INTEGRATION OF HFSW RADAR AND AIS DATA: SHIP DETECTION AND CLASSIFICATION

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ABSTRACT

This paper focuses on the possibility of combining Automatic Identification System (AIS) and High-Frequency Surface-Wave Radar (HFSWR) data for vessel detection, tracking and classification purposes. The test based on the Normalized Adaptive Matched Filter (NAMF) is applied for target detection in compound-Gaussian HF sea clutter. The unknown clutter covariance matrix is evaluated by means of three adaptive estimators. The detection algorithms are described and their performances evaluated based on data recorded in the Bay of Brest, France. Finally, the combined use of AIS plots provided by cooperative targets allows to evaluate the performances of the proposed algorithms and to discriminate uncooperative targets and possible threats.

1. INTRODUCTION

In recent years, both national and international organizations have put significant efforts in developing knowledge-based integrated maritime surveillance (IMS) systems. The aim is to have a clear picture of the position and movement of cooperative and uncooperative targets, for efficiently dealing with fisheries protection, drug interdiction, illegal immigration, terrorist threats, search and rescue operations. Each sensor (i.e. satellite-based, ground-based, shipborne or airborne) has its own task and, in such a context, low-power HFSWR radars can be reliable and inexpensive tools for long range early-warning applications in open waters. The WEllen Radar (WERA) system, developed at University of Hamburg, is such a sensor [1]. This paper focuses on the possibility of combining AIS and HFSWR data for vessel detection, tracking and classification purposes. The NAMF test is applied for target detection in compound-Gaussian HF sea clutter [2]. The unknown clutter covariance matrix is evaluated by means of three adaptive estimators, i.e. the Sample Covariance Matrix (SCM), the Normalized Sample Covariance Matrix (NSCM) and the Fixed Point (FP) or Approximate Maximum Likelihood (AML) [3]. The algorithms are described and their performances evaluated based on recorded data. Finally, the combined use of AIS plots provided by cooperative targets allows the operator to evaluate the performances of the proposed algorithms and to discriminate uncooperative targets and possible threats [4]. The concurrent exploitation of AIS and HFSWR data is presented and discussed by means of simulations with real data recorded during the NURC experiment in the in the Bay of Brest (France) in May 2008.

2. THE WERA RADAR SYSTEM

HFSWR systems have the capability to detect and track surface and airborne targets beyond the horizon. The radar operating frequency is in the 3 to 30 MHz range (with wavelengths spanning between 100 and 10 m). In this interval the radio waves still propagate in line-of-sight mode but vertically polarized HF waves have the added ability to propagate as surface waves as long as the surface is conductive due to salinity. This property gives HFSW radar the capability to operate beyond the horizon and makes it the only system that can address the requirement for affordable shore based radar capable of detecting and tracking cooperative and uncooperative targets beyond the 200 nautical mile limit of the EEZ. WERA is a shore-based low power HFSW radar developed at University of Hamburg, mainly for oceanic applications and remote sensing, i.e. wave spectra, winds and currents monitoring [1]. However, recently, it has been demonstrated that WERA can be effectively used also for detecting and tracking ships [5].

3. DETECTION IN COMPOUND-GAUSSIAN SEA CLUTTER

Sea clutter in the HF band can deviate from being a complex Gaussian process, however, it can be still modeled as a compound-Gaussian process [6]. Target detection in compound-Gaussian clutter has been the subject of intensive investigations and several papers appeared during the last 20 years [2], [3]. However, only a small amount of work has been done in this sense for HF systems. The problem of
detecting a target-originated signal in additive clutter can be posed in terms of the following binary hypotheses test:

\[
\begin{cases}
H_0: \mathbf{z} = \mathbf{c} \\
H_1: \mathbf{z} = \mathbf{s} + \mathbf{c'}
\end{cases}
\]

(1)

where \( \mathbf{z} \), \( \mathbf{s} \) and \( \mathbf{c} \) are \( \mathbb{C}^{N \times 1} \) vectors from the complex envelope of the received signal, the target and the clutter in the Cell Under Test (CUT), respectively. Unfortunately, clutter statistics, and thus the covariance matrix, are often unknown. A classical solution is to estimate the covariance matrix of the disturbance using training data from \( K \) adjacent range cells (where \( K > N \)), which are assumed free of targets and interferences. Denote by \{\( \mathbf{z}_i, \mathbf{z}_{i+1}, \ldots, \mathbf{z}_k \)\} the set training data vectors in \( K \) cells centered around the CUT. The signal is modeled as \( \mathbf{s} = \alpha \mathbf{p} \), where \( \mathbf{p} \) is the steering vector defined as:

\[
\mathbf{p} = [1 \ e^{j2\pi fT} \ \ldots \ e^{j2\pi(N-1)fT}]^T,
\]

(2)

and \( \alpha \) is an unknown parameter accounting for the channel propagation effect and the radar cross section. The clutter \( \mathbf{c} \) is modeled as a compound-Gaussian (CG) process which consists of a complex Gaussian process \( \mathbf{x} \) (“speckle”), modulated by a slowly-varying non-negative random process \( \tau \) (“texture”). It holds that \( \mathbf{c} = \sqrt{\tau} \mathbf{x} \), where the speckle vectors are a sequence of independent, identically distributed, circular complex Gaussian vectors with zero-mean, unit power and positive definite covariance matrix \( \mathbf{M}_c = E(\mathbf{x}\mathbf{x}^H) \). The structure of the NAMF test is then [2]:

\[
\frac{[\mathbf{p}'\mathbf{M}^{-1}\mathbf{z}]^H}{[\mathbf{p}'\mathbf{M}^{-1}\mathbf{p}]^{1/2}} \thicksim \chi_{\nu}^2,
\]

(3)

where \( \hat{\mathbf{M}} \) is an estimate of \( \mathbf{M} \) obtained from the training set and \( \mathbf{M} \) is the covariance matrix of the clutter:

\[
\mathbf{M} = E(\mathbf{c}\mathbf{c}^H) = E(\tau)E(\mathbf{x}\mathbf{x}^H) = \sigma^2 \mathbf{M}_c,
\]

(4)

where \( \sigma^2 = E(\tau) \) is the average clutter power. Note that the NAMF test requires the evaluation of \( \hat{\mathbf{M}} \). Three covariance matrix estimators have been considered: the SCM, the NSCM and the FP, also referred to as AML, expressed respectively by [6]:

\[
\hat{\mathbf{M}}_{\text{SCM}} = \frac{1}{K} \sum_{i=1}^{K} \mathbf{z}_i \mathbf{z}_i^H,
\]

(5)

\[
\hat{\mathbf{M}}^{(l+1)}_{\text{AML}} = \frac{N}{K} \sum_{k=1}^{K} \mathbf{z}_k^H [\hat{\mathbf{M}}^{(l)}_{\text{AML}}]^{-1} \mathbf{z}_k,
\]

(6)

\[
\hat{\mathbf{M}}^{(1)}_{\text{AML}} = \hat{\mathbf{M}}_{\text{NSCM}},
\]

(7)

where \( l \) is the \( l \)-th iteration. Generally 2 or 3 iterations are sufficient [3].

### 4. THE NURC EXPERIMENT

Data were collected during the NURC experiment at Brest (Brittany, France), on May 13, 2008. The two WERA systems, respectively located at the Bay of Brest, at Brezellec (Latitude 48° 4' 8'' N, Longitude 4° 46' 0'' W) and Garchine (Latitude 48° 30' 10'' N, Longitude 4° 46' 32'' W) are owned by the French Service Hydrographique et Océanographique de la Marine (SHOM) and operated by the company SAS ActiMar. The two radars, located parallel to the coast, point towards the true North with an angle of 20° and 339° respectively, as shown in Fig. 1.

Some results are presented in this paper and refer to 8 non consecutive datasets (8 minutes and 52 seconds each) collected at Garchine and Brezellec since 00:00:00 through 02:38:52 on May 13, 2008. The two detectors have been implemented by choosing two different types of window, i.e. \( K = 12, N = 8 \) and \( K = 24, N = 16 \). These choices have demonstrated a good compromise for assuming clutter as stationary both in space and time [6].

The Receiver Operating Characteristics (ROC) of the two radars have been evaluated. Figures 2,3 describe the behavior of \( P_\text{FA} \) as a function of the Signal-to-Clutter Ratio (SCR) and Doppler, given \( P_\text{FA} = 10^{-3} \) for range cells 30 and 80 respectively. The effect of sea clutter is unwelcome since detection performances significantly degrade in correspondence of the two Bragg peaks (Fig. 2). As range increases, sea clutter becomes negligible and performances tend to have a quasi-constant trend along Doppler (Fig. 3).

Several techniques can be successfully applied to deal with the problem of ship tracking in HF radars. A simple \( \alpha - \beta \) filter has been proposed and discussed, applied to the WERA system [5].

AIS plots provide a significant benefit for an operator to de-emphasize the known tracks and thereby focus on the unknown and potentially more threatening ones. This, of course, implies there are tracks for the unknown targets. Once the tracks are given, the Hough transform can be a precious tool for validating them [7].

A first distinction between cooperative and uncooperative targets is provided by comparing the HF track plots against the AIS data and verifying which of the tracks is originated.
by cooperative or uncooperative ships. Uncooperative targets can be also small fast going boats or immigrant boats which can need help because in great danger. Such events should be avoided.

5. CONCLUSIONS

In this paper an IMS system which exploits HFSWR and AIS data has been presented. Long range vessel detection and classification can be achieved with a very simple system composed of two concurrently operating WERA systems, whose detections are corroborated by AIS tracks. Three covariance matrix estimators typically employed with high resolution radars (i.e. the SCM, the NSCM and the AML) have been applied to the NAMF test for dealing with the problem of target detection in compound-Gaussian clutter. The detection capabilities of the WERA system have been analyzed and compared with ground truth data provided by AIS data from cooperative targets. On the other hands AIS tracks can be exploited for pruning cooperative tracks and instead focusing on more threatening ones.

8. REFERENCES


