Advances in Bistatic Inverse Synthetic Aperture Radar

(Invited Session on Advances in Inverse Synthetic Aperture Radar)

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Abstract—Bistatic geometries are enabled in scenarios where multiple separated transmitters and receivers are employed as well as when illuminators of opportunity are exploited. Bistatic Inverse Synthetic Aperture Radar (B-ISAR) becomes the radar imaging tool for obtaining non-cooperative target images in arbitrary bistatic configurations. Theoretical aspects and real data experiments have been conducted in recent years that have proven the effectiveness of B-ISAR. A review of both theory and results is provided in this paper and new perspectives are indicated.

I. INTRODUCTION

A significant amount of interest has been given to bistatic radar imaging in recent years; specifically to Bistatic Synthetic Aperture Radar (BiSAR). Theoretical aspects have been developed and experiments conducted that have demonstrated the capabilities of BiSAR systems. It will not be long before a BiSAR imagery will be consistently produced [1].

Bistatic radar imaging of non-cooperative targets and, in a more general sense, bistatic radar imaging that rely on the target motion, such as Bistatic Inverse Synthetic Aperture Radar (B-ISAR) has also progressed in the last years, pushed by the need of exploiting the availability of multiple sensor systems. Such systems tend to minimise the number of transmitters by using multiple receivers that exploit the signal transmitted by one or more platforms. In order to function, such systems must be able to form B-ISAR images.

The main difference between BiSAR and B-ISAR, as with SAR and ISAR, is the fact that the target motion provides a significant contribution to the image formation process; and this motion is, in general, not known a priori. This subtle difference causes major problems when defining suitable image formation algorithms.

In this paper, the latest results in the area of B-ISAR are summarised and future developments are indicated.

II. BISTATIC GEOMETRY AND SIGNAL MODELLING

In this section the terminology and theory for Bistatic ISAR imaging is introduced.

Bistatic Geometry

The geometry of the problem is illustrated in Fig. 1. In order to consider the most generic case, let Radar A and Radar B be two radars that can transmit radar signals and receive the reflected signals from either radar. In this case, three potential radar configurations can be obtained:

1) Monostatic configuration, Radar A: i.e. Transmit and receive using Radar A;
2) Monostatic configuration, Radar B: i.e. Transmit and receive using Radar B;
3) Two equivalent bistatic configurations (BI) involving either Radar A as the transmitter and Radar B as the receiver or vice versa.

Signal Modelling

After suitable signal pre-processing [2], including motion compensation, the received signal, for a generic radar configuration, can be written in a time-frequency format as follows:

$$S_R(f, t) = W(f, t) \int_V \zeta(x) e^{j\varphi(x, f, t)} dx$$  \hspace{1cm} (1)

where $W(f, t) = \text{rect}\left(\frac{t}{T_{obs}}\right) \text{rect}\left(\frac{f - f_0}{B}\right)$, $f_0$ represents the carrier frequency, $B$ is the transmitted signal bandwidth, $T_{obs}$ is the observation time, $V$ is the spatial region where the reflectivity function, $\zeta(x)$, is defined, and function $\text{rect}(x)$ yields 1 when $|x|<0.5$, and is 0 otherwise.

The phase term ($\varphi(x, f, t)$) in Eqn 1 is dependent on the radar configuration being considered. The phase terms relative to the three configurations, i.e. Radar A (MA), Radar B (MB) and the bistatic radar (BI), can be written as follows:
The term $K(t)$ carries information about the change in time of the bistatic geometry. This change in the bistatic angle during the coherent integration time significantly affects the B-ISAR image PSF. In this section the B-ISAR image PSF will be derived and the distortion introduced by the bistatic geometry will be related to the bistatic angle variation.

In deriving the PSF, two assumptions are made that will allow the application of the Range Doppler technique when reconstructing the ISAR image (following motion compensation). These two assumptions are: 1) far field condition, and 2) short integration time. These assumptions avoid the need for the consideration of non-constant target rotation vectors and the use of polar reformatting, and are generally satisfied in typical ISAR scenarios where the resolutions required are not exceptionally high.

When the target rotation vector is constant, the received signal backscattered by a single ideal scatterer located at a generic point may be rewritten (after motion compensation) in the following way:

$$S_R(f, t) = W(f, t) \int \int \zeta(x_1, x_2) e^{j\varphi_{BI}(x_{10}, x_{20}, f, t)} dx_1 dx_2$$

where:

$$\varphi_{BI}(x_{10}, x_{20}, f, t) = \frac{2\pi f}{c} \left[ R_{A}(t) + x \cdot i_{MA}(t) + R_{B}(t) + x \cdot i_{MB}(t) \right]$$

and where

$$K(t) = \left| \frac{i_{MA}(t) + i_{MB}(t)}{2} \right| = \cos \left( \frac{\theta(t)}{2} \right)$$

(5)

$$\theta = \arccos \left( i_{MA}(t) \cdot i_{MB}(t) \right)$$

(6)

In Eqs 2 - 7, $\theta$ is the bistatic angle, $c$ is the speed of light in free space, $R_A(t)$ and $R_B(t)$ are the distances between the two radars (Radar A and Radar B) and a focusing point $O$ on the target, $i_{MA}(t)$ and $i_{MB}(t)$ are the unit vectors that indicate the LoS for the two radars, and $x$ is the vector that locates a generic point on the target.

By substituting Eqs 2-4 into Eqn 1, the received signal model for the three configurations is obtained. The two monostatic configurations (MA and MB) can be treated in the same way in order to produce an ISAR image by means of any available ISAR technique. In fact, the two received signal models differ only in their aspect angle and their radar-target focusing point distance. The bistatic configuration (BI), whilst employing the same signal processing techniques, as its monostatic counterparts requires a little more attention. This is because the bistatic ISAR image is distorted by the bistatic geometry, as is indicated in the term $K(t)$ (Eqn. 5). An analysis of the effects of the bistatic geometry on the ISAR image Point Spread Function (PSF) follows.

### III. BISTATIC ISAR IMAGE FORMATION AND POINT SPREAD FUNCTION

The term $K(t)$ carries information about the change in time of the bistatic geometry. This change in the bistatic angle during the coherent integration time significantly affects the B-ISAR image PSF. In this section the B-ISAR image PSF will be derived and the distortion introduced by the bistatic geometry will be related to the bistatic angle variation.

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$$S_R(f, t) = W(f, t) \int \int \zeta(x_1, x_2) e^{j\varphi_{BI}(x_{10}, x_{20}, f, t)} dx_1 dx_2$$

where:

$$\varphi_{BI}(x_{10}, x_{20}, f, t) = \frac{2\pi f}{c} \left[ R_{A}(t) + x \cdot i_{MA}(t) + R_{B}(t) + x \cdot i_{MB}(t) \right]$$

and where the phase $\varphi_{BI}(x_{10}, x_{20}, f, t)$ may be written as:

$$\varphi_{BI}(x_{10}, x_{20}, f, t) = \frac{4\pi f}{c} \left[ K(t) \left( x_{10} \sin \Omega t + x_{20} \cos \Omega t \right) \right]$$

In Eqs 8 - 10, $\Omega$ is the target rotation vector, and $(x_{10}, x_{20}, x_{30})$ are the coordinates of a generic scatterer on the target with respect to a reference system centred on the target itself (see Fig. 1).

It is worth noting that the axis $x_3$ has been chosen in order to be coincident with the effective rotation vector [3]. This choice of reference system is arbitrary, yet it greatly simplifies the mathematical relations without introducing any new constraints.

Under assumptions 1) and 2) above, bistatic angle changes are relatively small, even when a target covers relatively large distances within the integration time. In particular, the bistatic angle can be well approximated with a first order Taylor (Maclaurin) polynomial:

$$\theta(t) \approx \theta(0) + \dot{\theta}(0)t$$

(11)

where $-T_{obs}/2 \leq t \leq T_{obs}/2$, and $\dot{\theta} = \frac{d\theta}{dt}$.

As a result, the term $K(t)$ can also be well approximated with its first order Taylor (Maclaurin) polynomial, and by using Eqn. 5 the following equation may be obtained:

$$K(t) \approx K(0) + K(t)0 t =$$

$$\cos \left( \frac{\theta(0)}{2} \right) - \frac{\dot{\theta}(0)}{2} \sin \left( \frac{\theta(0)}{2} \right) t = K_0 + K_1 t$$

(12)

Therefore, Eqn. 10 becomes:

$$\varphi_{BI}(x_{10}, x_{20}, f, t) = \frac{4\pi f}{c} \left[ (K_0 + K_1 t) \right.$$}

$$
\left. \left[ x_{10} \sin \Omega t + x_{20} \cos \Omega t \right] \right]$$

(13)

which for small integration angles (short integration time hypothesis) can be approximated as:

$$\varphi_{BI}(x_{10}, x_{20}, f, t) \approx$$
The ISAR image may be reconstructed by performing the following steps:

1) Radial motion compensation.
2) Image formation (by means of the RD technique)
   a) Range Compression: Fourier Transform (FT) along the frequency coordinate \( f \)
   b) Cross-range compression: FT along the time coordinate \( t \).

Radial Motion Compensation

In the absence of synchronisation errors, the radial motion compensation can be obtained by compensating the phase term \( \frac{2\pi f}{c} \left[ (K_0 + K_1 t) x_{20} \right] \). Any parametric or non-parametric technique used for monostatic ISAR is able to compensate this term with the desired accuracy [4].

Image Formation (derivation of the PSF)

After calculating the FT along the two coordinates, the B-ISAR system PSF is obtained, as shown in (15):

\[
PSF(\tau, \nu) = \int e^{-j \frac{2\pi f_0}{c} (K_0 + K_1 t) R_{\text{iso}} t_{10}} e^{j \omega t_{10}^0} \left[ \tau - \frac{2}{c} K_0 x_{20} \right] \otimes_\tau W(\tau, \nu) d\tau
\]

\[
= CH [\nu, \alpha_0, \alpha_1] \delta \left[ \tau - \frac{2}{c} K_0 x_{20} \right] \otimes_\tau \otimes_\nu w(\tau, \nu)
\]

where

\[
w(\tau, \nu) = BT_{\text{obs}} e^{-j 2\pi f_0 \tau} \text{sinc}(T_{\text{obs}} \nu) \text{sinc}(B \tau)
\]

\[
CH [\nu, \alpha_0, \alpha_1] = \text{FT} \left\{ ch [\nu, \alpha_0, \alpha_1] \right\}
\]

\[
ch [\nu, \alpha_0, \alpha_1] = e^{-j 2\pi (\alpha_0 + \alpha_1 \tau^2)}
\]

\[
\alpha_0 = \frac{2 f_0 \Omega_{x_{10}}}{c} \cos \left( \frac{\theta(0)}{2} \right)
\]

\[
\alpha_1 = -\frac{2 f_0 \Omega_{x_{10}}}{c} \sin \left( \frac{\theta(0)}{2} \right) \frac{\theta(0)}{2}
\]

and \( \otimes_\tau \) and \( \otimes_\nu \) are the convolution operator over the variables \( \tau \) and \( \nu \) respectively.

Therefore the PSF of Eqn. 15 can be rewritten as:

\[
PSF(\tau, \nu) = CH [\nu, \alpha_0, \alpha_1] \otimes_\nu w(\tau - \frac{2}{c} K_0 x_{20}, \nu)
\]

It is worth recalling that a convolution between an infinite duration chirp and a sinc function is equivalent to a FT of a finite duration chirp, where the parameter of the sinc function is equivalent to the duration of the chirp.

As can be seen from Eqs (18 - 20), the chirp rate depends on the position of the scatterer along the cross-range direction. The defocussing effect of a chirp signal on an ISAR image has been largely studied in [5], where a new technique was proposed that eliminated such effects.

Details about the limits of applicability of Range-Doppler to B-ISAR imaging have been studied in [6].

IV. SYNCHRONISATION ERRORS

Phase synchronisation errors can be modelled in terms of frequency errors, which will be addressed in this work as Frequency Jitter (FJ). The FJ that will be taken into consideration is composed of an offset \( \eta_0 \), a linear term \( \eta_1 t \) and a random term \( \delta F(t) \), as formalised in (22):

\[
\Delta f(t) = \eta_0 + \eta_1 t + \delta F(t)
\]

Eq. (4) is therefore modified by introducing the FJ term, as modelled in (23):

\[
\varphi_{BI}(x, f, t) = \frac{4\pi [f + \Delta f(t)]}{c} \left[ \frac{R_s(t) + R_B(t)}{2} + K(t) x \cdot i_{BI}(t) \right]
\]

In presence of FJ and bistatic angle changes, the distortion effects on the B-ISAR image cannot be separated into distortion induced by only the synchronisation error or by only the bistatic angle change, as highlighted by the analytical expression of the PSF in (24) when neglecting the FJ term \( \Delta f(t) \):

\[
PSF(\tau, \nu) = B \text{sinc} \left\{ B \left[ \tau - \frac{2}{c} K_0 x_{20} \right] \right\} \exp \left\{ -j 2\pi f_0 \tau \right\}
\]

\[
\otimes_\nu \delta \left[ \nu - \frac{2}{c} (f_0 - \eta_0) K_0 \Omega x_{10} \right]
\]

\[
\otimes_\tau D(\eta_0, \eta_1, K_0, K_1, x_{10}, x_{20})
\]

where

\[
D(\eta_0, \eta_1, K_0, K_1, x_{10}, x_{20}) = \int \exp \left\{ \frac{4\pi}{c} \left( \gamma_1 t + \gamma_2 l^2 + \gamma_3 l^3 \right) \right\} \exp \left\{ -j 2\pi \nu \tau \right\} d\tau
\]

and

\[
\gamma_1 = (f_0 + \eta_0) (K_0 \Omega x_{10} + K_1 x_{20}) + \eta_1 K_0 x_{20}
\]

\[
\gamma_2 = (f_0 + \eta_0) K_1 \Omega x_{10} + \eta_1 (K_0 \Omega x_{10} + K_1 x_{20})
\]

\[
\gamma_3 = \eta_1 K_1 \Omega x_{10}
\]

More details the effects of synchronisation errors on the B-ISAR image can be found in [7].
V. APPLICATION: EMULATED BISTATIC ISAR

In certain cases, such as over the open ocean, an Emulated Bistatic Radar (EBR) [8], [9], [10] configuration can be established. This may permit a B-ISAR image formation process on a monostatic platform, as shown in Fig. 2. An EBR system has the ability to provide both the standard monostatic radars (i.e. Radar A and Radar B) via the direct (MC in Fig. 2) and double indirect (EMC) paths and the bistatic radar element via the direct-indirect (EBC) path, without requiring either a secondary transmitter or receiver.

A. Emulated Bistatic SAR and signal phase noise

By using the sea surface multipath, as shown in Fig. 2, an EBR system is able to form both monostatic and bistatic ISAR images. The image quality of the EBC and EMC paths are, however, contingent on the the sea surface reflected signals maintaining coherence. Sea surface reflections have been employed in a number of detection systems in recent times, mostly for remote sensing purposes. These applications have demonstrated the coherence aspect of certain sea surface reflections (i.e. signals reflected in the specular and quasi-specular reflection region) [11], [12], [13], [14], [15].

In contrast with the true bistatic system discussed above, the principal difference of the EBR system is the source of the signal errors. Whilst FJ is no longer an issue, as there are no synchronisation difficulties between the transmitter and receiver, phase noise on the indirect paths (i.e. EBC and EMC) due to the sea surface is an issue that must be considered. Visual estimates of the effects due to phase degradation as a result of the roughened and moving sea surface may be taken from the Emulated Bistatic SAR [16] images in Figs. 3 - 6. In these figures, EB-SAR images of the Golden Gate bridge, taken with NASA’s Jet Propulsion Laboratory’s AIRSAR C-Band fully polarimetric radar, are displayed. In each figure, the left hand bridge image corresponds to the standard monostatic (MC) path, the middle bridge is from the bistatic (EBC) path and the right hand bridge is from the emulated monostatic (EMC) path.

As the target is static, and the standard monostatic image has formed correctly (i.e. the platform’s motion has been properly compensated), the causes of the image degradation present in the EBC and EMC path images may be isolated. As all other system effects are accounted for, the degradation of these images can only be a result of the roughened surface and the change in the surface during the coherent processing interval (i.e. first and second order surface motion effects). Whilst somewhat degraded, these images demonstrate that even without phase compensation of the sea surface effects, sufficient coherence to allow recognisable images to be formed is retained for, at least, some sea states.
Table I
RADAR PARAMETERS (SHIP)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>No of sweeps</td>
<td>256</td>
</tr>
<tr>
<td>No of transmitted frequencies</td>
<td>256</td>
</tr>
<tr>
<td>Lowest frequency</td>
<td>9.16 GHz</td>
</tr>
<tr>
<td>Frequency step</td>
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<tr>
<td>Range resolution</td>
<td>0.97 m</td>
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<tr>
<td>Target type</td>
<td>Bulk Loader</td>
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<tr>
<td>PRF/Sweep Rate</td>
<td>20 kHz / 78.13 Hz</td>
</tr>
</tbody>
</table>
ISAR. The bistatic angle change and synchronisation errors are two examples of problems that have been analysed in the recent years. The analytical derivation of the B-ISAR PSF in presence of bistatic angle changes and synchronisation errors suggests using parametric autofocusing techniques [7] and Time-Frequency Analysis (TFA) for Range-Doppler image formation [18]. Bistatic angle change estimation and compensation must also be investigated in order to improve image formation [18].

Results obtained in B-ISAR opens the way to multistatic ISAR imaging systems where a number of monostatic and bistatic configurations are enabled at the same time. Scenarios where multiple transmitters, including illuminators of opportunity, and multiple receivers will be exploited in order to obtain simultaneous multiview ISAR imaging and/or enhanced ISAR image capabilities, such as higher resolution images and 3D images.

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REFERENCES