EVIDENCE OF RAINFALL SIGNATURE ON X-BAND SPACEBORNE SYNTHETIC APERTURE RADAR RESPONSE BY MODEL ANALYSIS AND SPACEBORNE IMAGERY

Mori Saverio¹, Frank S. Marzano¹,², James A. Weinman³, Luca Pulvirenti¹, Mario Montopoli² and Marco Chini⁴

¹ Dipartimento di Ingegneria Elettronica, Sapienza University of Rome, Italy  
² Centro di Eccellenza CETEMPS, University of L’Aquila, Italy  
³ Department of Atmospheric Sciences, University of Washington, Seattle, USA  
⁴ Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy

ABSTRACT

The recently launched spaceborne Synthetic Aperture Radars (SARs) operating at X band could offer a new opportunity to investigate the structure of precipitating clouds. In this paper is presented the model that we have developed to simulate the Normalized Radar Cross Section (NRCS) SAR response and analyze the X-SAR inversion framework that we are developing. Quantitative retrievals obtained by our inversion routines on a TerraSAR-X 2008 case study are also presented.

1. INTRODUCTION

Weather and climate models requires global precipitation measurements because their performances are affected by the release of latent heating. Such kind of measurements is also required to facilitate management strategies for hydrology, transportation and agriculture. In the last three decades most of our understanding of global precipitation has been provided by the measurements of spaceborne passive microwaves radiometers [1] and Ku-band radars, such as the Precipitation Radar (PR) aboard the Tropical Rainfall Measurement Mission (TRMM) satellite [2]. Unfortunately microwave radiometers are very sensitive to the scattering of ice in the upper regions of precipitating clouds which is poorly related to surface rainfall rates, and have a reduced resolution of several kilometers. Also PR with a resolution of a few kilometers can miss small precipitation cells.

A new opportunity to investigate the structure of precipitating clouds is offered by Synthetic Aperture Radars (SARs) operating at X band. Their nominal spatial resolutions is of the order of meters even if it is degraded to the order of hundreds of meters when observing precipitating clouds, due to the turbulent motion of the storm hydrometeors. X-band SAR are traditionally considered all-weather sensors but since many years spaceborne platforms have provided experimental evidences of their sensitivity to rainfall. The interest towards X-band SARs is witnessed by several new platforms that are currently or will soon be placed in orbit, such as COSMO-SkyMed (CSK) [3], TerraSAR-X (TSX) [4] or the X-SAR/Ku-SAR CoRe-H2O mission now in development [5].

To the purpose of characterize spaceborne X-SAR precipitation response, we have developed a theoretical and numerical model accounting for the side-looking SAR geometry [6]. This framework will be used for sensitivity analysis and calibration of our X-SAR inversion framework [7] in which quantitative rainfall signatures are estimated by X-SAR data.

In this work we will introduce our forward model framework and we will show quantitative retrievals obtained by our inversion routines on a TSX 2008 case study, verified with co-registered weather radar (WR) imagery available during the TSX overpass.

2. FORWARD MODEL OF SAR RESPONSE

In the presence of rainfall, the measured Normalized Radar Cross Section (NRCS) $\sigma_{\text{SAR}}$, due to SAR slant geometry, consists of the backscattering section $\sigma_{\text{off}}$ from the surface and the volume backscattering $\sigma_{\text{vol}}$ from precipitation [6, 7]:

$$\sigma_{\text{SAR}}(x, y) = \sigma_{\text{off}}(x, y) + \sigma_{\text{vol}}(x, y)$$

(1)

with $x$ and $y$ the cross-track and the along-track direction in a Cartesian coordinate system at ground, $z$ the altitude. We will consider the cross-track sections $x-z$, assuming that the along-track resolution $\Delta y$ has been achieved by means of a proper SAR processing algorithm. Equation (1) will be discussed in the next sections.

2.1. Precipitation cross-section model

Realistic representations of the precipitating cloud can be obtained by Cloud Resolving Models (CRMs). In this work we have considered the CRM System for Atmospheric Modeling (SAM) described in [8]. SAM simulates the distribution of several hydrometeors (cloud liquid, cloud ice, rain, snow, graupel) at the high resolution of 250 m. Hydrometeor distributions are expressed in terms of water
content g/m³, which is more appropriate to represent both liquid and frozen hydrometeors. An example of vertical section of four SAM hydrometeor distribution is in Fig. 1.

2.2. SAR response model due to precipitation

The SAR response can be estimated considering a plane-wave incident approximation [7]; returns are computed at each incidence position of the plane-wave on the ground, so we can express eq. 1 along the cross-track axis x as:

\[ \sigma_{\text{surf}}(x) = \sigma^0(x) \cdot \left| L_1[N_1(x)] \right|^2 \]
\[ \sigma_{\text{vol}}(x) = \sin(\theta) \cdot \left| \int n(t) \cdot L_2[N_2(x)]^2 \, dt \right| \]

(2)

where \( \sigma^0 \) is the surface radar cross-section coefficient, \( \eta \) is the radar volume reflectivity, \( \{L_1[N_1(x)]\} \) and \( \{L_2[N_2(x)]\} \) are the one-way loss factors for a path within hydrometeors ending respectively at the soil and at the scattering slice, \( \theta \) is the off-nadir angle in degree, \( \mathcal{N}_1 \) and \( \mathcal{N}_2 \) are respectively the longitudinal (radial) and transverse path increments along the incident direction \( l \) and the orthogonal (transverse) one \( t \). In our simulations the ground response \( \sigma^0 \) is modeled by the bare soil Semi-Empirical Model (SEM) described in [9] with added Gaussian noise on its input parameters. From eq. 2 it is possible derive an explicit formula where the loss factors are expressed in terms of the specific attenuation factor \( k(x,z) \) and the reflectivity in terms of the Rayleigh-equivalent reflectivity factor \( Z_r(x,z) \) [6, 7]. The relationship between these parameters and the precipitation rate \( R(x,z) \) significantly depend on the particle size distribution, shape and composition, and commonly is modeled as:

\[ k(x,z) = a \cdot [R(x,z)]^b \]
\[ Z_r(x,z) = c \cdot [R(x,z)]^d \]

(3)

where \( a, b, c, d \) are empirical coefficients depending on the wavelength, polarization and precipitation regime. In our simulations their values are obtained by the HESS T-Matrix radar scattering model described in [10], used to simulate the polarimetric signature of several hydrometeor classes for X, Ku and Ka band frequencies. A comparison with some literature models is in [11].

![Fig. 1 - Water content [g/m³] distribution of several hydrometeors (Cloud Ice, Rain, Snow, Graupel) for a vertical section obtained from a System for Atmospheric Modeling (SAM) simulation.](image1)

![Fig. 2 - NRCS for X, Ku and Ka band at horizontal polarization for the rain cell of Fig. 1, using HESS T-Matrix parameters.](image2)

Figure 2 shows the \( \sigma_{\text{SAR}} \) responses [dB] due to the section of Fig. 1, at X, Ku and Ka bands, horizontal polarization and 40° incident angle. Reduction in NRCS is mainly due to rain attenuation while increasing is mainly due to frozen hydrometeors. Differences due to observing frequency are also evident.

3. INVERSION OF SAR MEASUREMENTS

The solution of eq. (2) allows to estimate the precipitation rate of the observed phenomenon. In our work we have investigated an inversion technique based on Volterra Integral Equation (VIE) method [12]; another technique based on Model-Oriented Statistical (MOS) method is described in [7]. Two more simplified ones have been also developed, a Regression Empirical Algorithm (REA) and a Probability Matching Algorithm (PMA) [13]. REA and PMA can be used as benchmark for VIE and MOS. Based on REA we will show some retrievals obtained from a TSX 2008 case study.

3.1. Rain Retrievals by TerraSAR-X data

The capability of X-SARs of observe and measure precipitation rate could be verified by co-registered and synchronous weather radar (WR) measurements. In this work we have used WR data ingested with X-SAR ones to calibrate the PMA and REA inversion algorithms.

The study case here presented refers to TSX acquisition of Hurricane “Gustav” over south-eastern Louisiana on September 2, 2008 at 12:00 UTC, at around 30.5° N x 89.5°
The WR data was obtained by the NEXRAD WSR-88D S-Band radar located in Mobile (Alabama), with a time difference respect to TSX acquisition of about 1 minute.

TSX data was obtained in ScanSAR Multi-look Ground-range Detected (MGD) format, characterized by reduced speckle, a geometric projection in azimuth and ground range with WGS84 ellipsoid and no terrain correction. The resolution on ground is about 18x18 m$^2$. TSX counts were calibrated into backscattering coefficient $\sigma_{\text{SAR}}(x,y)$. WR data was obtained in terms of Level-2 horizontally-polarized radar reflectivity factor $Z$ by plan position indicator (PPI) at 0.86° elevation. Spatial resolution is about 0.25 km in range and 0.5° in azimuth [14]. In order to make TSX and WR data comparable, both of them were co-registered, degraded at 0.5 km resolution through a moving average filter and down-sampled at 0.5 km ground resolution. Finally they were projected adopting Universal Transverse Mercator (UTM) coordinate system.

The REA retrieval formula is modeled on the power-law expression in terms of the differential NRCS (in dB) at co-polar state HH along the cross-track direction $x$:

$$\tilde{R}(x) = a \left[ \sigma_{\text{SAR}}^0(x) - \sigma_{\text{SARdB}}(x) \right]^b$$

where $\sigma_{\text{SAR}}^0$ is the ground reference NRCS in dB at co-polar state HH, $\sigma_{\text{SARdB}}$ is the X-SAR observed NRCS in dB at co-polar state HH, $R$ is the estimated cross-track profile in mm/h, while $a$, $b$ are empirical coefficients. The argument $\Delta \sigma_{\text{SARdB}}$ of the power law is usually positive for rainfall observations. The empirical coefficients $a$, $b$ were obtained on a Region Of Interest (ROI) by linear regression from the rain rate estimated by WR reflectivity through Marshall-Palmer Z-R relation. Considering a TSX incident angle $\theta$ of 42° and a constant $\sigma_{\text{SAR}}^0 = -8$ dB their value is $a = 3.37$ and $b = 1.55$. For the selected case study the mean overestimation error of REA retrieval over the whole scene respect WR measures is 1.8 mm/h, the root mean square error (RMSE) is 10.9 mm/h, the fractional RMSE respect WR rain rate is 63% and the correlation coefficient is 0.76 [13]. In Fig. 3 are shown the REA estimated rain rate and the WR measured one.

**Fig. 3** - (Left) Map of the estimated rain rate at 500-m resolution from TSX X-SAR, using the Regression Empirical Algorithm (REA) for the selected case study. (Right) Colocated rain rate map, retrieved from NEXRAD weather radar.

5. REFERENCES


