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PRECIPITATING CLOUD EFFECTS ON THE RADAR POLARIMETRIC SIGNATURE AT KA BAND

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WHY CLOUDS DEALING WITH SAR ?

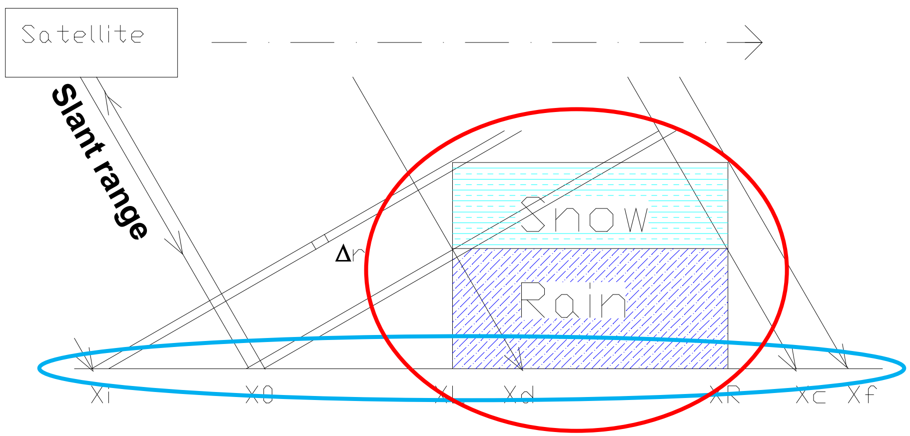
- **POTENTIAL of X/Ku/Ka-band SAR for RAIN retrieval**
  - At higher frequency precipitating clouds may produce significant **attenuation/scattering/depolarization** effects
  - The high spatial resolution of SAR sensors might provide new insights into the **structure of precipitating clouds** from space.
  - **Large availability of a new generation of X-SAR satellites** near fully polarimetric

- **Atmospheric artifacts on high frequency radar imaging**
  - **Rainfall signatures** have been already revealed by previous X-SARs measurements (e.g. SAR-X SIR-C in 1994)
  - It can affect the interpretation of SAR data at X and higher frequencies, **modifying the polarimetric signature** of the ground
  - Assessing these effect can support to the **design and performance assessment** of future high frequency radar (e.g., Ka band interferometer, ESA funded project N. 4000109477/13/nl/lvh)

Outline

- **Introduction**
  - Context and examples
- **Modeling of SAR observations due to precipitation**
  - SAR response model
  - Polarimetric SAR observables
  - High-resolution polarimetric simulated scenarios
- **Polarimetric signature of precipitation**
  - Sensitivity analysis
  - Polarimetric frequency diversity
- **Parametric estimation of precipitation from X-SAR**
  - Case study
- **Conclusions**

SAR cloud response and observables



Plane-wave incidence (avoid spherical wave front corrections)

SAR polarimetric observables

$$\sigma^\circ_{SAR}(x) = \sigma^\circ_{SRF}(x) + \sigma^\circ_{VOL}(x)$$

$$Z_{SARco}(x) = \frac{\sigma^0_{SARhh}(x)}{\sigma^0_{SARvv}(x)}$$

$$\rho_{SARco}(x) = \frac{< S_{SARhh}(x) S_{SARvv}^{*}(x) >}{\sqrt{< \left| S_{SARhh}(x) \right|^2 >} \sqrt{< \left| S_{SARvv}(x) \right|^2 >}} = \left| \rho_{SARco}(x) \right| e^{j\Psi_{SARco}(x)}$$

- σ^0_{SARpq}: ***pq*-polarized normalized radar cross section (NRCS)**

- Z_{SARco}: **co-polar ratio**
- ρ_{SARco}: **complex correlation coefficient**

Modelling SAR response: NRCS

- **For a given pixel (*x,y*) the SAR NRCS can be formally expressed as follows:**

$$\sigma^0_{SARpq}(x,y)=\sigma^0_{SRFpq}(x,y)+\sigma^0_{VOLpq}(x,y)$$

- $\sigma^0_{SRFpq}(x,y)$: surface backscatter, attenuated by the two-way path through the precipitating atmosphere
- $\sigma^0_{VOLpq}(x,y)$: volume backscattering due to hydrometeor reflectivity, weighted by the two-way path through precipitating atmosphere

$$\sigma^0_{SRFpq}(x,y)=\sigma^{ground}_{pq}(x,y)\exp\left(-\int_{\Delta l(x,y)} k_{pp}(l)dl-\int_{\Delta l(x,y)} k_{qq}(l)dl\right)$$

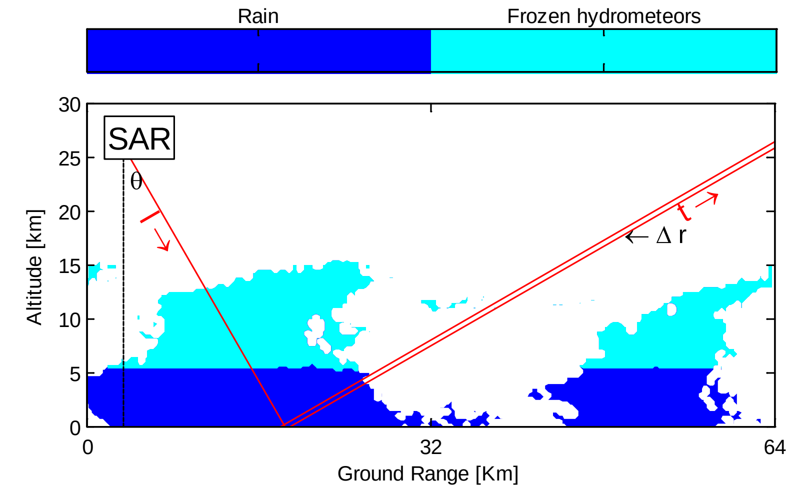
$$\sigma^0_{VOLpq}(x,y)=\int_{\Delta t(x,y)}\eta_{pq}(t)\exp\left(-\int_{\Delta l(x,y)} k_{pp}(l)dl-\int_{\Delta l(x,y)} k_{qq}(l)dl\right)dt$$

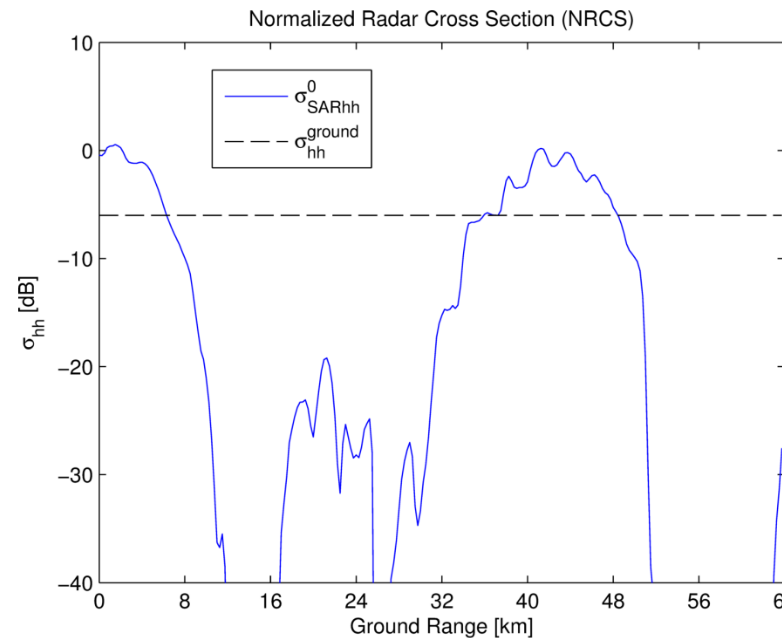
- σ^{ground}_{pq}: surface target NRCS
- η_{pq}, k_{pq}: hydrometeors reflectivity and specific attenuation

$$\eta_{pq}=4\pi<|S_{pq}|^2>=\int_0^{\infty}\int_0^{\pi/2}8\pi^2|S_{pq}(D,\phi)|^2 N(D)p(\phi)dD\sin\phi d\phi$$

$$k_{pq}=-2\lambda<\mathrm{Im}(F_{pq})>$$

- S_{pq}, F_{pq} : element of the complex back or forward hydrometeor scattering matrix
- $N(D)$: particle size distribution
- $p(\phi)$: particle orientation probability density function
- λ: wavelength





Modelling SAR response: Correlation Coeff.

- **For a ground point (*x,y*) the observable SAR complex correlation coefficient is given by:**

$$\rho_{SARco} = \frac{\sqrt{\sigma^0{}_{hh}}\sqrt{\sigma^0{}_{vv}}\,\rho_{co}^{ground}\, e^{-\int_{\Delta l(x)} k_{hh}(l)dl}\, e^{-\int_{\Delta l(x)} k_{vv}(l)dl}\, e^{j2\Phi co(x)} + sen\theta \int_{\Delta t(x)} C_{VOL}(t)dt}{\sqrt{\sigma^0_{SARhh}}\sqrt{\sigma^0_{SARvv}}}$$

$$\Psi_{SARco}(x,y) = \arg\{\rho_{SARco}(x,y)\}$$

$$C_{VOL}(t) = \sqrt{\eta(t)_{vv}}\sqrt{\eta(t)_{hh}}\,\rho_{co}^{vol}(t)\exp\left(-\int_{\Delta l(t)} k_{vv}(l)dl\right)\exp\left(-\int_{\Delta l(t)} k_{hh}(l)dl\right)e^{j2\Phi_{co}(t)}$$

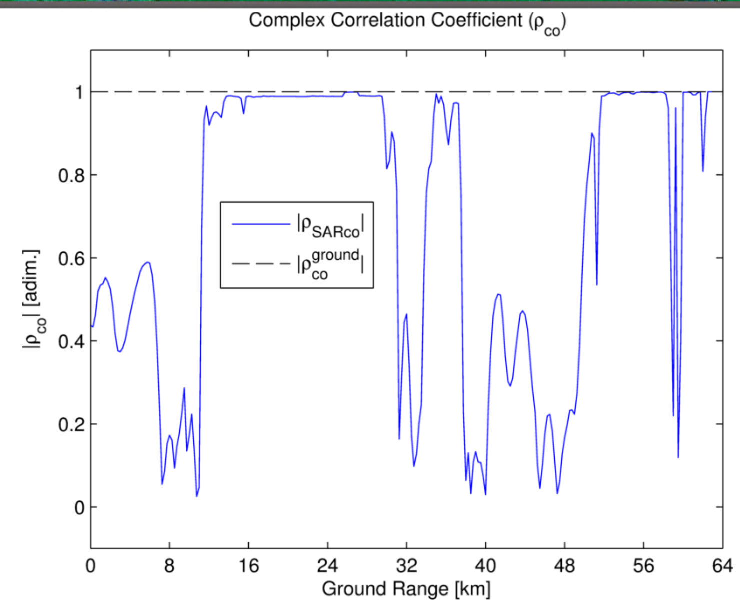
$$\rho_{co} = |\rho_{co}|\, e^{j\delta_{co}}$$

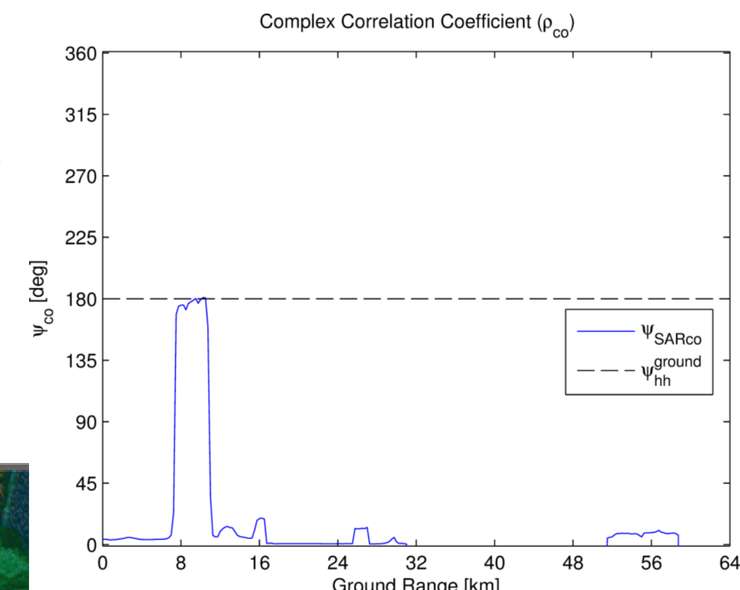
$$\delta_{co} = \delta_{vv} - \delta_{hh} = \arg(\rho_{co})$$

$$K_{co} = \lambda < \mathrm{Re}(F_{hh} - F_{vv}) >$$

$$\Phi_{co} = \int_{\Delta l(t)} K_{co}(l)dl$$

- ρ_{SARco}, ρ_{co}^{ground}, ρ_{co}^{vol} **:** complex correlation coefficients of observed resolution cell, surface target and volume bin
- δ_{co} : backscatter differential phase
- S_{pq}, F_{pq} : elements of the hydrometeros complex back or forward scattering matrix
- η_{pq}: hydrometeor reflectivity
- K_{co}: hydrometeor copolar specific differential phase





Hydrometeor e.m. parameterization

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Hydrometeors polarimetric parameters can be modelled as function of water content by mean of power laws:

$$Z_{epq}(x,y,z) = \frac{\lambda^4}{\pi^5 |K|^2} \eta_{pq}(x,y,z) = a_{Zpq} W(x,y,z)^{b_{Zpq}}$$

$$k_{pq}(x,y,z) = a_{kpq} W(x,y,z)^{b_{kpq}}$$

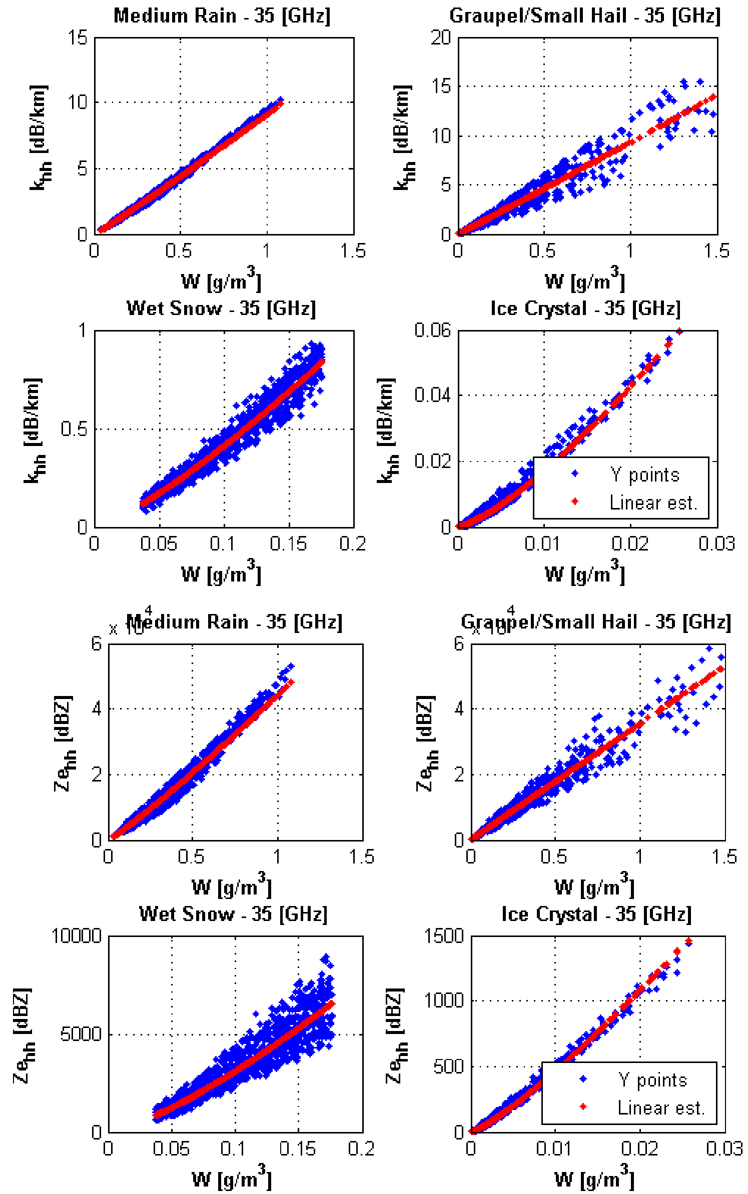
$$K_{co}(x,y,z) = a_{Kco} W(x,y,z)^{b_{Kco}}$$

$$|\rho_{co}|(x,y,z) = a_{\rho co} W(x,y,z)^{b_{\rho co}}$$

$$\delta_{co}(x,y,z) = a_{\delta co} W(x,y,z)^{b_{\delta co}}$$

- **W** = water content [g/m^3]
- K_{co}= differential phase. [°/km]
- k_{pq} = specific attenuation [dB/km]
- Z_{epq} = equivalent reflectivity [mm^6/m^3]
- $|\rho_{co}|$ = mod. of the copolar corr. Coefficient
- δ_{co}= arg. of the copolar corr. coefficient
- λ= wavelength [cm]
- **|K|^2** = 0.93 for water and 0.19 for ice

a_{Xpq}, b_{Xpq} coefficients have been obtained by using **HESS T-Matrix radar scattering model**, as described in [Marzano et al., 2007] and [Marzano et al., 2010].



Simulation case studies

- The proposed SAR response model requires as input a
  - **cloud structure** (2D geometry, hydrometeor types, hydrometeor water content distribution, hydrometeor e.m. response parameterization) and
  - the polarimetric characterization of the **ground target**

- The ground target polarimetric covariance matrix can be given by:
  - **Models** (e.g., bare soil polarimetric response by [Oh et al., 2002]
  - Polarimetric signature of **canonical targets** (i.e., spheres with ρ_{co}^{ground}=1, dihedrals with ρ_{co}^{ground}=-1, others
- The cloud structure (i.e., hydrometeors distributions) can be derived by
  - ad-hoc **synthetic distributions**, with simplified shape (e.g. parallelepiped), to assess main effects in a simple environment.
  - Realistic fields simulated by a **3-D high-resolution mesoscale** cloud-resolving models (CRMs)

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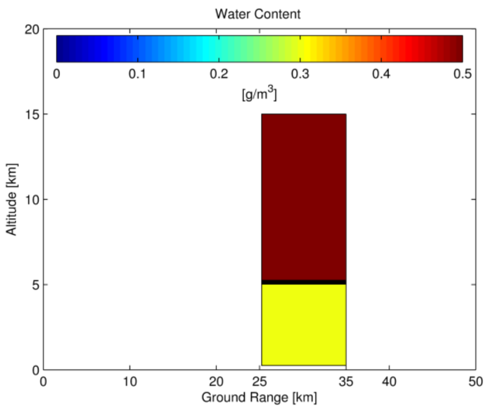
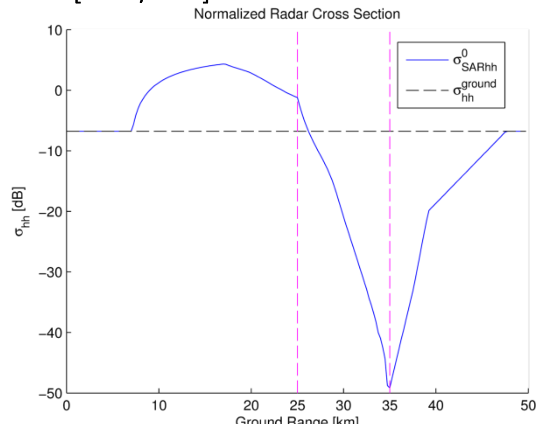
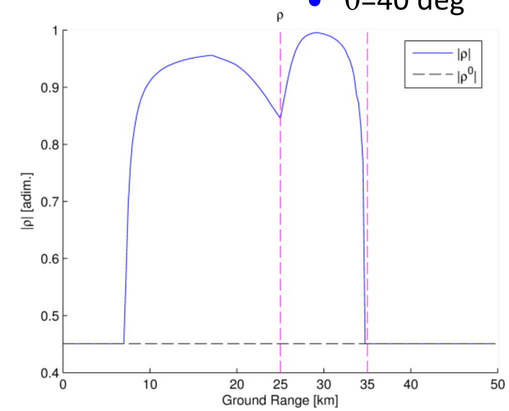
Synthetic cloud 1: Rectangular cumulonimbus

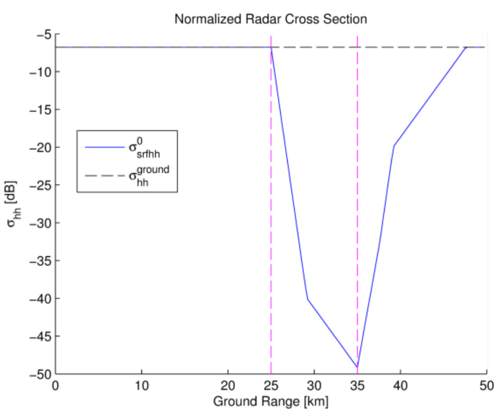
- Parallelepiped structure
- Horizontal uniform 10 km wide hydrometeor density
- 2 vertical layers: raindrops 0.3 g/m^3 and snoflakes 0.5 g/m^3 water content, with 15 km overall height
- E. M. parameters from HESS T-Matrix model [Marzano et al., 2007]
- Homogenous background from bare soil model [Oh et al., 2002]: Rms Height (k_s) 1.5 cm, Correlation Lenght (k_l) 5.0 cm, Volumetric soil moisture content (m_v) 0.25 [cm^3 /cm^3]

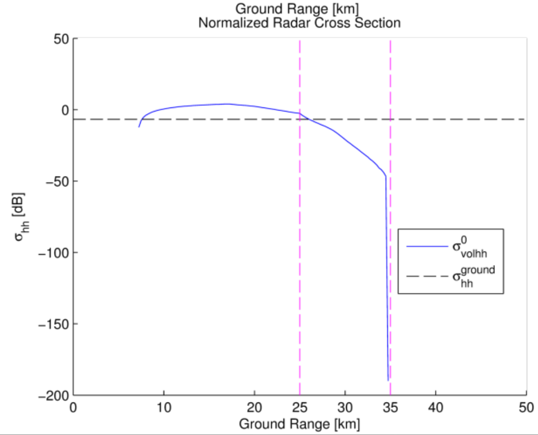
- Zero °C @4.9 km
- $\sigma^{ground} \cong$ -6 dB
- f = 35 GHz
- θ=40 deg

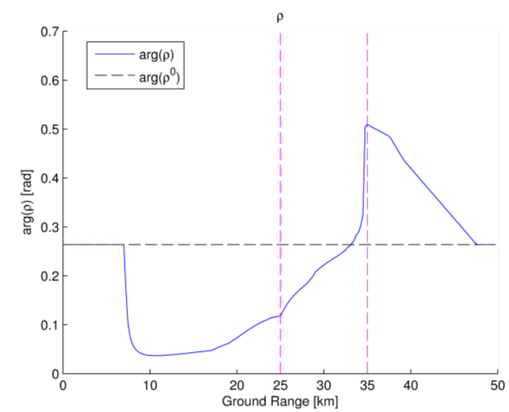




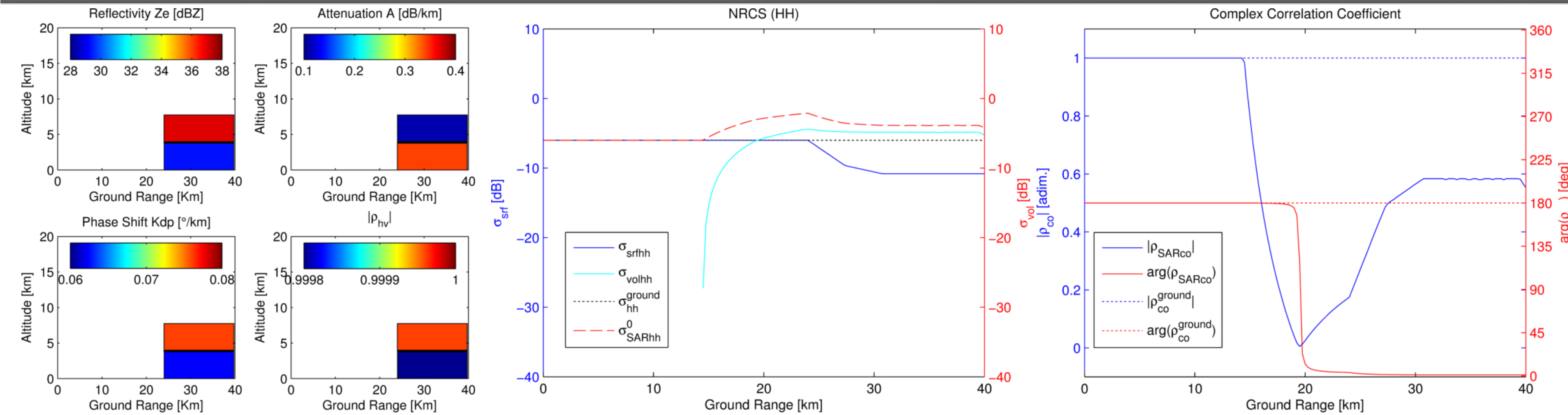




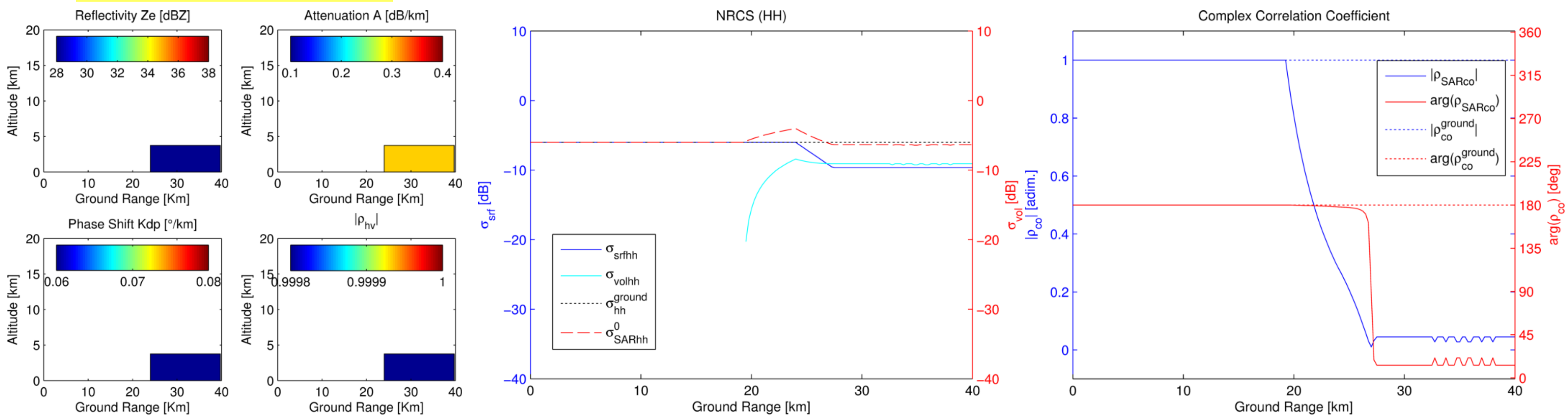




Case 2: Stratiform cloud with and without ice



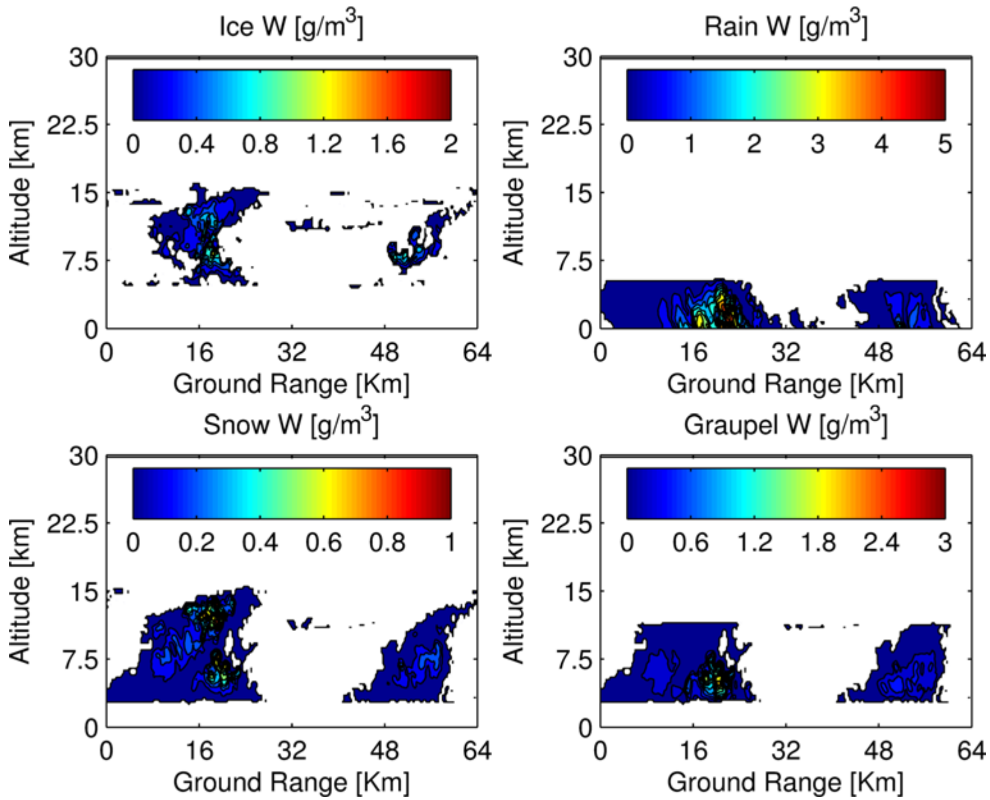
Dihedrals – NRCS c.a. -6dB



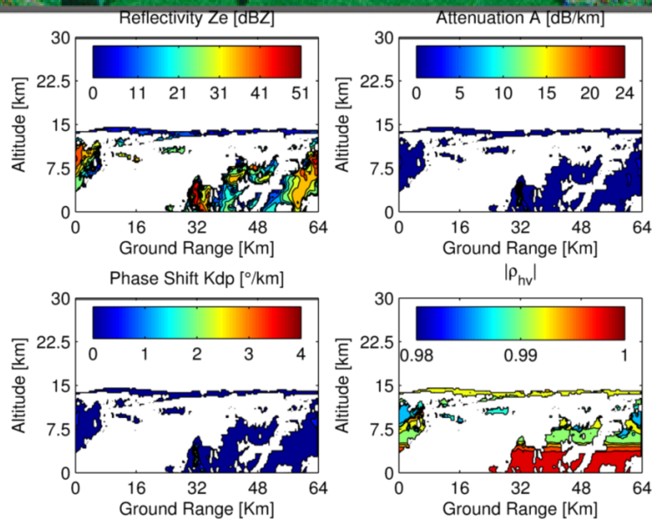
High-resolution realistic clouds

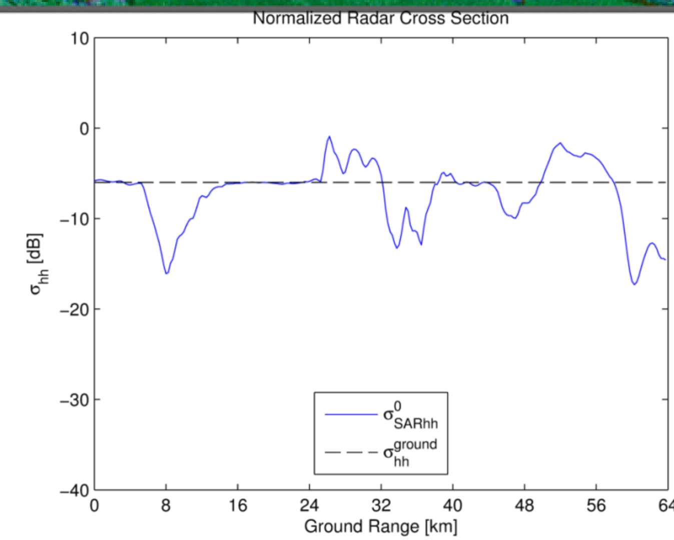
- The simulated **hydrometeors distributions** can be derived by simulated field through **3-D high-resolution mesoscale cloud-resolving models (CRMs)**
- The **System for Atmospheric Modeling** (SAM) CRM [Blossey et al., 2007] allows at simulating the distribution of Cloud, Rain, Ice, Snow, Graupel particles at 250 m resolution

Examples of horizontal and vertical distribution of densities of different hydrometeors predicted by model at a given epoch



Case 3. Realistic spread thin cloud





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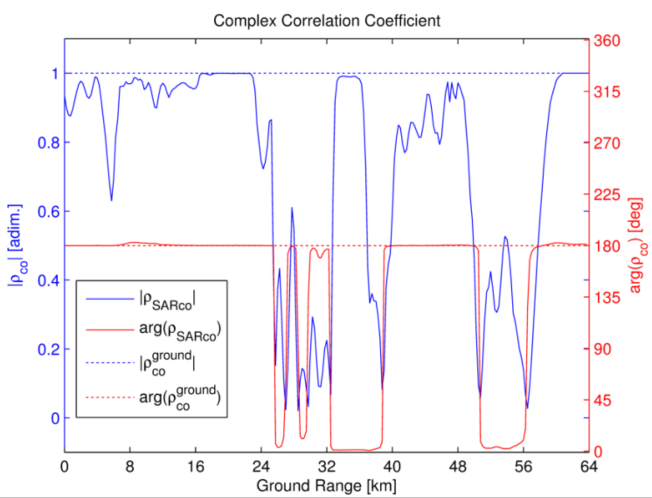
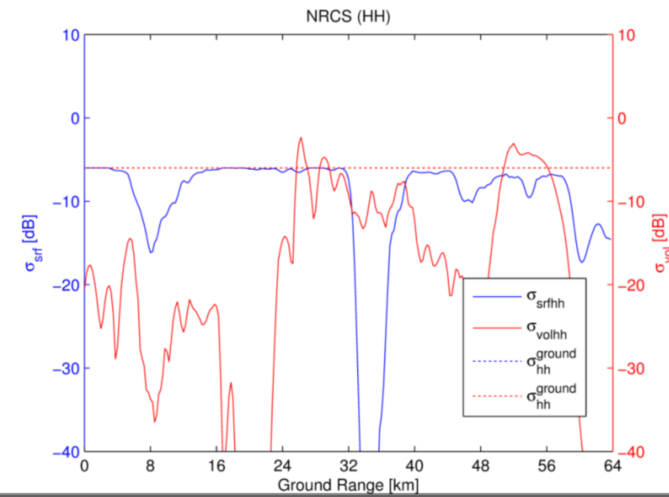
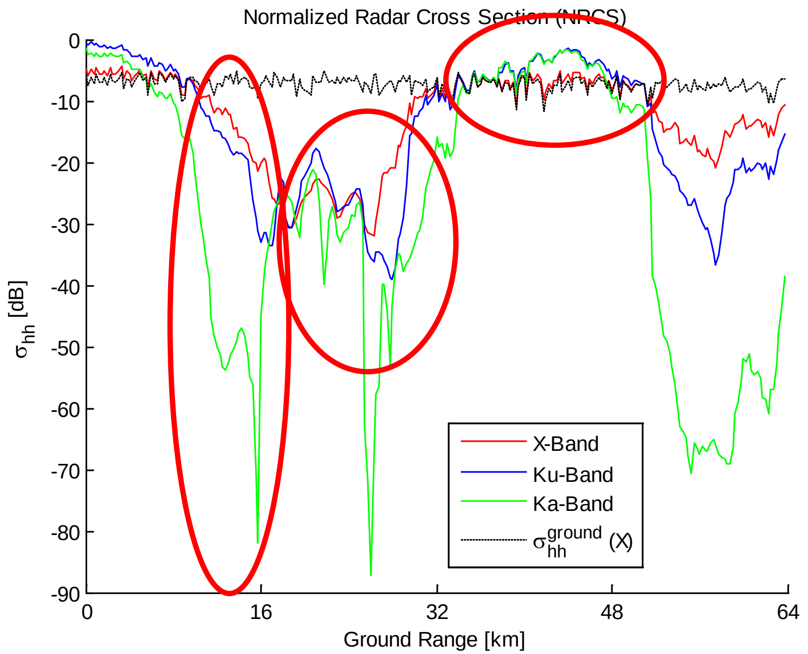
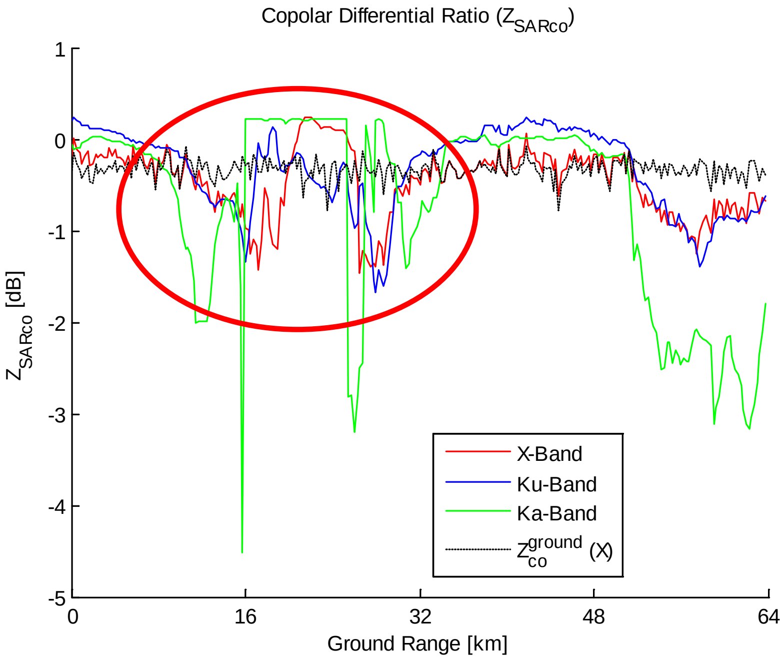




Dependence on frequency

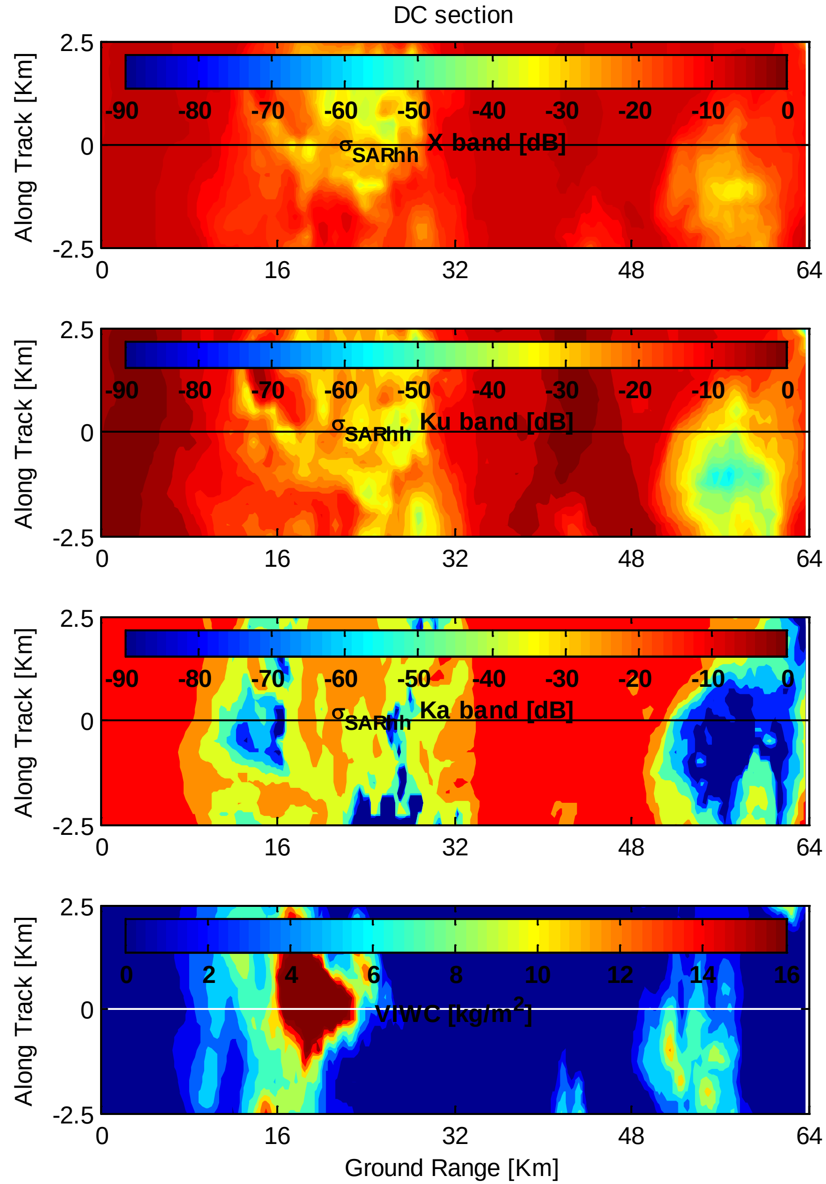
- **Both negative and positive peaks of NRCS increase with frequency**
  - Ka-band NCRS appears more sensitive to attenuation and less to reflectivity
  - X and Ku bands show a comparable dynamic range
- **Presence of dissimilar behavior**
  - Peak shifting, peak present only in one or two frequencies
- **Z_{SARco} similar to NRCS**
  - Small positive values (presence of spherically-shaped frozen hydrometeors)
  - Large negative peaks (presence of intense precipitation with oblate raindrops)
  - Ka-band quite dissimilar from X and Ku ones





Simulates NRCS image at X/Ku/Ka bands

- Ground plane σ^0_{SARhh} for X, Ku and Ka band, *hh* polarization plus the total vertically-integrated columnar content (VIWC).
- The ground response has been considered as constant (about -7 dB at X-band), and so the incident angle (40°).
- The images of the storm are simulated in ground range (the x-y plane), 5 km width, spread all the cross range dimension (64 km).



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X-SAR retrievals: Hurricane “GUSTAV” case

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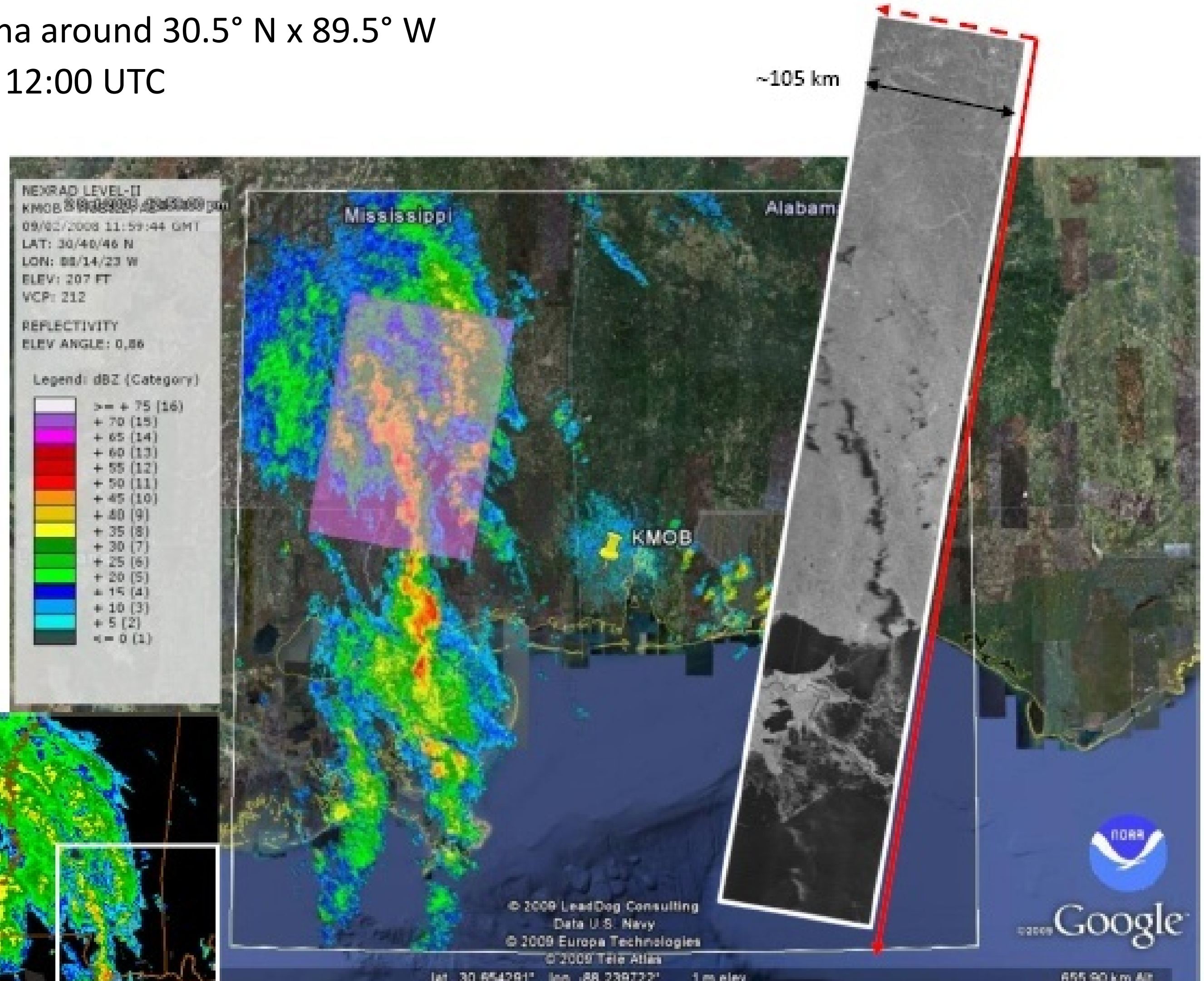
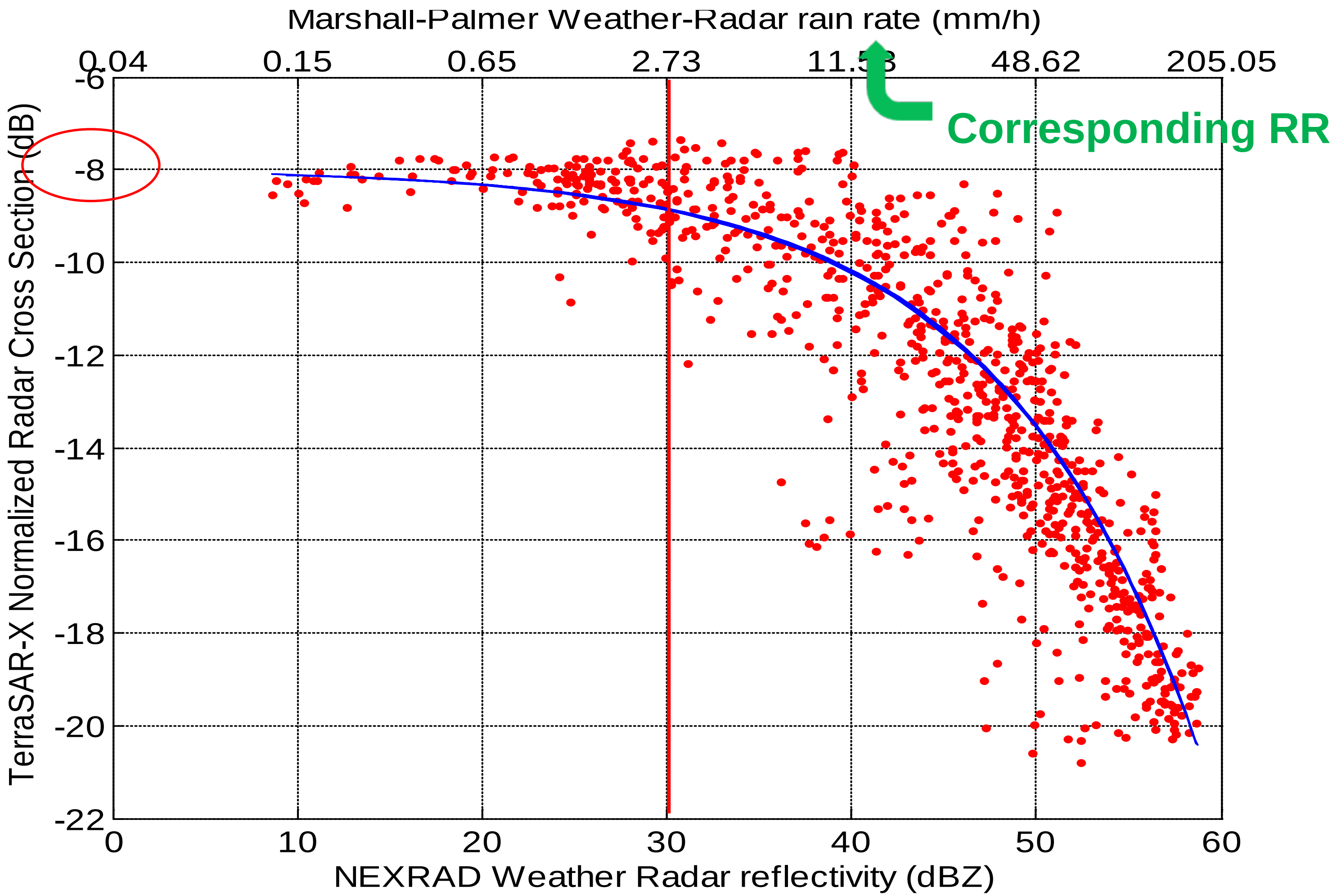
- South eastern Louisiana around 30.5° N x 89.5° W
- September 2, 2008 at 12:00 UTC

TerraSAR-X:
HH pol data

NEXRAD:
S-band reflectivity
PPI at 0.86 deg
KMOB site



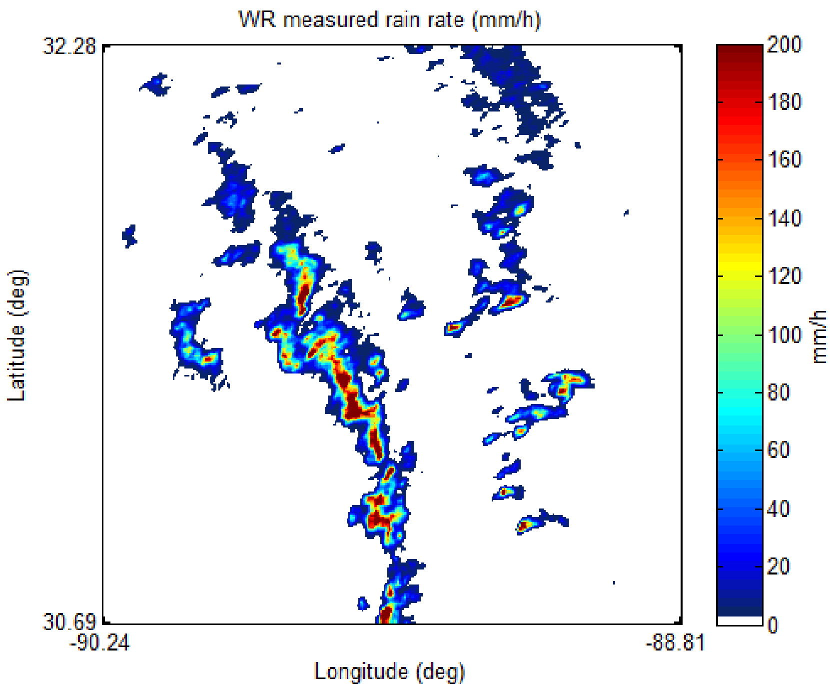
X-SAR retrievals : Hurricane “GUSTAV” case



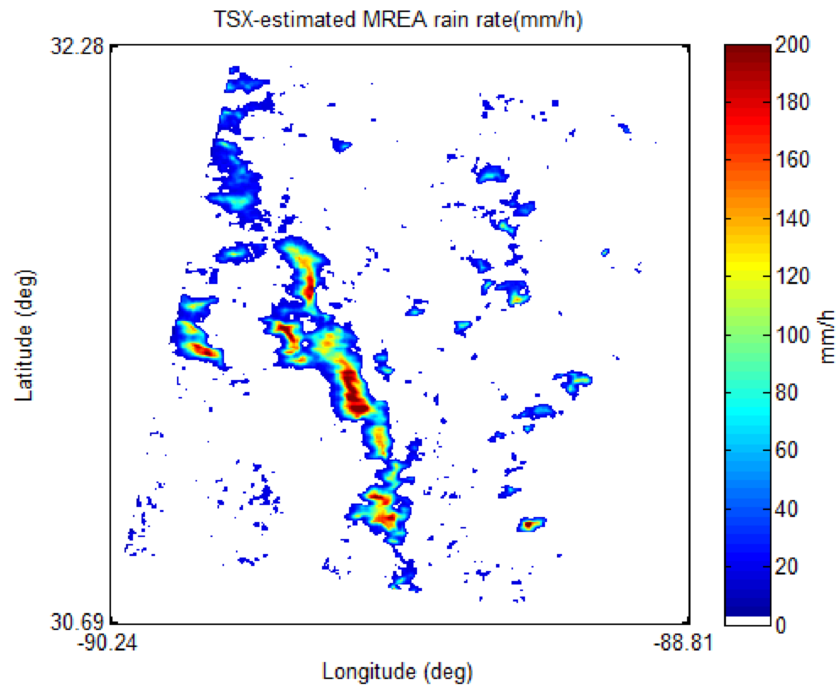
Correlation between NRCS values σ_{SAR} against co-located and co-registered NEXRAD WR reflectivity *Z*, for the selected region of interest (ROI)

X-SAR retrievals: Hurricane “GUSTAV” case

Precipitation rate [mm/h]



Ground Weather Radar



Spaceborne X-SAR

- **Corr = 0.75**
- **Bias = -0.66 mm/h**
- **RMSE = 22.28 mm/h**
- **FRMSE = 0.98**

Conclusions

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- **A 2D/3D simulator of the polarimetric response of a SAR in presence of precipitating clouds has been developed**
- **Considering simple synthetic clouds as well as realistic clouds predicted by a mesoscale model we found that:**
- **Bad news**
  - The impact of clouds on X and especially Ka band SAR can be significant, even for clouds with relatively high occurrence
  - The polarimetric signature of the ground target can be significantly modified or even completely masked
- **Good news**
  - Both copolar ratio and differential phase exhibit a good correlation with columnar contents.
  - SAR remote sensing of clouds has spatial resolution useful for water budget, water management and hydrological model initialization

Thank you!

Acknowledgments

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  - ESA/ESTEC contract N. 4000109477/13/nl/lvh) “Ka-Band SAR Backscatter Analysis in Support of Future Applications”
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Marzano et al., TGRS, 2012
Pulvirenti et al., TGRS 2014