First Radar Measurements of Ionospheric Electric Fields at Sub-Second Temporal Resolution

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Abstract

We describe a new multipulse sounding technique used by SuperDARN radars that significantly improves the temporal resolution of Doppler velocity measurements. The new technique allows Doppler velocities to be determined from each multipulse sequence transmitted by the radar (5 Hz measurement rate). We have adopted one of the 6-pulse sounding sequences identified by Farley in the early 1970s, but transmit the sequence in forward and reverse order. This greatly reduces interference from transmitter pulses and backscatter returns from unwanted ranges. We demonstrate the effectiveness of the technique by presenting observations of a 14 second Doppler oscillation.

1. Introduction

In this paper, we report on a recent advance in Doppler velocity determination with the Wallops Island and Goose Bay SuperDARN radars. This advance has been made possible through the development of a new multipulse transmission sequence that significantly improves the quality of autocorrelation functions (ACFs) derived from the backscattered radar signals and has allowed high quality Doppler measurements to be obtained from individual multipulse sequences. The technique has reduced the time required for the determination of the Doppler velocity from once every 3-7 seconds to 5 per second, an improvement of more than an order of magnitude over the highest temporal resolution achieved with SuperDARN to date. To our knowledge, this is the highest temporal resolution ever achieved with ionospheric radars. We can now study many highly dynamic processes in the subauroral, auroral, and polar cap ionospheres and investigate their impacts on the ionosphere, thermosphere, and magnetosphere. In this paper, we describe the new analysis technique and demonstrate it with the first radar observations of electric fields associated with short period (14-20 s) Pi 1 pulsations.

2.1 Advanced Multipulse Analysis Technique

The use of multipulse sequences for radar applications was first suggested by [1] as a means of determining unambiguously the autocorrelation function (ACF) and spectral properties of backscattered signals as a function of range. Since that time the multipulse technique has been widely used in incoherent scatter radar applications [2] and in SuperDARN [3]. Although multipulse sequences have desirable properties, they also have shortcomings because they introduce considerable unwanted noise to the analysis. This occurs when transmitter pulses and/or backscattered signals from unwanted ranges overlap data being analyzed and render one or more lags of the desired ACF unusable. The new approach is based on a previously unrecognized property of multipulse sequences that, if utilized, greatly reduces the impact of this undesirable noise and produces ACFs with larger numbers of good lags.

Multipulse sequences are based on the mathematical concept of “Golomb Rulers” (See http://en.wikipedia.org/wiki/Golomb_ruler/). In the mathematical sense, the objective is to identify the minimum pattern of marks that are needed on a ruler to measure all integer distances (i.e. 1,2,3,….) and not have any distance measured more than once. In the radar case, the objective is to identify the minimum pattern of transmitted pulses that are needed to determine all lags of an ACF. In reality, there are no perfect rulers or multipulse sequences with more than four marks or transmitter pulses. There will always be missing distances (lags). However, there are sequences that are optimal [1] and we have chosen to adopt one of these as the basis for our new multipulse transmission sequence.

The new multipulse transmission sequence being used at the Wallops Island and Goose Bay radars is shown in Figure 1. The top trace shows the full transmission sequence which is comprised of 13 transmitter pulses. The signal returns from the first transmitted pulse are used to determine the strength of the backscattered signals as a function of range from the radar. Knowledge of this profile is important if one wants to maximize the benefits of the new multipulse sequence. Profile measurements are typically made to a range of 4600 km. The next 6 transmitted pulses represent one of the multipulse sequences identified by [1]. A blow-up of this sequence is represented by the tall and narrow pulses in the bottom left of the figure. The sequence has gaps of 1, 7, 4, 2, and 3τ between transmitter pulses, where τ is the minimum time separation between transmissions. This sequence is an optimal ruler. The only gaps that cannot be measured are 10τ and 15τ. The final six pulses in the upper trace represent the same Farley sequence in reverse order. These are expanded at the bottom right of Figure 1. This sequence is separated from the first sequence by 15τ as is the first sequence from the initial transmitted pulse. Thus with the exception of 10τ, there are two possible alternative choices for all lags of the ACF from τ to 17τ

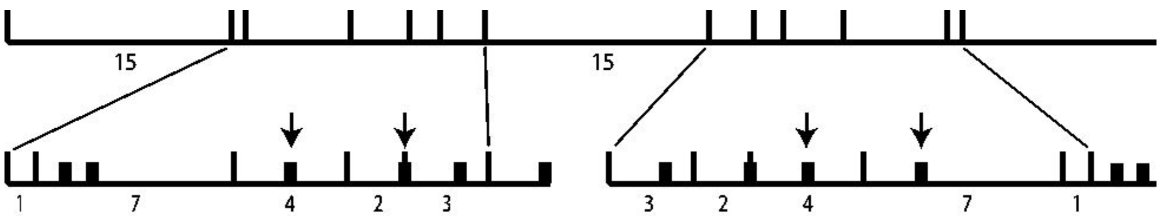

Figure 1. New multipulse sequence being used at the SuperDARN Wallops Island and Goose Bay radar sites. The sequence provides two opportunities to measure each of the first 17 lags of the autocorrelation function with the exception of lag 10.

We shall now see how the use of a reversed non-redundant multipulse sequence mitigates interference from transmitter pulses and unwanted noise in multipulse Doppler measurements. The short wide pulses in the lower traces of Figure 1 represent backscattered returns from each of the transmitted pulses. Note that they occur at a fixed delay following each transmission. The downward pointing arrows identify two of these returns that are associated with transmitter pulses separated by 4τ in each of the forward and reversed sequences. Careful examination of the bottom trace to the left shows that the backscattered signals due to the second transmitter pulse are received at the same time as another pulse is transmitted. Since monostatic radars cannot transmit and receive at the same time, these data are unusable and cannot contribute to the ACF determination. However, the same backscattered signals in the trace at the bottom right are unaffected by transmitter pulses and therefore yield good measurements. The interested reader may confirm that each sequence has 5 bad lags at this delay. Together the two sequences have 9 bad lags, but only lag 2τ is bad for both sequences. Thus, by using forward and reverse sequences, the researcher can reduce the number of bad lags in the ACF from 5 to 1. Similar arguments that we do not report here show that strong backscatter returns from unwanted ranges cause similar problems and since they occur at a specific delay following each transmitter pulse, they can be mitigated by forward and reverse sequences.

The new multipulse sequence shown in Figure 1 requires slightly more than 200 ms for transmission and reception of the data. Over a 7 s integration time, approximately 33 sequences are transmitted and received and either a mean or median fit to the resulting complex ACFs is determined. The Doppler velocity is derived from a least squares fit to the slope of the time-dependent phase of the backscattered signal defined as:

$$\langle\phi(n\tau, r)\rangle = \tan^{-1} (\langle ACF_{imag}(n\tau, r)\rangle/\langle ACF_{real}(n\tau, r)\rangle)$$

where <> denotes mean or median, τ is the minimum lag of the multipulse sequence (i.e. the inverse of the sampling frequency at any particular range), n is the lag number, ϕ is the phase of the ACF at lag nτ, and r is the range to the ionospheric region under investigation.

During the development of the new sequence, all receiver samples were saved as raw sample files at the Wallops radar site so that the new processing technique could be evaluated retrospectively and refined in a controlled manner. As part of this evaluation process, ACFs were determined for individual multipuse sequences and their phases were plotted as a function of lag. The top three panels in Figure 2 were obtained from three sequential multipulse sequences separated by slightly more than 200 ms. Each sequence is labeled with a Doppler velocity determined from a least squares fit to the measured phases. It can be seen that the velocity is steadily decreasing at ~27 m/s per sequence or ~135 m/s^2. The bottom panel in Figure 2 was obtained from the median values of the complex ACF for the 7 s integration (33 multipulse sequences). Note that the median value of the Doppler velocity was 223 m/s and that the phase scatter of the data points in the median slope is comparable to the phase scatter of the data in the individual sequences. Also note that in these examples all lags are present with the exception of the missing lag 10τ and lag 2τ. The latter lag corresponds to the range gate shown in Figure 1 that lies on a transmitter pulse.

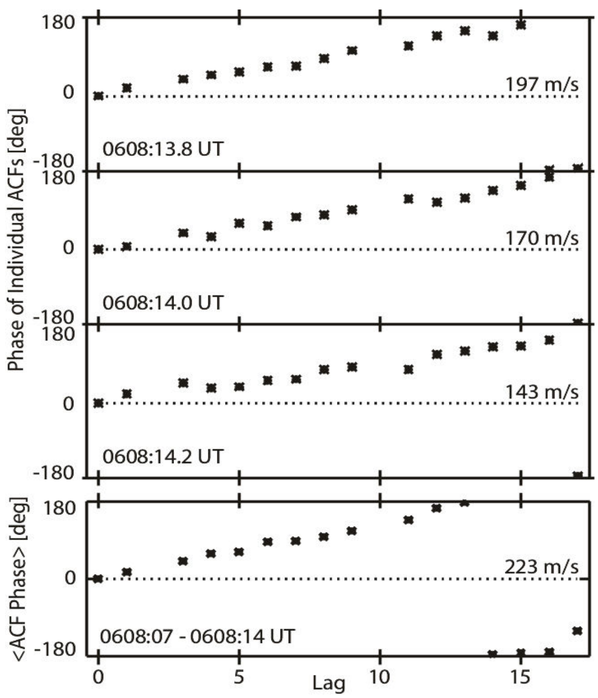

Figure 2. Phase versus lag profiles of data obtained on 1 August 2007 with the Wallops Island radar. The upper 3 panels show the phase versus lag profile of ACFs at a fixed range derived from backscatter returns for three sequential multipulse sequences. The Doppler velocity is derived from the phase slope and is indicated at the right of each panel. The lower panel shows the median phase slope for 7 seconds of data on the same beam and range. Note that the phase noise

It should be quite clear from Figure 2 that the data samples from a single multiple sequence are capable of yielding quality Doppler velocity measurements at a rate of 200 ms per observation (5 Hz). There are, however, two minor caveats. First, the data samples must be saved at the radar for retrospective analysis. The analysis is computationally intensive and cannot be done in real time. Second, the procedure requires good signal to noise ratios (SNR) (~7-10 dB) for the phase scatter to be as small as shown in the upper panels of Figure 2. Ranges with lower SNR will exhibit more phase scatter, but may still yield Doppler measurements of acceptable quality.

2.2 High-Temporal Resolution Velocity Measurements with the Wallops Radar

We now present a more extended view of the data shown in Figure 2. The data we show were obtained shortly after 06 UT on 1 August 2007 during a disturbed Kp = 4 period in which there were several substorm intensifications. The Wallops radar was in the post-midnight sector at ~02 MLT and was being scanned through 16 beam directions. Backscattered signals from the subauroral F-region ionosphere had been observed continuously for 4 hours on 4 -7 range gates from each of the most poleward 5-6 beam directions. These beam directions were clustered about 21° east of geographic north. The observations showed no systematic range dependence so all Doppler velocities derived from each multipulse sequence have been averaged to yield a mean Doppler velocity for each 200 ms interval. We also found that the data exhibited temporal continuity as the radar was scanned from one beam direction to the next. Noting this, we have simply plotted the data as a continuous time series of Doppler measurements, rather than trying to project the Doppler measurements into some assumed flow direction. Because of the relatively small angle between geographic north and the beam pointing directions, north-south drifts dominate east-west drifts in the Doppler measurements as long as the two drifts are of comparable magnitude. Therefore, we assume that we are observing approximately north-south plasma velocity oscillations driven by east-west oscillations in the ionospheric electric field.

Forty-two seconds of data are plotted for the 0604 UT scan and 35 seconds of data are plotted for each of the remaining scans. The gaps between the data occur as the radar is scanned toward lower geomagnetic latitudes where no ionospheric backscatter was observed. This is either due to an absence of irregularities in these viewing directions, or to the radar signals undergoing insufficient ionospheric refraction to achieve orthogonality with any irregularities that might have been present in these directions. A strong pulsation in the Doppler velocity is easily seen during the 0608 UT scan shown in Figure 3a. The oscillation in the plasma drift had a maximum peak-to-peak amplitude of 80 m/s (equivalent to a peak-to-peak electric field oscillation of 4 mV/m). This pulsation is expanded in Figure 3b and clearly shows evidence of a 13-14 s periodicity. Evidence of another pulsation is readily seen in the 0606 UT scan. This pulsation is weaker and appears to have a period of ~20 s. The scans at 0604 UT and 0610 UT also show some evidence of even weaker velocity pulsations.

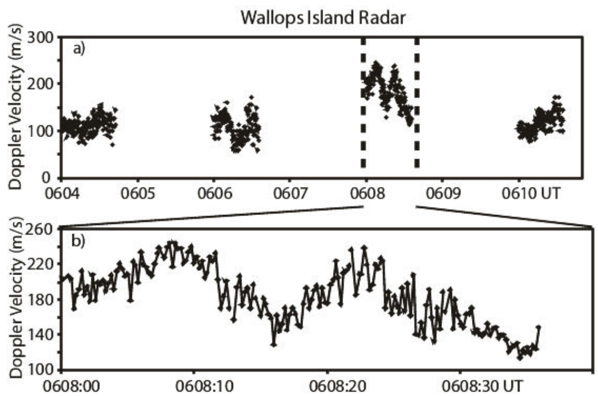

Figure 3. Rapid Doppler velocity pulsations observed with the Wallops Island radar on 1 August 2007. The observed periods range from 13-20 seconds. The lower panel is a blow up of the strongest velocity oscillation.

3. Summary

In this letter, we have described a new multipulse sounding sequence that substantially reduces the noise inherent in multipulse sounding techniques and greatly improves the temporal resolution of SuperDARN Doppler velocity measurements. Previously, the best temporal resolution attained with SuperDARN was 3 s integrations. With the new technique, Doppler measurements can be derived from each of the new 200 ms multipulse sequences. The new technique extends the applicability of SuperDARN velocity and electric field measurements to many new areas of research including short period pulsations, storm and substorm dynamics, and short-term variability in Joule heating. It may lead to improved understanding of velocity turbulence in the ionosphere.

We have demonstrated the success of the new multipulse analysis technique by showing that the Wallops radar is capable of detecting very short period electric field pulsations in the subauroral ionosphere. The peak-to-peak amplitude of these pulsations ranged from 2-4 mV/m and the periods ranged from ~14-20 seconds. Magnetic field pulsations with similar periods and peak-to-peak amplitudes of 1-2 nT were observed concurrently with the nearby Ottawa magnetometer.

Although the Doppler measurements reported here were limited to a few scans of the Wallops Island radar, the results demonstrate the potential of the higher temporal resolution plasma velocity and electric field measurements that are now available. The data set we presented was intermittent because the Wallops radar was being scanned and only certain beam directions detected backscatter from ionospheric irregularities. Fortunately, many SuperDARN radars are currently able to collect data in two operating modes concurrently. It is therefore possible to perform SuperDARN azimuth scans to allow large area coverage while simultaneously performing continuous measurements along a fixed viewing direction. This will allow continuous coordinated measurements between SuperDARN radars and magnetometers or other ground based instrumentation.

4. Acknowledgements

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