NOTES AND CORRESPONDENCE

Frequency Domain Interferometry Using the 1290-MHz Søndre Strømfjord Radar: First Results

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ABSTRACT

First results from the implementation of frequency domain interferometry (FDI) using an L-band frequency of 1290 MHz are presented. To our knowledge, FDI has not previously been applied to such high-frequency measurements. The experiment was conducted in September 1991 using the radar facility located in Søndre Strømfjord, Greenland. The Søndre Strømfjord radar is typically used for incoherent scatter measurements in the ionosphere, but these are some of the first lower-atmospheric results, namely, 8.6–13.4 km, since the new data-taking system was implemented. At the time of the experiment, the steerability of the 32-m dish antenna was hampered because of a faulty elevation-scanning bearing. Therefore, the measurements were taken from an approximately vertical direction for the duration of the experiment. The spectra and the correlation functions obtained from the FDI data are compared to previous results at other frequencies. The data show the Søndre Strømfjord radar is providing reliable wind measurements in the lower atmosphere and that FDI can be implemented at L band.

1. Introduction

The need for information about ever smaller scales of motion in the atmosphere make instrument resolution a major concern. The mesosphere–stratosphere–troposphere (MST) radar technique has become increasingly important over the last decade as a tool for studying the winds, waves, and turbulent structure within the atmosphere. The signals received by these radars are produced by scattering and, in some cases, reflection from turbulent fluctuations in the refractive index. Often the structure manifests itself as well-defined layers with vertical scale sizes on the order of tens of meters (Woodman 1980). Such small scales cannot be resolved by most MST radars, which typically have a minimum-range resolution of 150–300 m.

The frequency domain interferometry (FDI) technique was developed by Kudeki and Stitt (1987) as a means for overcoming the range resolution limitation and was first implemented by them using a VHF radar. Subsequently, the technique has been given much attention in the literature (Franke 1990; Kudeki and Stitt 1990; Palmer et al. 1990; Stitt and Kudeki 1991; Chu and Franke 1991). By varying the transmitter frequency from pulse to pulse, the cross-correlation functions or cross-spectra between the two signals can be used to determine the location and thickness of a scattering layer within the resolution volume of the radar. If the layer is diffuse and relatively thick, in comparison to the resolution volume, the FDI measurements will provide results comparable to what can be achieved with the normal range resolution of the radar. On the other hand, if a single thin scatter layer exists within the range volume, the FDI technique can be used to determine the location and width of the layer.

In this paper, the first results from FDI measurements at an L-band frequency of 1290 MHz are presented. The radar wavelengths used previously for such measurements have all been in a range that is strongly affected by aspect sensitivity in which there is an enhancement of the scatter for incidence angles near vertical. At 1290 MHz, there is no significant aspect sen-

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sitivity. The incoherent scatter radar located in Søndre Strømfjord, Greenland, was used for the experiment and observations were made in the troposphere and lower stratosphere. The next section summarizes the basic analysis techniques used for FDI observations. Following sections show the FDI cross-spectra and cross-correlation functions, and analysis is provided to verify the operation of the FDI system. Conclusions are provided in the final section.

2. Frequency domain interferometry

The extent of the resolution volume is inversely proportional to the bandwidth of the radar system and proportional to the length τ of the transmitted pulse. By decreasing τ, the range resolution is improved, but a limit exists because of the restricted bandwidth of the radar. Although observations have been made at 2380 MHz with an improved resolution of 30 m (Woodman 1980), typical MST radars are limited to a range resolution of 150 m, or worse.

FDI uses the phase difference of two signals separated in frequency by Δf to determine the position of a high-reflectivity layer within the resolution volume (Kudeki and Stitt 1987). A vertically pointing beam is typically used although, in principle, off-vertical beam directions can also be employed. The frequency difference should be chosen such that $\Delta f = f_h - f_l \leq 1/\tau$, which assures that there is no 2π ambiguity in the phase difference. If $\Delta f = 1/\tau$, the range of possible phase differences between the two signals would range from 0 to 2π between the lower and upper boundaries of the resolution volume. Even though such a situation is desirable, it is by no means necessary for the successful implementation of the technique. As the position of the scattering layer changes, the phase difference will change accordingly so that the phase difference can be used to produce an estimate of the *relative* layer position. The absolute position of the scattering layer cannot be determined unless the initial transmitted phase is known.

The FDI technique can be used to determine the

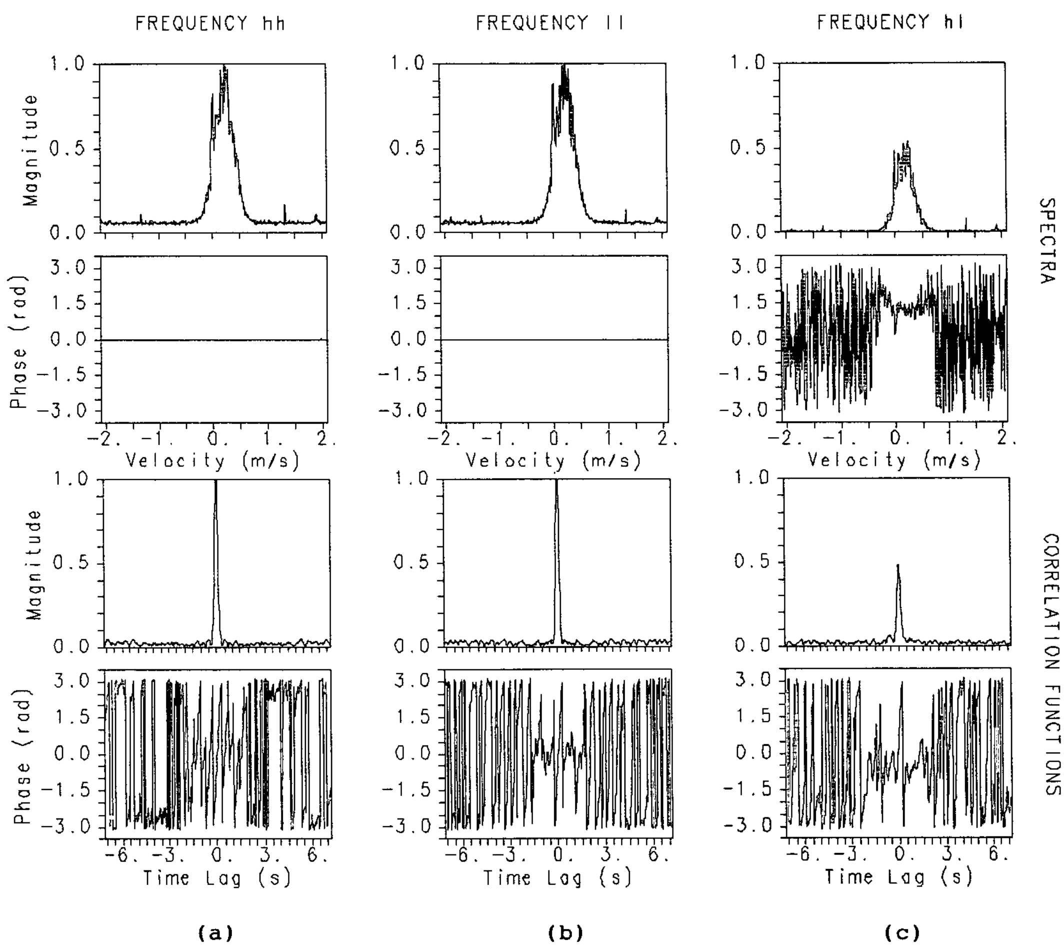

FIG. 1. A typical 25-min average of autospectra and autocorrelation functions [panels (a) and (b)], and (c) cross-spectrum and cross-correlation function at a height of 11 km. The data were obtained from 1432 to 1457 LT. Notice the nonrandom cross-spectral phase in the region of high signal power, which is a typical phase characteristic for FDI measurements. The spectral magnitudes have been normalized to the average of the peaks in the auto-spectra.

location of a single scattering layer within the resolution volume. The technique fails if there is more than one layer within the range volume. Of course, the probability of having only a single layer can be improved by having a smaller initial resolution. With only a single scattering layer, the accuracy of the estimated location is a function only of the statistical uncertainty of the phase estimate (Kudeki and Stitt 1987).

Data from a standard FDI experiment is analyzed by calculating the normalized cross-spectrum between the signals at the different frequencies using

$$S_{hl}(v_r) = \frac{\langle V_h(v_r) V_l^*(v_r) \rangle}{[\langle |V_h(v_r)|^2 \rangle \langle |V_l(v_r)|^2 \rangle]^{1/2}} \quad (1)$$

where $V_h(v_r)$ and $V_l(v_r)$ are the Fourier transforms of the signals at the high and low frequencies, respectively, and $\langle\,\rangle$ represents the expected value operator. The magnitude and phase of $S_{hl}(v_r)$ are given by

$$|S_{hl}(v_r)| = \exp[-2\Delta k^2 \sigma_r^2(v_r)], \quad (2)$$

$$\phi(v_r) = 2\Delta k \langle r(v_r) \rangle, \quad (3)$$

where Δk is the difference in the wavenumbers between the two frequencies, that is, $\Delta k = 2\pi\Delta f/c$ and c is the speed of light. The relative location and thickness of the scattering layer are given by $\langle r(v_r) \rangle$ and $2\sigma_r(v_r)$, respectively. It should also be noted that $|S_{hl}(v_r)|$ is the so-called coherence function. By finding the normalized cross-spectrum and using (2) and (3), the relative range and thickness can be estimated.

In a recent study, Franke (1990) developed FDI equations, which take into account the effects of wave front curvature. As he showed, the effect is more pronounced for wider beamwidths. In the present study, the effect can be ignored because of the narrow beamwidth of the Søndre Strømfjord radar, that is, 0.5°.

3. Experimental configuration and results

An FDI experiment was conducted on 24 September 1991, using the incoherent scatter radar located in Søndre Strømfjord, Greenland (67°N, 50°E) (Kelly 1990). The Søndre Strømfjord radar, which operates at an L-band frequency of 1290 MHz, is typically used

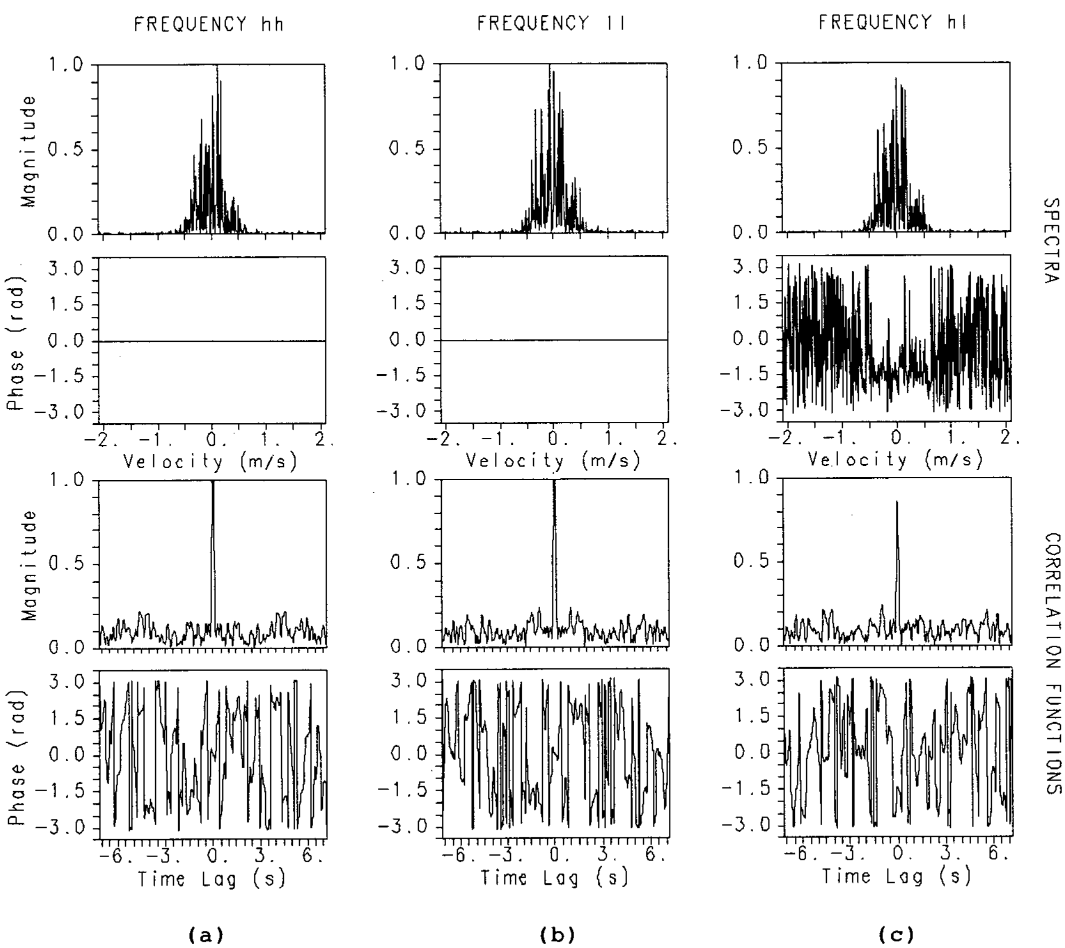

FIG. 2. Same as Fig. 1 except with no incoherent integrations and at a height of 13.1 km. The data are from the initial 15 s of the time period from Fig. 1.

for incoherent scatter radar measurements of ionospheric parameters, although the instrument is also well suited for MST radar studies of the lower atmosphere. To achieve the dual-frequency transmission needed for FDI, alternating pulses were transmitted with frequencies of f_l = 1290 MHz and f_h = 1290.45 MHz. The pulse length τ was set to 2 μs providing a range resolution of 300 m.

The interpulse period (IPP) was set to 1 ms, but alternate frequencies were transmitted on alternate pulses so that the effective IPP was 2 ms. Fourteen coherent integrations were used, providing an aliasing velocity of 2.07 m s^{-1}. Coding of the transmitted pulse was not employed. At the time of the experiment, the elevation-scanning bearings of the dish were not functioning properly. As a result, all measurements were taken at elevation and azimuth angles of 89.6° and 0°, respectively. The beam-pointing accuracy of the Søndre Strømfjord radar is approximately ±0.2° and the one-way, half-power beamwidth is approximately 0.5°. Therefore, one can consider the results to be essentially from a vertically pointing beam. Future campaigns are planned where the full steerability of the dish will be utilized. Measurements with adequate signal-to-noise ratios were taken in the altitude range of 8.6–13.4 km, with a gate spacing and resolution of 300 m. Using the above sampling time, 512 points of raw data for each frequency were stored on magnetic tape approximately every 15 s. These 512-point datasets were used to produce spectra and correlation functions shown in Figs. 1 and 2. Figure 1 represents the data at a height of 11 km after 100 incoherent integrations. Figure 2 is identical to Fig. 1 except that no incoherent integrations were performed and the altitude was 13.1 km. The data shown in Fig. 1 were obtained from 1432 to 1457 LT, while the data shown in Fig. 2 were obtained from the initial 15-s dataset.

The first two rows of Figs. 1 and 2 display the magnitude and phase of the auto- and cross-spectra, respectively. Autospectra are shown in the first two columns while the cross-spectrum is in the last column. As should be expected, the two autospectra from the combination of signals at frequencies *hh* and *ll* are very similar. In Fig. 1, a ground clutter signal can be seen at zero Doppler shift and a symmetric 60-Hz signal is also present at approximately ±1.4 m s^{-1}. In the last column, the cross-spectrum has a smaller magnitude than the auto-spectra because of the decorrelation effects of the Δf frequency shift. The constant noise level, observed in the autospectra, is gone as a result of the independence of the two noise sequences from the frequency-separated signals.

The phase of the cross-spectrum is the quantity of primary interest for FDI measurements. In a recent article, Palmer et al. (1992) presented a model that showed the FDI cross-spectral phase to have an approximate parabolic structure centered close to zero Doppler frequency. The concavity of the parabola can

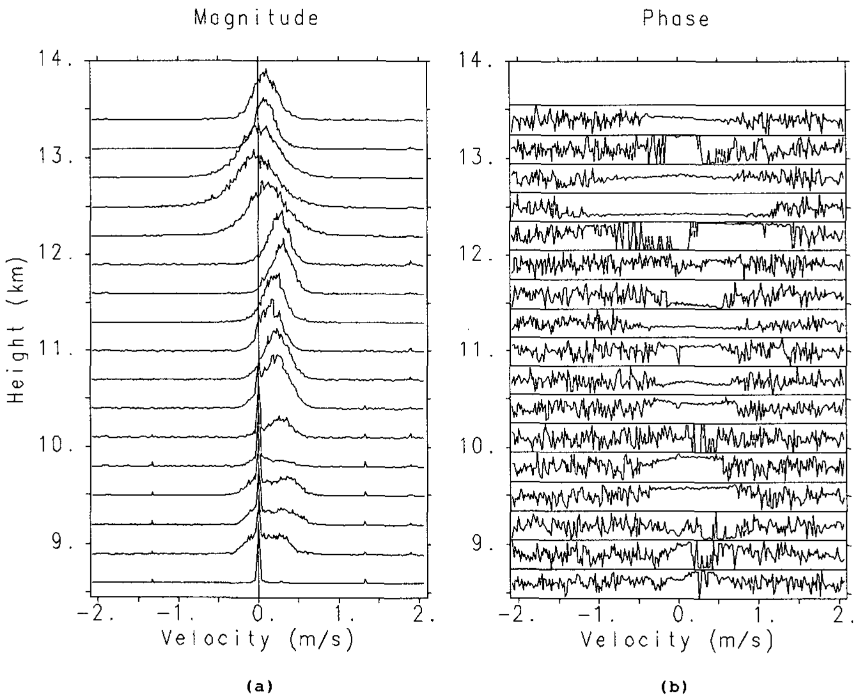

FIG. 3. Profiles of (a) magnitude and (b) phase of the cross-spectra in the region 8.6–13.4 km. The horizontal lines in the phase plot represent the boundaries between the neighboring gates. Cross-spectral phase in a FDI experiment represents the relative location of a scattering layer within the resolution volume.

be upward or downward and slightly shifted from center depending on the beam position, horizontal wind speed, and any layer tilting. This concavity can be understood by realizing that scatterers with larger Doppler shift will be located at larger zenith angles. For the same height, the larger zenith angles represent longer phase paths. Therefore, the phase in the cross-spectra should have an approximate parabolic variation with radial velocity.

The cross-spectral phase, shown in Fig. 1, confirms the approximate parabolic structure. The data are from a 25-min average at a height of 11 km. For completeness, the last two rows of the figures show the auto- and cross-correlation functions obtained by the inverse Fourier transform. Of course, the information contained in the cross-spectrum can also be obtained from the cross-correlation function. If only the average location of the layer is desired, the phase at lag zero of the cross-correlation function is useful because of its small statistical fluctuations. On the other hand, wavefront curvature can cause the coherence, obtained from the cross-correlation function, to be biased toward smaller values (Franke 1990). In contrast, the cross-spectrum sorts the different regions of the layer by Doppler velocity. Therefore, a better understanding of the true layer structure is provided by using the cross-spectrum.

As in standard Doppler measurements, incoherent integration reduces the variability in the spectra. Figure 2 shows the increased variance in the auto- and cross-spectra for no incoherent integration. Nevertheless, the cross-spectral phase is reasonably consistent for values of radial velocity close to zero.

Figures 3a and 3b show the 25-min-averaged profiles of magnitude and phase of the cross-spectra for the 17 useful gates. The horizontal lines in the cross-spectral phase plot represent the boundaries between the adjacent gates. As in Fig. 1, the ground clutter and 60-Hz signals are readily seen. A Doppler shift is present in the profile, which could be due to a vertical wind or to a small component of the horizontal wind since the beam actually has a small but not negligible zenith angle of 0.4°. The consistent portions of the phase curves follow the peak in the cross-spectral magnitude and have either a slight upward or downward concavity.

The first few gates show more randomness in the cross-spectral phase. Coherence, given by (2), provides a means of estimating the thickness of scattering layers. It is possible that thin scattering layers can exist when the echo power is small. An example of this case can be seen in Figs. 4a and 4b, where profiles of echo power and coherence are given, respectively. At approximately 9.5 km, relatively low echo power is observed but the coherence is rather large. In Fig. 3b, this region has a nonrandom cross-spectral phase, and therefore a well-defined, thin, scattering layer is present. Comparing the coherence profile with the cross-spectral phase plots shows that the existence of the well-defined layer can be predicted by either a large coherence or a nonrandom, cross-spectral phase. It is interesting to note that the largest coherence value, for this particular experiment, was approximately 0.75.

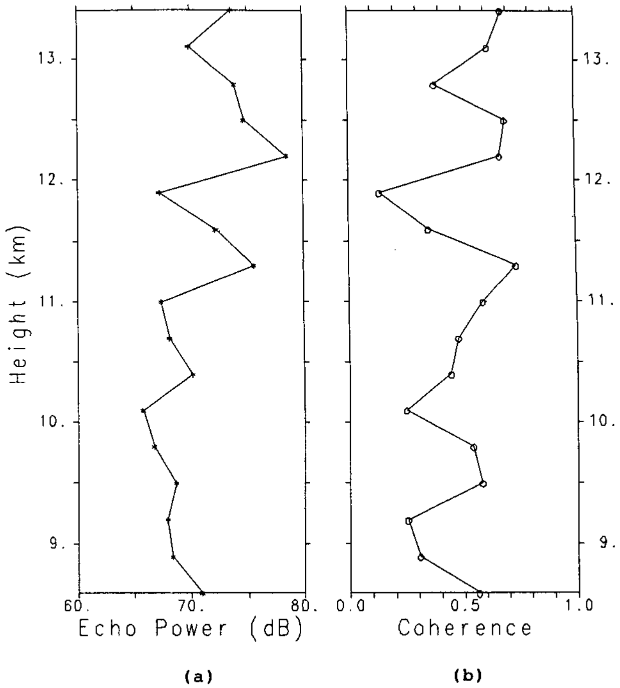

FIG. 4. Profiles of (a) echo power and (b) coherence. Large coherence values represent a stable layer within the resolution volume and can also be used to estimate the layer thickness. The maximum of the coherence profile is approximately 0.75.

The coherence not only depends on the layer thickness, but also Δf and signal-to-noise ratio (SNR). Therefore, it is difficult to directly compare the coherence values stated above with those from previous work. The experiments described by Kudeki and Stitt (1987, 1990) and Stitt and Kudeki (1991), for example, were conducted with $\Delta f = 100$ kHz at a VHF frequency. Their data show a maximum coherence of approximately 0.98, which is larger than our value of 0.75. The discrepancy is expected since the coherence increases with decreasing Δf. Chu and Franke (1991) presented FDI data for various Δf values, again at a VHF frequency. For Δf equal to 500 kHz, their results showed a coherence range of 0.45–0.85. Our results at an L-band frequency and with $\Delta f = 450$ kHz are similar to those of Chu and Franke (1991). One should be reminded that our results are from a limited amount of data. Therefore, the comparisons can only provide a rough idea of the differences in coherence to be expected at VHF and L band. More extensive experiments are planned for comparison of these two frequencies. The obvious question is whether scattering layers observed with such different wavelengths will exhibit an inherent difference in thickness.

4. Conclusions

The new data-taking system that has been implemented at the Søndre Strømfjord radar has been verified for wind measurements in the troposphere and lower stratosphere, and the first results from FDI measurements using an L-band Doppler radar have been presented. The auto- and cross-spectra and correlation functions obtained from the FDI data are similar to previously reported results at longer wavelengths, which are typically affected by aspect sensitivity in the scatter. Our results show that the FDI method can be implemented successfully at higher frequencies and that the method is not dependent on aspect-sensitive or anisotropic scatter. An advantage of the Søndre Strømfjord radar is that the antenna is fully steerable to within a few degrees of the horizon in all azimuth directions. As a result, the location of turbulent layer structures can be mapped in three dimensions over a broad region in a relatively short time. Future experiments will use the flexible beam steering of the Søndre Strømfjord radar in conjunction with FDI analysis in order to study the spatial and temporal variations in the turbulent structure in more detail.

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