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An SPM/PO-based Polarimetric Two-Scale Model

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Abstract

A polarimetric two-scale scattering model employed to retrieve the surface parameters of bare soils from polarimetric SAR data is presented. The scattering surface is here considered as composed of randomly tilted rough facets, for which the SPM or the PO hold. The facet random tilt causes a random variation of the local incidence angle, and a random rotation of the local incidence plane around the line-of-sight, which in turn causes a random rotation of the facet scattering matrix. Unlike other similar already existing approaches, our method considers both these effects. The proposed scattering model is then used to retrieve bare soil moisture and large-scale roughness from the co-polarized and cross-polarized ratios.

Keywords: Polarimetry, retrieval of natural parameters, SAR.

Introduction

Nowadays, several applications require the knowledge of many ground physical parameters (i.e., permittivity, ground roughness, soil moisture content, vegetation biomass-index, etc..) relevant to wide natural areas and, of course, remote sensing technologies are the best candidates to provide this information in a comparatively short time. In fact, using multi-angle and/or multi-polarimetric Synthetic Aperture Radar (SAR) data allows us estimating ground parameters, on condition that retrieval techniques are founded on reliable and realistic, but at the same time not too involved, models describing electromagnetic scattering phenomena. Besides, concerning this issue, during the last years several papers were addressed to develop effective techniques able to estimate ground parameters and founded on models able to describe low frequency (L, P bands) polarimetric scattering from natural areas, e.g. [Mo et al., 1988; van Zyl et al., 1991; Oh et al., 1992; Dubois et al., 1995; Altese et al., 1996; Shi et al., 1997; Le Hégarat-Mascle et al., 2002; Hajnsek et al., 2003]. To this aim, recently we proposed a Polarimetric Two-Scale Model (PTSM) [Iodice et al., 2010, 2011], used to retrieve the surface parameters of bare soils from polarimetric SAR data. However, latest European SAR missions make use of sensors operating at X-band (i.e., the German TerraSAR-X and the Italian COSMO-SkyMed), and so aforesaid methods turn out to be inappropriate to describe measured scattering data in this range of frequencies. So, as PTSM provides good retrieval results using low frequency scattering data, in order to retrieve ground parameters using data provided by these X-band remote sensing

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missions, here we also present a Physical Optics based PTSM (PO-PTSM). In such model the scattering surface is considered as composed of rough randomly tilted facets but, differently from what is presented in [Iodice et al., 2010, 2011], due to the short wavelength, here the PO is used instead of the Small Perturbation Method (SPM) to describe the rough facet scattering. The facet random tilt causes a random rotation of the local incidence plane around the line-of-sight and, moreover, a stochastic drift of the local incidence angle around the radar look-angle. Unlike other similar already existing approaches [Hajnsek et. al, 2003; Martone et al., 2010], our method takes into account both these effects, relating their analytical formulation to the stochastic description of the scattering surface. Based on this model, soil moisture and roughness can be retrieved from co- and cross-polarised ratios by using a procedure similar to the one of [Iodice et al., 2010, 2011].

Theoretical Setup

Surface model

We consider a bare soil surface as composed of large-scale variations on which a small-scale roughness is superimposed; then we employ a two-scale model for the scattering surface.
Concerning the large-scale roughness, it is locally treated by replacing the surface with a rough tilted facet, whose slope is the same of the smoothed surface at the center of the pertinent facet.

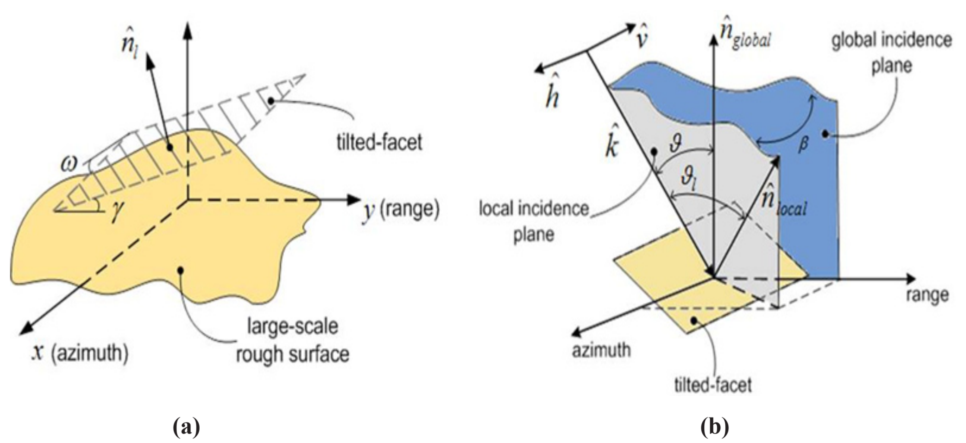


Figure 1 - a) 3D view of a generic tilted facet. b) Local incidence angle rotation.

Therefore, by using the reference system depicted in Figure 1a, the randomly rough and randomly tilted facets are defined through the following formula:

$$z(x,y) = \tan\omega(x - x_i) + \tan\gamma(y - y_i) + z_i + \zeta(x,y), \forall (x,y \in D_i) \quad [1]$$

where tanω and tanγ are the local azimuth and range slopes, respectively, x_i,y_i,z_i are the coordinates of the *i*-th facet center, $\zeta(x,y)$ describes the small-scale roughness, and D_i is the *i*-th facet domain. We assume that the facet slopes along range and azimuth directions are independent identically distributed zero-mean σ^2-variance Gaussian random variables, i.e., $\tan\omega$, $\tan\gamma \sim N(0,\sigma^2)$. This assumption only requires that the large-scale roughness is a Gaussian statistically isotropic stationary-increment (i.e., locally homogeneous) process.

Concerning the small-scale roughness $\zeta(x,y)$, it is modeled as a zero-mean stochastic process. In the following, we assume that $\zeta(x,y)$ is a (band-limited) fractional Brownian motion (fBm) process because it is well recognized by now that fractal models are proper to describe natural surfaces.

Single facet return

The facet's random tilt causes two main effects (Fig. 1b): a stochastic drift of the local incidence angle ϑ_l around the radar look-angle ϑ and a random rotation β of the local incidence plane around the line-of-sight (LOS).

Both these effects can be related to the facet's slopes by [Lee et al., 2000]

$$\cos\theta_l = \frac{\cos\theta + \tan\omega\sin\theta}{\sqrt{1+\tan^2\omega+\tan^2\gamma}} \quad [2]$$

and

$$\tan\beta = \frac{\tan\omega}{-\tan\gamma\cos\theta+\sin\theta} \quad [3]$$

In the backscattering direction the (incoherent) field E^s_{pq} is given by [Tsang et al., 2000]:

$$E^s_{pq} = \frac{E^i_p k^2\cos^2\theta_l}{\pi r}\chi_{pq}(\theta_l,\beta)I(\theta_l)\exp\{-jkr\} \quad [4]$$

where E^i_p is the incident field, $k=2\pi/\lambda$ is the wavenumber, r is the radar-to-target distance, $I(\theta_l)$ is a polarization-independent function depending on microscopic roughness, p and q are the polarizations of the incident and scattered field, respectively, and can each stand for H (horizontal) or V (vertical) and $\chi_{pq}(\theta_l,\beta)$ are the elements of the rotated scattering matrix $\underline{\underline{S}}^{facet}$

$$\underline{\underline{\chi}}(\theta_l,\beta) = \underline{\underline{R_2}}(\beta)\cdot\underline{\underline{S}}^{facet}(\theta_l)\cdot\underline{\underline{R_2}}^{-1}(\beta) = \begin{bmatrix}\cos\beta & \sin\beta\\ -\sin\beta & \cos\beta\end{bmatrix}\cdot\begin{bmatrix}F_H(\theta_l) & 0\\ 0 & F_V(\theta_l)\end{bmatrix}\cdot\begin{bmatrix}\cos\beta & -\sin\beta\\ \sin\beta & \cos\beta\end{bmatrix} \quad [5]$$

Concerning $\underline{\underline{S}}^{facet}$, it is the scattering matrix of a single facet, while the analytical expression of F_H and F_V depends on which solution is adopted for the electromagnetic scattering. Notice that the PTSM is the only model that takes into account both the local incidence plane rotation around the LOS and the local incidence variations in the expression of the scattered field.

The facet normalized radar cross section (NRCS) is defined as:

$$\sigma^0_{pq} = \frac{4\pi r^2 \left\langle \left| E^5_{pq} \right| \right\rangle_{|\zeta}}{A \left| E^i_p \right|^2} \quad [6]$$

where A is the facet's area and the symbol $\langle f \rangle_{|\zeta}$ stands for "the mean of f with respect to the random variable ξ". So, using [4] in [6], we obtain:

$$\sigma^0_{pq} = \frac{4}{\pi} k^4 \cos^4\theta_l \left| \chi_{pq} \right|^2 W(2k\sin\theta_l) \quad [7]$$

where W is the mean of the square-modulus of I (normalized by A) and its expression again depends on the adopted scattering solution.

Total scattered power

If the large-scale roughness height variations are larger than the wavelength and the facet size is larger than small-scale roughness correlation length, then the returns from different facets are uncorrelated, so NRCS of the whole surface can be obtained by averaging that of a single facet over β and θ_l, or, equivalently, over $tan\omega$ and $tan\gamma$.

Unfortunately, it is not possible to compute in closed form such statistical averages but, assuming small values for facet's slopes, the MacLaurin expansion for NRCS can be employed, thus obtaining:

$$\left\langle \sigma^0_{pq} \right\rangle_{|\tan\omega,\tan\gamma} = \sum_{n=0}^{+\infty} \left[\frac{1}{n!} \sum_{k=0}^{n} \binom{n}{k} \frac{\partial^n \sigma^0_{pq}}{\partial (\tan\omega)^k \, \partial (\tan\gamma)^{n-k}} \right|_{\tan\omega = \tan\gamma = 0} \left\langle (\tan\omega)^k \right\rangle \left\langle (\tan\gamma)^{n-k} \right\rangle \Bigg] \quad [8]$$

So, considering Taylor expansion terms up to the second order, we attain the following expression for the NRCS pertinent to the whole surface, which we refer to as PTSM solution for the polarimetric scattering:

$$\left\langle \sigma^0_{pq} \right\rangle_{\tan\omega,\tan\gamma} = C^{pq}_{k,n-k} + \left(C^{pq}_{2,0} + C^{pq}_{0,2} \right) \sigma^2 \quad [9]$$

where $C^{pq}_{k,n-k}$ are the series expansion coefficients, defined as

$$C^{pq}_{k,n-k} = \frac{1}{n!} \binom{n}{k} \frac{\partial^n \sigma^0_{pq}}{\partial (\tan\omega)^k \, \partial (\tan\gamma)^{n-k}} \Bigg|_{\tan\omega = \tan\gamma = 0} \quad [10]$$

Obviously, closed forms for the NRCS in [9] rely on the method chosen to solve the scattering problem from the microscopic roughness, i.e. on the specific expression assumed by F_H, F_V and W.

In particular, if the PTSM is used to describe the polarimetric scattering at lower bands (L, P bands), then the SPM is suitable to compute the electromagnetic scattering from the small-scale surface variations (SPM-PTSM). Accordingly, in this case F_H and F_V represent the Bragg coefficients, while W is the power spectral density of the fBm process describing the small-scale roughness [Iodice et al., 2011].

Conversely, if the PTSM is used to retrieve ground parameters from X-band data, then the Kirchhoff Approach can be used (PO-PTSM), and so in this case F_H and F_V are the Fresnel reflection coefficients, and the full expression of W can be found for instance in [Franceschetti et al., 2001].

Retrieval procedure

Once the proper PTSM solution is chosen according to previous criteria, NRCS can be used to build up numerical charts based on the co-polar and cross-polar ratios, parameterized only by the large-scale roughness σ and the relative dielectric constant ε (or the correspondent volumetric soil moisture content m_v).Indeed, the dependence on microscopic roughness almost completely cancels out in both co-pol and cross-pol ratios, although the small-scale roughness affects the behavior of the single NRCS [Iodice et al., 2011]. Moreover, we here neglect the imaginary part of the permittivity in the retrieval procedure, because for usual soils it is much smaller than the real part at microwave frequencies (see, e.g., [Hallikainen et al., 1985]); however, a relationship between the real and imaginary parts of the dielectric constant at the considered frequency is available, [Hallikainen et al., 1985], so that, if desired, above simplifying assumption can be relaxed (see also [Iodice et al., 2011]).

It is also important to notice that our retrieval procedure implicitly provides a reduction of the speckle. Indeed, because of the significant correlation between the noise realizations which affect different polarimetric channels [Franceschetti et al., 2000], the speckle tends to cancel out in the images of the ratios. Nevertheless, a further speckle reduction is performed using spatial multilook techniques on each of NRCS images.

Finally, notice that in the SPM-PTSM solution the sigma naught for the *HH* channel is always lower than that relevant to the *VV* channel, whereas the opposite happens for PO-PTSM. Accordingly, in our charts, in order to deal always with positive values (in dB), we define the co-polar ratio as the ratio between $\sigma°_{vv}$ and $\sigma°_{hh}$ in the SPM-PTSM or, conversely, as the ratio between $\sigma°_{hh}$ and $\sigma°_{vv}$ in the PO-PTSM; in both cases the cross-polar ratio is defined as the ratio between $\sigma°_{hv}$ and $\sigma°_{vv}$.

Above mentioned charts, an example of which is shown in Figure 2, can be used to get the soil moisture content and the large-scale roughness from a pair of co-pol, cross-pol measured data and, of course, this approach can be performed in an unsupervised way, simply making use of dedicated look-up algorithms.It is worthwhile underlining that performances of the retrieval procedure deteriorate as the permittivity and the roughness increase, since higher values of parameters turn out in a reduction of co-pol/cross-pol loci dynamic ranges and then in a reduced sensitivity on roughness and permittivity (or, equivalently, in a greater sensitivity to measurement errors.

Method Validation

To validate the Polarimetric Two-Scale Model, retrieval results obtained from the above mentioned algorithm relevant to a wide variety of scattering data at different frequencies, incidence angles, surface roughness and soil moisture contents, in conjunction, if it is possible, with the corresponding ground truth, has been used. In particular, hereafter we consider both L-band AIRSAR data and X-band COSMO-SkyMed data retrieval results.

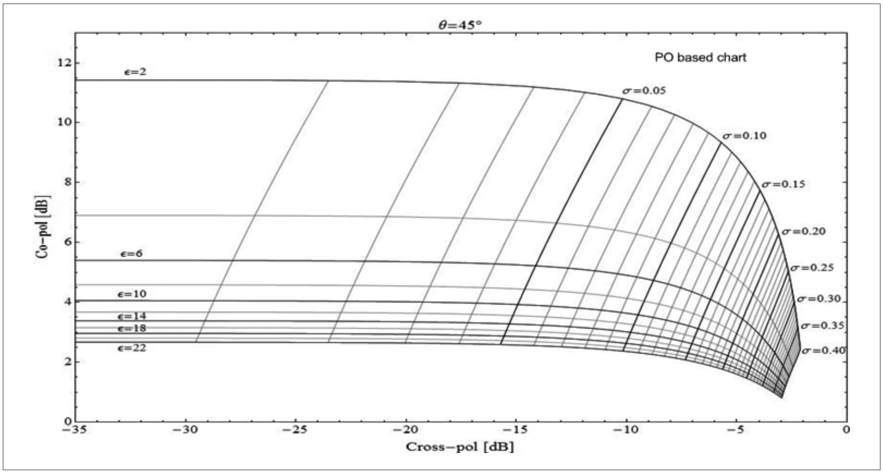


Figure 2 - PO based PTSM Co-pol Cross-pol ratio chart for ϑ=45°. Of course, it is possible to get a similar chart parameterized by the soil moisture content instead of the permittivity, using the mixing model presented in [Hallikainen et al., 1985]; in this case the soil moisture spans from m_v=0 (at ε=2) to m_v=0.35 (at ε=22).

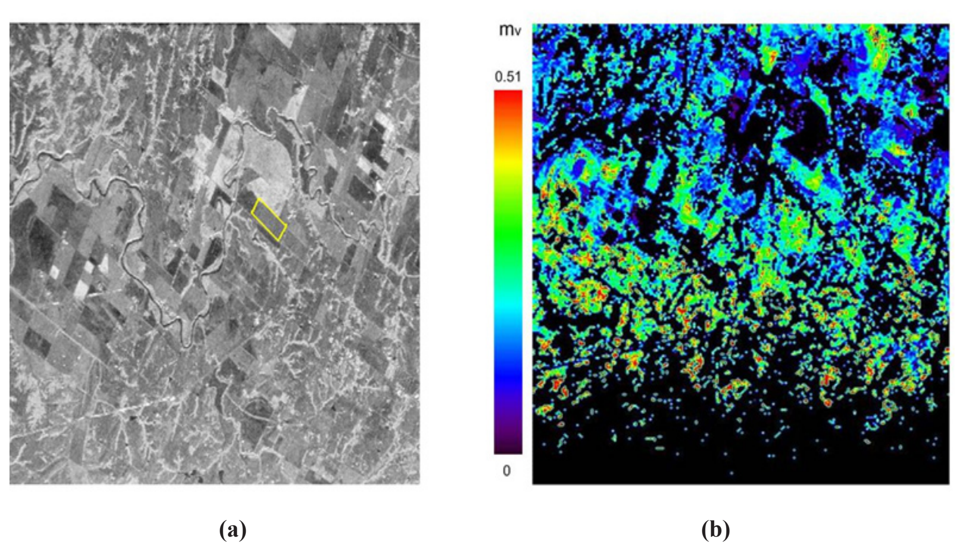
L-band retrieval results

Concerning the method validation at L-band, here we consider AIRSAR data (*f=1.2* GHz, look-angle ranging from 15° to 60°) acquired on several different days during a measurement campaign in the Little Washita basin, in June 1992 (see Figure 3-a, in which the HH backscattering coefficient acquired on 10/06/92 is depicted). We select the bare soil field labeled as AG002 in [http://hydrolab.arsusda.gov/washita92/wash92.htm] (the yellow rectangle in Figure 3-a), for which the volumetric soil moisture content was monitored "in situ", and we perform on it the dielectric constant retrieval using the mentioned unsupervised procedure (final map of about 60x60 m^2 resolution). The retrieved values of the relative dielectric constant are converted into volumetric moisture values m_v by using the mixing model of [Hallikainen et al., 1985]. The soil moisture map for the entire area is shown in Figure 3-b, where black pixels indicate areas for which the algorithm does not work, most likely because a significant volumetric scattering component is present.

As for the site AG002, the (average) retrieved results from AIRSAR images acquired on different days for PTSM and other existing, well established, theoretical [Hajnsek et al., 2003] or empirical [Oh et al., 1992; Shi et al., 1997] methods are reported in Table 1, together with "in situ" measured values.

Table 1 – Retrieval results AIRSAR data.

Day	SPM/PTSM	X-Bragg	Oh	Shi	In Situ
10/06/92	0.247±0.091	0.146±0.054	0.301±0.104	0.161±0.048	**0.287**
13/06/92	0.217±0.080	0.135±0.070	0.294±0.100	0.131±0.032	**0.214**
14/06/92	0.127±0.063	0.076±0.055	0.186±0.083	0.105±0.025	**0.181**
16/06/92	0.110±0.079	0.082±0.055	0.153±0.084	0.087±0.012	**0.173**
18/06/92	0.107±0.092	0.101±0.068	0.130±0.092	0.078±0.018	**0.114**



(a) (b)

Figure 3 - a) HH Polarization AIRSAR image acquired on 10/06/92 over Little Washita. b) Soil moisture map of 10/06/92 for Little Washita basin.

Notice that at L-band SPM based PTSM always provides better results than other methods, with the exception, in some days, of the Oh empirical method. In particular, retrieval results of our method are always in better agreement with ground truth with respect the X-Bragg ones, most likely because in that method the drift of the local incidence angle is ignored and the random rotation of the local incidence plane does not depend on the surface description, but it is heuristically forced to be an uniform random variable [Hajnsek et al., 2003].
A wider discussion on the performances of our retrieval method in the SPM-PTSM case is presented in [Iodice et al., 2011], where a more extensive radar dataset together with related in situ measurements are employed.

X-band retrieval results

With regard to the method validation at X-band, here we consider COSMO-SkyMed images (*f=9.6* GHz, look-angle equal to 40°) acquired on 03/05/2010 (VV and VH channels) and 04/05/2010 (VV and HH channels) over the area of Collazzone, in Italy, and again we perform on these data the retrieval procedure, obtaining the soil moisture map depicted in Figure 4-b (final map of about 100x100 m^2 resolution). As it might be expected, due to the lower penetration depth, the overall appearance of the retrieval map in X-band turns out to be noisier than L-band ones but, nevertheless, retrieved values seem to be reasonable. Unfortunately, in situ measurements in conjunction with COSMO-SkyMed acquisitions are not available until now, so we cannot provide a direct method validation at X-band yet.
However, just to get an idea of the potentialities of the PO based PTSM, a simulated COSMO-SkyMed image is here used. In particular, we use COSMO-SkyMed parameters to simulate [Franceschetti et al., 1992] bare soil SAR images at the variance of the permittivity and the roughness (Fig. 5).

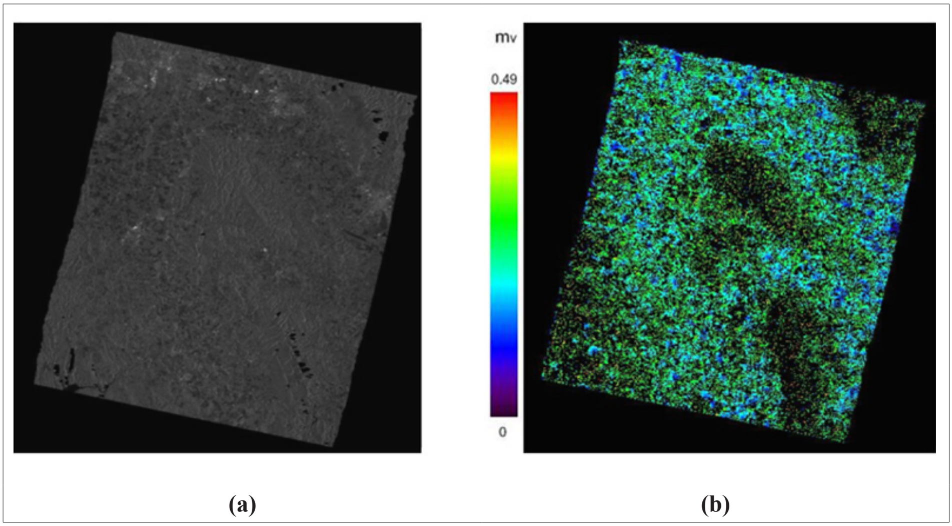


Figure 4 - a) HH polarization COSMO-SkyMed image acquired on 04/05/2010 over Collazzone. b) Soil moisture map of 04/05/2010 for the area of Collazzone.

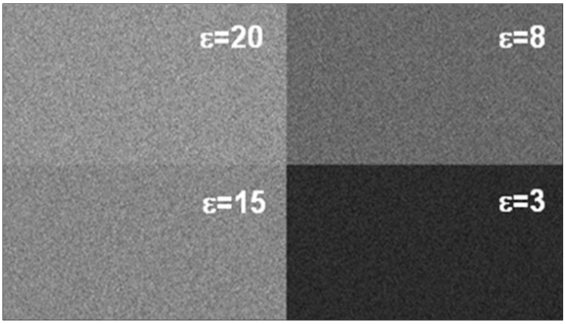


Figure 5 - simulated COSMO-SkyMed image with areas with different relative dielectric constants.

Accordingly, we apply on this simulated data set all the retrieval techniques previously considered, but in this case only the PO based PTSM provides physically meaningful results (see Table 2), while other methods provide retrieval results out of the reasonable ranges (permittivity values lower than 2 or larger than 40).

Table 2 – Retrieval Results for simulated COSMO -SkyMed data.

Simulated ε	PO/PTSM ($\sigma = 0.01$)	PO/PTSM ($\sigma = 0.1$)
3	3.31	2.55
8	8.27	6.64
15	15.00	12.2
20	20.00	16.2

Conclusion

A polarimetric two-scale surface scattering model (PTSM) has been introduced and employed to retrieve the surface parameters of bare soils from both L- and X- band polarimetric SAR data. Unlike other similar existing approaches, here both the random drift of local incidence angle and the local incidence plane rotation, due to the macroscopic roughness local slope, have been considered. The resulting scattering model can be used to retrieve soil moisture and large-scale roughness by using co- and cross-polarized ratios. The method is tested using SAR data together with "in situ" measurements (when possible) and very promising retrieval results are obtained both at L- and X-bands. Future work is needed first of all to further validate use of the PTSM at X-band, employing measurement campaigns planned at times of acquisition of COSMO-SkyMed or TerraSAR-X.

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