Simulations and experiments on bistatic Synthetic Aperture Radar

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Abstract: SAR images are used in many applications which highlight the monostatic configuration limitations. Thus, we study in this paper a new imaging scheme: the bistatic configuration which seems to overcome some of the monostatic limitations. In order to validate the interest of this particular geometrical configuration, we developed a bistatic SAR simulator and validated the obtained results by experiments in an anechoic chamber.

Keywords: SAR, Bistatic SAR simulations, Bistatic ISAR experimentations.

1. Introduction

Synthetic Aperture Radar (SAR) is one of the most significant advance in radar systems. This processing is used to image targets. The synthetic aperture radar imaging principle consists in using the antenna displacement for simulating an antenna of sufficient size to obtain high resolution radar images [1]. This technique is very useful since it doesn't depend on the weather condition. Indeed, radars use electromagnetic emissions with sufficiently large wavelength so that it is not very sensitive to the clouds and the fog, and sufficiently small to be able to be concentrated and directed by metal reflector, or to cross the ionosphere. Moreover, radar waves may describe drifted ices in aquatic surfaces; they can penetrate vegetation and even slightly into the basement.

This kind of radar images has been largely studied and gives additional information on the targets than optical imaging techniques, especially in warfare context. But, the multiplication of stealth targets and a need for more accurate observation imply the search for new radar imaging configuration and processing.

A scheme who answers to this problem is the bistatic case. A bistatic radar configuration is presented by Willis in [2]. Basically, bistatic radar operate with separated transmitting and receiving antennas (figure 1).

Of course, the transmitting antenna can be monostatic, that is transmitting and receiving, and consequently it is possible to join monostatic and bistatic data reflected by common covered areas. This configuration has been known for a long time, but it was not used due to its complexity. Bistatic data acquisition should provide additional qualitative and quantitative measurements of surface microwave scattering properties [3][4]. The potential of bistatic measurements for detecting low-observable targets motivates its studies. For example, targets designed to minimize backscatter (monostatic scattering) by reflecting radar energy into other directions might be easily detected by a bistatic system. Moreover, the bistatic configuration can be used when the user (receiver) does not wish to be detected and use some opportunity illuminator [5].

Figure 1 : Bistatic radar geometrical configuration with one transmitter (E) and two receivers (R₁ et R₂)

2. Bistatic SAR

First, we interest in the received signal of a bistatic configuration in the general case, presented in [6], where the transmitters, the target and the receiver are moving. If we interest in the polarimetric case, the electromagnetic field can be describe by the Jones vector which takes into account the horizontally and vertically polarisation.

The signal radiated by an antenna is written as a vectorial formulation by multiplying the transmitting radiation matrix [gᵣ] by the transmitted waveform S(t) and the transmitting Jones vector qₑ depending on whether the transmitting antenna is vertically or horizontally polarized.

\[ E^+(t) = E_0 S_0(t) \cdot [g^+] \cdot qₑ \]  

where \( E_0 \) is the electromagnetic field amplitude.

Then, the receiving electromagnetic field can be expressed from the transmitting electromagnetic wave and the scattering matrix as follow:

\[ \vec{E}^-(t) = [S] \cdot \vec{E}^+(t) \]  

The scattering matrix \([S]\) depends on the geometrical and physical features of the target. It is function of the target observation angles and of the transmitted wave frequency.

The detected voltage at the receiving antenna is then:

\[ V(t) = \vec{q_r} \cdot [g^+] \cdot \vec{E}^-(t) \]  

where:
- \( \vec{q_r} \) is the receiving Jones vector
- \( [g^+] \) is the receiving antenna radiation pattern

The general expression of the detected voltage is:

\[ V(t) = \frac{E_0 S_0(t) - \delta_{ER}(t)}{c} \cdot \frac{\vec{q_r} \cdot [g^+] \cdot [S] \cdot [g^+] \cdot \vec{E}^+(t)}{\delta_{CR}(t) + \delta_{EC}(t)} \]  

where \( \delta_{ER}, \delta_{CR} \) and \( \delta_{EC} \) represent respectively the transmitter-receiver, the target-receiver and the target-receiver propagation time.
Now, we interest in the SAR imaging system. In the monostatic configuration (figure 2), the radial and azimuth resolutions depend on the geometrical configuration and on the emitted signal. If the emitted signal is a chirp with a carrier frequency $f_0$ and a bandwidth $\Delta f$, the radial and azimuth resolution can be expressed as follow [1] [7]:

$$\Delta R_{\text{rad}} = \frac{c}{2\Delta f \cos(\phi)}$$  \hspace{1cm} (5-a)$$

$$\Delta R_{\text{azi}} = \frac{\lambda}{2\gamma}$$  \hspace{1cm} (5-b)

where $c$ is the light velocity, $\lambda$ the wavelength for the carrier frequency, $\gamma$ the angle subtended by the synthetic aperture and $\phi$ the look angle.

In bistatic configuration, the resolutions expressions are more complex [8]. As in the monostatic case, the bistatic SAR resolution strongly depends on the signal bandwidth and on the size of the synthetic antenna, but one particularities of the bistatic case relies on the strongly effects of the geometrical parameters on the resolutions.

In this paper, we limit our study in the case of a bistatic SAR system with a stationary receiver as show in figure 3. In this figure, $T_r$ is the transmitter moving with a velocity $V$, $T_a$ is the target located on the ground plane $XY$ and $R$ is the receiver. $\beta$ is the bistatic angle, $(B)$ is the bistatic bisector, $(B_{XY})$ is the projection of $(B)$ on the $XY$ plane and $\phi_B$ is the angle between $(B)$ and $(B_{XY})$. $V_{||}$ and $V_\perp$ are respectively the orthogonal components of $V$ in the directions parallel and perpendicular to $(T_aT_r)$, $\phi_A$ is the angle between $V_\perp$ and its projection on the $XY$ plane and $(A_{XY})$ is the line in the $XY$ plane which passes through the target and which is parallel to $V_{\perp XY}$. The resolution determined by the signal bandwidth and the size of the aperture are respectively expressed in the direction $(A_{XY})$ and $(B_{XY})$. This two directions are the line in the $XY$ plane which pass through the target and are perpendicular to $(A_{XY})$ and $(B_{XY})$ respectively [8]. In this configuration, the bistatic SAR resolutions are given by:

$$\Delta R_{\text{rad}}(A_{XY}) = \frac{c}{2\Delta f \cos(\beta/2) \cos(\phi_A) \cos(\alpha)}$$  \hspace{1cm} (6-a)$$

$$\Delta R_{\text{azi}}(B_{XY}) = \frac{\lambda}{\gamma \cos(\phi_A) \cos(\alpha)}$$  \hspace{1cm} (6-b)

where $\alpha$ is the angle between $(A_{XY})$ and $(B_{XY})$ and between $(B_{XY})$ and $(A_{XY})$. Independently with the configuration, we note that the azimuthal resolution ($\Delta R_{\text{azi}}$) is two times less than the monostatic SAR, this is due to the fact that here the Doppler shift is only caused by the transmitter motion.

Note that the transmitter, target and receiver positions will strongly influence the resolutions [9].

In the case of a moving receiver, a new component is introduced due to the receiver aperture and a complete study of the configuration is necessary [10].

3. Simulations

Our objective is to propose an algorithm for bistatic radar imaging in order to validate the interest of this configuration. We developed a bistatic SAR simulator starting from monostatic SAR algorithms. Monostatic SAR images are obtained in two principal stages : distance processing followed by a transverse processing.

With regard to the bistatic imagery, to carry out the bistatic radar imaging processing, it is first necessary to know precisely the complete radar link, and specially the bistatic geometrical configuration which is the main difference with the monostatic SAR case. In fact, the image formation needs to take into account a lot of elements : the coordinates and velocities of each entities (transmitter, target, receiver), antenna’s diagrams, wave interaction with the atmosphere, the shape of the emitted signal. Moreover, bistatic observation requires accurate time synchronisation and antennas pointing between transmitter and receiver.

In our simulations, we used the received signal, described by equation (4), for a general polarimetric bistatic radar configuration when the transmitter, the target and the receiver are moving. The processing chain is presented in figure 4.

The acquired data can be expressed by $s(t,u)$ where $u$ is the acquisition number and $t$ is the during time acquisition. The first stage consists in readjusting the received signals in order to compensate the transmitter-target-receiver distance variation during the acquisition. To do that we multiply in the frequential field each acquisition by $e^{-j\gamma(Dt + Dr)t}$ where $Dt$ corresponds to the...
transmitter-target distance compensation and \(Dr\) corresponds to the target-receiver distance compensation. Since we work with high bandwidth signals, then, we carry out a matched filtering on each acquisition in order to improve the range resolution. The reference signal used to the matched filtering is the emitted signal \(s_e\) for each acquisition and we obtain:

\[
s(x, u) = \int_{-\infty}^{\infty} s_e^*(t-t', u) s(t', u) dt'
\]

where \(x = c t\).

Finally, we use the Doppler shift caused by the transmitter and receiver motions in order to carry out a transverse matched filtering. Thus, the referenced signal will depend on relative speeds between the transmitter and the target \(v_t\) and the relative speeds between the receiver and the target \(v_r\).

\[
s(x, y) = \int_{-\infty}^{\infty} s_r(x, y' - y) s(x, y) dy'
\]

where \(s_r\) is:

\[
s_r(x, u) = e^{-2\pi i f_s u} (v_t(u) - v_r(u))u
\]

Following this theoretical considerations, we implemented our SAR simulator. First, we consider the monostatic configuration and our first work was to compare the resolution obtained by our simulations with the theoretical ones. The configuration used was: one isotropic target located at \((15,15,0)\) in the \((X,Y,Z)\) coordinate system; emitter/receiver co-located at \((0,-5000,2000)\); emitter/receiver velocity \((100,0,0)\); observation time 0.3s; carrier frequency 5 GHz; bandwidth 60 MHz.

<table>
<thead>
<tr>
<th>Emitter/receiver location</th>
<th>((0,-5000,2000))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emitter/receiver velocity</td>
<td>((100,0,0))</td>
</tr>
<tr>
<td>Observation time</td>
<td>0.3 s</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>5 GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>60 MHz</td>
</tr>
</tbody>
</table>

**Table I: Radar parameters**

In this configuration, the theoretical resolutions given by equation (5) are: \(\Delta R_{\text{rad}} = 2.7\) m and \(\Delta R_{\text{azi}} = 5.4\) m.

**Figure 5: Measured range and cross-range resolution on simulated data**

The simulated results (figure 5) give the same value than the theoretical ones, which prove the validity of our algorithms from the resolution point of view.

Secondly we interest in a scene with three isotropic scatter centers, with location chosen to highlight some monostatic SAR limitations. The targets location at the ground plane are is given in table II.

<table>
<thead>
<tr>
<th>Target 1</th>
<th>Target 2</th>
<th>Target 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>y</td>
<td></td>
</tr>
<tr>
<td>10.15</td>
<td>15.77</td>
<td>20</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>21.54</td>
</tr>
</tbody>
</table>

**Table II: Targets location in the \((X,Y)\) plane (in m)**

Firstly, we observe this scene with the radar parameters given in table I, and the obtained transverse resolution was worse than the distance resolution as illustrated on figure 9-a. Indeed, the azimuth resolution depend of the synthetic antenna size and it is not always possible to have an antenna of the sufficient size. Secondly, we show that with particular geometrical configuration some targets can be partially or completely masked by other. For example, if we observe the preceding scene with a radar on the ground, i.e. a initial radar position: \((0, -5000, 0)\), in this case the target 3 will be masked by the target 2. The masked target will not be present in the constructed image or will appear with a less intensity (figure 10-a).

Thirdly, we interest in a bistatic configuration. We observe the scene given by table II with a stationary receiver at \((0,0,0)\) and two moving transmitters: first transmitter position \((0,-5000,0)\); first transmitter velocity \((100,0,0)\); second transmitter position \((-5000,0,2000)\); second transmitter velocity \((0,100,0)\) (figure 6). In this two case the observation time was 0.4s.

**Figure 6: Bistatic simulation for three isotropic scattering centers**

The obtained images with the first and the second transmitter are given in figure (7-a) and (7-b) respectively. After fusion, we obtain the figure (7-c) which makes it possible to find a better targets location.
Finally, we interest in a multi-view configuration, i.e. a monostatic SAR that observes the same target under two distinct angles (figure 8). This configuration will enable us to answer some monostatic SAR limitations. Indeed, the data fusion allow amongst other things to solve resolution and masking problems highlight previously. More this configuration enable us to compare our simulator results with the experiments carried out in the anechoic room (see §3).

![Figure 8: Multi-view configuration](image)

From resolution point of view, the obtained images with this two observations are given in figure (9-a) and (9-b) respectively. The fusion of this two acquisitions will then make it possible to obtain an image with a better resolution as illustrated on figure 9-c ($\Delta R_{rad} = 2.7$ m and $\Delta R_{azi} = 5.4$ m for figure 9-a and 9-b vs. $\Delta R_{rad} = 2.3$ m and $\Delta R_{azi} = 2.3$ m for figure 9-c).

![Figure 9: Multi-view simulation results for three isotropics scattering centers](image)

In the same way, the observation under two different angles will make it possible to find all the targets when some are masked by other one (figure 10).

![Figure 10: Partially masked target simulation results for three isotropic scatters](image)

Simulations carried out previously show the interest in observing targets under various angles and thus confirm the interest of using multistatic configurations.

3. Experiments on multi-view ISAR configurations

To illustrate the interest of the bistatic radar imaging configuration presented in the previous section, real data were obtained in the anechoic chamber of ENSIETA (Brest, France) for three spherical isotropic scatterers, made by metallic spheres and positioned as follow :

![Figure 11: geometrical positions of the three spherical isotropic scatterers used for real data acquisition](image)

Figure 12 illustrates our measurement system. This system is controlled by a PC which allow a very smooth operation using the Labview software.
Figure 12: Experimental set-up

The vectorial network analyzer is a WILTRON 360 type and it can operate in 10MHz – 18Ghz range. This analyzer controls the frequency synthesizer and guides the generated signal to the Cornet antenna (2Ghz – 18Ghz effective range). The reflected signal is received with an identical antenna and is amplified with a MITEK low noise amplifier (6 Ghz – 18 Ghz effective range).

A frequency stepped signal was used in the acquisition phase. Each data snapshot has been obtained for 128 frequency steps of \( \Delta f = 50 \) MHz, uniformly swept over the band \( B=[11.65;18] \) GHz. Consequently, the slant range resolution and ambiguity window are given by:

\[
\Delta R_{\text{sl}} = \frac{c}{2B} = 2.3 \text{ cm}
\]

\[
W_{\text{sl}} = \frac{c}{2\Delta f} = 3 \text{ m}
\]

The target was successively illuminated on two \( \Omega = [86°;94°] \) and \( \Omega = [86°;94°] \) degrees intervals centered respectively on 0° and 90° target presentation angles, and with an angular increment of \( \Delta \alpha = 0.5° \). Thus, the cross-range resolution and ambiguity window are given by:

\[
\Delta R_{\text{azi}} = \frac{\lambda_{\text{mean}}}{2\Omega} = 7.2 \text{ cm}
\]

\[
W_{\text{azi}} = \frac{\lambda_{\text{mean}}}{2\Delta \alpha} = 1.14 \text{ m}
\]

Table III: Experimental conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target diameter</td>
<td>30 mm</td>
</tr>
<tr>
<td>Scatterers coordinates</td>
<td></td>
</tr>
<tr>
<td>(relatively to the rotation</td>
<td></td>
</tr>
<tr>
<td>axis, in meters)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \left( \begin{array}{ccc} 0.125 &amp; 0.0785 &amp; 0.125 \ 0 &amp; 0.1175 &amp; 0.0785 \ 0 &amp; 0.1175 &amp; -0.1175 \end{array} \right) )</td>
</tr>
<tr>
<td>Frequency band</td>
<td>( B=[11.65;18] ) GHz</td>
</tr>
<tr>
<td>Frequency increment</td>
<td>( \Delta f = 50 ) MHz</td>
</tr>
<tr>
<td>Angular excursion</td>
<td>( \Omega = [86°;94°] ) and ( \Omega = [86°;94°] )</td>
</tr>
<tr>
<td>Angular increment</td>
<td>( \Delta \alpha = 0.5° )</td>
</tr>
<tr>
<td>Range resolution</td>
<td>( \Delta R_{\text{sl}} = \frac{c}{2B} = 2.3 \text{ cm} )</td>
</tr>
<tr>
<td>Range ambiguity window</td>
<td>( W_{\text{sl}} = \frac{c}{2\Delta f} = 3 \text{ m} )</td>
</tr>
<tr>
<td>Cross-range resolution</td>
<td>( \Delta R_{\text{azi}} = \frac{\lambda_{\text{mean}}}{2\Omega} = 7.2 \text{ cm} )</td>
</tr>
<tr>
<td>Cross-range ambiguity window</td>
<td>( W_{\text{azi}} = \frac{\lambda_{\text{mean}}}{2\Delta \alpha} = 1.14 \text{ m} )</td>
</tr>
</tbody>
</table>

Figure 13 illustrates the ISAR imaging processing for a stepped frequency (SF) waveform [11].

The radar transmits a sequence of \( N \) bursts. Each burst consists of \( M \) narrow band radio pulses. Within each burst, the center frequency \( f_m \) of each successive pulse is increased by a constant step \( \Delta f \). The total bandwidth of the burst, i.e., \( M \) times the frequency step \( \Delta f \), determines the radar range resolution. The total number of bursts \( N \) for given imaging time duration determines the Doppler or cross-range resolution. The returned pulse is heterodyned and quadrature detected in the radar receiver. To form a radar image, after measuring the returned in-phase (I-channel) and quadrature-phase (Q-channel) signals at base band with a pulse repetition rate at \( M \times N \) time instants \( t_{m,n}=(m+nM)\Delta t \), the \( M \) by \( N \) complex data are organized into a 2-D array which represents the unprocessed spatial frequency signature of the target \( S(f_{m,n}) \) where \( m=0...M-1 \), \( n=0...N-1 \) and \( \Delta t \) denotes time interval between pulses.

The radar processing algorithm uses the frequency signatures as the row data to perform range compression and the standard motion compensation.
For the Stepped-Frequency signals, the range compression performs an M-point Inverse Fourier Transform for each of the N received frequency signatures as:

\[ G(r_{m,n}) = IFT_m \{ S(f_{m,n}) \} \]  

(10)

IFT<sub>m</sub> denotes the Inverse Fourier Transform operation with respect to the variable m.

Therefore, N range profiles (i.e. the distribution of the target reflective points in range), each containing M range cells, can be obtained. At each range cell, the N range profiles constitute a new time history series. Then, the motion compensated range profiles become \( G(r_{m,n}) \), \( m=0\ldots M-1 \), \( n=0\ldots N-1 \). Notes that in our experimental conditions this motion compensation processing is not necessary.

The Fourier imaging approach takes the fast Fourier transform of the time history series and generates an N point Doppler spectrum, as Doppler profile. By combining the N Doppler spectra at M range cells, finally, the M by N image is formed:

\[ I(r_m, f_n) = FFT_n \{ G(r_{m,n}) \} \]  

(11)

Therefore, the radar image \( I(r_m, f_n) \) is the target’s reflective points mapped onto the range-Doppler plane [12].

Because the target is illuminated under a discrete angular range and with a discrete frequency set, the complex measured samples are in polar coordinates. The 2-D Fourier transform can be applied to the data set only if the sampling of the arguments is uniform. This is true in polar coordinates (\( \theta, f \)), but not in the rectangular coordinates system, as it can be observed in figure 14. So, it is necessary to interpolate the initial data for achieving an artificial sampling set in an rectangular \(( k_x, k_y )\) coordinates system. Then, the radar target image is obtained when the 2-D Fourier transform is applied to the interpolated data.

\[ \text{Figure 14 : Measured data in polar coordinates and interpolated data in Cartesian coordinates} \]

This two dimensional Fourier processing was used to construct the 2D radar image of the target described above and the results are presented on the following pictures.

\[ \text{Figure 15 : 2D radar image of the target} \]

\[ a) 0^\circ \text{ presentation angle} \quad b) 90^\circ \text{ presentation angle} \]

In this picture we find the same characteristic than with our simulator (resolution, masked targets). This experimental results thus confirm the observation made on our simulated results.

4. Conclusion

In spite of many potentialities and applications, monostatic SAR imaging presents now some limitations especially for stealth targets detection or in electronic warfare context. The need of new radar imaging configuration conduct to develop more complex scheme. First we interest in a multi-view configuration, but this configuration is expensive (we need transmitter and receiver for each acquisition) and it doesn’t answer to all monostatic SAR limitation like stealth targets. So we study a bistatic radar configuration for imaging targets. We assessed here, by our simulations and experiments, some potentialities of the proposed bistatic imaging system. The fusion of the obtained data by the simultaneous acquisition of different transmitters enables us to obtain relevant information on the observed target. It is for example possible to reveal hidden target by other or to improve the resolution when the integration time was too short.

In order to complete this study we plan to observe more complex targets (dihedrals, ellipsoids) to compare monostatic and bistatic target signatures. We will also interest in the sea surface characterisation. We saw that the resolution in bistatic configuration can be worse than in monostatic configuration. So, a more precise study of a multistatic configuration will allow to improve the bistatic resolution and to obtain a three-dimensional target visualisation.

5. References


