Abstract—High Frequency (HF) skywave over-the-horizon (OTH) radar is routinely affected by radio frequency interference (RFI) from natural sources (e.g. lightning), and transmissions from other users, such as continuous-wave (CW) signals. Although adaptive processing effectively mitigates interference and noise, it can impact negatively upon target detection in some cases. This paper describes a simple filtering technique, harmonic least-squares fitting (HLSF), which has potential for application throughout the OTH radar signal processing chain. In this paper we illustrate HLSF application for clutter suppression, transient detection, and CW interference suppression. In each instance HLSF application demonstrates advantages over commonly used techniques.

I. INTRODUCTION

High frequency (HF) skywave over-the-horizon (OTH) radar uses the ionosphere as a propagation medium, allowing target detection and tracking at ground ranges from 1000 to 3000 km [1]. OTH radar performance is primarily influenced by the ionosphere and the HF interference and noise field. Current generation OTH radars incorporate a frequency management system (FMS) [2] which continuously monitors the ionosphere using vertical, oblique and backscatter sounders, and a scaled-down version of the radar known as the mini-radar. The FMS also employs a HF spectrum monitor, and while every attempt is made to select clear frequency channels, it is impossible to completely avoid radio frequency interference (RFI) since natural RF sources and transmissions from other HF users may overlap the receiver bandwidth intermittently and unpredictably.

The HF interference and noise environment motivates the use of adaptive processing in OTH radar. The adaptive processing is usually applied after range processing, and in most cases, after beamforming. Transient interference, such as lightning, ionospheric sounders and meteor echoes, is typically suppressed using auto-regressive (AR) linear prediction to replace bad samples [3]. Interference present throughout the radar dwell is typically suppressed using sample matrix inversion (SMI) minimum variance distortionless response (MVDR) techniques [4]. The MVDR approach yielding best target detection and tracking performance is dependent on the prevailing interference and noise conditions. Although MVDR adaptive processing effectively mitigates interference and noise, it can impact upon target detection in two ways. First, weak targets may be included in the training data, and hence can be suppressed with the interference and noise. Second, MVDR processing can produce target copy [5], where targets and/or ionospheric clutter (e.g. meteor echoes, spread Doppler clutter) are copied into other surveillance beams (or ranges) from sidelobes in the adaptive beam (range) pattern.

There is increasing interest in cognitive radar throughout the radar community [6]. Current generation OTH radars incorporate cognitive radar concepts through the FMS, which demonstrates receiver-transmitter feedback by providing advice on operating frequency and waveform parameters. Intelligent signal processing has been demonstrated through the development of a performance assessment (PA) module [7], allowing selection of the MVDR adaptive processing algorithm best suited to mitigating the prevailing interference and noise conditions from an adaptive processing suite, and the selection of appropriate data windows for azimuth, range and Doppler processing [8]. Receiver-transmitter feedback can be extended using environmental information (e.g. surface clutter power) available from radar surveillance. However, the effectiveness of this approach is currently limited by the MVDR adaptive processing, which can corrupt the clutter signal due to target-copy effects. Intelligent signal processing can also be extended by expanding the adaptive processing suite to include algorithms tailored to mitigate specific interference types, such as continuous-wave (CW) interference. The limitations of MVDR adaptive processing also motivates the investigation of alternative adaptive processing approaches which minimise the impact upon subsequent processing steps.

This paper describes a simple filtering technique, harmonic least-squares fitting (HLSF), which has application to clutter suppression, transient detection, and CW interference suppression. The paper is organised as follows. Section 2 describes CW interference and its impact upon OTH radar. Section 3 describes the HLSF technique. Section 4 describes HLSF application of clutter suppression and transient detection for azimuth-range-time (ART) data. Section 5 describes HLSF application for CW interference suppression using pre-range data. Section 6 presents the conclusions.
II. CONTINUOUS-WAVE (CW) INTERFERENCE

After range and Doppler processing, a CW signal with carrier frequency $f_0$ is observed at all ranges at Doppler frequency $d_0 = \text{mod} (f_0 - f, f_w)$, where $f$ is the radar operating frequency and $f_w$ is the waveform repetition frequency. An example of CW interference observed for a selected beam of azimuth-range-Doppler (ARD) data during an experimental data collection with typical air-mode surveillance system parameters using the JORN Laverton OTH radar is shown in Figure 1a. The CW interference is observed at Doppler index $d = 34$, and has the potential to deny detection of targets with this Doppler index. The signal centered on zero Doppler is surface clutter, while the signal observed at multiple Doppler indices at range index $r = 70$ is a meteor echo. A weak target-like signal is seen at $(r, d) = (6, 50)$. A synthetic target with power comparable to the CW interference has been inserted into the CW interference at $(r, d) = (50, 34)$.

The main source of CW interference in OTH radar is amplitude modulated (AM) radio transmissions. Other forms of CW interference include on-off keying (OOK), amplitude shift keying (ASK) and phase shift keying (PSK) signals from military and amateur communication systems. Strong CW interference is typically detected by the FMS spectral monitor, and the offending frequency is precluded from the clear frequency channel list used for radar surveillance. However, due to the increased sensitivity of the surveillance system with respect to the FMS system, weaker CW interference that is not detectable by the FMS spectral monitor may still be sufficiently strong to impact upon surveillance ARD data. AM radio transmissions also contain sideband signals which spread homogeneously throughout range-Doppler space. Sideband interference is typically observed at power levels 20-30 dB below the CW interference, potentially denying target detection at all ranges and Dopplers. However, AM radio transmissions strong enough to produce sideband interference are typically detected by the FMS spectral monitor.

CW interference may also be observed due to other HF users commencing transmission within the current surveillance frequency channel, or due to changes in ionospheric conditions allowing propagation paths between a CW transmitter and the radar receiver that were previously unavailable. In these instances, the FMS spectral monitor will eventually detect the new interference, preclude the offending frequency from the clear frequency channel list, and change operating frequency accordingly. However, any dwellings collected in the interim will necessarily be affected by the CW interference. These scenarios motivate the use of adaptive processing to mitigate CW interference.

In addition to the target detection impacts described in section I, MVDR adaptive processing can also oversuppress CW interference. MVDR adaptive processing is typically applied using the sample support condition $Q < P/2$, where $P$ is the number of training samples and $Q$ is the number of adaptive degrees of freedom [4]. This condition ensures the adaptively processed data power loss is less than 3 dB. If the training data is dominated by CW interference, the number of training samples becomes effectively equal to the number of Doppler frequencies occupied by the CW interference. Thus although the total number of training samples may satisfy the sample support condition, the total number of CW interference samples does not, resulting in the oversuppression of the CW interference and any targets beneath. Figure 1b shows the results of applying space-time adaptive processing (STAP) [9] to the data shown in Figure 1a. STAP is applied using training data from all ranges and Doppler indices where surface clutter is not present. STAP fails to remove all of the CW interference, except around $r = 60$, where the CW interference is oversuppressed. The synthetic target has been significantly attenuated, and the meteor echo has been spread to all Doppler indices. The clutter signal has also been corrupted, particularly around $(r, d) = (39, 2)$ and $(50, 62)$, thereby affecting surface clutter power estimation accuracy.

The limitations of MVDR adaptive processing for suppressing CW interference motivates the investigation of alternative approaches, such as the filtering techniques described in the following section.
III. HARMONIC LEAST-SQUARES FITTING (HLSF)

Consider the common problem of filtering a known frequency $f_0$ from a signal

$$x = [x_1, ..., x_i, ..., x_N]^T$$

sampled at times $t_i = (i - 1)/f_s, i = 1, ..., N$, where $f_s$ is the sampling frequency, and $T$ denotes matrix transpose. This problem can be addressed using a notch (band stop) filter to attenuate frequencies about $f_0$ while passing most other frequencies unaltered. However, notch filters are problematic for filtering data with limited samples, such as range-processed OTH radar dwells which typically contain 64-256 sweeps, as the filter delay limits the filter order (number of filter taps) that can be used. Since the stop band width is inversely proportional to the filter order, the required low filter order produces a stop band which also includes frequencies adjacent to that which we seek to notch. This problem is exacerbated if we seek to remove a number of adjacent or discrete frequencies.

An alternative approach to this problem is through the use of harmonic least-squares fitting (HLSF) [e.g. 10]. Given an arbitrary set of harmonic frequencies $f_j, j = 1, ..., M, M \leq N$, that we seek to remove, we describe the signal $x$ in terms of a weighted sum of the orthogonal complex harmonics and a residual $\hat{x}$

$$x = \sum_{j=1}^{M} w_j^* w_{t_i} \exp(j2\pi f_j t_i) + \hat{x}. \quad (2)$$

where $w_j$ is the complex valued weight for frequency $f_j$, $w_{t_i} \in [0, 1]$ is the real valued sample weight applied to each sample $t_i$, and * represents complex conjugate. This can be expressed in matrix form as

$$x = W^t A w^H + \hat{x}. \quad (3)$$

where $w = [w_1, ..., w_i, ..., w_M]^T$ is the frequency weight vector, $A$ is the harmonic matrix with elements

$$A_{ij} = \exp(j2\pi f_j t_i), \quad (4)$$

$W$ is the diagonal matrix of sample weights with elements $W_{t_i} = w_{t_i}$, and $H$ denotes Hermitian (complex conjugate). The weight vector $w$ can be determined by minimising the residual using least-squares, yielding

$$\hat{w} = (A^H W_t A)^{-1} A^H W_t x. \quad (5)$$

The filtered signal is then given by

$$x_h = x - A \hat{w}^H. \quad (6)$$

HLSF can be applied in three ways, as demonstrated throughout this paper:

1) using unity sample weights
2) using unity sample weights, except for outlier samples (e.g. missing data, strong impulses) where zero sample weights are used
3) iteratively, with unity sample weights for the first iteration, and sample weights set to the reciprocal of the filtered signal amplitude for subsequent iterations.

HLSF offers two significant advantages over the notch filter: it has no filter delay, and the stop band is limited to the frequencies used in the fit. The latter is a consequence of the orthogonality of the complex harmonics used in the fit.

IV. HLSF APPLICATION FOR CLUTTER SUPPRESSION OF AZIMUTH-RANGE-TIME DATA

Clutter suppression of ART data $z(b, r)$ at beam/range indices $(b, r)$ is typically performed during the OTH radar signal processing chain for two purposes:

1) detection of transient signals, such as lightning, ionospheric sounders and meteor echoes.
2) training data provision for MVDR adaptive processing.

The clutter signal $z_c(b, r)$ is often modelled using an adaptive finite impulse response (FIR) filter with coefficients derived from an auto-regressive (AR) model [3]. Transient signal samples $t_{bs}, i = 1, ..., K$, are typically detected by calculating the residual of the original and clutter signals

$$z_c(b, r) = z(b, r) - z_e(b, r) \quad (7)$$

and using amplitude thresholding

$$|z_c(b, r)| > T, \quad (8)$$

where $T$ is a selected threshold. The AR-FIR filtering technique is limited by the FIR filter delay, which prohibits the ability to detect transients in the first $L$ samples, where $L$ is the FIR filter order. The AR-FIR filtering technique is also limited by transient effects, and can be seduced by the transient signals, as is illustrated below.

HLSF provides an alternative to the AR-FIR filter for ART data clutter suppression. In this case, the clutter Doppler frequencies represent the harmonic frequencies to be filtered from the time-series. The harmonic frequencies can be determined by finding all Doppler frequencies $d_j$ about zero Hz where the power spectrum exceeds a pre-selected threshold above the noise floor. Figure 2 shows clutter Doppler frequency selection for a typical beam/range of air-mode surveillance ARD data, and the resulting HLSF clutter filtered data. The HLSF clutter filter removes only the clutter Doppler frequencies, leaving the remaining Doppler frequencies unchanged. Unlike the AR-FIR filter which models clutter and strong targets, the HLSF models only the clutter. For transient detection, special care must therefore be taken to ensure that high valued HLSF residual target samples are not mistaken as transients. This can be achieved using a detection threshold $T$ dependent upon the median signal level of the residual time-series.
Figure 3 illustrates the application of the AR-FIR and HLSF clutter suppression techniques for a selected beam of air-mode ART data. The AR-FIR data is applied using a 7-th order AR model \((L = 7)\), while the HLSF is applied iteratively using two iterations. A transient signal is seen at all ranges at sweep index \(t = 41\), indicating a signal which is not coherent with the transmitted radar waveform. This response is typical of a lightning echo or a frequency swept ionospheric sounder. The transient is well defined in the HLSF data, but it is smeared to subsequent samples in the AR-FIR data due to the transient response of the FIR filter. A meteor echo is seen at \((r, t) = (67, 30)\) in the HLSF data, but is only weakly evident in the AR-FIR data. This suggests that the meteor echo is incorporated into the AR model, and is therefore not recognised as a transient signal. This occurs occasionally for meteor echoes, with the result that some meteor echoes are not detected, and therefore not suppressed, using AR-FIR filtering. The AR-FIR data also has a higher background level, making weaker transient echoes harder to detect. On the other hand, the main limitation of the HLSF technique is illustrated at \(r = 27\), where a target-like echo is observed.

V. HLSF APPLICATION FOR CW INTERFERENCE SUPPRESSION

HLSF provides a means of applying CW interference suppression to ART data. In this instance, the harmonic Doppler frequencies \(d_j\) to be filtered can be determined by finding all non-clutter Doppler frequencies exceeding a pre-selected threshold above the noise floor. However, as can be observed for the clutter filter in Figure 2, the HLSF removes most of the signal energy at the harmonic Doppler frequencies used in the fit. Application of the HLSF to CW interference Doppler frequencies produces the same result, thereby potentially denying the detection of any targets beneath the CW interference. We therefore investigate the application of CW interference suppression prior to formation of the ART data.

The ART data \(z(b, r)\) can be obtained from the receiver pre-range data \(x(s)\) as illustrated in Figure 4. The receiver pre-range data is beamformed (Beamforming) to produce beamformed pre-range data \(y(b)\), matched filter processed (Matched Filtering) using a reference waveform (typically a windowed and time-reversed conjugate of the transmitted waveform) to yield matched filtered data \(y_m(b)\), resampled at a sampling rate equal to the reciprocal of the transmitted waveform bandwidth (Resampling) to yield resampled matched filtered data \(y_{mr}(b)\), and reformatted (3D Reformatting) into 3-dim ART data \(z(b, r)\). If a CW signal with frequency \(f_0\) is present within the radar bandwidth during the dwell, this signal will appear at this frequency in the pre-range, matched filtered, and resampled matched filtered data. This suggests that all three data types are suitable candidates for use in HLSF based CW interference suppression. However, filtering the pre-range data is not ideal, as this has the potential to introduce mismatched between the data and the matched filtering reference waveform, thereby potentially introducing range sidelobes in the range processed data. Furthermore, clutter, target and meteor echoes are localised in time according to their range delay in the matched filtered and resampled matched filtered data, which provides some benefits for the filtering process, as described below. We therefore limit our investigation of CW interference suppression to matched filtered and resampled matched filtered data. The following describes CW interference suppression for matched filtered data, but is equally applicable for resampled matched filtered data.

CW interference suppression is dependent on the ability to accurately estimate the frequency \(f_0\) of the CW signal, which is typically significantly weaker than the clutter signal. The clutter signal can be suppressed from the matched filtered data as illustrated by the blue processing blocks in Figure 5. The
matched filtered data \( y_m(b) \) is reformatted (3D Reformatting) into 3-dim (range oversampled) ART data \( z_m(b, r) \), clutter suppressed using the HLSF clutter filter described in section IV (HLSF - Clutter) to yield clutter filtered ART data \( z_{mf}(b, r) \), and reformatted (2D Reformatting) into 2-dim clutter-matched filtered data \( y_{mf}(b) \). Typical power spectrum of matched filtered and clutter-matched filtered data affected by CW interference are shown in Figure 6. The clutter-matched filtered data shows substantial clutter suppression, allowing CW interference frequency determination.

Having determined \( f_0 \), we can apply CW interference suppression to the matched filtered data as described by the red processing blocks in Figure 5. CW interference suppression (CW suppression) is applied to yield CW-matched filtered data \( y_{mf1}(b) \), resampled (Resampling) to yield resampled CW-matched filtered data \( y_{mf1r}(b) \), and reformatted (3D Reformatting) into CW-filtered ART data \( z_{mf}(b, r) \). The large number of samples available allows the use of notch filtering to suppress the CW interference. Figure 7a shows the results of applying a two-pole notch filter to the matched filtered data for the data shown in Figure 1a. The notch filter has removed the CW interference and exposed the synthetic target, albeit at an attenuated power level. The noise level has also been reduced, and the weak target-like echo at \((r, d) = (6, 50)\) has been attenuated. These effects are attributed to the finite stop band width of the notch filter, which removes target and noise power from the matched filtered data in addition to the CW interference. The notch filter has also caused range spreading of the meteor echo and target due to filter transient effects.

The corresponding result obtained applying HLSF CW interference suppression to the matched filtered data using unity sample weights and frequencies \( f_i \) satisfying \(|f_i - f_0| < f_h\), where \( f_h = 1 \) Hz, is shown in Figure 7b. The CW interference has been suppressed, and the synthetic target has been exposed without any attenuation. However, two additional undesirable artifacts are observed. These artifacts can result from the presence of any strong range localised signals in the matched filtered data, such as surface clutter, meteor echoes, or strong "target-like" echoes, such as radar transponders. The artifact centered at \( d = 24 \) results from the strong meteor echo seen at \( r = 70 \), while the artifact centered at \( d = 43 \) results from the presence of surface clutter.
The artifacts illustrated in Figure 7b can be suppressed by applying HLSF CW interference suppression to the clutter-matched filtered data, as described by the green processing blocks in Figure 5. HLSF CW interference suppression (CW suppression) is applied to the clutter-matched filtered data \( y_{mf}(b) \) to yield CW-clutter-matched filtered data \( y_{mf,h2}(b) \), combined with the matched filtered clutter data \( y_{mc}(b) \) (Summing) to yield CW-matched filtered data \( y_{mh2}(b) \), resampled (Resampling) to yield resampled CW-matched filtered data \( y_{mh2r}(b) \), and reformatted (3D reformatting) into CW filtered ART data \( z_{h2}(b,r) \). Meteor echoes and strong target-like samples are precluded from the fit by the holding the clutter-matched filtered data and setting the sample weights \( W_{si} \) for any high valued samples \( i \) to zero (High samp det). The results of this process are shown in Figure 7c, which shows CW interference suppression without target attenuation or any additional undesirable artifacts.

The application of HLSF to the clutter-matched filtered data \( y_{mf}(b) \) provides a successful method for CW interference suppression of OTH radar data. The technique has been applied to multiple data-sets and found to be effective and robust. The main limitation with the technique is that it is unable to suppress CW interference which is aliased into Doppler frequencies containing clutter. This is because the HLSF clutter suppression also suppresses the CW interference, such that the CW interference is precluded from the clutter-matched filtered data used for CW interference suppression. However, this is usually not problematic as the clutter signal is typically considerably stronger than the CW interference. It is also worth noting that the HLSF CW interference suppression technique only suppresses the CW carrier signal - it does not suppress AM radio sideband interference.

VI. CONCLUSIONS

This paper describes a simple filtering technique, harmonic least-squares fitting (HLSF), which has potential for application throughout the OTH radar signal processing chain. HLSF application has been demonstrated for clutter suppression, transient detection, and CW interference suppression. In each instance the application of HLSF has demonstrated advantages over commonly used techniques.

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