Airborne Laser Challenge Project II

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ABSTRACT

This is a joint effort of the Directed Energy (DE) and Space Vehicles (VS) Directorates of the Air Force Research Laboratory (AFRL) in support of the Airborne Laser (ABL) and the associated technology program. Two complementary facets of the ABL problem are being investigated. The DE effort concerns the modeling of optical propagation phenomena associated with stratospheric turbulence and the effects of these phenomena on optical tracking and adaptive optics systems. The VS effort concerns the modeling of the strength, distribution and spatial spectrum of stratospheric turbulence. The proposed work is a natural continuation and expansion of investigations that have been pursued for the past three years under the current ABL Challenge Project.

From its inception, the ABL program has assumed that we can accurately simulate the effects of atmospheric turbulence on the ability to deliver lethal fluence to a target many kilometers distant from the ABL; and that through a combination of carefully chosen experiments and computer simulation, we can determine how well the degrading effects of the atmosphere can be alleviated by appropriate adaptive optical compensation. The Challenge Project addresses fundamental propagation, adaptive optics and turbulence phenomenology issues which must be understood to successfully implement the philosophy embodied in this approach to ABL design and evaluation.

The problems being addressed are extremely challenging, involving: 1.) detailed optical propagation and adaptive optics studies relevant to ABL design and performance evaluation; 2.) high-resolution stratified turbulence simulations which address the fundamental nature of stratospheric turbulence and its effect on optical propagation; and 3) the development, thru DNS microscale turbulence modeling, of improved turbulence microscale parametrization models for use in state of the art mesoscale turbulence models such as MM5 for optical turbulence forecasting. Understanding the nature of turbulence in the stratosphere; deducing its impact on laser propagation and ultimately ABL performance; and attempting to forecast likely locations of optically-significant atmospheric turbulence embodies three cutting-edge research fields—all of which require the significant computational resources and high-priority access afforded by the DoD Challenge Program.

In addition to providing fundamental design and evaluation tools for ABL, the simulations discussed here have intrinsic scientific value and application in other problems of interest to the DoD—e.g., fundamental results on the strength, distribution and spatial spectrum of stratospheric turbulence and on the phenomenology of optical propagation through strong turbulence, evaluation of advanced tracking and adaptive optics concepts, and information on imaging and surveillance on nearly horizontal paths where scintillation effects are important.

1. Introduction

This is a joint effort of the Directed Energy (DE) and Space Vehicles (VS) Directorates of the Air Force Research Laboratory (AFRL) in support of the Airborne Laser (ABL) and the associated technology program. Two complementary facets of the ABL problem are being investigated. The DE effort concerns the modeling of optical propagation phenomena associated with stratospheric turbulence and the effects of these phenomena on optical tracking and adaptive optics systems. The VS effort concerns the modeling of the strength, distribution and spatial spectrum of stratospheric turbulence. From its inception, the ABL program has assumed that we can accurately simulate the effects of atmospheric turbulence on the ability to deliver lethal fluence to a target many kilometers distant from the ABL and that through a combination of carefully chosen experiments and computer simulation, we can determine how well the degrading effects of the atmosphere can be alleviated by appropriate adaptive optical compensation. The Challenge Project addresses fundamental propagation, adaptive optics and turbulence phenomenology issues of importance to ABL and is designed to provide answers crucial to the successful design and operation of the ABL system.

The proposed work is a natural continuation and expansion of investigations that have been pursued for the past three years under the current ABL Challenge Project. The optical propagation and adaptive optics compensation studies will be continued along the directions taken during the current Challenge Project. We will also continue to study the fundamentals of turbulence generation processes in stratified flows—e.g., the role of the Kelvin-Helmholtz instabilities and gravity-wave phenomena in the generation of stratospheric turbulence. In addition, we will expand the scope of these studies to include investigation of techniques for forecasting the strength and distribution of stratospheric turbulence based on mesoscale turbulence models coupled with turbulence microscale parametrizations developed from direct numerical simulations (DNS) of turbulence microscale; and, in the absence of the DNS information, with improved turbulence closure models developed by other means. These new efforts are tied directly to the interest in developing an Atmospheric Decision Aid (ADA) for use in improving the deployment and positioning of ABL assets, as well as ultimately developing an ABL performance forecasting capability.

Work performed on the existing ABL Challenge Project has contributed significantly to our understanding of optical propagation and turbulence phenomena of concern to ABL and has supported key experimental investigations performed to characterize propagation phenomena in the free atmosphere. Pertinent examples are:

- The design and analysis of stellar scintillometry experiments used to determine the strength of turbulence along atmospheric slant paths pertinent to ABL.
- Calibration of ground-based propagation and adaptive optics experiments using scintillometry.
- Interpretation of balloon and aircraft turbulence measurements
- Quantitative description of turbulence spatial and temporal structure provided by DNS modeling of the Kelvin Helmholtz instability.
- Assessment of illuminator coherence effects on target imagery and tracking.

The investigations being performed under the current Challenge Project and those to be performed as a part of the proposed continuation of this project are at the leading edge of scientific investigation of the optical and turbulence phenomena of interest in the context of the ABL system. The optical propagation and adaptive optics investigations provide a means of establishing the limits of scintillation on adaptive compensation of the effects of turbulence in a highly scintillating environment. The turbulence phenomenology studies

provide a significant improvement in the understanding and estimation of turbulence in the free atmosphere—providing the possibility of obtaining viable tools for predicting turbulence strength and distribution in the ABL battlefield environment and seeking to ultimately contribute to the development of an ABL performance prediction capability.

2. Justification/DoD Relevance

Existing analytical theories of optical propagation—e.g., the Rytov approximation as developed by Tatarski and others (see Ishimaru (1978))— are not valid under the conditions that will exist in typical ABL scenarios. For this reason, the design, and performance evaluation of the ABL is strongly dependent on experimental and computer simulation results. The basic philosophy developed to support the development of the ABL is to utilize the results from carefully designed/scaled experiments and computer simulations. Computer simulation is an extremely important part of the analysis procedures because it is usually much more cost effective; and, in some cases, allows us to investigate issues that are impractical to explore with current experimental technology. In addition to minimizing the cost of ABL system design and evaluation, the utilization of computer simulation will ultimately provide the insight required to obtain a better performing ABL weapon—through a better understanding and characterization/prediction/forecasting of free atmospheric turbulence phenomena and ultimately through the development of improved adaptive optics sensors/correctors and control algorithms. The development of an Atmospheric Decision Aid capability for forecasting turbulence strength and distribution will clearly enhance the performance capabilities of the ABL weapon system.

The ABL program is one of the highest priority Air Force projects currently underway. In addition, the technology and understanding developed as a result of these simulations will have application in other areas of interest to the DoD—e.g., evaluation of advanced tracking and adaptive optics concepts for imaging and surveillance on nearly horizontal terrestrial path and prediction of the resulting system performance.

3. Technical Approach

3.1 Technical Goals

3.1.1 Optical Propagation Studies. The overall goals of the optical propagation studies are:

- Investigate the effects of upper atmospheric turbulence on the performance of optical tracking, imaging and adaptive optics systems such as those to be employed in the Airborne Laser weapons system. Establish the fundamental limitations on the performance capabilities of such systems given both idealized implementations having infinite spatial and temporal bandwidth and also more practical implementations having finite spatial and temporal bandwidth.
- Explore the sensitivity of the results obtained in the above investigations to the spatial distribution and spectrum of the stratospheric turbulence —accounting for intermittency effects and the possibility of non-Kolmogorov turbulence spectra. These studies will rely, in part, on the results obtained in the turbulence simulation studies discussed below.

3.1.2 Turbulence Phenomenology and Forecasting Studies. The overall goals of the turbulence phenomenology and forecasting studies are:

- Utilize a DNS code to investigate the fundamental nature of stratospheric turbulence. In these studies two sources of stratospheric turbulence will be studied in detail: 1) shear instability in stratified flows; and 2) gravity-wave breaking and its transition to

turbulence. These studies will be focused so as to provide a better understanding of the physical properties of most concern to optical propagation through turbulence—such as turbulence intermittency, spatial spectra and structure functions, and flow morphology and coherence in the interface regions between turbulent and quiescent fluid where refractive index fluctuations are largest.

- Utilize input from mesoscale meteorological codes such as the Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) mesoscale model (MM5) as input to a microscale DNS code to explore the possibility of developing a parametrized, fast, subroutine that can be used in conjunction with MM5 for the forecasting of the 3 dimensional strength distribution of turbulence. If successful, the output of this effort will provide an invaluable tool for ABL. The current state of the art is limited to vertical profile models whose performance along long quasi-horizontal paths is limited.
- Utilize suitably modified versions of the mesoscale codes COAMPS (Coupled Ocean Atmosphere Mesoscale Prediction System) and MM5 to develop a fast turbulence forecasting code that can be utilized in the ABL ADA effort. This task is an alternative, less computationally intensive, approach to the turbulence parameterization problem—which relies strongly on the ability to develop appropriate closure models based largely on physical insight rather than direct numerical simulation of the fine scale details of the turbulence phenomena.

It should be emphasized that the two DNS components of this research are addressing separate aspects of the ABL-design needs. The first is a continuation and extension of work performed on the current ABL Challenge Project. It addresses the smallest-scale properties of atmospheric turbulence phenomena and the resulting index of refraction. These solutions will be used in the laser propagation studies to construct atmospheric models which accurately represent the intermittency observed on small-scales; as well as for the development of improved sub-grid-level models for large scale simulation codes. The second task involves extensive DNS-based microscale modeling of optical turbulence strength under a wide range of conditions from which simple parametrization models will be developed; providing closure modeling for microscales rather than mesoscales.

3.2 Program Plan and Key Personnel

As indicated above, the proposed computational project has four tasks. Each of these is manned by scientists who have considerable previous experience in related areas of research. The optical propagation and adaptive optics simulation studies will be performed in the Airborne Laser Technology Branch of the Directed Energy Directorate of the Air Force Research Laboratories (AFRL/DEBA). The principal participant in that group will be Dr. Wilbur Brown, who is a Fellow of the Optical Society of America and Principal Investigator on the current Airborne Laser Challenge Project. He will continue to be Principal Investigator on the new Challenge Project. Dr. Brown has more than 25 years of experience in the modeling of optical propagation in turbulent media and in the simulation of adaptive optical compensation for the effects of turbulence. We expect that 2 to 3 other individuals from AFRL/DEBA will be involved in the planning and implementation of the propagation and adaptive optics simulation studies.

The three tasks in the turbulence phenomenology and forecasting studies will be performed by scientists from three different organizations. The work performed by these groups will be coordinated by Drs. Robert Beland and Jeremy Winick of the Space Vehicles Directorate of AFRL (AFRL/VS). Dr Winick is the Co-Principal Investigator on the current ABL Challenge Project. Dr. Beland is the chief of the Tactical Environmental Support

Branch (AFRL/VSBL) and leads efforts in turbulence measurements and modeling, numerical weather prediction using MM5, cloud modeling and weather impact decision aids. He has more than 15 years experience in atmospheric turbulence phenomenology, including development of the Clear 1 model, the baseline for the ABL design. He is also the AFRL laboratory task manager for the AFOSR-sponsored project focused on modeling turbulence in the free atmosphere for the ABL. Additional scientists from AFRL/VSBL who are involved in turbulence and MM5-based modeling will also participate. The organizations and individuals who will be performing the turbulence studies are: 1) Drs. David Fritts and Joseph Werne of Colorado Research Associates will perform the turbulence phenomenology studies. They have been involved in the Airborne Laser Challenge Project from its inception and are recognized worldwide as experts on the phenomenology and modeling of atmospheric turbulence. They have close ties and contacts with similar ongoing studies at the University of Colorado and the National Center For Atmospheric Research (NCAR); 2) Professors Basil Nicolaenko and Alex Mahalov of Arizona State University (ASU) will perform the DNS studies aimed at obtaining improved parametrizations to be used in conjunction with the MM5 mesoscale code. Again, both of these individuals have extensive experience in the mathematics and physics of turbulent phenomena and are recognized worldwide as experts in the theory and phenomenology of turbulence. The work of Professors Nicolaenko and Mahalov is supported by AFOSR. Currently, they are performing related numerical simulations at Los Alamos National Laboratories (LANL) on the LANL Blue Mountain Machine; and 3) Professors Donald Walters and Douglas Miller of the Naval Postgraduate School (NPS) will be performing the other ADA related study. Professor Walters has experience both in the measurement of turbulence phenomenology and in the development of closure models for the prediction of turbulence strength from mesoscale model outputs. Professor Miller, who is a meteorologist, has extensive experience in the utilization of the mesoscale codes COAMPS and MM5.

3.3 Schedule and Milestones

We anticipate that there will be a continuing need for optical propagation simulations for ABL over an extended period of time. In addition, the two turbulence simulation tasks involving DNS studies will undoubtedly require two to three years to complete. Thus, we are proposing that the new ABL Challenge Project be a three year effort in which it is understood that continued year to year support is contingent on the demonstration of adequate progress toward our research goals and on the need for continued support to achieve these goals. By the end of FY01 we expect to have:

- Obtained an extensive database of realistic target imagery for use in studies of advanced tracking concepts for ABL. This database will be made available to organizations performing such studies.
- Simulated the effect of adaptive optics (AO) reference illuminator partial coherence on the performance of the ABL AO system.
- Provided computational support to the experimental programs being conducted as a part of the ABL technology program and the atmospheric characterization campaign.
- Utilized the new user-friendly AO system simulation software (WAVETRAIN) to simulate the closed-loop performance of optical tracking and adaptive optics systems
- Conducted optical propagation simulations which explore the effects of turbulence intermittency and non-Kolmogorov spectra. These simulations will utilize turbulence phenomenology results obtained by the Fritts/Werne and Mahalov/Nicolaenko studies (see Refs. 2, 3, and 10).
- Completed the single-wave, wave-breaking simulations currently underway for two values

of stratification (weak and strong) up to Re=24,000 (see Section 4.2).

- Initiated a series of turbulence phenomenology simulations at Ri=0.1 with optimal initial conditions (see discussion in Section 4.2).
- Initiated multiple-wave, wave-breaking simulations at one value of stratification (weak) (see discussion in Section 4.2).
- Established an initial database of DNS results that can be used to develop a parametrized microscale turbulence model for use in mesoscale codes such as MM5 for forecasting of the turbulence refractive index structure constant C_N^2 (see Section 4.3).
- Utilized both COAMPS and MM5 mesoscale models with modified turbulence closure relations, run on a daily basis, to compute C_N^2 forecasts; and validate these forecasts with microthermal balloon results collected by the USAF and the US Naval Postgraduate School.

3.4 Computational Methodology and Efficiency

3.4.1 Optical Propagation and Adaptive Optics Simulations. Atmospheric turbulence does not affect the polarization of laser light to a measurable extent. Therefore, the propagation of such light is well-described by scalar diffraction theory, as embodied in the Helmholtz equation. Moreover, the scattering produced by atmospheric turbulence is strongly forward-directed at optical wavelengths; and thus, the Helmholtz equation can be solved in the paraxial approximation—which yields a parabolic PDE which can be solved using spectral techniques. The solution is implemented by a split-operator method which divides the propagation into a sequence of two-step processes whereby the field at location z is free-space propagated to z+dz, and then subsequently adjusted to account for the phase shift introduced by the inhomogeneities between z and z+dz. The properties of the atmospheric turbulence are incorporated by generating phase screens having a prescribed spatial spectrum in the plane transverse to the propagation direction. Usually, we assume that the turbulence has an inertial subrange where the three-dimensional spectrum has a $K^{-11/3}$ behavior of Kolmogorov turbulence and inner and outer scale lengths which describe the small and large scale behavior. We can, however, utilize more general spectra such as those that might result from the turbulence phenomenology studies being pursued on this project. The free-space propagation and turbulence phase screen generation are accomplished using a 2-D FFT.

To parallelize the propagation code we: 1) divide the columns of the field and turbulence phase screen arrays among the processors; and 2) use a parallel 2d FFT to compute the Fourier transforms. This provides an extremely simple and powerful implementation since we can not only propagate one laser using multiple nodes, but can also simultaneous propagate multiple laser beams. This is accomplished by partitioning the nodes into separately identifiable communication groups using the MPI_COMM_SPLIT routine. Each communication group defines a multi-node propagator. We use this capability in our simulations of extended target imaging with noncoherent and partially coherent light and in related adaptive optics simulations. For example, in the case of the simulation of the imaging of an extended target illuminated by noncoherent light, we use the fact that a noncoherent image can be approximated by a finite sum of independent coherent speckled images—each image being computed by one of the propagator node groups.

The propagation software was originally developed for use on the distributed memory IBM SP nodes and, as indicated above, used MPI for message passing. The resulting codes scale very well as the number of nodes is increased. This is especially true of those codes which propagate multiple laser beams simultaneously—because the message passing efficiency of the FFT algorithm is improved when multiple beams are propagated on a given number

of nodes—i.e., if we want to propagate eight laser beams using 32 nodes, it is better to propagate simultaneously the eight beams using 4 processors per beam than to propagate sequentially the eight beams using 32 processors per beam. This behavior is due to reduced switch contention when multiple beams are propagated simultaneously.

We have ported the MPI-based codes to the new IBM P3 SMP nodes at MHPCC with only minor changes and find that they perform well if we keep the FFT's on the SMP nodes—i.e., we use no more than 4 processors to compute a FFT. We are currently working on OpenMP and Pthreads techniques to further improve performance on the new SMP nodes.

3.4.2 DNS Studies of Turbulence Phenomenology. The numerical algorithm used to simulate stratified turbulence is a pseudo-spectral, 3D, Navier-Stokes solver that employs Fourier expansions in all three dimensions. Such a formulation allows for the highest spatial resolution possible. Horizontal boundary conditions for the model are periodic, whereas the top and bottom boundaries can be either stress-free or periodic.

The Boussinesq approximation, which includes compressibility only in the buoyancy term, is used because shallow regions in the atmosphere of a km or less in depth are targeted. The solenoidal velocity field ($\vec{\nabla} \cdot \vec{v} = 0$) can be represented exactly with a double stream function (ψ and ϕ) formulation: $\vec{v} = \vec{\nabla} \times \vec{\psi} + \vec{\nabla} \times \vec{\nabla} \times \phi + \vec{U}_{\perp}(z)$. Here $\vec{\psi} = \psi\hat{z}$ and $\vec{\phi} = \phi\hat{z}$, and $\vec{U}_{\perp}$ is the mean horizontal velocity.

The stream functions, mean velocity and density are advanced in Fourier space using a variable-timestep, hybrid-implicit/explicit, third-order Runge-Kutta scheme with storage requirements equivalent to most second-order schemes (Spalart et al. (1991)). The code operates stably with a CFL of 0.68; diffusive and buoyancy terms are handled implicitly, while nonlinear terms are treated explicitly in physical space and projected to Fourier space using Fast Fourier transforms (FFTs), which comprise 75% of the execution time. Single-processor optimization has been facilitated with several strategies for enhancing cache performance: loop unrolling, cache alignment, data streams, etc. Communication is carried out on the T3E with the Cray shmem library. The code achieves 110 Mflops/(CRAY T3E processing element) and generates in excess of 150 Gigabytes of data during the course of a typical 12-hour run. Several of these runs are required to complete the large turbulence simulations we have been performing—the largest to date having a domain of $1000 \times 350 \times 2000$ spectral components. Thus, the code has a restart capability to accommodate these large simulations on a system shared with other users.

3.4.3 Microscale Meteorological Modeling From DNS. It needs to be understood that we do not intend to embed DNS within a mesoscale forecasting model such as MM5. Rather we will be using DNS to develop improved microscale parametrization relations that can be used ultimately in mesoscale codes for forecasting. Specifically: 1) MM5 provides "coarse grid" input to the DNS code; 2) the input consists of meteorological fields including such unbalanced quantities as ageostrophic winds, thermal wind imbalances and divergent velocity potential; 3) the output from the DNS code is a microscale modeling of the refractive index structure parameter C_N^2, which describes the strength of the refractive index fluctuations; and 4) we will use this information to develop simpler parametrization models to predict the influence of intermittency, non-stationarity and Ozmidov scales on C_N^2—with the goal of obtaining fast, robust subroutines based on these models.

The numerical technique to be used in the DNS studies is a 3D adaptive spectral domain decomposition method (Tse et al. (2000)) in which the Navier-Stokes equations are also solved in the Boussinesq approximation where the compressibility effects are neglected

except in the buoyancy term. The computational grid is centered at the tropopause with a horizontal extent of 5 km and a vertical dimension from 2 to 4 km. The solution variables are transformed to Fourier space in the horizontal direction and periodic boundary conditions are assumed in these directions. Adaptive spectral domain decomposition is used in the vertical direction. The order of the interpolation for the central 3 subdomains is 6 while the order is 5 elsewhere. Hence, with 127 total subdomains, there are 512 grid points in the vertical direction with a resolution from 4 to 8 meters—sufficient to resolve the Ozmidov scale, which is believed to be the maximum possible scale below which isotropic turbulence exists in a stably stratified environment. In each subdomain a mixture of collocation and variational methods are used.

The time discretization follows the pressure projection method, which separates the time derivatives into three steps: the nonlinear terms, Coriolis and buoyancy terms are advanced in the first substep; the pressure Poisson equations are solved and the pressure terms advanced in the second substep; and the dissipation term in the third substep. A second-order Adams-Bashford scheme is used for the nonlinear terms. The calculation of derivatives used in the nonlinear terms is done in physical space using collocation methods.

The code was developed and optimized on the DOE Blue Mountain computer at Los Alamos and is now at the production job level. MPI is used for message passing and the FFT's are computed using a global matrix transpose in conjunction with an on-processor computation of 1D FFT's. The resulting code is highly efficient in terms of its CPU utilization and message passing performance. For example, we are currently running jobs which use a $256 \times 256 \times 512$ computational grid on the Blue Mountain machine and have obtained the performance numbers given in Table 1. The speedup column in this table is the ratio of the processor hours required to complete the job using 4 processors to that required with varying numbers of processors. Note that performance scales better than linearly up to 64 processors—which is undoubtedly due to improved cache performance as the number of processors is increased. We attribute the decrease in message passing efficiency observed in these runs to the fact that the problem size was held fixed as the number of processors was increased. A truer, test would have been to increase the problem size as the number of processors is increased—thereby keeping the message size relatively constant. We are confident that the performance would have been even more impressive had this been done.

Number of Processors	Cpu Time Per Processor	Communication Time	Speedup Speedup
4	524.24	50.45	1
8	225.36	25.42	1.16
16	115.67	13.02	1.13
32	43.98	5.04	1.49
64	23.38	5.73	1.40

Table I. Computational efficiency of the adaptive spectral domain decomposition DNS code.

3.4.4 Use of Mesoscale Turbulence Models and Improved Closure Relations In ADA. This work will utilize state-of-the-art mesoscale codes such as COAMPS, and MM5 in which the closure relations have been suitably modified to optimize "operational"

turbulence forecasting capabilities. The closure relations used to do this are based on the relation $C_T^2 = L_o^{4/3}(d\theta/dz)^2$ proposed by Tatarski—where C_T^2 is the temperature structure constant, L_o is a turbulence scale length related to the outer scale, θ is the potential temperature and z is the altitude. COAMPS and MM5 compute the potential temperature from prognostic equations. Thus, if we can estimate the outer scale length L_o we have a way to compute the strength of optical turbulence. For stable atmospheres, Deardorf suggested a buoyancy length $L_o = a\sqrt{TKE}/N$ where TKE is the turbulent kinetic energy and N is the Brunt-Vaisala frequency. Mesoscale models such as COAMPS that use the Mellor-Yamada level 2.5 parametrization include prognostic equations for TKE.

During the last year, we have had good success in using COMAMPS for computing optical turbulence using these techniques. Comparison of these forecasts with balloon measurements of C_T^2 encourages us to continue these studies. The mesoscale codes of interest are available for the CRAY T90 computer, which is our platform of choice for this work. Typically, the codes will be run using 4 processors of a T90.

3.5 Progress to Date

3.5.1 Optical Propagation and Adaptive Optics. The determination of the strength and distribution of turbulence is one of the most important and controversial areas of research being pursued in support of the ABL. At the inception of the ABL program the atmosphere was characterized mainly by a series of balloon measurements that date back several years. These balloon data were used to generate a characterization of the altitude dependence of atmospheric turbulence known as the Clear profiles. Later airborne optical and anemometer measurements were made in a series of experiments known as ABLE ACE. While certainly valuable, the results of these experiments were still criticized because they were not taken over slant paths of the type that the ABL weapon system will operate. Thus, during the past two years the Air Force has conducted experiments in which we are inferring the strength of the turbulence along slant paths by a measurement of stellar scintillation. In the face of the fact that such scintillations are not well described by existing propagation theories, the success of these stellar scintillometry experiments is strongly dependent on numerical simulation of the stellar scintillation phenomenon. Over the past two years we have performed numerous simulations in support of the stellar scintillation measurement program. The simulations that we have performed are unique in that they account in detail for all the phenomena that affect this measurement: 1) the effect of the spatial averaging that occurs in a detection system having a finite aperture; 2) the effect of the detector spectral bandwidth; 3) the related effect of refractive index chromatic dispersion on the scintillation from a broadband source; and 4) the effect of the saturation of stellar scintillation in strong turbulence. We have generated results which allow one to uniquely determine a measure of the strength of turbulence along paths of interest using results from stellar scintillometry measurement at two wavelengths. The code which has been used to compute these results simulates the propagation of broadband light by propagating simultaneously several narrow-band light signals over the paths of interest and combining the resulting detector responses over the spectral passband of the receiver.

In another set of simulations we have explored the effects of illuminator laser temporal coherence on the imaging of targets illuminated by such a source. In these simulations the effect of illuminator temporal coherence, target depth and the finite response time of the imaging system are accounted for. These simulations again use the unique multi-beam propagation capability of our codes, which can only be realized on the massively parallel computer systems such as those provided by the Challenge program. These simulations are being used to provide realistic target imagery for use in the study of advanced tracking

concepts—e.g., concepts which require a proper representation of the temporal correlation of the target images.

We have also performed simulations of the effects of phase ambiguities on the performance of adaptive optics systems. In contrast to astronomical adaptive optics systems , the ABL will operate in a propagation environment where scintillation effects are important. Phase ambiguities occur at those points in the scintillation pattern where the field goes to zero. It can be shown that wavefront sensors that utilization a least squares reconstructor fail to see the ambiguities and therefore do not properly reconstruct the phase of the adaptive optics reference field. We have performed simulations that quantify the magnitude of the degradation imposed by these effects and have shown how much performance could be improved if we were able to implement systems which correctly sensed and applied the adaptive optics reference phase.

3.5.2 Turbulence Phenomenology. We have performed simulations of stratified shear turbulence as a function of the Richardson number (Ri), the Reynolds number (Re) and the morphology of the initial conditions. Our approach is to extrapolate our lower-Re solutions to atmospheric values. We have completed solutions from Re=3,000 to Re=30,000 for Ri=0.05. A similar series at Ri=0.1 is currently being computed. The highest value of Re achieved (Re=30,000) required 1000x350x2000 spectral modes, cost 250,000 hours running on 500 Cray T3E nodes, and generated over a Tbyte of numerical data. It represents an invaluable resource for the laser propagation simulations and SGS turbulence model development we propose here.

Figure 1 illustrates the importance of the DNS simulations to the ABL program; it represents one of our earlier simulations at Re=24,000. The fields shown are thermal dissipation $\xi = \kappa \partial_i T \partial_i T$ (blue) and viscous dissipation $\epsilon = 2\nu S_{ij} S_{ij}$ (yellow). Here κ and ν are the thermal diffusivity and the viscosity respectively. T is the temperature field, and $S_{ij} = (\partial_i u_j + \partial_j u_i)/2$ is the velocity stress tensor. ∂_i and u_i represent the spatial derivative and the velocity in the i direction. Note the two, thin blue interface layers at the edges of the turbulent shear layer where velocity fluctuations are relatively weak (i.e., yellow is dilute near the edges). In the atmosphere such edge layers (blue) are 3 to 10 meters in depth and represent the largest contribution to the index of refraction (both mean and variance). Understanding the impact of these highly intermittent edge layers (and other departures from homogeneous/isotropic turbulence) through direct optical propagation studies is part of what we propose in the coming year (see Section 4.1). Comparison of the solutions depicted in Figure 1 (through profiles of temperature, temperature fluctuation, and the local Richardson number, not shown) are in excellent agreement with balloon measurements (Coulman et al. 1995) which indicate such layers are prolific throughout the troposphere and stratosphere. Coulman et al. observe 14 of these layers with a single nighttime balloon ascension. Comparison of Figure 1 with high-resolution radar backscatter measurements (Ierkic et al. 1990) also indicate the relevance of the DNS results to the stratosphere during daytime observation.

These Challenge simulations have been showcased on the cover of Geophysical Research Letters (Werne & Fritts, "Stratified Shear Turbulence: Evolution and Statistics", GRL, 1999), in the June Issue of the CEWES MSRC Journal (Strelitz & Werne, "DoD Challenge Project Studies AirBorne Lasers", CEWES MSRC, Spring 1999) and in the ERDC MSRC Resource Newsletter (to appear, March 2000). Other related publications are listed with the references.

3.5.3 Microscale Meteorological Modeling from DNS. As a part of our AFOSR-sponsored research program, we have performed simulations of the strong nonlinear interac-

Werne & Fritts 1999

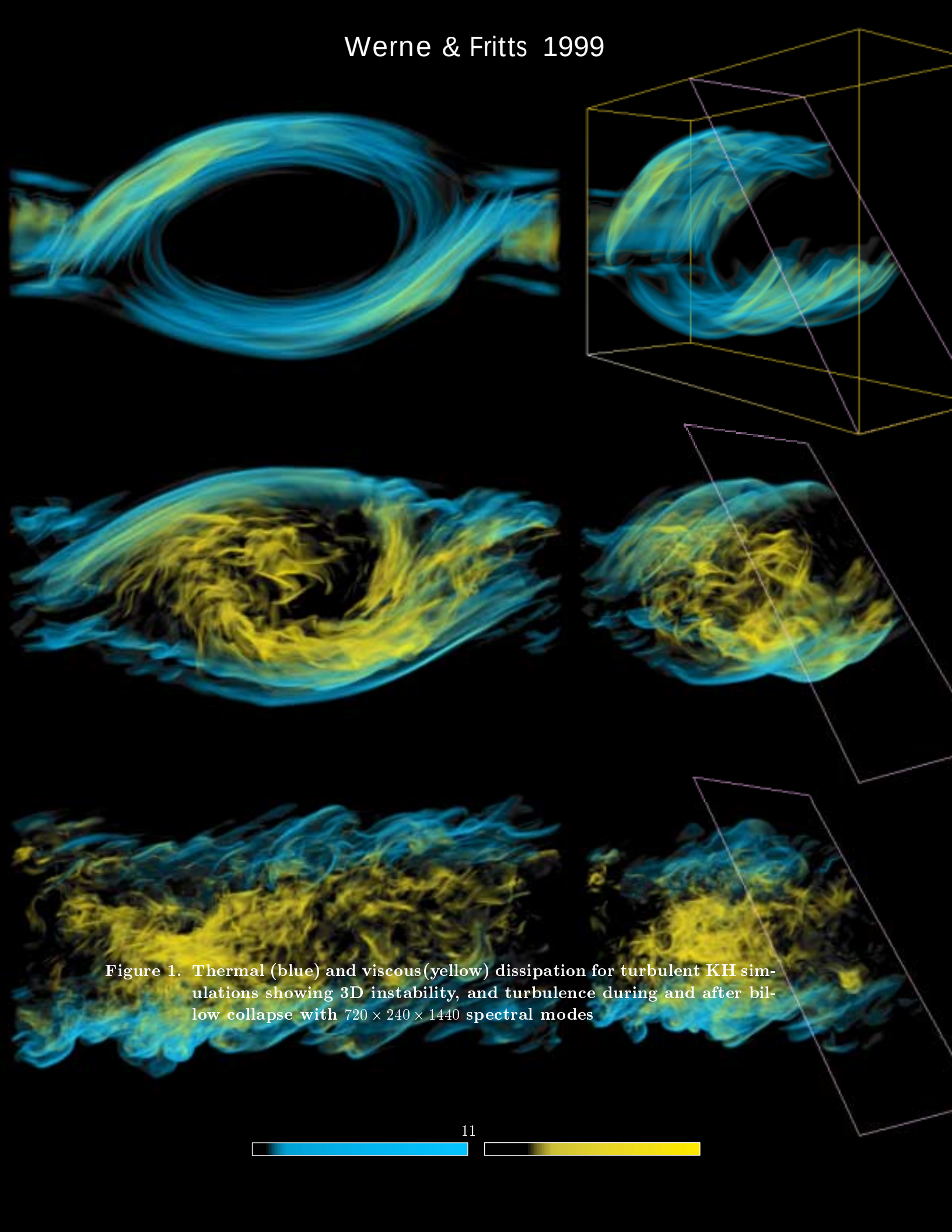

Figure 1. Thermal (blue) and viscous(yellow) dissipation for turbulent KH simulations showing 3D instability, and turbulence during and after billow collapse with $720 \times 240 \times 1440$ spectral modes

tions of a jet stream and inertio-gravity waves at the tropopause. In these simulations the Brunt-Vaisala frequency changes smoothly by a factor of two as one passes through the jet stream. The simulations were done in a computational box having the dimension $5 \times 5 \times 2$ km. We are currently using such simulations to explore the dependence of quantities such as variances, covariances, skewness, Reynolds stresses and turbulence budgets on the following parameters: jet profile stiffness (with Richardson numbers less than 0.1 on the jet edges); averaged vertical Brunt-Vaisala profiles; and different initial conditions such as thermal wind balance and divergent velocity profile. We have obtained a series of horizontally-averaged vertical profiles of the refractive index structure parameter C_N^2, which is commonly used as a measure of the strength of optical turbulence. One of the principal results of these studies is the observation that the C_N^2 profile has two maxima located above and below the core of the jet stream; the largest one coinciding with the vertical level at the edge of the jet stream where the temperature variance is maximal. The turbulence is highly intermittent in this region. Most of these results are published in references 2 and 3.

3.6 HPC Resource Utilization and Need

The current ABL Challenge Project is utilizing HPC resources at MHPCC (IBM SP), ERDC (T3E), and NAVO (T3E). The Challenge Project proposed here would continue to utilize these resources plus additional resources at the ARL MSRC (SGI Origin 2000 and CRAY T90). This work needs to be done as a DoD Challenge Project because the magnitude of the computational effort required to accomplish our objectives cannot be realized unless we have high-priority access to significant HPC resources.

4. Required Resources and Justification

4.1 Optical Propagation and Adaptive Optics Simulations

Optical propagation and adaptive optics simulations are to be performed in at least five areas: 1) simulation of realistic target imagery to be given to researchers working on the development and evaluation of advanced tracking algorithms; 2) simulation of extended target and illuminator partial coherence effects on the adaptive optics reference and the resultant effects on wavefront sensing and adaptive optics compensation; 3) simulations performed in support of ABL experiments such as the stellar scintillometry experiments we are currently supporting, and the Airborne Laser Atmospheric Compensation Testbed (ABLACT) experiments underway at North Oscura Peak (NOP); 4) ABL systems simulations to be performed using a new user-friendly system code (WAVETRAIN); and 5) propagation simulations conducted to explore the impact of results obtained in the turbulence phenomenology simulations.

Our propagation software is tuned to perform well on the IBM P2SC and the IBM P3 SMP machines at MHPCC and we would like to continue to use these machines for the propagation and adaptive optics simulations. Based on our experience on the current ABL Challenge Project, we estimate that the pursuit of the 5 computational tasks outlined above will require 175,000 processor hours of P2SC and P3 SMP time per year for each of the next 3 years—FY01, 02 and 03. To illustrate the process by which we have obtained this estimate, consider the case of the simulation of realistic target imagery. In this simulation we model the effects of illuminator partial coherence on the image obtained with a receiver having a finite temporal response time considerably longer than the temporal coherence time of the illuminator. The simulation of this process entails the summation of the several images over the response time of the imaging detector—and the computational time to obtain one target image on the time scale of the detector is approximate 6.4 processor hours on the P2SC. Typically, if one is exploring the performance of an advanced tracker it is

required to have at least 1000 time samples. Thus, to obtain results pertinent to one set of atmospheric and tracker system parameters requires 6400 processor hours of computational effort. And, of course, many such cases need to be explored to determine optimal tracker performance and design. Similar computational requirements and comments apply to the simulation of extended target and illuminator partial coherence effects. As another example, the simulations we have performed in support of the stellar scintillometry measurement program have consumed a considerable amount of computational effort. In this simulations, a typical job involves a computation that require 560 processor hours on the P2SC. This yields a result pertinent to the stellar scintillation at one wavelength along a path at a particular elevation angle. To support an entire stellar measurement campaign might typically require 50 to 100 such runs. Thus far in FY00, we have used approximately 40,000 processor hours to support the stellar scintillometry measurement program.

4.2 Turbulence Phenomenology Simulations

In order to evaluate the dependence of solutions on Re, we have carried out simulations with Re as high as 30,000. As a result of this work we have deduced that Re=24,000 is sufficient for the purpose of examining the dependence of stratified shear turbulence on the Richardson number and initial conditions. We anticipate that two series of such simulations will be needed to complete our investigation of these effects in the next allocation. Both of these will be done at the values of Ri used in our current studies (0.05 and 0.1), but with initial conditions consistent with low-amplitude, streamwise-aligned vortex tubes—the so-called optimal perturbation described by Butler and Farrell(1992), and Farrell and Ioannou(1993). These runs are required to ensure that we capture possible differences in the evolution and end state of the density field for flows with embedded streamwise-aligned vortex tubes. We expect that such an initial condition could create persistent streamwise-aligned flow structures in shear flow because vortex stretching will act to amplify and maintain such an initial perturbation. On the other hand, it is possible that turbulent mixing may destroy the coherence of such structures, resulting in a similar end state to that which we have already computed. In either case, it is important to know the optical ramifications of such an initial condition with different values of Ri. These simulations require domains that are three times longer than we used for our previous studies; therefore, although the computational effort required is reduced below that of our previous largest simulation because Re is smaller—24,000 vs 30,000—the requirement for longer domains increase the computational needs. We estimate that 760,000 T3E node hours will be needed for these simulations.

In addition to shear turbulence, we will also examine gravity-wave breaking and its transition to turbulence. To date, we have completed two gravity-wave breaking simulations. These explore the breakdown of a single wavelength with an initial amplitude that is sufficient to spontaneously overturn and instigate a nonlinear cascade to smaller length scales of motion. With our next allocation we would like to continue this preliminary effort, eventually moving on to multiple-wave interactions that give rise to local overturning. Based on the single-wavelength solutions we have already computed at Re=16,000 and a numerical domain of $900 \times 300 \times 300$ spectral modes, we anticipate two series of solutions which will require twice this grid in each spatial direction, and will demand roughly 240,000 hours each.

We have listed here the simulations with the most demanding computational requirements so that we may estimate our total computational needs. These runs reflect a culmination of simulations conducted with increasing values of Re, with the lower values of Re requiring less computational effort. In order to support the required lower-Re simulations we estimate that the total requirement will be 30% beyond that required for the largest jobs—bring the total needs for the DNS turbulence phenomenology simulations to 540,000

T3E processor hours per year for each of the next three years.

4.3 Microscale Meteorological Modeling From DNS

The computational grid of the microscale code is centered at the tropopause with a horizontal dimension of 5 km and a vertical dimension from 2 to 4 km. With 512 horizontal grid points the physics are resolved to 10 meters, which we believe may be necessary to capture the relevant phenomena. Likewise, we estimate that up to 1024 mesh points may be required in the vertical direction—yielding an upper bound on the computational mesh requirement of $512 \times 512 \times 1024$. A typical microscale turbulence simulation takes 10000 time steps to reach a quasi-equilibrium. Based on the code performance results discussed in Section 3.4.3, we estimate that a job utilizing this computational mesh will require approximately 35000 processor hours for 10000 time steps on an SGI Origin 2000—e.g., if we used 32 processors the time to compute 10000 time steps on the LANL machine is $8 \times 49 \times 32 \times 10000/3600 = 34,844$ processor-hours. The program requires that 15 words be stored per mesh point and thus 32Gbyte of memory is require to run the largest jobs.

Many code runs will be required to develop the desired parametrized microscale meteorological turbulence forecasting model for ABL. In addition to the large runs discussed above, we will also be submitting runs utilizing a reduced resolution mesh. We estimate that a total of 500,000 processor hours will be required for each of the next 3 years. These estimates are based on the use of the use of a SGI Origin 2000 SMP with R12000 processors running at 300MHz; e.g., the machines available at the Army Research Laboratory MSRC. Use of the slower R10000 processors would require an adjustment in these estimates.

4.4 Use of Mesoscale Turbulence Models and Improved Closure Relations In ADA

In this task we will be running the standard mesoscale codes COAMPS and MM5. We request that these runs be made on the CRAY T90 at the ARL MSRC. We plan on making approximately one run per day throughout the next three years. Previous experience obtained from running these codes on the T90 indicates that 8000 processor hours per year will be required for these runs (5 hours of computation time on 4 processors of a T90 for each run, with 1 to 2 Gbytes of memory required in a typical run).

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DoD Challenge Project Resource Request—FY01

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Section II: Resource Requirements

	Location		Resources (processor-hours)	
Platforms	First Choice	Second Choice	Request	Minimum
IBM P3 SMP	MHPCC	ERDC	175,000	150,000
T3E*	ERDC	NAVO	270,000	250,000
T3E*	NAVO	ERDC	270,000	250,000
SGI O2K	ARL	ASC	500,000	450,000
CRAY T90	ARL		8,000	6,000

*The total requirement for T3E processor hours is 540,000—which we recommend be divided between the ERDC and NAVO MSRC's. Similarly, the 500,000 processor-hour request for the SGI O2K could be divided equally between the ARL and ASC MSRC's

Platforms	Typical # Processors	Max # Processors	Typical Job Mem, GB	Max Job Mem, GB	Typical Job Disk, GB	Max Job Disk, GB
IBM P3 SMP	16	64	4	16	1	5
T3E	100	600	10	100	10	50
SGI O2K	64	128	4	32	10	40
CRAY T90	4	8	1	2	1	2

Section III: Related Requirements Projects

Related Requirements Project Numbers: 0017, 0263

DoD Challenge Project Resource Request—FY02

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Section II: Resource Requirements

	Location		Resources (processor-hours)	
Platforms	First Choice	Second Choice	Request	Minimum
IBM P3 SMP	MHPCC	ERDC	175,000	150,000
T3E*	ERDC	NAVO	270,000	250,000
T3E*	NAVO	ERDC	270,000	250,000
SGI O2K	ARL	ASC	500,000	400,000
CRAY T90	ARL		8,000	6,000

*The total requirement for T3E processor hours is 540,000—which we recommend be divided between the ERDC and NAVO MSRC's. Similarly, the 500,000 processor-hour request for the SGI O2K could be divided equally between the ARL and ASC MSRC's

Platforms	Typical # Processors	Max # Processors	Typical Job Mem, GB	Max Job Mem, GB	Typical Job Disk, GB	Max Job Disk, GB
IBM P3 SMP	16	64	4	16	1	5
T3E	100	600	10	100	10	50
SGI O2K	64	128	4	32	10	40
CRAY T90	4	8	2	4	1	2

Section III: Related Requirements Projects

Related Requirements Project Numbers: 0017, 0263

DoD Challenge Project Resource Request—FY03

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Section II: Resource Requirements

	Location		Resources (processor-ho urs)	
Platforms	First Choice	Second Choice	Request	Minimum
IBM P3 SMP	MHPCC	ERDC	175,000	150,000
T3E*	ERDC	NAVO	270,000	250,000
T3E*	NAVO	ERDC	270,000	250,000
SGI O2K	ARL	ASC	500,000	400,000
CRAY T90	ARL		8,000	6,000

*The total requirement for T3E processor hours is 540,000—which we recommend be divided between the ERDC and NAVO MSRC's. Similarly, the 500,000 processor-hour request for the SGI O2K could be divided equally between the ARL and ASC MSRC's

Platforms	Typical # Processors	Max # Processors	Typical Job Mem, GB	Max Job Mem, GB	Typical Job Disk, GB	Max Job Disk, GB
IBM P3 SMP	16	64	4	16	1	5
T3E	100	600	10	100	10	50
SGI O2K	64	128	4	32	10	40
CRAY T90	4	8	2	4	1	2

Section III: Related Requirements Projects

Related Requirements Project Numbers: 0017, 0263

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1993-1999: Principal Investigator, Atmospheric turbulence program in support of the Airborne Laser Program, AFRL/VSBL, Hanscom AFB, MA. Chief scientist and team leader of in-house team performing balloon-borne measurements of atmospheric turbulence and related analysis and modeling. Led team in performing 11 overseas measurement campaigns for the ABL in Korea and the Middle East that were critical in the ABL's favorable Authority to Proceed decision in 1998.
1991-1993: Director, Data Analysis Center, PL/GP, Hanscom AFB, MA. Established and managed the data processing and analysis center responsible for processing up to 8GB of raw data per day for the Mid-Course Space Experiment (MSX). Managed team of in- house computer specialists and contractors to establish the hardware and software infrastructure for the automated processing and interactive analysis of MSX satellite data.
1983-1991: Physicist, Air Force Geophysics Laboratory, Hanscom AFB, MA. Performed measurements, data analysis and modeling of atmospheric optical turbulence. Designed and carried out experiments using both optical and balloon-borne instrumentation. Carried out Clear 1 data collection campaign and performed analysis and developed the Clear 1 model.

Relevant Publications/Presentations:
R.R. Beland,"Propagation through Atmospheric Optical Turbulence", Chapter 2, Volume 2, in *The Infrared and Electro-Optic Handbook*, 3rd Edn., SPIE, 1993.
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R. R. Beland and J. Krause-Polstorff, Lidar Measurement of Optical Turbulence: Theory of the Crossed Path Technique, Phillips Laboratory Technical Report, PL-TR-91-2139, July 1991.

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Experience. Dr. Brown has 42 years of experience related to the theory of propagation, scattering and diffraction of electromagnetic waves and the application of these theories in the analysis of communication, radar, imaging and other optical systems. Recent work has been concerned primarily with the modeling and analysis of laser propagation over turbulent paths sufficiently long that scintillation effects are important. In earlier work he developed and utilized numerical techniques for solving nonlinear optical propagation problems such as two-wave mixing in photorefractive materials, four-wave mixing in gases, and stimulated Raman and Brillouin scattering. He was one of the first to develop numerical simulations of linear and, thermally-induced, nonlinear propagation in atmospheric turbulence. This work included the development, in the middle and late 1970's, of a detailed, time-dependent simulation of adaptive optical compensation of such effects. Other work included analytical and numerical studies of terrestrial and deep-space compensated imaging. During the period from 1965–1975 Dr. Brown worked on the theory of optical propagation in atmospheric turbulence and on the asymptotic theory of diffraction from convex scatterers.
In addition to the expertise in optical physics, Dr. Brown has considerable experience in high-performance computing (HPC) and its application in the modeling of optical phenomena and systems. His first exposure to HPC was the CDC 7600 at Lawrence Berkeley Laboratories in the middle 1970's. This was followed by the use of various CRAY computers such as the CRAY-1, CRAY-XMP, CRAY-2, CRAY-YMP and, more recently, the CRAY C90. Experience on parallel supercomputers includes the development of parallel propagation codes on the INTEL IPSC-860, and the IBM SP1, SP2, P2SC and P3 SMP computers at the Maui High Performance Computing Center (MHPCC). He is currently principal investigator of the DoD ABL Challenge Project and is responsible for the optical propagation and adaptive optics simulation studies being performed on that project at MHPCC.
In 1993, Dr. Brown was named a Fellow of the Optical Society of America in recognition of his contributions to the theoretical understanding and numerical modeling of optical propagation through atmospheric turbulence and of adaptive optical systems used for the compensation of the related propagation effects.

Professional Affiliations: Optical Society of America, International Scientific Radio Union (URSI)

Honors: Fellow Optical Society of America, Elected member of URSI, IRE Outstanding Student Award University of Michigan 1956, Oreon E Scott Memorial Scholar University of Michigan 1956, Sigma Xi, RESA, Tau Beta Pi, Eta Kappa Nu.

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Dave has held numerous professional appointments, including Associate Editor for the Journal of the Atmospheric Sciences and the Journal of Geophysical Research, membership on the National Academy of Sciences Committee on Solar-Terrestrial Relations (CSTR) and numerous other advisory committees and panels. He has served as chairman of the Middle Atmosphere Program subcommittee on gravity waves and turbulence (GRATMAP), as chairman of the Middle Atmosphere Continuation project subcommittee on Upward Coupling of Wave Energy (UCWE), and as President of the International Commission on the Middle Atmosphere (ICMA) within IAMAS (1995 - 1999).

Of relevance to this proposal, Dave has extensive experience with numerical modeling of wave, instability, and turbulence processes. His more recent contributions include the first studies of wave breaking and the transition to turbulence using a 3D model, the first studies of KH shear instability in 3D, studies of turbulence vortex dynamics, and the recent, and currently highest-resolution, simulations of KH instability and turbulence to date. The latter efforts were performed as a part of the current ABL Challenge Project on which he is a Co Principal Investigator.

Relevant Publications:

Andreassen, Ø., P. Ø. Hvidsten, D. C. Fritts, and S. Arendt, 1998:“ Vorticity dynamics in a breaking gravity wave, 1. Initial instability evolution,” *J. Fluid Mech.* ,**367**,27–46.

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Fritts, D. C., J. R. Isler, G. E. Thomas, and Ø. Andreassen, 1993:“Wave breaking signatures in noctilucent clouds,”*J. Geophys. Res.* ,**20**, 2039–2042.

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Fritts, D. C., J. F. Garten, and Ø. Andreassen, 1996:“Wave breaking and transition to turbulence in stratified shear flows,” *J. Atmos. Sci.* ,**53**, 1057–1085.

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A spectral domain decomposition method and its application to simulation of shear-stratified turbulence (with B. Nicolaenko and F. Tse), *Lecture Notes in Physics*, Springer-Verlag, to appear (2000).

A numerical study of an operator splitting method for rotating flows with large ageostrophic initial data (with D. A. Jones and B. Nicolaenko), *Theor. and Comp. Fluid Dyn.*, **13**, 143-159 (1999).

Energy spectra of strongly stratified and rotating turbulence (with B. Nicolaenko and Y. Zhou), *Phys. Rev. E*, **57**, 6187-6190 (1998).

On the nonlinear baroclinic waves and adjustment of pancake dynamics (with A. Babin and B. Nicolaenko), *Theor. and Comp. Fluid Dyn.*, **11**, 215-235 (1998).

Analytical and phenomenological studies of rotating turbulence (with Y. Zhou), *Phys. of Fluids*, **8**, 2138-2152 (1996).

Synergistic activities: My research activities for the past seven years have focused on Atmosphere and Ocean Flows (stratified and rotating flows) and Environmental Fluid Dynamics. This involves close collaboration with the Center for Environmental Fluid Dynamics at ASU, the High Performance Computing Center Climate Modeling program at Los Alamos and the UK Meteorological Office at Bracknell, England. This has resulted in archival publications and invitations to present our work at numerous national and international conferences. Our current research is focused on problems of optical turbulence for the Air Force Air Borne Laser Program (research funded by the AFOSR).

Post-Doctoral Fellows: Rafael Pacheco, Frank Tse
Graduate Students: Chandran Nair, Haruhito Murakami

Collaborators (past 48 months): D. Armbruster, A. Babin, J. Fernando, J. Guckenheimer, H. Kruse, J. Marsden, B. Nicolaenko, Y. Zhou

Basil Nicols (Nicolaenko)
Professor of Applied Mathematics
Department of Applied Mathematics
Arizona State University
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ACADEMIC:

1964	Civil Engineer Diploma	National Superior School of Engineering, Paris
1964	M.S. (Licence) (Mathematics)	University of Paris
1966	Doctorat 3rd Cycle (Applied Mathematics)	University of Paris
1968	Ph.D. (Mathematical Physics)	University of Michigan

PROFESSIONAL EXPERIENCE:
1968–69: **Post Doctoral Fellow**, Brookhaven National Laboratory, (L.I.,N.Y.).
1969–75: **Assistant Professor of Mathematics**, Courant Institute of Mathematical Sciences, New York University.
1975–89: **Staff Member**, Mathematical Analysis Group T-7, Los Alamos National Laboratory.
1980–82: **Deputy Center Director**, Center for Nonlinear Studies, Los Alamos National Laboratory.
1980–86: **Group Leader**, Mathematical Analysis Group T-7, Los Alamos National Laboratory.
1989–now: **Collaborator, Center for Nonlinear Studies** (CNLS)(Los Alamos National Laboratory)
1989–now: **Professor of Applied Mathematics**, Arizona State University.
1997 **Condorcet Chair**, Ecole Normale Supérieure, Paris (Visiting Chair).

RESEARCH INTERESTS
Geophysical Fluid Dynamics (Atmosphere and Oceans), Mathematical Fluid Dynamics, Large Scale Computations of Transitions to Chaos and Turbulence, Scientific Computing, the Connection between Dynamical Systems and Partial Differential Equations Continuum, Mechanics, Infinite Dimensional Dynamical Systems, Asymptotic Analysis, Mathematics of Moving Fronts and Free Boundaries, Deflagration and Combustion Waves, Boltzmann Equations and Radiative Transfer Equations, Kinetic Theory of Gases.

FIVE PUBLICATIONS MOST CLOSELY RELATED TO THE PROPOSAL
1. A spectral domain decomposition method and its application to simulation of shear-stratified turbulence (with A. Mahalov and F. Tse), Springer-Verlag Lecture Notes in Physics, to appear (2000).
2. Remarks on the energy spectra and dimensionality of strongly-stratified and rotating/stratified turbulence (with A. Mahalov and Y. Zhou), *Phys. Rev. E.*, **57**, 6187–6190 (1998).
3. On asymptotic regimes and the strongly stratified limit of rotating Boussinesq equations (with A. Babin, A. Mahalov, and Y. Zhou),*J. Theor. and Comp. Fluid Dyn.* ,**9**, No. 3–4, 223–251 (1997).
4. On the nonlinear baroclinic waves and adjustment of pancake dynamics (with A. Babin, A. Mahalov),*J. Theor. and Comp. Fluid Dyn.* ,**11**, 215–235 (1998).
5. A numerical study of an operator splitting method for rotating flows with large ageostrophic initial data (with D. A. Jones and A. Mahalov),*J. Theor. and Comp. Fluid Dyn.* ,**13**, 143–159 (1999).

EXPERTISE IN HIGH PERFORMANCE COMPUTING:
Since joining Los Alamos in 1975, Professor Nicolaenko has been a heavy user of supercomputers on all successive generations of supercomputers at LANL: from the very first CRAY-1 to the CRAY-T3E, from the Thinking Corporation's Connection Machines CM-2000 to their CM-5. Currently, he is a heavy user of the massively parallel, scalable architecture Blue Mountain Machine at LANL for his simulations of Atmospheric and Ocean Flows.

SYNERGISTIC ACTIVITIES: For the past five years, Professor Nicolaenko's research activities have been focused on Atmospheric and Ocean Flows (stratified and rotating flows) and Environmental Flows. This work has involved close collaboration with the Center For Environmental Fluid Dynamics at ASU and the High Performance Computing Center Climate Modeling Program at Los Alamos. He is also working on problems of optical propagation for the Airborne Laser Program (research funded by AFOSR).

DOCTORAL GRADUATE STUDENTS:
Nejib Smaoui, Le Dung, Robert Hedges, Bong-Sik Kim, Tae-Chang Jo

POSTDOCTORAL FELLOWS:
Weijie Qian, Frank Tse

COLLABORATORS AND CO-AUTHORS WITHIN THE PAST 4 YEARS
D. Armbruster, A. Babin, P. Chossat, P. Constantin, P. Fabrie, C. Foias, A. Mahalov, N. Smaoui, R. Temam, Y. Zhou

Donald L. Walters
Associate Professor
Department of Physics
US Naval Postgraduate School
Monterey, CA

Education:
1971 Ph.D., Physics, Kansas State University
Specialization: Numerical Computational Quantum Mechanics
Thesis Advisor: C. P. Bhalla
Dissertation: "Nonrelativistic Auger and X-ray Transition Probabilities using the Hartree-Fock Model
Fellowship: NDEA Title IV 1966 to 1969
1966 B.S., Physics, Kansas State University

Chronology of Professional History

1971–1973: lLT, US Army Signal Corps. Served in a Major's position as an action officer involved with the conceptual design and analysis of high energy laser systems, night vision techniques and electro-optical hardware of Field Artillery interest. Was the author of the Required Operational Capability (ROC) documents, formal specifications for development, of the Ground Laser Locator Designator for Copperhead and the Field Artillery version of the AN/GVS-5 laser rangefinder.
1972–1982: RESEARCH PHYSICIST (GS 12-13), US Army Atmospheric Sciences Laboratory. Principal scientist and team leader for high-energy laser atmospheric characterization for the US Navy MIRACL High Energy Laser and two USAF ground based laser systems. Responsibilities included the development of plans, measurement techniques and instrumentation needed to execute focused field measurement programs. Because of these efforts the Office of the Under Secretary for Defense, Research and Engineering designated the Atmospheric Sciences Laboratory the lead laboratory for high-energy laser atmospheric characterization in 1979.
October 1982-June 1983: SENIOR SCIENTIST, Optimetrics Inc., Las Cruces, NM. Research in atmospheric optics specializing in high-energy laser propagation characterization and remote atmospheric sensor development.
1983–Present: ASSOCIATE PROFESSOR, Physics, Naval Postgraduate School. Tenure 1987.

Teaching:
Upper division and graduate courses in lasers, electro-optics, synthetic and inverse synthetic aperture radars, quantum mechanics, statistical physics and atmospheric turbulence.

Reasearch: Development of methods, techniques and instrumentation for the measurement of optical degradations in the turbulence atmosphere using acoustic and remote optical techniques. Developed instrumentation and techniques to measure stratospheric turbulence that have become a national reference standard. Developed a high-resolution synthetic aperture sonar system for mine identification and classification. Provided database, atmospheric characterization and expert consultation for National Technical TS/SCI programs.

Selected Relevant Publications:
D. L. Walters and D. K. Miller,"Use of Mellor-Yamada level 2.5 mesoscale models to compute stable atmospheric turbulence." submitted *J. Appl. Meteorology*, 1999.

D. H. Nelson, D. L. Walters, Edward P. MacKerrow, Mark J. Schmitt, Charles R. Quick, William M. Porch and Roger R. Petrin, "Wave optics simulation of atmospheric turbulence and reflective speckle effects in CO2 differential absorption LIDAR (DIAL)," submitted *Appl. Opt.*, 1999.

D. L. Walters and L. W. Bradford,"Measurement of r_o, θ_o: two decades and 18 sites," *Appl. Opt.* ,**36**, 7876–7886, 1997.

D. L. Walters,"Measurement of optical turbulence with higher-order structure functions," *Appl. Opt.* ,**34**, 1591–1597, 1995.

Charles A. Davis and D. L. Walters,"Atmospheric inner scale-effects on normalized irradiance variance," *Appl. Opt.* ,**33**, 8406–8411, 1994.

J. Krause-Polstorff, E. A. Murphy and D. L. Walters, "Instrument comparison: corrected stellar scintillometer versus isoplanometer," *Appl. Opt.* ,**32**, 4051–4057, 1993.

J. Krause- Polstorff and D. L. Walters."Refractive turbulence profiling using an orbiting light source," *Appl. Opt.* ,**29**, 1877–1885, 1990.

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Experience: Joe Werne received his degrees in Mechanical Engineering & Mechanics: B.S. (summa) and Physics: B.S. (summa) in 1987 from Old Dominion University and Ph.D. in 1993 from The University of Chicago (Robert Rosner, advisor). While at the University of Chicago, he taught elementary physics for four summers in the Summer MCAT Program, Biological Sciences Division and The Pritzker School of Medicine (1989-92). He was a post-doctoral fellow in the Advanced Study Program at NCAR (1992-94), an NCAR visiting scientist (1994-95), and then a research associate in the Joint Institute for Laboratory Astrophysics (1995-97), the Laboratory for Atmospheric and Space Physics (1995-96), and the Program in Atmospheric and Ocean Sciences (1995-96) at CU. He is currently a research scientist at NWRA/CoRA and an affiliated faculty member of the Department of Applied Mathematics at CU.

Joe's primary research areas include turbulent fluid motion with application to geophysical and astrophysical flows. Examples include both unstably stratified flows (such as penetrative convection, rotating incompressible convection, and boundary effects in turbulent convection) and stably stratified dynamics (including the Kelvin-Helmholtz instability, wave-breaking instability, and vortex-tube motion and instability). Particular emphasis is placed on coherent structures, their transport and organization of large-scale flows, mean-flow generation and maintenance, and accurate spectral numerical methods. He has developed several computer codes to conduct large-scale 3D computing on the Cray T3D and T3E, the IBM SP2, and the SGI/Cray Origin 2000 as part of the NSF HPCC Grand Challenge Applications Group in Geo- and Astro-physical Fluid Dynamics and in support of the stratified shear turbulence studies being performed on the current ABL Challenge Project.

Relevant Publications:

Werne, J. A., and D. C. Fritts, 1999:"Using massively parallel supercomputers to study clear air turbulence," *Science*in preparation.

Fritts, D. C., J. A. Werne, and T. L. Palmer, 1999:"Dynamics of turbulence in stratified shear flows at high Reynolds number," *nature*, submitted.

Fritts, D. C., S. Arendt, and Ø. Andreassen, 1999:"The vorticity dynamics of instability and turbulence in a breaking internal gravity wave," *Earth Planets Space* in press.

Werne, J. and D. C. Fritts, 1999:"Turbulence and Mixing in a Stratified Shear Layer: 3D K-H Simulations at $Re = 24,000$," European Geophysical Society, XXIV General Assembly. April 1999, The Hague.

Werne, J. and D. C. Fritts, 1999:"Stratified shear turbulence: Evolution and Statistics," (cover article),*Geophys. Res. Lett.* ,**26**, 439–442.

Werne, J. and D. C. Fritts, 1998:"Turbulence in Stratified and Sheared Fluids: T3E Simulations." HPCMO Users Group Conference, Ed. N. Sidki, Rice University, Houston, TX.

Julien, K., J. Werne, J. C. McWilliams, and S. Legg, 1997:"The effect of rotation on convective overshoot." *Solar Convection and Oscillations*, Eds. F. P. Pijpers, J. Christensen-Dalsgaard & C. S. Rosenthal, Kluwer Acad. Publ., p. 227.

Julien, K., J. Werne, J. C. McWilliams, and S. Legg, 1997:"The effect of rotation on the global dynamics of turbulent convection."*Solar Convection and Oscillations*, Eds. F. P. Pijpers, J. Christensen-Dalsgaard & C. S. Rosenthal, Kluwer Acad. Publ., p. 231.

Julien, K., Legg, S., McWilliams, J., and J. Werne, 1996: "Penetrative convection in rapidly rotating flows: Preliminary results from numerical simulation," *Dyn. Atmos. Oceans*,**24**, 237.

Werne, J., 1994:"Plume model for the boundary-layer dynamics in hard turbulence,",Phys. Rev. E, **49**, 4072–4076.

Werne, J., 1998:"Turbulent convection: what has rotation taught us?",*Geophysical and Astrophysical Convection*, Gordon and Breach Science Publishers, (in press).

Julien, K. A., S. Legg, J. C. McWilliams, and J. Werne, 1996:"Rapidly rotating Rayleigh-Bénard convection,"*J. Fluid Mech.* , **322** 243.
Werne, J., 1995:"Turbulent Rotating Rayleigh-Bénard Convection with Comments on 2/7." *Woods Hole Oceanog. Inst. Tech. Rept.*, WHOI 95 27.
Julien, K. A., S. Legg, J. C. McWilliams, and J. Werne, 1996c:"Hard turbulence in rotating Rayleigh-Bénard convection' Phys. Rev. E, **53**, 5557R.
Werne, J., 1995:"Incompressibility and no-slip boundaries in the Chebyshev-Tau approximation: Correction to Kleiser and Schumannś influence-matrix solution,"*J. Comp. Phys.* ,**120**, 260–265.

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Education:
1976 Ph.D., Chemical Physics, Harvard University
1969 B.S., Chemistry, University of Rochester

Scientific Background:
Jeremy R. Winick is a Physicist in the Battlespace Environment Division of the Air Force Research Laboratory (AFRL) at Hanscom Air Force Base in Massachusetts. He came to the field of aeronomy like many others from a background in atomic and molecular physics. After obtaining his Ph.D. in chemical physics, he was a research associate at the University of Colorado Laboratory for Atmospheric and Space Physics (LASP). Work at LASP involved photochemical modeling of ozone photochemistry in the earth's stratosphere and modeling of sulfur chemistry in the Venus atmosphere in conjunction with the Pioneer Venus ultraviolet spectrometer experiment. He then spent 1980-81 as a National Research Council Resident Research Associate at the Aeronomy Laboratory/NOAA in Boulder, Colorado extending photochemical models to include the positive and negative ion chemistry of the D-region.
Upon joining the Air Force Geophysics Laboratory in 1982, he became part of the upper atmospheric infrared group. There he added radiative transfer expertise to his photochemical modeling and chemical physics background. He was instrumental in producing the Air Force Auroral Atmospheric Radiance Code (AARC) for modeling Infrared enhancement from aurora. He was a key player in the development of the more comprehensive line-by-line non-LTE infrared Atmospheric Radiance Code. Much of his work at ARFL has been in the continued development of this state of the art non- LTE code for CO2 and CO radiance and its validation by analysis of many infrared field programs. Code development and validation has been undertaken with data from SPIRE, FWI, SISSI, MAPWINE, and EXCEDE rocket experiments and with CIRRIS 1A shuttle data. As a guest investigator on the MSX earthlimb team, he is actively engaged with analyzing both quiescent and auroral data from the SPIRIT III radiometer arrays. He also is a member of the NASA TIMED SABER retrieval algorithm team, helping with development of non-LTE retrieval codes.
In recent years, in response to DoD needs, he has expanded the non-LTE radiance modeling to include sources of radiance structure. He has been a participant in AFOSR (Air Force Office of Scientific Research) MAPSTAR and SOAR programs. A model of airglow response to internal gravity waves has been developed and applied to the OH Meinel, O(1S) green line, O2 atmospheric bands and the sodium D-line emissions. He is currently investigating structure in MSX images that are apparently produced by gravity.
Dr. Winick is a co-investigator for the current Airborne Laser Challenge Project along with Dr. Wilbur Brown of AFRL/DEBA and Dr. David Fritts of Colorado Research Associates. This project is using direct numerical simulation to study the spatial and temporal evolution of turbulence generation in shear flows and gravity wave breaking events with application to laser propagation through such turbulent structures. Dr. Winick is also a principal investigator on two NASA Office of Space Science ITM (Ionosphere, Thermosphere Mesosphere) programs. (1) Analysis of gravity-wave parameters from spacecraft-measured structured radiance starting 1 April, 2000; and (2) Coordinated Investigation of 15 ?m CO2 Cooling rates in the Upper Mesosphere and Lower Thermosphere Utilizing MSX Multispectral Data, during the period April 1998- March 2000.

Societies, Honors:
Federal Service Performance Awards 1984-1997
National Research Council Resident Research Associate Award 1979 - 1981
Member American Geophysical Union 1978- present
Phi Beta Kappa, University of Rochester, 1969

Selected Publications:
Miller, S.M, J.R. Winick, H. E. Snell,"Non-LTE effect on retrieval of Temperature from the CO2 Laser Band using CIRRIS 1A data," accepted, *J. Geophys. Res.* ,**105**, 2000.

Makhlouf, U.B., R.H. Picard, J.R. Winick, and T.F. Tuan,"A model for the response of the atomic oxygen 557.7nm and the OH Meinel airglow to atmospheric gravity waves in a realistic atmosphere," *J. Geophys. Res.* ,**103**, 6261-6269, 1998.

R. H. Picard, R. R. O'Neil, H. A. Gardiner, J. Gibson, J. R. Winick, W. O. Gallery, P. P. Wintersteiner, E.R. Hegblom, and E. Richards,"Remote Sensing of Discrete Stratospheric Gravity-Wave Structure in 4.3 ?m CO2 Emission from the MSX Satellite.,"*Geophys. Res. Lett.* , **25**, 2809-2812, 1998.

R.H. Picard, U.S. Inan, V.P. Pasko, J.R. Winick, and P.P. Wintersteiner,"Infrared Glow Above Thunderstorms?," *Geophys. Res. Lett.* ,**24** 2635-2638,1997.

U.B. Makhlouf, R.H. Picard, M.J. Taylor, and J.R. Winick,"Gravity waves and vertical diffusion in the lower thermosphere from 557.7 nm airglow," *Adv. Space Res.* ,**19**, 583-586, 1997.

U.B. Makhlouf, R.H. Picard, and J.R. Winick,"Photochemical-dynamical modeling of the measured response of airglow to gravity waves. 1. Basic model for OH airglow,"*J. Geophys. Res.* , **100**, 11289-11211, 1995.