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The structure and dynamics of inertia-gravity waves in the upper troposphere and lower stratosphere have been studied using data from a wind profiler that was temporarily located in Kansas, data from the Arecibo Observatory 430 MHz radar, data from the SOUSY-VHF-Radar located in Germany, and data from the MU radar in Japan. The radar data has shown that low-frequency inertia-gravity wave oscillations are a persistent feature of the region near the tropopause and in the lower stratosphere. Some of our analysis indicates that the wave structure is likely generated by the interaction of the surface winds and the orography. However, the frequency in the earth-fixed frame corresponds to a period of 24 hr and is not zero. The latter effect is presumably due to the strong diurnal cycle in the surface winds. Other results have shown that there is strong vertical circulation near the tropopause with a reversal in direction at the height of the wind maximum. The observed vertical velocities are larger than expected but otherwise agree with the predictions of earlier theoretical analyses. We have also investigated the relationship between turbulent layers in the upper troposphere and lower stratosphere and the low-frequency inertia-gravity waves. The

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turbulent layers are observed to move in the same direction as the phase progression of the background waves, indicating that the turbulent layers occur at a particular wave phase where the wave-perturbed flow becomes unstable.



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Final Technical Report

WIND PROFILER INVESTIGATIONS OF LOW-FREQUENCY

GRAVITY-INERTIA WAVES AROUND THE JET STREAM

AFOSR Contract # F49620-88-C0121

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## 1. INTRODUCTION

The focus of the research project has been on high-resolution radar studies of the dynamics of low-frequency inertia-gravity waves in the troposphere and lower stratosphere, the relationship between such waves and the evolution of frontal zones, and the interaction between the waves and small-scale turbulence. Four different radars have been used in the investigation, including the SOUSY-VHF-Radar located in the Harz Mountains in Germany; the Flatland VHF radar located near Urbana, Illinois; a VHF radar wind profiler operated on a temporary basis by Radian Corporation in MacPherson, Kansas; and, most recently, the MU radar located near Kyoto, Japan. The results have been described in a number of journal articles, most of which have been published already. A few articles are still in press or nearing acceptance by the journal editor. A cumulative list of publications is attached at the back of the report in the Appendix.

## 2. DESCRIPTION OF RESEARCH RESULTS

The work has involved studies of low-frequency inertia-gravity waves using the Arecibo Observatory radar (Cornish and Larsen, 1989) and the Flatland Radar in Illinois; studies of short-term and small spatial-scale variability in connection with a squall-line passage using a VHF radar wind profiler that was located in MacPherson, Kansas (Yoe, 1990; Yoe et al., 1989, 1991); studies of vertical velocities in and around frontal zones using the SOUSY VHF radar located in Germany (Larsen et al., 1988); studies of the average circulation around the jetstream using the MU radar in Japan

(Fukao et al., 1991a); investigations of the spaced antenna/radar interferometer techniques using data from the MU (Larsen et al., 1991c; Palmer et al., 1990, 1991) and SOUSY radars (Larsen and Röttger, 1991); and studies of the biases in vertical velocity measurements introduced by aspect sensitivity, i.e., tilted refractive index layer, effects (Larsen et al., 1991a). A common theme in these studies has been the development of techniques for and analysis of the measured parameters critical to our understanding of the generation and propagation of waves within frontal zones and precipitating systems; the transport of mass, energy, and momentum by the mean circulation and by waves within such systems; and the interaction of the waves with larger and smaller scales. A cumulative list of publications which describe the research results in more detail is attached at the back. In addition, brief summaries of some of the key research results are provided in the following subsections.

#### **(a) Vertical Velocity and Refractivity Layer Inclination Angle Studies**

In the past ten years, numerous studies of radar wind profiler vertical velocity measurements have been carried out (see, e.g., Röttger and Larsen, 1990). Such measurements have been of interest because they provide information about dynamics and transport in the atmosphere that is difficult, if not impossible, to obtain by other means. The vertical velocities obtained from the radars have been in qualitative agreement with expected behavior, but direct verification of the values has been extremely difficult. Nastrom et al. (1985) and Larsen et al. (1988) attempted comparisons of the radar values with the vertical velocities inferred from surrounding rawinsonde measurements and numerical forecast model initializations, respectively. While there was general agreement, the details in the values used for the comparisons showed significant differences. Poor agreement between inferred or calculated vertical

velocities and those that are measured may be due to differences in the measurement techniques, to differences in the inherent averaging of the data, or to spatial separation between the measurements. Thus, the quality and possible biases in vertical velocity measurements have been difficult to assess.

Within the last two years, significant progress has been made with regard to improving our understanding of Doppler wind profiler vertical velocity measurements by making use of the spaced antenna/radar interferometer techniques (see, e.g., Larsen and Röttger, 1991; Larsen et al., 1991c). Specifically, interferometer/spaced antenna measurements can be used to determine the incidence angles of echoes within the beam. The latter has been critical in determining when the vertical velocities measured by the Doppler method are likely to be biased. The article by Larsen et al. (1991b) summarizes recent results related to vertical velocity measurements and vertical velocity correction techniques.

At longer wavelengths, such as those around 6 m or longer, the backscatter is known to depend strongly on the pointing direction (e.g., Tsuda et al., 1986). Measurements made with a beam pointed within a few degrees of vertical will show much larger reflectivities than measurements made with beams pointed a few degrees off-vertical. Reflectivity differences of 10-14 dB are common. Such aspect sensitive echoes are produced by turbulent layers in a stratified atmosphere.

As long as the layers are horizontal so that the strongest scatter comes from the vertical direction, no bias is introduced. However, if the layers are inclined with respect to the horizontal, the strongest scatter will come from a direction slightly off vertical. The large difference in the magnitude of the horizontal and vertical winds then results in large errors in the vertical velocity estimates, even if the off-vertical angles amount

to only a degree or less. The latter effect has been discussed in detail by Larsen and Röttger (1991). The effective beam pattern becomes a convolution of the instrumental and aspect sensitivity beam pattern. A relatively narrow aspect sensitivity pattern in relation to the instrumental beam pattern leads to an effective pointing direction which is nearly identical to the layer inclination angle.

When measurements are made by transmitting on a single antenna and receiving on two or more spaced receiving antennas, the phase differences between the signals in the receiving antennas can be used to determine the direction of arrival of the signals. The phase path for one antenna becomes longer than the path for the other when the incidence angles are off-vertical. The line-of-sight velocity also has contributions from both the vertical and horizontal winds when the effective beam-pointing direction is off vertical. In the analysis procedure, the phase of the cross-correlation at zero lag yields the phase difference which can then be related to the inclination angle by simple geometry. Larsen and Röttger (1991) used this technique to measure refractivity layer inclination angles over a period of four days at the SOUSY-VHF-Radar located in the Harz Mountains in Germany. Typical magnitudes of the inclination angles were  $1^\circ$  or less when averaged over 6 hr.

The interferometer/spaced antenna technique provides a method for measuring the incidence angles so that the effective pointing direction of the nominally vertical beam can be determined. However, in vertical beam Doppler measurements using a single transmitting and receiving antenna, the effective pointing direction is unknown. Typical beamwidths are in the range of  $5^\circ$  to  $15^\circ$  so that layer inclinations anywhere within a few degrees of vertical will be within the beam. As a result, the line-of-sight Doppler velocity along the effective pointing direction will have components from the

projections of both the horizontal and vertical velocities. Larsen and Röttger (1991) determined the errors introduced by such effects and found them to range from 0% to over 100%, depending on the conditions.

While the aspect sensitivity effect is not the only potential source of bias in vertical velocity measurements, the studies to date indicate that it may be prevalent. Layer inclination measurements such as those of Larsen and Röttger (1991) show that the incidence angle will almost never be directly from the vertical, even in regions of the atmosphere that are relatively well mixed. A possible correction is to use a high frequency, i.e., short wavelength, system which is not susceptible to aspect sensitivity effects. Measurements with the 430-MHz radar at the Arecibo Observatory, for example, show no evidence of aspect sensitivity effects. With such a system, vertical beam measurements should be equivalent to true vertical velocity measurements. However, the higher frequency radars are also very sensitive to scatter from precipitation. Larsen and Röttger (1987) have shown that the 430-MHz Arecibo radar echoes will be dominated by precipitation scatter even for relatively light rainfall rates. Therefore, the high-frequency solution is only applicable in clear air, and direct vertical velocity measurements will not be possible in precipitating environments.

#### (b) Radar Interferometer Data

We have already shown that the radar interferometer and spaced antenna techniques are equivalent (Larsen et al., 1991c). However, there appear to be advantages associated with using the radar interferometer technique for the analysis, as described in the latter article. Work was completed on the development of a set of analysis programs that can be applied routinely to the radar interferometer data from the MU radar. The parameters yielded by the analysis include the horizontal winds,



the true vertical velocities, and the zonal and meridional components of the refractivity layer tilt angles. The latter values were extracted from several extended observations carried out with the MU radar in Japan during the spring of 1990. The observations included both stable conditions associated with high pressure and unstable conditions characteristic of frontal passages. The corrected vertical velocities derived from the analyses were used to investigate the circulations around the jet stream.

### (c) Oblique Spaced Antenna Measurements

Recently Liu et al. (1991) have described the first results from an application of the oblique spaced antenna (OSA) technique for measurements of three-dimensional wind vectors. The conventional spaced antenna (SA) method utilizes a vertically-pointing transmitter array and three or more spatially-separated receiving antenna arrays. The turbulent refractive index structure drifting past the arrays creates a diffraction pattern on the ground. Correlations between received signals can then be used to estimate the horizontal drift velocities which, in turn, can be used to calculate the horizontal winds. Vertical velocities are usually estimated directly from the Doppler spectra derived from the vertical beam measurements. Larsen and Röttger (1989) have described the conventional spaced antenna technique in more detail.

The oblique spaced antenna method uses an analysis technique that is essentially identical to the vertical spaced antenna method. The primary difference is that the transmitting and receiving arrays are all phased so that they point off vertical at a particular azimuth. The measurements presented by Liu et al. (1991) showed good agreement between the wind magnitudes and directions estimated from the oblique and the vertical SAD measurements, indicating that the technique is inherently sound. Those authors also pointed out that a potential advantage of the OSA method is that

complete vector winds can be measured at spatially-separated locations surrounding the radar location. Three or more such measurements can be used to calculate the vorticity and divergence in the proximity of the radar. Radial line-of-sight Doppler measurements can be used to calculate the divergence but not the vorticity. The latter result is well known from VAD analysis (e.g., Browning and Wexler, 1972) in which measurements are made around an azimuth circle at constant elevation. A simple analytical analysis can be used to show that no combination of azimuth and elevation angles will yield the vorticity from radial Doppler velocities.

An oblique spaced antenna experiment was carried out at the MU radar in Japan in February 1990 during a five-month visit by the P.I. The observation period was characterized by the passage of a strong frontal system that was arguably the most intense of the spring, followed by a weaker frontal passage a few days later. The variation of the vorticity calculated from the measurements was qualitatively in agreement with expectations based on the meteorological conditions, i.e., the vorticity was large and positive in the vicinity of the fronts and small at other times. The initial analysis of the results has been completed, and the preliminary results indicate that the measurement technique is yielding realistic values. The MU radar vorticity and divergence values were compared to the vorticity and divergence calculated from the horizontal wind data from the four rawinsonde stations surrounding the MU radar location. The magnitude of the radar vorticity and divergence was found to be a factor of approximately ten greater than the rawinsonde values but otherwise the variation in the values was similar. The difference in magnitudes can be explained nonrigorously by the scaling of the vorticity which varies inversely with the scale length. The separation between rawinsonde stations was approximately 100 km while the separation between

beam sampling positions was approximately 10 km.

A preprint article by Fukao et al. (1991b) summarizes the preliminary results from the oblique spaced antenna measurements.

#### (d) Dynamical Studies

The study by Cornish and Larsen (1989) found that low-frequency inertio-gravity waves observed in the lower stratosphere were apparently generated by diurnal forcing due to either surface heating or surface wind variability with a 24-hr periodicity. The waves were found to be a persistent feature of the tropopause and lower stratosphere region above Puerto Rico and had amplitudes of  $3\text{-}5 \text{ m s}^{-1}$  and vertical wavelengths of  $\sim 1.5 \text{ km}$ . The analysis of the wave structure showed that the waves were encountering an inertial level where the intrinsic frequency was equal to the inertial frequency at a height in the lower stratosphere. A significant deceleration of the mean flow was inferred from the variation of the wave amplitude with height and the measured wave parameters. Such wave structure appears to be an efficient means for communicating the effects of heating or orography to higher altitudes.

The thesis by Yoe (1990) and the articles by Yoe et al. (1989, 1991) showed that a squall-line passage in Kansas produced a significant enhancement in the high-frequency gravity wave energy at periods of a few minutes to one hour in the rear outflow aloft. Specifically, the frequency power spectrum of the vertical velocity oscillations was enhanced by a factor of as much as 10 at periods of 5 min. The enhancement tapered off to zero at periods close to one hour. The increase in high-frequency energy was produced as the air traveled through the updraft core within the squall-line. The results of the study indicate that the oscillations produced within the

storm may be a rapid and efficient way to propagate energy away from the updraft region and that the energy in the high-frequency oscillations may constitute an important fraction of the energy budget for the storm system.

The work by Fukao et al. (1991a) showed that a strong vertical circulation exists around the jetstream core even when long-term averaging is applied to the data. Typical amplitudes for a four-day period were  $10\text{-}20 \text{ cm s}^{-1}$  with downward velocities below the horizontal wind speed maximum and upward velocities above. Comparisons with the potential temperature-surface slopes estimated from rawinsonde data from the surrounding stations showed that the flow must have been characterized by significant temporal variations or diabatic flow in at least half the cases. In the remaining cases, the vertical circulation was found to be such that it would tend to enhance the horizontal temperature gradient that produced the jet. The analysis indicated that the observed vertical flow would tend to maintain the jet in the presence of dissipation.

The study by Larsen and Röttger (1991) used spaced antenna/interferometer data obtained with the SOUSY-VHF-Radar located in Germany to examine the vertical circulation around a weak warm front that passed the radar site. The corrected vertical velocities showed better qualitative agreement with expectations based on the meteorological conditions. For example, the uncorrected velocities showed a vertical circulation extending 3-4 km above the frontal boundary into the lower stratosphere and a weak circulation around the wind speed maximum near the tropopause. The corrected velocities showed stronger upward velocities at lower heights near the front and a stronger vertical circulation near the wind speed maximum. The average vertical velocity profile for a four-day period showed a feature similar to that found by Fukao et al. (1991a) in the MU radar data, except that the sign of the velocities was reversed.

The difference in sign was explained, however, by the location of the jetstream relative to the radar site.

#### (e) Momentum Flux Measurements

The techniques described earlier in the report for correcting radar vertical velocity measurements have been applied to data covering a four-day observation period when a frontal zone passed the radar site. The combination of the corrected vertical velocities and the horizontal velocities available for the same period allows us to calculate the corrected vertical momentum fluxes in the troposphere and lower stratosphere associated with the frontal passages. The momentum fluxes associated with the passage of the mesoscale convective system have also been analyzed (Yoe, 1990). The results showed that the accelerations induced by the vertical fluxes of momentum produced by high-frequency gravity waves accounted for an important component of the dynamics of the system. The accelerations amounted to approximately 100% of the magnitude of the winds in a period of a few hours. Since such large accelerations are not observed, the gravity-wave induced accelerations must be balanced by other effects. However, the results indicate that the high-frequency motions should not be ignored in theoretical analyses or modeling studies of such systems.

### 3. SUMMARY

The conclusions of the studies are twofold. First, care has to be taken in the analysis of standard radar wind profiler measurements of vertical velocities. Our results have shown that the biases introduced by aspect sensitivity effects, for example, can amount to over 100% of the magnitude of the wind. However, the biases can be

eliminated with appropriate measurement techniques, namely the multiple receiver techniques such as the spaced antenna or interferometer techniques. The advantages of the latter are that, in addition to eliminating the biases, the techniques provide additional information about the medium, such as the distribution of the turbulent structure within the illuminated volume. Second, the small-scale wave structure has been found to be an important component of the dynamics of the upper troposphere and lower stratosphere region. The low-frequency inertia-gravity waves appear to be an important agent in transmitting orographic braking to the upper tropospheric heights. High-frequency waves have been found to be a significant component in the balance of forces of a mesoscale convective system. The preliminary conclusion from the studies described here is that the small-scale components of the flow cannot be ignored, even if the larger-scale dynamics are of primary interest.

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**APPENDIX**

**List of Publications (Aug. 1, 1988 - Sep. 30, 1991)**

### Publications

Larsen, M. F., J. Röttger, and T. S. Dennis, A comparison of operational analysis and VHF wind profiler vertical velocities, *Mon. Wea. Rev.*, **116**, 48-59, 1988.

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