The Multi-Pulse Technique

Some ionospheric radars, such as the Super Dual Auroral Radar Network (SuperDARN) radar, take advantage of long-distance multi-hop propagation that is possible in the high-frequency (HF) band. Greenwald et al., 1995. The multi-pulse technique is used to overcome range Doppler ambiguities characteristic of overpropagation ionospheric targets (long range: > 1000 km; high velocity: ~ 1 km/s) at the expense of introducing self-clutter. Farley (1972) first discussed estimating the self-clutter for incoherent scatter radars assuming uniform scattering. The present study discusses a generalized algorithm for more accurately estimating self-clutter by utilizing measurements of echo power, allowing for an improved estimate of the mean square error in the radar observations.

A multi-pulse sequence can be identified by 4 characteristics: the pulse length \( (\Delta t) \), the pulse repetition time or time lag \( (\gamma) \), the number of pulses transmitted \( n_p \), and the pulse fake (pfa). Pulse spacings in multi-pulse sequences are non-constant and integer multiples of \( \Delta t \). The multi-pulse sequence in Figure 1 (Left) was made using \( \Delta t = 2.4 \) ms, \( n_p = 300 \) ps, \( n_p = 3 \), and \( \gamma = [8,1,3] \). The three possible pairs of pulses give three samples of the auto-correlation function (ACF) obtained using correlations between the received signals from pulse pairs. It is clear from Figure 1 that each sample contains signals from both the range of interest (red diamonds) and unwanted ranges (black diamonds). The signal from unwanted ranges is referred to as self-clutter. Self-clutter is pulse sequence-dependent as seen by comparing the left and right plots in Figure 1.

Previously Farley (1972) discussed estimating the self-clutter introduced by the multi-pulse technique for incoherent scatter radars. He assumed uniform scattering, and that all pulses are transmitted before any signal is received. The estimate was given as

\[
C = (n_p - 1)S
\]

meaning that the signal-to-clutter ratio \( (S/C) \) is a function of the number of transmitted pulses and is constant for all ranges. For a 7 pulse sequence, Equation 1 gives \( S/C = -7.8 \) dB and for an 8 pulse sequence, \( S/C = -8.5 \) dB.

Comparing Assumptions

Assumptions

Farley (1972) Estimate: Uniform scattering (equal echo power)

Farley (1972):

- Non-uniform scattering
- Transmission of pulses is not complete before receiving signal
- Correlations between ranges are estimated

The assumptions for Farley (1972)'s self-clutter estimate break down for HF ionospheric radars. For example, SuperDARN radars start receiving signal before all the pulses from a multi-pulse sequence are sent and scatter is typically received at quasi-periodic ranges as HF radar waves travel between the atmosphere and the ground. Therefore, the signal-to-clutter ratio (SCR) is expected to be anything but constant for long-range HF radars.

The generalized estimate is blind to ranges not covered by echo power measurements. If echo power is not measured to sufficiently large range, the generalized estimate will fail to include potentially large contributions of self-clutter from long-range echoes.

Illustrating the ACF: SuperDARN

Ionospheric radars measure the autocorrelation function \( (ACF) \) of a plasma target and extract plasma parameters from it. Received signals are linear in range (as referred to a range gate). The ACF at time \( t \) is the correlation between two signal samples separated by time \( t \). For Figure 1 (Left), the ACF at time \( t = 2 \tau \) is the correlation between \( 4 \Delta t \) and \( 6 \Delta t \), the sum of 9 correlations: between the signals from the range of interest, 4 between the interfering ranges and the range of interest, and 4 between the interfering ranges.

Figure 2 shows a typical ACF measured by a SuperDARN radar using an 8 pulse multiple-pulse sequence. Each complex value of the ACF is calculated from a pair of pulses and plotted as a function of the separation between the pulses (multiples of the pulse repetition time, \( \tau \)).

| Fig. 1: ACF measured by the Cycle 40 SuperDARN radar using the 4 pulse "katscan" multiple-pulse sequence. The real and imaginary parts of the ACF function are indicated by blue and green curves, respectively. The period of oscillation is proportional to the Doppler shift expressed by a moving plasma target. For example, the real and imaginary values of the ACF measured at \( t = 10 \Delta t \) (log range 10) were obtained by correlating samples of received signal separated by a time of \( t = 10 \Delta t \). In Figure 1 (Right), the ACF at \( t = 10 \Delta t \) for range gate 10 is obtained from the second and fourth samples (blue markers). |

Generalized Estimation of Self-Clutter

Generally, ionospheric radars measure echo power as a function of range. The self-clutter can be estimated using the voltage samples from the echo power measurements. Sometimes, the voltage samples are not kept (large amount of storage required) or only the power profile is available when retransmitting processing raw data. In such cases, an upper-bound of self-clutter may still be estimated (see the following equations). Following the discussion in the previous section, "Illustrating the ACF", the generalized estimate for self-clutter was derived by using the sum of terms in the sample correlations that include interfering ranges. In general, when two samples are correlated, there will be \( N \) interfering ranges in one of the samples and \( M \) interfering ranges in the other sample.

Using voltage samples, the multipole self-clutter can be estimated as

\[
C = \sqrt{\sum P_i^2 \sum P_j^2 \rho_{ij}^2} + \sum P_i^2 \rho_{ij} \rho_{il},
\]

where \( P_i \) is the echo power (square of the magnitude of voltage) with subscripts indicating origin of the power. Subscript \( R \) indicates the range of interest (red diamonds, Figure 1). Subscript \( i \) and \( j \) indicate interfering ranges (black diamonds, Figure 1) with \( P_i \) being the ith interfering power from \( N \) interfering ranges and with \( P_j \) being the jth interfering power from \( M \) interfering ranges. \( \rho \) is the normalized correlation between echo powers.

Knowing only the power at each range (only magnitude of voltage is known, no phase information), one cannot calculate \( \rho \). To be conservative, we set \( \rho = 1 \) to obtain the upper estimate of the self-clutter.

\[
C = \sqrt{\sum P_i^2 \sum P_j^2 \rho_{ij}^2} + \sum P_i^2 \rho_{ij} \rho_{il}.
\]

Mean-Square Error

It is now possible to estimate the measurement error of the radar data using the estimate for self-clutter. Radar measurements are subject to random fluctuations. The mean-square error in the estimate of the ACF, in the presence of noise and clutter, to leading order, is given by Farley (1972) as

\[
\langle (\delta S)^2 \rangle = \frac{S}{N} + C^2 \frac{S}{N} + 2 \langle S - C \rangle^2 \frac{S}{N}.
\]

where \( S, N, \) and \( C \) are the signal, noise, and clutter powers, respectively. \( K \) is the number of samples. Using Equation 4 and the average signal-to-clutter ratio as depicted in Figure 3, the average mean-square error was calculated for 1 hour of raw data from the Saskatoon SuperDARN radar.

Results and Conclusions

There are now error estimates for measured data from SuperDARN radars.

Future Work

- Checking signal-to-clutter estimates against radar data simulators
- Implementing weighted least-squares fitting using cross-range to extract plasma parameters
- Running experiments to test the voltage-based estimate given by Equation 2
- Prototyping voltage-based estimate in day-to-day radar operation

Acknowledgements

Support: This work was supported through grants from Natural Sciences and Engineering Research Council (NSERC) of Canada and the Canadian Foundation for Innovation. The authors wish to express their gratitude to Professor R. A. Greenwald and Dr. K. B. Baker for their support and encouragement.

References


机构名称: Space and Atmospheric Studies, University of Saskatchewan