Final Report for NASA Contract NAS5-02069

"Layers in the Equatorial Mesosphere, Motions and Aerosol Rocket and Radar Study (LEMMA)"

PI: D. C. Fritts

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1. Science Investigation Summary

Our role in the LEMMA rocket and radar measurement program had several components corresponding to the various phases of the research effort. Our initial efforts focused on definition of the experimental configuration and measurement requirements following the decision to move the experiment to Kwajalein. At this stage of the research, the PI of this subtask consulted with the project PI, Dr. Gerald Lehmacher, and other participants in defining the atmospheric conditions that would allow optimal measurements and the radar modes that would best characterize the structures we hoped to observe. This proved to be a challenge, as the ALTAIR radar, despite its substantial capabilities, did not have a representative suite of software control and analysis capabilities. Once the experiment and timing were defined, our role shifted to numerical characterization of potential radar backscatter and in situ turbulence signatures accompanying various dynamical processes. Following completion of the measurement program, we supported the analysis and interpretation of the experimental data.

Following definition of the measurement program, our efforts focused on the computation of radar backscatter employing the Borne approximation. The method is described by Franke et al. (2005) and allows us to specify radar pulse lengths and beam widths of various shapes in order to assess the implications for various radar systems. We also developed a spectral transform method to allow us to incline the radar beam relative to the orientation of the dynamics simulated with our direct numerical simulation (DNS) codes. Our intent was to examine the implications of specularity and the structure and evolution of turbulent flows for radar measurement biases introduced by off-zenith viewing and the anisotropic distributions of energy dissipation rate and temperature fine structure within the evolving turbulence layers. The implications of turbulence dynamics due to KH instability for several radar configurations throughout the KH billow evolution was examined by Fritts et al. (2005). Applications of these results in the interpretation of the LEMMA measurements were reported by Lehmacher et al. (2005a, b).

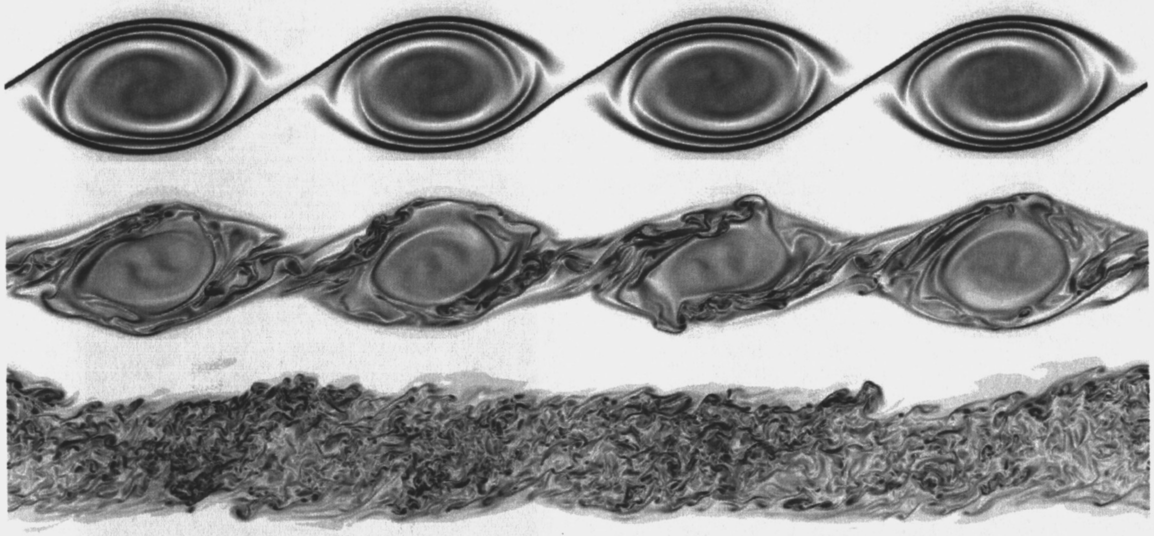

Figure 1. Evolution of a train of Kelvin-Helmholtz (KH) during initial billow roll-up (top), initial secondary instability (middle), and later stages as the layer extends horizontally (bottom). We expect, based on our radar simulations to date, that each stage will have distinct radar signatures, and depend on radar parameters and viewing angles.

2. Research Results

Our radar backscatter assessments employed direct numerical simulations (DNS) of the dominant processes contributing to atmospheric turbulence, primarily Kelvin-Helmholtz (KH) instability occurring at unstable shear flows and gravity wave breaking. The DNS of KH instability for an initial Richardson number Ri = 0.05 at a Reynolds number Re = 2500 is shown at three times in Figure 1 to illustrate the flow evolution and the different characteristics that arise at different times. Here Re = Uh/ν, and U is the half velocity difference, h is the half depth of the shear layer, and ν is kinematic viscosity. The corresponding "turbulence" Reynolds number is Re = 30,000 (based on the turbulence layer depth and velocity difference), and these are the highest-resolution DNS ever performed.

The KH results were employed by Franke et al. (2005) to evaluate the radar backscatter at several stages in the evolution in order to evaluate the assumptions and assess the biases inherent in radar measurements of similar dynamics in the atmosphere. An example of the various components of the input and received signals are shown in Figure 2 for the backscatter from one scattering volume. The signals for any volume for a series of times (typically 32 to 128 samples separated by ~1 s) are then averaged and employed to assess the various spectral moments. With precise knowledge of the turbulence character in the DNS volumes throughout the KH evolution, we are then prepared to test the assumptions employed using radars to probe these dynamics and to guide a more accurate interpretation in the presence of measurement biases resulting from previous overly simplistic assumptions (i.e., steady, homogeneous, isotropic turbulence – in this case, the acronym is appropriate).

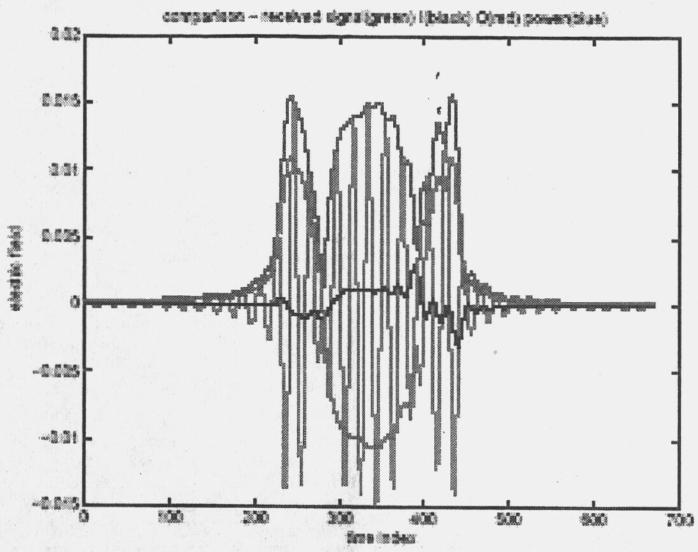

Figure 2. An example of the reference and backscattered radar signals. Here the black and red curves are the carrier (I) and quadrature (Q) signals and the blue curve shows the signal (green) amplitude. The signal phase is obtained as $\tan^{-1}$ (Q/I).

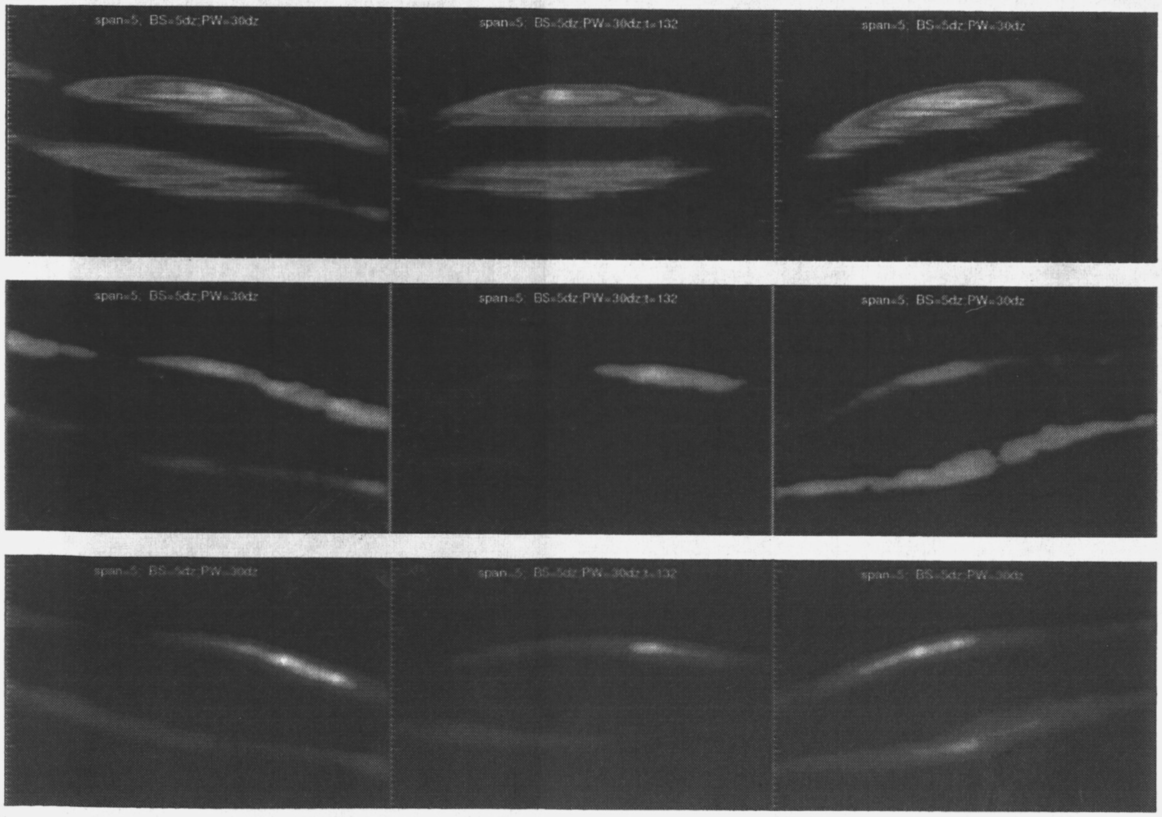

Figure 3. Radar backscatter moments computed for a KH billow during the transition to turbulence (middle panels in Figure 1). Panels here are for the backscatter power (top), Doppler velocity (first moment, middle), and spectral width (second moment, bottom). Panels left to right are for a radar beam inclined 20° the left of zenith, vertical, and 20° right from zenith. In all cases, the pulsè length was assumed to be six times the Bragg scale. In the top panels, red/yellow is strong; in the middle panels, red/yellow is towards and green is away from the radar.

We have also evaluated the radar backscatter responses to KH instability throughout the KH evolution and described these results in Fritts et al. (2005). The backscatter moments for one realization of radar frequency, beam width, and pulse length are shown with backscatter spectral moments at three beam angles in Figure 3. Note that backscatter power is not as sensitive to beam (or viewing) angle as the first and second moments (radial Doppler velocity and spectral width, often, and sometimes mistakenly, interpreted as turbulence broadening). Both the first and second moments, however, display significant variability and aspect sensitivity which suggests that care must be taken in interpreting such results in the atmosphere. This point is made more forcefully when one views the entire KH evolution, because the biases that are apparent vary significantly in time. The most obvious example is the relative insensitivity of any radar to the highly turbulent cores of the KH billows after they have become fully mixed because of the lack of refractive index variations thereafter. The strongest backscatter at this stage comes from the braid regions surrounding the cores, despite the fact that turbulence in these regions are much weaker than in the billow interiors.

We also developed a method for extending our simulations of radar backscatter to smaller scales and higher Reynolds numbers than can be achieved with large-scale DNS simulations. This was done through "seeding" turbulence structures with lower-Re initial fields and tracking their evolution with a large-eddy simulation (LES) scheme. Initial tests were very positive (we typically achieved a factor or $\sim 3 - 10$ increase in resolution, hence also Re, and an improvement of $\sim Re^3$ in computational requirements), and we anticipate that this will enable us to apply DNS results and backscatter computation methods to a much greater range of radar frequencies and parameters in the future.

Finally, we participated in the analysis of LEMMA data collected during the rocket program and in the preparation of two publications based on these results. These findings were reported by Lehmacher et al. (2005a, b).

3. Publications Citing this Research Support

1. Franke, P. M., K. Wan, D. C. Fritts, J. Werne, and T. Lund, 2005: Computation of radar backscatter from realistic turbulence volumes, *Radio Sci.*, to be submitted.

2. Fritts, D. C., P. M. Franke, K. Wan, T. Lund, and J. Werne, 2005: Computation of radar backscatter from realistic turbulence volumes, II: Backscatter Moments Throughout the Lifecycle of a Kelvin-Helmholtz Instability, *Radio Sci.*, to be submitted.

3. Lehmacher, G. A., et al., 2005a: Layers in the Equatorial Mesosphere: results from rocket and radar measurements during EQUIS II, Proc. 11th ESA Symposium on European Rocket and Balloon Programmes and Related Research, Sondefjord, Norway, *ESA-SP 590*.

4. Lehmacher, G. A., C. L. Croskey, J. D. Mitchell, M. Friedrich, F.-J. Luebken, M. Rapp, E. Kudeki, and D. C. Fritts, 2005b: Intense turbulence observed above mesospheric temperature inversion at equatorial latitude, *GRL*, submitted.

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Dr. D. C. Fritts

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Northwest Research Associates, Inc.
14508 N.E. 20th St.
Bellevue, WA 98007-3713

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