Effect of forests on the retrieval of snow parameters from backscatter measurements

Giovanni Macelloni*, Marco Brogioni, Francesco Montomoli and Giacomo Fontanelli

CNR –Istituto di fisica applicata “Nello Carrara” (IFAC),
Via Madonna del Piano 10 – 50019 Sesto Fiorentino (FI) – Italy
*Corresponding author, e-mail address: G.Macelloni@ifac.cnr.it

Abstract
In preparation for the CoReH2O satellite mission, one of the three missions selected for scientific and technical feasibility studies within the Earth Explorer Programme of the ESA, experimental and theoretical studies have been under way in order to improve methods for the retrieval of snow physical properties from SAR data. The aim of this paper is to investigate the impact of vegetation in the retrieval of snow parameters from microwave backscattering measurements. ARTT model capable of simulating scattering from a snow-covered vegetated terrain was developed and implemented to study the sensitivity to snow and vegetation parameters. A procedure for correcting the vegetation effect in the SWE retrieval algorithm has been suggested.

Keywords: SAR, snow, vegetation, CoReH2O.

Introduction
The COld REgions Hydrology High-resolution Observatory (CoReH2O) is one of the three satellite missions selected for scientific and technical feasibility studies (Phase-A) within the Earth Explorer Program of the European Space Agency (ESA) [ESA, 2008], [Rott et al., 2010]. The principal objective of the CoReH2O mission is to carry out the frequent spatially-detailed measurements of snow and ice in order to advance our knowledge and prediction of the water cycle in cold regions and to improve the representation of the cryosphere in climate models. The sensor proposed is a dual frequency SAR, operating at Ku-band (17.2 GHz) and X-band (9.6 GHz), VV and VH polarizations, with a swath width of about 100 km. The principal products obtained from the mission will be the estimations of the extent, the water equivalent (SWE) and melting state of the seasonal snow cover and the snow accumulation on glaciers. In order to estimate the SWE from the backscattering measurements, it is necessary to separate the signal of the snow volume from the contribution of the background target (which is dependent on soil features such as roughness and steepness, vegetation cover, etc.) and also to account for effects of grain size on scattering. The presence of vegetation has a significant impact on the propagation of the radar signal at X- and Ku-band, depending on its structure, biomass, water content and cover fraction. In particular for dense forest (even in case of a moderate biomass), scattering of vegetation strongly hides the signal from snow and, consequently, compromises the sensitivity to snow parameters [ESA, 2008]. Due to the lack of data, in order to improve our understanding
of the effect of vegetation on the retrieval of snow parameters, a radiative transfer model for snow-covered vegetated terrain was developed and tested for the CoReH2O configuration. Moreover, use of the model has been a reasonable option for consolidating the relationship between vegetation type/age and vegetation parameters (e.g. the shape and dimensions of trunks and branches, etc.) among different cover types. The aim of this paper is to investigate the impact of vegetation on the retrieval of snow parameters from backscattering measurements at the X- and Ku-bands, using an electromagnetic model that is able to simulate scattering from a snow-covered vegetated terrain. The model is briefly described in the first section of the paper, while the second part contains an analysis of sensitivity to vegetation and snow parameters which was conducted on coniferous forests.

**The snow-vegetation model**

In order to simulate the backscattering from a snow-covered forested terrain, we needed to combine a model for a snowpack with a model for vegetation. Among the possible electromagnetic models, an incoherent RTT model was selected that was originally developed at IFAC for the simulation of agricultural crops [Macelloni et al., 2001] [Ulaby et al., 1990], and then modified for forest vegetation [ESA, 2008]. This e.m. model was developed and tested during Phase-0 of the CoReH2O mission [ESA, 2008], and was recently improved.

The main advantages of this model are that:

- it can easily be combined with the snow model that was developed within the CoReH2O project;
- it can be applied to the simulation of several vegetation types;
- its inputs are related to measurable vegetation parameters, and are easily connected to the developed tree and forest model.

In the vegetation e.m. model, the canopy is divided into a certain number of horizontal layers over a snow-covered terrain. Each layer contains different groups of scatterers, and each group is assumed to be composed of identical scatterers with a certain density (number of elements per m$^3$), which are uniformly distributed in the azimuth direction. The number of layers, as well as their thickness, depends on the vegetation type. The scatterers are then characterized by extinction and scattering properties, as a function of shape and size, using different approaches. The scattering amplitudes and the extinction cross sections of needles (representing coniferous forest leaves) were computed by using the model proposed by Karam et al. [1989]. For cylinders (representing trunks and branches in forest) the “infinite length” approximation can be adopted. In this case, extinction and bistatic scattering formulas were made available in [Karam et al., 1988].

According to this approach, the electric field inside the cylinder was represented as a combination of vector cylindrical waves, and the scattered field was expressed by an integral of surface fields by applying the Huygens principle. The extinction cross sections were obtained from the scattering amplitude tensor elements by applying the forward scattering theorem. The permittivity of vegetation elements was obtained from [Magagi et al., 2002].

The radiative-transfer equation was solved by iteration for the first-order (i.e. single-scattering) backscattering coefficients (co- and cross-polarized terms at V and H pol).
The total backscattering coefficient in polarization $pq$ can be expressed as the incoherent sum of three terms, as in [Magagi et al., 2002]:

$$\sigma_{pq\text{totcan}} = \sigma_{pq\text{veg}} + \sigma_{pq\text{snow}}L_{qveg}L_{pveg} + \sigma_{pq\text{veg-snow}} \tag{1}$$

where:

- $\sigma_{pq\text{snow}}$ = Direct Scattering from snow-covered terrain (attenuated by vegetation loss $L$);
- $\sigma_{pq\text{veg}}$ = Direct Scattering from vegetation;
- $\sigma_{pq\text{veg-snow}}$ = Interaction between terrain and vegetation (including both vegetation-ground and ground-vegetation contributions attenuated by vegetation). These two terms have a complex formulation as expressed in [Fung, 1994], and are not repeated here.

$L_p = \exp(-\tau_p \sec \theta)$ = one-way attenuation factor of vegetation at $p$ polarization.

In the last expression, $p$ is the polarization (H or V), $\theta$ is the incidence angle, and

$$\tau_p = \sum_{i=1}^{N} k_{epi} h_i \tag{2}$$

where:

- $N$ = number of layers;
- $h_i$ = thickness of the $i$-layer;
- $k_{epi}$ = extinction coefficient of the $i$-layer, which can be expressed as:

$$k_{epi} = \sum_{j=1}^{M} \sigma_{epj} \rho_j \left[ \text{m}^{-1} \right] \tag{3}$$

$M$ = number of scatterer types in the $i$-layer;

- $\sigma_{epj}$ = average extinction cross section of the scatterer type $j$ [m$^2$];
- $\rho_j$ = volumetric density of scatterer type $j$ [m$^{-3}$].

Expression for direct scattering from vegetation can be found in [Karam et al., 1995]-[Fung, 1994], while scattering from snow is described in [Esa, 2008].

Equation 1 is applicable for a homogeneous canopy such as an agricultural crop, herbaceous vegetation, or a closed forest. For a sparse forest, as several ones at boreal latitudes, this equation must be modified by taking into account the fact that a portion of the area observed by the sensor is not covered by forest. By introducing a cover fraction factor $C_f$, equation 1 becomes, as defined in [Magagi et al., 2002]:

$$\sigma_{pq\text{tot}} = \sigma_{pq\text{totcan}} C_f + (1 - C_f)\left(\sigma_{pq\text{snow}} + \sigma_{pq\text{veg-snow}}\right) \tag{4}$$

where:
\[ \sigma_{pq - t o t v e g}^0 = \text{backscattering coefficient for a close canopy (i.e. equation 1)} \]
\[ \sigma_{pq - s n o w}^0 = \text{direct Scattering from snow-covered terrain} \]
\[ \sigma_{pq - v e g - s n o w}^0 = \text{interaction between a forested area and a non-forested area as defined in} \]
[Magagi et al., 2002].

Moreover, it should be considered that the scattering of the area not covered by forest is partially affected by the shadowing induced by trees (which attenuates the signal coming from snowpack). This effect obviously depends on the dimensions of the trees (e.g. height, diameter), the density of the forest and the incidence angle of observation. By introducing the additional factor \( C_s \) (area affected by shadow) in (4) we obtain the following equation, which includes both the cover fraction and the shadowing effect:

\[ \sigma_{pq - t o t}^0 = \sigma_{pq - t o t c a n}^0 + (1 - C_f)(C_s L_p (\sigma_{pq - s n o w}^0 + \sigma_{pq - v e g - s n o w}^0) + (1 - C_s)(\sigma_{pq - s n o w}^0 + \sigma_{pq - v e g - s n o w}^0)) \]  \[ 5 \]

A representation of the model scheme as indicated in equation 5 is represented in Figure 1.

![Figure 1- Schematic representation of the e.m. model adopted. Cf = part of the scene occupied by dense forest; 1-Cf = part of the scene occupied by bare (or snow covered) soil; Cs = part of the scene (fraction of 1-Cf) affected by shadow.](image)

The developed e.m. model was primarily tested on coniferous forest which, as pointed out in [ESA, 2008], is the most representative stand at the highest latitude of the globe. Several inputs are required for testing the RTT model, and these include a detailed geometrical description of tree components and information about tree density and cover fraction. Unfortunately, information available on this species in the literature is limited to the parameters most relevant to forestry applications (e.g. forest biomass, tree height or diameter at breast height,dbh). In order to obtain all the parameters necessary as inputs to the e.m. code, a tree model was developed starting from data in the literature [Magagi et al., 2002]. To collect new data that take into account the main features of the northern boreal forests,
an appropriate test site was identified in the Italian Alps. The test site is located near Cortina
d’Ampezzo, close to the Giau Pass (46.5105° N, 12.0859° E), at an altitude of about 1.600 m
a.s.l. Two exemplars of spruce, one taller (29.5 m) and one shorter (13 m), were examined, and
for both of them trunk, branch and needle dimensions (e.g. radius, length), as well as orientations
(with respect to the zenith) and densities (number of elements/ha), were measured.
By using datasets both from the literature and from experimental reports, some allometric
relations (e.g. dbh as a function of biomass and tree height) were developed and validated with
existing ones [Jenkins et al., 2004]. By starting from these equations, four “reference” trees
were simulated in the 5-9, 10-15, 16-20, and higher than 20 height ranges. For each range,
the height, the dbh, and the biomass could be obtained by using the allometric equations,
while the branch and needle parameters derived from real data remained unaltered. The
vegetation moisture and the derived dielectric constant used in the e.m. model were obtained
from [Magagi et al., 2002].

![Figure 2 – Comparison between Measured and Simulated biomasses of six different coniferous trees. Reference data were obtained from [Cannel, 1982]. Blue Diamond=total biomass; Brown square = trunk biomass; Green triangle = branches.](image)

The tree was divided in two main parts that represented the bottom part of the trunk
and the crown. The crown was then divided in several layers, in order to make them
(i.e. the top of the tree, the middle part and the basal part) as homogeneous as possible.
For each layer, the types of different elements, such as the needles, trunk, and various
kind of branches, were considered. The density of the layer elements was estimated
according to the number of trees per hectare. Furthermore, to keep the biomass value
per hectare unchanged when calculating (5) and, consequently, the volumetric scattering
contribution, the density had to be divided by the factor $C_f$. In order to assess the tree
model behavior over a large range of variability, bibliography data of forest biomass
were also examined [Cannel MGR, 1982]. A first test was performed over 6 test sites distributed in Northern Europe, where the trees are similar to those used in the model. A comparison between measured and modeled biomass is shown in Figure 2. The test confirmed a good agreement between estimated and measured data: the RMSE obtained in the 0-300 ton/ha range was 24 ton/ha for total biomass, 20 ton/ha for trunk, and 17 ton/ha for branches.

In order to study the effect of tree shadowing on the backscattering, a method to estimate the percentage of area covered by vegetation and the percentage of area affected by shading (for a given forest) was developed. The structure of the forest was represented by using a CAD software. The cover fraction, as well as the shaded area, was computed as a function of the incidence angle using ray-tracing and image processing tools. The forest was built by randomly replicating a sample tree represented in a simplified way as a cone above a cylinder (representing the crown and the trunk, respectively). Forests with two different tree heights and dimensions (depending on the tree model) were developed. A vegetation cover fraction variability was obtained by changing the tree density from 200 to 1100 trees/ha for the shorter tree and between 200 and 400 trees/ha for the taller one. By illuminating the forest with a light at different incident angles (25°, 45° and 65°) the shadow area was generated over the entire scene and the cover fractions were then estimated. As expected, by establishing a vegetation cover fraction, the shadowing increased at increasing angles. On the other hand, at a fixed angle, as $C_f$ increased, the shadow cover fraction saturated and then decreased. A simple relationship between shadow and the vegetation cover fraction was obtained for different forest parameters.

**Model Sensitivity**

In order to evaluate the response of the developed model to the variability of the inputs, a sensitivity analysis was conducted as a function of SWE and vegetation parameters. As a first step, the sensitivity of $\sigma^0$ to SWE was conducted for different biomass values in order to evaluate the maximum biomass (or cover fraction) acceptable for retrieval purposes. Simulations were carried out at both X- and Ku-band at 40° of incidence angle, with an SWE ranging from 0 to 250 mm. The latter was obtained by increasing the snow depth from 0 and 1 m and assuming a constant snow density value of 250 kg/m$^3$. In order to simplify the analysis, a single snow layer model was used and the grain radius was kept constant at 1mm. For forest, two biomass values, 100 m$^3$/ha and 200 m$^3$/ha, were considered. The biomass variation was obtained by keeping the tree dimension fixed and varying the density (i.e. by increasing the cover fraction and biomass). The results are presented in Figure 3. In this figure, the non-forested area (biomass = 0) is also represented as a reference. As expected, the backscattering increased when the biomass value increased, and the sensitivity to SWE was higher for low values of biomass. By increasing the frequency from 9.6 to 17.2 GHz, the sensitivity became higher due to the increase in the snow volumetric scattering. Similar behavior occurred when the grain radius increased, due, also in this case, to the increase in the snow volumetric contribution. In all the cases considered, when the biomass was equal to or higher than 150 m$^3$/ha, the sensitivity to SWE disappeared at all frequencies and polarizations, and the applicability of a retrieval algorithm for SWE became questionable.
Figure 3 - Backscattering coefficient as a function of SWE at an incidence angle of 40° at 9.6 GHz (top) and 17.2 GHz (bottom) for biomass values of 100 and 200 m³/ha and Cf values, respectively, of 0.4 and 0.8. VV and VH polarization are represented by continuous and dashed lines, respectively. Grain size = 1 mm.

Simulations were then carried out also for different tree heights, for a fixed cover fraction value of 0.2 and an incidence angle of 40°. It is important to note that, because the dimensions of trees increased, the biomass values also increased.
Figure 4 - Backscattering coefficient as a function of SWE at an incidence angle of 40° at 9.6 (top) and 17.2 GHz (bottom) for a fixed CF of 0.2 and different tree heights (i.e. different biomass). VV and VH polarization are represented by continuous and dashed lines, respectively.

From Figure 4 it is possible to observe that $\sigma^0$ trends are very similar at least up to a tree height of 22 m, and that the sensitivity to SWE remains almost the same (whereas the backscattering increases when tree height increases). It is worth noting that, by fixing a CF value, the sensitivity of backscattering to SWE decreases for all frequencies and polarizations as the tree height increases. Also, by increasing the CF value, the sensitivity to SWE further decreases.
Figure 5 - Backscattering coefficient as a function of SWE at 9.6 (top) and 17.2 GHz (bottom) at 40° for a fixed biomass of 100 m³/ha and different tree height (i.e. different CF). VV and VH pol are represented by continuous and dashed lines, respectively.

The sensitivity to SWE as a function of tree height variability was also investigated by considering a fixed biomass value of 100 m³/ha and by modifying the tree height. Even in this case, it is important to note that when the tree height increased, the CF decreased. The results provided in Figure 5 show that, when the tree height increased, the backscattering
coefficient increased, as a consequence of the increasing of CF, but the variability for the different three heights was no higher than 0.8 dB at VV polarization and 1.5 dB and VH polarization.

Applications
The analysis conducted on previous sections clearly pointed out that vegetation strongly influences the sensitivity of backscattering to snow parameters: in particular, by increasing biomass, tree heights or cover fraction, the sensitivity to SWE decreases until it becomes negligible. While the simulations were limited to a single forest type and in a reduced number of cases, the results obtained clearly showed that the sensitivity to SWE disappeared at all frequencies and polarizations for biomass greater (of more) than 150 m$^3$/ha and for a CF of more than 0.3-0.4. This is an important issue in the CoReH2O perspective for the development of the retrieval algorithms in forested areas, which requires a minimum backscatter variability (at least some dB) over the expected SWE range (of around 0-300 mm). From an operational point of view, these areas must be classified by using a global vegetation database and masked out in the retrieval process line of the mission. When the cover fraction is in the 0-0.3 range or when the biomass varies between 0 and 150 m$^3$/ha, an operative procedure could be applied to take into account the effect of vegetation in the retrieval algorithm. The procedure could be based on the following steps:
- the area must be precisely classified as to vegetation type and vegetation cover fraction or as to biomass (the availability of ancillary data is fundamental);
- the CoReH2O L1 product (backscattering coefficient at VV, VH polarization at X and Ku band) must be degraded to a lower resolution of 1 km (instead of the L1 nominal product resolution of 200m), in order to take into account the variability of the local vegetation;
- on the basis of the theoretical model and available vegetation parameters, the vegetation effect could be estimated by comparing the measured and the modeled backscattering coefficients when the terrain is not covered by snow. For this step, the electromagnetic model must be trained over a larger number of cases and accurately validated using real vegetation and SAR data. It is also recommended that the nearest pixel of the image in the considered area not covered by vegetation (in this case, a threshold distance must be defined to identify the nearest pixel) be used as a reference value for the ground signal;
- the estimated vegetation effect is considered during the snow season in order to estimate the SWE value. Also in this case, a comparison of the obtained results with those obtained in a non-vegetated area is recommended.

This procedure will be implemented and better defined during future preparatory phases of the CoReH2O mission as soon as actual SAR data are available.

Conclusions
In this paper, several aspects of the effect of vegetation on backscattering on snow-covered terrains were pointed out. The study was focused on coniferous forests, which are the most representative stand at the latitudes involved in the CoReH2O mission [ESA 2008]. In the first part of the paper, the selected and implemented model was briefly described. Although the model is similar to the one developed in [ESA 2008], it has been carefully
revised, and additional features have been added (for example, the effect of tree shadow on backscattering). The second section was devoted to a sensitivity study of the model. The parameters considered were biomass, tree height, and cover fraction. The analysis was conducted at both X- and Ku-band for the VV and VH pol. As expected, vegetation strongly influences the sensitivity of backscattering to snow parameters: in particular, by increasing biomass, tree height, or cover fraction. Sensitivity to SWE decreases until it becomes negligible.

Above all, it was found that for a biomass greater than 150 m$^3$/ha and/or for a CF of more than 0.3-0.4, the sensitivity to SWE disappeared at all frequencies and polarizations. From an operational point of view, this means that areas showing these values must be masked out on the retrieval process line of the mission. For lower values, a procedure that takes into account the effect of vegetation in the retrieval algorithm, which will be implemented and better defined during future phases of the CoReH2O, has been briefly described.

**References**

Cannel M.G.R. (1982) - *World Forest Biomass and Primary Production*. Academic Press, London.

European Space Agency (2008) - *Candidate Earth Explorer Core Missions*. Reports for Assessment, ESA SP 1313 (3), Mission Science Division, ESA-ESTEC, Noordwijk, The Netherlands, ISSN 0379-6566, p. 104. doi: http://www.congrex.nl/09c01/.

Fung A.K. (1994) - *Microwave scattering and emission models and their applications*. Artech House Inc., Boston.

Jenkins J.C., Chojnacky D.C, Heath L.S, Birdsey R.A. (2004) - *Comprehensive database of diameter-based biomass regressions for North American Tree Species*. General Technical Report NE-319 U.S. Department of Agriculture, Forest Service, Northeneastern Research Station, p. 45.

Karam M.A., Fung A.K (1988) - *Electromagnetic scattering from a layer of finite length, randomly oriented, dielectric, circular cylinders over a rough interface with application to vegetation*. Int. J. Remote Sensing, 9: 1109-1134. doi: http://dx.doi.org/10.1080/01431168808954918.

Karam M.A., Fung A.K. (1989) - *Leaf shape effect in electromagnetic wave scattering from vegetation*. IEEE Trans. Geosci. Remote Sensing, vol. 27: 687-697. doi: http://dx.doi.org/10.1109/TGRS.1989.1398241.

Karam M.A., Amar F., Fung A.K., Mougin E., Lopes A., LeVine D.M, Beaudoin A. (1995) - *A microwave polarimetric scattering model for forest canopies based on vector radiative transfer theory*. Remote Sensing Environ., 53: 16–30. doi: http://dx.doi.org/10.1016/0034-4257(95)00048-6

Macelloni G., Paloscia S., Pampaloni P., Marliani F., Gai M. (2001) - *The Relationship between the Backscattering Coefficient and the Biomass of Narrow and Broad Leaf crops*. IEEE Transactions on Geoscience and Remote Sensing, GRS, 39 (4): 873-884. doi: http://dx.doi.org/10.1109/36.917914.

Magagi R., Bernier M., Chhun-Huor Ung (2002) - *Quantitative analysis of RADARSAT SAR data over a sparse forest canopy*. Geoscience and Remote Sensing, IEEE Transactions on, 40 (6): 1301- 1313.

Rott H., Yueh S.H., Cline D.W., Duguay C., Essery R., Haas C., Hélière F., Kern M., Macelloni
G., Malnes E., Nagler T., Pulliainen J., Rebhan H., Thompson A. (2010) - *Cold Regions Hydrology High-Resolution Observatory for Snow and Cold Land Processes*. IEEE Proceedings, 98 (5): 752-765. doi: http://dx.doi.org/10.1109/JPROC.2009.2038947.

Ulaby F.T., Sarabandi K., McDonald K., Whitt M., Dobson M.C. (1990) - *Michigan microwave canopy scattering model*. Int. J. Remote Sensing, 11: 1223-1253. doi: http://dx.doi.org/10.1080/01431169008955090.

Received 18/04/2011, accepted 09/11/2011

© 2012 by the authors; licensee Italian Society of Remote Sensing (AIT). This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution license (http://creativecommons.org/licenses/by/4.0/).