Velocity-ISAR: On the Application of ISAR Techniques to Multichannel SAR Imaging

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Abstract—The U.S. Naval Research Laboratory (NRL) Multichannel Synthetic Aperture Radar (MSAR) consists of multiple receive channels arranged along the flight direction and is unique in its ability to measure and correct for radial motion at each pixel in the scene. A well-known algorithm for performing MSAR imaging, and which have we applied for the first time to data captured by an airborne system, is the Velocity Synthetic Aperture Radar (VSAR) algorithm. VSAR calculates the distribution of Doppler radial velocities associated with each pixel and subsequently compensates for the velocities in order to combat motion blur. However, as we demonstrate in this paper, the VSAR algorithm does not fully exploit the special structure associated with the motion dynamics of rigid bodies (including translational and roll-pitch-yaw motions) in maritime conditions. To this end we propose the use of Inverse Synthetic Aperture Radar (ISAR) based motion compensation techniques—in conjunction with velocity filtering—as a means of accomplishing this objective for MSAR imaging. After describing the rudiments of the NRL MSAR system and the basics of ISAR processing, we subsequently proceed to describe our proposed Velocity-ISAR (VISAR) imaging algorithm. We demonstrate the performance of our VISAR algorithm by imaging boats captured by our airborne NRL MSAR system; and highlight its relative advantages over VSAR in imaging maritime targets.

Keywords—Imaging; Synthetic Aperture Radar (SAR); Multichannel SAR (MSAR); Inverse SAR (ISAR); Velocity SAR (VSAR); Motion Compensation; Phase compensation

I. INTRODUCTION

Synthetic Aperture Radar (SAR) is a radar imaging modality wherein multiple pulses are transmitted from a moving platform such that the received signals are subsequently combined to form a high quality image of the ground-terrain of interest. A well-known limitation of the SAR imaging modality is the inability to distinguish between platform and scene motions, resulting in distortions and smearing in the formed image [1-3]. Numerous ways to mitigate this effect have been proposed over the past few decades [4-5], but the most elegant and robust of these approaches is simply to add additional antenna receive elements aligned along the flight direction [6-8]. We refer to such a radar imaging system as a Multichannel SAR (MSAR) radar. The additional receiver channels provide new and independent information about the scene that can be used to automatically correct for the underlying scene motion.

The system parameters of interest in MSAR are (i) the number of channels M , (ii) the ground range-to-platform speed ratio R/V_p and (iii) the total collection duration T . The collected data can then be sliced and processed in numerous ways to yield desired information and products. One such well-known processing approach, which we have applied for the first time (in this paper and in [13]) to data captured by an airborne system, is Velocity SAR (VSAR) [6].

In the VSAR approach, each MSAR channel is treated independently by coherently summing pulses across the whole collection T , as one would with a single channel SAR. This approach creates M images, one per channel. The next step is to perform a Fast Fourier Transform (FFT) for each pixel along the time stack. The result is a velocity profile (i.e. distribution of scatterer velocities) for each pixel location. In order to correct for the platform and target motion, we then shift each velocity component back to the origin and then sum the resulting images [6].

An important factor that directly impacts the performance of MSAR imaging is the maintenance of phase coherence of the various scatterers associated with each range bin (that impacts the quality of single channel imaging) and across channels (that impacts velocity filtering). When imaging rigid bodies undergoing motions in the general affine group, it is well known that ISAR imaging controls the phase error (associated with each range bin) much more effectively than generic SAR imaging techniques [9-10]. Furthermore, as explained in Section IV, this decrease in phase error also positively impacts the effectiveness of velocity filtering in sorting out the various scatterer velocities via the Discrete Fourier Transform (DFT) operator. Based on these and other insights described in this paper we accordingly define a new radar imaging modality called VISAR (Velocity ISAR) wherein ISAR processing, in conjunction with velocity based filtering, is leveraged to correct for motion artifacts in the final image.

After briefly introducing our NRL (Naval Research Laboratory) airborne MSAR system in the next section, we proceed to give a brief overview of ISAR imaging in Section III, a detailed description of our VISAR algorithm in Section IV, and experimental results in Section V wherein we demonstrate the effectiveness of the VISAR algorithm in imaging boats using the NRL MSAR system.

II. THE NRL MSAR SYSTEM

In September 2014, we successfully demonstrated an operational airborne MSAR system. Fig. 1 shows a schematic of our airborne system that was deployed for data collection of land and maritime targets. In addition we also have a ground based surrogate called Focused Phased Array Imaging Radar (FOPAIR), that we use for experimental purposes [11-12] and which can be used to emulate many aspects of the airborne MSAR [11-12].

The airborne MSAR system consists of two modularly constructed 16 channel sections from FOPAIR. This was the largest number of channels that could be sampled given the high data rate and still provide sufficient velocity resolution. To improve the system still further we used two independent transmitters, one of either end of the array to effectively double the number phase centers (and halving the minimum detectable velocity). This system provides up to 32 velocity bins from 1 to 20 m/s with a resolution of 0.7 m/s.

Each phase center of our MSAR system operates at X-band with a center frequency of 9.875 GHz and uses linear FM chirped waveforms with a bandwidth of 200 MHz to achieve a range resolution of approximately 0.7 m. The peak radiated power is 1.4 kW, while the aggregate pulse repetition frequency (PRF) of 25 kHz and pulse length of 6 μ s produce an average power of 210 W. The system flies on a Saab 340 aircraft using a belly-mounted radome with a nominal incidence angle of 70°.

All antennas are vertically polarized. During odd-numbered pulse repetition intervals (PRIs), the aft-mounted horn transmits an ‘up’ chirp, while during even PRIs, the fore-mounted horn radiates a ‘down’ chirp. During each pair of up-down PRIs, four of the 16 receive antennas are connected to a four-channel receiver and sampled by a high speed data recorder. After each pair of PRIs, a bank of microwave switches is reconfigured to connect the next group of four receive antennas to the receiver and data recorder. After a total of 4 up-chirp/down-chirp PRI pairs (320 μ s), this scan sequence is repeated. In this manner, 32 phase centers corresponding to each combination of transmit and receive antennas are generated and sampled at a per phase-center PRF of 3.125 kHz. This PRF is sufficient to allow production of 32 SAR images, one corresponding to each phase center, that are free from azimuthal (cross-range) ambiguities. Since the location of a given phase center is halfway between the corresponding transmit and receive antennas, the along track spacing between these phase centers is 5.24 cm, half the physical spacing between the receive elements. Note that given the spacing between the two transmit horns, four of the phase centers corresponding to the aft-mounted transmit horn are collocated with four produced by the fore-mounted horn. Thus the total number of independent phase centers is 28 with total length of 141.5 cm. Finally, in our current hardware configuration there is a slight offset in the center frequency between the up-chirp and down-chirp signals. Though this can be adjusted by post-processing, in our experimental results in Section V we focus only on the first 16 up-chirp phase centers.

Further details of our MSAR system and its performance are given in the companion paper [13].

III. ISAR IMAGING AND MOTION COMPENSATION

A fundamental problem in radar imaging is the control and compensation of the spatial migration of point-scatterers arising due to the relative motion between the radar and scene of interest [9-10]. Once this has been accomplished, the effective system can be approximately modeled as a linear shift-invariant transformation—thus rendering the resulting signals amenable to efficient Fourier analysis tools for the purposes of image formation.

Motion compensation refers to a set of techniques that are employed for accurately tracking the spatial migration of point scatterers in the scene during the imaging process. Autofocus refers to a subset of motion compensation techniques where the estimation of motion parameters is obtained purely from the radar data (i.e. without any extraneous knowledge of the radar imaging geometry). In this paper we are exclusively concerned with autofocus techniques in VISAR imaging.

Much of the insight into motion compensation issues in ISAR imaging of rigid bodies can be obtained by studying the scattering response of a single point scatterer in relative motion with respect to the sensing radar. Fig. 2 shows the geometry of radar imaging of a target [9-10]. The radar coordinate system is fixed and associated with the radar that illuminates the target. There is also a local coordinate system that is centered at the center of gravity (CoG) of the target and which subtends a (slow-) time varying angle θ with respect to the radar coordinate axis. Likewise the CoG associated with the target subtends a (slow-) time varying angle α with respect to the radar coordinate system. It is assumed that the angles α and θ vary on a pulse-to-pulse basis (slow-time t) i.e. are assumed to remain constant for a pulse duration.

Given this it is straightforward to show that under the far-field approximation, the received signal due to the point scatterer has the following form [9-10]:

$$s_R(t) = \exp\left(-\frac{j4\pi f_0 R(t)}{c}\right) \iint_{-\infty}^{\infty} (\rho(x, y) \exp\{-j2\pi[xf_x(t) - yf_y(t)]\}) dx dy \quad (1)$$

Where,

$\rho(x, y) \equiv$ Unknown target reflectivity (to be estimated by the imaging algorithm)

$$f_x(t) = \frac{2f_0}{c} \cos(\theta(t))$$

$$f_y(t) = \frac{2f_0}{c} \sin(\theta(t))$$

$$f_0 \equiv \text{Carrier frequency}$$

$$R(t) = R_0 + v_0 t + \frac{1}{2} a_0 t^2$$

$$\theta(t) = \theta_0 + \Omega_0 t + \frac{1}{2} \gamma_0 t^2$$

$$c \equiv \text{Speed of light}$$

$$t \equiv \text{Slow-time}$$

Once the instantaneous range $R(t)$ is accurately tracked, we can see from (1) that the translational component of the relative motion, encapsulated in the multiplicative phase term $\exp\left(-\frac{j4\pi f_0 R(t)}{c}\right)$, can easily be compensated. This is the goal of the *range compensation* part of autofocus algorithms wherein the range profiles corresponding to the different

pulses are aligned by tracking the migration of a prominent point scatterer in the scene. There are many different approaches to range compensation in the literature [9-10] with various tradeoffs in terms of computational complexity and error stability. In the next section we describe the particular approach that we employed for range compensation in our application domain.

If perfect range compensation is performed then the resulting signal has the form:

$$s_R(t) = \iint_{-\infty}^{\infty} (\rho(x, y) \exp\{-j2\pi[xf_x(t) - yf_y(t)]\}) dx dy \quad (2)$$

In light of (1-2), we can see that perfect reconstruction of the target reflectivity $\rho(x, y)$ given $s_R(t)$ via the DFT operator entails that the spatial frequencies $(f_x(t), f_y(t))$ be stationary with respect to slow time—in other words that the phase of the each scatterer, associated with a range bin, be coherent within the observation interval. Note that this non-stationary structure in the Doppler return is due entirely to the rotational component of the target motion which, according to (1), consists of the rotation rate Ω_0 and acceleration rate γ_0 . Doppler tracking techniques aim to compensate for these finer sub-pixel migrations of the scatterers due to the effective rotational components of motion.

There are many different schemes for performing Doppler tracking including the sub-aperture approach, cross-range centroid tracking approach, and the PGA (phase gradient autofocus) [2, 9-10]. All these methods consider the Doppler frequency shifts of the target as a whole, and apply the same correction vector to all of the scatterers in the image. In the next section we describe a novel approach to Doppler autofocus that we employ for our VISAR algorithm.

When imaging targets in a 3D collection geometry, the ISAR image is formed by projecting the various scatterers onto the imaging plane that is defined by the cross-product of the LOS (line-of-sight) and the average rotation vector of the target during the observation interval. Given this the effective roll-pitch-yaw motion of a rigid body can be decomposed, as above, into its translational and rotational components.

Thus unlike backprojection algorithms [14]—of which all SAR imaging algorithms are approximations [15]—where the imaging plane is fixed *a priori* (typically to a fixed height below the plane and parallel to the flat earth), ISAR imaging dynamically changes the imaging plane based on the average 3D rotation motion of the rigid body during the observation interval. As we shall see in the next section, this has very important consequences in terms of enhancing the focusing ability of the ISAR algorithm relative to backprojection.

Finally we remark that the applicability of the above analysis to a large ensemble of scatterers hinges on the validity of the rigid body hypothesis by virtue of its imposition of important structural constraints on the space of possible motion dynamics and consequently on the structure of phase variations in the aggregate Doppler response.

IV. THE VISAR (VELOCITY-ISAR) ALGORITHM

To obtain deeper insight, we first generalize the analysis in Section III to a more realistic scenario in which there are errors in both range and phase estimations; and then explore its consequences in multichannel imaging.

First it is clear that the presence of residual errors in range estimation (due to limitations of range compensation algorithms) entails that the received signal at the m^{th} channel assumes the form:

$$s_R^m(t) = \exp\left(-\frac{j4\pi f_0 \Delta R^m(t)}{c}\right) \iint_{-\infty}^{\infty} (\rho(x, y) \exp\{-j2\pi[xf_x^m(t) - yf_y^m(t)]\}) dx dy \quad (3)$$

Where,

$$\begin{aligned} \Delta R^m(t) &\equiv \text{Residual error in range estimation in the } m^{\text{th}} \text{ channel} \\ f_x^m(t) &= \frac{2f_0}{c} \cos(\theta^m(t)) \\ f_y^m(t) &= \frac{2f_0}{c} \sin(\theta^m(t)) \\ \theta^m(t) &\equiv \text{Angle subtended by target as seen by the } m^{\text{th}} \text{ channel} \end{aligned}$$

If the spatial frequencies $(f_x^m(t), f_y^m(t))$ in (3) were indeed stationary, then velocity filtering [6] could be invoked to sort out and compensate for the radial velocities associated with the residual range migrations $\{\Delta R^m(t)\}_m$ across the channels. However, in reality the scatterers associated with a range bin will not be perfectly phase coherent. We can model this situation more precisely as follows:

$$\begin{aligned} s_R^m(t) &= \exp\left(-\frac{j4\pi f_0 \Delta R^m(t)}{c}\right) \iint_{-\infty}^{\infty} (\rho(x, y) \exp\{-j2\pi[(xf_x - yf_y) + v^m(t)]\}) dx dy \quad (4) \\ &= \exp\left(-\frac{j4\pi f_0 (\Delta R^m(t) + \tilde{v}^m(t))}{c}\right) \iint_{-\infty}^{\infty} (\rho(x, y) \exp\{-j2\pi[(xf_x - yf_y)]\}) dx dy \quad (5) \end{aligned}$$

Where,

$$\begin{aligned} \tilde{v}^m(t) &\equiv v^m(t) \cdot c/2f_0 \\ v^m(t) &\equiv \text{Phase noise that is assumed to be uncorrelated in slow-time} \end{aligned}$$

It is clear from (5) that in order to optimize the performance of velocity filtering, the noise term $\tilde{v}^m(t)$ must be minimized. ISAR imaging algorithms—unlike generic backprojection techniques—*explicitly aim to minimize* $v^m(t)$ (via Doppler tracking algorithms). Furthermore, as explained in Section 3, ISAR imaging algorithms dynamically adjust the imaging plane based on the dynamic motion of the target being imaged. From these two factors we theoretically expect the combination of ISAR imaging with velocity filtering to be inherently superior to the traditional VSAR algorithm for the case of imaging rigid bodies in realistic maritime conditions. This is substantiated by our experimental results in Section 5.

Motivated by this we now delve into extending the capabilities of single-channel ISAR to the multichannel scenario. As explained above, range and phase compensations are both important in maintaining phase coherence within a range-bin and across the channels. In our work we employed

an entropy-based approach to range compensation. This technique exploits the observation that range profiles which are correctly aligned and normalized to a probability distribution will have minimum entropy. A single prominent point scatterer, in particular, will resemble a perfect spike and therefore have zero entropy. Conversely if the range profiles are not correctly aligned, then the prominent point scatterer will be spread to different positions (as function of slow-time) as a result of which the entropy of the resulting normalized average profile will be closer to that of a uniform distribution (i.e. will tend towards a maximum value). We first modeled the range migration across slow-time by a 2nd order polynomial:

$$\delta R(t) = c_2 t^2 + c_1 t + 1 \quad (6)$$

where $\delta R(t)$ models the migration of the point scatterers across slow-time. In order to reduce the computational complexity, we sequentially optimize over the parameters (c_1, c_2) until the resulting entropy is minimized.

After this we employ a simple split-aperture autofocus technique, also called the phase difference algorithm [2], to perform Doppler tracking. We first divide the slow-time aperture (pulses) into two sub-apertures, multiply the first sub-aperture by the conjugate of the second (element by element for all range bins), perform the FFT of the product, sum the magnitude profiles over all range bins, and finally find the peak. The location of this peak measures the Doppler drift during the observation interval. The summing over range bins tends to boost the signal-to-noise ratio and thus improve the accuracy of the phase estimates. There is a little bit of subtlety involved in the peak location operation stemming from the fact that the resolution of the peak estimate is potentially limited by the azimuthal resolution. In order to obtain finer estimates we use a model based approach wherein a Gaussian profile is fitted around the peak structure followed by a simple interpolation technique described in [16].

Due to channel and antenna imperfections, additional processing may be needed to further enhance phase coherency across channels. It was shown in [17] that during along-track data acquisition, the phase mismatch comprises a linear term due to the along track displacement of the phase centers, a non-linear term due to the changing aircraft position along the scene, and also a third nonlinear component due to the antenna mismatch and the unbalanced radar hardware. The algorithm that we selected for balancing these mismatches between the channels is the ‘adaptive 2D calibration’ detailed in [17] wherein the transfer functions of the different channels are matched to a reference channel by a least-squares optimization method with the aim of equalizing the histograms of the data from each channel. Not surprisingly our VISAR algorithm is less sensitive to these channel balancing issues as compared to VSAR inasmuch as its performance is not significantly degraded in the absence of channel balancing.

Based on the above exposition, our VISAR algorithm can now be succinctly summarized as follows:

- 1) Perform basic radar pre-processing steps such as pulse compression [18] to obtain the range profile corresponding to each phase center
- 2) For each frame, perform ISAR imaging using the

techniques described above

- 3) Perform an optional channel balancing [17] step
- 4) Coherently combine the ISAR image frames obtained above by incorporating a velocity filtering and adjustment similar to that employed in VSAR [6]
- 5) The magnitude of the image obtained in (4) is the VISAR image. Alternatively the maximum at each pixel can be calculated to obtain the dominant velocity map corresponding to the target being imaged

In the next section we demonstrate the performance of our VISAR algorithm in imaging boats captured by our airborne NRL MSAR system.

V. EXPERIMENTAL RESULTS

In Figure 3 we show the performance of the VISAR and VSAR algorithms on a small boat that we captured with our NRL MSAR system during our September 2014 data collection campaign. Similar to [13] we used 16 up-chirp channels to generate the experimental results in this paper.

When capturing this particular dataset our plane (which was a Saab 340 aircraft) flew at an altitude of about 6 km and performed a circular track of radius 2.5 km. During this time the boat, which was the 14 m small boat shown in Fig. 3(a), was stationary. We estimate that the sea-state level was low during this time. For this collection geometry, the boat was roughly at the center of the antenna beam (which encompassed a circle on the ground-plane with radius of approximately 500m) for the entire duration of the collection interval. There were no other significant interfering targets within this beamwidth during the data capture. The results that we show in Fig. 3 correspond to a CPI (coherent processing interval) of 0.5s.

Figs. 3(b-c) show the performance of our VISAR algorithm for 2 different cases. Specifically, Fig. 3(b) and 3(c) show the results, respectively, with and without range compensation. In both cases Doppler tracking has been applied. Many times if the CPI is small enough and there is not much rotational motion associated with the target, it may suffice to forego the range alignment step. In this case we do see noticeable, though subtle, improvements in the focusing of the scatterers when incorporating range compensation. From this we can conclude that there was some amount of raw-pitch-yaw motion present in the boat apart from the relative translational velocity due to the motion of the plane. Fig. 3(d) shows the VSAR performance for the same CPI interval where the images corresponding to each of the sensors are formed via the backprojection algorithm.

Since the ISAR algorithm picks up on the roll-pitch-yaw motion of the boat and also dynamically adjusts the image plane based on the relative motion of the boat, we can see that VISAR performs much better at bringing out features of the boat as compared to the VSAR algorithm.

Furthermore, as expected, the VISAR and VSAR algorithms show relative improvements in image quality compared to their single-channel counterparts shown in Fig. 3(e) and Fig. 3(f) respectively.

VI. DISCUSSION

This paper effectively defines a new mode of processing for MSAR imaging, called VISAR, wherein ISAR processing, in conjunction with velocity based filtering, is leveraged to correct for motion artifacts in the final image. We have discussed some of the theoretical underpinnings of the VISAR algorithm and have shown how it is superior to VSAR for the case of imaging rigid bodies in typical maritime conditions.

We then applied the VISAR and VSAR imaging techniques on real experimental data captured by our NRL MSAR system. As expected the VISAR results demonstrate a clear improvement in focusing the target when compared to traditional VSAR processing since it is better able to exploit the special structure associated with the motion dynamics of rigid bodies in typical maritime conditions. In future work we will explore the application of PGA [9-10] and other kinds of autofocus algorithms on the performance of VISAR imaging; and will also explore the use of VISAR imaging in Automatic Target Recognition (ATR) [19] applications.

Finally though we have limited ourselves to Fourier processing in this paper we envision that even more powerful signal processing techniques such as [20] can be applied for obtaining high quality imagery under ever lower CPI conditions.

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Figure 1: Schematic of the NRL Airborne MSAR System (successfully deployed in September 2014)

Figure 2: ISAR Imaging Geometry

Fig. 3(a) Small Boat (14m. length)

Fig. 3(b) VISAR: without range compensation

Fig. 3(c) VISAR: with range compensation

Fig. 3(d) VSAR Image

Fig. 3(e) Single channel ISAR

Fig. 3(f) Single channel Backprojection

Figure 3: VISAR and VSAR processing of a Small Boat (that was captured by our NRL MSAR airborne system in September 2014) together with their single channel counterparts