Precipitation signature on imagery of spaceborne Synthetic Aperture Radar at X-Band and above: model, interpretation and analysis

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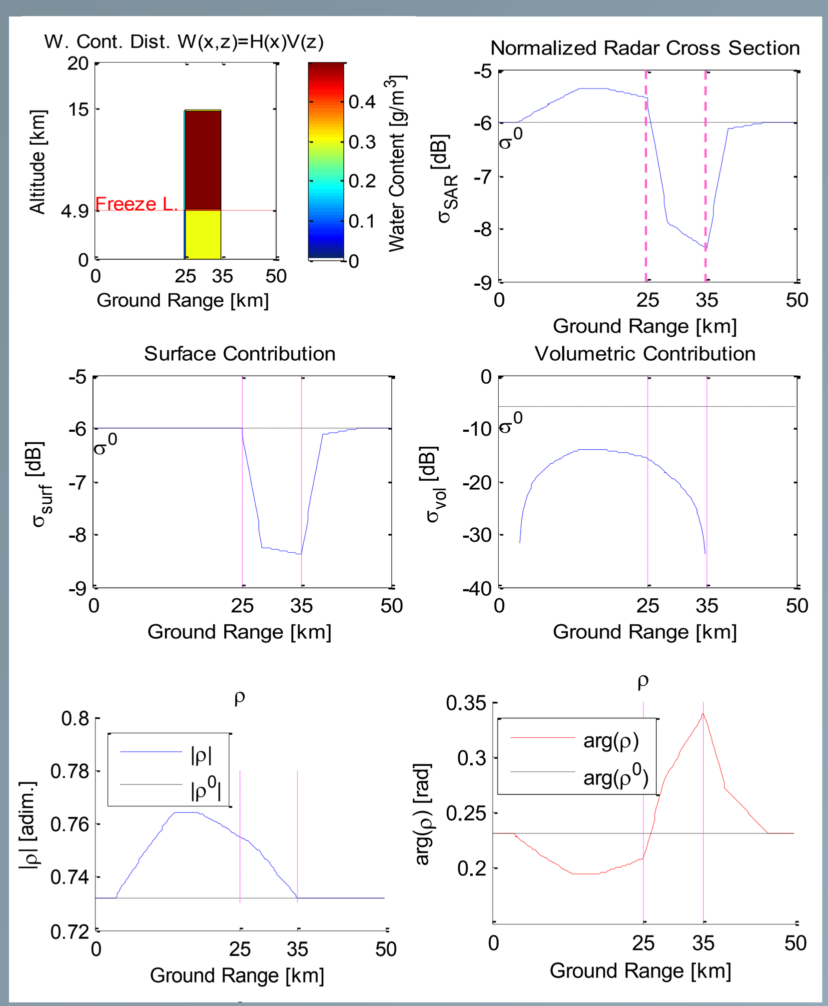
ABSTRACT

Spaceborne synthetic aperture radars (SARs) operating at X-band and above allow observations of Earth surface at very high spatial resolution. Moreover, recent polarimetric SARs enable the complete characterization of target scattering and extinction properties. Nowadays several spaceborne X-band SAR systems are operative, and plans exist for systems operating at higher frequency bands (i.e. Ku, Ka and W). Although higher frequencies may have interesting and distinctive applications, atmospheric effects, especially in precipitating conditions, may affect the surface SAR response in both the signal amplitude and its phase, as assessed by numerous works in the last years. A valid tool to analyze and characterize the SAR response in these conditions is represented by forward modeling, where a known synthetic scenario, which is described by user-selected surface and atmospheric conditions, is considered. Thus, the SAR echoes corresponding to the synthetic scenarios are simulated using electromagnetic models. In this work a 3-D realistic polarimetric SAR response numerical simulator is presented. The proposed model framework accounts for the SAR slant observing geometry and it is able to characterize the polarimetric response both in amplitude and phase. In this work we have considered X, Ku and Ka bands, thus exploring the atmospheric effects for the present and future polarimetric systems. The atmospheric conditions are simulated using the System for Atmospheric Modeling (SAM) which is an high-resolution mesoscale model. SAM is used to define the three-dimensional distribution of hydrometeors which are among the inputs used in the Hydrometeor Ensemble Scattering Simulator (HESS) T-Matrix which allow simulating the SAR signal due to the atmospheric component. The SAR surface component is, instead, simulated by a Semi Empirical Model (SEM) for bare-soils conditions. The proposed methodology has been applied in this work to assess the sensitivity of the considered frequency bands to different hydrometeor spatial distributions above some examples surface backgrounds. Other application of the proposed SAR forward model is the development and test of inverse algorithms to estimate precipitation intensity in a quantitative way. A preliminary example of precipitation rate estimation algorithm is reported in the final part of this work, where the estimated rain rate is compared with co-located measurements of ground weather radar.



Simulating polarimetric SAR

$$\sigma^0_{SAR}(x) = \sigma^0_{srf}(x) + \sigma^0_{vol}(x)$$

$$\sigma^0_{srf}(x) = \sigma^{0ground}(x) \cdot L^2[\Delta l(x)]$$

$$\sigma^0_{vol}(x) = \sin(\theta) \cdot \int_{\Delta t(x)} \eta(t) \cdot L^2[\Delta l(x)] dt$$

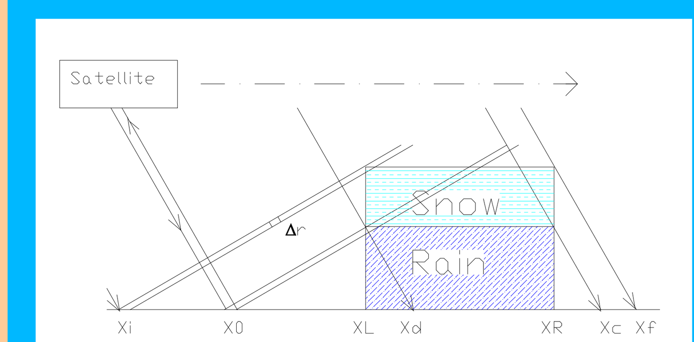
- σ^0_{ground} = surface radar cross-section coeff. [dB]
- η = radar volume reflectivity [1/m]
- L = one-way atmospheric loss factor [adim.]
- θ = off-nadir angle [deg]
- t, l = transverse and radial coord. [m]
- S_{SARpq} : *elements of the complex backscattering matrix*

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

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

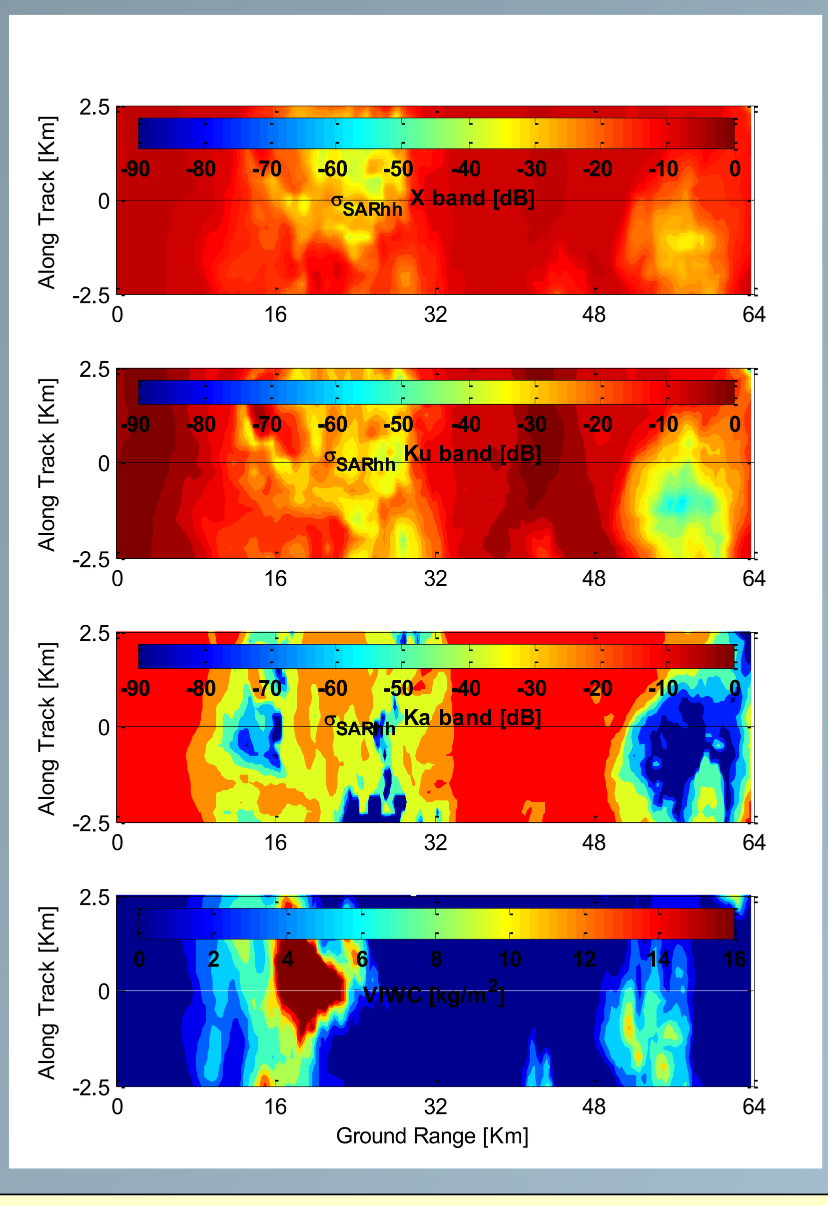
- **σ^0_{SARpq}: *pq*-polarized normalized radar cross section (NRCS)**
- **Z_{SARco}: copolar ratio**
- **ρ_{SARco}: complex correlation coefficient**

- 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]
- Zero °C at 4.9 km, $\sigma^{0ground} \cong$ -6 dB, f = 9.6 GHz, θ=35 deg



Plane-wave incidence (avoid spherical wave front corrections)

Normalized Radar Cross Section σ^0_{SARhh} [dB], co-polar differential ratio Z_{SARco} [dB], complex correlation coefficient ρ_{SARco} for X, Ku and Ka band relative to the indicated SAM synthetic cloud and a noisy SEM bare soil .



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

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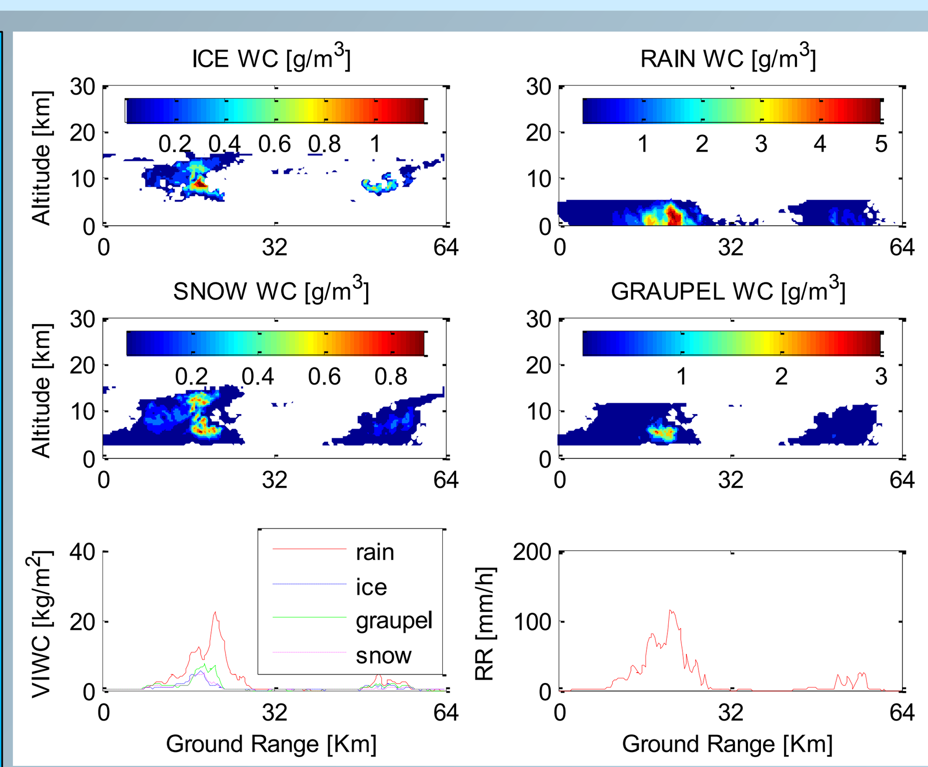
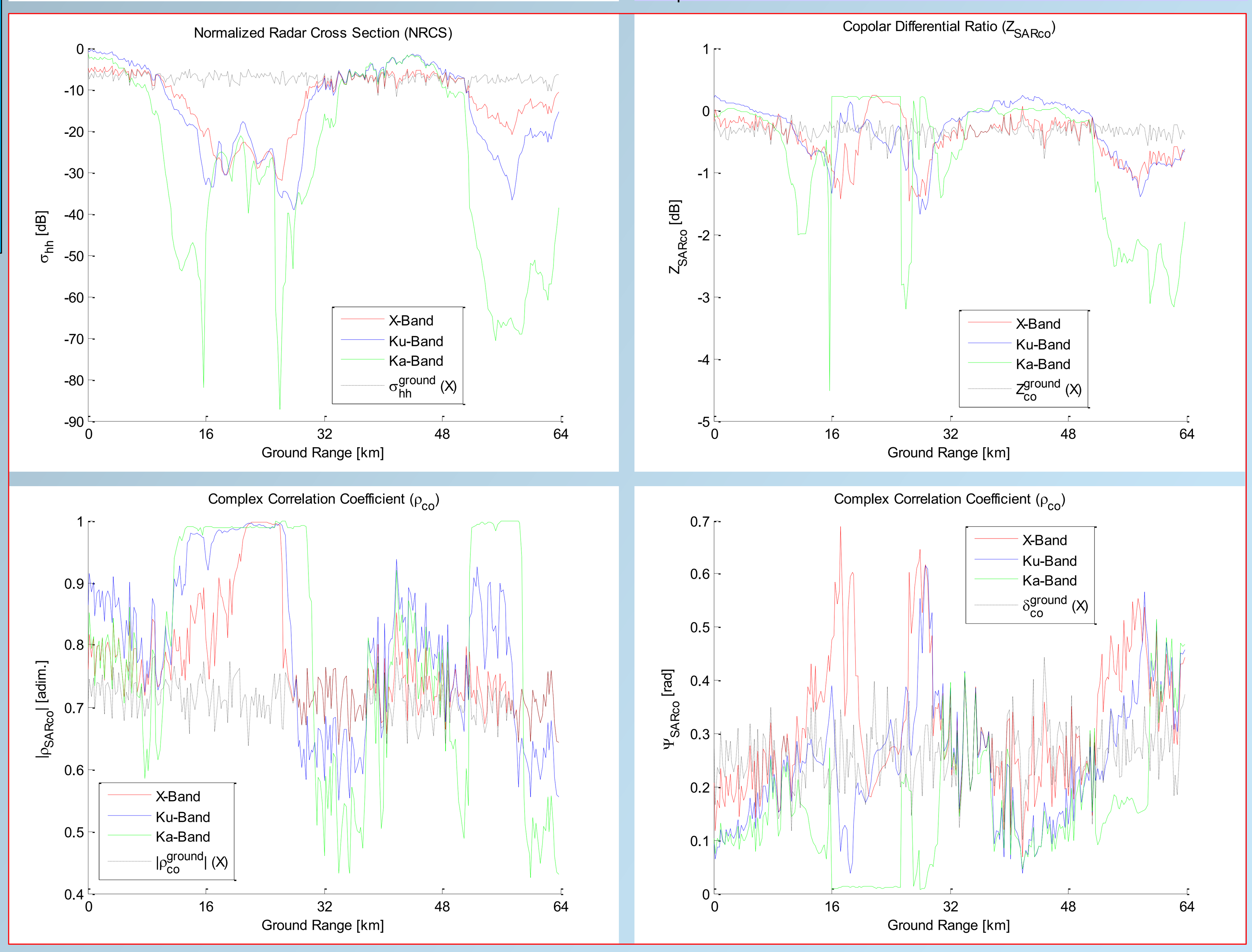


Atmospheric and ground models

- The **System for Atmospheric Modeling (SAM)** is a 3-D high-resolution mesoscale cloud-resolving model (CRM) [Blossey et al., 2007].
  - Water content *W* [g/m^2] distribution of Rain, Ice, Snow, Graupel at 250 m resolution.
- The **Hydrometeor Ensemble Scattering Simulator (HESS)** T-Matrix model [Marzano et al., 2007] allows to obtain simulated fields of the radar observables by power laws of the form $P=a \cdot W^b$
  - *a,b* best-fitting regressive coefficients; for specific attenuation *k* [dB/km], equivalent reflectivity Z_e [mm^6/m^3], specific differential phase K_{co} [°/km] , copolar corr. coefficient ρ_{co}.
- The **Semi-Empircal Model (SEM)** [Oh et al., 2002] allows to simulate bare soil SAR echoes.
  - NRCS both HH and VV, degree of correlation, co-polarized phase difference. Variability introduced adding a gaussian noise on input parameters

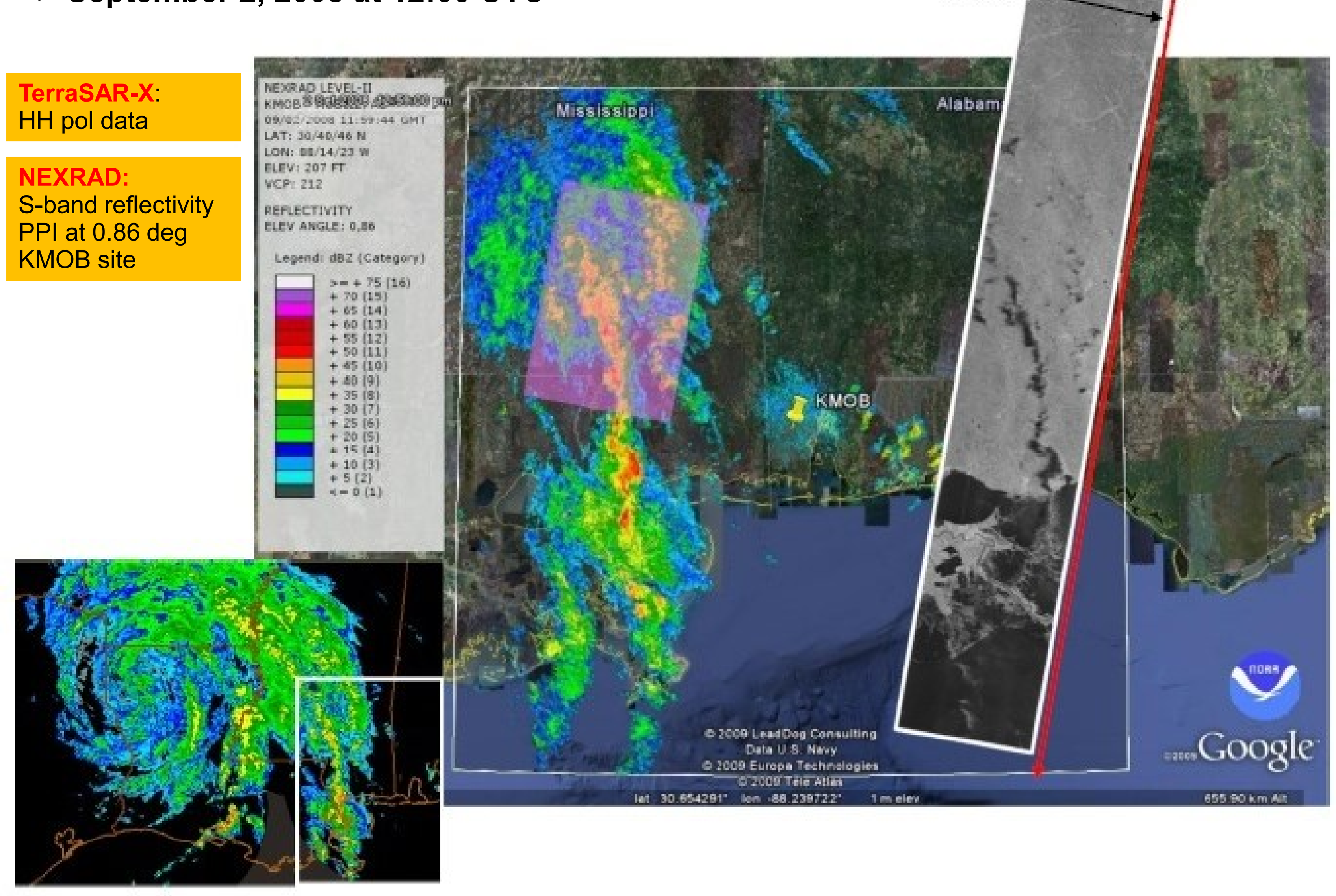


X-SAR Precipitation rate estimations: Hurricane "GUSTAV" case

- **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

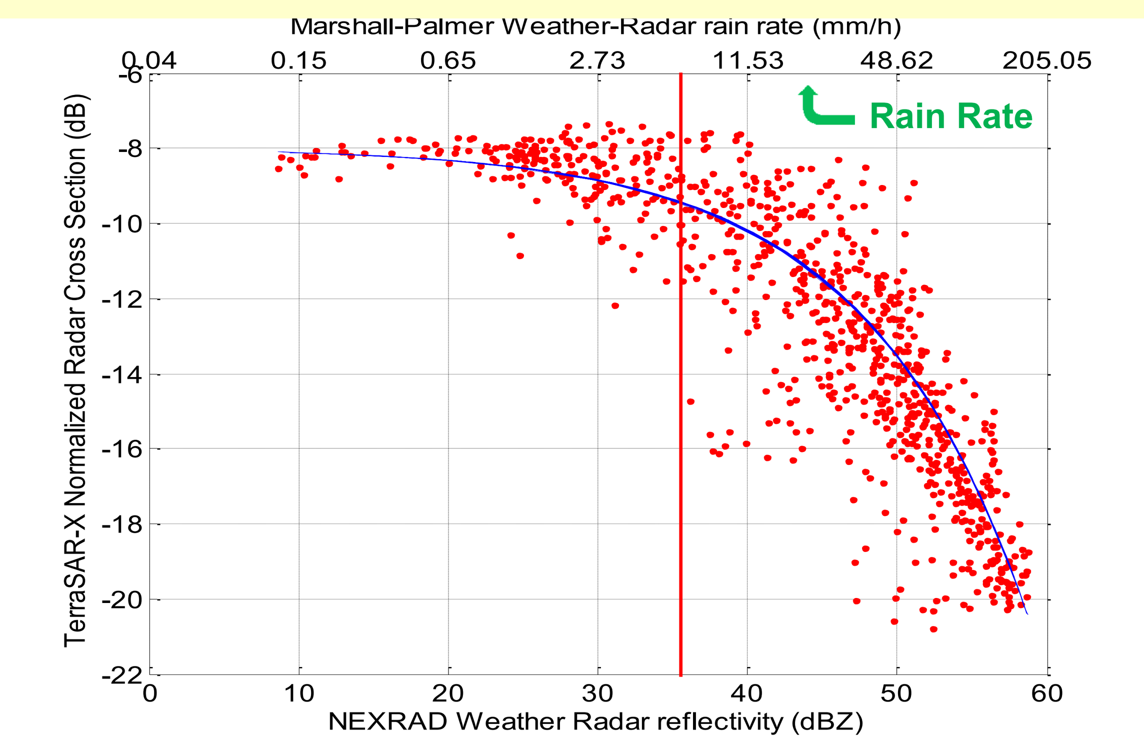


$$\hat{R}_{MREA}(x) = \begin{cases} \left[\frac{\Delta\sigma_{SARdB}(x) + 0.1216\,\Delta\sigma^{3.8979}_{SARdB}(x)}{0.0089}\right]^{1/2.4595} \left[\frac{1}{(x-x_0)}\right]^{-0.0230} & x_0 + \varepsilon \le x \le x_0 + w \\ 0 & otherwise \end{cases}$$

$$\Delta\sigma_{SARdB}(x) = \sigma^0_{dB}(x) - \sigma_{SARdB}(x) \qquad (1\,\mathrm{dB\,threshold})$$

- x_0 = near range edge cloud
- w = cloud width
- FRMSE=RMSE/RMS(R_{WR})

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



Correlation between NRCS values σ^0_{SAR} against co-located and co-registered NEXRAD WR reflectivity Z, for the selected region of interest (ROI)