# BUILDING HEIGHT RETRIEVAL FROM RADIOMETRIC PARAMETERS ON SAR IMAGES

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**ABSTRACT:**
Urban structure detection, in terms of both geometric and electromagnetic features, from a single Synthetic Aperture Radar (SAR) image is, nowadays, an interesting still open challenge. Within this framework a new deterministic approach for the extraction of the height of an isolated building on a rough terrain is presented. The approach is based on a sound electromagnetic model which fully represents the electromagnetic return from an isolated building to an active microwave sensor, analytically evaluated in closed form. In particular, building height is extracted from double scattering contribution to the radar cross section measured on the SAR image. Some simulation examples, relative to canonical scenes, accompany and validate the proposed approach.

## 1. INTRODUCTION

The growth of urban centers calls for a real time monitoring able to check any change in this kind of scenario. Synthetic Aperture Radar (SAR) represents a powerful instrument allowing any weather conditions monitoring and, in particular operating modes, e.g. spotlight, very fine resolutions on data collected.

In the last years, some attempts to retrieve information on man-made objects from SAR images have been carried out. This inverse procedure can be motivated: as shown in [1], a set of analytical relationships among radiometric and geometric parameters of the scene and of the SAR image, can be found; it turns out that some scene parameters could be in principle estimated from even a single SAR image.

But actually, within this framework, only in a few works [6] information is retrieved from single SAR images, being, in most cases, extracted from multiaspect [3,8] or interferometric [7] SAR data and, usually, it is limited to the building dimensions estimation [2,3] or to its shape [7] from geometric parameters on the SAR image. In most of these works, particular attention is focused on building height retrieval. In fact, range extensions of layover and shadow areas are simply related to building height [1,2,7], so that height retrieval is immediate when the extension of these areas can be easily estimated on a SAR image. But the error affecting the measure is dependent on the SAR acquisition geometry and on the SAR image range resolution; for spaceborne SAR this approach often leads to building height estimation affected by unacceptable measurements errors.

A new way to extract height information is presented in this work.

The idea of building height retrieval from radiometric parameters measurable on SAR image is here presented. The proposed method relies on an electromagnetic model that quantifies the radar return from an isolated building on a rough terrain [4]-[5].

The model takes into account any relevant macroscopic geometrical parameters of the building [4] and evaluates the corresponding radar cross section.

Single, double and triple scattering are considered as main contributions to the backscattered field [4]. Moreover, multiple scattering twists together with layover and shadowing effects to form the SAR image in a non trivial way according to the geometric (building dimensions) and electromagnetic (ground roughness, complex dielectric constants of soil and building) parameters in the scene and the radar functioning mode (look angle, polarization, frequency..).

Particularly, we observed that building heights affect notably SAR image formation not only in the pixel extension of some contributions but also in their intensities.

In the follow this consideration is explained in details in order to motivate our approach in building height retrieval from radiometric parameters and, particularly, from double scattering contribution to the radar cross section.

Different simulation examples relative to canonical urban scenes have been conducted letting radar parameters and scene features vary. All them proved not only the reasonableness of the methodology proposed but also its major effectiveness in many actual cases respect to height retrieval from geometric parameters. The SAR raw signal simulator adopted here [5] is coherent with the scattering model considered for the feature extraction, as it takes into account all multiple reflections arising in the geometric model illustrated in the following paragraph.

In these years other simulation techniques of SAR images have been developed for urban structures, but they do not fit our idea of feature extraction because not all contributions to the radar cross section are considered. In fact, usually only layover and shadow [9] are taken into account, or, even if double bounce is accounted for, soil roughness is ignored [10].

## 2. GEOMETRIC AND ELECTROMAGNETIC MODEL

Let us consider the simple urban scene represented in Fig.1. A single building, modelled as a parallelepiped with smooth roof and walls, is placed on a rough terrain. Any direction $\varphi$ respect to the radar flight trajectory can be considered.

For the model adopted all main building and ground parameters are defined: the height $h$, the length $l$ and the width $w$ of the building together with its complex dielectric constants ($\varepsilon_r$ for the roof and $\varepsilon_w$ for the walls); the correlation length $L$ and deviation standard $\sigma$ of the stochastic process describing the roughness of the soil and its complex dielectric constant $\varepsilon_s$.
Really, for our analysis, we do not need strictly of a scene with a single building. Many buildings can be present together provided that they are isolated in electromagnetic sense, i.e. their contributions to the (processed) SAR image do not overlap. In such a manner, our attention can be focused on each building separately from others. This hypothesis, which can be relaxed in future, is important in this work where, for the first time in literature, an attempt of retrieve geometric parameters from electromagnetic ones, measurable on the SAR image, has been lead.

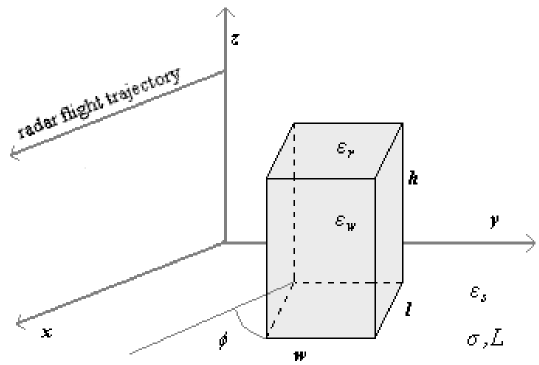



Figure 1. Geometric model of the scene

In fact, as shown in Fig.2 where single, double and triple scattering have been considered, for a single building we already expect a very complex composition of different contributions on SAR image.
As far as the adopted electromagnetic model I concerned, a few words are now needed.
High frequency allows us to adopt Kirchhoff approach to compute electromagnetic field backscattered towards the radar, in Geometric Optics (GO) or Physics Optics (PO) approximation according to the soil roughness [4]. For the geometrical model studied, contributions till third order are demonstrated to be sufficient for a realistic description of backscattered field, [4], which can be written as:

$$\begin{bmatrix} E_{Sh} \\ E_{Sv} \end{bmatrix} = jk\frac{e^{jkr}}{4\pi r}\begin{pmatrix} S_{hh} & S_{vh} \\ S_{hv} & S_{vv} \end{pmatrix}\begin{bmatrix} E_{0h} \\ E_{0v} \end{bmatrix} I_S \qquad (1)$$

where $E_0$ is the incident field, $E_s$ is the backscattered field, $r$ is the range distance between the target and the sensor, $h$ and $v$ stand for horizontal and vertical polarization, respectively, $k$ is the wave number, $S_{pq}$ is the generic element of scattering matrix, with $p$ and $q$ each standing for $h$ or $v$, $I_s$ is the surface integral accounting for the portion of surface invested by radiation. Complete expressions of the quantities appearing in eq.(1) are reported in Ref.[4]. In particular, as shown in [4], under the hypothesis above $I_s$ can be written in closed form and it assumes different expressions according to the order of contribution (single, double and triple scattering) and the approximation (GO or PO) considered. All these forms, each in a different way, involve geometric and electromagnetic parameters previously defined to describe the scene under detection. That is why, in principle, an inversion of direct formulation in [4] can be thought. How this has been applied to building height is shown in the following.

## 3. BUILDING HEIGHT RETRIEVAL

As demonstrated in literature [2], building height can be retrieved from geometric parameters measurable on SAR image, i.e., layover and shadow range extensions. Unfortunately, as shown in the next Section by means of simulation, not always these extensions can be appreciated on a real SAR image affected by speckle. Appreciating layover extension can be difficult and also shadow area can be not meaningful for height retrieval.. In fact, the extension of this area is not always directly linked to the height because, depending on the building height/width ratio, the shadow can be partly canceled by triple reflection [5], see the lower part of Fig.2. Moreover, even if we are able to measure these areas, our evaluation of the building height will be always affected by an error linked to the range resolution of the SAR image.
So, when SAR image resolution is not very high or when building height can not be retrieved from layover and shadow, an alternative approach is worth to be studied and it is what we present in this paper.
Starting from [1] and [4] we found that building height involves single reflection from wall, double reflection and triple reflection. But triple scattering, the contribution of which has been emphasized in Fig.2, is weak and difficult to be extracted; single reflection from wall (layover) is usually mixed with single scattering from roof and from ground and so not immediately available; double reflection, instead, is always easily distinguishable for its peaked value. Then, a building height retrieval from double scattering contribution can be attempted.

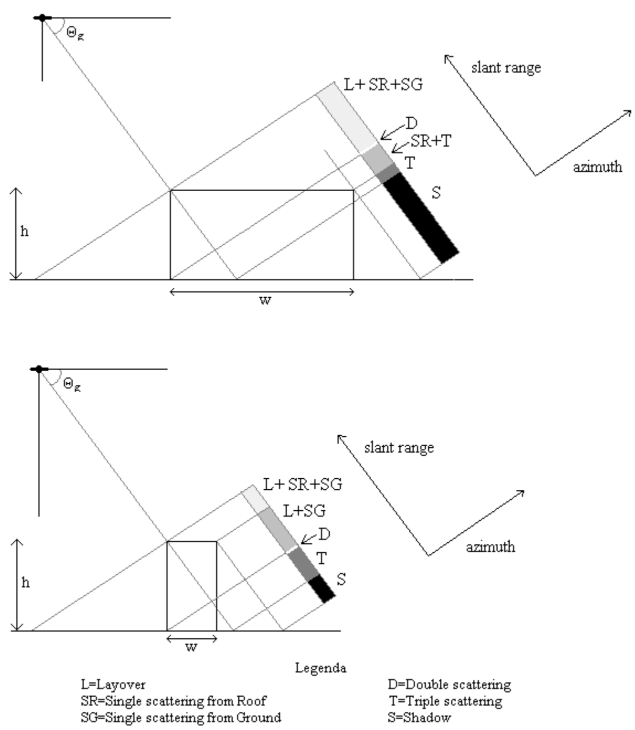



Figure 2. Composition of different contributions on SAR image relative to a canonical scene with an isolated building.

Now, let us suppose that, for roughness parameters involved, Geometric Optics (GO) can represent a reasonable approximation for both bounces of double scattering. This is the case, for example, of a building with a garden in front, whatever is the working frequency in the microwave range. But if the building is placed on a bare soil, it will appear rough in the Ka band and smooth in the L one [11]; that is why the same approach with different approximations has to be adopted according to the surface roughness.

In the hypothesis above, the link between the building height and the integral surface $I_s$ found in [4, eq.(5.8)] can be inverted giving

$$h = \frac{\left\langle I_S \cdot I^*_S \right\rangle}{l \tan\vartheta \cos\varphi \dfrac{1+\tan^2\vartheta \sin^2\varphi}{4k^2\cos^2\vartheta \cdot 2\pi\sigma^2 C''(0)} \exp\left[-\dfrac{\tan^2\vartheta \sin^2\varphi}{2\sigma^2 C''(0)}\right]} . \tag{2}$$

where $\theta$ is the radar look angle, $C''(\cdot)$ is the second derivative of normalized correlation function of stochastic process describing the microscopic profile of ground, $(x_0,y_0)$ are the coordinates of building base centre onto the ground plane and $< I_S \cdot I_S^* >$ represents the mean square value of $I_s$.

In Eq. (2) the building height can be expressed in terms of the radar and scene parameters. On one hand, this shows the generality of the retrieval approach according to which other interesting parameters can be extracted; on the other hand, it means that a high a priori knowledge of ground truth as well as of radar parameters is needed for the retrieval of only one unknown.

Now, what we measure on the SAR image is the radar cross section *RCS* linked to the backscattered field, and hence to the surface integral $I_S$, by the well known expression:

$$RCS = \frac{4\pi r^2 < |E_s|^2 >}{|E_o|^2} . \tag{3}$$

Equations (1), (2), (3) have been used in the next section in evaluating building height after having measured *RCS* relative to double scattering on the SAR image.

Some considerations are now in order. As anticipated, a high a priori knowledge of the scene is needed. In the simulation examples we will suppose each parameter describing the scene, except the height, to be known but actually some of them can be extracted from the image itself. In particular, $l$ and $\varphi$ can be evaluated in a very simple way by means of geometric considerations. Moreover, being SAR image not calibrated, we need the presence of two buildings with known height to compute the two unknown calibration constants. Note that in a more general case, in a scene with $n$ buildings, the height of only two of them has to be known to evaluate the heights of the remaining $n-2$.

Many simulation examples have been realized letting radar and scene parameters vary. Some of them, presented in the follow, are accompanied by interesting results showing the efficiency of the approach adopted.

## 4. SIMULATION EXAMPLES

The urban canonical scene simulated in the next examples is represented by three buildings aligned along a direction in general not parallel with radar trajectory flight. As anticipated, all geometric and electromagnetic parameters in the scene are assumed to be known except for the height of the central building that we propose to retrieve. We let these parameters, as well as radar ones, vary.

Double reflection is always easily distinguishable, and so extractable, on SAR image.

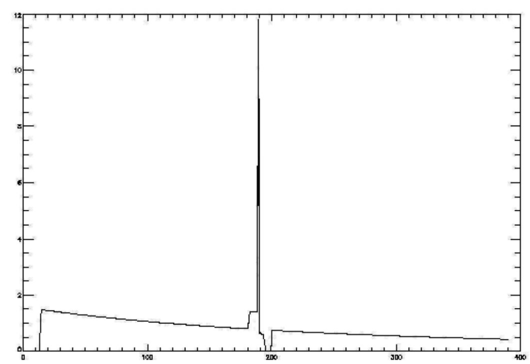
In fact, see Fig.3, if we plot a range cut of the amplitude $|E_S|$ of the field backscattered by the central building, we realize that every contribution can be recognized only in absence of speckle. For example, in Fig.3a, we first distinguish the backscattering from ground and then the different contributions from the building (in order we have layover, double reflection, backscattering from roof and shadow) But when speckle is present, see Fig.3b, this operation becomes critical for most contributions. Only double scattering remains particularly peaked in the plot.

The major difficulty in this approach appears when we manually cut the double scattering line in the image. This step, simple for buildings aligned with radar flight trajectory, becomes crucial for $\varphi$ increasing. In order to overcome this problem cross polarization can be adopted. In fact, in this case, backscattering from ground and roof is very weak and double reflection is perfectly isolated on the image.

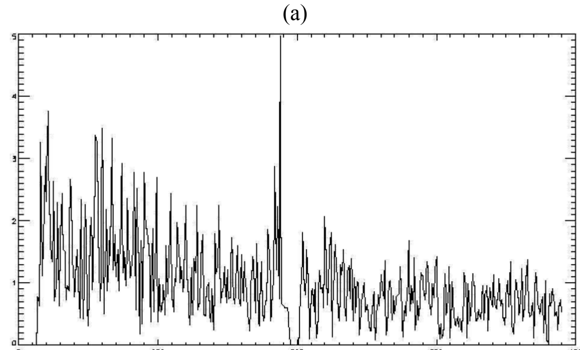
Anyway, the height error is always independent of SAR range resolution and the height evaluation is often better than that retrieved from geometrical parameters.

An example is given for the simulated SAR image in Fig.4 relative to $\varphi$=0° and in presence of speckle. Horizontal polarization has been considered both in transmitting and receiving mode. Radar parameters adopted are relative to a hypothetic, but not really existing, airborne sensor functioning in L-band with a look angle of 30 degrees.

Scene parameters are synthesized in Table 1. The heights considered are relative to buildings of about 3, 6 and 9 floors.



(a)



(b)

Figure 3. Range cut of the amplitude $|E_S|$ backscattered by the central building: (a) in absence of speckle; (b) in presence of speckle.

Length and width dimensions are not typical of buildings in urban centres but they have been chosen so large in order to compare our method with height extraction from shadow. For the sake of simplicity we have supposed the buildings having the same dielectric constants, but a different electromagnetic behaviour can be considered for each of them. The hypothesis of rough soil is true in L band, according to the Rayleigh criterion, only for some kinds of surfaces (like grass or bushes) with the given look angle [11], but also this assumption can be generalized taking into account smooth grounds and, consequently, the appropriate scattering model. We realize from the last row in Table 1 that the height estimation error is about 0.09 m.

By means of a range cut of simulated SAR image around the central building, a shadow area of 4 pixels in slant range has been measured. Considering SAR resolution and look angle, a central building height of 17.52 m can be retrieved from shadow, so with an error of 2.48 m.

A more realistic instance has been considered in Fig.5, in which a wall direction of 30° respect to the SAR flight trajectory has been simulated. The difference in building heights (3 metres) is also smaller than in the previous example as probably happens in real scenes. Most of other parameters remain unchanged, as summarised in Table 2. In this case we also tried to improve height estimation from shadow by measuring the extension of this area with more range cuts and by operating a mean of all measured pixel extensions. In this way we found for the shadow area an extension of 4.375 pixels that corresponds to a height of 18.70 m and an error of 4.3 m. Instead, by applying deterministic extraction from double reflection (last row in Table 2) we find that the building height is retrieved with an error of 1.8 m. In all of the other performed simulations, the error is even smaller, often inferior to one meter.

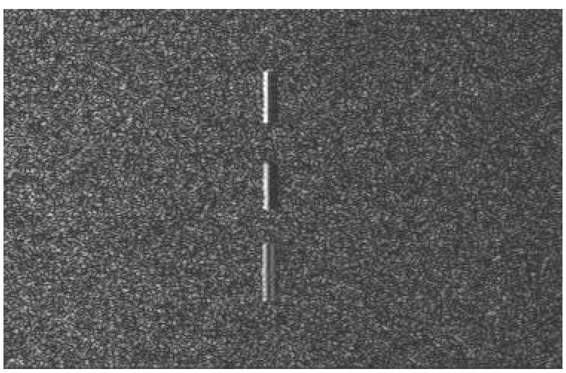


Figure 4. Simulated SAR image relative to three buildings aligned along the direction φ=0°.

| | |
|---|---|
| Top building dimensions (length x width x height) | 90 m x 90 m x 30 m |
| Central building dimensions (length x width x height) | 80 m x 80 m x 20 m |
| Bottom building dimensions (length x width x height) | 100 m x 100 m x10 m |
| Roof and wall dielectric constant | 3 |
| Roof and wall conductivity | 0.01 S/m |
| Ground dielectric constant | 4 |
| Ground conductivity | 0.001 S/m |
| Ground standard deviation | 0.19 m |
| Ground correlation length | 1.54 m |
| Image resolution (range x azimuth) | 4.839 m x 2.571 m |
| Central building height estimation | 19.91 m |

Table 1. Scene parameters relative to the simulated SAR image in Fig.4

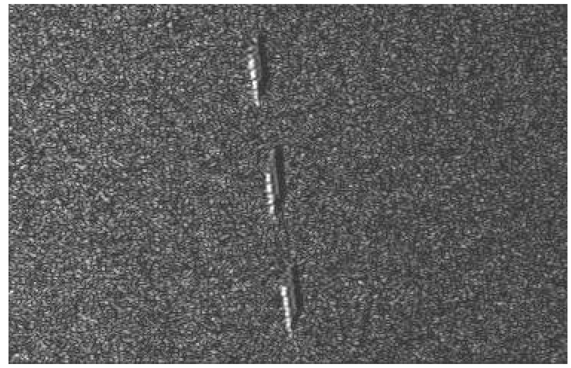


Figure 5. Simulated SAR image relative to three buildings aligned along the direction φ=30°.

| | |
|---|---|
| Buildings length and width | 100 m x 100 m |
| Buildings height | 20,23,26 m |
| Roof and wall dielectric constant | 3 |
| Roof and wall conductivity | 0.01 S/m |
| Ground dielectric constant | 4 |
| Ground conductivity | 0.001 S/m |
| Ground standard deviation | 0.19 m |
| Ground correlation length | 1.54 m |
| Image resolution (range x azimuth) | 4.839 m x 2.571 m |
| Central building height estimation | 21.22 m |

Table 2. Scene parameters relative to the simulated SAR image in Fig.5

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## 5. CONCLUSIONS

The need of not conventional approaches to retrieve geometrical features from single SAR image has been highlighted. Particularly, building height retrieval from radiometric parameters, such as intensity of double reflection region, has been described in details. The suggested approach has been applied to simulated canonical scenes with a few buildings. It results to be efficient, being the measure independent of SAR resolution image, and the obtained first results encourage application to real data. At the moment, the main limitation of our method is that it does not take into account mutual interactions among different buildings in the scene. Inclusion of this effect is currently under study.

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