Remote sensing of volcanic ash plumes using ground-based microwave weather radars

Frank S. Marzano[1,2]

E. Picciotti [2], G. Vulpiani [2] and M. Montopoli [2]

[1] Dept. Information Eng., Sapienza University of Rome, Italy

[2] CETEMPS Center of Excellence, Univ. of L'Aquila, Italy

[3] Italian Civil Protection Dept. (DPC), Rome, Italy

MOTIVATION AND OUTLINE

- **Monitoring of volcanic ash plumes**
  - **Inference of Strombolian and sub-Plinian eruption processes**
  - **Air trafic control safety and civil protection alarming**

- **Remote sensing techinques of volcanic eruptions**
  - **Sub-glacial eruption on Nov. 2004**
  - **Radar data from Iceland**
- **Microwave radar reflectivity model**
  - **Microphysical model**
  - **Radar backscattering**
- **Quantitative radar retrieval of valcanic ash clouds**
  - **Methodology**
  - **Application to Grímsvötn volcanic eruption**
- **Open issues**
- **Conclusions**

REMOTE SENSING OF VOLCANIC ERUPTIONS

- **Geostationary and Low-Earth-Orbit satellites**
  - **Eruption of Grimsvötn volcano (Iceland) on Nov. 2, 2004 from LEO MODIS radiometer**

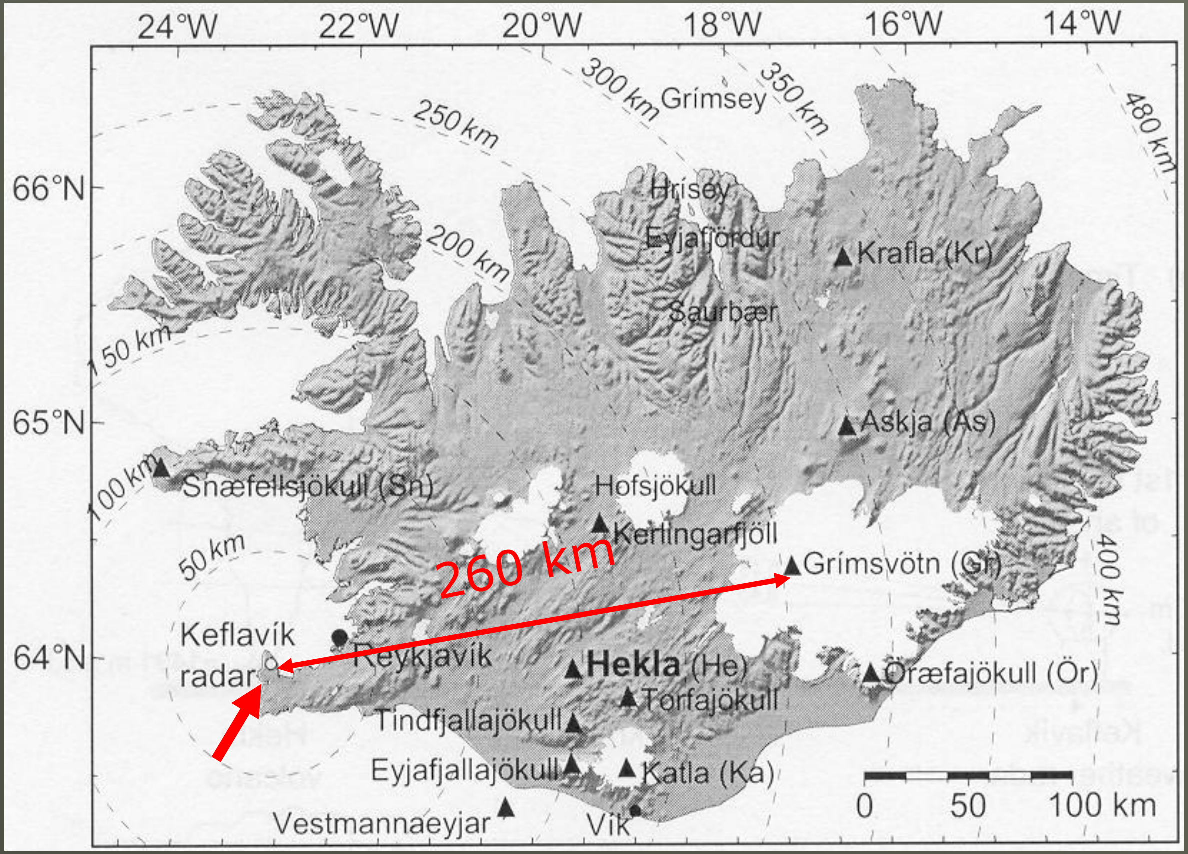
- **Other ground-based remote sensing tools**
  - **GPS receivers at L band**
  - **Wind profiler system at L band**
  - **Lidar**
  - **Anything else????????????...............**

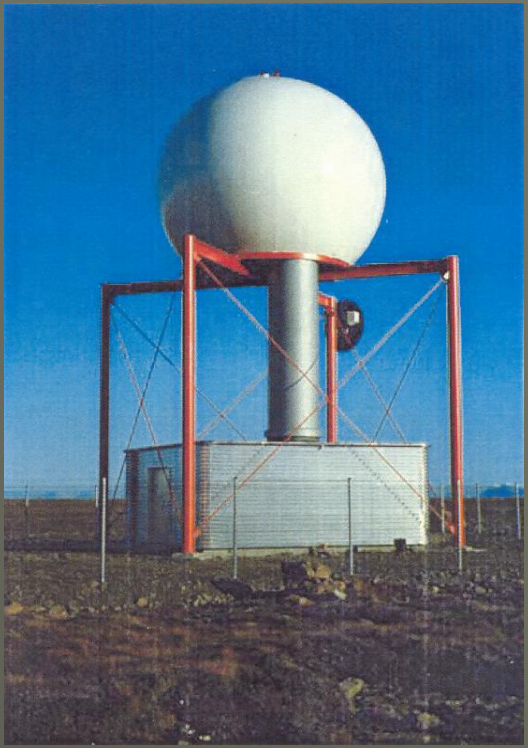
GRIMSVOTN ERUPTION ON NOV. 2, 2004

Eruption observed by the Keflavik C-band weather radar

at about 20 km far from Reykjavik

at about 260 km from the volcano vent.

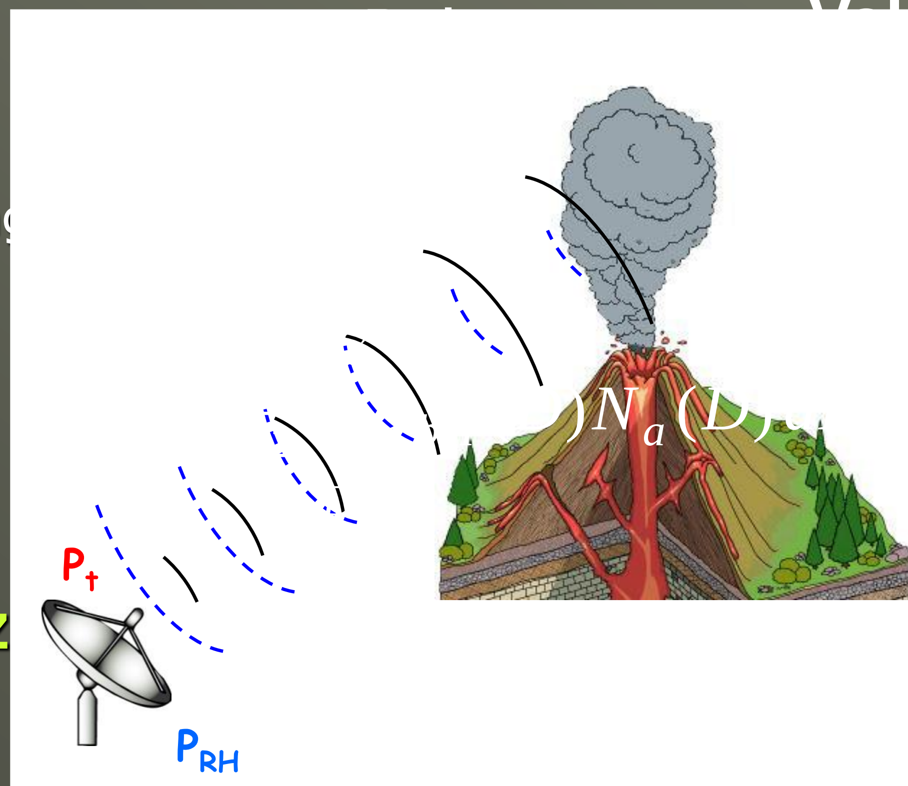




VEÐURSTOFA ÍSLANDS

RADAR BACKSCATTERING MODEL

$$\bar{P}_{RH}(r) = \underbrace{\frac{\pi^{5}10^{-19}}{2^{10}1.08\ln(2)}}_{\text{constants}} \underbrace{\frac{\tau\,\theta_3\,\phi_3\,G_0^2}{\lambda^2}P_t}_{} \underbrace{\frac{Z_H(r)}{r^2}\left|K\right|^2 L_H^2(r)}_{\text{Volcanic target}}$$



Under Mie scatterin … Z_H is:

$$Z_H \quad \ldots \quad)N_a(D)\ldots$$

The expression of Z … alized on radar system screens.

$$dBZ = 10 \cdot Log_{10}(Z_H)$$

CONICAL SCAN (PPI) OF RADAR REFLECTIVITY

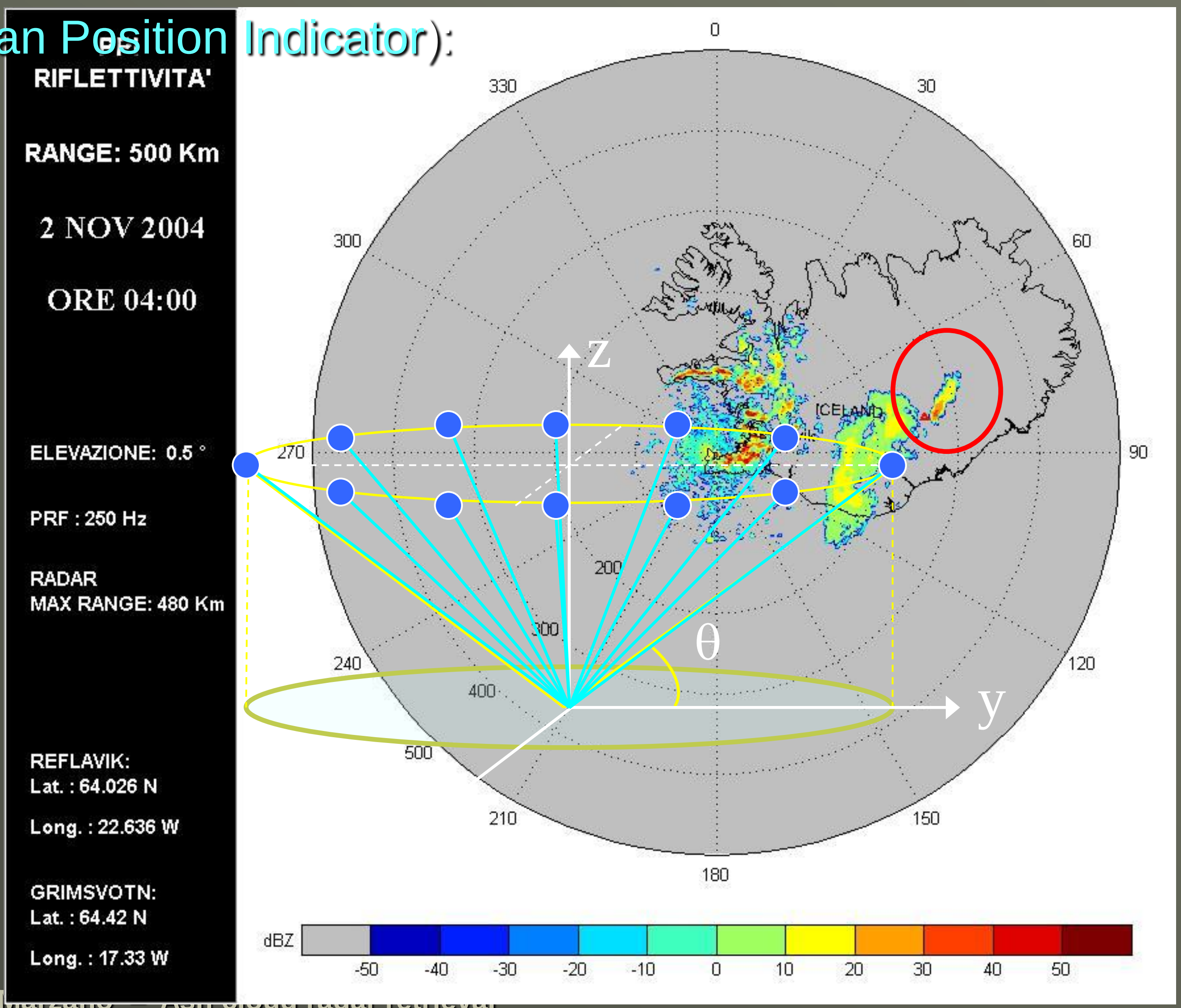
Some Radar products:

PPI image at: h. 04:00 GMT.

- PPI image of the Grimsvotn volcano eruption:

ore 05:05 06:05

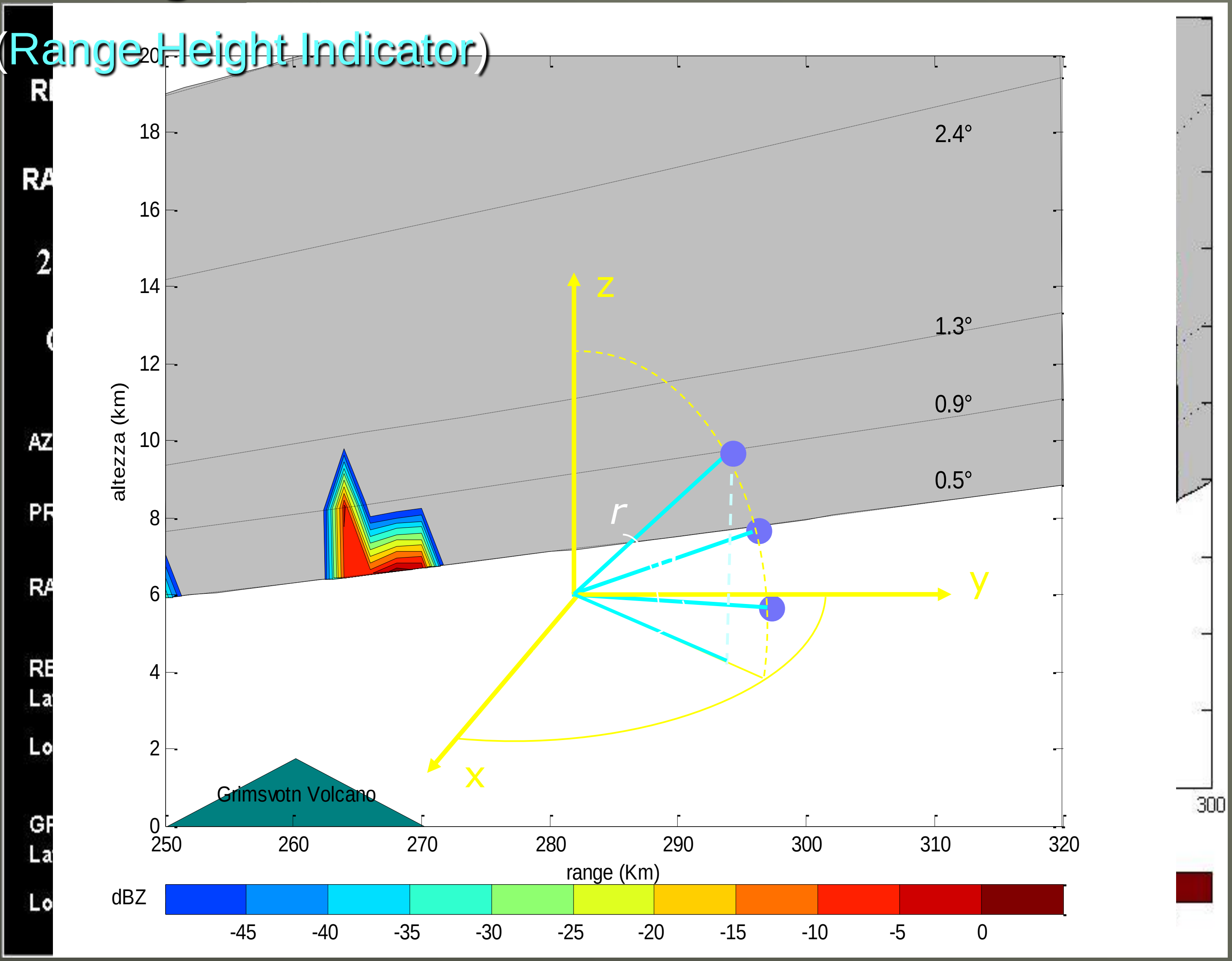
PPI (Plan Position Indicator):



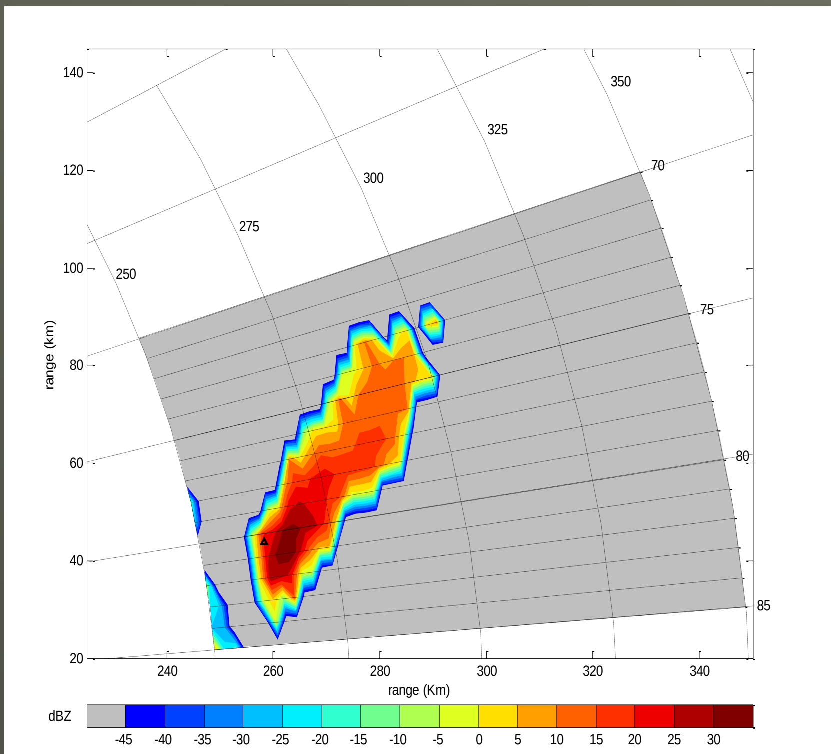
SECTOR SCAN (RHI) OF RADAR REFLECTIVITY

- Another useful Radar product
- RHI image at 04:00 GMT:
- Grimsvotn eruption: ore 06:05 ore 05:05

RHI (Range Height Indicator)



VOLCANIC CLOUD RADAR REMOTE SENSING

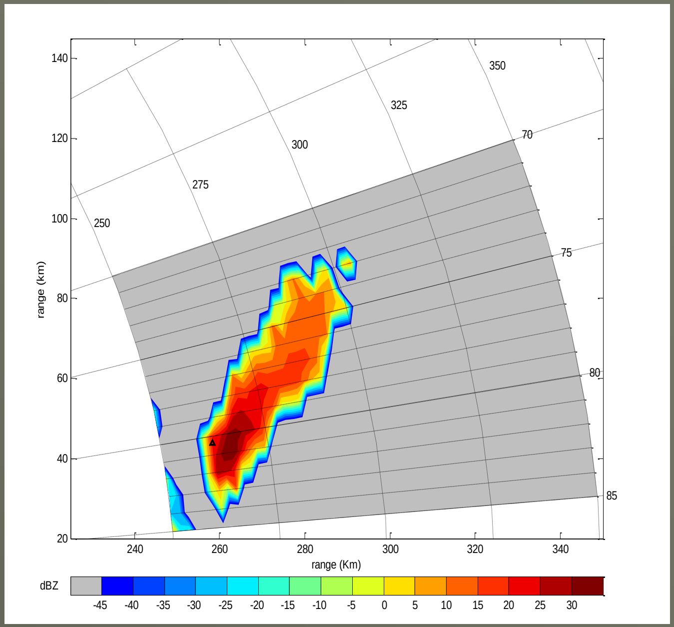


RADAR volume measurement

Ash concentration and ash fallout

PHYSICAL RADAR REMOTE SENSING

Forward physical-electromagnetic model



Volcaninc eruptive cloud

Synthetic Reflectivity

?

Inverse problem methodology

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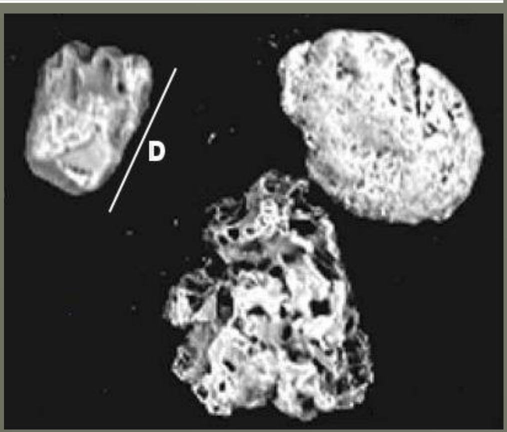
ASH PARTICLE SIZES



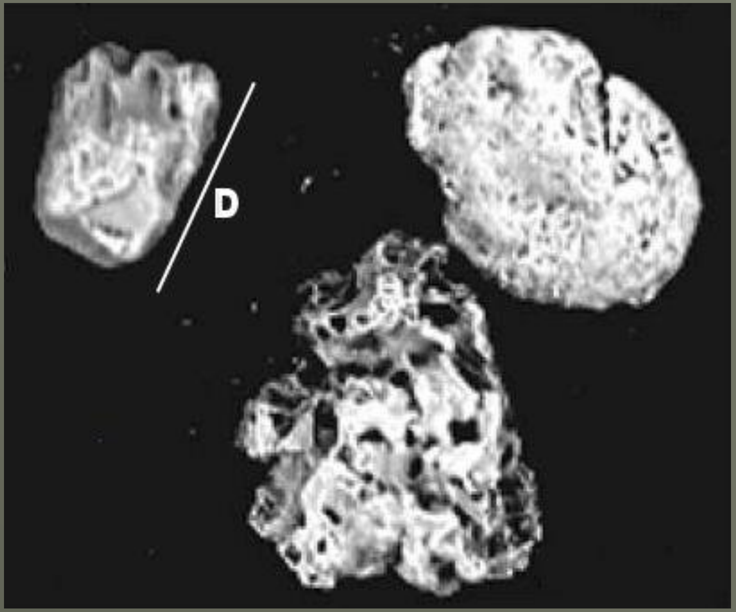
THEPRA: Materials of all types and sizes, erupting from a crater or volcanic vent as a result of an intensive magma and rock fragmentation.
This term describes volcanic ash and coarser detritus that are projected through the air. Tephra is chiefly characterized by clast size, shape, vesicularity, and composition.

TEPRHA		Particle type	Particle size	Distance from the volcano vent	Residence time in the atmosphere
	Ash	*Fine ash (FA)*	Less than 70 µm	Hundred to thousand kilometers	Day to month
		Coarse ash (CA)	From 70 µm to 2 mm	Few to hundred kilometers	Day
	Lapilli	*Small lapilli (SL)*	From 2 mm to 30 mm	Few to ten kilometers	Few seconds
		Large lapilli (LL)	From 30 mm to 64 mm	Few to ten kilometers	Seconds to minutes
	Block	*Blocks and bombs (BB)*	Greater than 64 mm	Few kilometers	Seconds to minutes

ASH PARTICLE MICROPHYSICS

- **Sphere-particle size distribution (Gamma or Weibull):**

$$N_a(D) = N_n\left(\frac{D}{D_n}\right)^{\mu} \cdot e^{-\Lambda_n\left(\frac{D}{D_n}\right)^{\nu}}$$



- **Ash mass concentration:**

$$C_a = \int_{D_1}^{D_2} m_a(D)\, N_a(D)\, dD = \frac{\pi}{6}\rho_a m_3$$

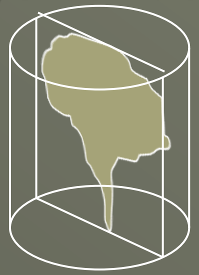
- **Rayleigh radar reflectivity (Mie at X band and above):**

$$Z_H = \frac{\lambda^4}{\pi^5 |K|^2}\int_{D_1}^{D_2} \sigma_{bH}(D) N_a(D)\, dD \cong \int_{D_1}^{D_2} D^6 N_a(D)\, dD = m_6$$

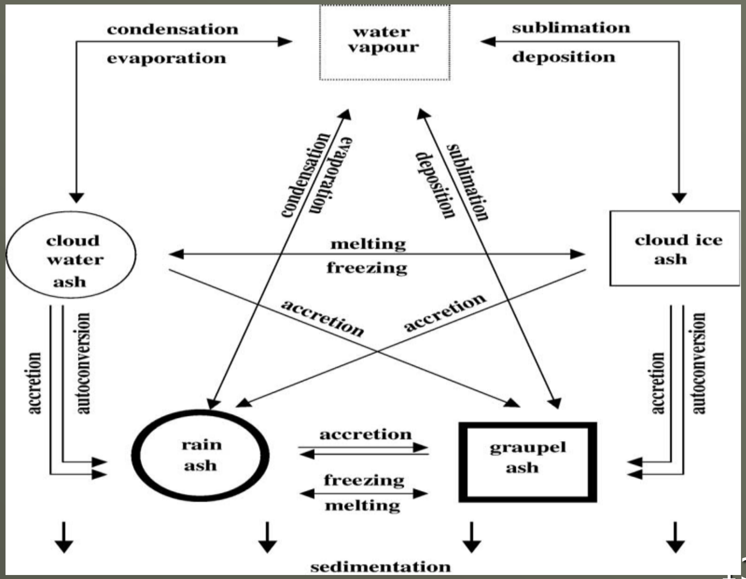
NUMERICAL MODEL ATHAM (UCambridge)

- ATHAM (Active Tracer High Resolution Atmospheric Model) :
  - 2D Plume model designed to simulate the dispersal of an eruption column resulting from an explosive volcanic event
  - Authors: H.F. Graf, <u>M. Herzog</u>, C. Textor et al. (1998-2010)

- Microphysical formulation based on the microphysical concept for usual atmospheric clouds
  - Used to investigate processes leading to particle aggregation
  - Used to study impact of aggregates on radar reflectivity

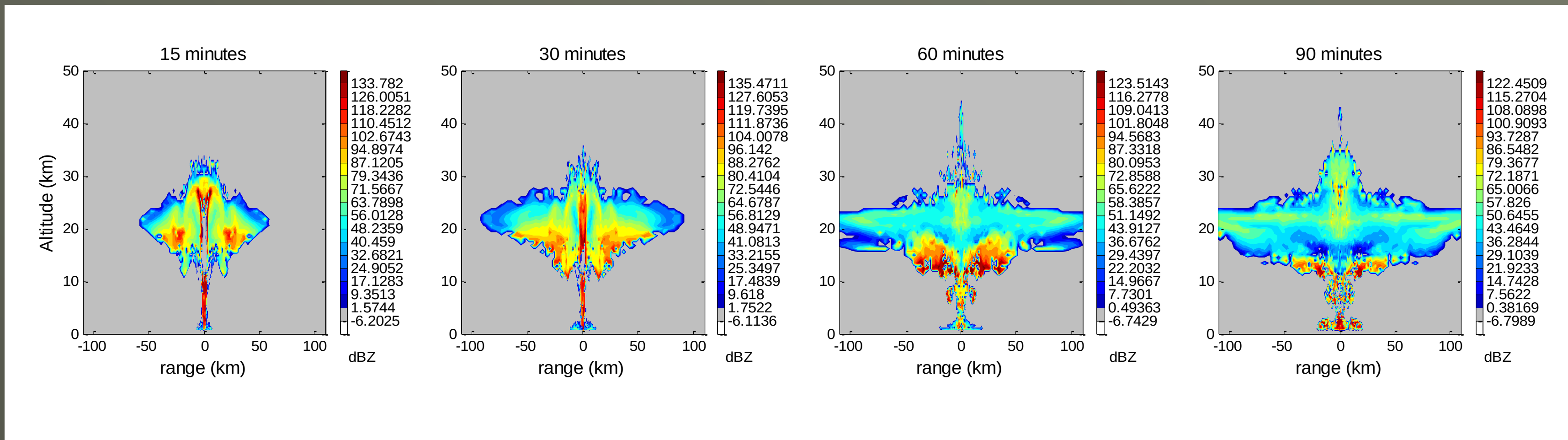


Ash q_{ax}	4 CLASSES:
Hydrometeors q_x	• Large cold $T<T_0$ • Large warm $T>T_0$ • Small cold $T<T_0$ • Small warm $T>T_0$
Aggregates $q_{px}=q_{ax}+q_x$	

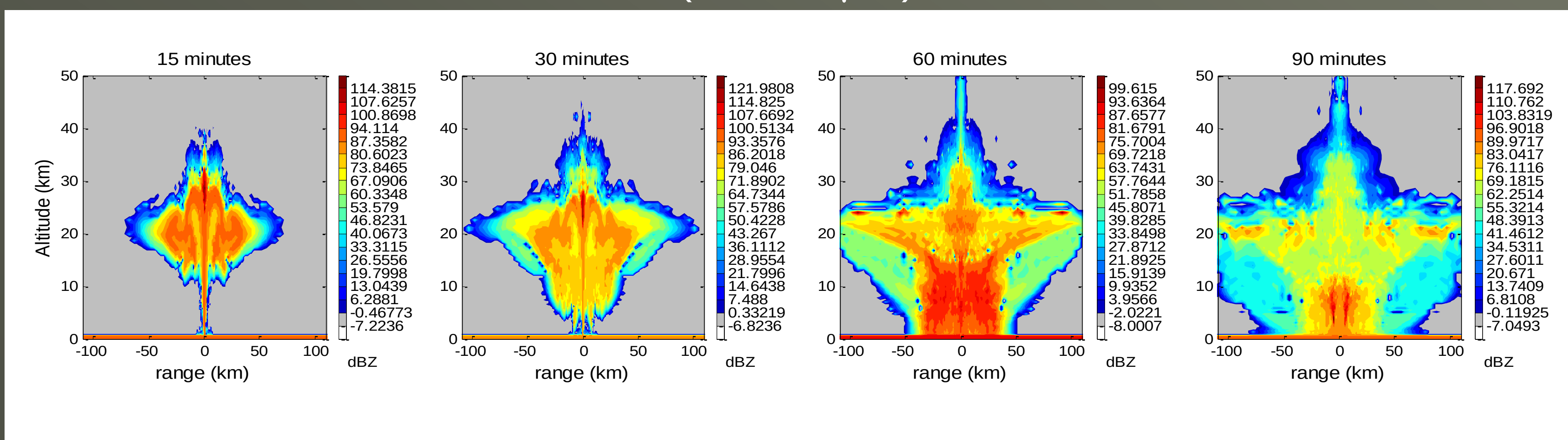


ATHAM SIMULATION OF RADAR REFLECTIVITY

EXP NO AGG - initialization with particle modes at 10 μm and 100 μm



EXP1(10-100 μm)



Marzano F.S., S. Marchiotto, C. Textor and D. Schneider, "Model-based Weather Radar Remote Sensing of Explosive Volcanic Ash Eruption", IEEE Trans. Geosci. Rem. Sensing, ISSN: 0196-2892, vol. 48, pp. 3591-3607, 2010.

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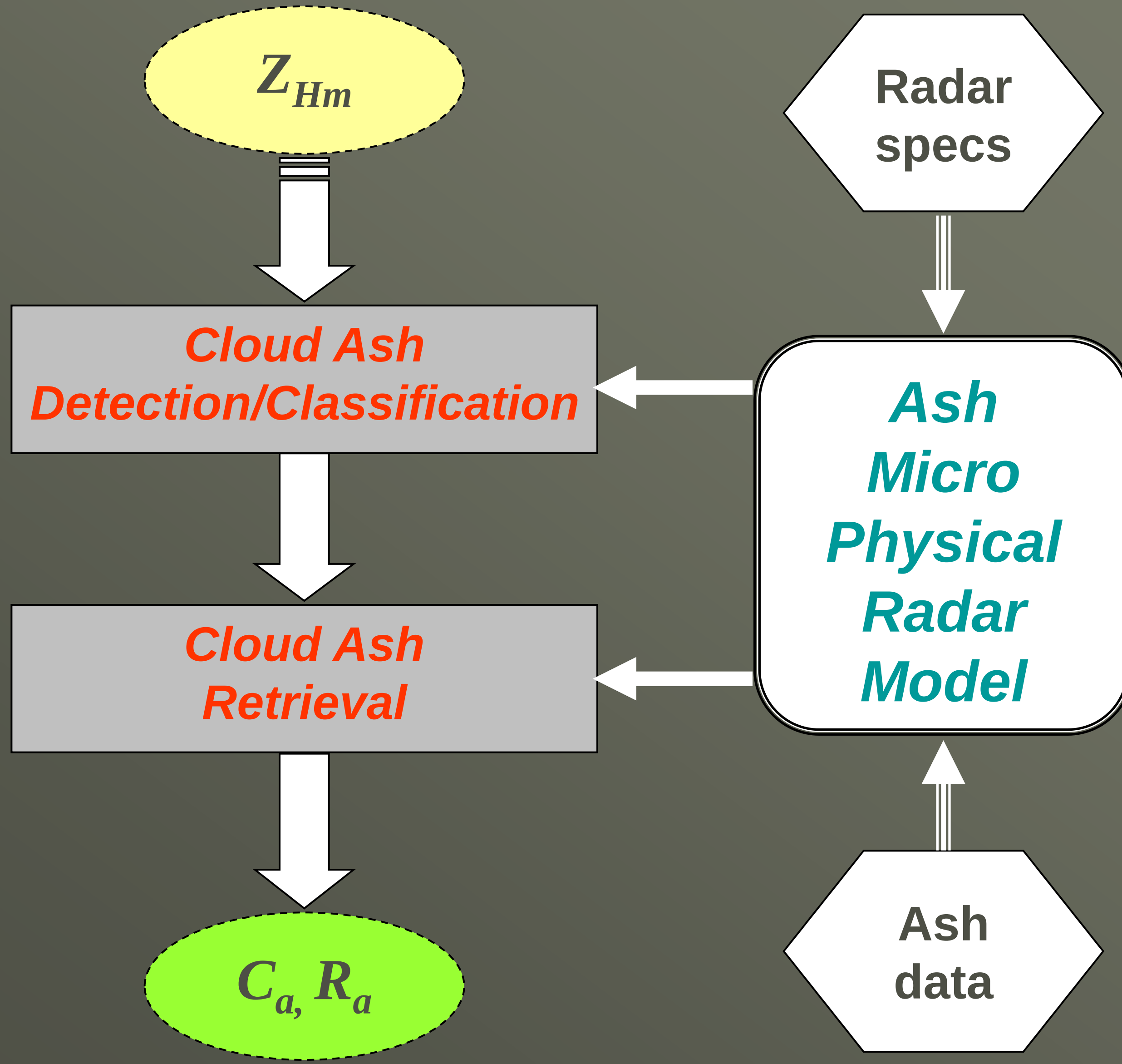
CLOUD ASH RETRIEVAL METHODOLOGY



CLASSIFICATION AND RETRIEVAL

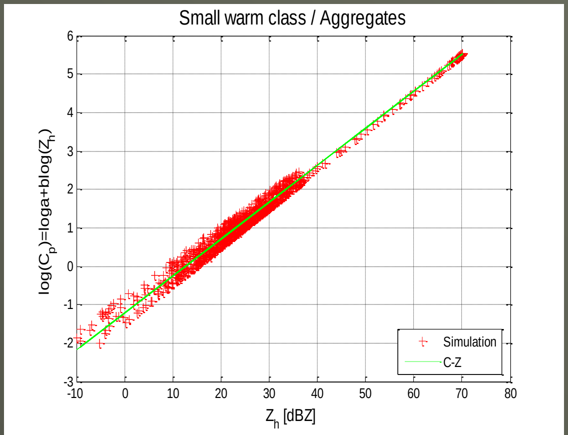
- **Volcanic cloud retrieval**

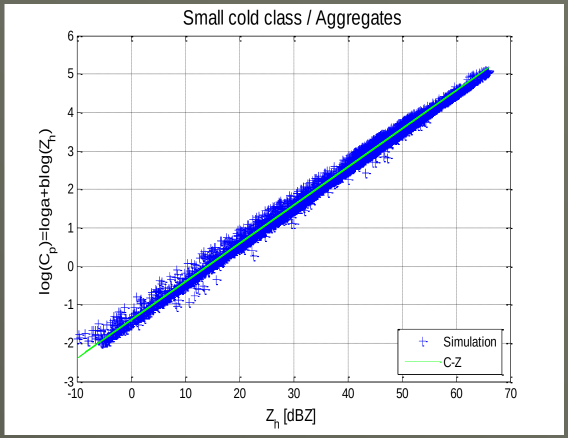
1. **Maximum A Posteriori classification**
2. **Regression estimation:**

Power-law model

$$\hat{c} = Mode_c \left[-\frac{\left(Z_{Hm} - m_{Z_{Hc}}\right)^2}{\sigma^2_{Z_{Hc}}} - \ln(2\pi) - \ln\left(\sigma^2_{Z_{Hc}}\right) + 2\ln\ p(c) \right]$$

$$\boxed{\hat{C}_p^{(c)} = a\left[Z_{Hm}\right]^b}$$





Marzano F.S., S. Barbieri, G. Vulpiani and W.I. Rose, “Volcanic cloud retrieval by ground-based microwave weather radar”, IEEE Trans. Geosci. Rem. Sens., ISSN: 0196-2892, vol. 44, n.11, pp. 3235-3246, 2006.

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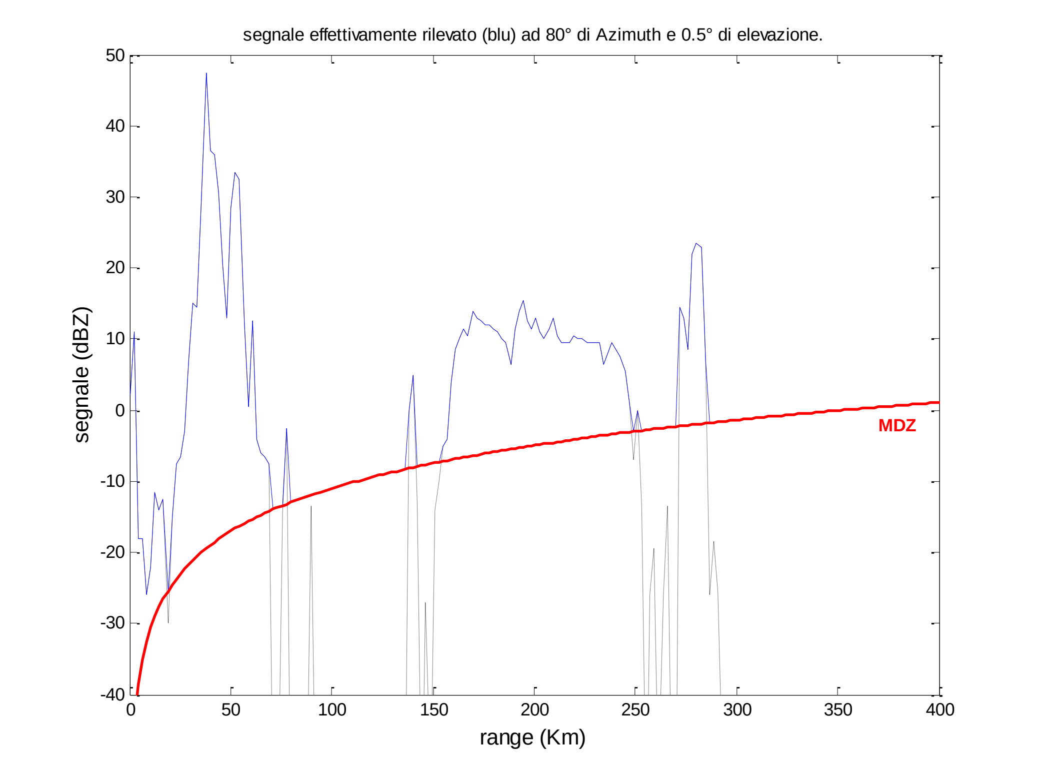
RADAR RETRIEVAL SENSITIVITY

- **Ash plume range model**
  - Gaussian shapes
  - Minimum Detectable reflectivity (MDZ)
  - Peak at 60 km
- **Weather Radar specifications**
  - C band:5.6 GHz
  - TX peak power: 250 kW
  - Range: 0-120 km
  - Range resolution: 300 m
  - Antenna max gain: 45 dBi
  - Minimum detectable power (MDS): -113 dBm

$$MDZ(r) = \frac{2^{10} 1.08 \ln(2)}{\pi^5 10^{-19}} \frac{\lambda^2}{\tau \theta_3 \phi_3 G_0^2 |K|^2 P_t} r^2 MDS$$



Effect of range and range averaging

At distances > 50 km, only coarse ash particles (> 50 microns) can be detecetd by ground microwave C-X-band radars !

C-BAND RADAR: REFLECTIVITY DATA

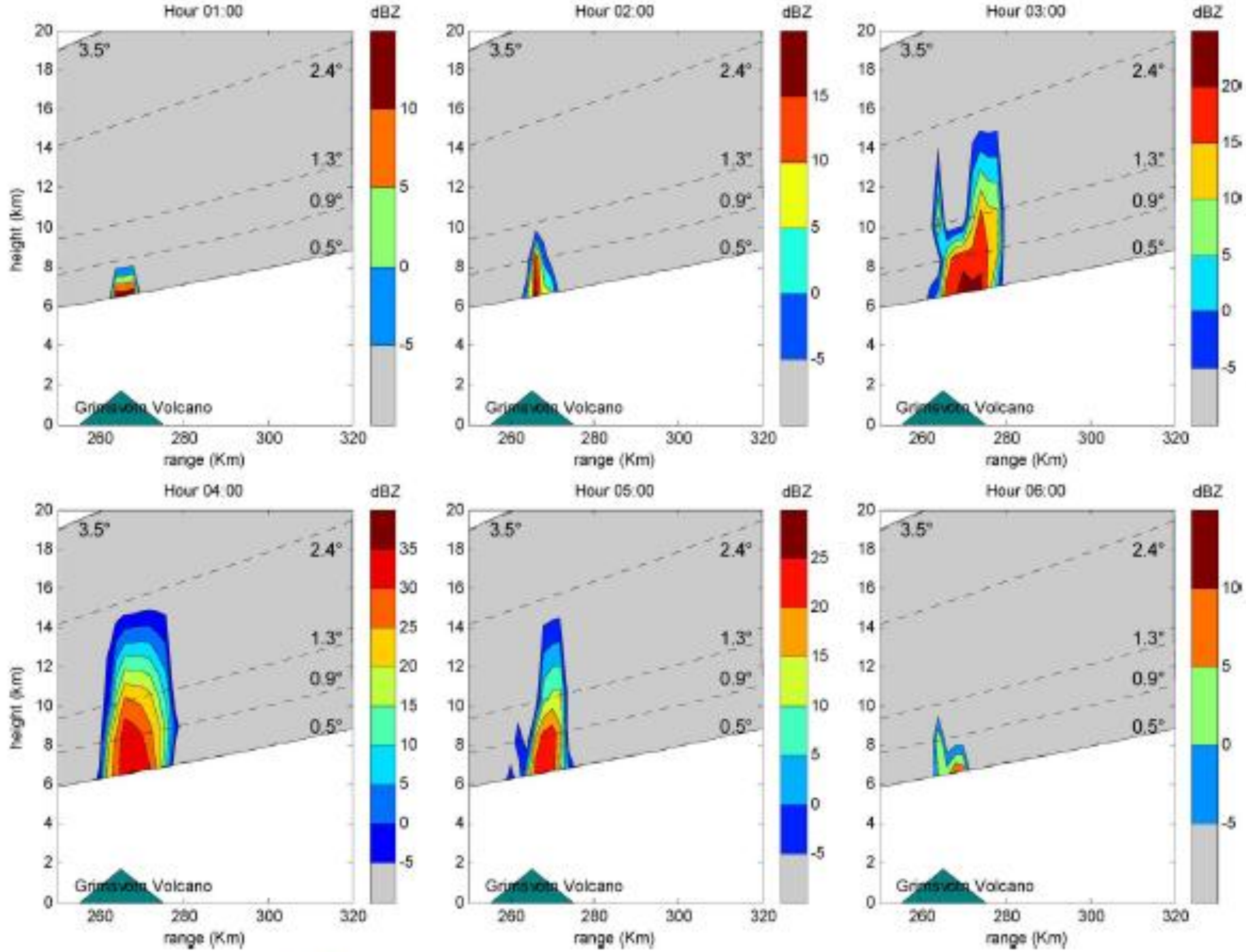


Fig. 6. Same as in Fig. 5, but for the RHI radar sections along the line of sight linking the Keflavik radar and the Grímsvötn volcano vent about 265 km long. The volcano vent is indicated by a triangle.

C-BAND RADAR: ASH CLASSES

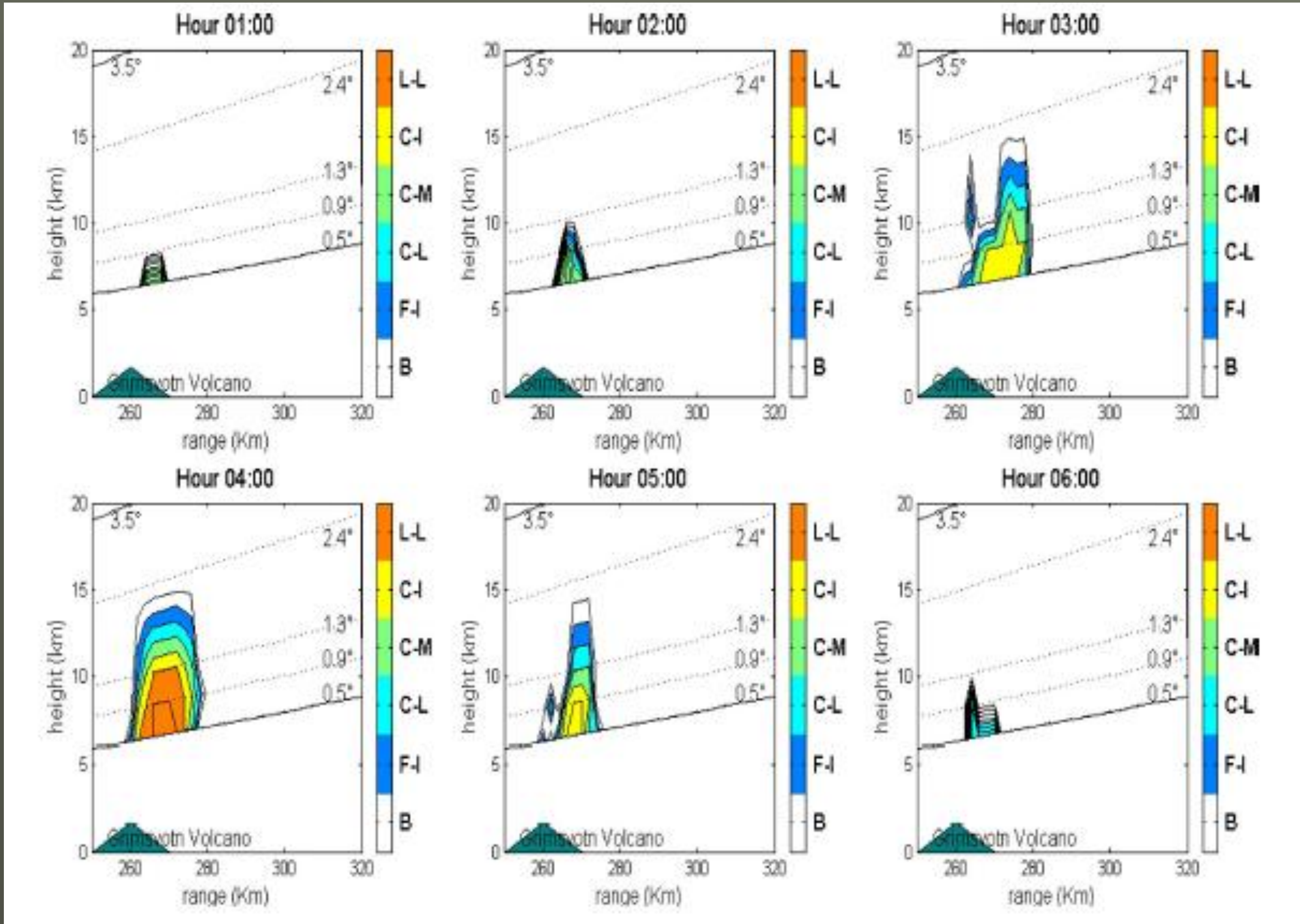


Fig. 7. As in Fig. 6, but for the estimated ash classes. (F-I) Fine ash with intense concentration. (C-L) Coarse ash with light concentration. (C-M) Coarse ash with moderate concentration. (C-I) Coarse ash with intense concentration. (L-L) Lapilli with light concentration. (B) Background clear air.

C-BAND RADAR: ASH CONCENTRATION

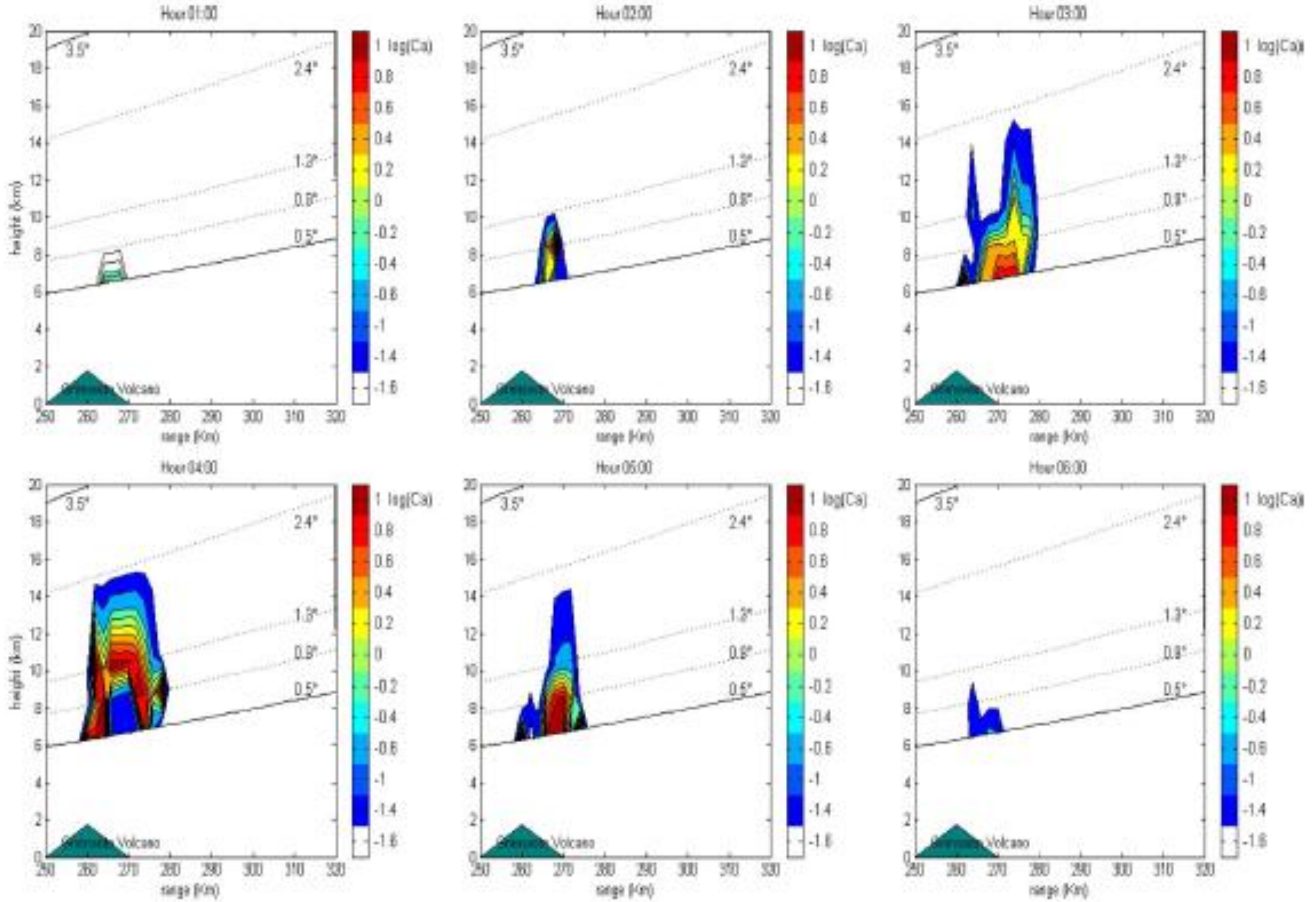
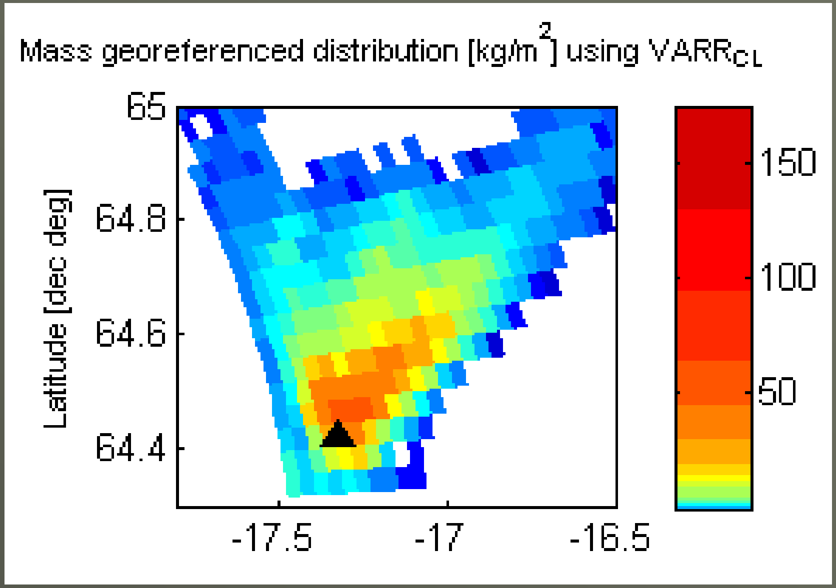
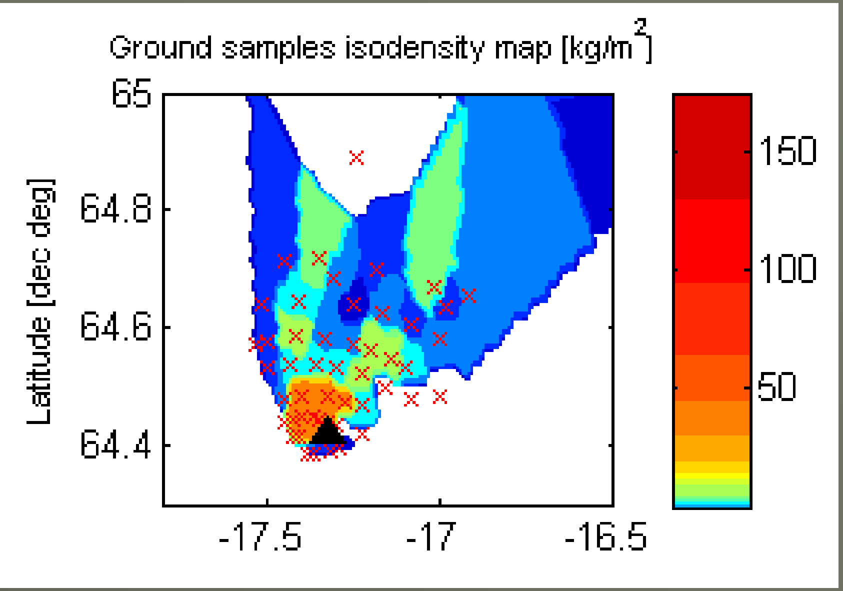


Fig. 8. As in Fig. 7, but for the estimated ash concentration C_a (in grams per cubic meter) expressed in $\log_{10}[C_a]$ for plot convenience.

C-BAND RADAR: GROUND VALIDATION on 2004





Marzano F.S., M. Lamantea, M. Montopoli, B. Oddsson and M.T. Gudmundsson, "Validating sub-glacial volcanic eruption using ground-based C-band radar imagery", IEEE Trans. Geosci. Rem. Sens., ISSN: 0196-2892, vol. 50, pp. 1266-1282, 2012.

Source	Total mass [kg]	Total volume [m^3]
VARR$_D$ (Default VARR)	$0.36\ 10^{10}$	$0.30\ 10^{7}$
VARR$_{CL}$ (Calibrated Lowest-bin VARR)	$1.43\ 10^{10}$	$1.19\ 10^{7}$
VARR$_{CLS}$ (Calibrated Lowest-bin Size-class VARR)	$0.33\ 10^{10}$	$0.27\ 10^{7}$
VARR$_{CLA}$ (Calibrated Lowest-bin Advection VARR)	$5.72\ 10^{10}$	$4.77\ 10^{7}$
Ground mass loading measured values	$5.60\ 10^{10}$	$4.70\ 10^{7}$

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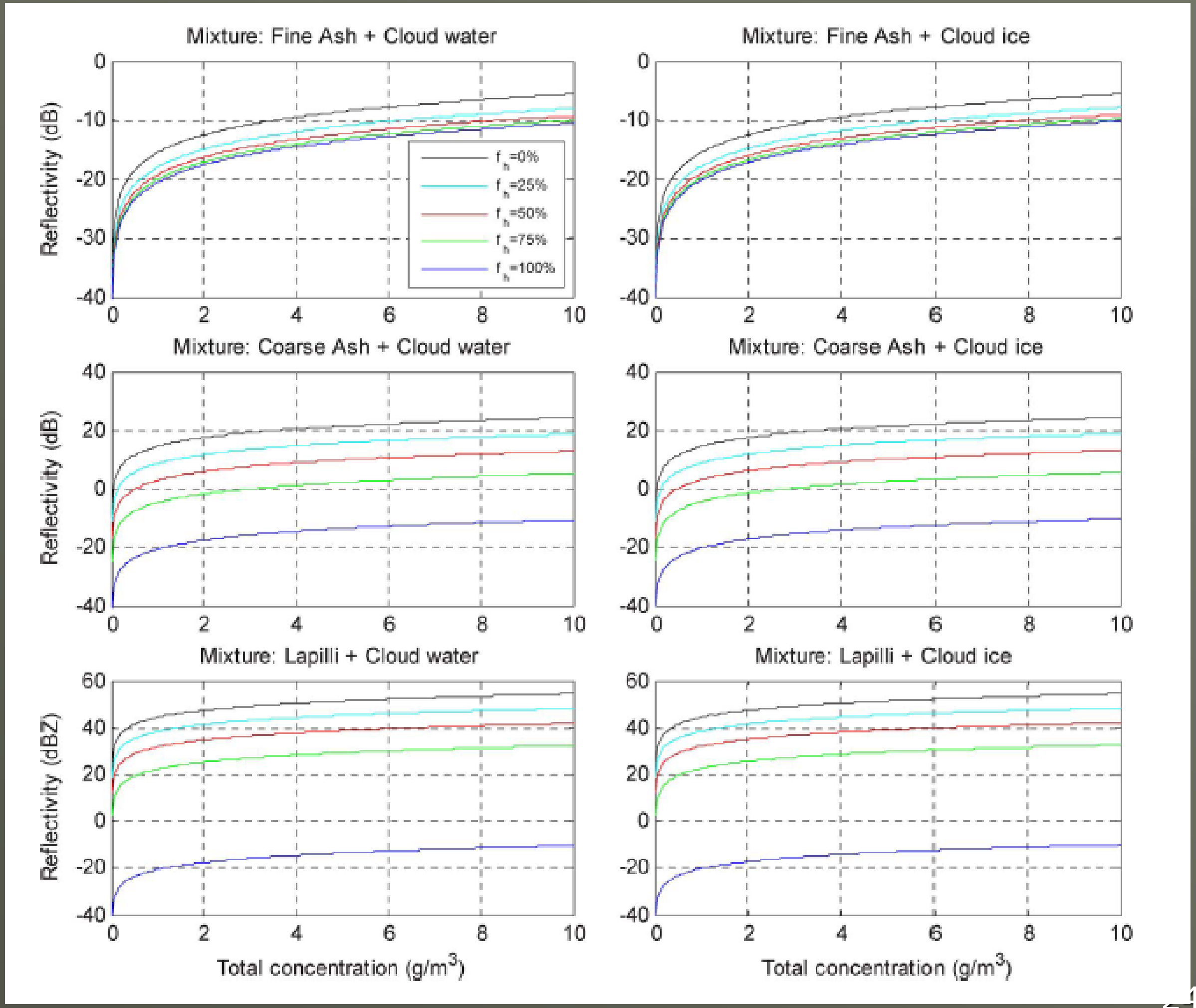
ISSUE1: ASH-WATER PARTICLE AGGREGATION

- **Mixture of ash and cloud water/ice particles**
  - **Fine ash (0.01 mm), Coarse ash (0.1 mm), Lapilli (1 mm)**
  - **Mixture with cloud droplets (0.01 mm) and ice (0.01 mm)**

For fine and coarse ashes within a fractional combination of 50%, the expected reflectivity **reduction is generally less than 1 dB for coexistence and less than 5 dB for mixture** with respect to the measured values.

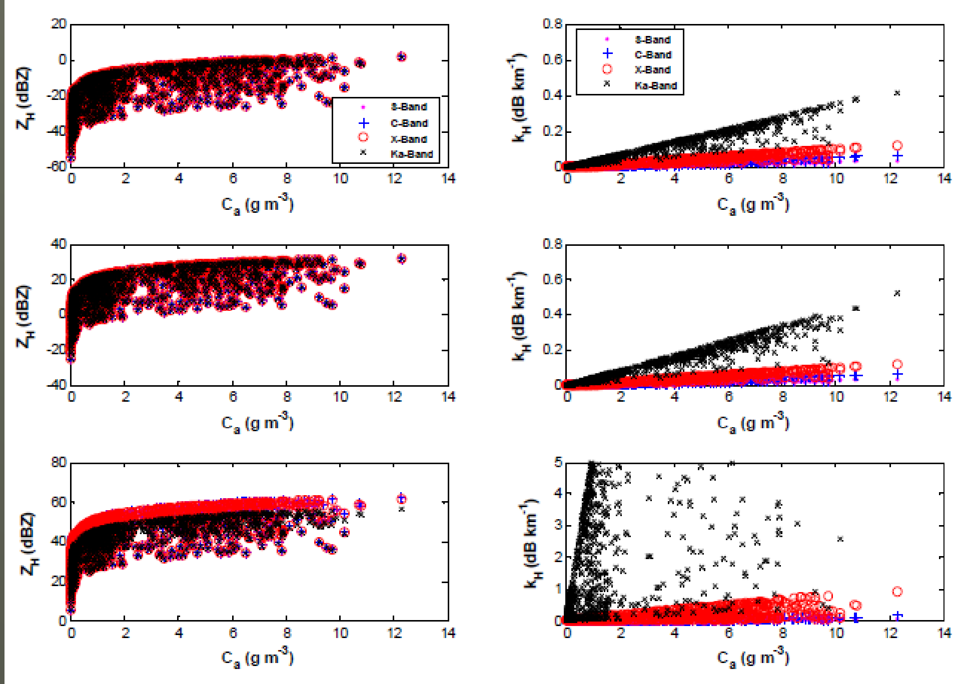
Note that the received power will also depend that the dielectric factor $|K|^2$ = *0.18 for ice and* $|K|^2$ = *0.93 for water* (causing a difference of about 7.1 dB)



ISSUE2: MICROWAVE RADAR FREQUENCY

- Ash backscattering and absorption
  - X-band more sensitive than C- band S-band (λ^{-4})
  - Ka-band wave is more attenuated than X-band (λ^{-2})
  - Higher freq., as W band (90 GHz), to be avoided

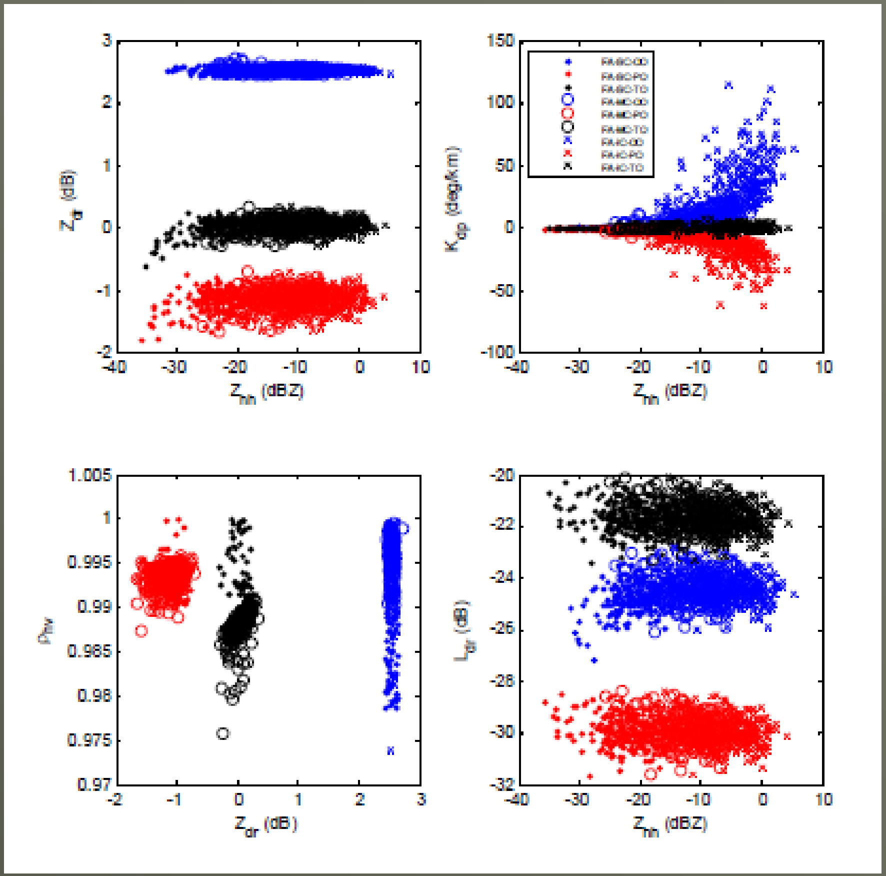
- **X-band system aspects With respect to C- and S- band systems**
  - ADVANTAGES
    - Compact system
    - Portable
    - RX/TX behind antenna
    - Directive antenna
    - More sensitive to ash
  - DISADVANTAGES
    - Less TX power
    - Possible attenuation
    - Lower Doppler winds
    - Higher RX noise



ed horizontally-polarized reflectivity factor Z_H, (left column) and specific attenuation k_H (right column
he classes of fine ash (top row), coarse ash (middle (row) and lapilli (bottom row), defined in Tab. II
ed assuming ρ_a=1 g cm^{-3}.

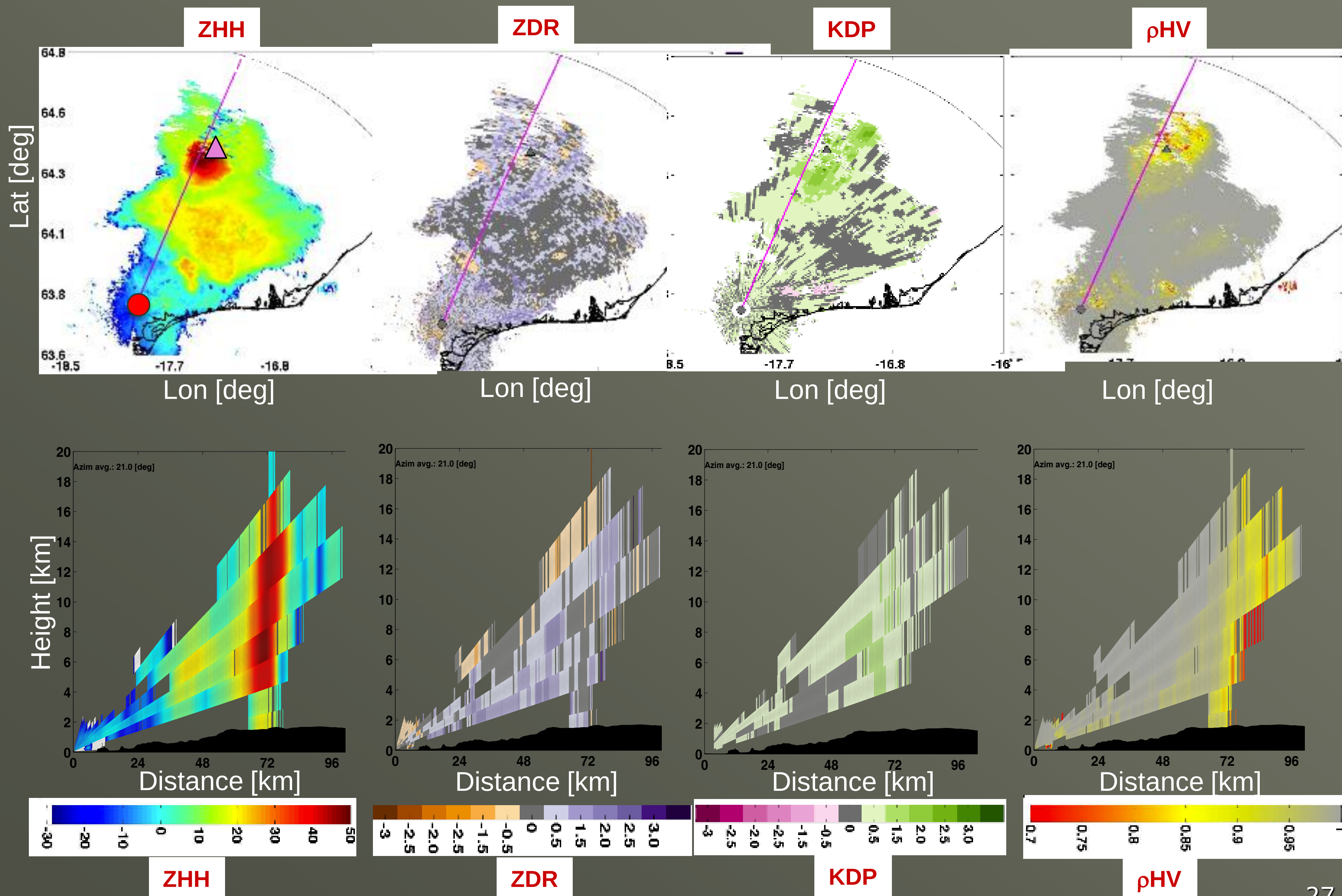
ISSUE4: X-BAND RADAR POLARIMETRY

- Dual-polarized detection of ash category
  - Fine ash with prolate, oblate, tumbling orientation
  - Multiple observations
    - Co-polar reflectivity
      Zhh
    - Differential reflectivity
      Zdr
    - Differential phase
      Kdp
    - Co-polar correlation
      ρhv
    - Depolarization ratio
      Ldr
  - Advantages
    - Classification
    - Data quality
    - Clutter removal



Marzano F.S., E. Picciotti, G. Vulpiani and M. Montopoli, "Synthetic Signatures of Volcanic Ash Cloud Particles from X-band Dual-Polarization Radar", IEEE Trans. Geosci. Rem. Sens., ISSN: 0196-2892, vol. 50, pp. 193-211, 2012

ISSUE4: X-BAND POL from GRIMSVOTN 2011



CONCLUSIONS

- Ash cloud radar remote sensing: possible!
  - Physically-based retrieval scheme
  - Retrieval sensitivity
    - Good sensitivity for coarse ash and lapilli at S and C band
    - Fine ash detectable only if increased sensitivity:
  - Analysis of volcanic plumes in Iceland, Italy, Alaska
- Final issues
  - Application of the VARR scheme
    - Operational weather radar close to active volcanoes
    - Ground validation of ash radar retrievals
  - Sensor ynergy and development
    - Exploitation of Doppler polarimetric capability
    - Synergy with satellite and other ground sensors

Pulvis es
et pulvis reverteris…

GRAZIE…
for your
patience.

F.S. Marzano, E. Picciotti, M. Montopoli, G. Vulpiani, ***INSIDE VOLCANIC CLOUDS: Remote Sensing of Ash Plumes Using Microwave Weather Radars,*** *Bull. American Met. Society (BAMS), p. 1567, October 2013 (free access on line).*