Microwave radiometry of clouds and precipitation: the contribution of the Sapienza group and Giovanni d'Auria

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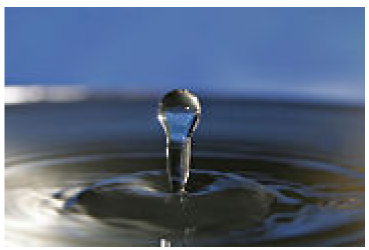
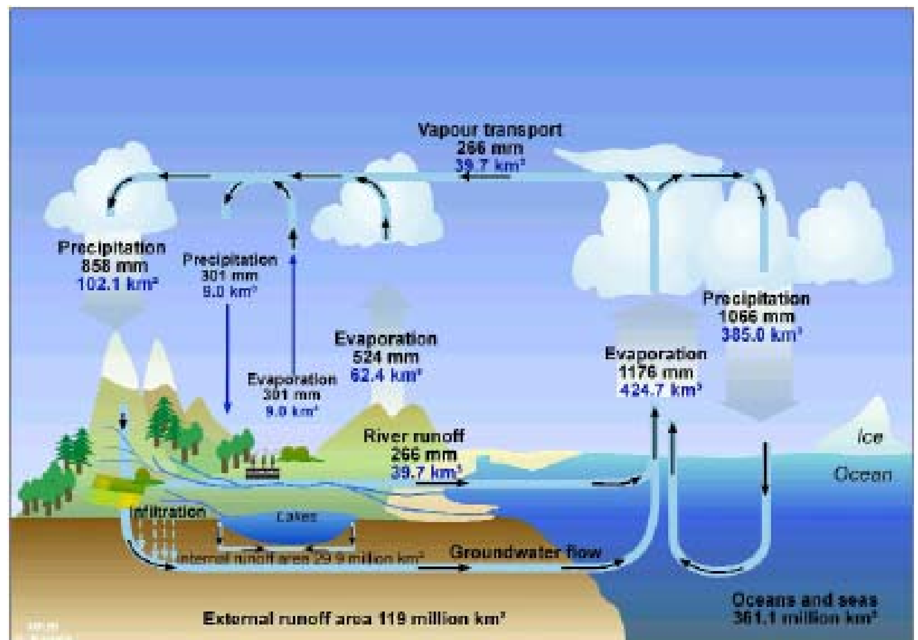
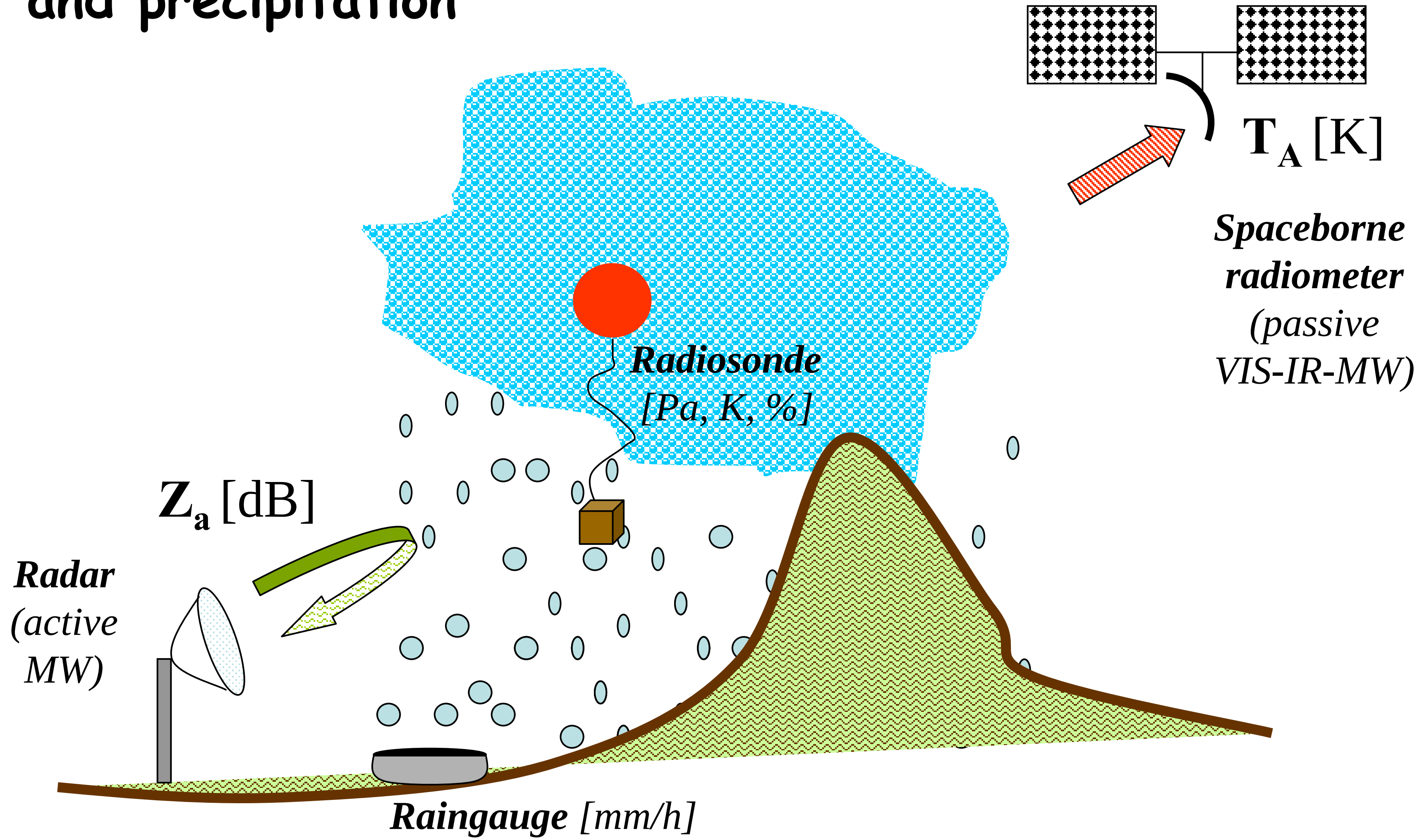
Outline of the presentation

- When did we start?
- Why did we start?
- What did we look for?
- How Prof. d'Auria (and not D'Auria!) ….



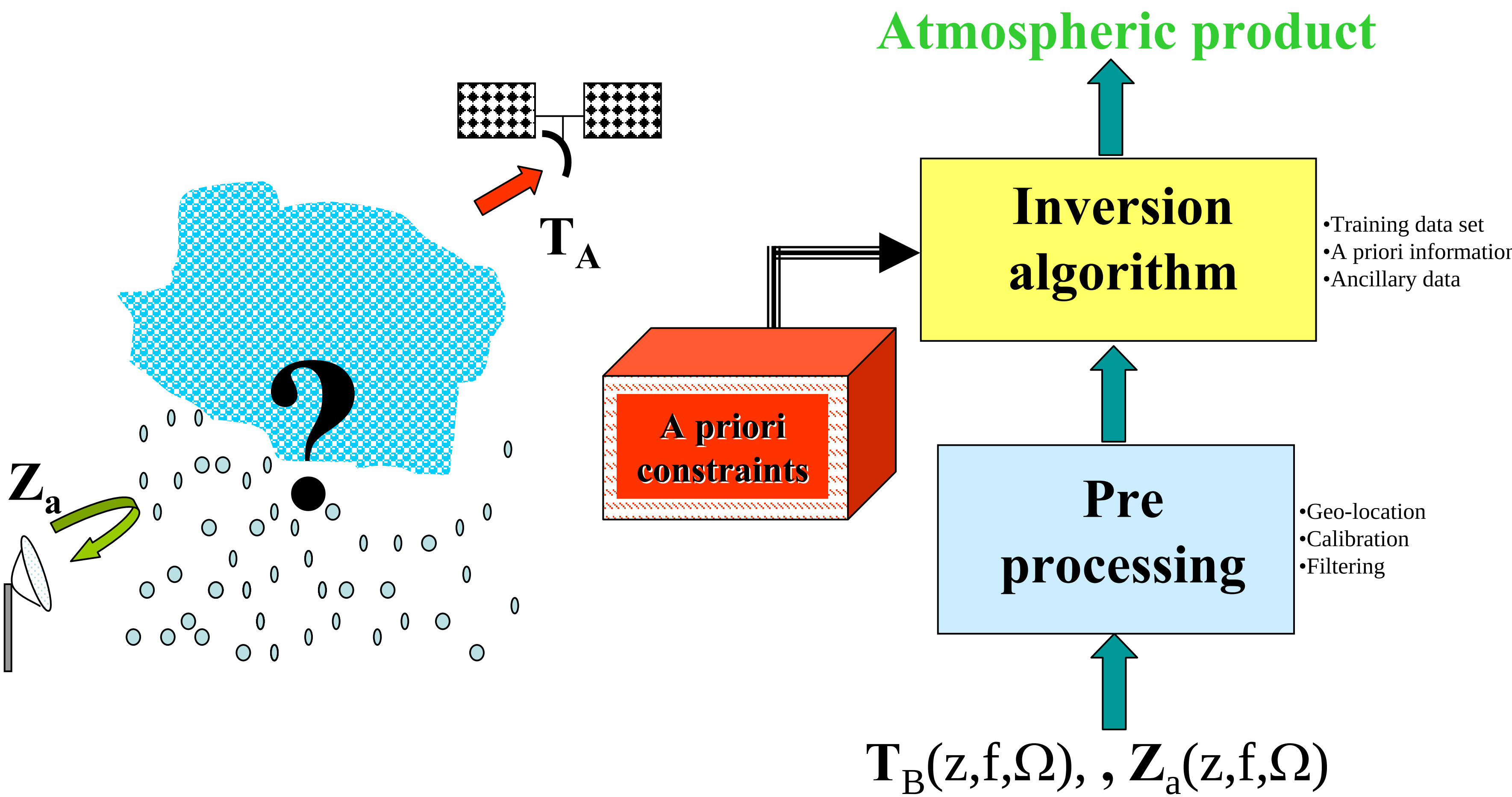


Measurements of tropospheric temperature, clouds and precipitation



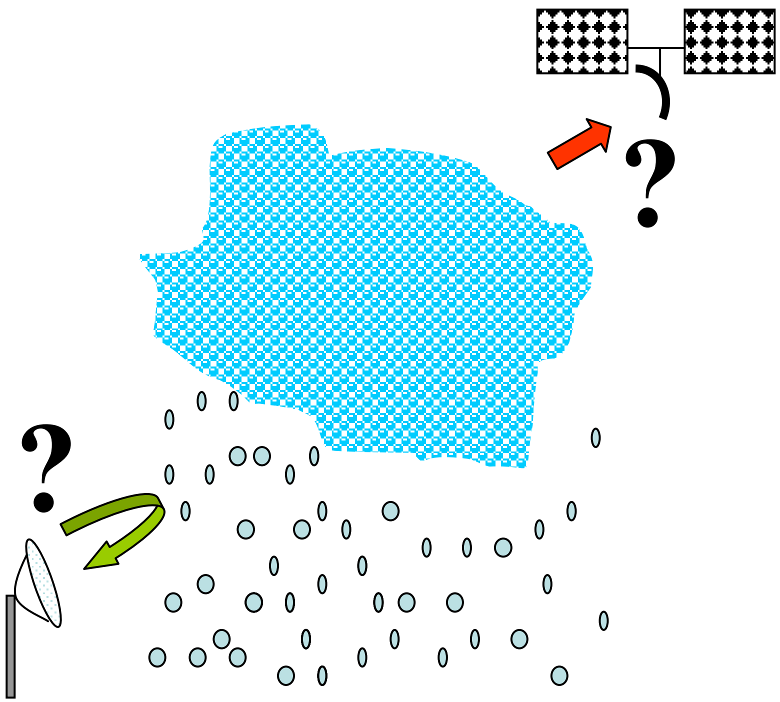
A point of view on remote sensing

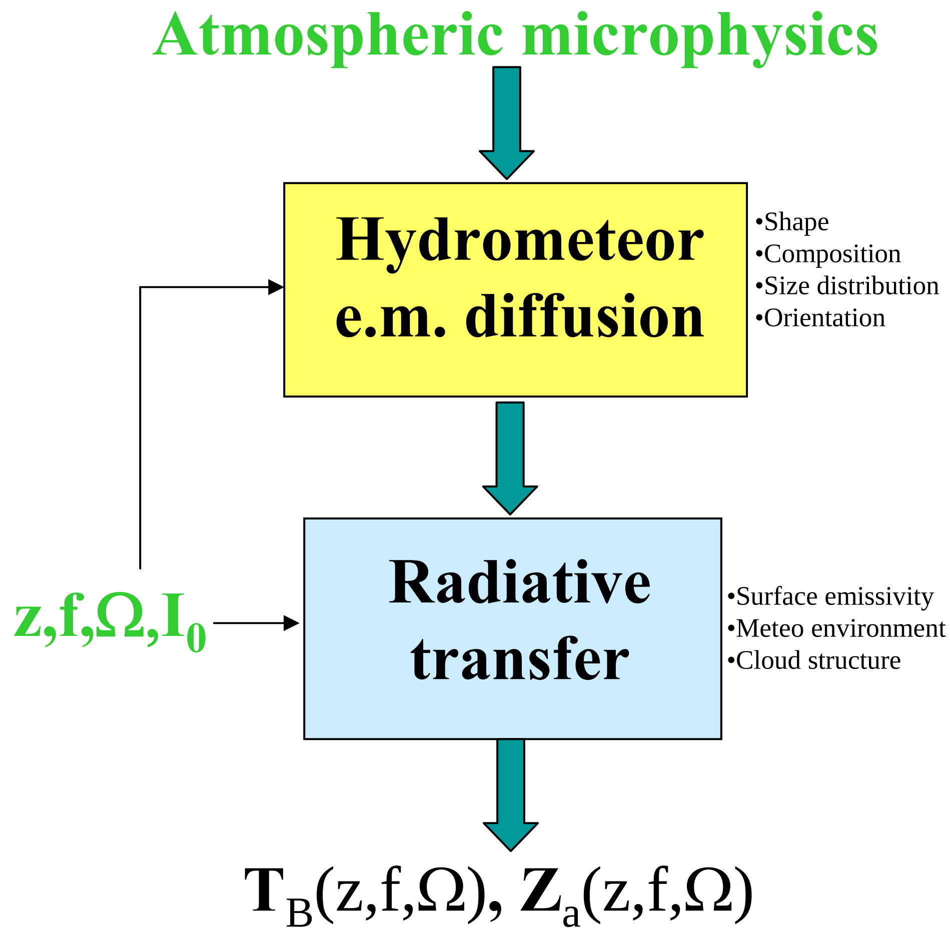
- An inverse problem in the information theory



The importance of forward modeling

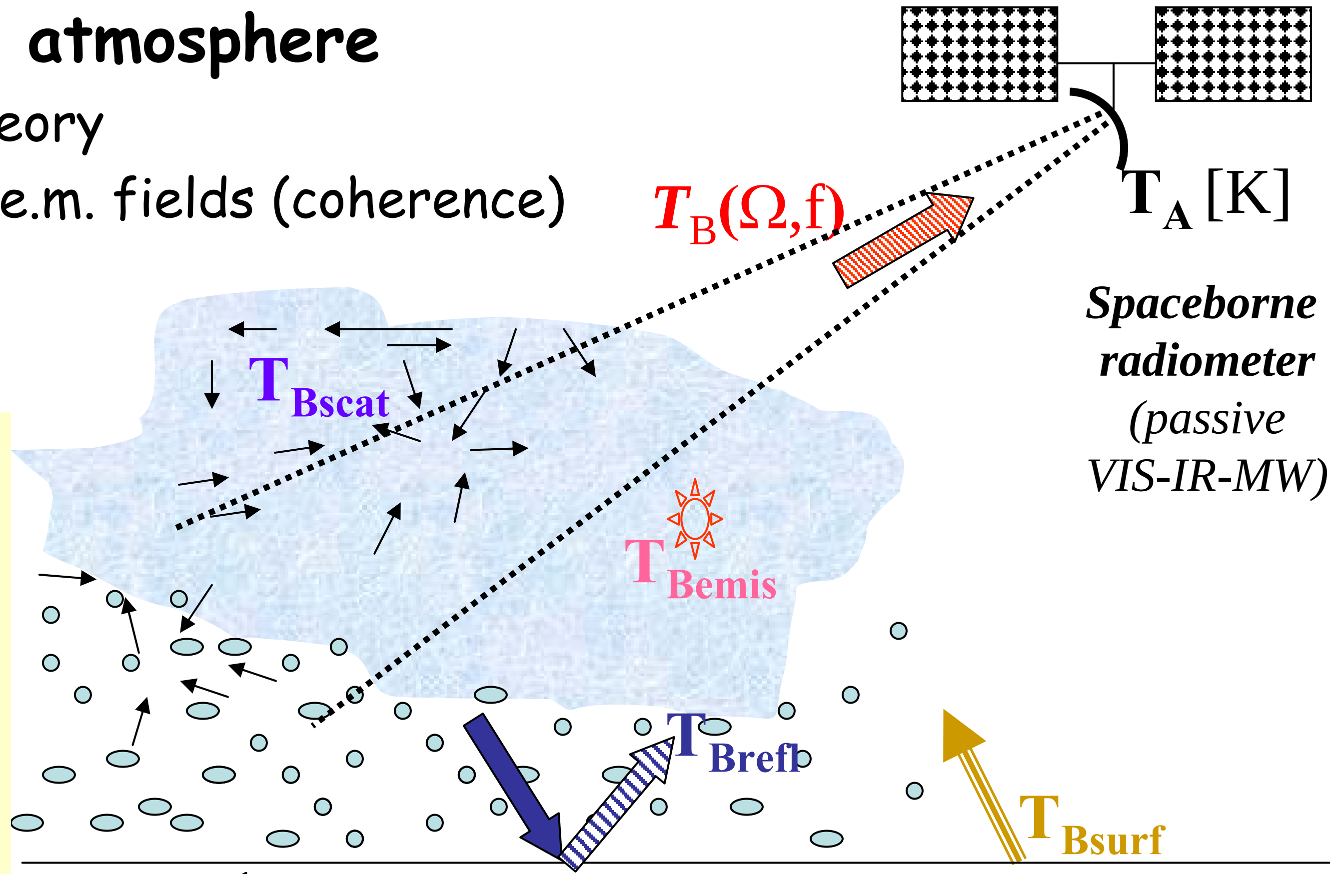
- **Remote sensing: the physical-electromagnetic problem**





Modeling microwave brightness temperature

- **Microwave Radiative Transfer through the atmosphere**
  - Antenna theory
  - Statistical e.m. fields (coherence)



Spaceborne radiometer *(passive VIS-IR-MW)*

Forward modeling

1. *Wilheit et al., 1977*
2. *Weinman et al., 1978*
3. *Stamnes et al., 1988*
4. *Mugnai and Smith, 1988*
5. *Gasiewskii and Staelinn, 1990*

$$T_A = \frac{1}{4\pi}\int_{4\pi} D(\theta,\varphi)T_B(\theta,\varphi)d\Omega$$

Radiative transfer in scattering atmosphere

- **Microwave Radiative Transfer equation**
  - Atmospheric optical thickness t(*z*)
  - Atmospheric albedo w and temperature *T*
  - Scattering phase function *p*(Ω,Ω')

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

⇒ Integro-differential equation (numerical solution)

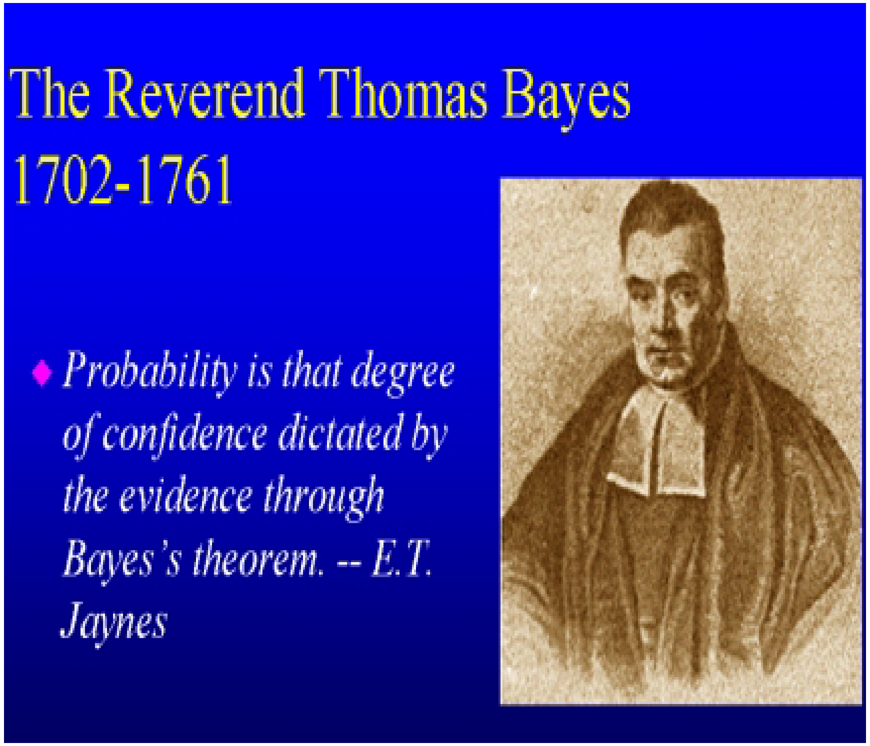
- **Formal solution**
  - Non-scattering atmosphere
    - Weighting function W
    - Temperature sounding

$$T_B(\tau,\Omega) = \int_{\Delta r} W(\tau,\tau')T(\tau')d\tau'$$

  - Uniform atmosphere

$$T_B(\tau,\Omega) = T_0(1-e^{-\tau_0})$$

A Bayesian (a posteriori) story



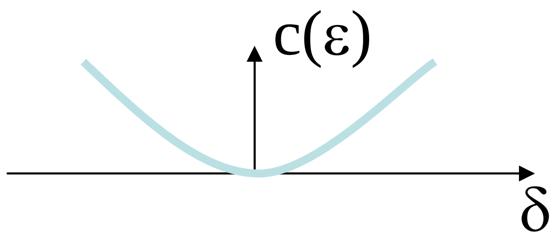
- Thomas Bayes was born in London in 1702 (?).
- In 1719 he enrolled at the University of Edinburgh to study logic and theology: as a **Nonconformist**, Oxford and Cambridge were closed to him.Rev.
- He died on 1761 in London: the tomb is in Bunhill Field cemetery, London
- "***An essay towards solving a problem in the doctrine of chances***", Phil. Trans. Roy. Sc., 53, 370-418, 1763, published posthumously by his friend Richard Price

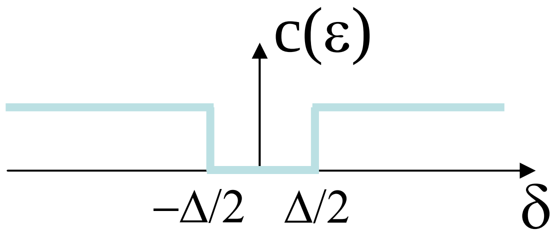
"Courts have consistently held that academic license does not extend to shouting "Bayesian" in a crowded lecture hall" (W. Press et al., 1982)

Bayesian approach to estimation (1)

- **Point of view**
  - Subjectivistic probability (de Finetti, 1970)
    - Opposite to *Kolmogorov's* assiomatic theory (1930)
  - Parameter estimation and decision theory (Wald, 1950)

- **Parameter estimation approach**
  - Error: $\boldsymbol{\varepsilon} = \mathbf{x} - \hat{\mathbf{x}}$ $\quad \begin{cases} \mathbf{x} : \textit{true values} \\ \hat{\mathbf{x}} : \textit{estimates} \end{cases}$
  - Squared cost: $c(\mathbf{x}, \hat{\mathbf{x}}) = c(\boldsymbol{\varepsilon}) = \boldsymbol{\varepsilon}^2$
  - Uniform cost $c(\mathbf{x}, \hat{\mathbf{x}}) = c(\boldsymbol{\varepsilon}) = u(|\boldsymbol{\varepsilon}|, \Delta)$





Bayesian approach to estimation (2)

- **Risk function:**

  ⇒ Estimator: minimize the risk function with a given cost

$$Risk = \langle c(\varepsilon) \rangle = \int_0^{\infty}\int_0^{\infty} c(\mathbf{x},\hat{\mathbf{x}})\, p_j(\mathbf{x},\mathbf{t}_m)\, d\mathbf{x}\, d\mathbf{t}_m$$

- **Squared cost: Minimum Mean Square (MMS) estimator**

$$\hat{\mathbf{x}}_{MMS} = Mean[p_p(\mathbf{x}|\mathbf{t}_m)] = \int_0^{\infty} \mathbf{x}\cdot p_p(\mathbf{x}|\mathbf{t}_m)\,d\mathbf{x} = \int_0^{\infty} \mathbf{x}\cdot \frac{p_l(\mathbf{t}_m|\mathbf{x})\,p_a(\mathbf{x})}{p_m(\mathbf{t}_m)}\,d\mathbf{x}$$

- **Uniform cost: Max A posteriori Probability (MAP) estimator**

$$\hat{\mathbf{x}}_{MAP} = Mode_x[p_p(\mathbf{x}|\mathbf{t}_m)] \quad \Leftrightarrow \quad \frac{\partial \ln[p_p(\mathbf{x}|\mathbf{t}_m)]}{\partial \mathbf{x}} = 0$$

A comparison and a choice

- **IGARSS95, Florence, 1995**

Rain retrieval algorithms for passive microwave observations:
a comparison and a choice

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Abstract -- Estimation techniques, currently using passive microwave observations for rainfall retrieval, are illustrated within a common theoretical framework. Comparisons of the various retrieval approaches are carried out on a simulated database, generated from a microphysical cloud model and a plane-parallel radiative transfer algorithm.

In this work, different cases of Bayesian estimates are considered together with particular and simplified cases. For most of them, the errors included in the estimation are given and commented on. The Bayesian approach does not require assumption of linearity and therefore a comparison with linear regression methods is also given. Since the

IGARSS95: some fundamental results

The Bayesian estimation requires the knowledge of the joint pdf expressed as p(g,t), which can be derived from the conditional and marginal pdf's:

$$p(g,t) = p(t|g)\,p(g) = p(g|t)\,p(t) \qquad (1)$$

The estimated value g' can be obtained by minimizing the expected value of the cost function C(g,g') :

$$< C(g,g') > = \int\int C(g,g')\,p(g,t)\,dt\,dg \qquad (2)$$

where the square brackets represent the ensemble average. Different forms of the cost function furnish different kinds of estimation. From the given database, p(t|g), or specifically p(t|R), can be obtained through the transfer equation. For a given R, the random values of g produce a distribution of values of t. Viceversa, a given set of simulated values of t is associated to a distribution of R values (*a posteriori* pdf).

Since 1995, almost all approach to spaceborne radiomery have been based on **Bayesian techniques**

- Evans et al., 1996
- Kummerow et al., 1996
- Pierdicca et al., 1996
- Marzano et al., 1999

Tab. 1 Comparison of the accuracies of various estimators

5000-point database	MAP Estim.	MMS Estim.	EMD Estim.	SMR Estim.	MMR Estim.
Rmse (mm/h)	2.51	1.87	5.81	6.28	6.27

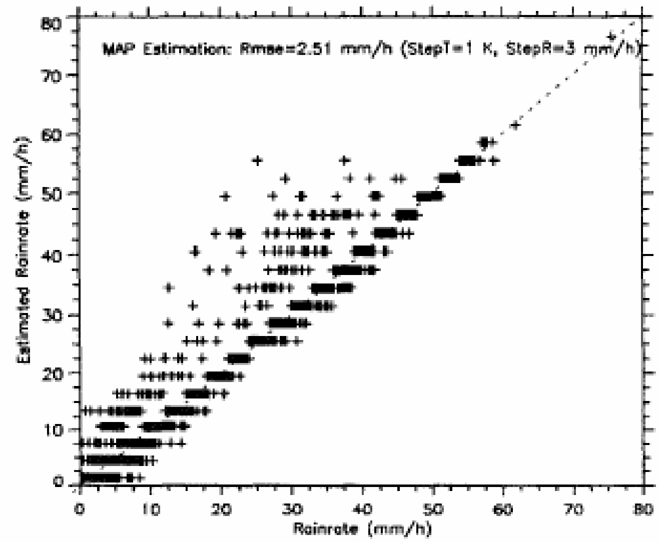


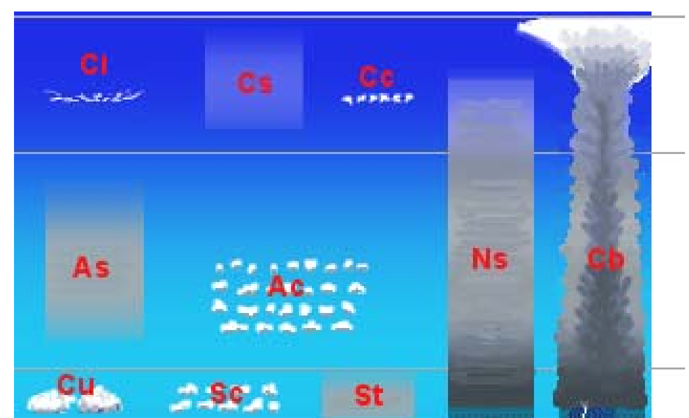
Fig.1 Scatterplot of R and estimated R' for MAP.

A Howardian point of view

- **Luke Howard** (November 28, 1772 – March 21, 1864), was a Quaker, later converting to the Plymouth Brethren, and a pharmacist by profession in London.
- His lasting contribution to science is a **nomenclature system for clouds**, presented in 1802 to the Askesian Society.
- *"Essay on the Modification of Clouds"*, which was published in 1803. Success of Howard's system was due to his use of universal Latin, as well as to his emphasis on the mutability of clouds

J.W. von Goethe (1749-1832):

But Howard gives us with his clear mind
The gain of lessons new to all mankind;
That which no hand can reach, no hand can clasp
He first has gained, first held with mental grasp



Cloud classification and MW radiometry

- **Radio Science, 1998**

Radio Science, Volume 33, Number 2, Pages 369–392, March–April 1998

Remotely sensing cloud properties from microwave radiometric observations by using a modeled cloud database

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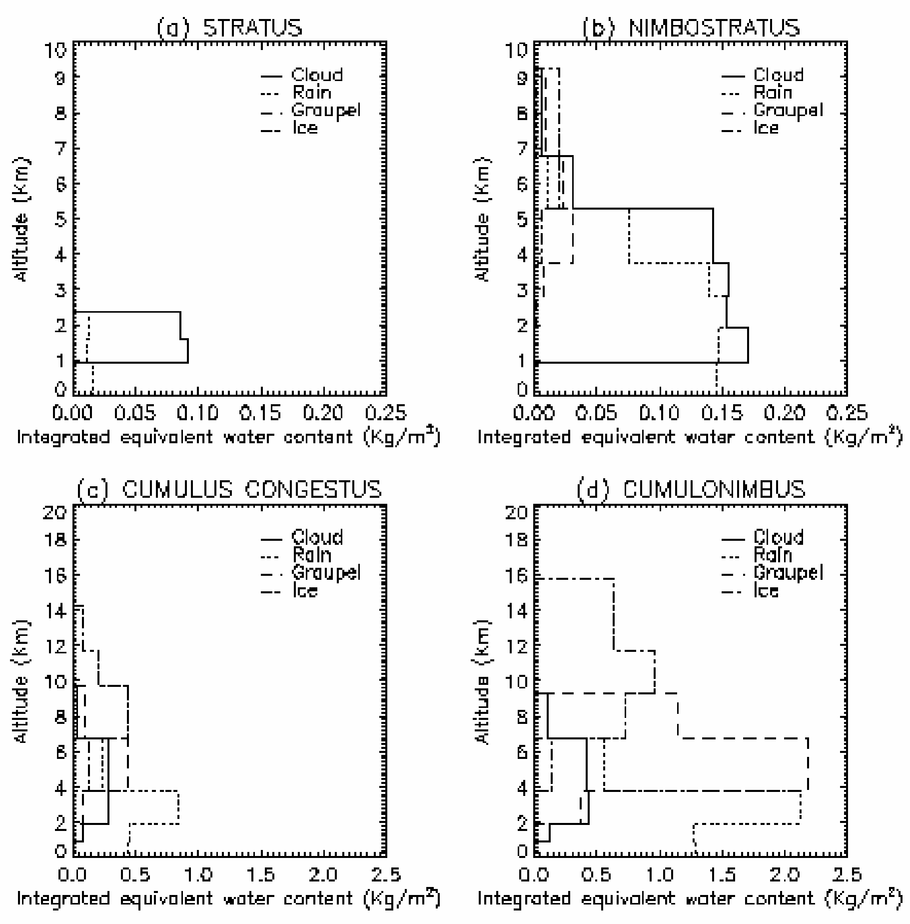
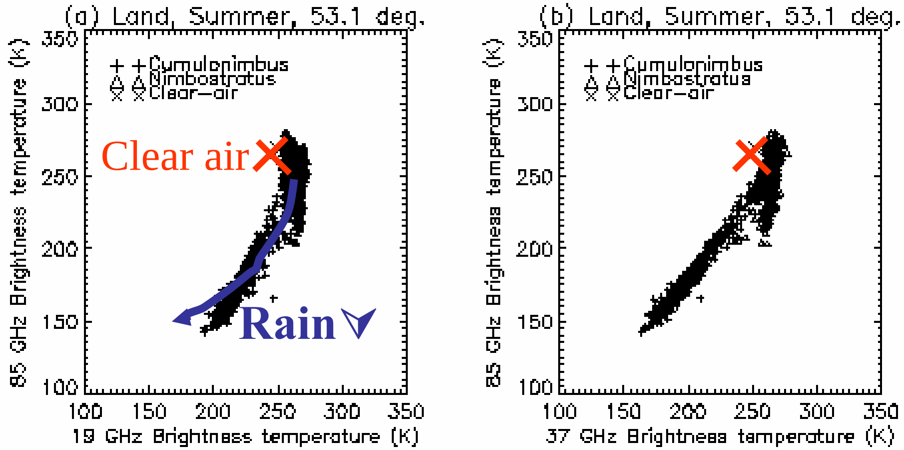
Abstract. As a first step for remote sensing cloud properties, a database of cloud genera has been established. This is derived from a microphysical model, and it considers the statistical profiles of four hydrometeor species for each cloud genus. From this database the corresponding radiative database is obtained making use of a radiative transfer model, so for each cloud genus the simulated microwave response at the special sensor microwave imager channels is found. The cloud and radiative databases allow the retrieval of the genera of the cloud and other relevant properties from satellite observations. An automatic cloud genus classifier has also been implemented. Several tests have been carried out, and the results are presented.

Modeled cloud structures

- **Average structures**
  - Taken from mesoscale models
  - Random generation of new structures using empirical stastistics
  - **Stratus**
    - Rainrate < 1 mm/h
    - negligible ice content
  - **Nimbostratus**
    - Rainrate < 20 mm/h
    - low ice content
  - **Cumulus congestus**
    - Rainrate < 50 mm/h
    - middle ice content
  - **Cumolonimbus**
    - Rainrate < 100 mm/h
    - Large ice content



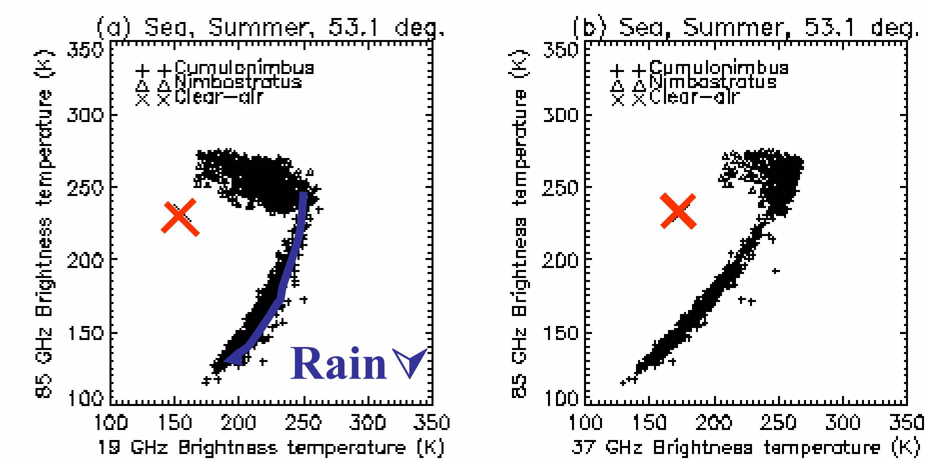
Spaceborne microwave response



Simulations over land

- Spherical hydrometeors
- Plane-parallel clouds
- SSM/I viewing angle

Simulations over ocean



Comparson with SSM/I observations

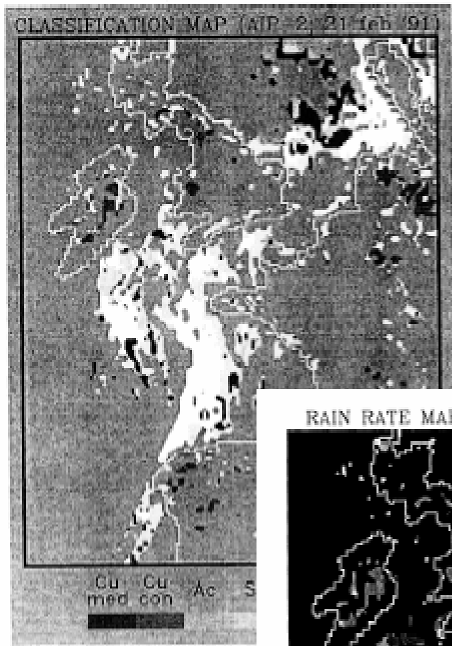


Figure 12. Cloud genera map acquired on February 21, 1991, at maximum-likelihood (ML) clas discriminating the cloud coverage,

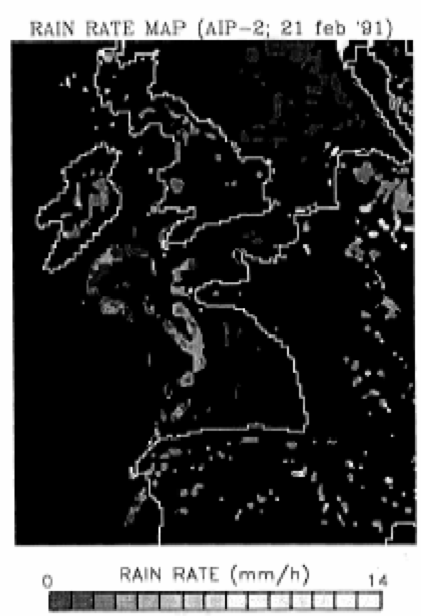


Figure 13. Rainfall rate maps estimated from SSM/I data acquired on February 21, 1991, at 0837 UTC by using the maximum a posteriori probability estimation method after applying the ML cloud classifier.

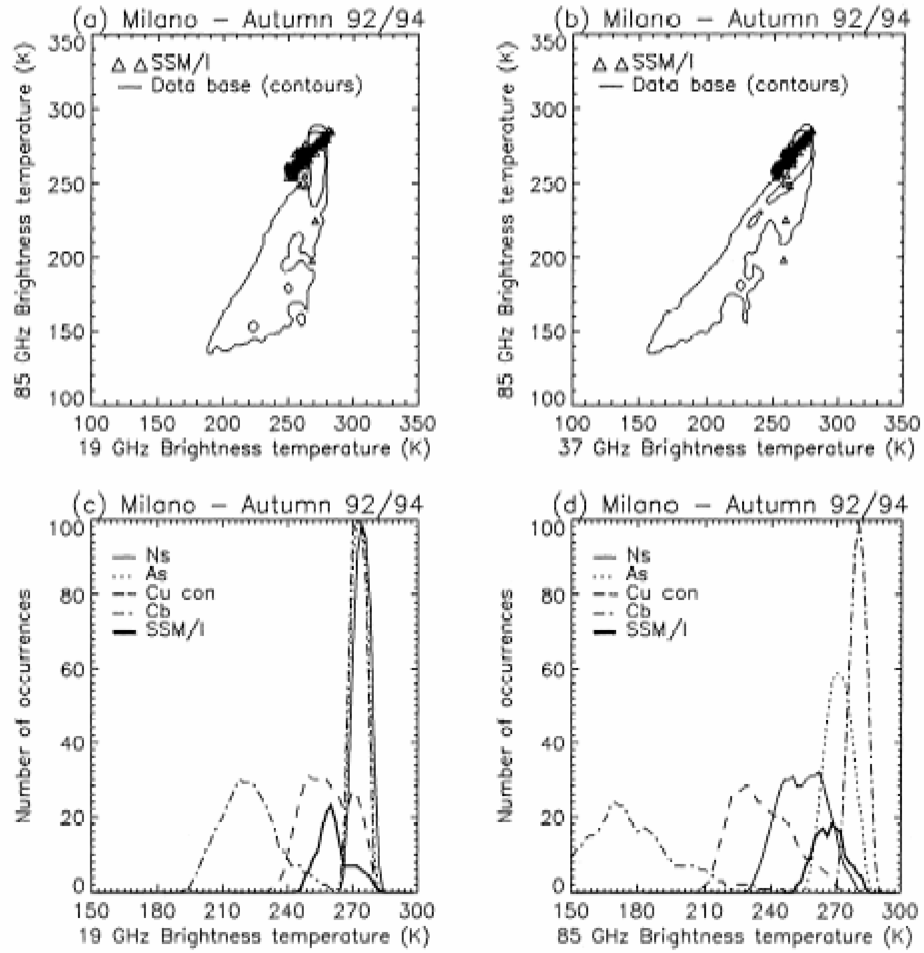


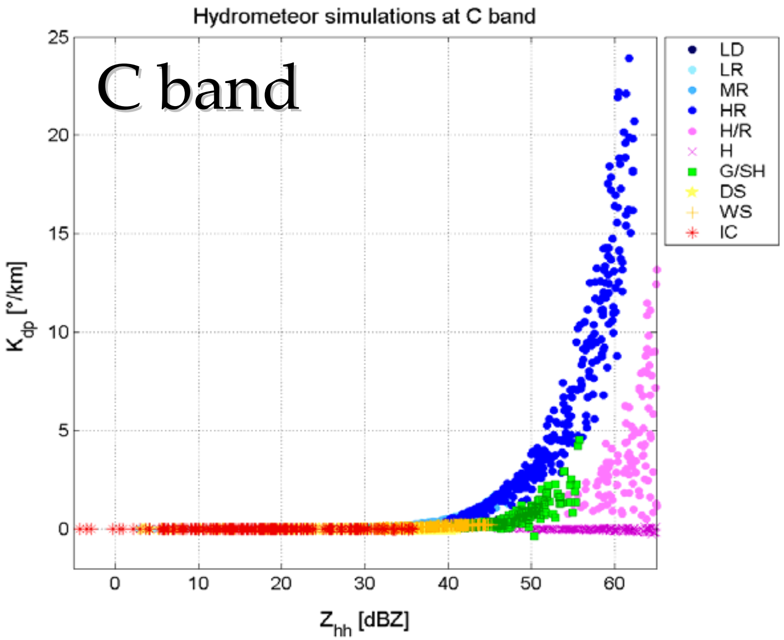
Figure 9. Scatterplots of SSM/I measurements (average of V and H polarizations) at (a) 19 and 85 GHz and (b) at 37 and 85 GHz, acquired over Milan, Italy, at 45.4° N, 9.5° E during the autumnal period of 1992 and 1994, superimposed over the whole modeled database (indicated on the T_B plane by contour lines of the point density histogram with a step of 350 and a bin of 5 K). Histograms of simulated (c) 19-GHz T_B and (d) 85-GHz T_B observed at 53.1° off-nadir angle over land during autumn for altostrati, nimbostrati, cumuli congesti, and cumulonimbi as compared to SSM/I measurements over Milan.

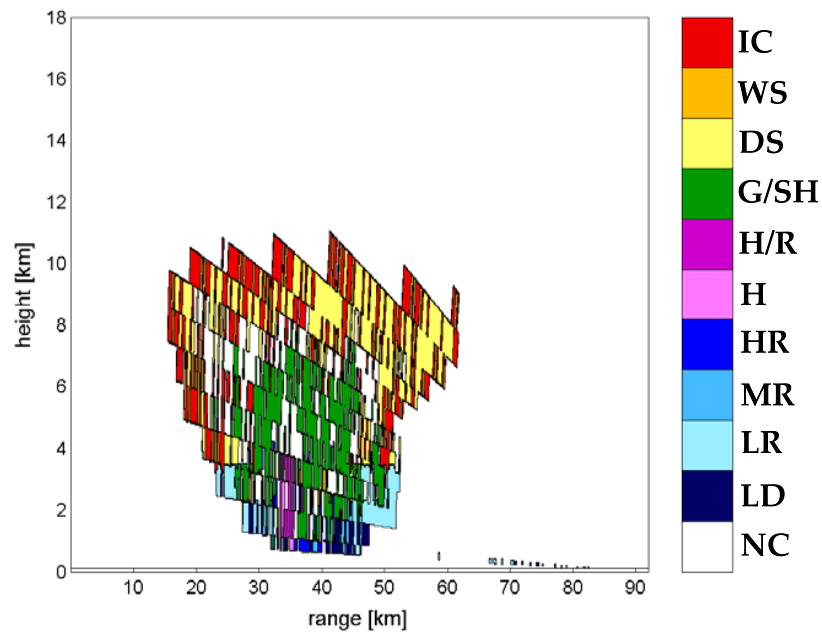
Applications of a rigorous methodology

- **Synergy of radiometers and radars**
  - Marzano F.S., A. Mugnai, G. Panegrossi, N. Pierdicca, E.A. Smith, and J. Turk, "**Bayesian estimation of precipitating cloud parameters from combined measurements of spaceborne microwave radiometer and radar**", IEEE Trans. Geosci. Remote Sens., vol. 37, pp. 596-613, 1999.
- **Ground-based radiometry of rainfall**
  - Marzano F.S., E. Fionda, P. Ciotti and A. Martellucci, "**Ground-based multi-frequency microwave radiometry for rainfall remote sensing**", IEEE Trans. Geosci. Rem. Sens., vol. 40, pp. 742-759, 2002.
- **Regional-scale meteorological retrieval**
  - Pulvirenti L., P. Castracane, F.S. Marzano, N. Pierdicca, and G. d'Auria, "**A Physical-Statistical Approach to Match Satellite Passive Microwave Retrieval to the Mediterranean climatology**", IEEE Trans. Geosci. Rem. Sens., vol. 40, n. 4, pp. 2271-2284, 2002
  - Pierdicca N., L. Pulvirenti, F.S. Marzano, G. d'Auria, P. Basili, and P. Ciotti, "**Intercomparison of inversion algorithms to retrieve rain-rate from SSM/I by using an extended validation set over the Mediterranean area**", IEEE Trans. Geosci. Rem. Sens., vol. 42, n.10, p. 2226-2239, 2004

Unexpected extensions to other fields

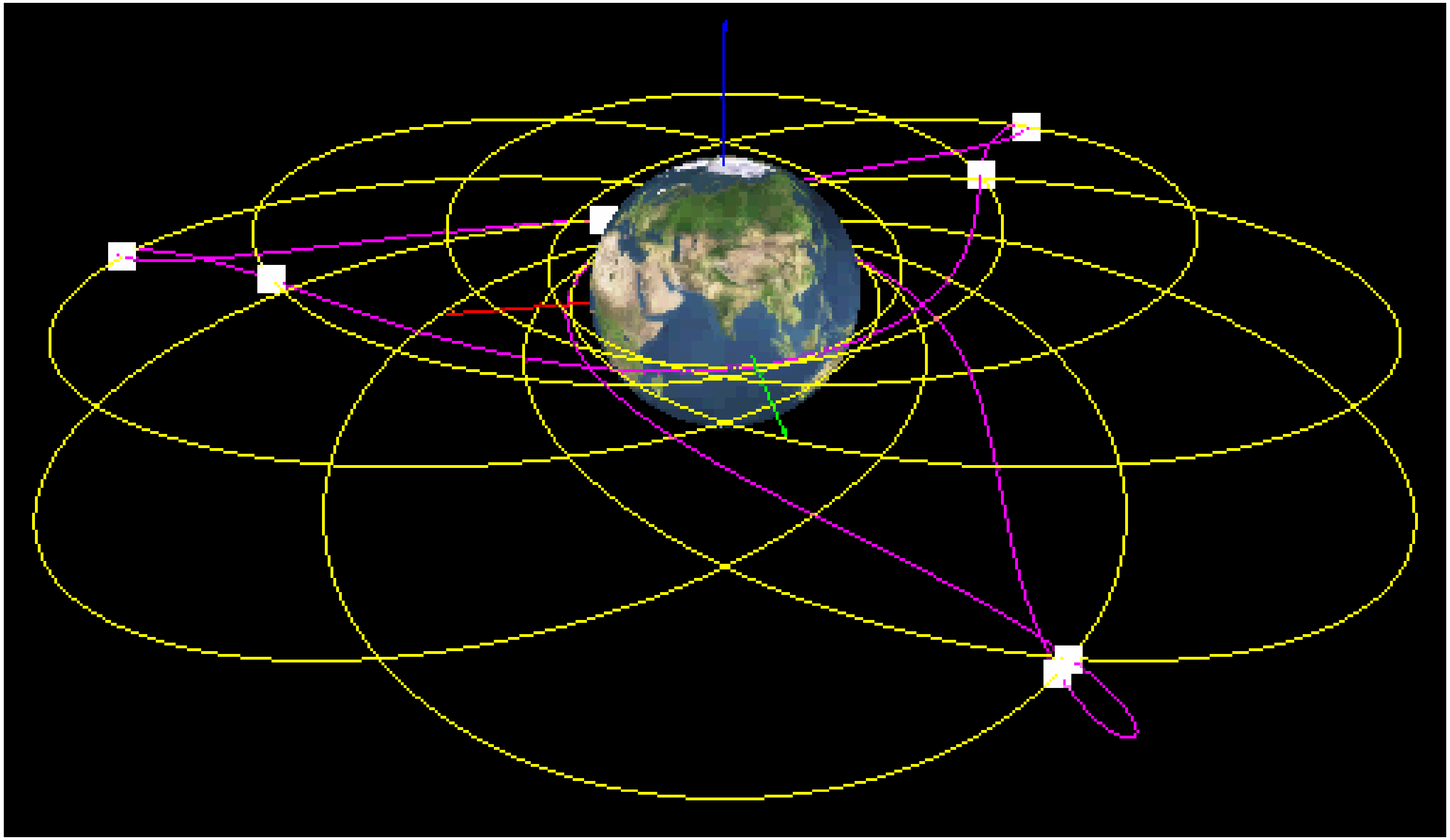
- **Weather-radar hydrometeor classification**
  - Marzano F.S., D. Scaranari, G. Vulpiani and M. Montopoli, "Supervised classification and estimation of hydrometeors using C-band dual-polarized radars: a Bayesian approach", IEEE Trans. Geosci. Rem. Sensing, n. 46, pp. 85-98, 2008.





FLORAD homage to Prof. d'Auria

Italian microwave radiometry in space ?



Conclusions ?

Percy B. Shelly (1792-1822)

" *The Cloud*" (1820)

……………………..
And the winds and sunbeams
with their convex gleams
Build up the blue dome of air,
I silently laugh at my own
cenotaph,
And out of the caverns of rain,
Like a child from the womb,
like a ghost from the tomb,
I arise, and unbuild it again.