GROUND CLUTTER SUBTRACTION ALGORITHM FOR VHF PASSIVE RADAR OBSERVATION OF THE UPPER ATMOSPHERE

Chucai Zhou(1), **John D. Sahr**(2),**Melissa G. Meyer**(3), **Dawn M. Gidner**(4)

(1)***University of Washington, Electrical Engineering, Box 352500 Seattle WA, 98195-2500, USA***
Tel: +1-206-221-6513, Fax: +1-206-543-3842, Email: chucai@rcs.ee.washington.edu
(2)***As (1) above, but Tel: +1-206-685-4816, Email: jdsahr@ee.washington.edu***
(3)***As (1) above, but Email: mgmeyer@u.washington.edu***
(4)***As (1) above, but Email: dawn@u.washington.edu***

ABSTRACT

We present work on algorithm development to reduce the deleterious effect of ground clutter in passive VHF radar applications. Our algorithm consists of three parts. First, the recently developed fractionally spaced equalization with constant modulus algorithm (FSE-CMA) is applied to restore the transmitted signal distorted by multipath. Second, the Least-Mean-Square technique is used to estimate the clutter coefficients in association with the coherent reference signal. Finally coherent subtraction is used to remove the clutter from the scattered observations. The expriments and simulations show that this algorithm works well on FM stereo broadcasts in a noise-like clutter environment.

INTRODUCTION

In the last few years we have demonstrated a powerful new passive VHF radar technique for the study of ionospheric irregularities [5, 3]. By carefully observing the scatter of the commercial FM broadcasts near 100MHz, we are able to estimate the range and Doppler velocity distributions of auroral E-region irregularities and meteor trails, with performance comparable to or exceeding conventional active VHF radars. Fundamentally, the transmitter signal is appropriately cross correlated with the scattered signal. Because the scatter is much weaker than the illumination, techniques must be developed to exclude the transmitter signal from the scattered signal. Our basic experimental technique succeeds substantially, but not completely. In this work, we present the initial results of methods to remove the transmitter clutter by modern signal processing algorithms.

To date we have relied primarily upon topographic shielding to separate the direct and scattered signals. The transmitter and receiver are separated by 100 km and a substantial mountain range. This natural shielding has sufficed for detection of auroral electrojet irregularities at 1100 km range. Recent improvements in the sensitivity of our receivers show that significant transmitter power leaks into the receivers through scatter from prominent mountain peaks, thus limiting the sensitivity of our clutter-limited system. An example is shown in Fig. 1; substantial ground clutter from Mount Rainier (left edge, 70 km) appears at the same time as a relatively weak auroral electrojet return at 1000 km. We would like to remove the clutter energy associated with Mount Rainier to better extract parameters of the aurora.

Several avenues lead to improved exclusion of the ground clutter path from the weak signal receiver. Higher performance antennas could have nulls pointed in the direction of the clutter path, and additional site search might yield significantly better shielded settings. However, these approaches are time consuming, expensive, and inflexible. Since our receivers now generate very high quality samples with very low quantization noise, we wish to investigate signal processing algorithms which reduce clutter, in effect synthesizing better antennas (through array phasing) and better isolation (through coherent clutter subtraction).

BACKGROUND AND PROBLEM STATEMENT

Our radar consists of two synchronized receiver systems: one near the transmitter, copies the actual broadcast; one far from the transmitter collects scatter and ground clutter. By correlating these two signals and their Doppler shifts, we form the cross-ambiguity of the two signals, producing range-Doppler power estimates. There are two practical problems with this scenario. First, the local reception of the transmitter signal is itself corrupted by multipath. If no attempt is made to reduce the multipath, then a distorted version of the reference signal will be correlated with the scattered signal, degrading the resolution. Second, significant transmitter power leaks directly into the scatter receiver. This is usually the strongest signal present, and since the sensitivity is determined by decorrelation of the noise-like clutter, there is strong motivation to remove this the ground clutter component.

To address the first issue, we'll show the results of applying recent developments in the Constant Modulus Algorithm (CMA) [1], [9] with fractional spaced equalization (FSE) [6], [7]. Although the transmitted signal (analog stereo FM modulation) does not fit the model of identical, independent bauds used to design blind equalization techniques, our experiments show that the typical FSE-CMA algorithm can provide remarkable improvement, decreasing multipath power by 20 dB or more.

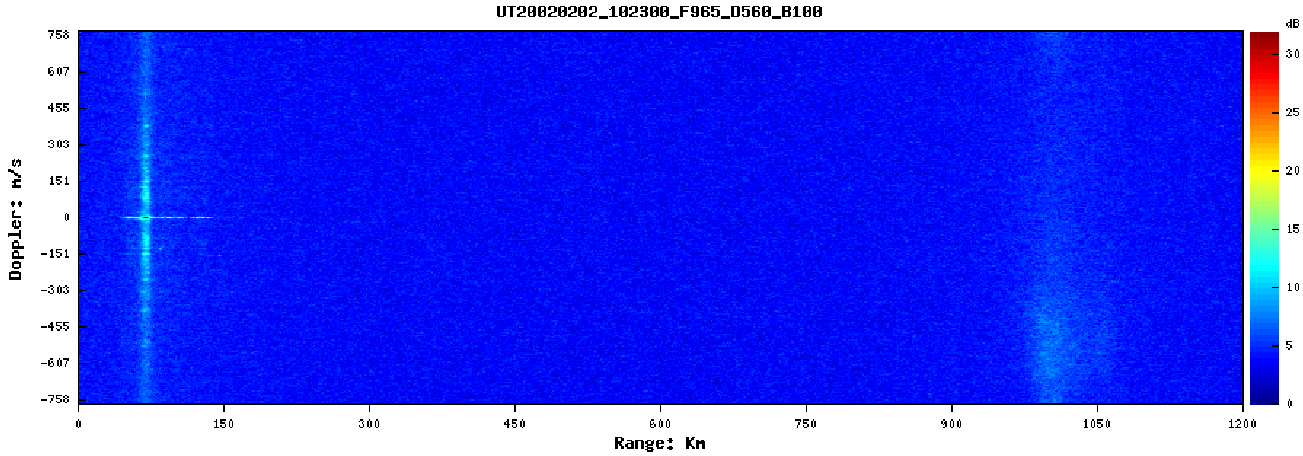

Figure 1: a caption.

The second issue is addressed by estimating the strength of the transmitter signal in the scatter signal at those ranges for which ground clutter is significant, and then coherently subtracting the signal. This is made possible by the completely independent observation of the transmitter signal. It is important to understand that this procedure has no effect on the antenna pattern — it is not a beamformer, in which all signals are affected by angle of arrival, introducing blind directions. We can, in effect "look past" clutter which has been coherently subtracted even though the illumination has 100 percent duty cycle.

These techniques directly benefit interferometric observations, which are quite sensitive to correlated signals arriving at the two (or more) scatter antennas. The well-separated reference and scatter antennas permit the development of a new optimization criterion for CMA algorithms: the minimization of cross ambiguity power in delay/Doppler space. This is actually the most desirable system metric. It may be computationally quite expensive, but optimization work will be left for the future. (First interferometric results for a passive radar are also presented at this meeting [4].)

ALGORITHMS

As a whole, the suggested algorithm consists of three processors: restoring the reference signal, estimating the clutter coefficients and coherently subtracting an estimate of the clutter signal from the scatter receiver.

To correct the local receiver, an adaptive equalizer is designed with blind equalization techniques. The FSE-CMA algorithm is applied due to its simplicity and surprising capacity to achieve 'perfect recovery' in some conditions [6], and the constant modulas property of the FM signal. Specifically, the baseband samples of the received signal at 400 kHz sampling rate are processed to restore the transmitted signal at 200 kHz (FCC allotted bandwidth) by employing factor-2 fractionally spaced equalization.

The output data from the equalizer is further down-sampled by 2, creating a net sample rate of 100 kHz, the speed we use for most of our radar processing. This further downsampling to is not used in a communications algorithm because it would result in a loss of half the bauds. However, a 100 kHz sample rate results in capture of most of the transmitter power, and reduces the computational burden for the range-Doppler estimates.

The scatter receiver also experiences multipath distortion in the ground clutter. However, the ground clutter signal power is comparable to the noise, and blind equalization algorithms (including CMA) generally require high SNR in order to work. Fortunately, the coherent, corrected reference signal is available after the FSE-CMA processing proposed above. The standard Least-Mean-Square (LMS) algorithm [8, 2] is easily implemented to estimate the clutter coefficients with the reference signal.

In formulating the LMS solution, the conjugates of the clutter coefficients are estimated for simplicity in evaluating matrix derivatives; the LMS error term is expressed as

$$y_c[k] = e[k] = y[k] - \mathbf{c}^H \mathbf{x}[k] \tag{1}$$

where $y_c[k]$ is the clean (ideal) scatter data without the clutter components and $y[k]$ is the raw data. In addition $\mathbf{c}^H = [c^*[0], c^*[1], \cdots, c^*[L-1]]$ are the clutter coefficients with L taps where ^{H} and * are the Hermitian and conjugate respectively. The corrected reference signal vector is $\mathbf{x}[k] = [x[k], x[k-1], \cdots, x[k-L+1]]^T$ at the same length L as clutter coefficients and ^{T} represents the transpose operator. The LMS solution is

$$\hat{\mathbf{c}} = \mathbf{R_{xx}}^{-1} \mathbf{r}_{y\mathbf{x}} \tag{2}$$

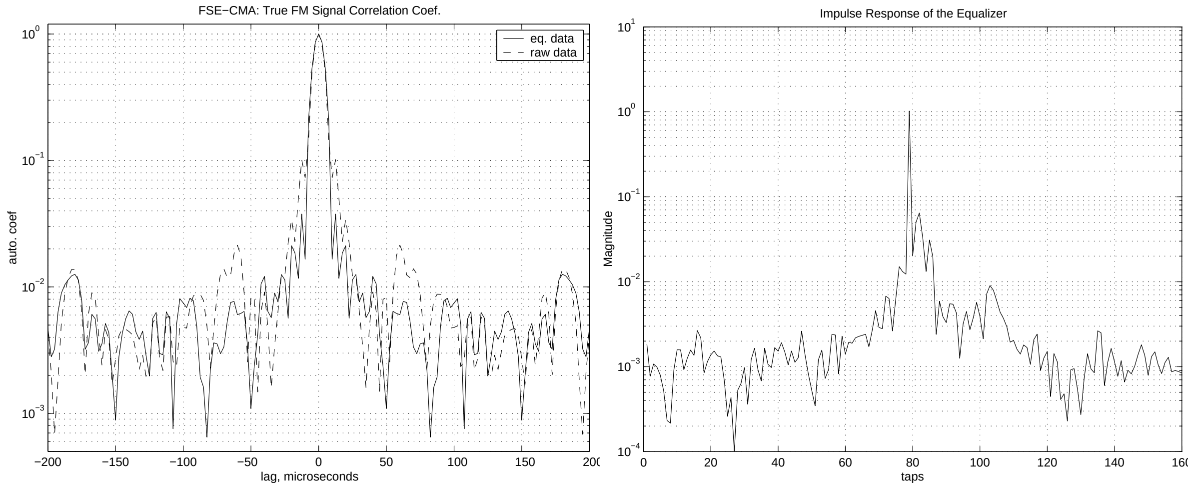

Figure 2: Example of a 96.5 MHz channel. The left panel shows the autocorrelation of a high SNR broadcast, estimated from 1 second of data. The dashed line represents the autocorrelation of the raw data; the solid line represents that of the corrected data with FSE-CMA at factor 2. The right panel shows the magnitude of the FSE-CMA equalizer coefficients which correct the channel.

where $\mathbf{R}_{\mathbf{xx}} = \langle \mathbf{x}\mathbf{x}^H \rangle$ is the autocorrelation matrix of vector $\mathbf{x}$ and $\mathbf{r}_{y\mathbf{x}} = \langle \mathbf{x} y^* \rangle$ is the cross correlation vector from the scattered data y and vector $\mathbf{x}$ as defined above in the delay line.

With the clutter coefficients $\hat{C}$ estimated, the clutter estimate is now coherently subtracted from the scatter receiver data, as

$$\hat{y}_c[k] = y[k] - \sum_{l=L_0}^{L-1} \hat{c}^*[l] x[k-l] \tag{3}$$

where $\hat{y_c}[k]$ is the estimate of the clean scatter data. Notice that the lower limit of the sum in (3) is not zero, but rather L_0. This is because the minimum possible delay is substantial, and is known *a priori*. In our system, for example, L_0 can be chosen at 60 when the sampling rate is 200KHz, which will ease the accumulation of the correlation matrix and computation of its inverse matrix as in equation (2).

EXPERIMENT AND SIMULATION RESULTS

To demonstrate FSE-CMA for restoration of the reference signal in the passive VHF radar, we apply it to data produced by our digital receiver. This receiver is an integrated device with high speed A/D which directly samples the RF, and digitally downconverts and decimates, producing nearly any desired output sample rate and channel filtering. It replaces and vastly outperforms the analog down converter and in-phase/quadrature mixer that we used until Autumn 2001. It produces extremely high quality data with perfectly balanced IQ components with unmeasurable crosstalk.

We usually intercept a station broadcasting 96.5MHz from Seattle, Washington. Although a 100 kHz sample rate suffices for uncorrected radar processing, the FSE-CMA algorithm requires data sampled at well in excess of the Nyquist rate. Thus we took data sampled at 400MHz (double the transmission bandwidth for FSE). In the left panel of Fig. 2 we show the autocorrelation of the raw data (dashed line). It reveals significant multipath effects at 12.5, 20, and 60 μs. When a twice-oversampled FSE-CMA algorithm with 80 taps is applied to equalize these effects, the multipath signals are reduced by (typically) 5 dB. The large tap count is selected to satisfy the requirement that the number of taps exceed the channel multipath extent, and the system delay is chosen to be half the tap count. This is conservative, and reflects the observation that the strongest signal may not be the first to arrive.

The FSE-CMA algorithm requires a convergence parameter, which is known to be bounded by the inverse of the signal energy and tap length, but in practice should be considerably smaller. In our experience a step size 1/20 of this bound provided good results. The resulting equalizer coefficients are shown in the right panel of Fig. 2, and represent an estimate of the channel impulse response which corrupted the signal.

With a technique for cleaning the reference signal, we proceed to the estimation and subtraction of the ground clutter in the scatter receiver. Our main effort has been to experiment with simulated ground clutter channels and real reference signals, where the ground clutter has power not greater than the noise level. Without going into great detail, the LMS algorithm very reliably estimates the ground clutter channel even if the ground clutter is at a level -25 dB compared to the noise.

We have also experimented with successively subtracting single clutter ranges from real data, with modest — but only modest — success. Doing so effectively assumes that R_{xx} is diagonal, which is false, so the effect is suboptimal. More importantly, these experiments reveal that the ground clutter at the scatter receiver evolves on a relatively short time scale — less than 1 second over the 100 km path. Thus care will be required to coherently subtract the ground clutter without accidently introducing new, artificial clutter based on an out-of-date model of the ground clutter.

The computation for cleaning the channel is not terribly expensive compared to the cross ambiguity estimates which extract the radar data. We have so far implemented the channel mitigation in floating point, and it is desirable to transfer this to 16 bit math. Although we expect clutter subtraction to improve the sensitivity of the radar, it is not yet clear just how much improvement can be gained.

CONCLUSION

In this paper, we present the initial signal processing techniques to improve the output quality from the passive VHF radar by removing the clutter from the scattered observations. The Fractionally Spaced Equalization extention of the Constant Modulus Algorithm can be used to correct multipath distortion in analog FM stereo broadcasts. With the relatively precise reference signal estimation, least mean square will be used to estimate the noise-like clutter components (isolated or distributed). Finally, knowledge of the clutter channel will be used to enable coherent subtraction of the principal ground clutter.

We gratefully acknowledge the National Science Foundation for its support of this work.

REFERENCES

[1] D.N. Godard. Self-recovering equalization and carrier tracking in two-dimensional data communication systems. *IEEE Trans. Commun*, COMM-28:1867–1875, 1980.

[2] Simon Haykin. *Adaptive Filter Theory*. Prentice-Hall INc., Upper Saddle River, NJ 07458, USA, 1996.

[3] F. Lind, J. Sahr, and D. Gidner. First passive radar observations of auroral e-region irregularities. *Geophys. Res. Lett.*, 26:2155–2158, 1999.

[4] M. G. Meyer, C. Zhou, D. M. Gidner, and J. D. Sahr. Passive vhf radar interferomter observations of meteor trails. In *2002 URSI General Assembly*, 2002.

[5] J.D. Sahr and F. D. Lind. The manastash ridge radar: A passive bistatic radar for upper atmospheric radio science. *Radio Sci.*, 32:2345–2358, 1997.

[6] L. Tong, G. Xu, and T. Kailath. A new approach to blind identification and equalization of multipath channels. *in 25th Asilomar Conf.*, pages 856–860, 1991.

[7] L. Tong, G. Xu, and T. Kailath. Blind identification and equalization based on second-order statistics: A time domain approach. *IEEE Trans. on Info. Theory*, 40:340–349, 1994.

[8] John R. Treichler, Jr. C. Richard Johnson, and Michael G. Larimore. *Theory and Design of Adaptive Filters*. John Wiley and Sons, Inc., U. S. A., 1987.

[9] J.R. Treichler and B.G. Agee. A new approach to multipath correction of constant modulus signals. *IEEE Trans. Acous., Speech and Sig. Proc.*, ASSP-31:459–471, 1983.