An Assessment of 3D Space Time Adaptive Processing (STAP) for Clutter Suppression

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Abstract

The performance of conventional slow-time STAP can be significantly degraded by factors such as range-dependent clutter, jammer movement, jammer multipath, receiver errors and bandwidth effects. These effects can be mitigated by the inclusion of fast-time varying weights and/or fast time adaptive degrees of freedom in a three dimensional STAP architecture, such that clutter suppression and hence target detectability may be maintained across a range of more complex interference environments.

Keywords: Radar, Clutter, Space Time Adaptive Processing, 3D STAP, Time Varying Weights

Introduction

Radar target detection is degraded by the presence of interference. This interference typically consists of thermal noise, clutter, direct path jamming and jammer multipath (also known as terrain scattered jamming (TSI) or hot clutter). Adaptive signal processing aims to maintain high gain towards a specified target position in angle, Doppler and range, whilst suppressing interference from all other positions, by exploiting the correlation of the received interference components in time and space.

Spatial-only adaptive processing is adept at cancelling direct path narrowband jamming by steering nulls in the antenna beam pattern, but is generally poor at cancelling clutter since this is typically distributed over a large angular extent. Two dimensional slow-time STAP performs much better, exploiting the pulse-to-pulse correlation of the clutter to steer nulls in angle-Doppler space. This approach is particularly useful for moving radar platforms (e.g. airborne and spaceborne radar), where the clutter Doppler varies with angle and platform velocity, and also bistatic radar, where the angle-Doppler relationship is a potentially complex function of the bistatic geometry. Fully adaptive STAP filters are not considered practical, due to their high computational cost and the requirement for a large number of secondary data samples with which to train the filter. A wide range of reduced complexity STAP architectures have been proposed, and shown to achieve near-optimal performance in stationary clutter environments. Data-independent approaches use fixed beamforming and/or Doppler filtering to reduce the number of degrees of freedom before adaptive processing. Data-dependent approaches include a range of techniques based on selecting a reduced set of eigenvectors as a basis for the clutter subspace, and also model-based techniques, where clutter is represented using a low-order parametric model.

The performance of such architectures can be significantly degraded in more complicated interference environments. Factors which reduce the signal-to-interference-plus-noise ratio (SINR) and hence also the minimum detectable target velocity include: (i) variation in clutter angle-Doppler with range; (ii) jammer movement; (iii) jammer multipath; (iv) receiver errors; (v) bandwidth effects.

Factors (i) and (ii) can be mitigated by the inclusion of fast-time (i.e. range) varying adaptive weights. Adaption is still carried out in two dimensions only – space and slow-time – but weights evolve in some deterministic manner from sample to sample. This is often implemented along the lines of Hayward's Extended Sample Matrix Inversion (ESMI) technique [1]. Factors (iii), (iv) and (v) can be mitigated by the inclusion of fast-time adaptive degrees of freedom. Two dimensional fast-time STAP architectures have been widely studied for the cancellation of jammer multipath (in the absence of clutter). Architectures combining slow-time, fast-time and spatial adaptive degrees of freedom are commonly known as 3D STAP, and are the subject of much current research.

This paper presents an initial assessment of the benefits of 2D and 3D STAP architectures incorporating fast-time varying weights and/or adaptive degrees of freedom to help maintain good clutter suppression in more challenging interference environments. Until recently, this was largely based on a review of previous simulation work at Roke Manor and published results from the literature. Work is ongoing to generate original simulation results, to provide a direct comparison with conventional methods and hence illustrate where the extra complexity of time-varying and 3D STAP may be justified.

Some Limitations of Slow-Time STAP

For an ideal sideways looking array, clutter angle-Doppler is independent of range [2]. In any other configuration, angle-Doppler is range dependent, since contours of constant look direction no longer align with contours of constant Doppler. In conventional STAP, a single set of adaptive weights is calculated and applied to all samples in a coherent processing interval (CPI). Hence, the null may not be steered exactly towards the clutter in a given range cell, so cancellation will be degraded. This particularly affects forward-looking arrays (e.g. seekers) at short range; spaceborne radar, which operates at high grazing angles; and bistatic radar, where the relationship between angle and Doppler is especially complex.

Apparent jammer movement during the CPI has a similar effect – if the jammer is no longer accurately nulled, this will degrade SINR across the Doppler band. Furthermore, if the jammer moves significantly during the collection of the secondary data used to calculate the weights, the processor will tend to place a relatively wide and shallow null in the mean jammer position and cancellation will be even poorer. Simulations of an X-band airborne phased array carried out at Roke Manor show a significant increase in the adapted residue for array rotation at more than 1 rad/sec, equivalent to approximately 0.04 beamwidths per CPI (see Figure 1). Results reported by Zatman [3] also demonstrated adaptive weights becoming 'stale' within a few hundredths of beamwidths of rotation.

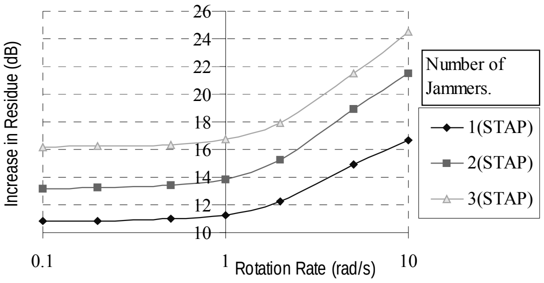

Figure 1: Effect of array rotation on jammer cancellation for slow-time STAP

Jammer multipath, i.e. indirect jamming signals received via reflections from the clutter, can also degrade the performance of slow-time STAP – see for example [4]. Not only may it be difficult to steer a spatial null towards signals received in the mainbeam, but jammer multipath is also highly non-stationary, due to variations in its bistatic Doppler and the multipath environment.

Work on spaceborne radar at Roke Manor has shown that the performance of both pre-Doppler and post-Doppler STAP is extremely sensitive to receiver channel errors (see Figure 2). In this work, it was found that errors should be kept to less than 0.1dB in amplitude (or correspondingly 0.5° in phase) to keep the loss in SINR below 3dB. Results in Klemm [2] show that receiver errors can have a significant effect on the performance of even an optimum, fully adaptive, STAP beamformer.

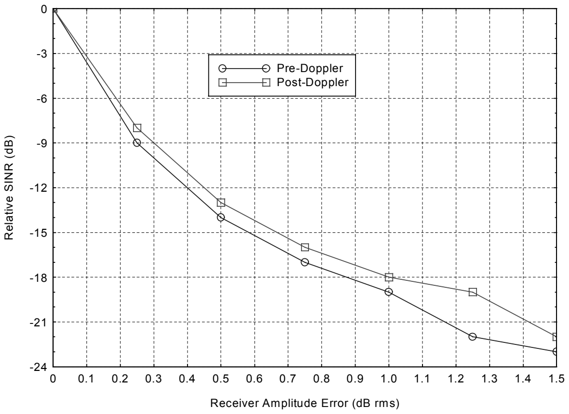

Figure 2: Effect of receiver errors on performance of slow-time STAP

Bandwidth effects may also affect performance in wideband radar systems. Dispersion across the array when a beam is steered away from broadside causes spatial decorrelation. Range walk could also be significant, since range cells are relatively small, leading to decorrelation in slow-time (but adding a degree of clutter correlation in fast-time).

These effects may all be mitigated in a single architecture using a combination of fast-time varying weights and the fast-time adaptive degrees of freedom, as described in the subsequent sections.

Time-Varying Weights

The ESMI technique for implementing fast-time varying weights in 2D slow-time STAP was first proposed in [1]. This uses the first order derivatives of the weights, $\mathbf{w}^{\bullet}$, to linearly update the weight values $\mathbf{w}_o$ calculated for some reference sample i_o, so that the adaptive weights applied to the i^{th} sample are given by:

$$\mathbf{w}_i = \mathbf{w}_o + \alpha(i - i_o)\mathbf{w}^{\bullet} \qquad (1)$$

where α is a normalizing factor. This implementation of ESMI effectively doubles the number of adaptive degrees of freedom in the STAP process. An alternative implementation, using a time-varying difference beam, has been suggested and would involve only a single extra adaptive degree of freedom.

The inclusion of time-varying weights helps compensate for progressive changes in clutter angle-Doppler with range, within a single unambiguous interval, or jammer movement relative to the radar platform across a longer CPI. Simulations of an airborne phased array at Roke Manor showed that ESMI could restrict the degradation in SINR to less than 1dB at jammer rotations of up to 10 rad/sec (0.4 beamwidths per CPI); results in [3] showed no significant degradation over a full beamwidth of rotation. Figure 3 shows adapted residue versus jammer strength for rotation at 10 rad/sec, for both the full ESMI algorithm and the time-varying difference beam implementation, for the Roke Manor simulations. Both algorithms show significant improvement relative to conventional spatial-only beamforming.

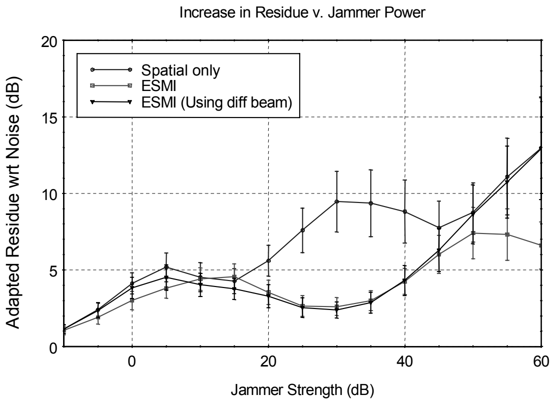

Figure 3: Effect of time-varying weights for array rotation at 10 rad/sec

Simulations of bistatic airborne radar by Melvin et al [5] showed that incorporating time-varying weights with the popular Joint Domain Localized (JDL) algorithm restored 5-10dB SINR across the Doppler band at relatively short bistatic ranges, where JDL alone was affected by clutter non-stationarity.

3D STAP Architectures

2D fast-time STAP has been widely studied for the cancellation of jammer multipath in the absence of clutter. One approach to 3D STAP is therefore to cascade two dimensional fast-time and slow-time stages, as illustrated in Figure 3. Results produced by Rabideau [6], for example, show that these factored architectures can achieve reasonable cancellation of both clutter and jammer multipath, but modulation of the clutter due to the regular updating of the fast-time STAP weights is likely to limit performance. Any targets present will also be modulated, which may affect detection and limit the accuracy of angle and Doppler measurements. The severity of the modulation effects depends, amongst other things, on the choice of STAP method for each stage: [6] showed that SINR loss could be minimized using a selected auxiliary fast-time stage in combination with a pre-Doppler slow-time stage.

Where multipath exists, this may in fact be exploited to assist in the mitigation of self-screening jammers, which cannot be effectively cancelled with spatial-only adaption. Including fast-time adaptive degrees of freedom in a 3D STAP architecture may provide an important extra capability in this respect.

Joint 3D STAP architectures, in which fast-time and slow-time degrees of freedom are applied simultaneously, typically offer less SINR loss than factored architectures and obviate any modulation effects. In practice, it may only be possible to include a very small number of temporal taps, given the computational cost and secondary data requirements of a system with a total of NMP degrees of freedom. However, $M = 3$ slow-time taps and $P = 2$ fast-time taps have been shown to give good performance for a system with $N = 16$ spatial channels – a total of 96 degrees of freedom.

Note that, whereas post-Doppler architectures are often preferred in conventional 2D STAP, a joint 3D post-Doppler method is unlikely to work well as the initial Doppler filtering stage will act to decorrelate jammer multipath. A factored 3D method using a post-Doppler clutter cancellation stage may in fact give a sharper clutter notch than a joint 3D pre-Doppler method, and hence better detection of slow moving targets, although overall cancellation performance may be poorer.

Other promising 3D STAP architectures discussed in the literature, using data-dependent approaches to reduce the rank of the STAP problem, include the 3D Multistage Wiener Filtering (MWF) algorithm of Guerci et al [7] and the model-based 3D Space-Time Autoregressive (STAR) algorithm proposed by Parker and Swindlehurst [8].

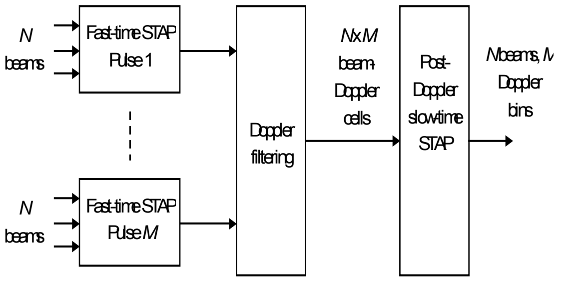

Figure 3: Factored post-Doppler 3D STAP architecture

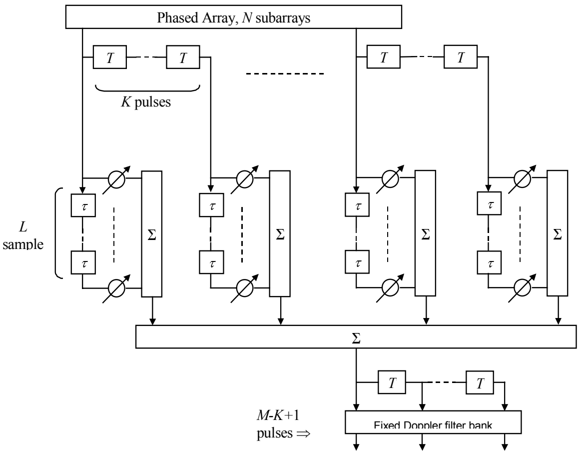

Figure 4: Joint pre-Doppler 3D STAP architecture

Performance of 3D STAP

Reference [6] showed joint pre-Doppler 3D STAP maintaining SINR over a greater percentage of range-Doppler space than any of the factored architectures considered (typically 3-5dB better than the best performing factored architecture) in the presence of clutter, jamming and jammer multipath. Simulations of joint 3D STAP at Roke Manor show how incorporating adaptive fast-time weights can increase tolerance of frequency-dependent receiver errors. Figure 5 illustrates a scenario with three jammers and receiver errors applied at 0.5dB / 2.5° rms. For spatial-only adaption (1 tap), SINR is degraded significantly in all look directions; using 3 fast-time taps, performance is restored to within approximately 2dB of the ideal level.

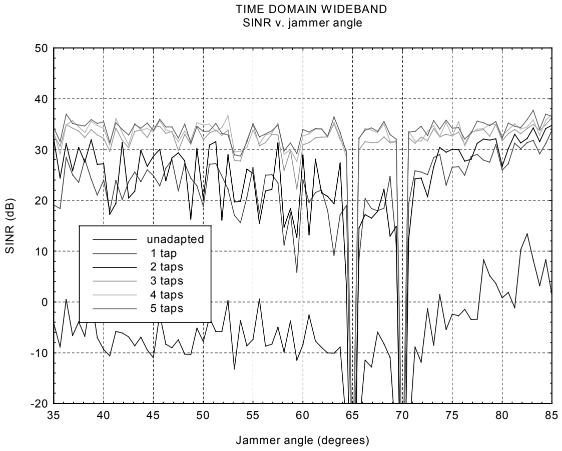

Figure 5: Compensation of frequency dependent receiver errors using adaptive fast-time taps

Work is ongoing, using Roke Manor's PHASAR phased array simulation software, to produce side by side comparisons of 2D and 3D STAP architectures in a range of interference environments.

Conclusions and Next Steps

A number of factors have been identified which may degrade the adaptive cancellation performance of slow-time only STAP and hence limit the detection of targets in clutter. Incorporating fast-time varying weights and/or fast-time adapative degrees of freedom in a 3D STAP architecture can mitigate these effects and help maintain performance in more complicated interference environments, as well as providing extra capability in areas such as the mitigation of self-screening jammers. Work will continue in the 2nd year of DTC funding to produce more detailed comparisons of various 2D and 3D STAP architectures, in a comprehensive range of interference environments. This will be done using both simulation and real radar data. A particular aim for the next phase is to study the performance and robustness of a model-based approach such as the 3D-STAR algorithm [8], in addition to the joint pre-Doppler 3D STAP architecture selected for initial simulation work.

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