Adaptive Transient and CW RF Interference Mitigation in HF OTH Radar: Experimental Results

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Abstract—We introduce an adaptive technique for the joint mitigation of transients and continuous-wave radio-frequency co-channel interference (CW RFI) in high-frequency (HF) over-the-horizon radars (OTHRs). The performance of this technique is illustrated using data from an operational surface-wave radar (SECAR) and from recent experimental trials with sky-wave (SW) and sky-wave–line-of-sight (SKYLOS) HF OTHRs.

I. PROBLEM FORMULATION

It is the various propagation modes of HF signals (5–30 MHz), involving sky-wave (ionospheric), surface-wave (over the highly conductive ocean surface) and line-of-sight propagation, that necessitate the variety of OTHR configurations and architectures. In addition to conventional sky-wave radars (such as the Australian JORN system [1]) and surface-wave radars (such as the Australian SECAR radar [2]), radar systems that exploit sky-wave–line-of-sight (SKYLOS) and sky-wave–surface-wave (SKYSURF) modes are under investigation. Each of these systems addresses different operational requirements and therefore their architectures may vary significantly. For instance, receive antenna arrays in modern sky-wave radars may consist of several hundreds of digitised sensors; in surface-wave radars the number rarely exceeds a few dozen, whilst a SKYLOS configuration may involve just a single receive element.

Yet each of these radar systems has to operate within the environment congested by human and natural interferences. The main sources of natural interferences are lightning strikes (atmospheric) which could be of very high power, with a duration of only a few (often just one) repetition intervals. Due to high sensitivities and receive antenna gains, modern sky-wave radars may consist of several hundreds of digitised sensors; in surface-wave radars the number rarely exceeds a few dozen, whilst a SKYLOS configuration may involve just a single receive element.

The mitigation algorithm which combines adaptive transient and CW RFI mitigation, may be outlined as follows:

1. Detect sweeps and ranges affected by transients arriving via the main beam (separately for each finger-beam within the coverage).
2. Select training ranges and sweeps that are free of transients affecting that particular beam direction, to be used as beam-specific training data for CW RFI mitigation via adaptive beamforming, and remove clutter.
3. Using the beam-specific estimates of the spatial covariance matrix \( R(\theta_j) \), perform adaptive beamforming for CW RFI and “sidelobe-transient” mitigation.
4. Perform transient mitigation by adaptive temporal processing at the output of the adaptive beamformer with
mitigated CW RFI and “sidelobe transients”. For SKYLOS configurations, steps 1 and 2 must be performed for each antenna element (i.e., no beamforming).

A. Impulsive Noise and Transient Detection

In some cases (surface-wave radars, for example) access to ranges not occupied by ground clutter may be available. These “training” ranges may be directly used for detecting lightning strikes (impulsive noise) and RFI training data. Yet, transients cannot be detected in the same way, since they are affecting only limited number of ranges (and usually operationally important ones). Moreover, in most current OTHR systems, digital range processing is performed for operationally important ranges only. Therefore, transient detection has to be performed within the background of strong clutter reflection.

To achieve this, an adaptive moving-target-indicator (MTI) filter is designed at the output of each conventionally formed finger-beam, with the minimal number of sweeps involved

$$W(j, d) = \frac{\hat{R}_n^{-1}(j, d) e_1}{e_1^T \hat{R}_n^{-1}(j, d) e_1}$$

where

$$\hat{R}_n(j, d) = \sum_{l=1}^{N-n} [X_l^d(j)(X_l^d(j))^H + J X_l^d(j)(X_l^d(j))^H]$$

with

$$X_l^d(j) = [x_l^d(j), x_{l+1}^d(j), \ldots, x_{l+n-1}^d(j)]^T$$

and $$x_l^d(j)$$ is the complex number that corresponds to the l-th repetition period sample for the d-th range cell at the output of the j-th finger-beam.

The shortest “memory” n of the MTI filter is required since it specifies the number of sweeps affected by a single impulse at the output of the MTI filter. This number depends on the radar operation mode, but even for a ship detection mode with the longest sweeps, the sufficient number is shown to be reasonably small.

Simple power comparison of the strong transients clearly detectable at the output of a single antenna element and a given beam allows us to discriminate such a strike as a “main-beam” or a “sidelobe” one. Typically, though, most of the transients detected are “main-beam” ones due to the high gain and low sidelobe level of conventional beamforming. Transients and impulsive-noise strikes are detected at the output of the MTI filter, and we declare that the entire sweep is affected by impulsive noise (not a transient) if most of the range cells are affected in the same sweep.

B. CW RFI Adaptive Mitigation

The main distinction of the proposed technique and conventional adaptive beamforming is the beam-dependent selection of the training data at the output of the antenna array elements. Specifically, when training data is collected for adaptive beamforming in the direction $$\hat{\Theta}_j$$, all transients (i.e., affected range cells and repetition intervals) detected in Stage A are removed. Since for each finger-beam direction, the set of affected range cells and repetition intervals is different, we end up with a beam-tailored set of training data. If, say, a conventional LSMI beamformer is used, then the M-element adaptive beamformer vector is calculated as

$$\hat{W}(\Theta_j) = \frac{\hat{R}_l(\Theta_j)^{-1} S(\Theta_j)}{S^H(\Theta_j) \hat{R}_l(\Theta_j)^{-1} S(\Theta_j)}$$

where

$$\hat{R}_l(\Theta_j) = \sum_{k\in\Omega_j} X_{k,\tau}(\Theta_j)X_{k,\tau}^H(\Theta_j) + \alpha I_M$$

$$\alpha$$ is loading factor; $$k, \tau$$ is the selected range and repetition interval; $$X_{k,\tau}(\Theta_j) \in C^{M \times 1}$$ is the M-variate vector collected at the output of the M-element antenna array at the range k and repetition interval $$\tau$$ at the output of the MTI filter; $$\Omega_j$$ is the set of all range cells and repetition intervals, selected as training for the direction $$\Theta_j$$.

Note that a more sophisticated time-varying adaptive techniques ("stochastically constrained" for example [4]) may be also applied using the direction-dependent set of training data.

C. Impulsive Noise and Transient Mitigation

As a result of CW RFI mitigation at the output of a particular adaptive beamformer, the clutter-to-noise ratio has increased. If required, steps A and B may now be repeated with better clutter mitigation and therefore weaker transient detection. Ultimately, when no further transients are detected, the RFI-cleared sweep data for each range cell and beam output may be once again used for clutter covariance matrix estimation via “sliding window” forward-backward averaging over the entire CPI. In this averaging, similar to (2), sweeps affected by transients are replaced by zeroes, and sufficiently homogeneous neighbouring range cells data may be averaged over to improve the statistical reliability of this covariance matrix estimate $$\hat{R}_d$$. In contrast with the MTI filter with minimal filter memory, the dimension of the covariance matrix $$k$$ is selected close to the maximum, $$k \sim N/3$$, where N is the number of sweeps in the CPI. The rationale behind maximal order $$k$$ selection is that within the k-long “sliding window” the number of “missing” sweeps affected by transients $$m$$ is still significantly smaller than the number of “proper” clutter samples, i.e.

$$k - m \gg m$$

which means that interpolation of the “missing” clutter sweeps is efficient.

Let us introduce a $$k \times (k - m)$$ incidence matrix $$H_m$$ that is constructed from the identity matrix with $$m$$ deleted rows at positions that correspond to the “missing” sweeps. Then the adaptive prediction filter that generates an estimate of the p-th missing data is defined as

$$W_p^d = \left[H_m^T \hat{R}_d H_m\right]^{-1} H_m v_{p}^d \quad p = 1, \ldots, m.$$  

where $$v_{p}^d$$ is the p-th column of the M-variate matrix $$\hat{R}_d$$. Correspondingly, the estimate $$\hat{z}_p^d$$ (for the range cell d and the particular beam) is calculated as

$$\hat{z}_p^d = \hat{W}_p^d H_m^T x_{p}^d \quad p = 1, \ldots, m.$$
where $X^d$ is the $k$-variate data within the “sliding window”, and $H^d_k X^d$ is the vector of $(k - m)$ “proper” sweeps.

When the number of sweeps affected by transients is reasonable high ($K - m \gtrsim m$), this step may be repeated, with predicted clutter values used instead of zeroes in the covariance matrix estimate.

We have described the main principles of our suggested routine, while it should be clear that the implemented operational routine requires some “fine tuning”.

III. EXPERIMENTAL RESULTS

An adaptive algorithm similar to one described above has been successfully implemented as an operational real-time algorithm in the SECAR surface-wave radar. The joint transient and CW RFI mitigation algorithm described above was implemented as a prototype algorithm for sky-wave radar in ship mode and also as a post-processing algorithm in the SKYLLOS experiment. In Fig 1, we illustrate the results of conventional beamforming and Doppler processing for surface-wave radar, compared with the post-adaptive processing results. A significant improvement in clutter visibility is clearly seen.

Fig 1(d) shows “non-Dopplerised” data (range-time data) in which one can clearly observe impulses created by lightning strikes in the “negative range” (below the direct-wave signal). As mentioned, in this application Step A is used for detecting transients created by reflections from meteors.

In Fig 2, we present the results of sky-wave radar data processing, collected in ship mode. We compare results of conventional beamforming and Doppler processing (Fig 2(a)), with the results of transient-mitigation only (Fig 2(b)) and the results of joint transient and CW RFI mitigation (Fig 2(c)). We again observe a significant reduction in the “noise floor” power. In particular, a transponder signal became clearly detectable as a result of the adaptive processing.

Finally, we present results using data from recent SKYLIOS trials that occurred during the launch of NASA Space Shuttle mission STS-118. The space shuttle was launched on 8 August 2007 at 22:36:46 UTC. We have processed the collected data by the above described method using one element (channel data), two and three elements (adaptively beamformed data). For the beamformed data we used only beam pointing in the direction of the shuttle’s flight. We used dwells consisting of 256 sweeps, with the shift between dwells being 32 sweeps (i.e., two consecutive dwells share 224 sweeps). We processed ten minutes of data which gives just over 920 dwells to evaluate.

In Fig 4(a), we show channel 1 after conventional processing. On the $y$ axis we show time; each line represents one dwell. On the $x$ axis we show Doppler cuts for six ranges (17–22) (i.e., the first 256 pixels are all the Dopplers for range 17, second 256 pixels are all the Dopplers for range 18 etc). Fig 4(b) shows channel 1 after impulsive-noise and transient mitigation only (as we need more than one element for SAP); Fig 4(c) shows adaptively beamformed data using channel 1 and 2; Fig 4(d) shows adaptively beamformed data using all three channels. The space shuttle track can be clearly seen in all three figures after our processing, whilst some portions of the track are not visible after conventional processing.

Fig 3 compares the median noise levels of the conventionally processed first channel, impulsive-noise mitigation of the first channel, impulsive and spread-noise mitigation using the first and second channels, and impulsive and spread noise mitigation using all three channels.

IV. CONCLUSIONS

The presented results demonstrate that the proposed combined adaptive processing technique gives a significant improvement of signal-to-noise ratio with respect to both transient and CW RFI in OTHRs with various configurations, specifically sky-wave, surface-wave and SKYLLOS.

REFERENCES


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Fig. 1. Surface-Wave OTHR data.
Fig. 2. Sky-Wave OTHR data.

Fig. 3. Comparison of median noise levels for SKYLOS data.
Fig. 4. Skylos OTHR data.