# Measurement and characterization of rain Drop Size Distribution

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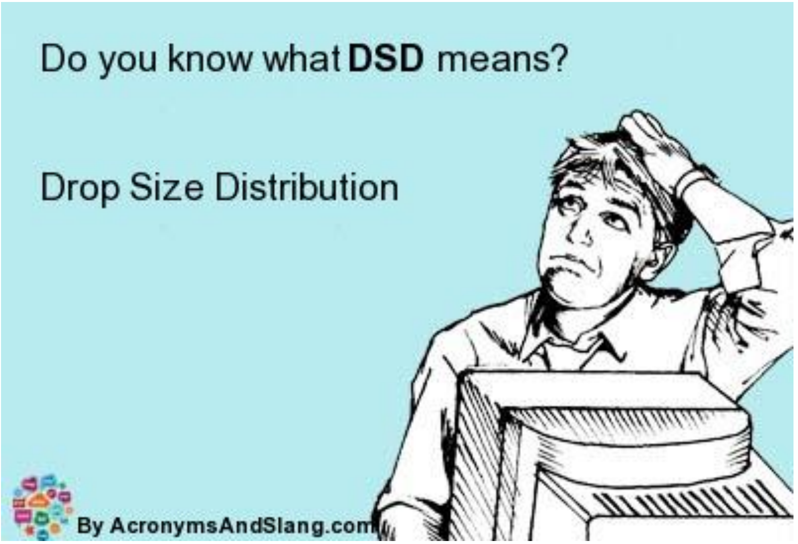
# OUTLINE

- Introduction
- DSD modelling
- Impact of DSD on radar rainfall estimation
- DSD in propagation studies
- Ongoing research and future perspectives

# Introduction

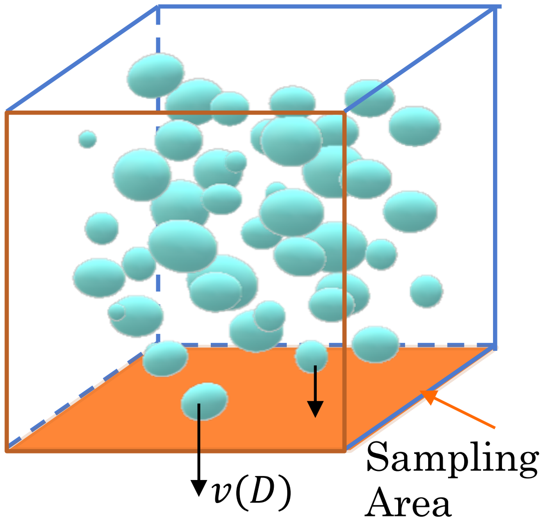
# Drop Size Distribution




DSD is defined as the number of drops per unit volume and diameter

$$N(D_i) = \frac{n_i}{A\,\Delta t\,\Delta D_i\,v(D_i)} \quad (mm^{-1}m^{-3})$$

n = number of drops with diameter D
A = virtual measuring area
Δt = time interval
ΔD = width of the class diameter
v(D) = terminal fall velocity




To date the three-parameter gamma distribution (Ulbrich 1983) is the most widely accepted and used by radar meteorologists and atmospheric physicists to model natural DSDs

$$N(D_i) = N_0\,D^{\mu}\exp(-\Lambda D)$$

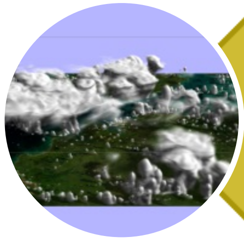
$N_0$ = intercept parameter ($mm^{-1-\mu}\ m^{-3}$)
$\mu$ = shape parameter
$\Lambda$= slope parameter ($mm^{-1}$)

$$R = 6\pi 10^{-4}\int_{D_{min}}^{D_{max}} v(D)N(D)D^3 dD \quad (mm\ h^{-1})$$

# DSD APPLICATIONS

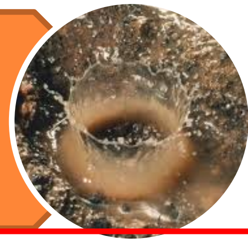
Precipitation estimation from remote sensing devices (satellite-borne sensors or ground based weather radars).

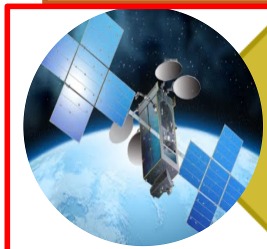
Characterization of rain microphysics and physical processes involved in the formation and evolution of precipitation



Impact of the DSD shape on the results of the numerical weather prediction models.

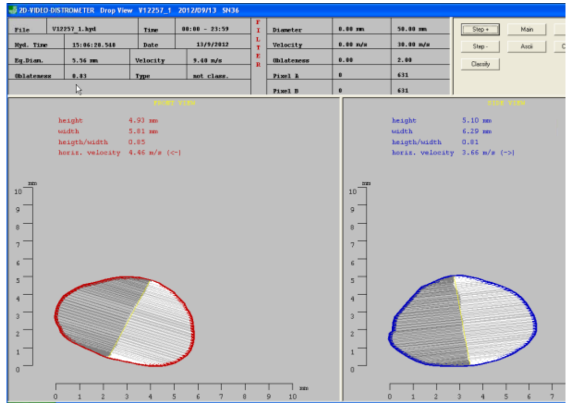
Estimation of the soil erosion caused by the impact of raindrops on the ground.

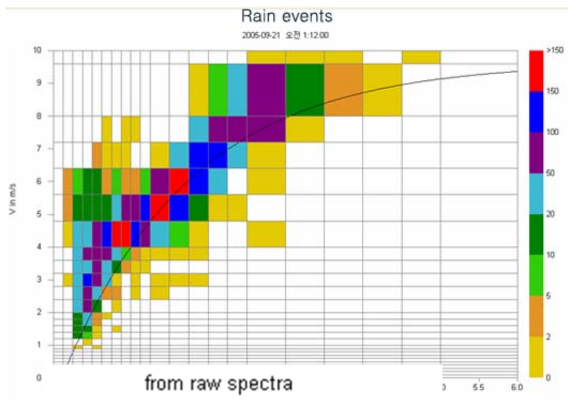


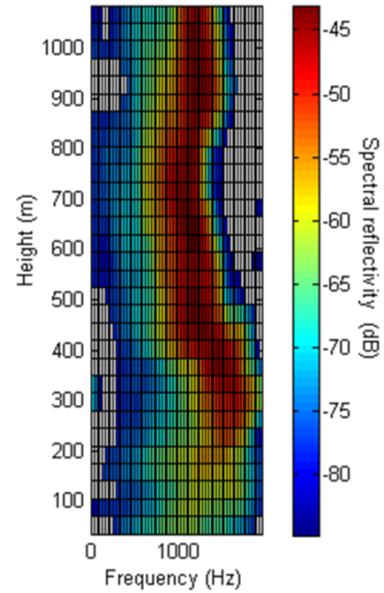


Microwave communications for dealing with rainfall attenuation that affects the propagation of waves.

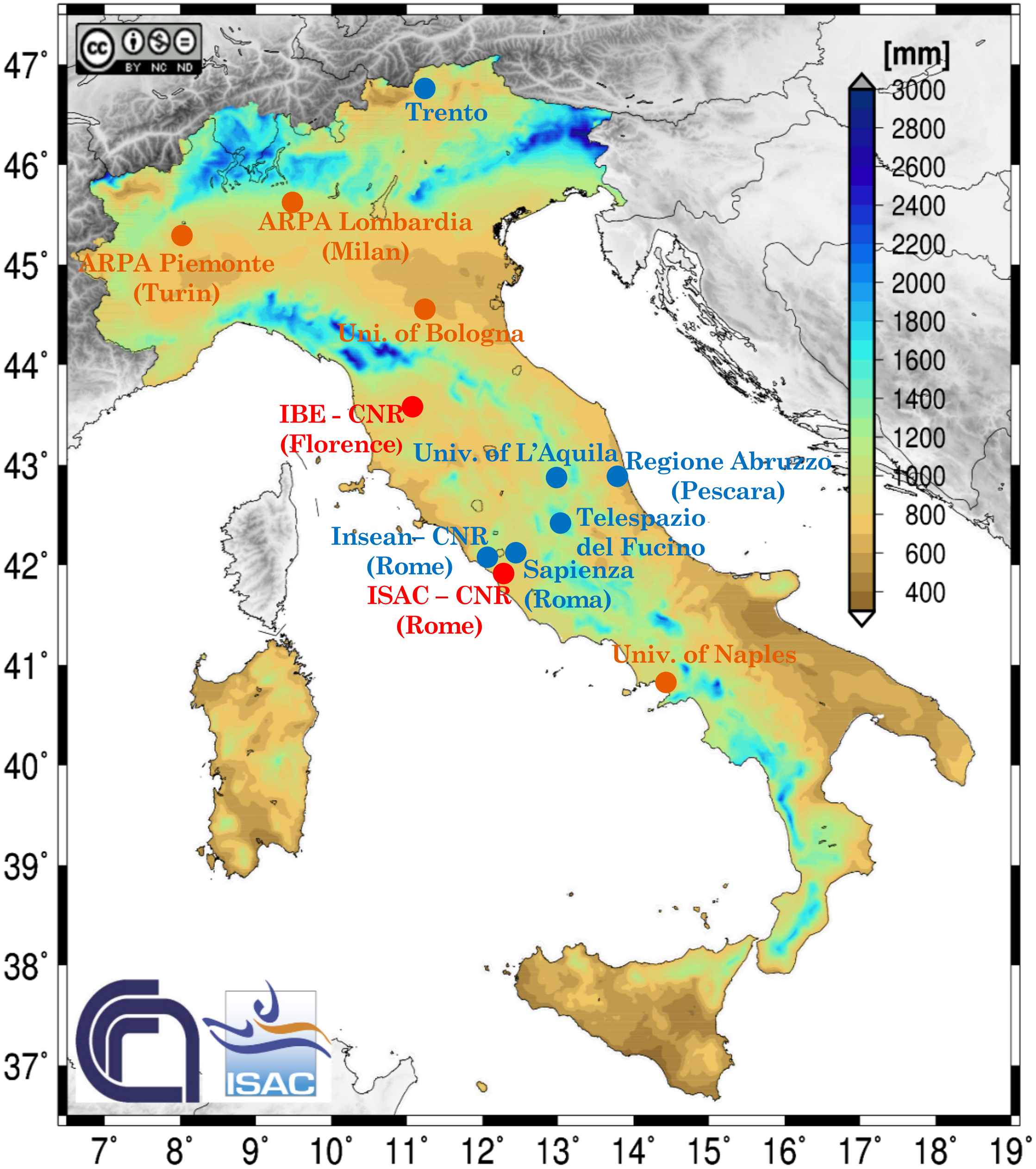
# DSD MEASUREMENT DEVICES



# DSD MEASUREMENTS IN ITALY




- Disdrometers of other Institutions (long time series)
- Disdrometers of ISAC (long time series)
- NASA disdrometers for a Special Observation Period (SOP1) of HyMeX project

Annual precipitation (1961-1990) from 6000 rain gauges) http://www.isac.cnr.it/climstor/climate_news.html.

# DSD MEASUREMENTS AT ISAC

## ISAC CNR

- Parsivel 2 (now at IBE-CNR in Florence). It is manly used for experimental field campaign thanks to an ad-hoc configuration. Data available from January 2016.
- Thies Clima (owner ARPA Piemonte) hosted at ISAC-CNR in Rome from September 2012.
- Parsivel (now at Mario Zucchelli Station in Antarctica). Data collected at ISAC-CNR in Rome from June 2010 to March 2016.
- Micro Rain Radar (now at Mario Zucchelli Station in Antarctica).

# DSD MODELLING

# BACKGROUND

In radar meteorology, modelling raindrop size distribution (DSD) is fundamental to develop reliable precipitation remote sensing products.

From a statistical point of view the DSD can be defined as

$$N(D) = n_c \, f_D(D) \quad (mm^{-3} \, m^{-1})$$

$n_c$ is the raindrop concentration; $f_D(D)$ is a probability density function (pdf)

- Exponential (Marshall and Palmer, 1948)
- Weibull (Sekine and Lind, 1982)
- Gamma (Ulbrich, 1983) with and without truncation
- Lognormal (Feingold and Levin, 1986)
- Normalized gamma distribution (Testud et al., 2001)
- Generalized Gamma (Lee et al., 2004)
- Johnson SB (Cugerone and De Michele, 2015)

# Performance of the different functional form in fitting measured DSD (1/3)

## *1. Statistical inference of $f(D)$*

The disdrometer measured drop size spectra are fitted by the **Maximum Likelihood Method** (ML) and the **Truncated Maximum Likelihood Method** (TML):

$$\boldsymbol{\mathcal{L}}(\beta,\gamma) = \prod_{i=1}^{M}[p(D_i;\beta,\gamma)]^{N_i}\,; \quad \boldsymbol{\mathcal{L}_T}(\beta,\gamma) = \prod_{i=1}^{M}\left[\frac{p(D_i;\beta,\gamma)}{1-P(D_{th};\,\beta,\gamma)}\right]^{N_i}$$

where β and γ are the scale and shape parameters, $N_i$ is given by the inverse of the volume of air (V), and $D_{th}$, equal to 0.2 mm, is the lower threshold under which the disdrometer is not able to detect drop diameters. The probability model considered in the fittings are the gamma, lognormal and Weibull distributions with positive shape and scale parameters:

$$p_{GA} = \frac{1}{\beta\,\Gamma(\gamma)}\left(\frac{D}{\beta}\right)^{\gamma-1} exp(-D/\beta); \qquad p_{LN} = \frac{1}{D\,\gamma\,\sqrt{\pi}}\,exp\left[-ln^2(D/\beta)^{\frac{1}{\gamma}}\right];$$

$$p_{WE} = \frac{\gamma}{\beta}\left(\frac{D}{\beta}\right)^{\gamma-1} exp(-D/\beta)^{\gamma}$$

# Performance of the different functional form in fitting measured DSD (2/3)

***2. Model testing***

The Kolmogorov-Smirnov (KS) test is used: a model assumption is accepted if

$$D_M < \Delta_M(\alpha)$$

where $D_M$ is

$$D_M = max_i \left| F(D_i) - \hat{F}(D_i) \right|$$

with the empirical cdf is simply computed

$$F(D_i) = \frac{1}{\sum_{z=1}^{M} 1/v(D_z)} \sum_{j=1}^{i} \frac{1}{v(D_j)}$$

and $\Delta_M(\alpha)$ is a critical reference value computed through Monte Carlo simulations because the parameters of the reference distributions are determined from the data.

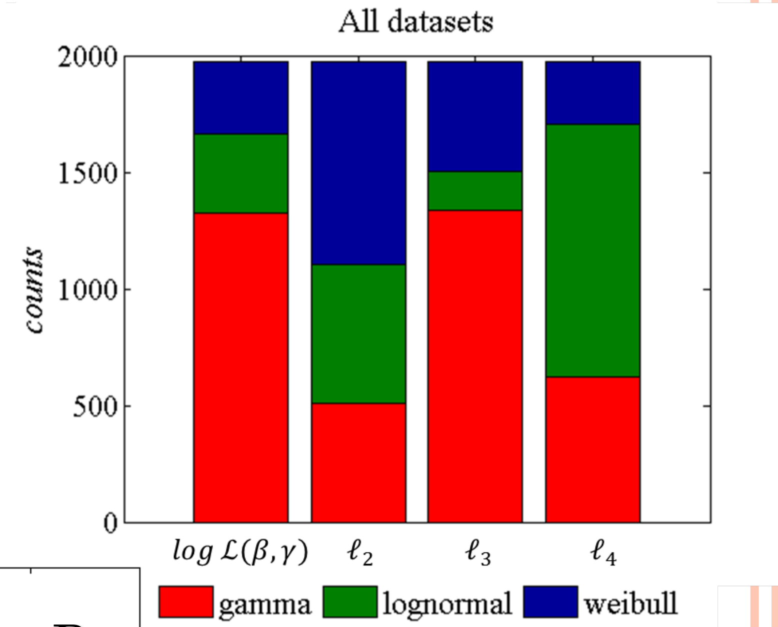
Among the samples that pass the KS test, the best model is the one with:

- maximum values of log-likelihood
- minimum difference between the sample and theoretical second, third or fourth L- moments

# PERFORMANCE OF THE DIFFERENT FUNCTIONAL FORM IN FITTING MEASURED DSD (3/3)

## *3. Main Results*

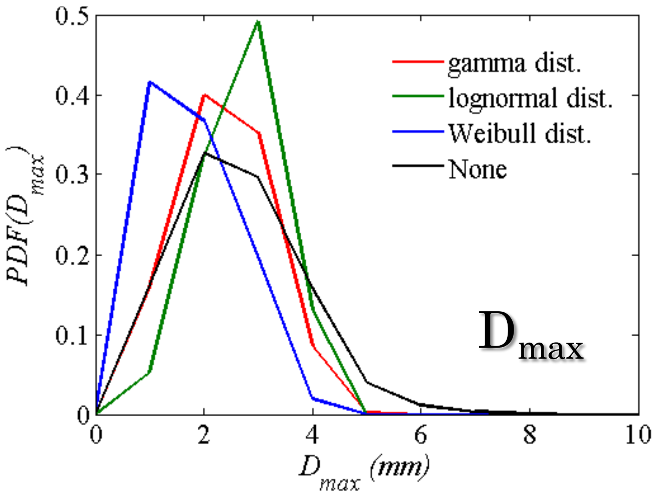
Best distribution

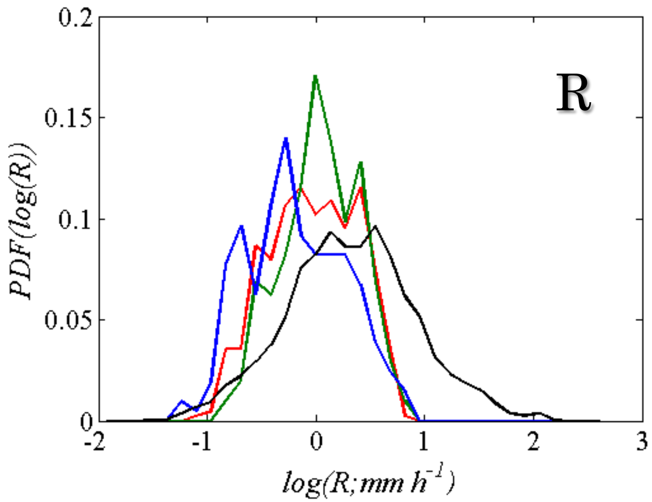



Rejection rate from KS test for ML

| | Fitting of $f(D)$ | | | |
|---|---|---|---|---|
| | HyMeX | MC3E | IFloodS | IPHEx |
| **gamma** | 77.3% | 73.9% | 83.7% | 76.7% |
| **lognormal** | 81.3% | 78.9% | 88.9% | 82.3% |
| **Weibull** | 85.5% | 82.2% | 85.9% | 82.3% |

Practical implications



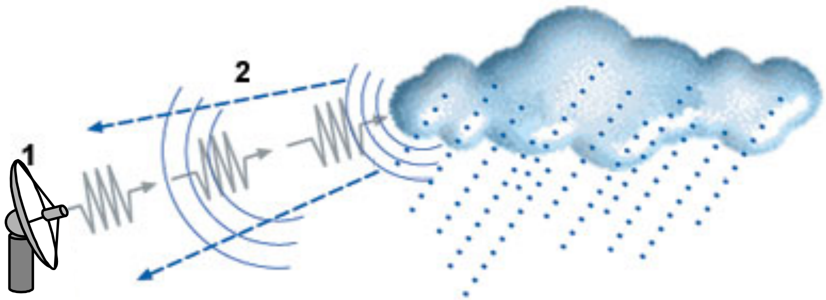






Adirosi et al. (2016)

# Impact of DSD on radar rainfall estimation

# Quantitative Precipitation Estimation (QPE)




- $Z_h$ in mm$^6$ m$^{-3}$ (or dBz) (horizontal reflectivity)
- $Z_{dr}$ in dB (differential reflectivity)
- $K_{dp}$ in ° km$^{-1}$ (specific differential propagation phase shift)

$$Z_{h,v} = \frac{4\,\lambda^4}{\pi^4\,|K_w|^2} \int |s_{h,v}(D)|^2\, N(D)dD \qquad (mm^6 m^{-3})$$

$$Z_{dr} = 10\, log_{10}(Z_h/Z_v) \qquad \text{(dB)}$$

$$K_{dp} = \frac{180\,\lambda}{\pi} \int [f_h(D) - f_v(D)]\; N(D)dD \qquad (°\, km^{-1})$$

**Precipitation retrieval algorithm** based on assumption related to the DSDs

R in mm (rain rate)

$$R = a\, Z_h^{\;b}$$

$$R = a\, K_{dp}$$

$$R = aZ_h^{\;b}\, Z_{dr}^{\;c}$$

$$R = a\, K_{dp}^{\;b}\, Z_{dr}^{\;c}$$

Can be affected by errors
- in radar measurements
- in the conversion of radar measurements into rainfall rate at ground

# PRECIPITATION RETRIEVAL ALGORITHMS

1. Statistically based: define rainfall algorithms analyzing rain measurements and corresponding radar measurements collected aloft by radar.

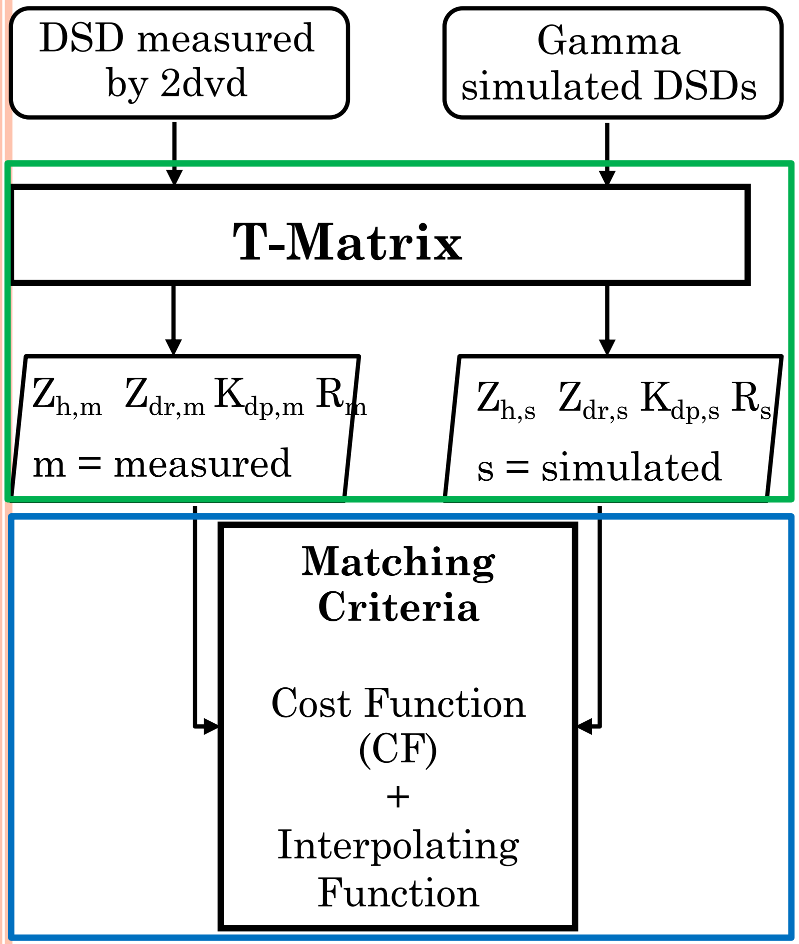
2. Physically based: require a microphysical model of rain coupled with an electromagnetic model for scattering and absorption

   a. Based on a set of **theoretical DSD** (generally a gamma-type)
      - an a priori analytical DSD model (such as the gamma) can not able to correctly model all the natural DSDs
      - the accuracy of parameter of the theoretical distribution depends on the fitting methods used (i.e. Johnson et al., 2011)

   b. Based on a set of **disdrometer-measured DSD.** Although the use of measured DSDs provides more significant weather radar algorithms from the climatologic point of view, errors due to
      - Sampling effects (Smith et al., 1993)
      - measurement fluctuation (i.e. Chandrasekar et al. 1990)
      - DSD variability (i.e. Ryzhkov et al. 2005)
      - raindrop shape-size relation (i.e. Gorgucci and Baldini 2009)
      - error structure of the measured drop spectra in relation to the kind of device used for the measurements.

# IMPACT OF GAMMA ASSUMPTION ON RADAR RAINFALL RETRIEVAL (1/2)

## *1. Methodology*

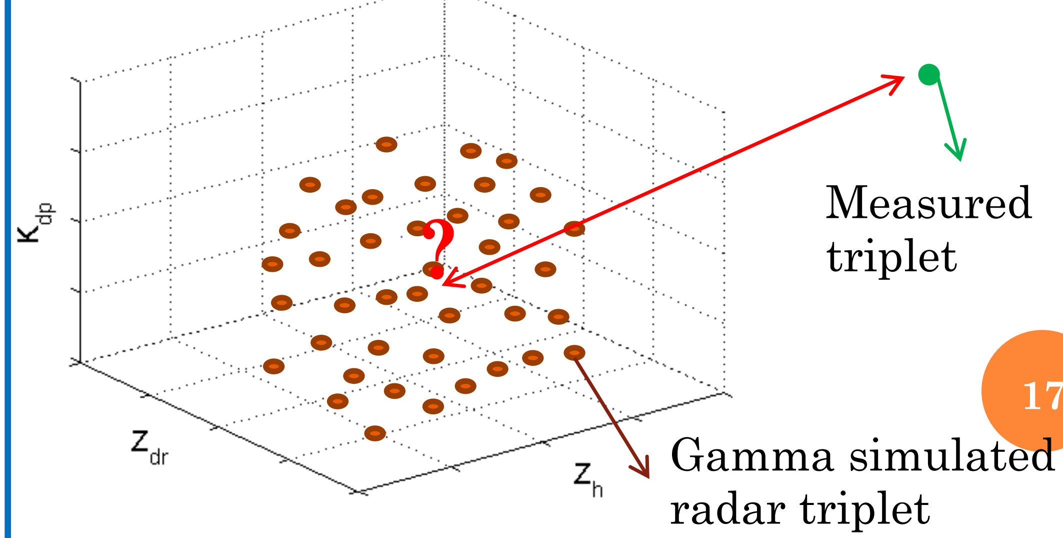



Given a DSD (simulated or measured) the **dual-polarization radar measurements** can be estimated using electromagnetic models, such as the T-matrix method. Assumption:

- ❑ Temperature: 20°C
- ❑ Standard deviation of the canting angle: 10°
- ❑ Frequency : 2.725 GHz (S-band), 5.6 GHz (C-band), and 9.375 GHz (X-band)
- ❑ Shape-size model

## Goal of the matching criteria

Gamma simulated dataset

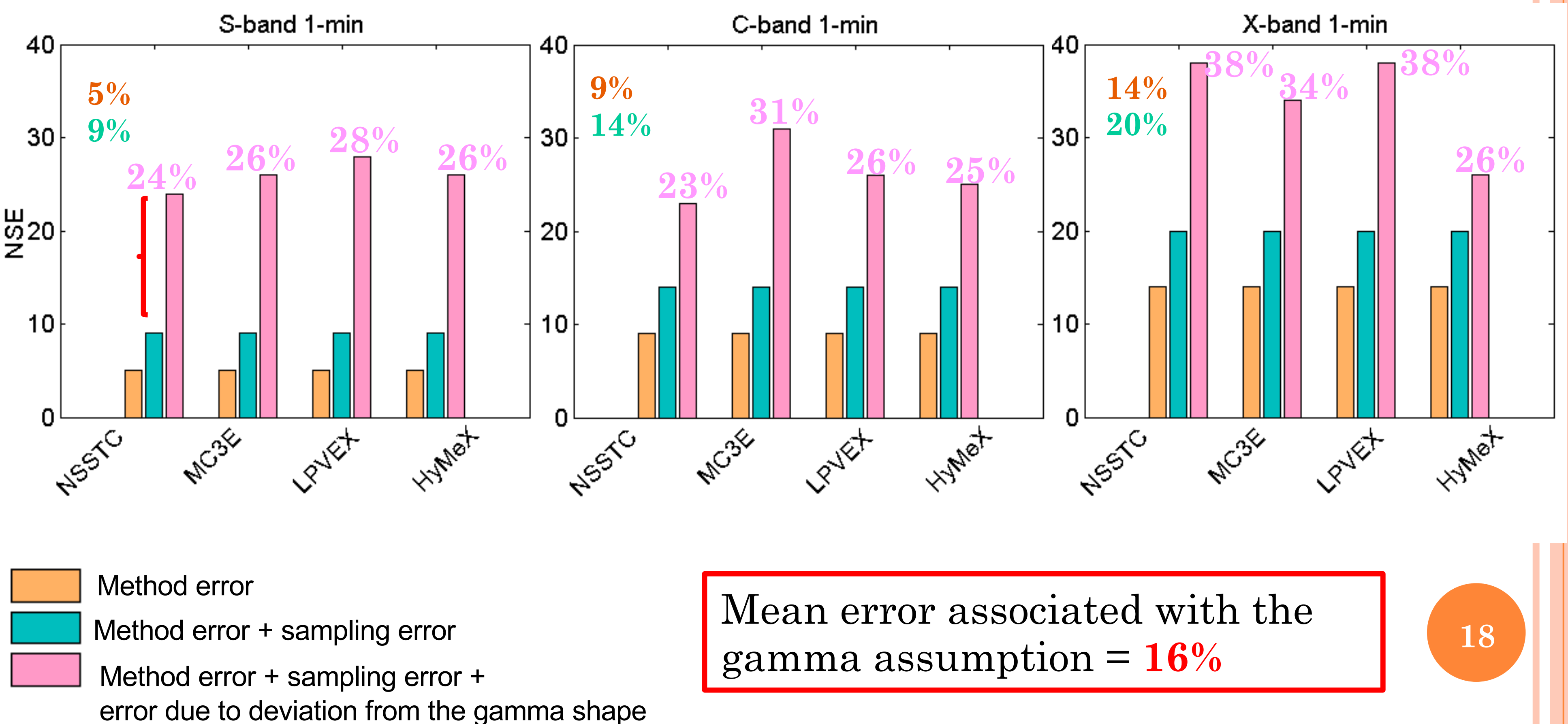


# IMPACT OF GAMMA RSSUMPTION ON RADAR RAINFALL RETRIEVAL (2/2)

## *2. Main results*

1-min, BC, different radar frequencies

**S-band** **C-band** **X-band**




Mean error associated with the gamma assumption = **16%**

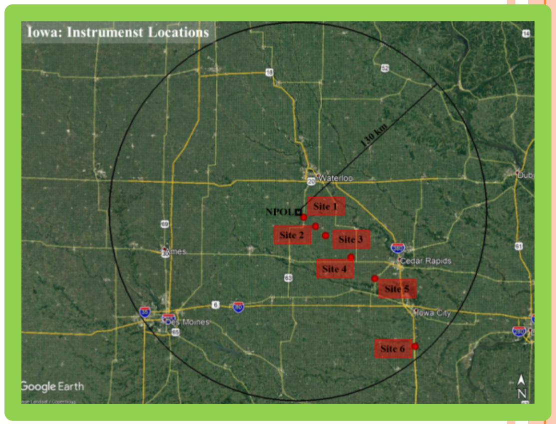
Adirosi et al. (2014)

# IMPACT OF DISDROMETER TYPE ON RADAR RAINFALL ALGORITHMS (1/2)

- Due to the differences in hardware and software co-located disdrometers can sample the DSD differently. The impact of the DSD disagreement varies from one parameter to another.

## ***1. Datasets***

| | dataset name | type of device | location | Time period |
|---|---|---|---|---|
| Long time series | ISAC-CNR P1 | P1 | Rome, IT | Jun.2010–Mar.2016 |
| | ISAC-CNR TC | TC | Rome, IT | Sep.2012–Nov.2017 |
| 2-month field campaign | HyMeX P2 | P2 | Rome, IT | Sep.-Nov. 2012 |
| | HyMeX 2DVD | 2DVD | Rome, IT | Sep.-Nov. 2012 |
| | IFloodS 2DVD | 2DVD | Iowa, USA | Apr.-Jun. 2013 |
| | IFloodS P2 | P2 | Iowa, USA | Apr.-Jun. 2013 |


Data quality

- ✓ Fall velocity filter (Tokay et al. 2001)
- ✓ Min. 4 adjacent filled bins and no «isolate» sample
- ✓ $D_{max} \cong 10\ mm$ , R < 300 mm $h^{-1}$ and $Z_{rayleigh}$ < 55 dBz

## ***2. Methodology***

T-matrix to simulate radar measurements

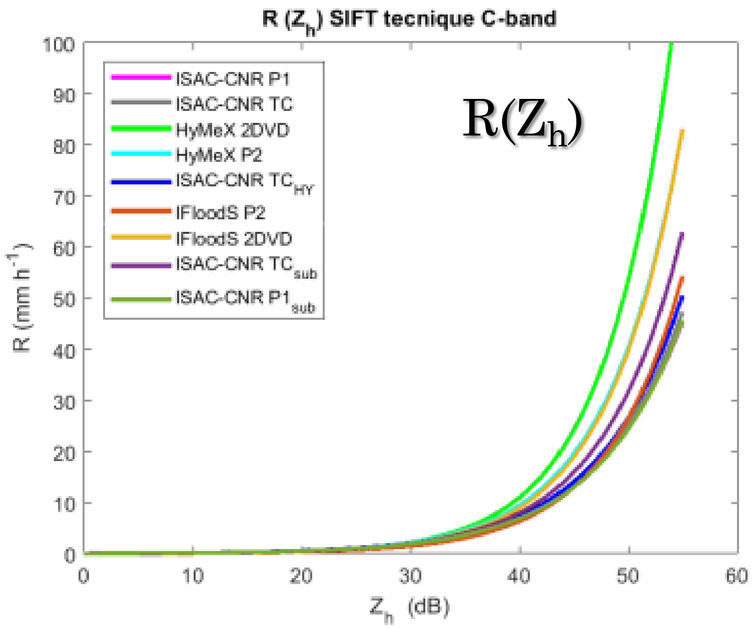
SIFT (sequential intensity filtering technique; Lee et al. 2005) and a non linear regression to obtain polarimetric radar algorithms:
$a_h(K_{dp})$, $a_d(K_{dp})$, $R(Z_h)$, $R(K_{dp})$, $R(Z_h,Z_{dr})$, $R(Z_{dp},Z_{dr})$

# Impact of disdrometer type on radar rainfall algorithms (2/2)

## *3. Main Results*

NMAE for pairwise comparison at C-band

| | ISAC-CNR P1 vs ISAC-CNR TC | ISAC-CNR $P1_{sub}$ vs ISAC-CNR $TC_{sub}$ | HyMeX 2DVD vs HyMeX P2 | IFloodS 2DVD vs IFloodS P2 |
|---|---|---|---|---|
| $a_h = \alpha_1 K_{dp}$ | 2% | 9% | 18% | 21% |
| $a_d = \alpha_2 K_{dp}$ | 9% | 6% | 34% | 34% |
| $R = \alpha_3 Z_h^{\beta 3}$ | 6% | 15% | 28% | 29% |
| $R = \alpha_4 Z_h^{\beta 4} Z_{dr}^{\gamma 4}$ | 4% | 10% | 16% | 6% |
| $R = \alpha_5 K_{dp}$ | 9% | 2% | 14% | 7% |
| $R = \alpha_6 Z_{dr}^{\beta 6} K_{dp}^{\gamma 6}$ | 5% | 2% | 6% | 5% |




- the comparison between different type of laser disdrometers (namely P1, P2 or TC) gives an error less than 15%
- the agreement between P2 and 2DVD is a bit lower (differences up to 30%),
- it is confirmed that polarimetric rain rate estimators seem to be less sensitive to the disdrometer type with respect to the $R(Z_h)$

**Weather radar algorithm optimized for Italian climatology has been obtained**

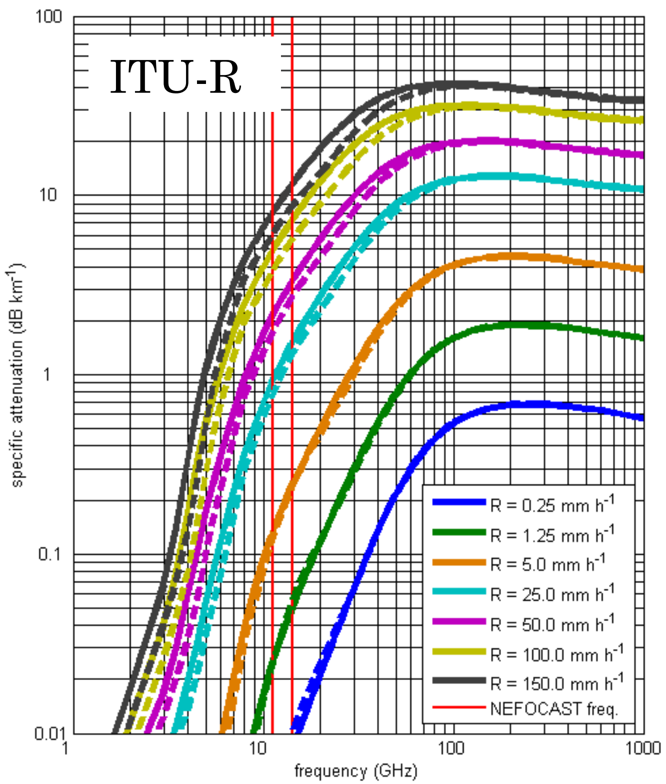


Adirosi et al. (2018)

# DSD IN PROPAGATION STUDIES

# BACKGROUND

- At frequencies higher than 5 GHz the electromagnetic waves that propagates from satellite to the Earth interacts with atmospheric gases and hydrometeors.
- At frequencies used for satellite communication purposes, the attenuation due to the presence of **liquid hydrometeors** is the **predominant mechanism** that produces the degradation of the signal (Oguchi 1983), however , the effects of hydrometeors in the mixing phase (such as wet snow, graupel and melting hydrometeors) cannot be neglected.




The **attenuation** of the signal produced by liquid particles (such as raindrops) can be expressed as

$$k = 4.343\ 10^{-3} \int_{0}^{D_{max}} \sigma_E(p, D, \lambda, T, h) N(D) dD$$

where $\sigma_E$ is the extinction cross section for the polarization $p$ , $\lambda$ is the wave length, $T$ is the environmental temperature, $h$ is the type of hydrometeor and N(D) is the drop size distribution.

**APPLICATIONS**

1. Satellite communication (direct method)
2. Meteorological applications (inverse method)

# NEFOCAST PROJECT

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FAS Fondo Aree Sottoutilizzate 2007-2013

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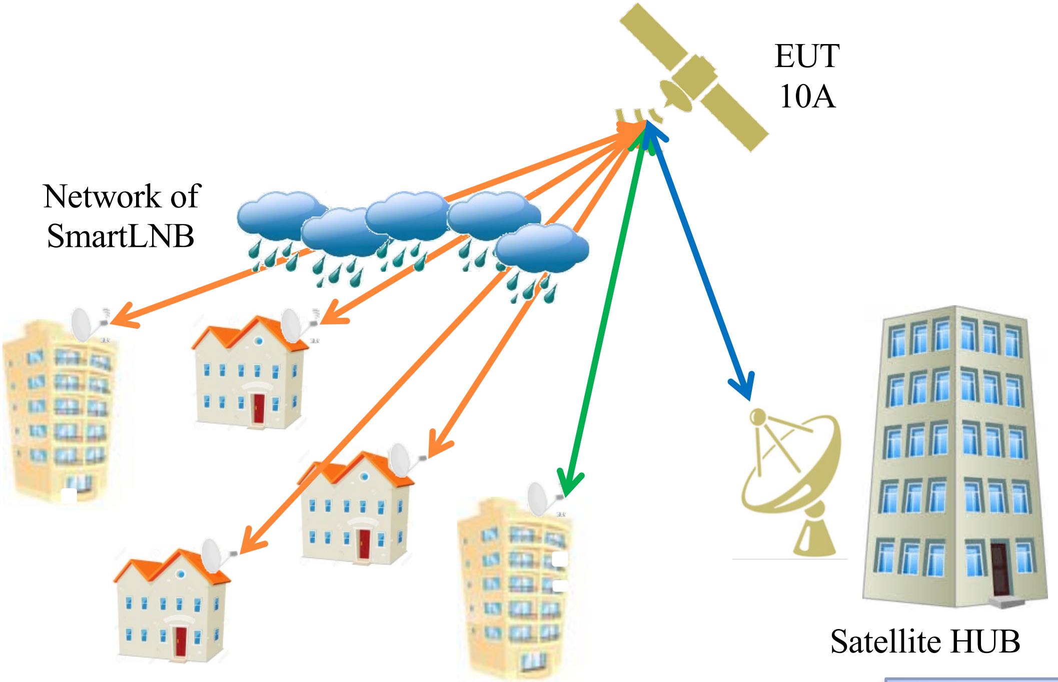


**OBJECTIVE**

**Setting up a system able to provide accurate precipitation maps in real time based on the attenuation measurements of a dense population of interactive satellite terminals (called SmartLNB) commercially used as bi-directional modem.**

**INPUT DATA**
ratio between received energy and noise ($\eta = E_s/N_0$)

→ Retrieval Algoritm →

**OUTPUT DATA**
Real time rain rate maps with high spatial resolution and accuracy

**1) Test phase**
- rain gauge
- 1 smartLNB terminal

**2) Validation phase**
- weather radar
- rain gauges
- 6 smartLNB
- disdrometer

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# NEFOCAST ALGORITHM

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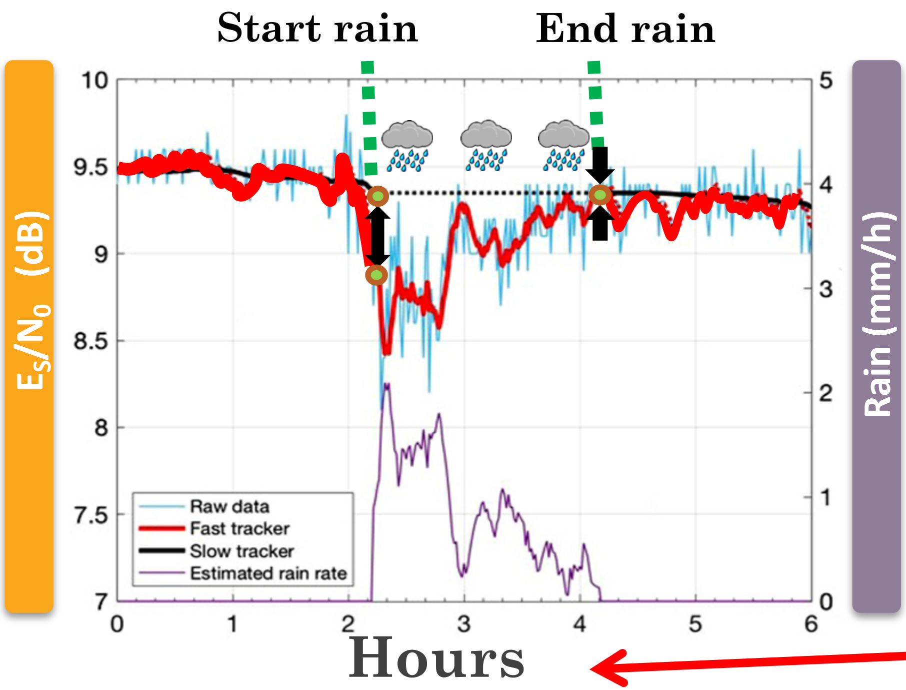
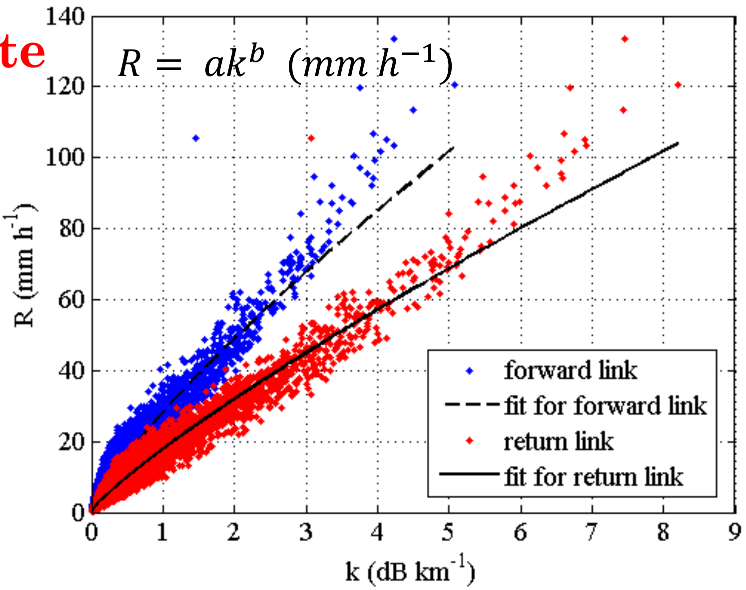



- Identification and correction of the non meteorological fluctuation (even in clear sky, such as the one due to gravitational orbit perturbations and tropospheric scintillation.
- Definition of a reliable clear-sky reference values
- Conversion of the attenuation into rainfall rate (R-k algorithm)

## Specific attenuation as a function of rain rate

- More than 6 years of DSDs collected each minute by OTT Parsivel disdrometer (85207 samples) have been used as input of T-matrix to compute the specific attenuation.

- Influence of DSD variability (from NMAE) is within 20%

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# NEFOCAST Results

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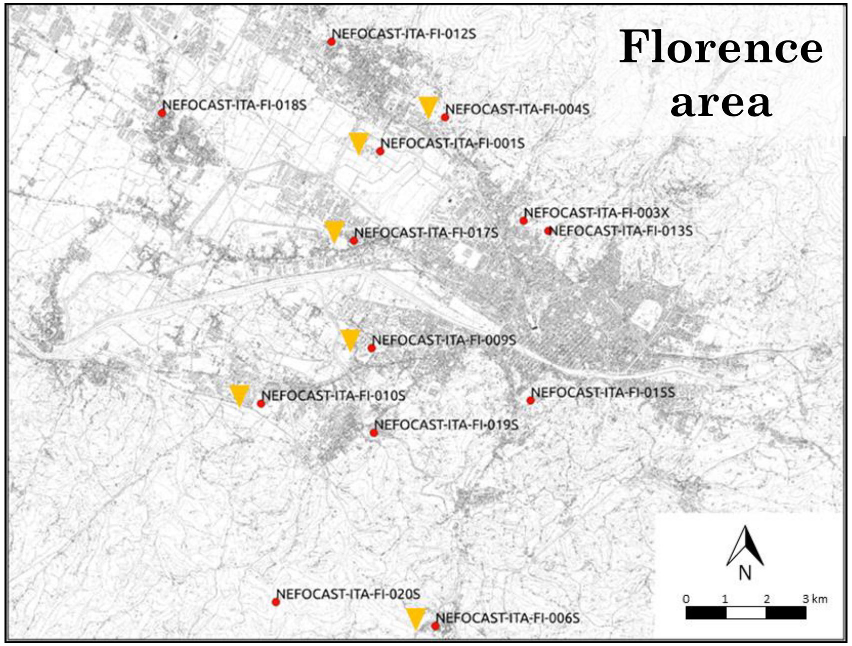


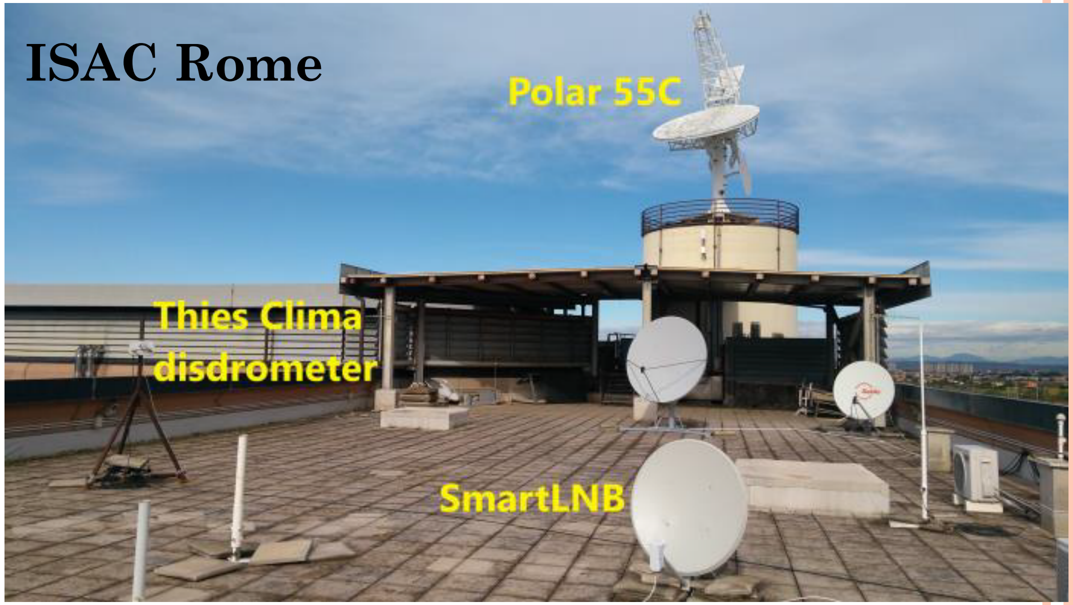


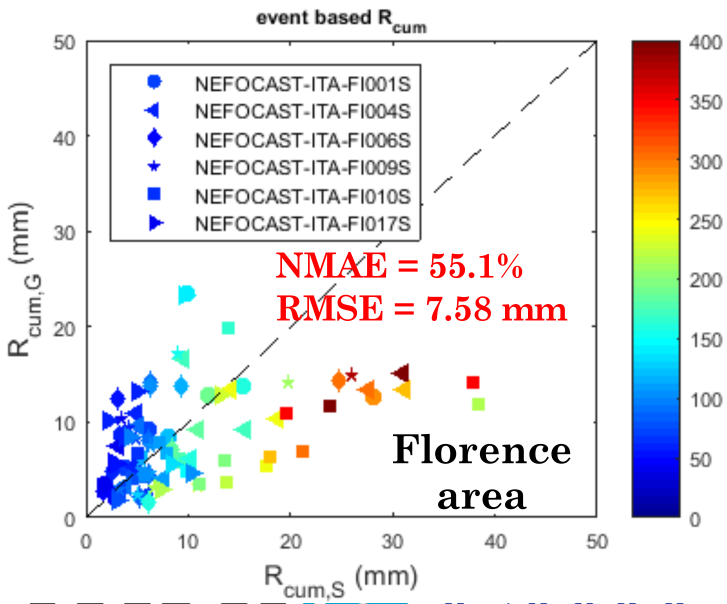


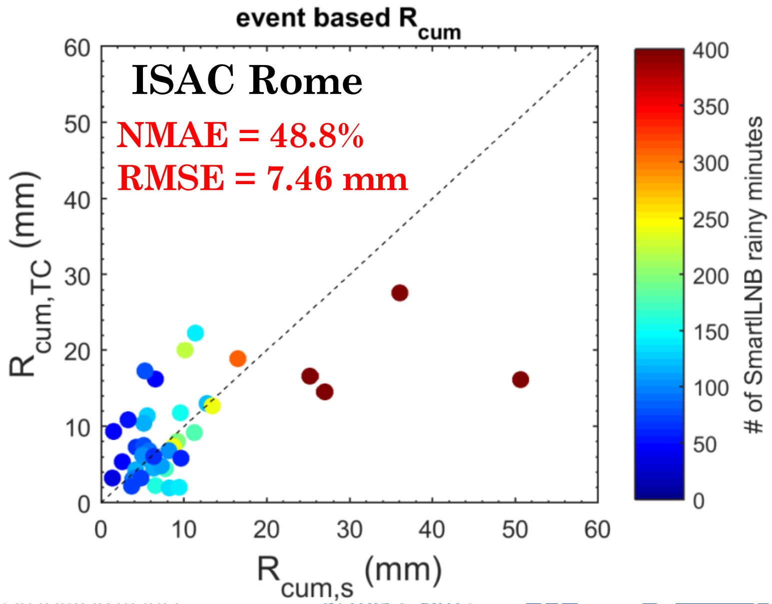


Rome set-up has been also used to evaluate the NEFOCAST algorithm intrinsic errors due to ML height (RMSE=0.63 mm $h^{-1}$ and NMAE=19.2%) and R-k relation (RMSE=0.90 mm $h^{-1}$ and NMAE=21.5%).

(Giannetti et al. 2017)

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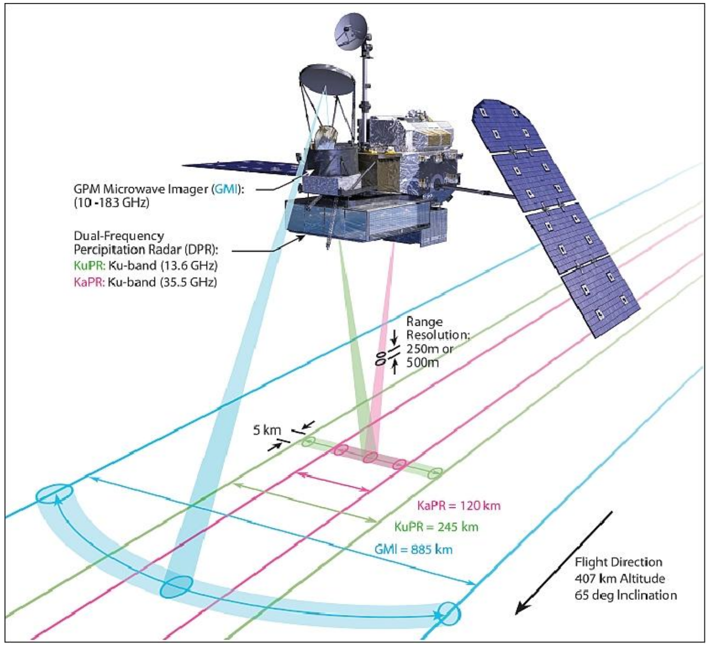
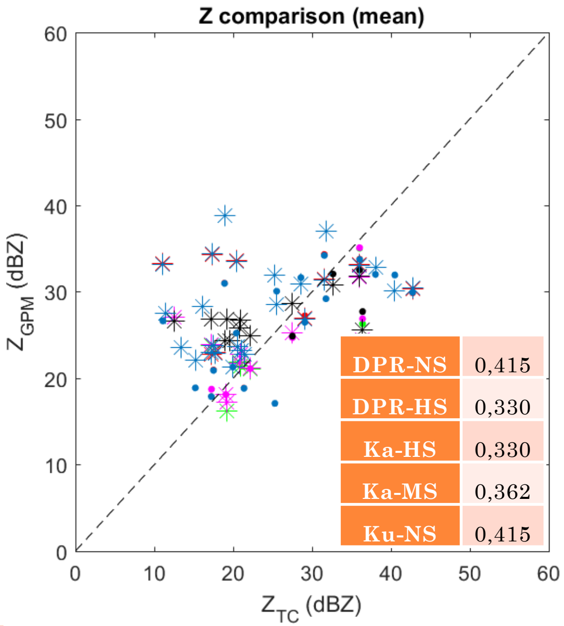
# ONGOING RESEARCH AND FUTURE PERSPECTIVES

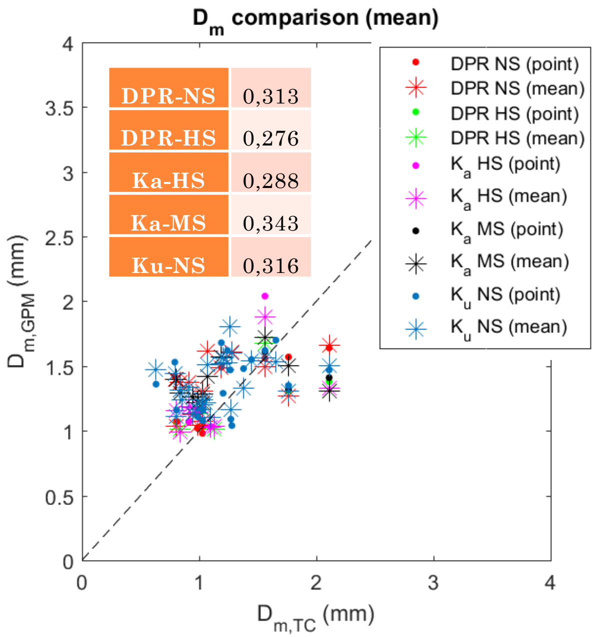
# GPM-DPR VALIDATION

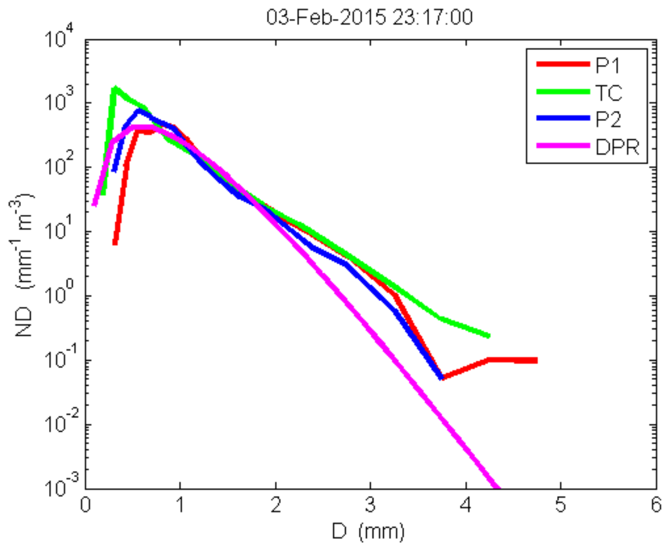



- NASA/JAXA mission for the estimation of rainfall rate from satellites
- The availability of two radar frequencies (Ku- and Ka-band) allows to retrieve the two parameters of the DSD along the vertical all over the world (±65°)
- GPM data from February 2014
- Using disdrometer data in Italy we validate GPM estimates of DSD and rainfall parameters

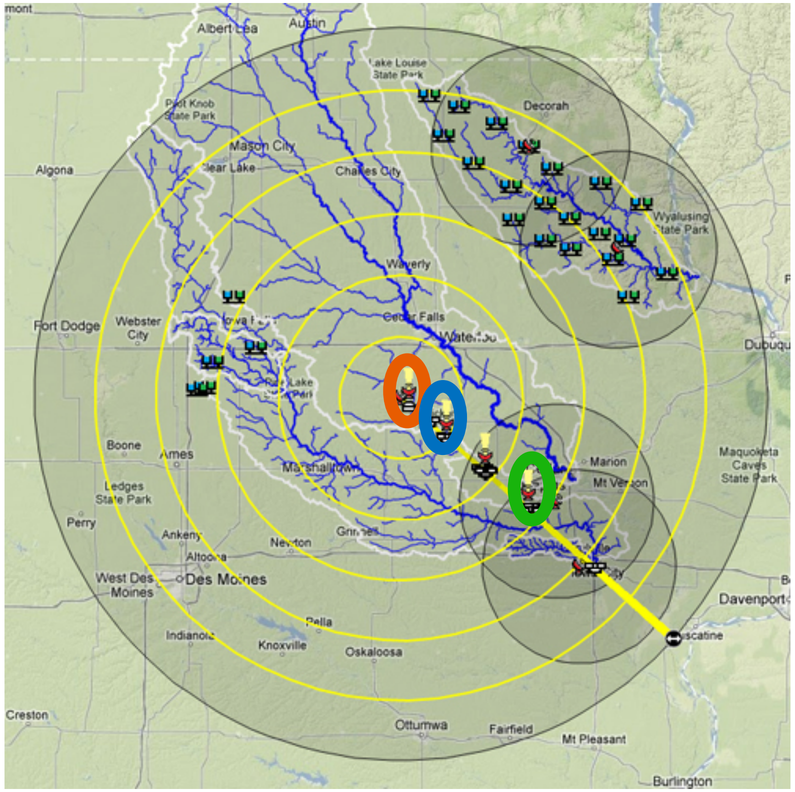
**Preliminary results over Rome (ISAC)**

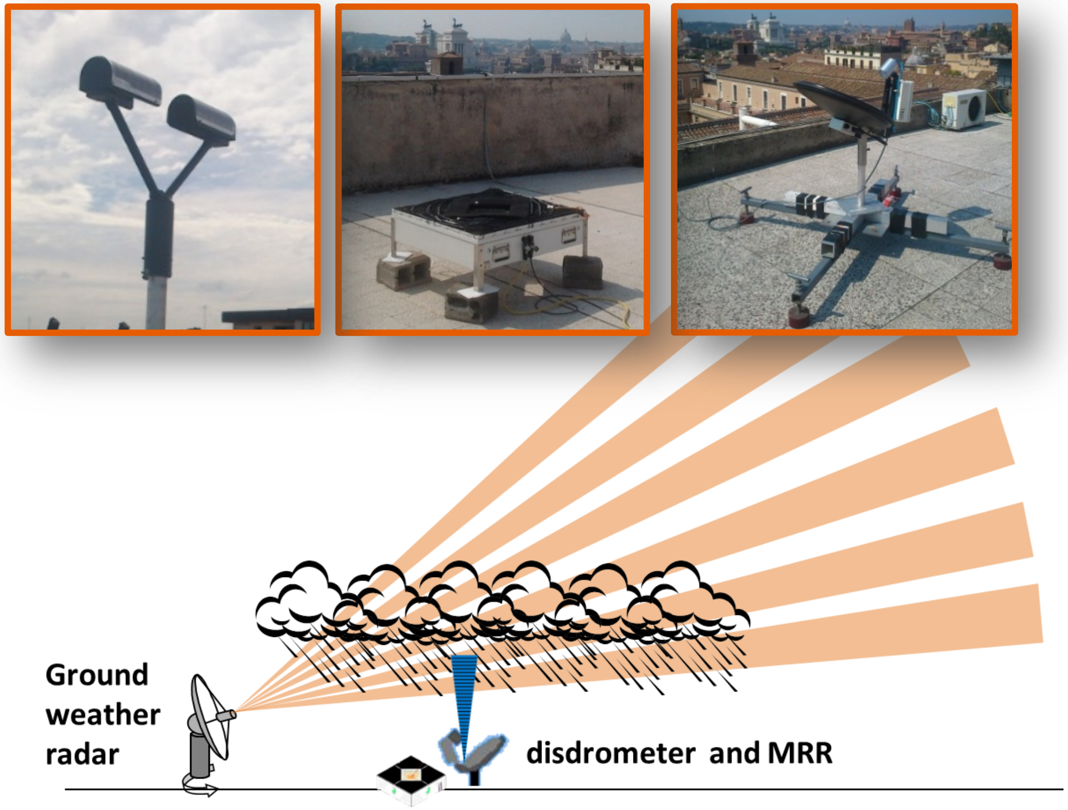


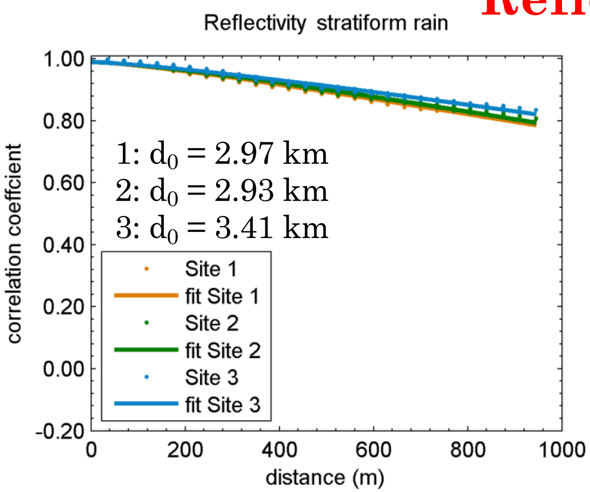



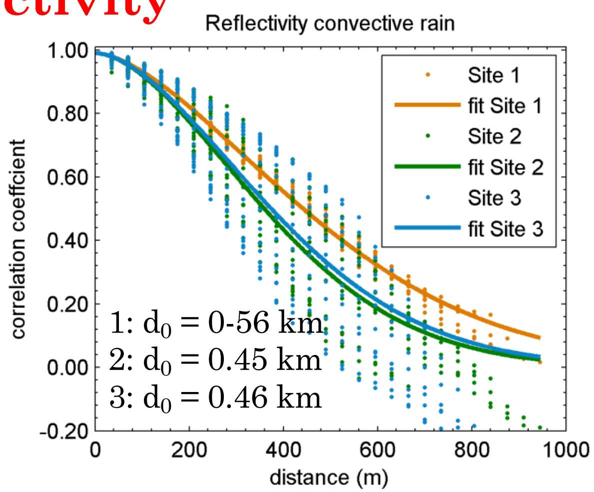
# Vertical variability of precipitation




## Reflectivity




$$r(d) = r_0 \, exp\left[-\left(\frac{d}{d_0}\right)^{s_0}\right]$$

r is the correlation coefficient, $r_0$ is the nugget parameter (set to 0.99), $s_0$ is the shape parameter, $d_0$ is the correlation distance, and $d$ is the distance between paired of MRR observations .

# Future Perspectives

- Rainfall estimation from signal of opportunities: upgrade of the NEFOCAST approach
- Fitting performance of the Generalized Gamma for a complete drop spectrum modelling
- Analysis of the long time series of disdrometer data (more than 10 years) in a «climatological» prospective
- Collaboration with new ISAC «Dipartimento Tecnologico Sperimentale»
- Synergy between Micro Rain Radar, disdrometer and scanning weather radar for the characterization of the vertical structure of precipitation
- …..
- Any collaboration is welcome!

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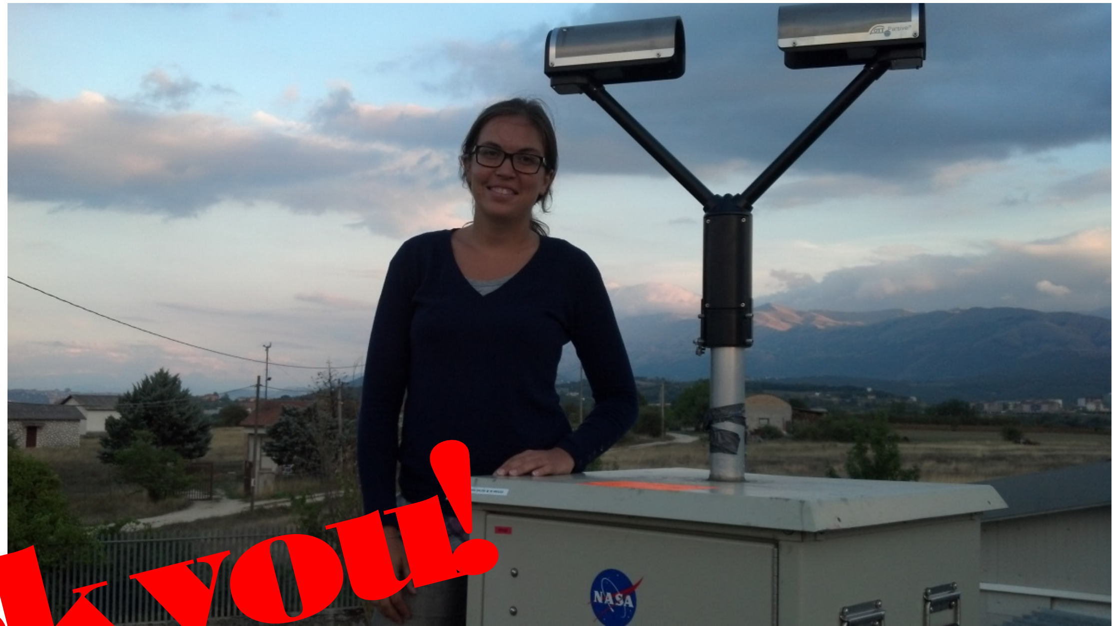


# Thank you!