Atmospheric distortions of spaceborne SAR polarimetric signatures at X and Ka-band

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WHY RAINCLOUDS and 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

**Rain effects on SAR imaging and retrieval opportunity**
- High-resolution microwave rain retrieval from SPACE at a scale below 1 km is only possible from SAR imaging data
- Rain effect can affect the interpretation of SAR data at X and higher frequencies, *modifying the polarimetric* signature of the ground
- *Is there a minimum RainSAR retrieval sensitivity at a given spatial resolution (less than 1 km) considering the uncertainty of the surface background?*
- *Is there an upper limit to RainSAR retrieval? Are there geometrical effects to be solved?*
X-SAR retrievals: Hurricane “GUSTAV” case

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

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

Precipitation rate [mm/h]

Ground Weather Radar

Spaceborne X-SAR
Outline

Introduction
  Context and examples

Parametric estimation of precipitation from X-SAR
  Case study

Modeling of SAR observations due to precipitation
  SAR response model
  Polarimetric SAR observables
  High-resolution polarimetric simulated scenarios

Polarimetric signature of precipitation
  Sensitivity analysis

Conclusions
SAR cloud response and observables

\[ \sigma_{SAR}^0(x) = \sigma_{SRF}^0(x) + \sigma_{VOL}^0(x) \]

\[ Z_{SAR_{co}}(x) = \frac{\sigma_{SAR_{hh}}^0(x)}{\sigma_{SAR_{vv}}^0(x)} \]

\[ \rho_{SAR_{co}}(x) = \frac{<S_{SAR_{hh}}(x)S_{SAR_{vv}}^*(x)>}{\sqrt{<|S_{SAR_{hh}}(x)|^2>\sqrt{<|S_{SAR_{vv}}(x)|^2>}}} = \rho_{SAR_{co}}(x)e^{j\phi_{SAR_{co}}(x)} \]

- \( \sigma_{SARpq}^0 \): pq-polarized normalized radar cross section (NRCS)
- \( Z_{SAR_{co}} \): co-polar ratio
- \( \rho_{SAR_{co}} \): complex correlation coefficient

Radar swath
Plane-wave incidence (avoid spherical wave front corrections)
For a given pixel \((x,y)\) the SAR NRCS can be formally expressed as follows:

\[
\sigma_{\text{SAR}pq}^0(x,y) = \sigma_{\text{SRF}pq}^0(x,y) + \sigma_{\text{VOL}pq}^0(x,y)
\]

- \(\sigma_{\text{SRF}pq}^0(x,y)\): surface backscattering, attenuated by the two-way path through the precipitating atmosphere
- \(\sigma_{\text{VOL}pq}^0(x,y)\): volume backscattering due to hydrometeor reflectivity, weighted by the two-way path through precipitating atmosphere

\[
\sigma_{\text{SRF}pq}^0(x,y) = \sigma_{pq}^\text{ground}(x,y)\exp\left(-\int_{\Delta l(x,y)} k_{pp}(l)\,dl - \int_{\Delta l(x,y)} k_{qq}(l)\,dl\right)
\]

\[
\sigma_{\text{VOL}pq}^0(x,y) = \int_{\Delta l(x,y)} \eta_{pq}(t)\exp\left(-\int_{\Delta l(x,y)} k_{pp}(l)\,dl - \int_{\Delta l(x,y)} k_{qq}(l)\,dl\right)dt
\]

- \(\sigma_{pq}^\text{ground}\): surface target NRCS
- \(\eta_{pq}, k_{pq}\): hydrometeors reflectivity and specific attenuation

\[
\eta_{pq} = 4\pi <\!|S_{pq}|^2\!> = \int_\phi_0^{\pi/2} \int_0^\pi 8\pi^2 <|S_{pq}(D,\phi)|^2> N(D)p(\phi)d\phi d\phi
\]

\[
k_{pq} = -2\lambda <\!\text{Im}(F_{pq})\!>
\]

- \(S_{pq}, F_{pq}\): element of the complex back or forward hydrometeor scattering matrix
- \(N(D)\): particle size distribution
- \(p(\phi)\): particle orientation probability density function
- \(\lambda\): wavelength
Modelling SAR response: Complex Correlation Coeff.

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

\[
\rho_{\text{SAR,co}} = \frac{\sqrt{\sigma_{hh}^0 \sigma_{vv}^0} \rho_{\text{co,ground}} e^{-\int_{\Delta l(i)} k_{hh}(l)dl} e^{-\int_{\Delta l(i)} k_{vv}(l)dl} e^{i2\Phi_{\text{co,vol}}(x)} + \text{sen} \theta \int C_{\text{VOL}}(t) dt}{\sqrt{\sigma_{Rhh}^0 \sigma_{Rvv}^0}}
\]

\[
\Psi_{\text{SAR,co}}(x,y) = \arg\{\rho_{\text{SAR,co}}(x,y)\}
\]

\[
C_{\text{VOL}}(t) = \sqrt{\eta(t)_{vv} \eta(t)_{hh}} \rho_{\text{co,vol}}^t(t) \exp\left(-\int_{\Delta l(i)} k_{vv}(l)dl\right) \exp\left(-\int_{\Delta l(i)} k_{hh}(l)dl\right) e^{i2\Phi_{\text{co,vol}}(t)}
\]

- \(\rho_{\text{SAR,co}}, \rho_{\text{co,ground}}, \rho_{\text{co,vol}}\): complex correlation coefficients of observed resolution cell, surface target and volume bin
- \(\delta_{\text{co}}\): backscatter differential phase
- \(S_{pq}, F_{pq}\): elements of the hydrometers complex back or forward scattering matrix
- \(\eta_{pq}\): hydrometeor reflectivity
- \(K_{\text{co}}\): hydrometeor copolar specific differential phase
Hydrometeors polarimetric parameters can be modelled as function of water content by mean of power laws:

\[ Z_{epq}(x, y, z) = \frac{\lambda^4}{\pi^3 |K|^2} \eta_{pq}(x, y, z) = a_{Zpq}W(x, y, z)^{b_{Zpq}} \]

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

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

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

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

- \( W \) = water content [g/m³]
- \( K_{co} \) = differential phase, [°/km]
- \( k_{pq} \) = specific attenuation [dB/km]
- \( Z_{epq} \) = equivalent reflectivity [mm⁶/m³]
- \( |\rho_{co}| \) = mod. of the copolar corr. Coefficient
- \( \delta_{co} \) = arg. of the copolar corr. coefficient
- \( \lambda \) = wavelength [cm]
- \(|K|^2 = 0.93\) for water and \(0.19\) for ice

\( a_{Xpq}, b_{Xpq} \) coefficients have been obtained by using APHESS 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 $\rho_{co,\text{ground}}=1$, dihedrals with $\rho_{co,\text{ground}}=-1$, 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)
Simulation of 3D realistic clouds SAR response

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

- Ground plane $\sigma^0_{SARhh}$ 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).
Example: Rectangular cumulonimbus at X-Band

- Parallelepiped structure
- Horizontal uniform 10 km wide hydrometeor density
- **2 vertical layers:** raindrops 0.3 g/m³ and snowflakes 0.5 g/m³ water content, with 15 km overall height
- E. M. parameters from revised APHESS T-Matrix model [e.g., 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 [cm³/cm³]

- Zero °C @4.9 km
- $\sigma_{\text{ground}}$ = -6 dB
- $f$ = 9.6 GHz
- $\theta$=40 deg
Example: Rectangular cumulonimbus at Ka-Band

- Parallelepiped structure
- Horizontal uniform 10 km wide hydrometeor density
- **2 vertical layers:** raindrops 0.3 g/m$^3$ and snowflakes 0.5 g/m$^3$ water content, with 15 km overall height
- E. M. parameters from revised APHESS T-Matrix model [e.g., Marzano et al., 2007]
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- Zero °C @4.9 km
- $\sigma_{\text{ground}}$ ≈ -6 dB
- $f = 35$ GHz
- $\theta = 40$ deg
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Case 1(A): Altostratus (liquid particles sensitivity)

- Non-precipitating cloud
- Ice crystals $0.5 \text{ g/m}^3$
  2km height
- Cloud Liquid $\{0.001, 0.01, 0.1, 1.0\} \text{ g/m}^3$
  2km height
- Ground: dihedral corner reflectors $0.025 \text{ m}$

- Detectable only at Ka-band, also $0.001 \text{ g/m}^3$ particles
- No phase rotation except Ka-band $1 \text{ g/m}^3$
- Polarimetric effects at X-Band, also at $0.001 \text{ g/m}^3$
Case 1(B): Altostratus (frozen particles sensitivity)

- Non-precipitating cloud
- Ice crystals \{0.001, 0.01, 0.1, 1.0\} g/m³
  2km height
- Cloud Liquid 0.2 g/m³
  2km height
- Ground: dihedral corner reflectors 0.025 m

- X-Band sensitive only to high densities of ice
- Ka-band sensitive to ice, especially for W > 0.01 g/m³
- Ka loss of polarimetric coherence for IC ~ CL
- Ka phase rotations for W >= 0.1 g/m³
Case 2(A): Nimbostratus (liquid particles sensitivity)

- Precipitating cloud
- Ice crystals 0.5 g/m³
  2km height
- Light Raindrops \{0.001, 0.01, 0.1, 1.0\} g/m³
  4km height
- Ground: dihedral corner reflectors 0.025 m

- Precipitation signature at Ka-band, for every density
- At X-Band only 1 g/m³ causes volumetric effects (actually not-detectable NRCS)
- Loss of polarimetric coherence for every band and density
- Phase rotation and increased coherence for highest densities
Case 2(B): Nimbostratus (frozen particles sensitivity)

- Precipitating cloud
- Ice crystals \{0.001, 0.01, 0.1, 1.0\} g/m³
  2km height
- Light Raindrops 0.2 g/m³
  4km height
- Ground: dihedral corner reflectors 0.025 m

- Loss of polarimetric coherence at every band and density (at Ka only for volume component)
- Phase rotation for highest density only (@Ka > 0.01 g/m³)
- Precipitation signature at Ka for every density, at X for W >= 0.1 g/m³
Conclusions

- 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:
  - The impact of clouds on X and 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
  - X Band NRCS shows an appreciable sensitivity to only “intense” events
  - Ka band confirms a great sensitivity to frozen particle, but also X band is affected
  - Complex correlation coefficient exhibits a good correlation with columnar contents.
  - SAR remote sensing of clouds has spatial resolution useful for water budget, water management and hydrological model initialization

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