SPECTRAL CHARACTERISTICS OF HIGH FREQUENCY (HF) BACKSCATTER FROM HIGH LATITUDE IONOSPHERIC IRREGULARITIES: PRELIMINARY ANALYSIS OF STATISTICAL PROPERTIES

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1.0 INTRODUCTION

Long range target detection via ionospheric propagation modes -- commonly known as over-the-horizon (OTH) detection -- has long been considered as a means of extending radar coverage to large distances. Many experimental studies have been conducted over the years and at the present time operational systems are under development. This mode of detection possesses several distinct advantages including an ability to detect targets to distances in excess of 3000 km. However, it also suffers from shortcomings which have tended to retard its development. Among these are the fact that ionospheric propagation modes require the frequency of operation to be less than approximately three times the ionospheric critical frequency -- ~ 10 MHz -- leading to a somewhat complex propagation analysis for precise target location. The problem is especially severe at high latitudes where the ionosphere is highly-variable as a result of auroral particle precipitation. In addition, particle precipitation may produce enhanced ionization of the D-region of the ionosphere which can lead to severe absorption of the energy in ionospheric propagation modes and an associated reduction in the radar sensitivity. Finally, radars utilizing ionospheric propagation paths are especially sensitive to ionospheric clutter from magnetic-field-aligned electron density irregularities. Radar signals backscattered from these irregularities can be very intense and any effort to mitigate against their influence requires knowledge of at least the Doppler shift and spread that they introduce in the backscattered signals.

In this report we concentrate on the third of these problems associated with OTH detection. Our knowledge of the Doppler spectral characteristics of HF signals backscattered from ionospheric irregularities has, in general, been quite poor. This has been especially true for backscatter from F-region irregularities at high latitudes. While experimental studies at high latitudes have been conducted the equipment has often been designed for OTH detection and not for an analysis of the spectral characteristics of ionospheric irregularities. Consequently, when Elkins (1980) produced a model for HF radar auroral clutter, he was forced to assume certain spectral properties for the signals backscattered from high latitude irregularities. We shall show in this report that these assumptions were of limited validity. In particular, we shall show that the variability in the magnitude and direction of the irregularity drift as well as the variability in spread of the Doppler returns make it difficult to discriminate against ionospheric clutter by Doppler techniques, alone.

The data presented in this report have been obtained with The Johns Hopkins University/Applied Physics Laboratory (APL) HF Radar located at the Air Force Geophysics Laboratory High Latitude Ionospheric Observatory in Goose Bay, Labrador. This is an auroral zone site and signals from the radar are subjected to all of the detrimental ionospheric effects described in the previous paragraphs. The radar was initially funded by the Atmospheric Sciences Division of the National Science Foundation and by the Atmospheric and Chemical Sciences Directorate of the Air Force Office of Scientific Research for the study of small-scale ionospheric irregularity structure. Subsequently, additional support, including a second receiving array for the antenna system, have been provided by the Electromagnetic Propagation Branch of Rome Air Development Center and by the Ionospheric Effects Division of the Defense Nuclear Agency. At the present time the radar is operating at a modest power level that is approximately 30 dB below that required for OTH detection. Improvements presently being made to the radar will increase the sensitivity by approximately 10 dB.

Since the APL radar was developed for the investigation of small-scale ionospheric structure, it has several capabilities that differentiate it from radar systems that have been utilized for OTH detection. Most notable of these is an unusual multipulse transmission pattern that yields unambiguous determinations of the autocorrelation functions of the backscattered signals as a function of range. The autocorrelation functions are calculated in real time by an on-line microcomputer and stored on digital tape. Subsequent processing at APL yields Doppler spectra of the backscattered signals. The approach as it is implemented on the radar provides for a Doppler bandwidth of $\sim$30 Hz about the transmitted frequency. At an operating frequency of 10 MHz, this bandwidth yields unambiguous line-of-sight velocity measurements up to nearly 2500 m/s.

In the following we present, first, a discussion of various procedures that one might use for spectral and/or autocorrelation analysis of backscattered radar signals. This discussion is derived from a similar analysis presented in an earlier RADC report (Greenwald, 1982). Next, we describe the method by which the autocorrelation functions obtained by the radar are processed at APL in order to remove contributions from ground backscatter and unwanted signal sources. The autocorrelation functions are then analyzed to determine their decorrelation time (inverse of the spectral bandwidth) and their period (inverse of the Doppler frequency). Finally, the parameters are converted to Doppler velocity width and shift through inversion and correction for frequency of operation. These values have been used in a statistical study of the occurrence and Doppler characteristics of backscatter from high latitude ionospheric irregularities. The results from this analysis are then discussed in terms of their implications on the operation of OTH radars in high latitude environments.

2.0 TECHNIQUES FOR DOPPLER ANALYSIS OF IONOSPHERIC CLUTTER

Small-scale ionospheric structure falls within a class of scatterer that is known as a distributed soft target. This type of scatterer often has a rather small volume scattering cross-section, often 10^{-10} - 10^{-14} m^2/m^3; however, as the total scattering volume may be quite large, for example 10^{13} m^3, the signals backscattered from the volume may be appreciable. The volume scattering cross-section associated with soft targets is determined from Fourier decomposition of the medium. Since the radar signals undergo Bragg scattering by the irregularities, the critical Fourier component is given by $k = k_{inc} - k_{scat}$. In the case of a backscatter radar, k_{inc} and k_{scat} are equal and oppositely directed; hence the Fourier component of interest has a wavelength that is equal to half the radar wavelength. The amplitude of this critical Fourier component is determined by the physical processes occurring in the medium. Examples of how it is obtained are given by Farley (1972) and in the case of HF backscatter by Walker et al. (1986). A detailed discussion of irregularity scattering cross-sections is beyond the scope of this report.

Let us now consider the phase variations of a signal backscattered from a given volume of ionospheric irregularities. If one compares the backscattered signal with a reference oscillator operating at the frequency of the transmitted signal, the phase difference between the two signals will vary with time. This phase variation is the Doppler effect due to the bulk motion of the scattering volume. In addition, one will note that the difference signal randomizes or loses phase memory after a relatively short time. This time is the decorrelation time of the medium and it transforms to the width of the Doppler spectrum (see Section 3.2). Precisely stated, the decorrelation time is related to the decay of the two-point time-dependent cross-correlation function of the process producing the irregularity structures. Physically, it may be thought of as due to the finite lifetimes of the individual irregularity structures and the random or turbulent velocities that exist in the scattering volume.

The question arises as to how one might analyze the signals returned from the scattering volume. In this report we consider four different approaches using pulsed transmissions (These as well as fm-cw transmissions have been discussed in an earlier report by Greenwald (1982)). The approaches have been selected so as to demonstrate that increasingly complex procedures will enable one to obtain unambiguous information from increasingly complex situations. The four approaches are:

1) long pulse,
2) repetitive pulse,
3) variable lag double pulse, and
4) multiple pulse.

We consider each of these pulse modes as they are implemented for HF radar systems. We shall assume that ionospheric backscatter may occur simultaneously over a range interval of 1500 km (10 ms in radar group delay), that it can exhibit Doppler shifts in excess of 1200 m/s (100 Hz at 12.5 MHz) and that it has a typical decorrelation time of 30 ms.

2.1 Long Pulse

Doppler analysis of the signals scattered from a single long transmitted pulse is performed as shown in Figure 1a. For this transmission mode the length of the transmitted pulse should approximate the decorrelation time of the medium. Hence we assume it to have a width of 30 ms. The signals scattered by the ionospheric structure are assumed to be referenced to the transmission frequency by passing them through a phase coherent receiver. The quadrature outputs of the receiver contain the desired Doppler information. In order to obtain the desired spectral bandwidth the receiver must have a bandwidth of at least 100 Hz and its outputs must be sampled at twice that rate. The sampled data forms a time series which may be denoted as

$$C(j) = A(j) + iB(j) \qquad 1 \le j \le N \tag{1}$$

where A(j) and B(j) represent the jth sample of the quadrature outputs of the receiver. This time series may be Fourier analyzed or it may be analyzed to yield the autocorrelation function of the backscattered signal. We shall determine the latter quantity to maintain uniformity between the various analysis procedures. It is given by

$$R(k) = \langle C(j)C^{*}(j+k)\rangle \qquad 1 \le k \le N-1 \tag{2}$$

where the asterisk represents the complex conjugate. The Doppler spectrum associated with R(k) may be obtained by Fourier transformation.

The disadvantage of the long pulse approach should be quite evident. Due to the length of the transmission, backscattered signals are received simultaneously from the entire 1500 km extent of the scattering region. Consequently, there is no way to resolve any range-dependent Doppler velocity structure that may be present.

2.2 Repetitive Pulse

In order to retain range-dependent Doppler information a somewhat more sophisticated pulse transmission technique is required. For example, it can be noted that the long pulse is transmitted for the entire length of the sampling sequence. This is not necessary and, in fact, one may replace the long transmission by a sequence of short transmitted pulses with one pulse preceding each sample of the received signal (See Figure 1b). With this pulse scheme, the bandwidth of the receiver is matched to the length of the transmitted pulse and the spatial resolution of the measurement is determined by the latter quantity. If the transmitted pulse were to have a typical length of 100 μs, then the range resolution would be 15 km.

With the repetitive pulse technique the sampled time series and the resulting autocorrelation function may be written as

$$C(t,j) = A(t,j) + iB(t,j) \qquad 1 \leq j \leq N \tag{3}$$

and

$$R(t,k) = \langle C(t,j)C^*(t,j+k)\rangle \qquad 1 \leq k \leq N-1 \tag{4}$$

respectively. Here, t represents the time delay between transmission of a pulse and sampling of the backscattered signal. Since the transmitted pulse length is short in comparison to the time between pulses (5 ms for a 200 Hz sampling frequency), it is entirely possible to analyze the backscattered signals from many different ranges, simultaneously.

Unfortunately, the repetitive pulse technique has a significant shortcoming. Initially, it had been assumed that the scattering region had a range extent of 1500 km. For the present discussion we will assume it to extend from 1000 to 2500 km. If t is set so that the data is sampled at a range of 1000 km (t = 6.7 ms), then the sample will also be of signals backscattered from the immediately preceding pulse due to ionospheric structure at a delay of 11.7 ms and a range of 1750 km. In fact, for every delay t that one might select there are two distinct ranges that can contribute to the backscattered signal. In practice the problem may be even more severe than demonstrated here since sampling frequencies in excess of 200 Hz may be required and scattering regions extended for more than 1500 km in range are entirely possible.

A particularly good example of the repetitive pulse technique as it is implemented at VHF frequencies for studies of the E-region radar aurora is given by Balsley and Ecklund (1972).

2.3 Variable-Lag Double Pulse

In order to avoid the problem of range ambiguity, while maintaining the requisite spectral bandwidth and resolution, it is necessary to utilize some non-repetitive multiple pulse technique. The simplest of these is the variable lag double pulse method (See Figure 1c). In this approach N pairs of pulses are transmitted with a spacing between pulses that is some multiple k of an elemental spacing T. The time between pulse pairs must be sufficiently long that no signals are received from the previous pulse pair while the data from the current pulse pair is being sampled. By referencing the time delay t to the time of the first pulse of a pulse pair, we can write the sampled returns from the transmissions as

$$C(t,j) = A(t,j) + iB(t,j) \qquad (5)$$

and

$$C(t+kT,j) = A(t+kT,j) + iB(t+kT,j) \qquad (6)$$

If we further allow the index k to be stepped through a range of values from 0 to M, we can write the autocorrelation function derived from this analysis procedure as

$$R(t,k) = \langle C(t,j)C^{*}(t+kT,j)\rangle \qquad 0 \le k \le M \qquad (7)$$

Let us consider the application of the double pulse approach to backscatter from extended regions of ionospheric structure. If we denote the subscript 1 as indicating a response due to the first transmitted pulse and the subscript 2 as due to the second transmitted pulse, 7) can be rewritten as

$$R(t,k) = \langle (C_1 (t,j)+C_2 (t,j))(C_1^{*} (t+kT,j)+C_2^{*} (t+kT,j))\rangle \qquad (8)$$

Now, by referencing the response of each transmitted pulse to the time of that pulse, explicitly noting the time delay between the two samples, and expanding the expectation value, (8) may be rewritten as

$$R(t,k) = \langle C_1 (t,j,0)C_1^{*} (t+kT,j,k)\rangle + \langle C_1 (t,j,0)C_2^{*} (t,j,k)\rangle$$

$$+ \langle C_2 (t-kT,j,0)C_1^{*} (t+kT,j,k)\rangle + \langle C_2 (t-kT,j,0)C_2^{*} (t,j,k)\rangle$$

$$0 \le k \le M \qquad (9)$$

Examination of (9) shows that only the second term on the right-hand-side involves a comparison of data from the same group delay. All other terms average to zero since the returns from two distinct ranges are uncorrelated. They contribute to the autocorrelation function only by raising the overall noise background of the measurement.

As in the case of the repetitive pulse, the variable lag double pulse method may be used for simultaneous examination of the Doppler characteristics of signals backscattered from many different ranges. Moveover, the elemental lag T and the number of lags M may be adjusted so that one can always perform a complete and correct Doppler analysis on the backscattered signals. Unfortunately, the method is very inefficient in terms of processing time. For the longer lags of the autocorrelation function one must wait for many tens of milliseconds to obtain the appropriate pulse separations. Since the lags are performed sequentially and N must be sufficiently large to obtain good statistics, it is highly questionable whether the high latitude ionosphere is sufficiently time stationary for this method to be used in the HF frequency regime. An example of its application to radar auroral backscatter at upper VHF frequencies is given by Nielsen et al.(1984).

2.4 Multipulse

It would be highly desirable to maintain the positive features of the double pulse technique while improving its efficiency. One might ask whether it is possible to transmit multiple pairs of double pulses with different lags in such a manner that the pulse pairs do not interfere with one another. This question has been answered in the affirmative and the solutions form the basis of multipulse transmission techniques (See Farley, 1972). With multipulse techniques one seeks to transmit a pattern of pulses such that the pulse separations contain most or all of the lags necessary for determining the autocorrelation function of the backscattered signal and such that there is little or no ambiguity in the ranges that contribute to any given lag. In practice, a four pulse transmission pattern is the longest that can be used to obtain a full seven lag (counting the zero lag) autocorrelation function with no range ambiguity. Patterns with a greater number of pulses either have gaps in their associated autocorrelation patterns or they have range ambiguity for certain lags.

Farley (1972) has suggested several six-pulse patterns that might be used to determine fifteen lags of a 17-lag (counting the zero lag) autocorrelation function. For the Goose Bay radar, we have adopted a 7-pulse pattern, shown in Figure 1d, that is used to determine a full 17-lag autocorrelation function. This pattern exhibits range ambiguity for k = 1,2,3,and 13; however, the large time separation between the two repetitions of k = 1,2,and 3, makes it extremely unlikely for two distinct range intervals to yield simultaneous backscattered signals. The remaining ambiguous lag is a problem. Either it can be dropped from the analysis or it can be ignored due to the small residual correlation that exists in the cross product analysis at these large lags.

In addition to retaining the benefits of the variable lag double pulse analysis, the multipulse technique is quite efficient from an analysis point of view. With it, the data for a full 17-lag autocorrelation function may be acquired in 16T. In contrast, at least 300T would be required to acquire the equivilent data using the variable lag double pulse technique. Thus, there is a speed enhancement of more than a factor of 18 in the data acquisition.

Some minor shortcomings of the multipulse approach are an increased noise background due to uncorrelated scatter from unwanted ranges and the occurrence of transmitter pulses at certain delays which affect the autocorrelation analysis. Fortunately, neither of these problems is particularly serious.

3.0 PROCESSING OF AUTOCORRELATION FUNCTIONS FROM THE GOOSE BAY RADAR

In the case of the APL Goose Bay radar, the analysis of the multipulse autocorrelation functions is carried out by a FORTRAN program, FITACF. This is a rather complex program, but its primary function is to fit a theoretical autocorrelation function to the observed data in order to determine the true backscattered power, the Doppler velocity, and the spectral width. Each 5 second integration is separately processed in two basic steps, Noise Reduction and Parameter fitting of each individual ACF.

3.1 Noise Reduction

There are several sources of noise which complicate the analysis of the radar data. The cosmic HF background noise is relatively constant in time but has a frequency dependence of the form $P \sim f^{(-5/2)}$. The multipulse technique, as noted above, causes strong scatter at some ranges to contribute to the noise level at other ranges. In addition, there are local sources of HF noise produced by nearby equipment, as well as the inherent noise of the receiver and digitizers. Finally, in the HF frequency band, there are nearly always remote radio transmitters that contribute to the noise background at varying intensity levels. Some of these transmitters are nearly CW sources while others are highly modulated or pulsed.

The first stage of the noise reduction process is the determination of the basic noise level and the "noise ACF." An initial noise level is determined from the average backscattered lag-0 power from the 10 weakest ranges. An average noise ACF is then formed from all the autocorrelation functions which have lag-0 power less than 1 dB above the initial estimate of the noise level. In a typical case where there are no external transmitters producing noise, the noise ACF will have a non-zero power at lag-0 and be nearly zero for all other lags. If a CW transmitter is present, however, it will be present at all range gates. In this case, the noise ACF will show a clear non-zero frequency. In either case, the noise ACF is then subtracted from the raw ACFs. This subtraction removes the excess lag-0 power due to pure random noise and may also remove or substantially reduce the effect of other coherent noise sources such as CW transmitters.

To see the effect of removing the noise ACF more clearly, let us consider what the combination of two separate sources produces for an auto-correlation function. For simplicity we shall assume each source is perfectly correlated with itself, but is not correlated with the other source. This will be the case when one source is an external transmitter and the other is a backscattered ionospheric signal with a very narrow Doppler spectrum. In such a case the autocorrelation function produced by a single transmission of the multipulse sequence will be

$$A^2 e^{i\omega_1 t} + AB\, e^{i(\omega_1 - \omega_2)t} e^{i\phi} + B^2 e^{i\omega_2 t} \qquad (10)$$

where ϕ is an arbitrary phase. When many pulse sequences are added up, the cross-term will tend to die out since the phase is different each time. The expected result is

$$A^2 e^{i\omega_1 t} + B^2 e^{i\omega_2 t} + \frac{AB}{\sqrt{N}} e^{i(\omega_1 - \omega_2)t} e^{i\phi} \tag{11}$$

where N is the number of pulse sequences produced during the 5 second integration. The value of N is typically around 60 and hence the cross term is suppressed by a factor of 7.7. Let us assume that the A^2 term is a noise transmitter and the B^2 term is the ionospheric signal. If A > B then on subtracting the A^2 term (the noise ACF) from the total ACF we are left with

$$B^2 e^{i\omega_2 t} + \frac{AB}{\sqrt{N}} e^{i(\omega_1 - \omega_2)t} e^{i\phi} \tag{12}$$

If we are to be able to extract the true ionospheric ACF from the remaining noise we must have

$$B^2 > \frac{AB}{\sqrt{N}} \tag{13}$$

In terms of power this may be rewritten as

$$\frac{A^2}{B^2} < N \tag{14}$$

For our case, where $N \approx 60$ this implies that the ionospheric signal can be detected and extracted from the noise even when it is 17 dB below the noise. Of course this is an ideal case and still requires an ionospheric signal larger than the true random noise present which in actual practice limits the usefulness of this technique to cases where the noise source and the ionospheric signal are comparable.

3.2 Parameter Fitting

Once the noise ACF has been removed from the data, it is possible to fit an assumed functional form to each of the ACFs. We have looked at two possible functional forms, an exponential decorrelation with time and a Gaussian decorrelation. If we assume an exponential decorrelation we will have

$$R_\lambda(t) = C_\lambda \, e^{i\omega t} \, e^{-\lambda t} \tag{15}$$

where C_λ is the power, ω is the Doppler frequency and λ is the decorrelation parameter. The Fourier transform of R_λ gives a Doppler spectrum of the form

$$S_\lambda(\omega') = \frac{2\lambda}{\lambda^2 + (\omega-\omega')^2} \tag{16}$$

which peaks at $\omega' = \omega$ and has a full width at half-maximum of 2λ radians/s. Alternatively, if we assume a Gaussian decorrelation we will have

$$R_\sigma(t) = C_\sigma \, e^{i\omega t} \, e^{-\sigma^2 t^2} \tag{17}$$

and the Doppler spectrum will be

$$S_\sigma(\omega^1) = \frac{\sqrt{\pi}}{\sigma} C_\sigma \, e^{\frac{-(\omega-\omega')^2}{4\sigma^2}} \tag{18}$$

which again peaks at $\omega' = \omega$ and has a width of $4\,\sigma \sqrt{\ell n\,(2)} = 2.76\,\sigma$. The parameters C_λ, λ, ω or C_σ, σ, ω are fitted using a power-weighted least-squares fit. Weighting by the power emphasizes the importance of the earlier lags where the power is greater and the errors and influence of noise are less. The Doppler frequency is found by doing a least-squares fit to the observed phase at each lag (Hanuise et al., 1985), while the decorrelation parameter and power (C_λ and λ or C_σ and σ) are found by doing a fit to the logarithm of the magnitude of the observed ACF.

There are several complications in doing the fit that must be considered. The primary difficulty is the problem of "bad lags". Since some samples are taken at the same time that the transmitter is on and the receiver is off, a range which uses one of these samples in computing its ACF will have one or more lags which are bad and should not be used in the fitting process. In addition to lags which are bad because of transmitter pulses, lag-13 has multiple redundancy in the multipulse sequence and can lead to range-aliased results. Finally, pulsed signals from remote signal sources can cause sudden changes in the received signal which affect only a few samples. The noise from these pulsed sources cannot be removed by the method described in the previous section, and each lag which uses one of the affected samples will be a bad lag.

The first step in performing the fit to the observed data is therefore to detect bad lags and eliminate them from the data used for the fit. The samples which are taken during transmitter pulses are readily determined and removed from the autocorrelation function analysis. In addition, because of the range aliasing problem, lag-13 for all ranges is considered a bad lag. The remaining lags are scanned and any lag which shows a large increase in magnitude over the preceding lags is considered a bad lag.

Once the bad lags have been removed the remaining lags are used to determine the parameter fit. Although the determination of C and λ (or C and σ) is straightforward, there is one additional complication in determining the Doppler frequency. To do a straight line fit to the phase we assume that the phase is either monotonically increasing or decreasing (or approaching receding Doppler velocities). The actual measured phase, however, is confined to the range $\pm \pi$. Multiples of 2π must therefore be added to the observed phase at the higher lags. The basic approach used is described by Hanuise, et al. (1985), but it has been modified to improve the determination of the 2π folding factor in cases where several lags are bad and cannot be used. In addition, the error in determining ω is estimated and used to determine the velocity error.

The question of which of the two functional forms for the ACF (Equations 15 and 17) is the more appropriate one to use is difficult to determine. If the decorrelation is due to the fact that we are observing multiple scatterers in the presence of velocity turbulence, then we would expect the Doppler spectrum to be Gaussian and Equations (17) and (18) to be the more appropriate ones. If, on the other hand, the decorrelation is due to the growth and decay of the plasma irregularity structures with little or no velocity turbulence, then the appropriate equations are (15) and (16).

To investigate this further, we have tried both fits on several different periods of data. An example is shown in Figure 2. The data were taken on January 6,1986 at 20:01:40 UT (Figure 2a) and 20:01:45 UT (Figure 2b) for the same range (1080 km). Table 1 gives the values of the parameter fit for the two methods and the power weighted error for each.

TABLE 1

	20:01:40	20:01:45
$\log(C_\lambda)$	11.71	11.51
λ	48.89	43.11
ε_λ	0.042	0.022
width (λ)	97.8 rad/s	86.2 rad/s
$\log(C_\sigma)$	11.48	11.25
σ	38.56	31.51
ε_σ	0.007	0.039
width (σ)	106.81 rad/s	87.3 rad/s

For the first case (Figure 2a), the Gaussian fit is clearly superior, but the physical results, power and width, are not markedly different. In the second case (Figure 2b), the exponential fit has the smaller error, but again, the physical results are very similar. Since these two examples are from the same range and are separated by only five seconds, it is unlikely that the physical process responsible for the decorrelation could have changed greatly. We conclude that from the data currently available, it is nearly impossible to determine which decorrelation model is the "correct" one and the power and spectral width determined by either method are very similar. For this statistical survey, we have used the exponential fit represented by Equation (15).

3.3 Separation of Ground Scatter and Ionospheric Scatter

Once the parameter fit has been performed on an ACF, it is possible to separate ground scatter from ionospheric scatter. Ground scatter is characterized by a very low Doppler frequency and a very small decorrelation parameter (i.e. large decorrelation time). After analyzing several hundred ACFs from many different periods we have determined a reasonable set of limits which define the spectra of ground backscattered signals:

1) Ground backscattered signals typically have $|\omega| < 18.85$ radians/s (3 Hz).

2) Ground backscattered signals have small $|\lambda|$. The actual limit depends on the power (C). As can be seen in Figure 3, weak ground scatter signals tend to have larger values of λ than strong signals. The limits we have used here are

$$|\lambda| < \begin{cases} 5\ s^{-1} & \text{for SNR} > 6\ \text{dB} \\ (12-\text{SNR})\ s^{-1} & \text{for } 0 \leq \text{SNR} \leq 6\ \text{dB} \\ 12\ s^{-1} & \text{for SNR} < 0\ \text{dB} \end{cases}$$

With these choices for the limits defining ground scatter we find that we misidentify approximately 5-10% of weak ground scatter signals as being true ionospheric signals. Also, a small percentage of weak ionospheric signals, which have very low velocities are misidentified as ground scatter, but it is difficult to determine exactly what this percentage is. Strong signals (> 10 dB) are almost never misidentified.

If the ACF has been identified as due to ground scatter, the ground scatter function defined by C, ω and λ is subtracted from the data and the residual is re-analyzed. If a reasonable fit is found for the parameters of the residual (i. e. $|\omega| > 18.85$ and relative error < 1) the ACF is identified as a mixture of ground scatter plus ionospheric scatter.