Joint Along Track Interferometry and Space-Time Adaptive Processing for Target Detection and Geolocation*

Faruk Uysal, Vinay Murthy & Ke Y. Li
C & P Technologies, Inc. Closter, NJ
faruk@cptnj.com, murthy@cptnj.com, kli@cptnj.com

S. Unnikrishna Pillai
C & P Technologies, Inc., Closter, NJ and Polytechnic Inst. of NYU, Brooklyn, NY

Mark E. Davis
medavis consulting Prospect, NY medavis@ieee.org

Abstract—This paper presents a new adaptive radar signal processing technique for target detection and geolocation using radar data from platforms capable of performing simultaneous Synthetic Aperture Radar (SAR) and Along-Track Interferometry (ATI). Space-Time Adaptive Processing (STAP) and ATI processing methodologies are combined in parallel to simultaneously image, detect and identify the geolocation of moving targets over clutter using data obtained from a single set of measurements. Proposed method allows use of a common data source and interconnected methods to fully exploit the information content of the measured data for improved target detection and geolocation.

I. INTRODUCTION

Remote sensing radar has been under development for the past several decades. It has provided a means for long-range continuous all-weather day/night observational capabilities that were not previously available. Target detection and identification of its geolocation are a key assets to obtaining complete situational awareness. The capability to continuously monitor all vehicles within a given scenario yielding a stream of actionable information is critical to achieving superiority in tactical scenarios. To this end integrating ATI and STAP together with SAR imaging in order to detect the presence, and identify the geolocation of moving targets over a long synthetic aperture using subaperture processing is crucial.

STAP is a well-known method used to process spatiotemporal data to detect moving targets by employing a whitening operation followed by matched filtering in the spatiotemporal domain [1]–[3]. ATI is a technique based on SAR images obtained from two phase centers separated by a certain distance in the along-track dimension [4], [5]. The advantage provided by ATI over SAR imaging is that by correlating the images from two different phase centers, the clutter scene (stationary background) can be cancelled out and moving targets are emphasized.

*The work described here was supported by the Information Innovation Office, Defense Advanced Research Project Agency (DARPA), Arlington, VA, under SBIR Phase II contract No. D11PC20007. The views expressed are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. Distribution Statement A (Approved for Public Release, Distribution Unlimited).

ATI along with STAP has been used for estimating the velocities of both endoclorutter and exoclorutter targets. Slow-moving targets that are within the Doppler ridge generated by the platform are referred to as being in endoclorutter while targets that are external to the Doppler ridge are referred to as being in exoclorutter [5]. ATI has an advantage over STAP when estimating the velocity of targets in endoclorutter whereas STAP is more efficient at detecting targets in exoclorutter [6].

II. SPACE-TIME ADAPTIVE PROCESSING

This section gives a brief summary of conventional STAP, for target detection, velocity and angle estimation. Robust target detection depends on joint manipulation of degrees of freedom in space and time. Towards this, consider an $N$-element linear phased array, so that [1]–[3]

$$a(\theta) = \left[ 1, e^{-j2\pi \frac{d \sin \theta}{\lambda}}, \ldots, e^{-j2\pi \frac{(N-1)d \sin \theta}{\lambda}} \right]^T$$

(1)

gives the spatial steering vector that results in a beam pointing at an angle $\theta$. Here, $\lambda$ is the carrier wavelength and $d$ is interelement spacing. This, together with the temporal steering vector

$$b(\omega_d) = \left[ 1, e^{-j\pi \omega_d}, e^{-j2\pi \omega_d}, \ldots, e^{-j(M-1)\pi \omega_d} \right]^T$$

(2)

for a series of $M$ pulses, with normalized Doppler component

$$\omega_d = \frac{2V T_r}{\lambda/2},$$

(3)

gives the $MN \times 1$ conventional space-time steering vector

$$s(\theta, \omega_d) = b(\omega_d) \otimes a(\theta)$$

(4)

associated with angle $\theta$ and Doppler component $\omega_d$ (or velocity $V$) [1]–[3]. In (4), the notation $\otimes$ represents the Kronecker product [2], [3]. In conventional STAP processing, the clutter $c(t)$ is adaptively cancelled using the adaptive weight vector given by [1]–[3],

$$w_c = R_c^{-1} s(\theta_t, \omega_{dt}) \quad R_c = E \{ c(t)c^*(t) \} > 0$$

(5)

where $R_c$ represents the clutter plus noise total interference covariance matrix, and $s(\theta_t, \omega_{dt})$ represents the space-time
steering vector associated with the target of interest located at angle $\theta_t$ and Doppler $\omega_d$. In practice $R_c$ is unknown, and is estimated from the neighbouring data under the promise of stationarity. To study the effect of the space-time adaptive canceller in (5), the output

$$P_c(\theta, \omega_d) = |w^*_c s(\theta, \omega_d)|^2$$

(6)
is generally used to compute the target’s velocity and angle [1]–[3].

III. ALONG TRACK INTERFEROMETRY (ATI)

Along-track interferometry can be accomplished by constructing an interferogram between the SAR images produced by two phase centers separated by some distance along the direction of motion (i.e. in the along-track dimension). The basic interferogram is the product of complex-valued SAR image A from the first phase center and the complex conjugate of the complex-valued SAR image B from the second phase center [7],

$$I = AB^*.$$  

(7)

Stationary targets can be accurately phase compensated in both of the images so that their power combines constructively in the magnitude $|AB^*|$ (Fig.1(d)) while combining destructively in the phase $\angle AB^*$ (Fig.1(e)). Therefore for a scene containing only stationary targets the interferogram phase should be zero. However since the phase for a moving target cannot be compensated without knowledge of the target’s motion, the phase of the interferogram should contain some information (or have nonzero values) for those pixels corresponding to the moving target’s signature.

An optical image (Fig. 1(a)) obtained from Google Maps covering an area of $180m \times 175m$ was used to simulate SAR/GMTI data as shown in Fig. 1. Initially the scattering centers were modelled as ideal point reflectors placed on a $1m \times 1m$ grid. Fig. 1(b) shows a high resolution SAR image integrated over a $5^\circ$ aperture with $1m \times 1m$ pixel resolution displayed at 15 dB dynamic range. In order to reduce the computational cost the scatterer spacing was increased to $2m \times 2m$ and the coherent integration period was reduced to a $1^\circ$ aperture with $2m \times 2m$ pixel resolution displayed with the same dynamic range (Fig. 1(c)). The Radar Cross Section (RCS) for the background pixels correspond to the image pixel grayscale intensity. A 150 MHz LFM waveform was used for the simulation with a PRF of 1.227 kHz yielding a 10 m/s maximum unambiguous line-of-sight velocity.

Two phase centers separated in the along-track dimension by 4 meters were simulated to obtain the ATI magnitude and phase as shown in Fig. 1(d) and Fig. 1(e), respectively. A moving target with velocity 1.5 m/s and heading 175$^\circ$ represented by 2 ideal reflectors was injected into the background data. Here we see that the magnitude of $I$, the complex-valued ATI product, contains information from all of the background scatterers. The target is not clearly visible in the magnitude however it stands out in the phase of $I$ as seen in Fig. 1(e). Thus, two stage thresholding is applied to interferogram magnitude and phase to boost the detection accuracy as described in [7]. SAR image obtained from the same snapshot is shown in Fig.1(f) along with the location of the detected moving target signature overlaid.

Moving targets generate delays that are uncompensated during standard SAR processing. Depending on the nature (e.g. linear, quadratic) of those additional delays both a Doppler shift and cross-range smearing of the target signature may be observed [8], [9]. In order to determine the true geolocation of the target, the observed shifts and/or smears must be correctly compensated.

IV. INTEGRATING SAR/ATI AND STAP

In this section we integrate SAR/ATI and STAP to determine the correct target geolocation by correcting the shifts due to the target motion.
A. Velocity & Heading Estimation using STAP

The line-of-sight velocity (i.e., downrange velocity) of a moving target can be estimated using the STAP output in (6).

The measurement geometry used is shown in Fig.2, yielding estimated velocity \( v_{\text{STAP}} \) which includes the projections of the platform velocity along the look direction (slant range) \( v_p = V_p \sin \theta \) and the target velocity \( v_r = v_x \cos \theta + v_y \sin \theta \). Thus

\[
v_{\text{STAP}} = v_r + v_p. \tag{8}
\]

the measured velocity \( v_{\text{STAP}} \) must be compensated to account for the platform velocity to obtain the target velocity estimate \( v_r \). We can estimate the complete (vector) velocity of the target by constructing two STAP estimates at sufficiently-spaced locations along the flight path as shown in Fig.3. After measuring velocities \( v_{ri} \) and \( v_{rj} \) from locations \( i \) and \( j \), respectively, the target’s velocity \( (v_x, v_y) \) can be determined as

\[
\begin{align}
  v_x &= \frac{v_{ri} \sin \theta_j - v_{rj} \sin \theta_i}{\sin \theta_i \sin \theta_j (\cot \theta_i - \cot \theta_j)}, \tag{9a} \\
  v_y &= \frac{v_{ri} \cos \theta_j - v_{rj} \cos \theta_i}{\cos \theta_i \cos \theta_j (\tan \theta_i - \tan \theta_j)}. \tag{9b}
\end{align}
\]

since the estimated range velocities at locations \( i \) and \( j \) are given by

\[
\begin{align}
  v_{ri} &= v_x \cos \theta_i + v_y \sin \theta_i, \tag{10a} \\
  v_{rj} &= v_x \cos \theta_j + v_y \sin \theta_j. \tag{10b}
\end{align}
\]

Considering a long SAR CPI, we can perform STAP over several sub-CPIs (sub-aperture) over the duration of the longer SAR CPI in order to estimate the range velocities \( v_{ri} \), \( i = 0, \ldots, N \) and the associated target angles \( \hat{\theta}_i \) (i.e., angle between platform and target measured from broadside). Using these estimates, multiple estimates \( (\hat{v}_x, \hat{v}_y) \) of the target velocity can be formed using the equations in (9) [10].

B. Estimating Target Geolocations

Over a long synthetic aperture, we can form multiple sub-CPIs (sub-apertures) and perform SAR, ATI and STAP over each of them in order to establish a stream of information covering the duration of the entire aperture. Specifically, we would like to establish target geolocations over the entire aperture accomplished by processing the measured (in this case, generated) data over each of the sub-apertures. During each sub-aperture we perform three types of processing:

- SAR for situational awareness,
- ATI for moving target detection and signature location, and
- STAP for target detection corroboration and target velocity estimation.

Fig. 3: Complete target velocity \( (v_x, v_y) \) estimated using two STAP velocity estimates.

Fig. 4: Flight path and sub-CPIs
ATI is useful for detecting the presence of moving targets in light-to-heavy, possibly non-homogeneous clutter environments and it is capable of discriminating slow-moving endo-clutter targets where other techniques (e.g. STAP) may not be effective.

Moving target detection is performed by applying dual thresholds to the magnitude and phase of the interferogram, respectively [7]. However the detected target signature will be shifted (and possibly distorted) from the target’s physical location over the CPI depending on its velocity and heading [8], [9]. The target’s velocity/heading must be incorporated with the detected target signature in the interferogram in order to estimate the target’s origin with respect to the subaperture, thereby establishing a point along a series of target geolocations formed over the entire aperture. ATI processing is combined with the STAP output in order to perform target origin estimation.

We form $K$ subapertures from a large aperture covering an angle $\Delta \theta_a$ for target detection and geolocationing as shown in Fig.4. In our simulations we have used 9 subapertures, each covering approximately 1° of the total aperture.

For each subaperture, we form one SAR images from each of the two phase centers and form the interferogram from the resulting pair. In parallel, $n_{\text{STAP}}$ pulses from the beginning and end from the subaperture are used to obtain velocity and angle estimates for the moving target yielding an estimate for the target velocity $(\hat{v}_x, \hat{v}_y)$ (see Fig.5). The number of pulses used for STAP $n_{\text{STAP}}$ should be chosen accordingly to minimize range walk and other unwanted effects while maximizing Doppler resolution.

Having obtained estimates for the target signature location and its velocity, we can estimate the target’s origin (geolocation) by compensating for the effects induced by the target’s motion in the resulting SAR image. A rotation matrix must be applied to the cross-range shift $\Delta_a$ and the range drift $\Delta_r$ given by [8], [9]

$$\Delta_r = \frac{1}{2} v_r T$$

$$\Delta_a = \frac{v_r}{V_p} R_0 + \frac{1}{2} v_a T.$$  \hspace{1cm} (11)

(12)

in order to obtain the estimated coordinates of the target $(\hat{x}, \hat{y})$ as illustrated in Fig.6. This compensation must also take into account the squint angle $\theta$ as

$$\begin{bmatrix} v_r \\ v_a \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} v_x \\ v_y \end{bmatrix}$$ \hspace{1cm} (13)

$$\begin{bmatrix} \hat{x} \\ \hat{y} \end{bmatrix} = \begin{bmatrix} x_s \\ y_s \end{bmatrix} + \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} -\Delta_r \\ \Delta_a \end{bmatrix}$$ \hspace{1cm} (14)

where $(x_s, y_s)$ are the observed target signature coordinates which computed by ATI processor.

Fig.7 shows the simulated geolocation performance for a target injected with a velocity of 4.46 m/s and heading 258° onto the clutter background consisting of ideal point reflectors with $2m \times 2m$ spacing and RCS corresponding to image pixel grayscale intensity. The simulation aperture was chosen to be $27^\circ$ with each subaperture covering a $1^\circ$ arc separated by $2^\circ$ from neighbouring subapertures yielding 9 simulated subapertures that in turn produced 8 velocity estimates. As before the two phase centers were simulated with a separation of 4m in the along-track dimension; for each velocity estimate obtained from STAP the ATI product from first of the corresponding two subapertures was used to obtain the target signature detection.

The target signature was correctly detected using ATI but the estimated geolocation of the target is far from the scene being imaged (Fig. 7). Here we see that after subaperture 3 the
geolocation estimates corresponding to subapertures 4-5 are erroneous. For the experimental configuration described above for subaperture 5 the target's velocity is nearly perpendicular to the line-of-sight between the platform and target placing its observed velocity below the STAP maximum detectable velocity (MDV). In such a case ATI can be used to supplement the target velocity estimate obtained from STAP [11]. By applying ATI velocity estimation for subapertures 5-8 we are able to successfully geo-locate the target with high accuracy as shown in (Fig 9).

C. Velocity Estimation Using ATI

The basic interferogram in (7) can be written more precisely for two phase center that are separated with $\Delta d$ as,

$$I(x, y)e^{j\phi(x, y)} = A(x, y)B^*(x, y).$$

where $A(x, y)$ and $B(x, y)$ represent the SAR images from the first and second phase center respectively. Then round trip phase delay can be written as,

$$\phi(x, y) = \frac{4\pi V_r \Delta d}{\lambda V_p}$$

for pixels containing the target signature; $\phi(x, y) = 0$ for background pixels (stationary clutter), where $(x, y)$ is the index of pixels in A and B corresponding to the same physical object. Then, the line of sight velocity for target pixels can be computed,

$$V_r = \frac{\phi \lambda V_p}{4\pi \Delta d}$$

The maximum unambiguous velocity can be formed by setting the $\phi$ to $2\pi$

$$V_{ambig} = \frac{\lambda V_p}{2\Delta d}$$

and the maximum unambiguous velocity that can be measured is bounded by $\pm V_{ambig}/2$.

Fig. 8 shows the ATI results along with the detected target signatures and their centroid for subaperture 8. Five pixels are detected that include target signature (shown with turquoise squares in Fig.8), the mean of their phases is used to determine the phase corresponding to the moving target.

$$\phi = \frac{1}{K} \sum_{k=1}^{K} \phi(x_k, y_k)$$

where $K = 5$ for this particular subaperture.

Applying STAP yields a velocity estimation of 0.317 m/s. For this case the true line of sight velocity is -0.188 m/s. In order to achieve a more accurate result, ATI velocity estimation from (17) and (19) was applied yielding an estimate of -0.185 m/s. The new, higher accuracy estimate is then used to obtain a higher accuracy target geolocation.

Fig. 9 shows the result of using ATI velocity estimation in place of STAP velocity estimation for subapertures 5-8 in
order to achieve higher accuracy target geolocation. It should be noted that although the maximum unambiguous velocity for ATI is only \( \pm 0.305 \) m/s, the ATI phase manually disambiguated in order to yield the correct target velocity. Future work will include methods for automatically estimating the appropriate ambiguity factor and correcting the measured ATI velocity to produce the true target range rate.

V. CONCLUSIONS

In this paper, various processing methodologies - synthetic aperture radar imaging, along-track interferometry and space-time adaptive processing- are combined in parallel in a suitable manner to image, detect, and identify the geolocation of moving targets over a clutter environment using data obtained from a single set of measurements. Velocity estimation using ATI processing is used to correct the velocities estimated by STAP in situations that have slow line-of-sight velocities. The success of the proposed method is shown with detailed simulations.

ACKNOWLEDGMENT

The authors wish to acknowledge Mr. Vincent Sabio, Program Manager, Strategic Technology Office at DARPA, for his support and active interest in this and other related topics. His visionary ideas on multi-sensor fusion have been a key factor for us in focusing on this problem. In addition, the authors wish to acknowledge the anonymous reviewers for pointing out several suggestions for improving the original manuscript.

U.S patent is pending for the proposed method under the application number 13/495,639 entitled "Method and Apparatus for Simultaneous Multi-Mode Processing Performing Target Detection and Tracking using Along Track Interferometry (ATI) and Space-Time Adaptive Processing (STAP)," filed on June 13, 2012.

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