RELEVANT SCATTERERS CHARACTERIZATION IN SAR IMAGES

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Abstract. Recognizing scenes in a single look meter resolution Synthetic Aperture Radar (SAR) images, requires the capability to identify relevant signal signatures in condition of variable image acquisition geometry, arbitrary objects poses and configurations. Among the methods to detect relevant scatterers in SAR images, we can mention the internal coherence. The SAR spectrum splitted in azimuth generates a series of images which preserve high coherence only for particular object scattering. The detection of relevant scatterers can be done by correlation study or Independent Component Analysis (ICA) methods. The present article deals with the state of the art for SAR internal correlation analysis and proposes further extensions using elements of inference based on information theory applied to complex valued signals. The set of azimuth looks images is analyzed using mutual information measures and an equivalent channel capacity is derived. The localization of the "target" requires analysis in a small image window, thus resulting in imprecise estimation of the second order statistics of the signal. For a better precision, a Hausdorff measure is introduced. The method is applied to detect and characterize relevant objects in urban areas.

Key Words: SAR, Internal Correlation, Mutual Information, Information Theory, Hausdorff Measure.

INTRODUCTION

With the rapid development of SAR technologies, the need for automatic processing of large-size SAR data is getting more important. Automatic Target Recognition (ATR) in SAR images is an area of ongoing research of high interest for the new generation of meter resolution SAR. The most common ATR system consists of three modules. They are (1) focus of attention that filters out all the Regions Of Interest (ROI), (2) index that labels target candidates and (3) a subsystem of predict-extract-match-search that verifies target identifications by matching predicted signatures in database with measured signatures.

In this article, we will focus on the two first steps of an ATR system. Our ROI will be the strong scatterers, such as corner reflectors, that may be found in high resolution SAR images. Indeed, with the increase of SAR sensor resolution, the extraction of some geometrical or topological structures from SAR images (specially for urban areas) becomes more important to process. Then, the second step of our work will consist in labeling these detected ROI, using some automatic measures, which provide a well-suited geometrical characterization.

The organization of this paper is as follows: In section 2 some basic SAR properties are given. Then, the section 3 is dedicated to target analysis using an azimuth sub-band decomposition. In section 4, some automatic measures are proposed to study the behavior of the targets. Finally, the results are discussed in section 5.

BASIC SAR

SAR synthesize a long antenna by transmitting pulsed signal and coherently adding the successively reflected and received pulses to obtain high resolution in flight (azimuth) direction. The resolution in range direction is achieved by transmitting either very short or otherwise large bandwidth pulses, called chirp.

Considering a single scatterer on the ground, it is noted that the exact distance, called range, from the moving antenna to the scatterer will be different for every received pulse. The change in range from pulse to pulse may only be a few millimeters, but that is enough to give the signal, which is received from the scatterer, a different phase at each pulse. This change in phase results in the Doppler effect, such as observed when a signal from a stationary object is observed from a moving point.

The SAR data acquisition is modeled as a linear range-variant operator transforming the complex reflectivity function of the scene to be imaged to the acquired raw data. The point scatterer response serves as a range-variant convolution kernel in this process.

A fully focused SAR image can be obtained by filtering the SAR raw data with a two-dimensional (2-D) space-variant function: the SAR impulse response. In other words, the image formation is modeled as a range-variant convolution of the raw data with the complex conjugate and time inverted point scatterer response.

Astonishingly, the range-variant natures of both, data acquisition and image formation cancel out and the end-to-end system behavior is *range-invariant*. Indeed, the complex image is related to the complex reflectivity function simply via convolution with the impulse response, which is definitively a function of the point scatterer response.

An important parameter in relation to the azimuth SAR processing is the Doppler centroid, which is the Doppler shift of a target positioned in the antenna boresight direction. For a SAR where the antenna is pointed perpendicular to the flight line, the Doppler centroid is ideally zero. However, if the antenna is off-set in angle (squinted) or if a satellite SAR orbiting a rotating Earth is considered, then the Doppler centroid will be different from zero. Basic SAR theory is described in more detail in [1].

SUB-BAND DECOMPOSITION OF SAR IMAGES

This section is dedicated to high resolution SAR image sub-band decomposition analysis. Such a decomposition is a promising tool to analyze the behavior of scatterers and to study some of their properties.

The azimuth direction is achieved along the flight axis and each position corresponds to some frequency variations due to the Doppler effect. Each point in the scene, is illuminated many times by the radar beam. A selection of an azimuth sub-aperture corresponds thus, to a selection of some viewing angles or sensor positions.

In our work, for sake of simplicity, we chose to undergo a division of the spectrum in the azimuth direction into n sub-bands with $n = 2$ (the cases of $n > 2$ could also be studied).

The principle of the high resolution SAR image sub-band decomposition is given by the figure 1.

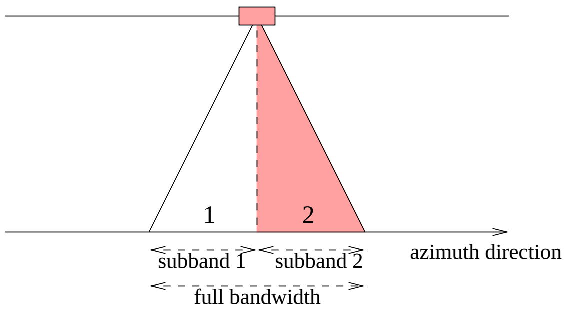

Figure 1. Illustration of the azimuth decomposition into 2 sub-bands.

An azimuth sub-band decomposition gives information about the directivity of the scattering on the different objects, depending on the orientation, the material, the surroundings surfaces... Indeed, an object with a low (respectively high) scattering directivity will (respectively will not) be seen in all the sub-bands.

Due to the particular fine backscattering phenomena in urban areas and the directivity property, the signal of a sub-band aperture can be quite different from the full spectrum signal.

For instance, rough surfaces are quasi-Lambertian and isotrope when the roughness is high according to the wavelength. Therefore, the same backscattering intensity will be observed in each sub-band. However, for some man-made objects in urban areas, such as dihedre, the backscattered signal is a function of the relative direction of the incidence wave and the object. In this case, the target could be faded or even disappear in some sub-bands.

The sub-aperture decomposition is made by the following steps [2]:

1. Direct Fourier transform
2. Doppler centroid estimation and compensation of Doppler shift (in [3], three Doppler centroid estimators were proposed);
3. Unweighting in azimuth;
4. Spectrum division into 2 sub-bands;
5. Centering the obtained sub-images;
6. Zero-padding and hamming weighting of each sub-band; and finally
7. Inverse Fourier transform.

It is noted that, the azimuth resolution of the regenerated signals is degraded by a factor of 2 according to the original resolution.

SCATTERERS BEHAVIOR ANALYSIS USING THE AZIMUTH SUB-BAND DECOMPOSITION

The sub-band images give many information about the scene, specially the man-made structures. Nevertheless, it would be useful to deal with automatic measures in order to fuse all these information to obtain both a better analysis and a finer description of the strong scatterers behavior.

In the following, different measures are used to enhance ROI and to extract the information given by the two sub-bands of the azimuth sub-aperture decomposition. The two first measures are based on the complex correlation, while the third and the forth ones rather on the mutual information. It should be noted that the 2 last quantities are computed using only the amplitude signals. Finally, to obtain a full characterization of the complex data, the Hausdorff distance is proposed.

It is noted that both the complex correlation and the Hausdorff distance will provide us with similarity measures on complex values, while the mutual information will concentrate on the statistical aspect of the ROI using only the amplitude of the signal.

Complex correlation

The complex correlation between 2 sub-bands B_1 and B_2 can be written at a pixel (i, j) as:

$$R_{B_1,B_2}(i,j) = \frac{< b_1.b_2^* >_{ij}}{(< b_1.b_1^* >_{ij}< b_2.b_2^* >_{ij})^{\frac{1}{2}}}$$

where:

- $< . >_{ij}$: spatial averaging in the vicinity of the pixel (i, j)
- b_k ($k = 1, 2$): complex matrix for a given vicinity of the pixel (i, j) associated with the sub-band $B_k(k = 1, 2)$

The numerator of R should play in favor of point targets, which are supposed to contribute symmetrically during the radar illumination time.

The use of R was found to be quite disappointing for target detection. The main reason is that the normalization of R (through the denominator) does not permit to consider radiometry in the detection aspect. To remove this drawback, it is proposed in [4] to use the Internal Hermitian Product (IHP).

The IHP correspond to the complex correlation R without normalization. It is defined at a pixel (i, j) as:

$$R^{herm}_{B_1,B_2}(i,j) =< b_1.b_2^* >_{ij}$$

The use of both the complex correlation and the IHP between the 2 sub-bands obtained after the azimuth sub-aperture decomposition, is a good candidate to detect and then characterize strong scatterers: the pixels for which the two sub-bands are well-cerrelated.

Transinformation

Suppose B is a random variable which takes values b in the set Ω according to a probability distribution P_B. The entropy of this probability distribution is defined as:

$$H_B = \sum_{b \in \Omega} -P_B(b) log_2(P_B(b))$$

For two variables B_1 and B_2, the joint entropy H_{B_1,B_2} is similarly defined through the joint probability function P_{B_1,B_2}. The transinformation between B_1 and B_2 is given by:

$$I_{B_1,B_2} = H_{B_1} + H_{B_2} - H_{B_1,B_2}$$

As mentioned in [5], the transinformation is considered as one of the most useful and important measures of information. Indeed, this is a measure of how much information can be obtained about one random variable B_1 by observing another B_2. It is null for two independent random variables. In the case of 2 images, it is demonstrated that:

$$I_{B_1,B_2} = \frac{1}{cardS} \sum_{s \in S} i_{B_1,B_2}(b_{1_s}, b_{2_s})$$

where:

- b_i: the observed realization of the random variable B_i for site s
- S: the considered set of pixels
- i_{B_1,B_2}: the mutual information defined as:

$$i_{B_1,B_2}(b_{1_s}, b_{2_s}) = -log_2(\frac{p_{B_1}(b_1) p_{B_2}(b_2)}{p_{B_1,B_2}(b_1, b_2)})$$

It is noted that $i_{B_1,B_2}(b_{1_s}, b_{2_s})$ represents the contribution of the site s to the I_{B_1,B_2}.

Hausdorff distance

The Hausdorff distance is a measure of the resemblance of two sets of geometric points (2 sub-bands in our case). It is the maximum distance of a set to the nearest point in the other set. More formally, Hausdorff distance from set (sub-band) B_1 to set B_2 is a maximum function, defined to be the quantity:

$$H_{B_1,B_2}(i,j) = \max_{b_1^{ij} \in B_1^{ij}} \{ \min_{b_2^{ij} \in B_2^{ij}} \{d(b_1^{ij}, b_2^{ij})\}\}$$

where:

- B_k^{ij}: a vicinity of the pixel (i,j) in the sub-band B_k
- b_k^{ij}: point of the complex set B_k^{ij}
- $d(b_1, b_2)$: a distance metric, usually the Euclidean distance

It turns out that through H_{B_1,B_2}, we not only learn what is common between the 2 sets but also better understand the differences.

RESULTS AND DISCUSSION

The figure 2 shows both the original SAR image and its sub-looks obtained after a two sub-band decomposition in the azimuth direction.

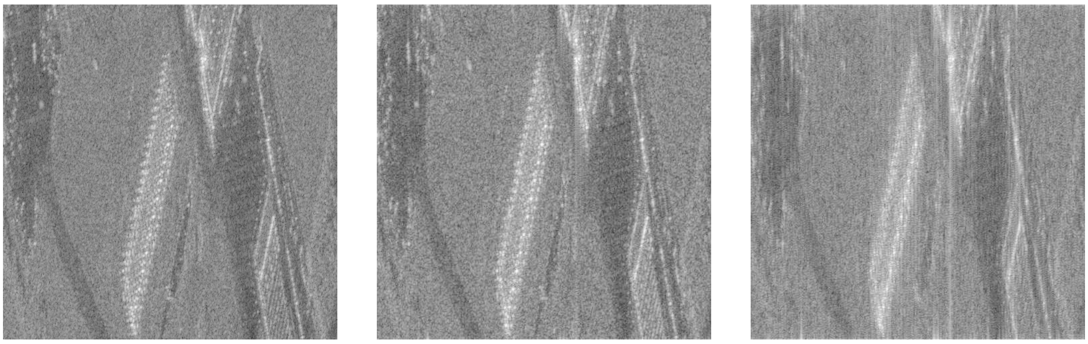

Figure 2. From left to right: original image, left sub-band and right sub-band obtained after a 2-sub-band azimuth decomposition.

The previously introduced automatic measures (complex correlation, IHP, transinformation, mutual information, Hausdorff distance) are displayed on the sub-bands of the figure 2. The results are shown in figure 3. For the complex correlation, the IHP and the Hausdorff distance, the averaging was conducted on a 7×7 cross-sized window, while the transinformation on a 64×64 cross-sized window.

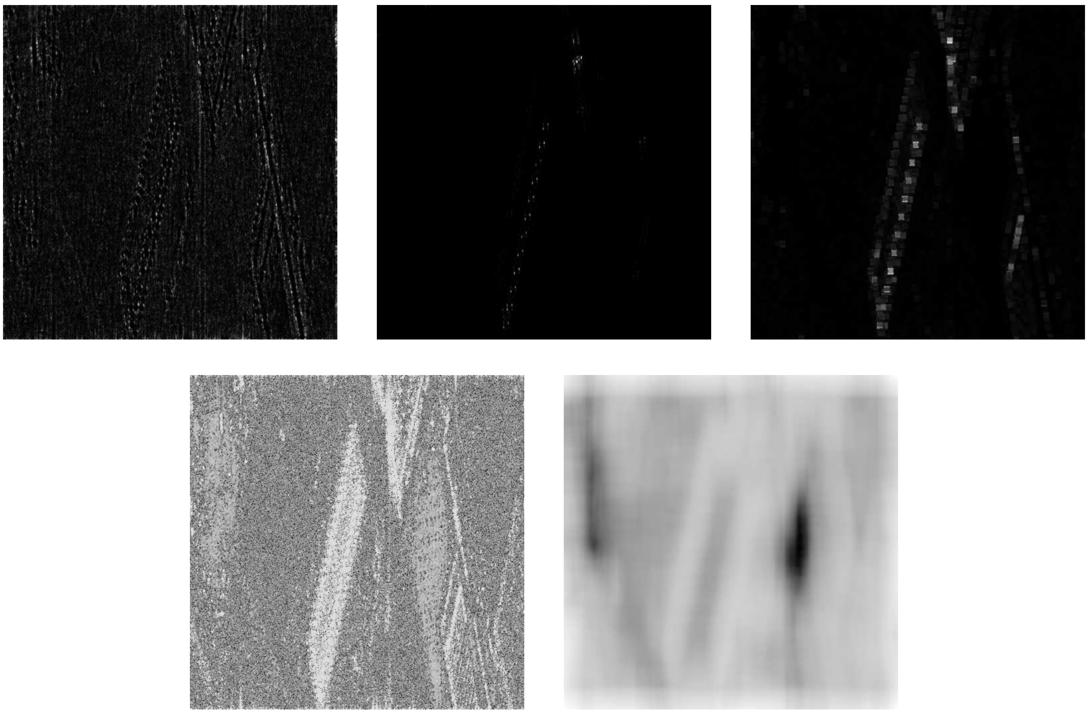

Figure 3. From left to right and top to bottom :the Complex correlation, the IHP, the Hausdorff distance, the mutual information and the Transinformation, computed between the 2 sub-bands.

From the figure 2, we can notice the following phenomenas:

- **Loss or fading of some structures in the sub-band images:**
  The right sub-band of the SAR image has a blurred aspect. In fact, the metallic structures have lost some particularities and shapes, according to the original image. This is the case of the structures whose backscattering depends on the relative direction of the incidence wave and the object.
- **Arise of some details which were not in the original images:**
  A vertical line between the two buildings has different appearances depending on the sub-bands. It was already in the original image but it has a stronger backscattering in both of the sub-bands.
- **Low directivity of the corner reflectors:**
  The corner reflectors wall/ground of the buildings appear in all the sub-bands with a high amplitude. In fact, their backscattering does not depend on the orientation of the sensor.

The interpretation of the figure 3 could be conducted following 2 different aspects, linear and statistical:

- **Linear aspect:**
  Most of the bright points showing up in both the complex correlation and the Hausdorff distance correspond to real strong scatterers (the contour of the buildings), according to the original SAR image. With the IHP, the strong scatterers are more distinguishable and the estimation noise is critically reduced. In fact, the complex correlation (with normalization) of the estimation noise is so close to zero (its theoretical value), that the later is estimated on a big number of samples, which may attenuate a target response. But, the use of the IHP makes the amplitude of the estimation noise smaller and the one of the target bigger. Thus, the contrast between natural targets and their surrounding environment (estimation noise) will be higher, which could be very useful for target detection. However, the IHP works properly only if the target response remains constant in magnitude and in phase throughout the whole illumination time, which is the case of strong scatterers. This discrimination between targets and noise is obviously illustrated by the three-dimensional layout of both the complex correlation and the IHP displayed in figure 4.

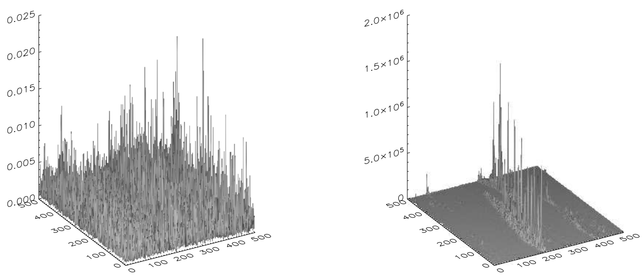

Figure 4. From left to right: three-dimentional layout of the complex correlation and the IHP.

Focussing on build areas, it is worth to note that linear structures are also well preserved by both the IHP and the Hausdorff distance. It might signify that these linear structures look like point targets along one of their dimension, with not more than one dominant scattering center per resolution cell.

- **Statistical aspect:**
When dealing with the mutual information i_{B_1,B_2}, it is obvious that the strong scatterers appear as very bright points. In fact, the joint probability function p_{B_1,B_2} becomes higher when it is computed between a couple of pixels with close radiometry, which is the case for the strong scatterers, such as corner reflectors. On the other hand, the very small mutual information values are obtained for structures which disappear from one band to another (structures for which the joint probability is small).
The transinformation I_{B_1,B_2} can be considered as an averaging of the mutual information. Unlike i_{B_1,B_2} which is calculated in each pixel, I_{B_1,B_2} is computed globally on the image. It gives robust results when dealing with reflectors, whose behavior is similar in the vicinity of the considered pixel, which is the case of strong scatterers. Indeed, it is clear that these scatterers (such as roofs) correspond to very bright points in the transinformation image.

CONCLUSIONS

The purpose of this paper was to present five automatic measures in order to be able to make a good strong scatterers detection and characterization. Our method was based on azimuth sub-aperture decomposition. This method provide extra-information than when dealing directly on the SAR single look complex image. This extra-information was useful to get a better characterization of the strong scatterers. Five measures of strong scatterers recognition were proposed: complex correlation, IHP, mutual information, transinformation and Hausdorff distance. Each one of these measures has its advantages and its drawbacks, but a combination of the five could be a powerful target descriptor.

These results could be used to undergo the next steps in the high resolution SAR ATR system: predict, extract, match and search processing steps.

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