm bckg)
    - Rainfall rates are related to the magnitude of the resulting brightness temperature depression.
    - **Strength**: can be applied to high-frequency channels: works over both land and ocean
    - **Weakness**: poor at detecting precipitation clouds with little or no ice (e.g. warm orographic clouds in the tropics)

- **Emission signal**
  - water in clouds emits radiation, (warm areas over cold bckg, e.g. ocean)
    - Rainfall rates are related to the magnitude of the resulting brightness temperature difference
    - **Strength**: sensitive to clouds with little or no ice
    - **Weakness**: must know terrestrial radiances without cloud beforehand; generally applicable over oceans but not land

Lower T_b above cloud

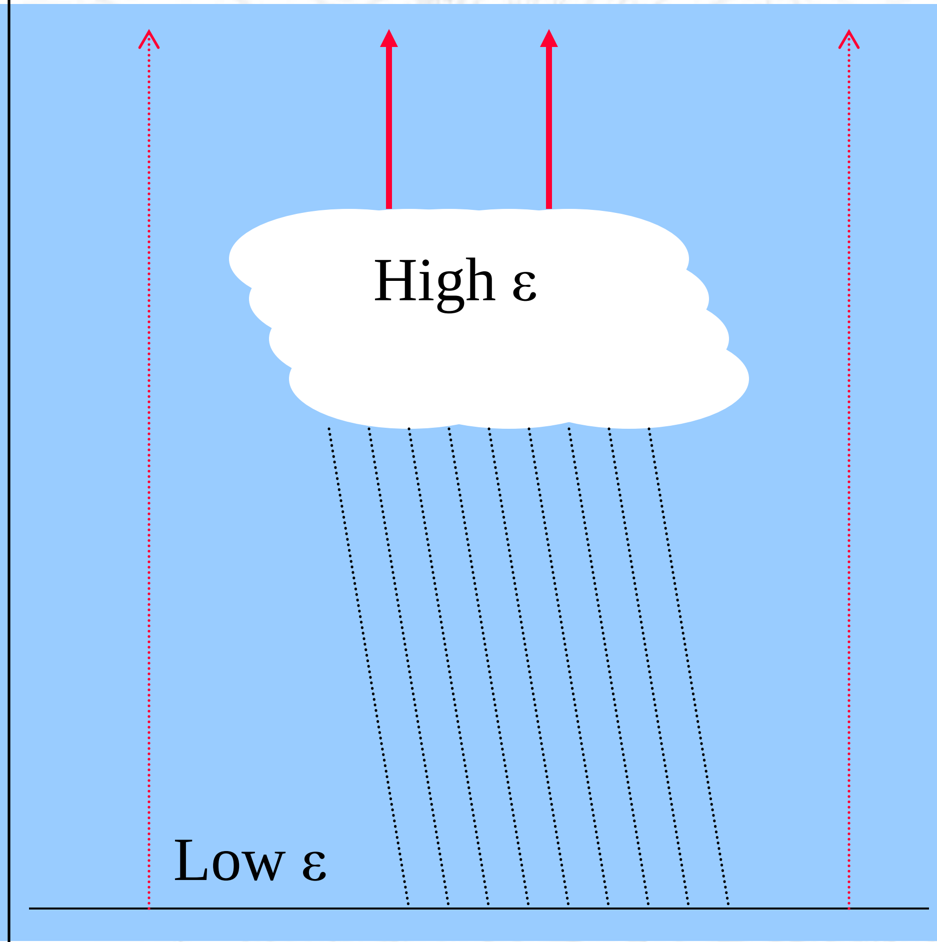
Higher T_b above clear air



Scattering

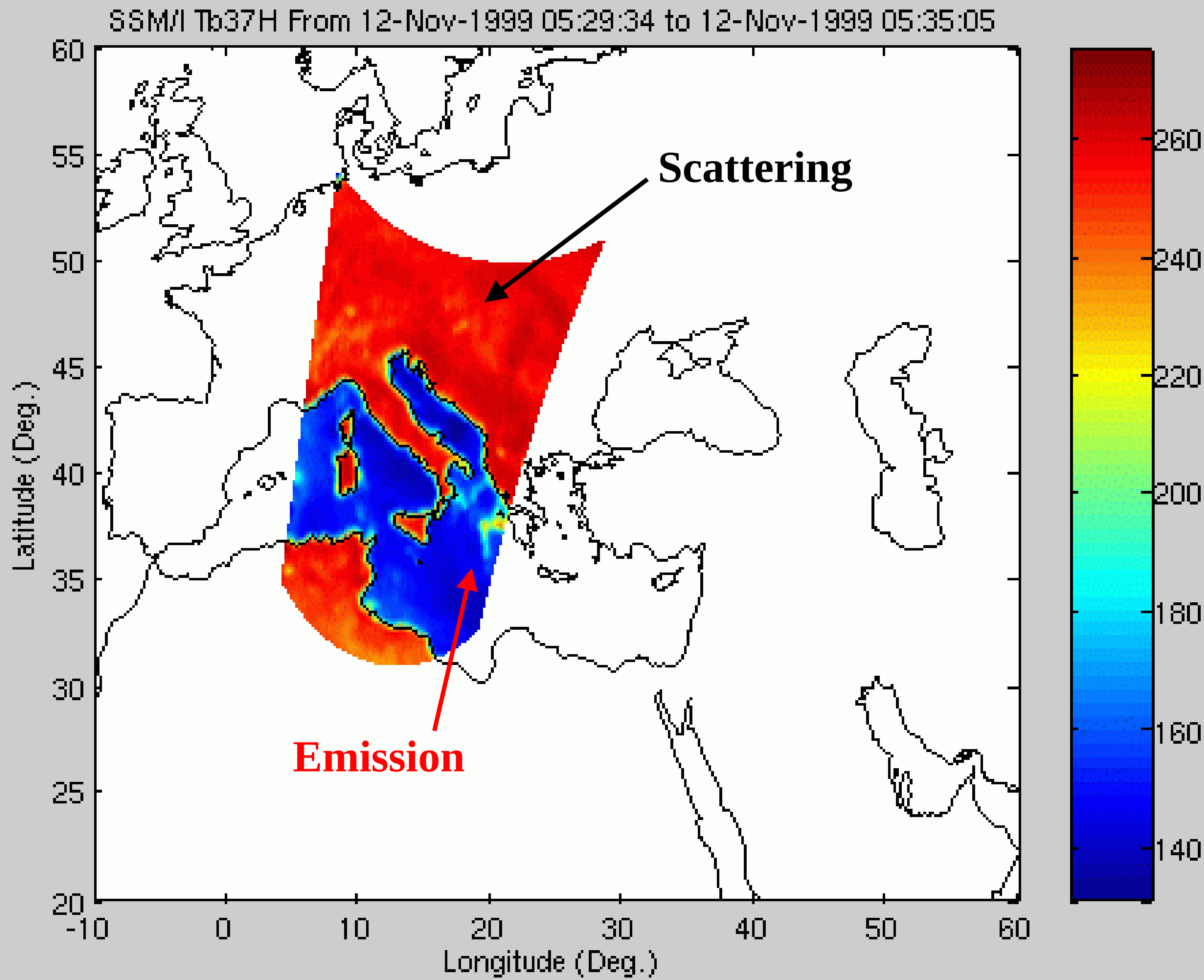
Higher T_b above cloud

Lower T_b above clear air



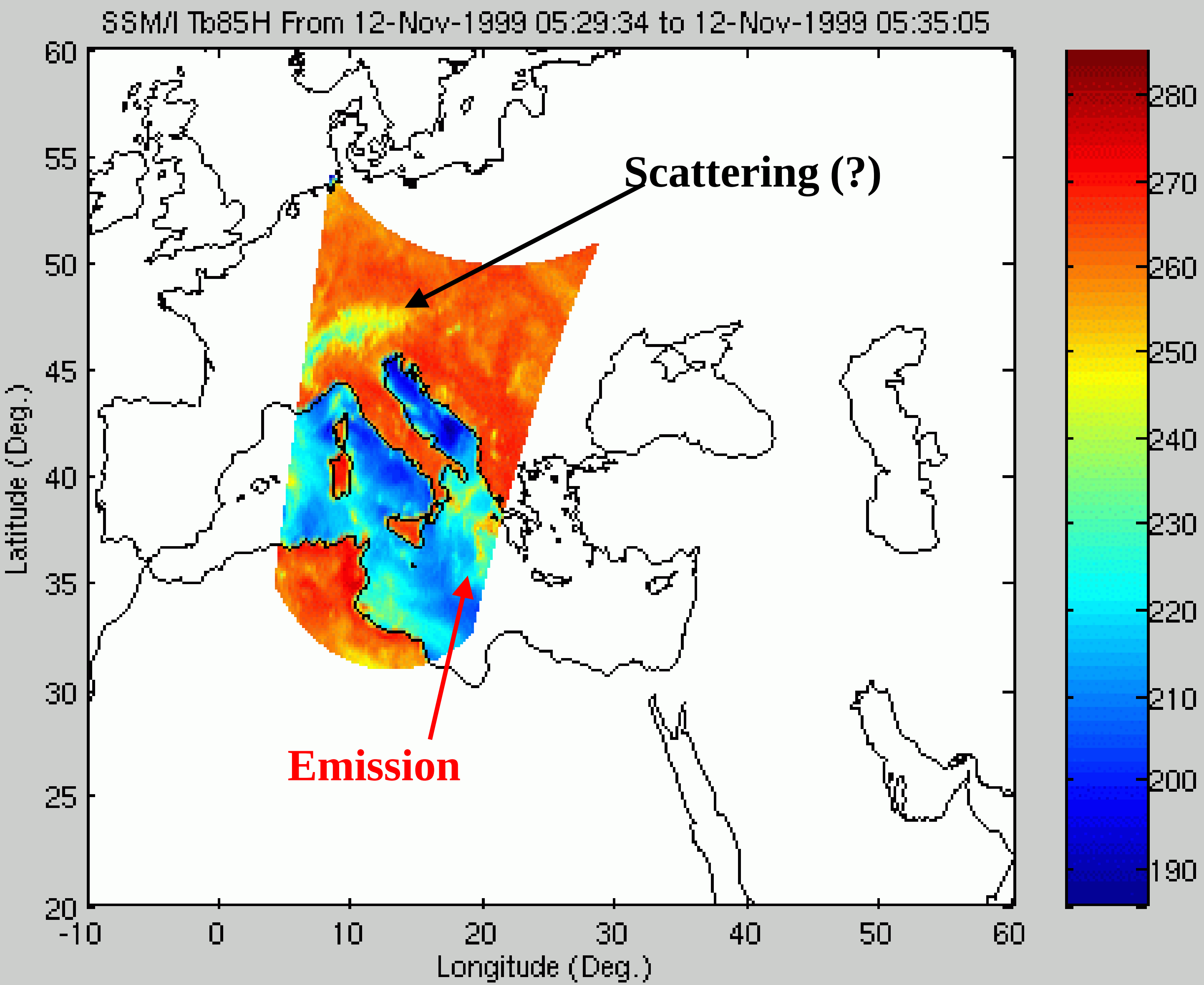
Emission (over ocean)

Tb at 37 GHz H

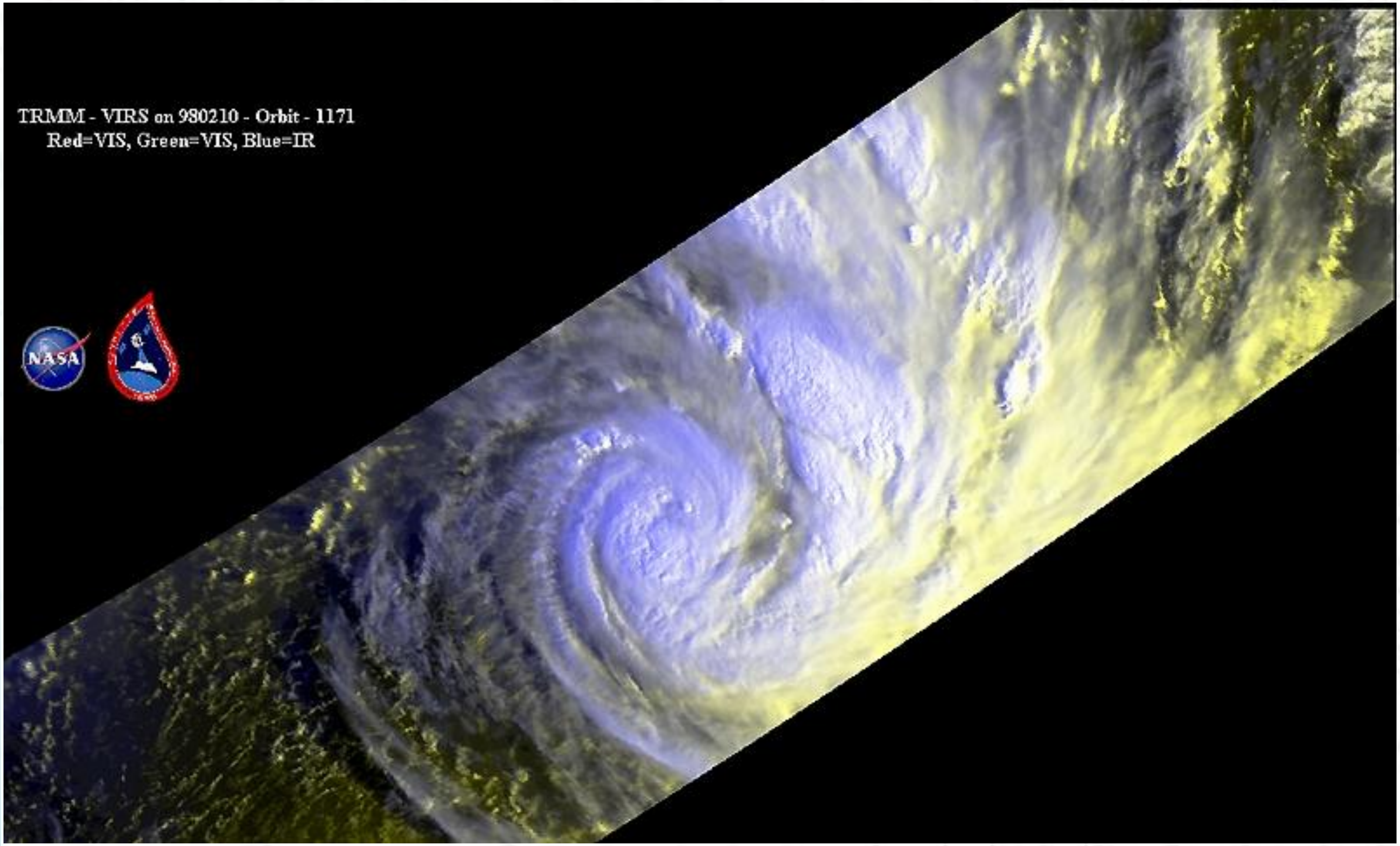


SSM/I Tb37H From 12-Nov-1999 05:29:34 to 12-Nov-1999 05:35:05
Scattering
Emission
Latitude (Deg.)
Longitude (Deg.)
60
55
50
45
40
35
30
25
20
-10
0
10
20
30
40
50
60
260
240
220
200
180
160
140

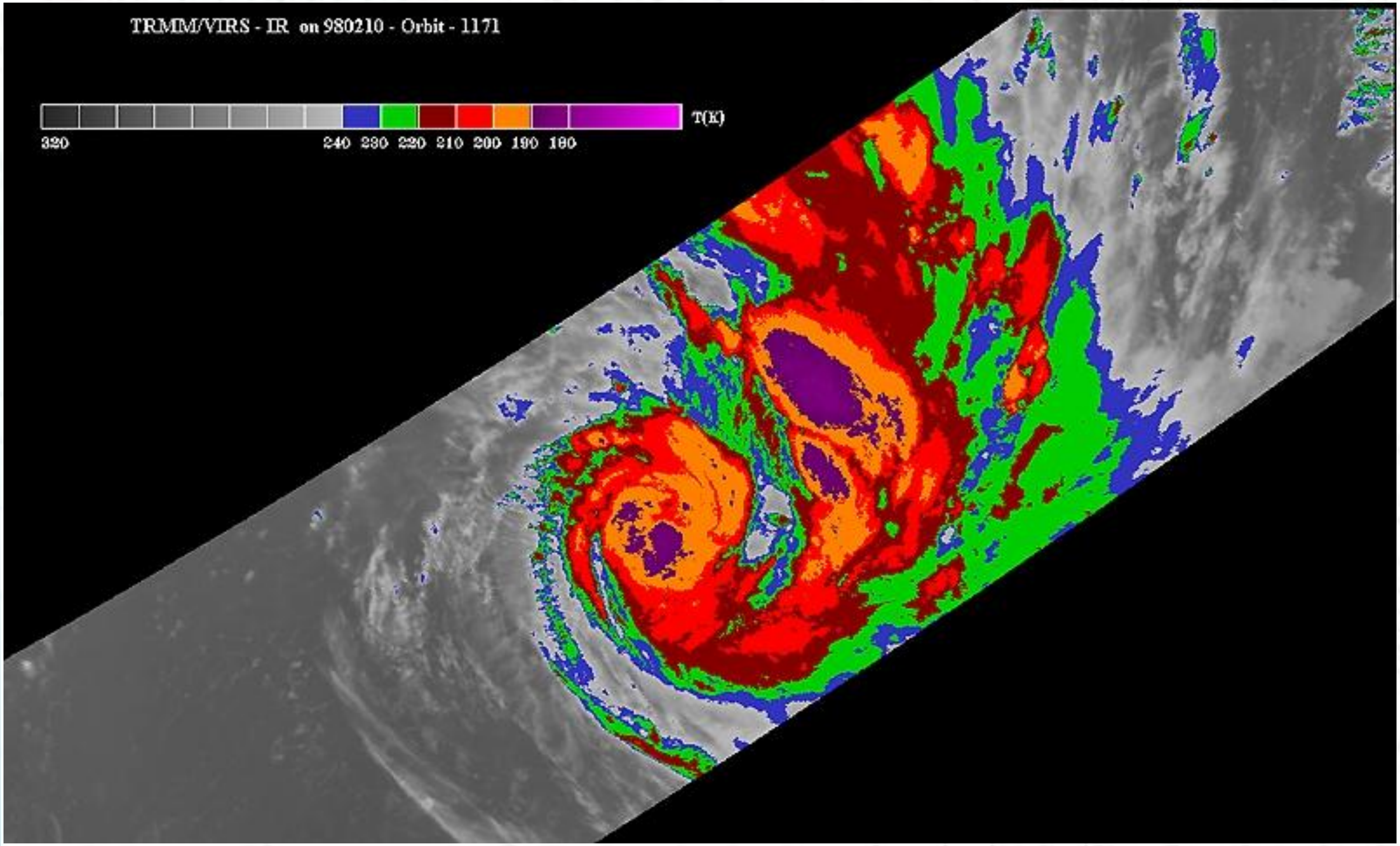
Tb at 85 GHz H


SSM/I Tb85H From 12-Nov-1999 05:29:34 to 12-Nov-1999 05:35:05
Scattering (?)
Emission
Latitude (Deg.)
Longitude (Deg.)
60
55
50
45
40
35
30
25
20
-10
0
10
20
30
40
50
60
280
270
260
250
240
230
220
210
200
190

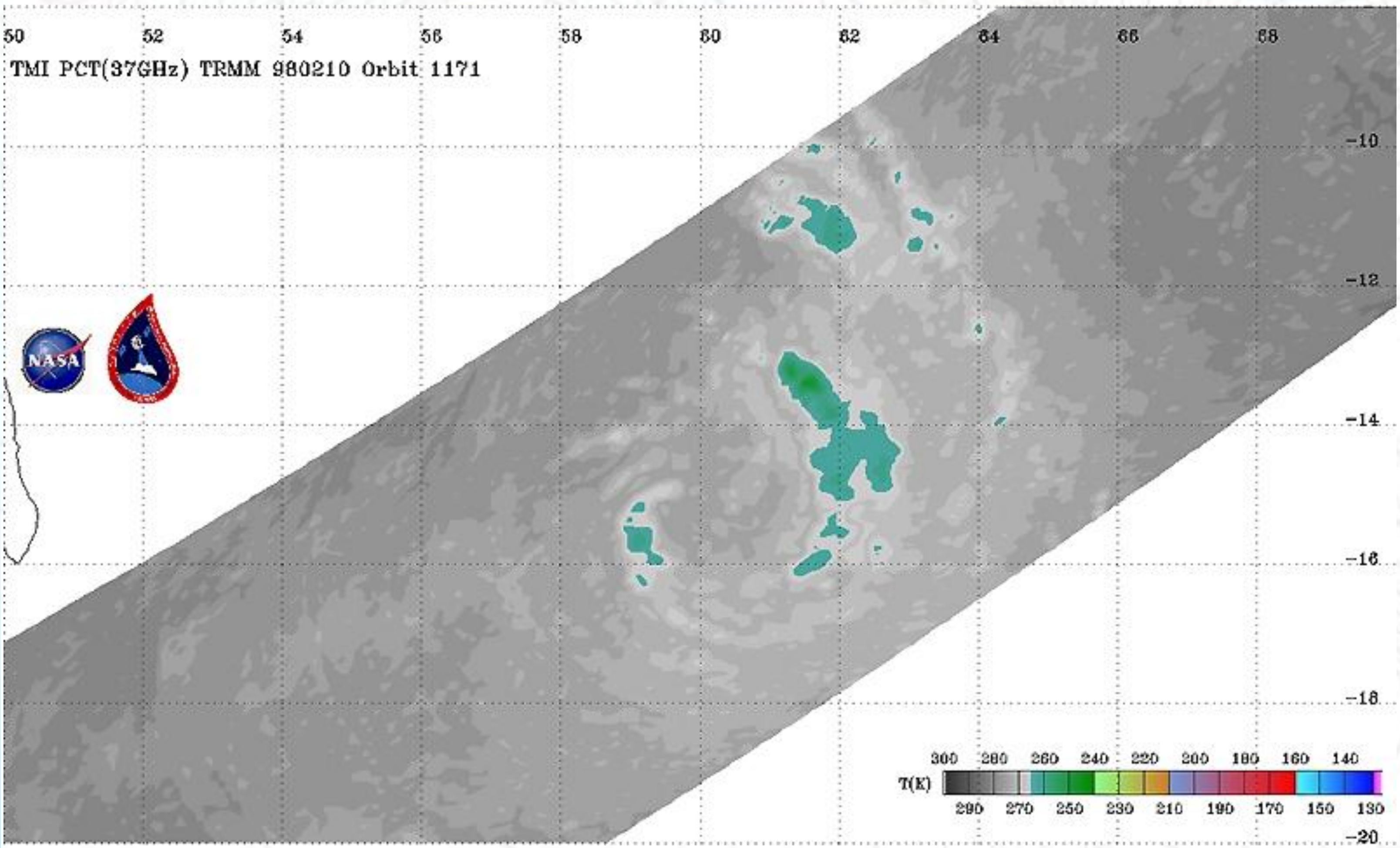
TRMM VIRS (RGB)



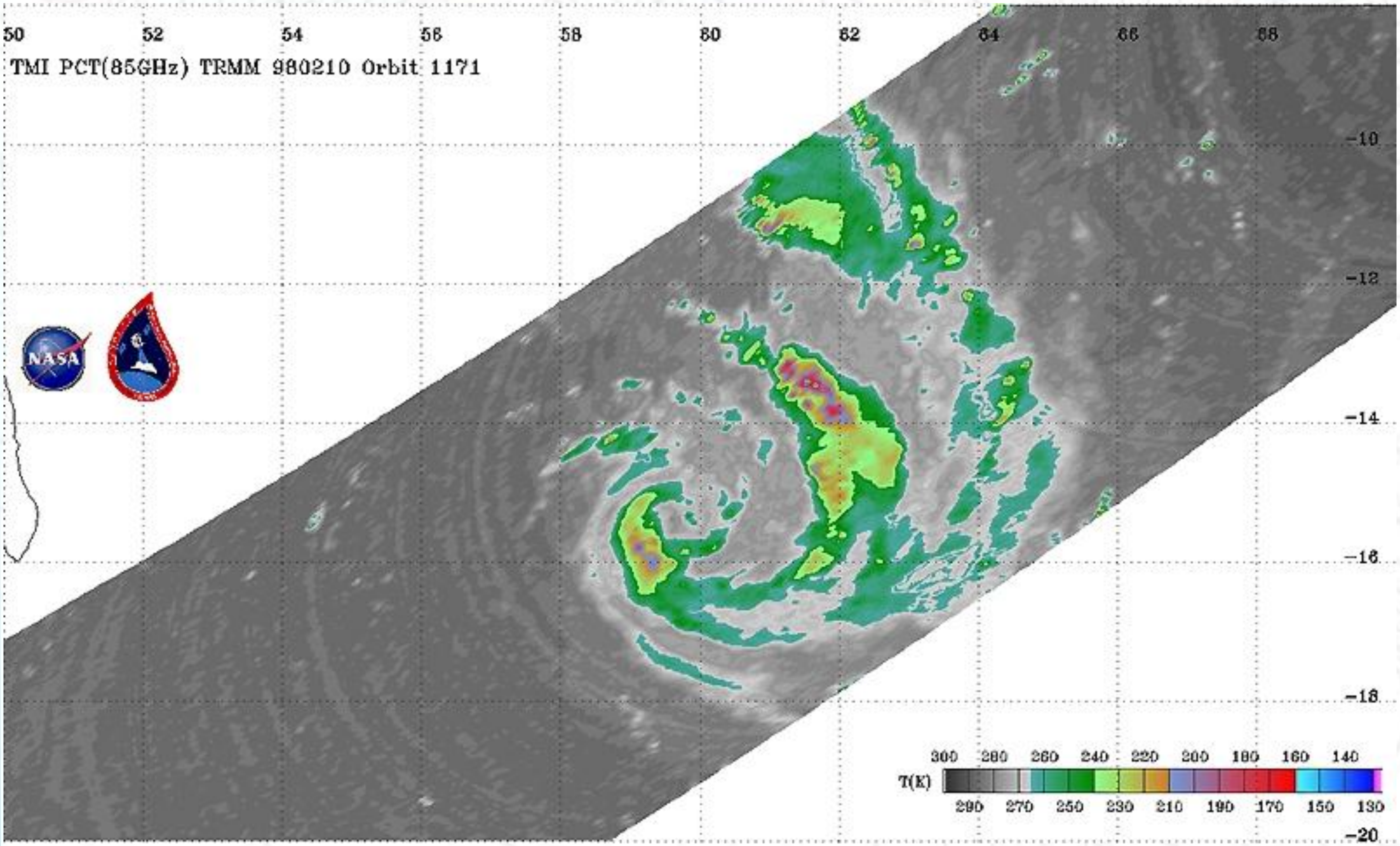
TRMM VIRS (IR)


TRMM/VIRS - IR on 980210 - Orbit - 1171
T(K)
320
240 230 220 210 200 190 180

TRMM MICROWAVE IMAGER (37GHz)



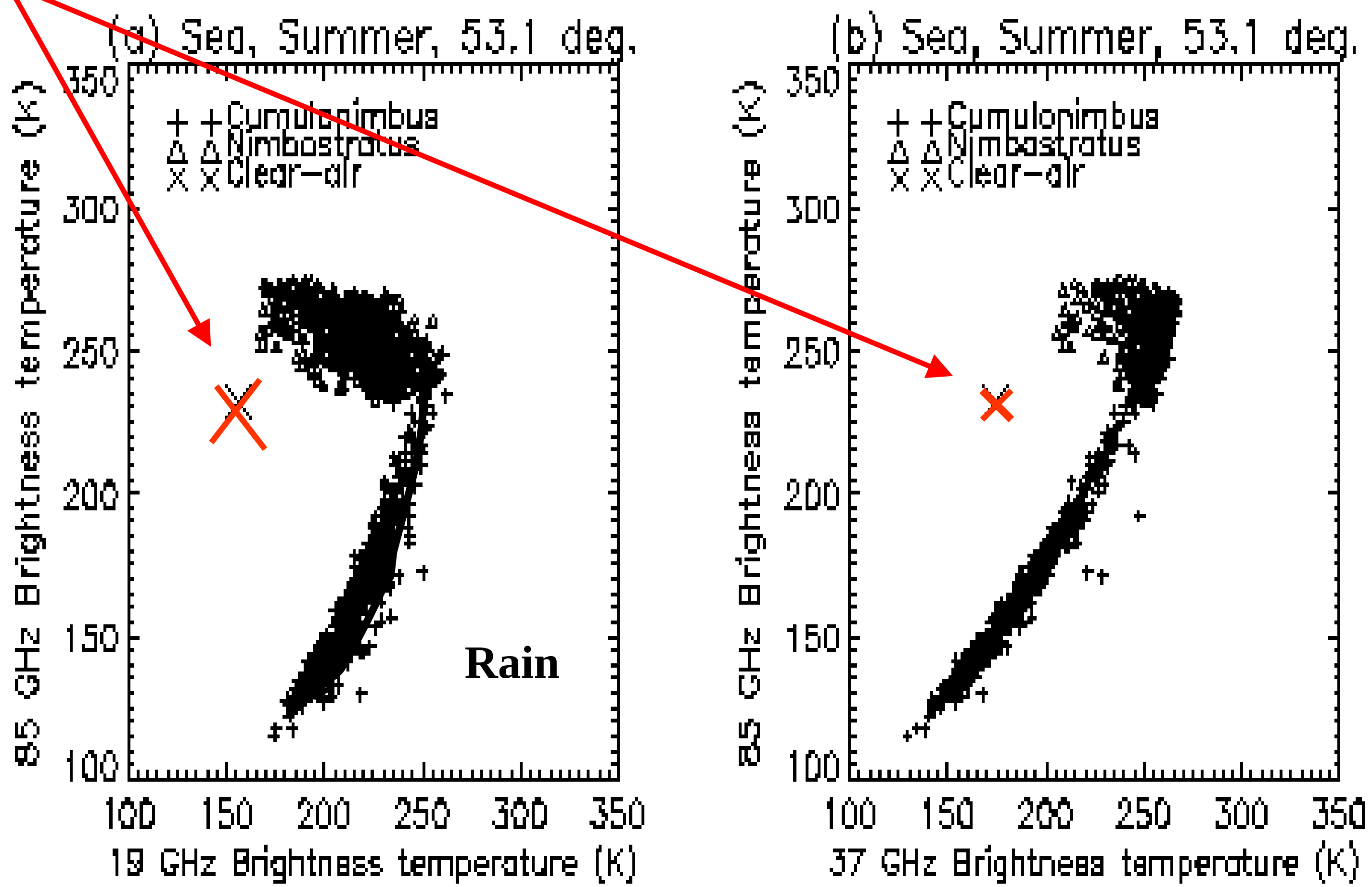
TRMM MICROWAVE IMAGER (85GHz)



FORWARD PROBLEM
Radiative transfer models

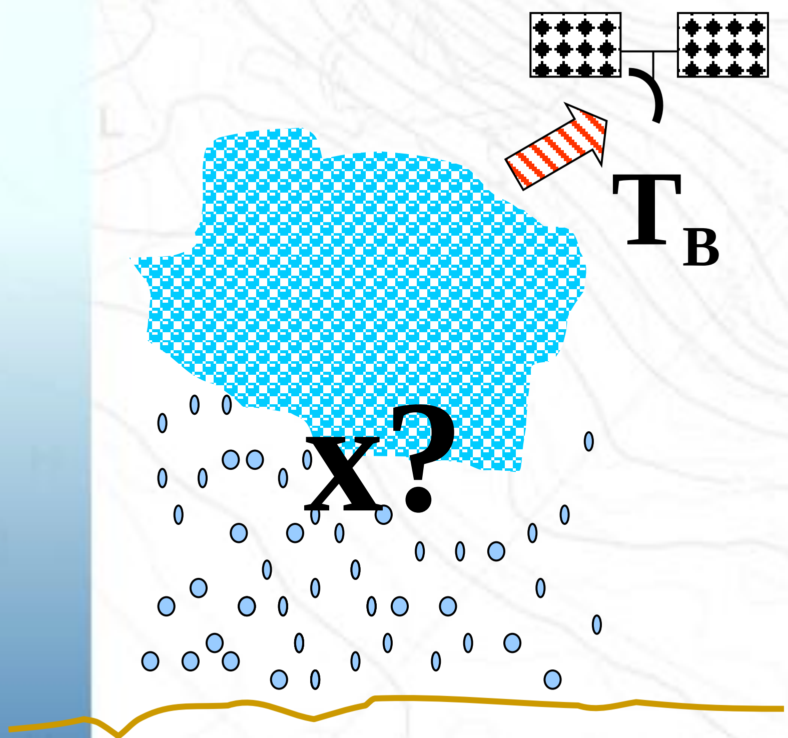
Clear air

T_B simulations over ocean



T_B *[e.g., 8 T_B's H/V at 10, 19, 37, 85 GHz]*

INVERSE PROBLEM
Rainfall retrieval



Product

- Hydrometeor profile
- Latent heat
- Rain rate

Inversion algorithm

- Training data set
- A priori information
- Ancillary data

Pre processing

- Geo-location
- Calibration
- Filtering
- Deconvolution

$T_B(z=H,f,\Omega;p)$

Instruments and Algorithms
Satellite passive microwave observations

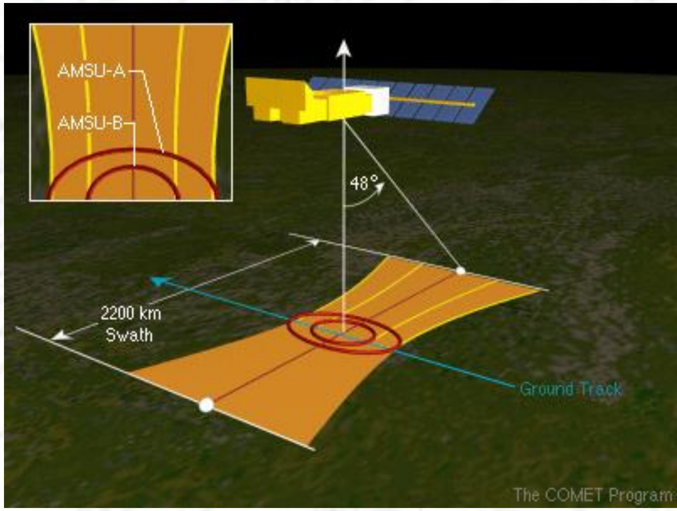
- Rainfall observations from satellite are performed operationally by several agencies using data from MW radiometers as SSM/I, AMSU-A/B, MHS.

- Here we use the surface rain rate estimated operationally at IMAA-CNR in collaboration with CETEMPS

  - **Algorithm**: PEMW (Precipitation Estimation from MicroWave observations) developed at IMAA-CNR
  - **Instrument**: MHS and AMSU-B
  - **Satellites**: NOAA N16-18-19; EUMETSAT MetOp A
  - **Orbit**: polar low-earth-obit (LEO)

Instruments and Algorithms
Satellite passive microwave observations

AMSU-B (Advanced Microwave Sounding Unit B)
MHS (Microwave Humidity Sounder)



- Cross-track linear scanning MW radiometers
- 5 channels
  - 2 window
  - 3 opaque
- Antenna beam width: 1.1°
- Spatial resolution: 16-17 km at nadir
- 90 consecutive FOV
- Coverage: Twice daily full global coverage

	AMSU-B				MHS			
# chan	*f (GHz)*	*# passband*	*bandwidth per passband (MHz)*	*POL*	*f (GHz)*	*# passband*	*bandwidth per passband (MHz)*	*POL*
1	89.0+-0.9	2	1000	V	89.0	1	2800	V
2	150.0+-0.9	2	1000	V	150.0	1	2800	V
3	183.31+-1.00	2	500	V	183.31+-1.00	2	500	H
4	183.31+-3.00	2	1000	V	183.31+-3.00	2	1000	H
5	183.31+-7.00	2	2200	V	190.31	1	2200	V

Instruments and Algorithms
Satellite passive microwave observations

Precipitation Estimation from AMSU-B / MHS

- Features:
  - Increased spatial resolution wrt lower freq instruments
  - Increased sensitivity to light rain wrt lower freq instruments
  - Good temporal coverage: some 7-10 daily overpasses with AMSU-B / MHS currently flying on 4 platforms

Instruments and Algorithms
PEMW Algorithm

- PEMW automatically selects the most appropriate atmospheric scenario from a pool of 81
- Each scenario is associated with coefficients which fit a model between the observations and rain rate
- Scenarios (and associated coefficients) were identified based on a data set of simulations and observations

Retrieval procedure

Di Tomaso et al., J. Geoph. Res., 2009

INPUT (MHS or AMSU-B)

$$(TB_1; TB_2; TB_3; TB_4; TB_5)$$

TB Differences

$$\Delta_1 = TB_1 - TB_2$$
$$\Delta_2 = TB_3 - TB_5$$
$$\Delta_3 = TB_4 - TB_5$$

Model

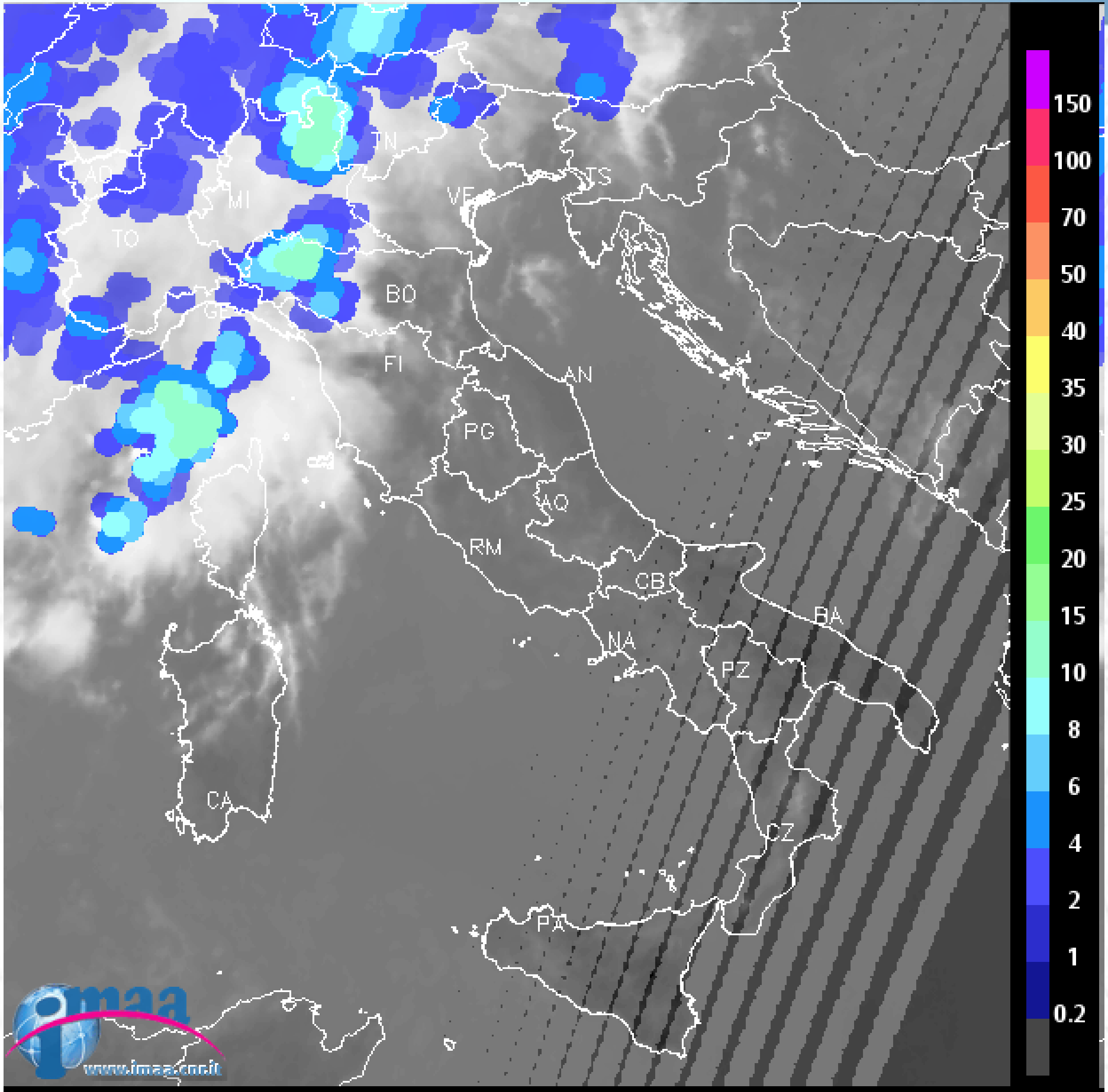
$$f\left(rr, \Delta_i \mid \theta_{i_1}, \ldots, \theta_{i_j}, \ldots, \theta_{i_c}\right)$$
$$i = 1,2,3$$
$$\Theta_k = \left\{\theta_{1_1}, \ldots, \theta_{1_c}, \ldots, \theta_{3_1}, \ldots, \theta_{3_c}\right\}$$
$$k = 1, \ldots, s$$

Scenario selection

OUTPUT

Surface rain rate (mm/h)

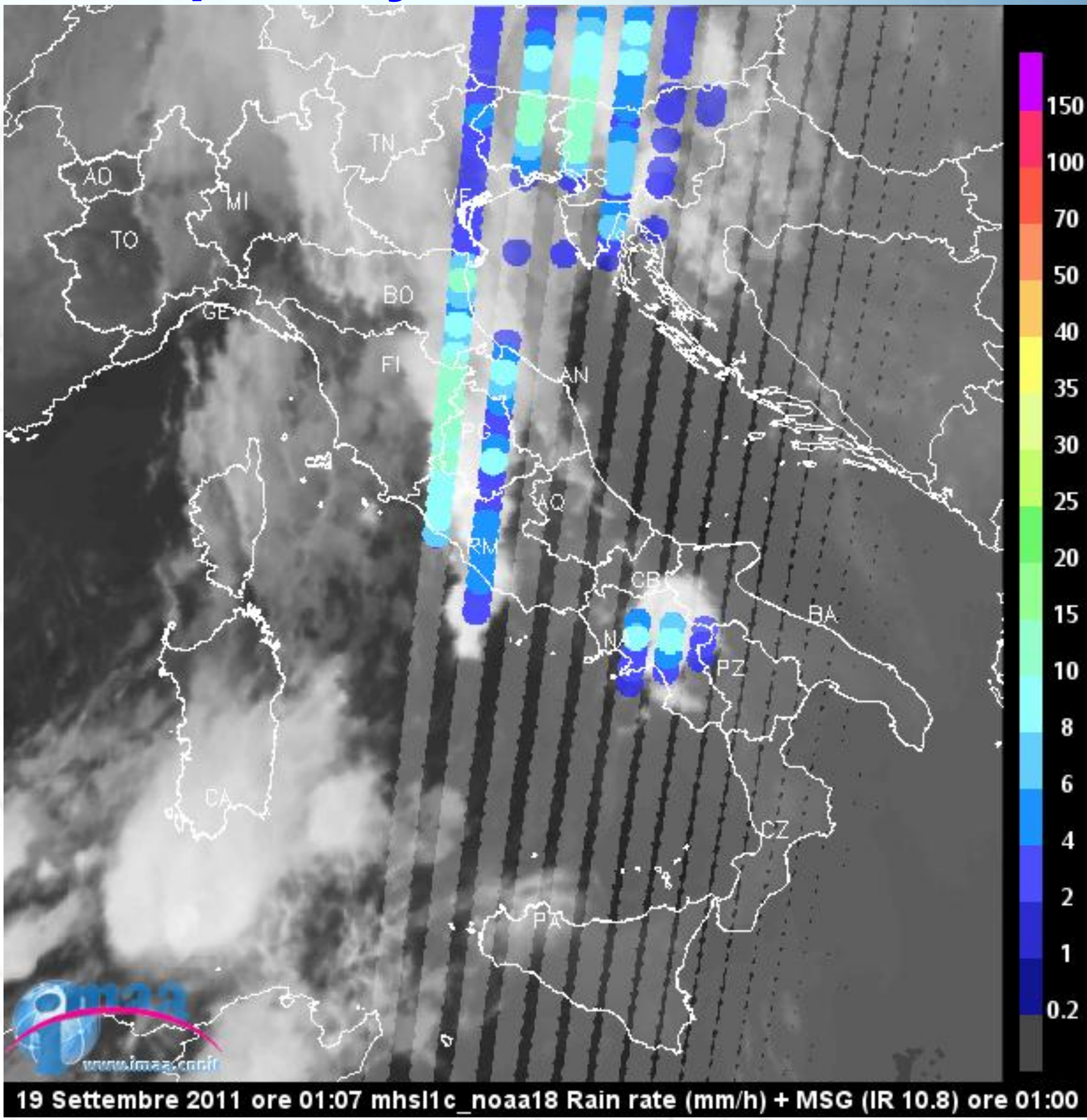
What's up today? 2011/09/18 11:27



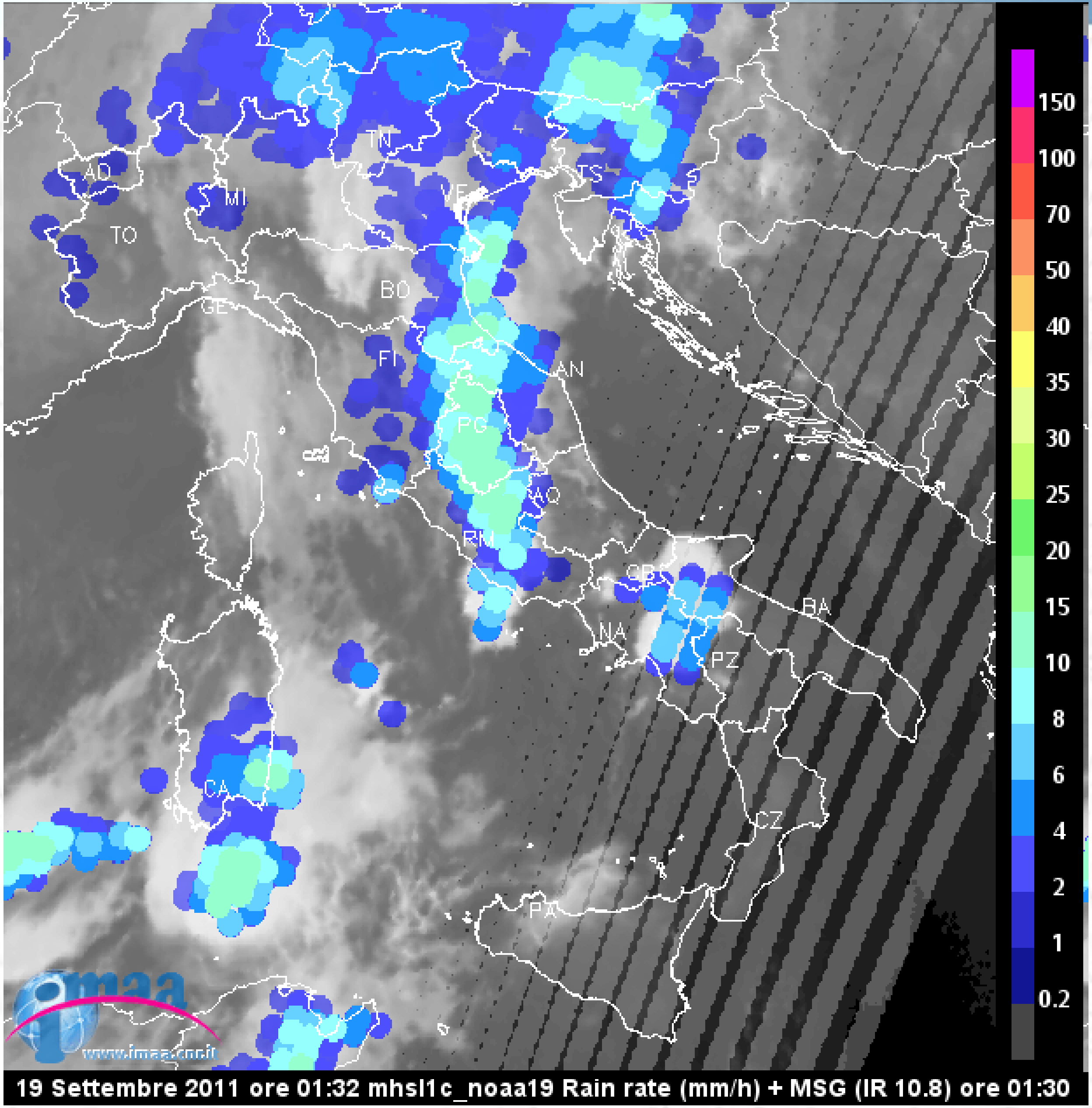
18 Settembre 2011 ore 09:27 mhsl1c_M02 Rain rate (mm/h) + MSG (IR 10.8) ore 09:00

imaa istituto di metodologie per l'analisi ambientale

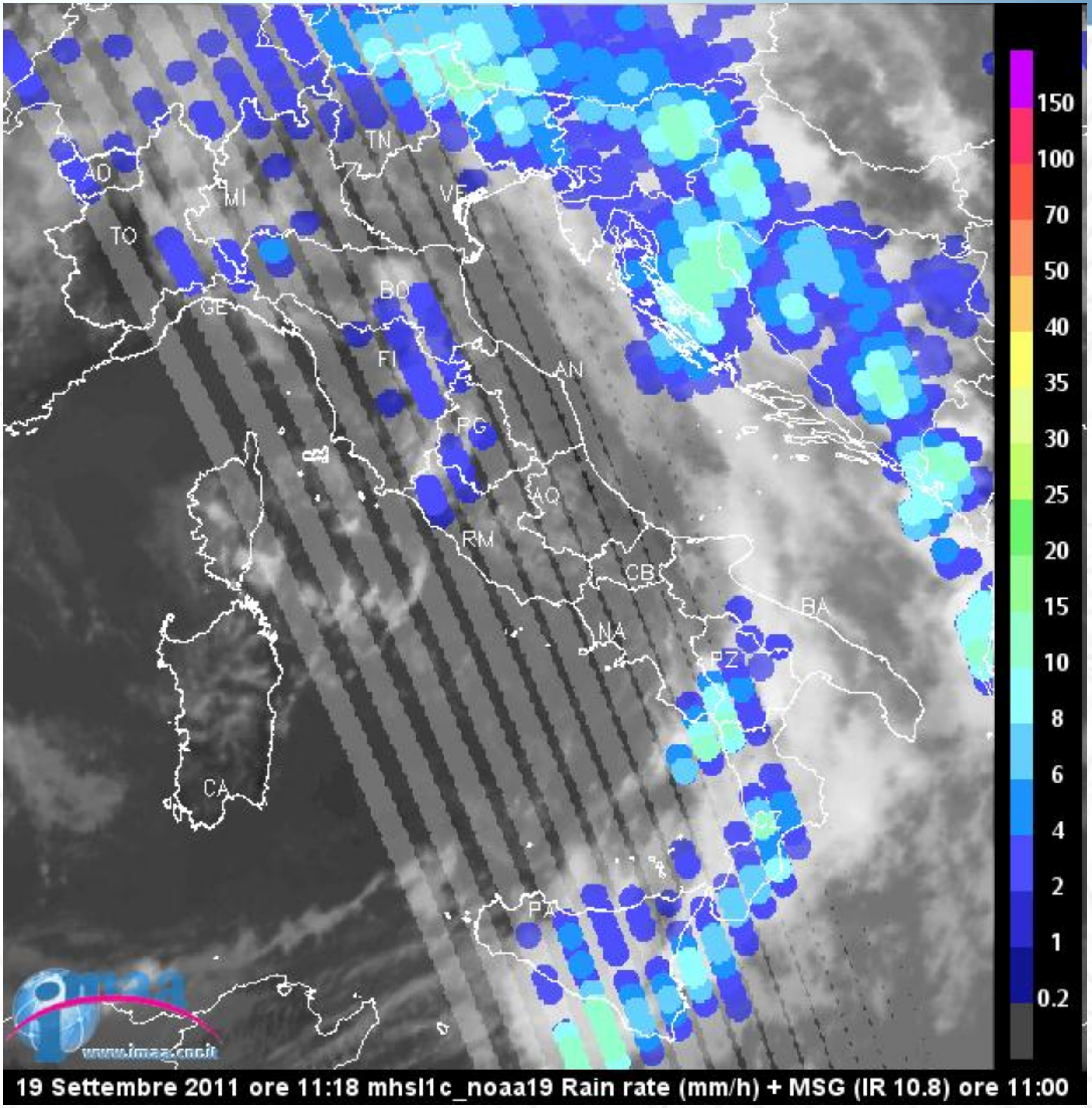
What's up today? 2011/09/19 03:07



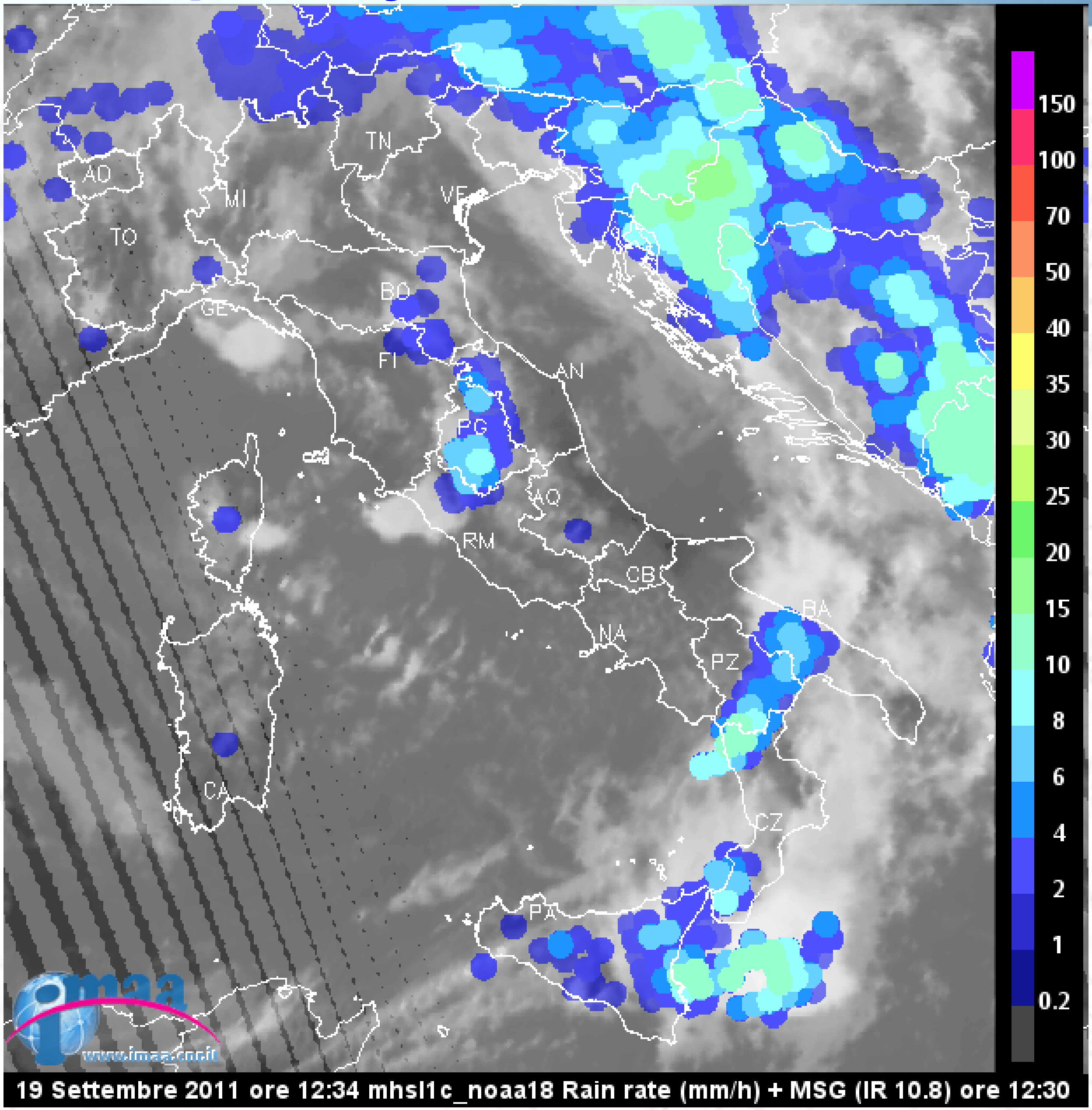
What's up today? 2011/09/19 03:32



What's up today? 2011/09/19 13:18



What's up today? 2011/09/19 14:34



Validation of PEMW with RNC

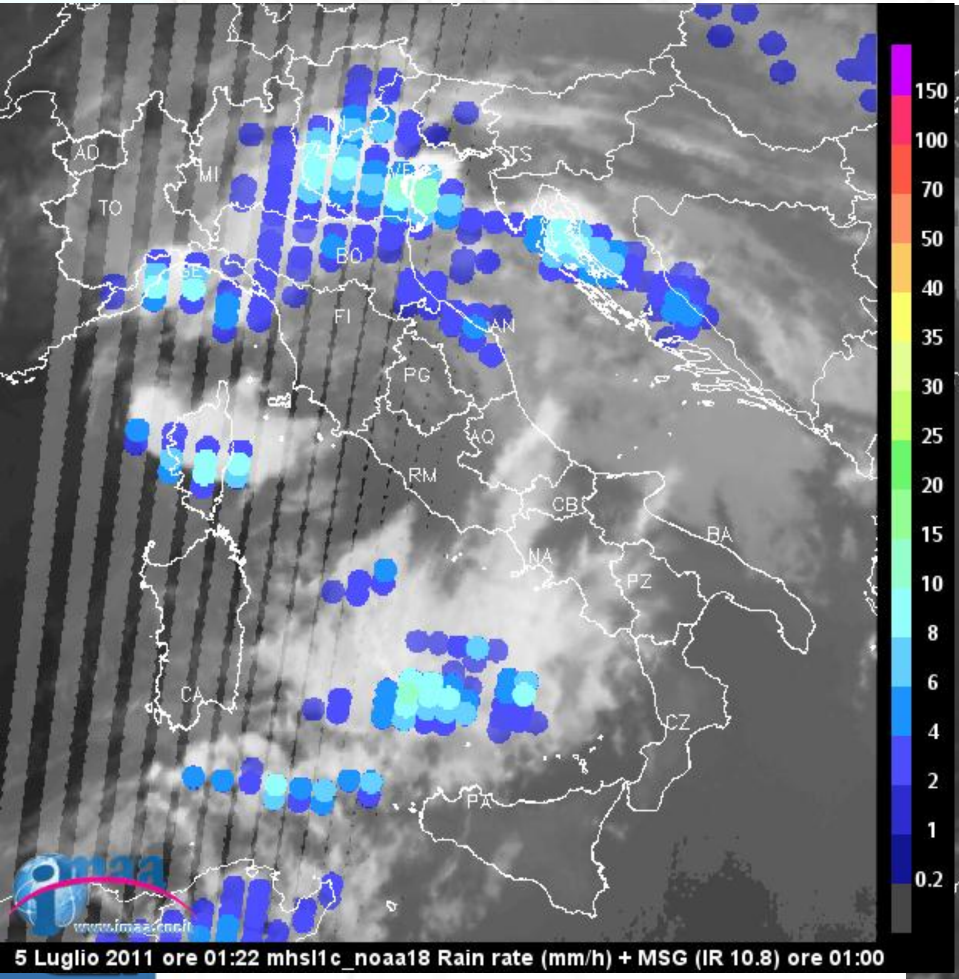
- How can we validate our product?!!??
  - Very difficult – no reference “truth” available
    - o Raingauge – point measurement
    - o Radar – volume measurement, but radial wrt to radar location

- Previously PEMW has been validated with selected case studies (using raingauges and France-UK radar network)

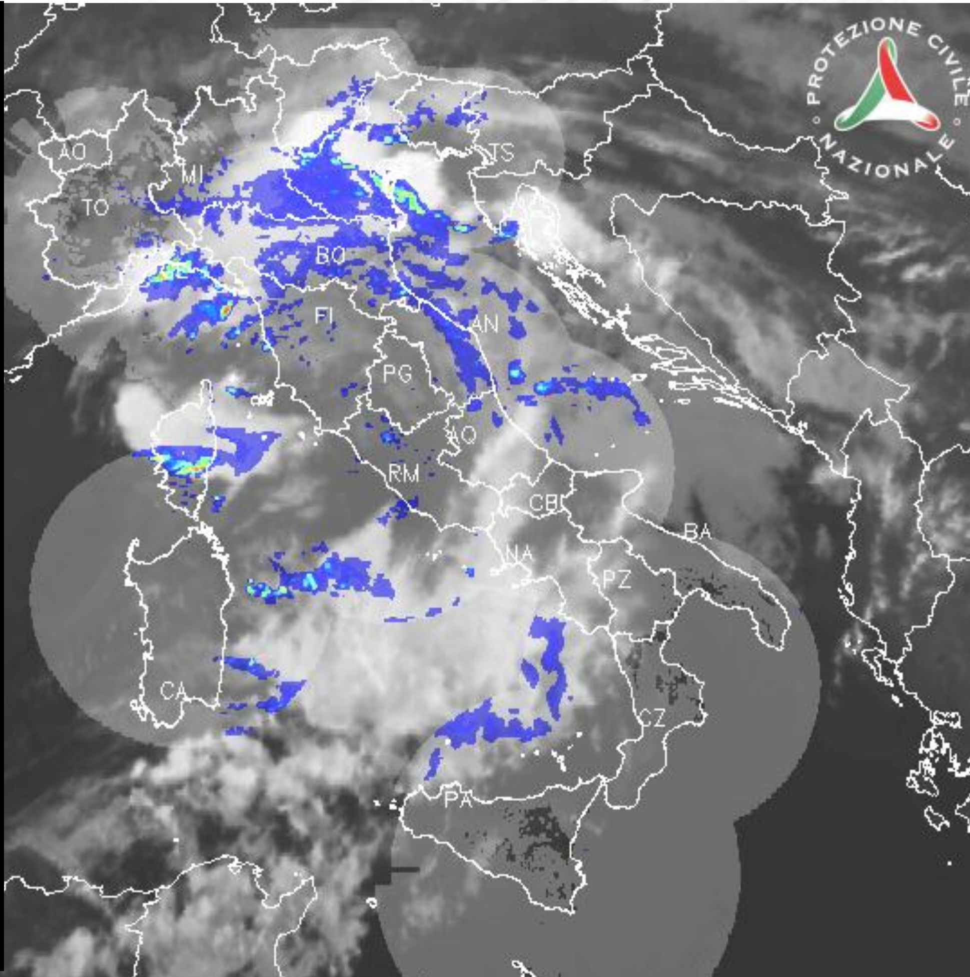
Case Studies
2011/07/05 01:22 UTC

Note: Storm in North East and southern Tyrrhenian

PEMW



RNC



Validation of PEMW with RNC

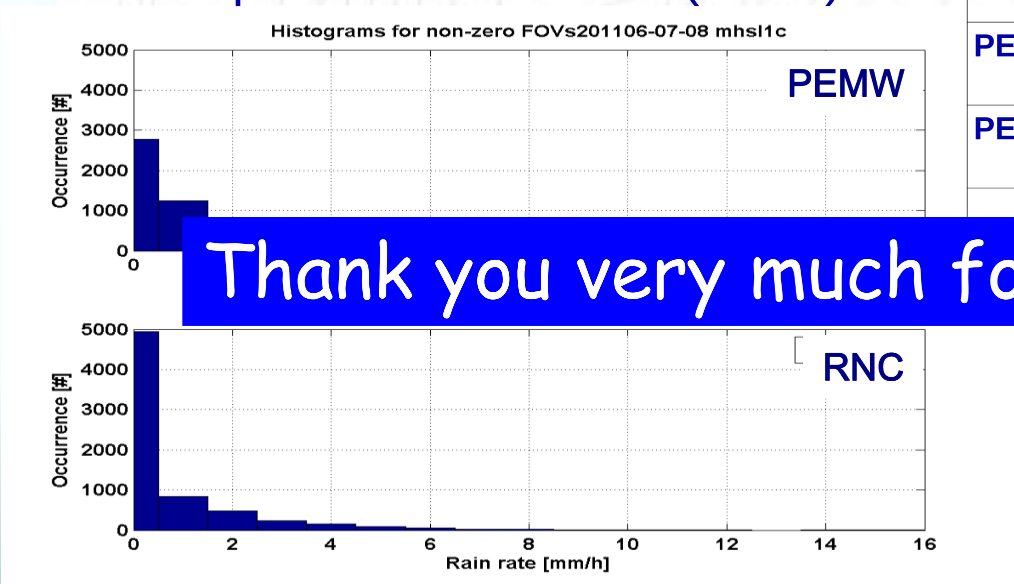
- Radar Network Composite allows a systematic validation of operational PEMW over Italy
  - Temporal colocation: RNC data within ±7.5 min of sat overpass
  - Spatial colocation: RNC data convoluted within PEMW FOVs

- Quantitative scores are computed to investigate the consistence between these two source of rainfall information
  - Dichotomous assessment
    - Contingency table, Accuracy, bias score, POD, FAR, HSS, PODN, CSI, HK, ISE, FOM, FOH, POFD, DFR, FOCN, TSS,…
  - Continuous assessment
    - Bias, rmse, FSE, FMR, FVR, NEB,…

Validation of PEMW with RNC
Seasonal product

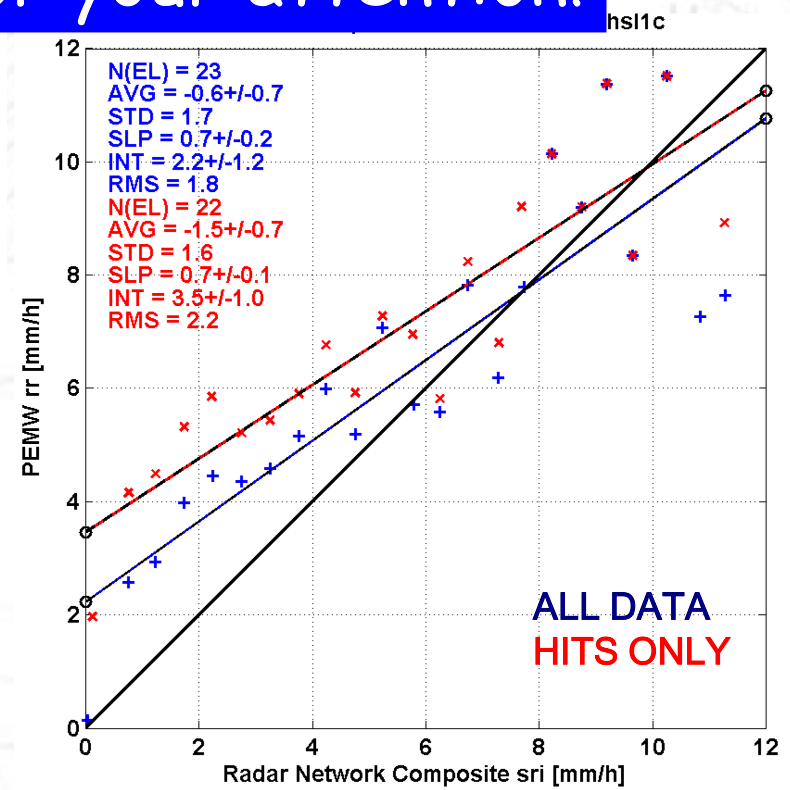
3-month colocated PEMW and RNC data set
Example: Summer 2011 (J-J-A)

	RNC (Y)	RNC (N)	
PEMW (Y)	H = 1797 H = 1348	F = 4024 F = 1738	5821 3086
PEMW (N)	M = 5100 M = 619	CN = 353173 CN = 360389	358273 361008
	6897 [illegible]	357197 [illegible]	364094 364094



Thank you very much for your attention!

	All FOVs	Neg. ≤ 0.5 mm/h	RNC ≥ 1 / 5 mm/h
Accuracy	0.97	0.99	-
Bias	0.84	1.57	-
POD	0.26	0.68	0.73 / 0.91
FAR	0.69	0.56	-
HSS	0.27	0.53	-



Publications

- Ricciardelli E., F. Romano, D. Cimini, F. S. Marzano, V.Cuomo,A statistical approach for rainfall confidence estimation using MSG-SEVIRI observations, EUMETSAT Meteorological Satellite Conference, Cordoba 20-24 September 2010
- Di Tomaso E., F. Romano, and V. Cuomo, Rainfall estimation from satellite passive microwave observations in the range 89 GHz to 190 GHz, J. of Geophysical Res., VOL. 114, 2009.
- Ricciardelli E., F. Romano, V. Cuomo, Physical and statistical approaches for cloud identification using MSG-SEVIRI data, Remote Sensing of Environment, 112 (2741-2760), 2008.
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- Marzano, F. S., D. Cimini, and F. J. Turk, Multivariate Probability Matching for Microwave Infrared Combined Rainfall Algorithm (MICRA), Measuring Precipitation from Space, Levizzani V., P. Bauer, and F. J. Turk Editors, Springer, 2007.
- Marzano F.S., D. Cimini, E. Coppola, M. Verdecchia, V. Levizzani, F. Tapiador and J. Turk, Satellite radiometric remote sensing of rainfall fields: multi-sensor retrieval techniques at geostationary scale, Adv. in Geosci., vol. 2, p. 267-272, 2005.
- Marzano, F. S., M. Palmacci, D. Cimini, G. Giuliani and J. F. Turk: Multivariate Statistical Integration of Satellite Infrared and Microwave Radiometric Measurements for Rainfall Retrieval at the Geostationary Scale, IEEE Transactions on Geoscience and Remote Sensing, Vol. 42, n. 5, pp. 1018-1032, 2004.