The Potential of Space-Time Adaptive Processing for Active Sonar

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Abstract

Space-time adaptive processing (STAP) is a technique for motion compensated detection of slow moving targets by a moving (air- or spaceborne) radar. The adaptive processor compensates implicitly for the Doppler spread of clutter returns, thus making the detection of slow moving targets possible which are normally buried in the clutter Doppler band. In this tutorial the principles of STAP are expanded and the application of STAP to active sonar is suggested.

1 Introduction

Waves are by nature functions of space and time. Consequently, processing of waves requires a temporal and a spatial dimension. For this purpose, waves have to be sampled in space and time before processing in a digital signal processor. In radar and sonar the spatial sampling is achieved by using an array of sensors. Temporal samples are either obtained by including echoes due to different coherent transmit pulses (pulse Doppler radar) or samples of a single received echo waveform (active sonar). Pulse Doppler Radar is based on coherent pulse trains. Therefore, there are two kinds of time scale, the ”fast” time (range equivalent) and the slow time (pulse-to-pulse). In normal active sonar applications target search is based on a single pulse only so that only the range equivalent samples are available for space-time processing.

The fundamental paper on adaptive radar [1] deals already with a space-time representation of signals and processing. In this work by time the ”fast” (range equivalent) time is understood. By including the time dimension in their theory the authors treat the more general case of broadband waves. In essence the paper deals with adaptive cancellation of jammers in a broadband array radar.

It should be noted that the seismic community started using adaptive techniques for noise cancellation and high resolution spectral analysis [3, 4]. The sonar people adopted many ideas created by the seismic community in the late 1960’s and early 1970’s, with application to cancellation of directive noise and superresolution (adaptive beamforming). At this time the radar RF and digital technology was not mature enough to implement adaptive array processing. With the advent of modern array radar technology strong interest in adaptive algorithms came up in the radar community.

In a later paper by the same authors [2] the theory was extended to space-slow time adaptive processing for MTI (moving target indication) radar. The main purpose of the space-time processor in a moving radar is to reject strong clutter returns reflected by the stationary background and detect slow moving targets which are buried in the clutter Doppler band whose width is determined by the platform velocity. Although the term space-time processing is much broader adaptive clutter suppression in a moving radar is what nowadays is understood by STAP.

As mentioned already space-time adaptive processing belongs to the family of adaptive array processing techniques. Other well-known applications are jammer cancellation, superresolution, terrain-bounced jamming mitigation etc. In Table 1 a summary of array processing techniques as used in radar is given.

To the knowledge of the author there are only a few attempts to apply STAP to active sonar. There are three more papers on STAP for sonar in this volume [5, 9, 10]. The paper by Maiwald et al. deals with the problem of suppression of reverberation in active sonar.

The purpose of this tutorial is give a brief description of the state-of-the art in STAP for radar, to point out the commonalities and differences between radar and active sonar, and to draw conclusions concerning the application of STAP to active sonar.

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Narrowband array, stationary platform	
Adaptive cancellation of directional noise	spatial weighting
Superresolution in direction	spatial weighting
Superresolution in range	weighting in fast time domain
Superresolution in Doppler	weighting in slow time domain
Broadband array, stationary platform	
Adaptive cancellation of directional noise	space-time weighting
Superresolution in direction	space-time weighting
Superresolution in range	weighting in fast time domain
Superresolution in Doppler	weighting in slow time domain
Adaptive noise cancellation	broadband band: space-fast time
Hot clutter rejection	space-fast time weighting
Narrowband array, moving platform	
Motion compensated clutter rejection	space-slow time weighting (STAP)
Hot clutter rejection, moving platform	space-fast & slow time weighting

Table 1: Array processing techniques for radar

2 Adaptive clutter suppression for moving platforms

2.1 The principle of STAP

Let us consider a moving sensor platform (aircraft, satellite, ship) carrying a sensor array with a sensor geometry as shown in Figure 2. Then the Doppler frequency of each clutter arrival is given by

$$f_{\mathrm{D}} = \frac{2v_{\mathrm{p}}}{\lambda} \cos \alpha \tag{1}$$

where v_p is the platform velocity, λ the wavelength and α the angle of arrival. The total of clutter arrivals from all possible directions sums up in a Doppler broadband clutter signal, with the bandwidth given by $[-2v_p/\lambda, 2v_p/\lambda]$. A conventional beamformer would face a more or less omnidirectional interference (spatially white noise) having a white Doppler spectrum in the limits $[-2v_p/\lambda, 2v_p/\lambda]$.

A STAP processor operating on space-time echo data makes use of the fact that the clutter Doppler frequency and the angular direction are connected via (1). The principle of STAP is illustrated in Figure 1.

The plot shows the angle-Doppler plane. According to (1) the clutter energy is distributed along the diagonal. The modulation by the transmit beam pattern can be recognised. Notice the main beam at 0° azimuth and the sidelobes.

Consider the case of purely temporal clutter filtering as is used in stationary radar systems. Such filter cancels the clutter by placing a null at zero Doppler (stationary background). Adaptive clutter filters would match to the shape of the clutter spectrum if necessary. If, however, the clutter is spread out because of the platform motion the best temporal filter that can be designed than the best filter that can be designed is the inverse of the inverse clutter spectrum projected on the Doppler axis. As can be seen in the back of Figure 1 the stop band of the temporal filter is determined by the width of the transmit beam. Obviously, slow targets (targets in the clutter Doppler band) fall in the stop band and are attenuated.

A purely spatial filter as being used to cancel directive noise places a broad null in the look direction of the antenna array (stop band on the left in Figure 1) so that the radar becomes blind through adaptive processing! The reason is that the main interference is in the look direction so that the adaptive processor places a spatial null whose width is determined by the transmit beam as in the case of temporal filtering.

A space-time clutter filter operates in both dimensions of the $f_d - \cos\varphi$ plane. It forms a narrow trench along the diagonal of the $f_d - \cos\varphi$ plane. It can, therefore, take into account that the clutter spectrum is in fact a narrow rigde along the diagonal. Therefore, the clutter notch can be made extremely narrow so that even slow targets fall into the passband and can be detected.

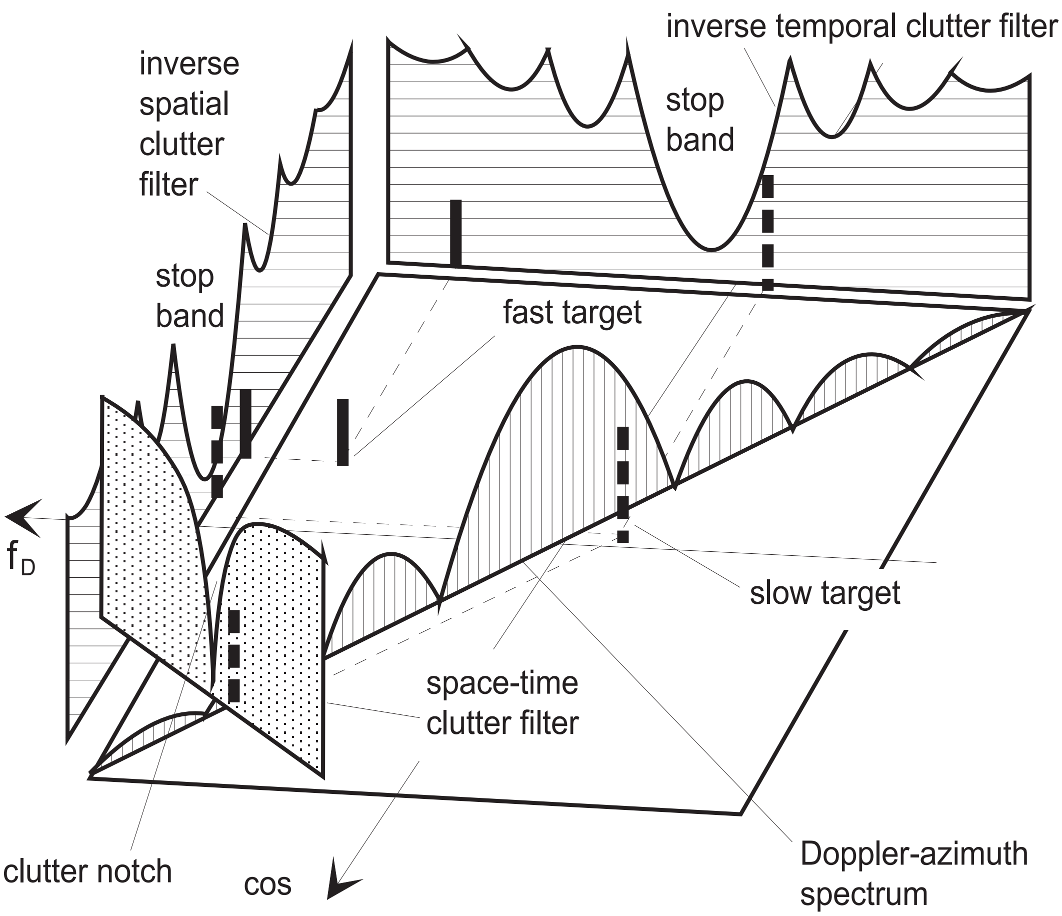


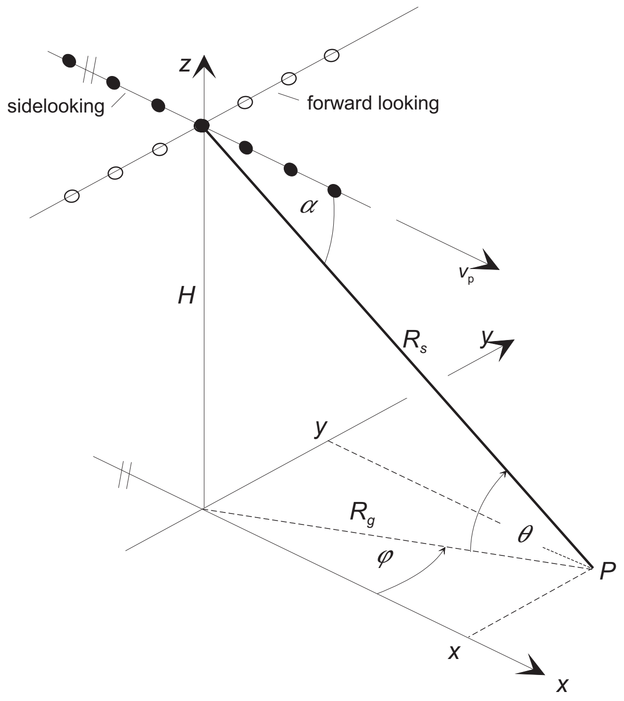
Figure 1: The principle of STAP

2.2 Some properties of moving radar clutter

Consider an airborne radar geometry as shown in Figure 2. For simplicity we assume a linear array of sensors in either sidelooking or forward looking configuration. The array moves in x-direction at speed v_p. The clutter returns due to ground reflections exhibit a Doppler colouring of the ground according to (1). In the case of a horizontal motion parallel to a flat earth the curves of constant Doppler (isodops) are hyperbolas as shown in Figure 3. The maximum Doppler occurs in flight direction (0°), positive for forward looking, negative for backward looking operation (180°). In the across-flight directions (90°,270°) one finds zero Doppler.

In Figure 4 the isodops have been depicted for one quadrant. In addition the footprints of array beams for different look directions are shown (thin lines). Since the geometry of the flight path coincides with the array geometry the beam traces on the ground have the same shape as the isodops, i.e., beam traces and isodops coincide. This means, however, that clutter arrivals have constant Doppler with range.

For a forward looking array (Figure 5) the beam trace pattern is rotated by 90°. As can be seen there are now many intersections between isodops and beam traces which indicates that the clutter Doppler is range dependent, in particular at short range.



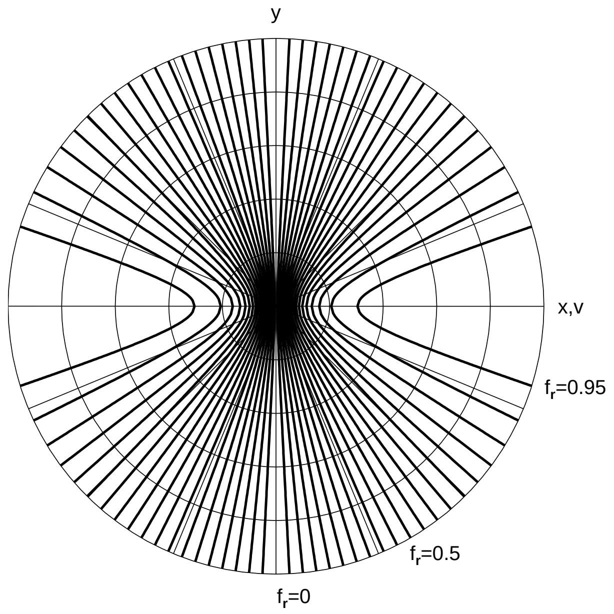


Figure 2: Airborne radar geometry

Figure 3: The isodops

RADAR	ACTIVE SONAR
coherent pulse trains	single pulse
Doppler by pulse-to-pulse phase comparison (slow time)	Doppler retrieved from single echo "fast time"
perfect spatial coherence	spatial decorrelation limits aperture
normally free space propagation occasionly multipath	waveguide conditions multipath, modes
narrowband clutter	reverberation at low sea state
clutter bandwidth due to internal motion (e.g., vegetation)	reverberation bandwidth due to surface and volume fluctuations

Table 2: Comparison of radar and active sonar

2.3 Optimum STAP algorithm

Let us write the received data in vector format

$$\mathbf{c} = \begin{pmatrix} \mathbf{c}_1 \\ \mathbf{c}_2 \\ \vdots \\ \mathbf{c}_M \end{pmatrix}; \quad \mathbf{s} = \begin{pmatrix} \mathbf{s}_1 \\ \mathbf{s}_2 \\ \vdots \\ \mathbf{s}_M \end{pmatrix}; \quad \mathbf{n} = \begin{pmatrix} \mathbf{n}_1 \\ \mathbf{n}_2 \\ \vdots \\ \mathbf{n}_M \end{pmatrix} \quad \mathbf{j} = \begin{pmatrix} \mathbf{j}_1 \\ \mathbf{j}_2 \\ \vdots \\ \mathbf{j}_M \end{pmatrix} \tag{2}$$

where $\mathbf{c}, \mathbf{s}, \mathbf{n}$ and $\mathbf{j}$ denote the space-time vectors of clutter, target signal, noise and jamming. Notice that the subvectors include the signals received at a certain instant of time while the temporal information lies in the relations between these subvectors. Accordingly, the space-time covariance matrix has the form

$$\mathbf{Q} = \begin{pmatrix} \mathbf{Q}_{11} & \mathbf{Q}_{12} & \dots & \mathbf{Q}_{1M} \\ \mathbf{Q}_{21} & \mathbf{Q}_{22} & \dots & \mathbf{Q}_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{Q}_{M1} & \mathbf{Q}_{M2} & \dots & \mathbf{Q}_{MM} \end{pmatrix} \tag{3}$$

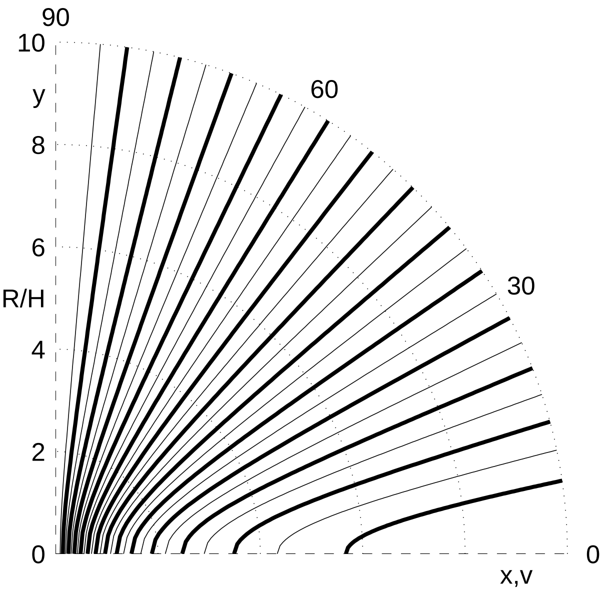


Figure 4: Beam traces (dark lines, only every two curves shown) and isodops for a sidelooking array

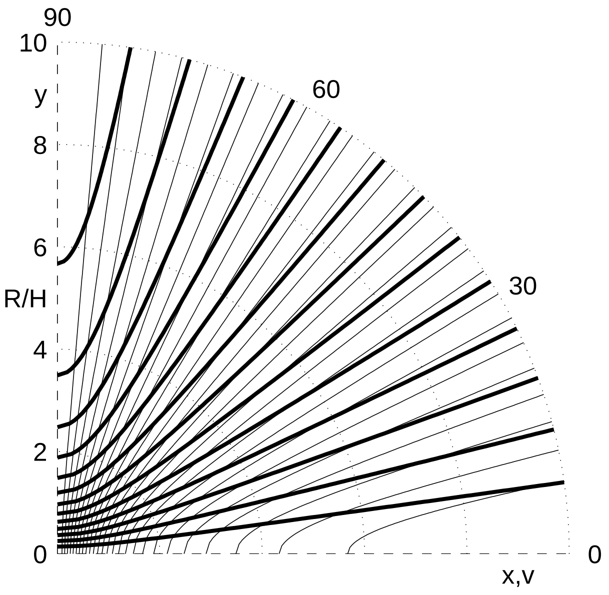


Figure 5: Beam traces (dark lines) and isodops for a forward looking array

Then the optimum processor has the form

$$\mathbf{w}_{\text{opt}} = \gamma \mathbf{Q}^{-1}\mathbf{s} \tag{4}$$

The efficiency of any array processor can be judged by calculating the improvement factor which is the ratio of the $SINR_{input}/SINR_{output}$ (SINR=signal-to-interference+noise ratio):

$$\mathrm{IF} = \frac{\frac{P_{\mathrm{s}}^{\mathrm{out}}}{P_{\mathrm{n}}^{\mathrm{out}}}}{\frac{P_{\mathrm{s}}^{\mathrm{in}}}{P_{\mathrm{n}}^{\mathrm{in}}}} = \frac{\frac{\mathbf{w}^*\mathbf{s}\mathbf{s}^*\mathbf{w}}{\mathbf{w}^*\mathbf{Q}\mathbf{w}}}{\frac{\mathbf{s}^*\mathbf{s}}{\mathrm{tr}(\mathbf{Q})}} = \frac{\mathbf{w}^*\mathbf{s}\mathbf{s}^*\mathbf{w}\cdot\mathrm{tr}(\mathbf{Q})}{\mathbf{w}^*\mathbf{Q}\mathbf{w}\cdot\mathbf{s}^*\mathbf{s}} \tag{5}$$

Figures 6 and 7 show Doppler-azimuth clutter spectra for sidelooking and forward looking linear arrays. In Figures 8 and 9 the improvement factor has been plotted versus the normalised Doppler frequency and azimuth for both array configurations (sidelooking, Figure 8, forward looking, Figure 9). The improvement factor has been normalised to the theoretical maximum. Notice that the maximum IF is reached everywhere in the Doppler-azimuth plane except for the clutter trajectory where the STAP filter generates a clutter trench.

3 Real-time processing aspects

The optimum processor is not realisable in practice if the number of array element and the number of temporal samples are large. A large amount of literature has been dedicated to the design of suboptimum processor architectures which promise clutter sppression in real time. For more details see [11] and [7, Chapters 5,6,7,9].

For example, a most efficient processor is depicted in Figure 10. In this processor the signal vector space has been reduced in two steps in order to reduce the amount of numerical operations required: 1. Reducing the number of antenna channels by forming overlapping or disjoint subarrays (reduction of the spatial dimension); 2. replacing the inverse matrix operation in (4) by a space-time FIR filter (reduction of the temporal dimension). In this way the size of the space time covariance matrix associated with clutter+noise can be reduced dramatically. The clutter suppression performance is near-optimum. There are other architectures with similar efficiency.

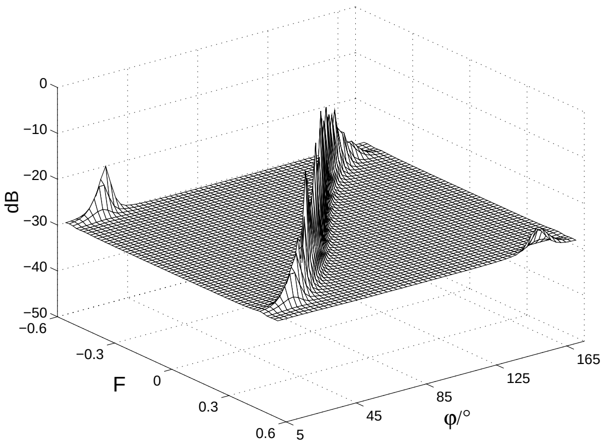


Figure 6: Minimum variance clutter spectrum (sidelooking array, $\varphi_{\mathrm{L}} = 45°$)

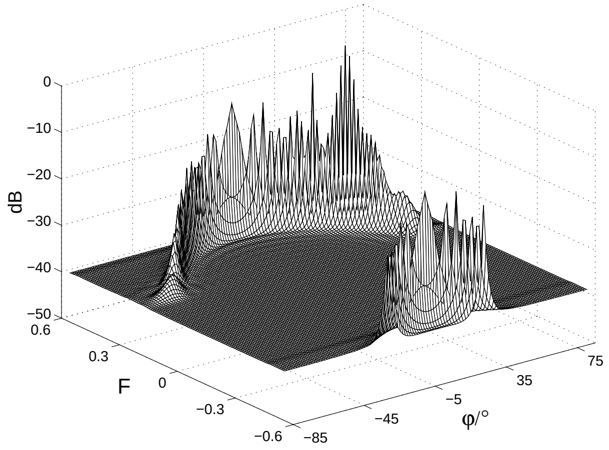


Figure 7: Minimum variance spectrum for forward looking linear array

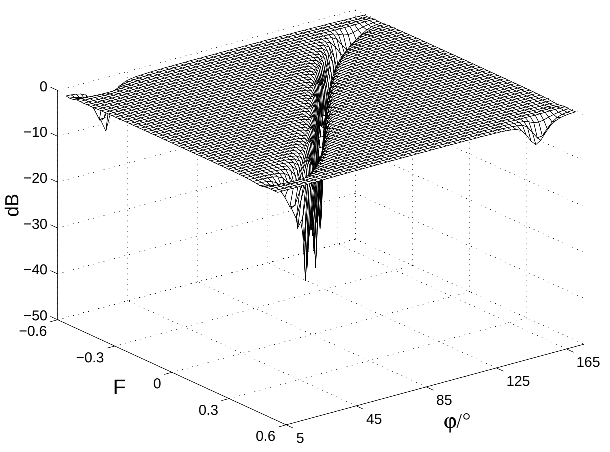


Figure 8: Improvement factor versus normalised Doppler and azimuth (sidelooking array)

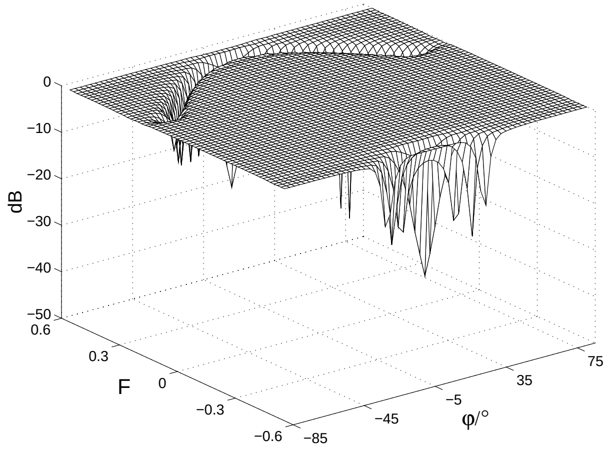


Figure 9: Improvement factor versus normalised Doppler and azimuth (forward looking array)

4 From clutter to reverberation

In Table 2 some properties of radar clutter are compared with sonar reverberation.

4.1 Sensor-background geometry

In airborne or spacebased radar the clutter returns come from an approximately flat or spherical surface. In accordance with (1) the Doppler frequency of the individual arrival is proportional to the cosine of the angle between the direction of arrival and the flight path.

In sonar target echoes as well as reverberation propagate on certain paths which can be described by either ray approximations or, more general, by normal modes. Each propagating mode is a plane wave in the horizontal which arrives at the receiver under a certain vertical and horizontal angle. The total angle between the arriving wavefront and the direction of the platform motion determines the associated reverberation Doppler. The total of all arrivals will sum up in a Doppler-azimuth reverberation spectrum which will look similar to the one shown in Figure 6.

4.2 Environmental conditions

Radar clutter is normally quite stable so that the echoes due to a coherent pulse train preserve their mutual phase relations. The phase history of an echo sequence is used to estimate the Doppler relative

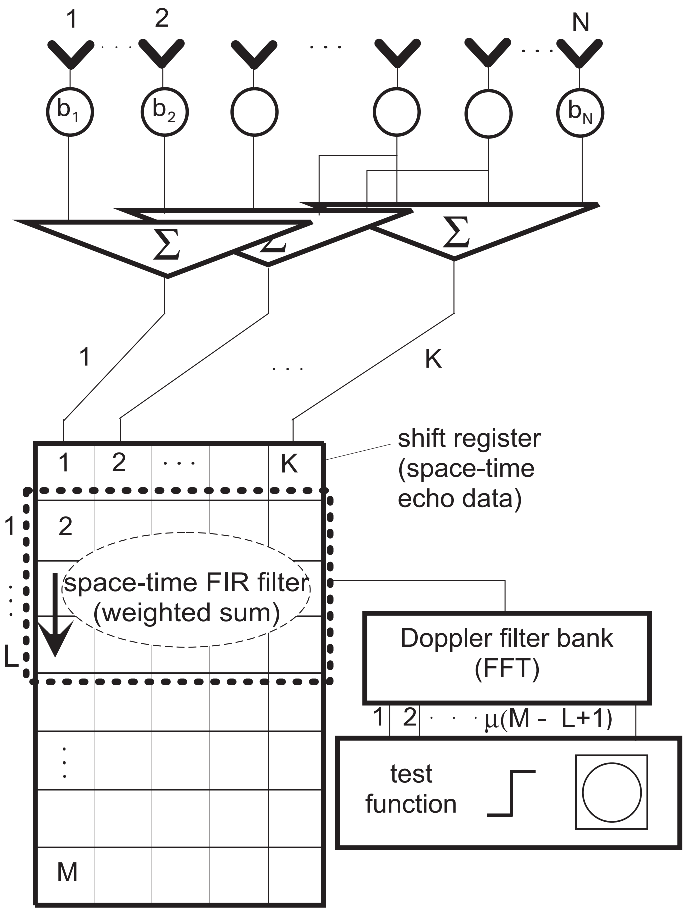


Figure 10: STAP processor with overlapping subarrays and space-time FIR filter

to the radar. Because of the high propagation velocity of electromagnetic waves the pulse repetition frequency can typically be chosen to be 1 to several KHz. Alternatively, it is hardly possible to discriminate a target Doppler of a few KHz at a radar frequency in the order of several GHz. The pulse-to-pulse phase stability, by the way, is the basis for high resolution imaging radar using the synthetic aperture principle. Wind-driven vegetation, clouds, and the sea surface may exhibit some decorrelation between echoes which can be interpreted as a broadening of the clutter Doppler spectrum.

Since the propagation velocity of acoustic waves in water is very low compared with EM waves a pulse-to-pulse processing is normally not possible. There are various sources of uncertainty in the propagation channel (first of all the surface waves, but also effects such as ocean currents, fish schools etc.). That means, normally no pulse-to-pulse signal processing is possible. There are exceptions, for instance short range sonar close to the seafloor. On the other hand, different from radar, the Doppler frequencies are in the order of magnitude of the sonar frequency so that the Doppler can be retrieved from the samples of a single echo.

4.3 Sensor configurations

In airborne radar normally antennas in either flight direction (sidelooking, see Figure 2) or in across-flight direction (forward looking, Figure 2) are used. The forward looking antenna is mainly used in the nose of a fighter aircraft while sidelooking geometries are used for surveillance radar. The antenna shape may be linear or planar or even conformal, with the aircraft fuselage serving as supporting construction.

In sonar basically different array shapes are possible, however the size of across-track apertures is limited due to an increase in flow resistance. Towed arrays are ideal candidates for the application of

STAP because they are linear and may be equipped with uniformly spaced hydrophones. As stated above linear equispaced arrays (and all related arrays with cylindrical shape in the horizontal plane) have a number of beneficial properties concerning the application of STAP:

- The Doppler frequency of clutter (reverbs) received by a moving radar (sonar) is independent of range. Therefore, STAP processing is range independent.
- Because the clutter Doppler is independent of range usually suffient amount of training data for adaptation are available.
- The STAP processor can compensate for spatial decorrelation caused by the system bandwidth
- Based on a linear equispaced array extremely economic STAP processor architectures can be designed (like the one shown in Figure 10).
- Due to the fact, that the Doppler is retrieved from phase variations of subsequent echo pulses, there may be range ambiguous clutter returns. For any array configuration other than sidelooking the ambiguous clutter arrivals may cause additional clutter notches, resulting in additional losses in slow target detection. In a single pulse system such as active sonar this cannot happen.

5 Conclusions

Space-time adaptive processing (STAP) is nowadays a mature technique for detection of slow targets in clutter by a moving radar. It is suggested to apply STAP to active sonar so as to compensate for the platform motion induced clutter Doppler spread. The companion papers in these proceedings [10, 9, 5] confirm that STAP may offer significant progress in active sonar signal processing.

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