Observed results on optimal sample support in space time adaptive processing in radar system

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Abstract: Space Time Adaptive processing (STAP) has been proposed to suppress the clutter in the airborne radar. In STAP covariance matrix of the received signal is employed to carry out the processing. This is often estimated by making use of returns from neighboring range bins of interest. In many simulation results, independent and identically distributed (IID) samples are assumed for the clutter. It is said that the more samples we consider in sample covariance matrix, the better signal-to-interference plus noise ratio (SINR) is achieved in STAP. However, we have found the optimum sample size to achieve maximum SINR in real circumstance. In this paper, we discuss the violation of IID assumption resulting in degradation of SINR using real sea clutter data observed by S-band side-looking airborne radar. The existence of the optimum samples is shown here.

Keywords: radar, clutter, signal processing, STAP

Classification: Sensing

References

[1] J. Ward, Space-Time Adaptive Processing for Airborne Radar, MIT Technical Report 1015, MIT Lincoln Laboratory, Dec. 1994.
[2] J. R. Guerci, Space-Time Adaptive Processing for Radar, Artech House Publishers, NY.
[3] R. Klemm, Space-Time Adaptive Processing Principles and Applications, The Institute of Electrical Engineers, UK.
[4] R. Klemm, “Principles of space-time adaptive processing,” IEE Radar, Sonar, Navigation and Avionics, 2002.
[5] I. S. Reed, J. D. Mallett, and L. E. Brennan, “Rapid convergence rate in adaptive arrays,” IEEE Trans. Aerospace Electron. Sys., vol. AES-10, no. 6, pp. 853–863, Nov. 1974. DOI:10.1109/TAES.1974.307893
1 Introduction

Space Time Adaptive Processing (STAP) is proposed to suppress the clutter in airborne radars [1, 2, 3, 4]. In STAP the covariance matrix of the received signal is employed. The covariance matrix \( R \) and the optimum weight \( w \) are (1) and (2) respectively.

\[
R = E\{C \cdot C^H\} \tag{1}
\]

\[
w = R^{-1}a \tag{2}
\]

where \( C \) and \( a \) denote the space-time interference vector corresponding to the clutter and uncorrelated receiver noise and the space-time steering vector corresponding to the target direction respectively. \( E \) is the operator to estimate its expected value, \( H \) denotes Hermitian transposition.

In real situation, the sample covariance matrix is used and the received signal is used instead of \( C \) with avoiding self-nulling.

The sample covariance matrix \( \hat{R} \) is estimated by making use of returns from neighboring range bins of interest described in (3).

\[
\hat{R} = \frac{1}{K} \sum_{k=1}^{K} X_k \cdot X_k^H \tag{3}
\]

where \( X_k \) denotes the space-time received sample vector for \( k \) th range bin and \( K \) denotes the number of samples used for processing.

Therefore the corresponding weight vector \( \hat{w} \) is described in (4).

\[
\hat{w} = \hat{R}^{-1}a \tag{4}
\]

The processed SINR depends on the number of the samples. In [5], the more samples are employed, the better SINR can be achieved. In [5], the ratio of the expected SINR to optimum SINR \( \rho \) is described in (5).

\[
\rho = \frac{K + 2 - N}{K + 1}, \quad K \geq N \tag{5}
\]
where $N$ is the degree of freedom, which is the product between the number of antenna elements and the number of the processed pulses during coherent processing interval.

According to previous studies [6], $K$ should be greater than or at least equal to $N$ because $\hat{R}$ must be nonsingular. When $N$ is a large number, we should sample the data up to the far range bin from the target range bin. Since the clutter property of far range bins is different from that of the target range bin, the accuracy of the estimated $\hat{R}$ may be degraded.

The simulation results [6] assume that all sample range bins are satisfied with IID, however the clutter property may not always satisfy IID in real environment. That indicates the IID assumption is violated in some real circumstances. Therefore employing too many samples for estimating $\hat{R}$ may degrade the processed SINR after STAP.

To evaluate the effects of the violation and to show the optimum number of samples, we have analyzed the real sea clutter data observed in S-band at the Sea of Japan in winter by the side-looking radar. In case of less samples used for the sample covariance matrix, $\hat{R}^{-1}$ may be singular or inaccurate matrix. Therefore we use the diagonal loading [7] for the small sample case.

Some observed results of STAP are shown in [8, 9]. In their studies, they are measured in X-band and HF and the observed clutter are ground clutter and ionospheric clutter respectively, which are different from sea clutter. And, they did not discuss the relation between the number of samples to make sample covariance matrix $\hat{R}$ and its resultant SINR.

In this paper, we introduce the STAP performance data about real sea clutter, which have seldom been reported. Furthermore, we discuss the violation of IID assumption resulting in degradation of SINR using real sea clutter data observed in S-band. The existence of the optimum samples is shown here.

## 2 Method of processing

We explain the method of signal processing to make sure of the effect on STAP.

First, we explain the way of making sample covariance matrix $\hat{R}$ (3). The received samples are taken from range bins around the target. $K/2$ samples of near ranges and $K/2$ samples of far ranges are used to estimate $\hat{R}$, the center of which is the target range bin. Note that 2 guard cells for both side are not used as samples to avoid self-nulling [2]. Thus, we estimated $\hat{R}$ various samples up to 1024.

Though fully adaptive STAP is difficult to compute $\hat{R}^{-1}$ due to the large matrix size, it is employed in this paper. That is why we want to evaluate the clutter property, though some algorithms are proposed such as JDL STAP [10] in order to reduce the computational load.

Next, we show the way of calculation of SINR. $S$ (Signal) is the amplitude of target’s range bin. $I$ plus $N$ (interference plus noise) are the average of amplitude neighboring 128 range bins except 2 guard cells. Then, we calculate $S/(I+N)$ and express it in decibel.

Note that ordinary S/N optimization filter method is to use only a steering vector as a weight vector,
where \( \mathbf{a} \) denotes the steering vector which is same as weight of STAP (2). After summing the received signals with (6), we applied the pulse compression.

3 Measurement of the clutter

We have observed the sea clutter at the Sea of Japan in winter by the side-looking radar. The radar is mounted on the left side of the aircraft. The array is a uniform linear array which consists of 8 elements. The measurement parameters are shown in Table I. According to the Table I, \( N \) is 256 which corresponds to the product between number of antenna elements 8 and number of processed pulses 32.

The sea state during the measurement is estimated to be 1 according to the wind speed which was 2.0 m/s on average.

| Parameters                          | Setting Value                  |
|-------------------------------------|--------------------------------|
| Aircraft speed                      | 91.47 m/s (177.8 knots)        |
| Aircraft altitude                   | 6,102 m (20,019 feet)          |
| Frequency band                      | S-band                         |
| Pulse Repetition Frequency          | 218 Hz                         |
| Array antenna’s interval            | 0.47 m                         |
| Number of the processed pulses      | 32                             |
| Number of antenna elements          | 8                              |
| Range bin                           | 30 m                           |

4 Results

In this section, we show the results of STAP which is applied for real sea clutter data received in S-band. We also show the comparison between SINR after STAP and one after the ordinary method.

4.1 Comparison between STAP and ordinary method

Fig. 1 shows the A-scope of the sea clutter and the real target signal. The target is a real ship. Amplitude is normalized with the maximum signal (or target’s signal). At the 1,271st range bin, around 60 km, the target is detected and its SINR is 18.2 dB after STAP. Note that in this case, the appropriate number of 400 samples, which corresponds to approximately 12 km, is employed to estimate the covariance matrix, and the diagonal loading is not employed here. Based on the peak search to Range-Doppler map, we decided the steering vector which corresponds to the target. Using STAP, the SINR is improved compared to conventional method. The difference between them is 5.4 dB. Therefore, STAP can improve the performance of SINR compared to ordinary method if the appropriate number of samples is applied.
4.2 Relation between the number of samples and SINR after STAP

Fig. 2(a) shows the relation between the number of range samples and SINR. Without STAP, which means ordinary method, SINR is constant since weight vector (6) does not depend on the number of samples.

In case with STAP with no loading, SINR is worse than one without STAP in the large sample region, the number of which is more than 800, which corresponds to approximately 24 km. This implies that the clutter’s characteristic of target’s range bin is different from the far range bins. Thus, the covariance matrix estimated by too large samples does not represent the clutter’s characteristics at target’s range bin.

We have calculated the statistical values about amplitude of Doppler spectrum. As a result, at far range area that is from approximately 66 km to 76 km, the peak of amplitude and average and standard deviation of Doppler frequency was different from ones at near and around target range from 45 km to 66 km. The difference in the peak positions of the amplitude distribution between far range area and around area is 20.4 Hz which corresponds to 3 Doppler bin and the difference of amplitude between them was 1.5 dB. Therefore, the statistical difference makes SINR worse than one after STAP applied 400 optimal sample support.

In the small sample region, the number of which is less than 256, which corresponds to approximately 7.68 km, the SINR performance is poor because $\hat{R}^{-1}$ may be singular or inaccurate matrix. Therefore we introduce the diagonal loading to estimate the covariance matrix, which can improve rank deficiency and find the contribution to the small samples.

In case with the diagonal loading, SINR is better than one without diagonal loading. When the diagonal loading is employed, the factor of which is 3 dB relative to its noise level, 230 samples are the optimal samples to maximize the SINR, which correspond to around 3.45 km area. In comparison with the components of eigenvalue between 230 samples with diagonal loading and 400 samples without diagonal loading, they are nearly similar. It suggests that the components of eigenvalue represent real clutter signal components precisely.
Fig. 2(b) shows the A-scope of the sea clutter and the real target signal when it is applied STAP with 3 dB diagonal loading with 230 samples support. Using the diagonal loading, the SINR is more improved and the difference between the diagonal loading case and the conventional case is 7.8 dB.

According to (5), the greater the number of samples is, the better SINR is achieved when $K \geq N$. If we use samples more than 800, it degrades the SINR performance compared to one of the ordinary method. This results show that IID cannot be always applied in real circumstance.

![Fig. 2. (a) SINR vs. number of samples including diagonal loading (b) A-scope of the sea clutter and the target signal by STAP with 3 dB diagonal loading with 230 samples support vs. ordinary method](image)

5 Conclusion

We have used the real sea clutter data observed in S-band at the Sea of Japan in winter to evaluate the SINR performance of STAP, which depends on the number of samples along the range. As a result, with the appropriate number of samples, we have found that STAP can improve the SINR better than ordinary method in the observed data, namely too large samples degrade its SINR. This means in real circumstance IID cannot be always applied. As the result of the above discussion, we show that, in the sea state of 1, the appropriate number of samples is 230. That means samples around only 3.45 km area should be used to carry out STAP for this case. To overcome the degradation of $\hat{R}^{-1}$ due to smaller number of samples mentioned above, the diagonal loading was applied. The resultant SINR was improved when 3 dB loading factor was chosen.

We will continue to collect the real sea clutter data about various conditions, for instance other sea state, weather condition, etc. Furthermore, we need to find the optimum samples in STAP according to sea clutter’s condition.

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