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Principal Investigator: Brian Argrow
Professor Department Aerospace Engineering Sciences
Director Integrated Remote & In Situ Sensing Program (IRISS)
Research & Engineering Center for Unmanned Vehicles (RECUV)
429 UCB, Boulder Colorado 80309-0429
Tel: 303-492-5312
Fax: 03-492-7881
Email: brian.argrow@colorado.edu

Team Members: University of Colorado (CU), University of Minnesota, and Embry Riddle Aeronautical University

Current DoD Grantee: AFRL/AFOSR/RTA-2, Dr. Frederica Darema, Tele: (703) 588-1926, DSN: 425-1926.

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1. Objective and Approach

Hypersonic vehicle aerothermodynamics and boundary layer stability in the middle and upper stratosphere are believed to be sensitive to particles and turbulence fluctuations extending to very small scales. Aero-optical propagation is likewise sensitive to smaller-scale turbulence and larger-scale coherent temperature gradients that accompany the environments driving turbulence events. Assessments of these effects require a detailed understanding of particle and stratospheric turbulence sources, characteristics, variability, intermittency, and the environments in which they arise. We propose to provide this needed understanding by answering, qualitatively and quantitatively, the following three research questions:

- ***What are the spatiotemporal statistics of small-scale turbulence in the middle and upper stratosphere, and to what extent are they dictated by larger-scale motions, primarily gravity waves (GWs) that arise from meteorological sources at lower altitudes?***
- ***What are the distributions of particles in the stratosphere, and their dependence on underlying meteorology?***
- ***What are the relative roles of particles and pre-existing atmospheric turbulence ("free-stream turbulence") for the laminar-turbulent transition at hypersonic speeds in the middle and upper stratosphere?***
- ***What are the effects of particles, temperature "sheets" and small-scale turbulence in the middle and upper stratosphere on long-range optical propagation, and how can these effects be accurately represented in computational simulations?***

We will address these questions and explore their implications for stratospheric turbulence prediction, hypersonic vehicle boundary layer stability, and aero-optical propagation through a comprehensive research program employing state-of-the-art *in-situ* measurements, modeling, and theoretical capabilities in every application. We propose three research thrusts shown in **Table 1**.

Table 1. Research Thrusts.

Research Thrusts		
Stratospheric Measurements & Analysis	**Atmospheric Modeling & Forecasting**	**Aerothermodynamics & Aero-Optical Modeling**
In-Situ Turbulence *In-Situ Particles*	*Direct Numerical Simulation* *Finite-Volume Modeling*	*Hypersonic Aerothermodynamics* *Aero-Optical Propagation*

Stratospheric measurements will quantify turbulence environments, characteristics, intensities, and sources using high-resolution *in-situ* instruments aboard balloons to altitudes of ~100,000 to 115,000 ft. Wind and temperature measurement capabilities will include improved versions of the 8-kHz sampling Leibniz Institute Turbulence Observations in the Stratosphere (**LITOS**) instrument flown on the BEXUS balloons (Schneider et al. 2015) and the University of Colorado (**CU**) *in-situ* instruments flown on small unmanned aircraft vehicles (**UAVs**) in various tropospheric measurement programs (Lawrence and Balsley 2013; Fritts et al. 2016a). Measurements will be performed at three sites providing sensitivity to the dominant GW sources: convection over Florida by Embry Riddle Aeronautical University (**ERAU**), topography over Colorado by CU, and fronts and jet streams over Norway with colleagues at the Leibniz Institute of Atmospheric Physics (**IAP**) in Germany. Particle concentrations and size distributions will be measured by the University of Minnesota (**UM**) in the stratosphere to help determine their potential roles in causing transitions to turbulence in hypersonic flight conditions.

Atmospheric modeling capabilities include compressible finite-volume (**CFV**) and spectral codes performing direct numerical simulations (**DNS**) addressing larger- and smaller-scale atmospheric dynamics. The CFV code solves the compressible Navier-Stokes equations in deep domains having variable resolution and the ability to describe GWs from their sources to instability scales in the stratosphere (Lund and Fritts 2016). The spectral code solves the Boussinesq Navier-Stokes equations in a smaller domain and addresses instability and turbulence dynamics at very high spatial resolution (Fritts et al. 2013; 2016a). It has been extensively employed in support of previous programs for the Air Force, Navy, and MDA (see below). Our GW and turbulence modeling will be guided by, and aid interpretation of, our turbulence measurements. They will additionally define spatiotemporal turbulence statistics at very small and larger event scales and provide the turbulence fields required as inputs for our hypersonic and aero-optical modeling, theoretical assessments, and design of a "strawman" forecast system.

Computational aerothermodynamics will use advanced simulation codes to study the role of atmospheric turbulence and particles in causing laminar to turbulent transition in hypersonic boundary layers. This work will use DNS, boundary layer stability theory, parabolized stability equations solvers, and hybrid particle/continuum computational fluid dynamics methods (see Candler et al. 2015, Johnson et al. 2010; Nopelis and Schwartzentruber 2013, for details). The atmospheric turbulence modeling will be used to provide inputs to the simulations to determine how the hypersonic flow field amplifies and distorts the turbulence, and provides forcing to the hypersonic boundary layer. Stability analyses will be used to quantify the receptivity to types of disturbances to determine relevant perturbation levels as a function of atmospheric state. Detailed simulations of flow field / particle interactions with rarefaction effects will be performed to determine how atmospheric particles interact with a hypersonic boundary layer, and whether they can cause transition to turbulence. This part of the MURI project will couple the DNS turbulence modeling guided by atmospheric measurements to the hypersonic flow field response to quantify mechanisms for initiating instability growth and transition to turbulence.

Aero-optical propagation through the stably stratified atmosphere will be investigated by means of theoretical analysis, computer simulations, and field observations. The theoretical and computational parts of this work will build on statistical electromagnetics in turbulent media, Fourier optics, and analytical and computational fluid dynamics **(CFD)**. Optical phase screens will be computed from CFD output data to compute realizations of complex-valued, beam-transverse, 2D electromagnetic fields at selected locations along the propagation path by means of standard techniques (geometrical optics, Rytov approximation, split-step Fourier optics). These simulation output data will be used to test and improve statistical models for long-range, optical propagation through classical and non-classical ("non-Kolmogorov") turbulence in the middle and upper stratosphere.

Optical field experiments using Co-PI Muschinski's telescopes, digital cameras and test-light arrays will be conducted side by side with Prof. Rieker's state-of-the-art direct phase spectroscopy with frequency combs, and simultaneous in situ temperature and 3D velocity measurements by means of Muschinski's ultrasonic anemometer-thermometers placed along the near-ground propagation path will serve as "ground truth".

The research on aero-optical propagation within this MURI will substantially benefit from and add value to Muschinski's and Rieker's other current and pending NSF- and DoD-sponsored research projects.

Applications of, and synergism between, our proposed measurement, modeling, and theoretical capabilities will fully address the goals of this MURI. These include the following:

1. ***Identify and quantify the dynamics accounting for stratospheric turbulence sources, characteristics, intensities, and their statistical dependence on the meteorology below;***
2. ***Resolve uncertainties regarding small- and larger-scale turbulence impacts on hypersonic vehicle boundary layers and aero-optical systems;***
3. ***Establish critical particle concentration levels that may drive transition to turbulence in hypersonic boundary layers, and***
4. ***Define the methodologies required for comprehensive, measurement- and physics-based, stratospheric turbulence forecasting, including a "strawman" forecasting system design.***

2. Relationship of Proposed Research to the State of the Art

2.1. Stratospheric waves and turbulence

There is considerable evidence accumulated over decades of observations in the stratosphere, and at lower and higher altitudes, that energy inputs to the stratosphere are driven primarily by atmospheric waves. The stratosphere is ***always*** populated by gravity waves (**GWs**) because of their ubiquitous and diverse sources and their propagation often over large horizontal distances (Fritts 1984). Their amplitude growth with altitude due to decreasing density drives instability dynamics of various forms that lead to turbulence having scales and intensities determined by the GW energy inputs (Fritts and Alexander 2003; Fritts et al. 2016a). As an example, strong turbulence in the lower stratosphere is known to accompany mountain wave (**MW**) breaking due to strong flow over topography (e.g., Lilly and Kennedy 1973; Lilly 1978; Fritts and Nastrom 1992; Jiang et al. 2002). Multiple aircraft turbulence encounters and radar measurements likewise demonstrate the role of GWs driven by strong convection in turbulence generation as high as 80,000 ft (Bedard et al. 1986; Sato et al., 1995; Fritts et al. 2016b).

Profiles exhibiting GWs from these sources extending into the middle stratosphere are shown in **Figure 1**. The upper panels reveal MWs that break at lower and higher altitudes in weaker and stronger stratospheric zonal winds over Colorado (black and red, respectively). The lower panels show apparent convective GWs at several vertical wavelengths (see zonal and meridional winds, black and red) breaking at higher altitudes over Florida.

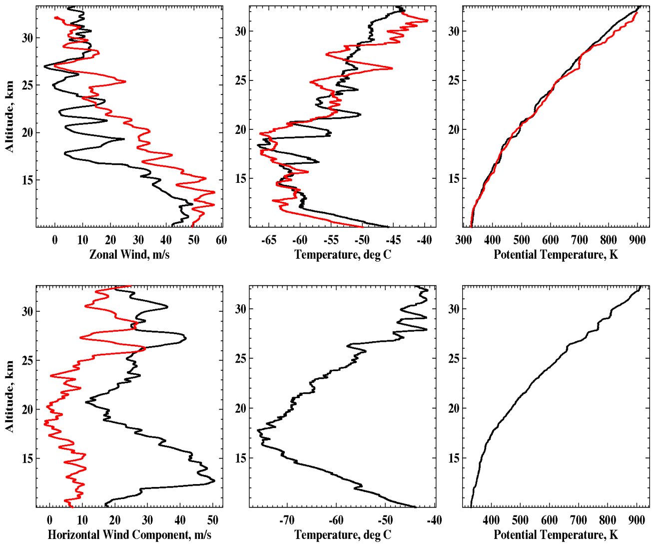


Figure 1. Data from two radiosondes launched from Grand Junction, CO in different MW events (top, red and black) and one from Tallahassee, FL during strong convection.

Other GW sources, e.g., fronts and jet streams, also generate GWs that induce strong wind shears and turbulence throughout the stratosphere (Nastrom and Fritts 1992). In many cases, however, the atmospheric GW spectrum is dominated by inertia-GWs (**IGWs**) having very large horizontal scales, slow vertical propagation, and small vertical energy fluxes (e.g., Allen and Vincent 1995; Wang and Geller 2003). Example profiles of temperature and horizontal winds exhibiting superposed GWs (including IGWs), throughout the stratosphere obtained by a radiosonde rising to >60 km are shown in **Figure 2**.

It is also well established by *in-situ* rocket and new imaging techniques that GWs are the major contributor to turbulence occurring in the mesosphere and lower thermosphere (MLT) from ~230,000-350,000 ft (Lübken 1997; Miller et al. 2015). These comparisons of high-resolution modeling and imaging demonstrate a rapidly-improving understanding of the GW and instability dynamics that account for the character, intensities, and statistics of turbulence events where high-resolution *in-situ* measurements and imaging have been performed (Fritts et al. 2016a, 2016c). Finally, GW theory predicts a roughly exponentially increasing mean turbulence energy dissipation rate, ε, that agrees reasonably with observations below ~100,000 ft and above ~230,000 ft, and which also anticipates significant ε at altitudes from ~100,000-200,000 ft (Fritts and VanZandt 1993). ***What remains to be explored is whether (as we suspect) the same turbulence sources are also largely responsible for, and dictate the variability and intensities of, turbulence in the middle and upper stratosphere.***

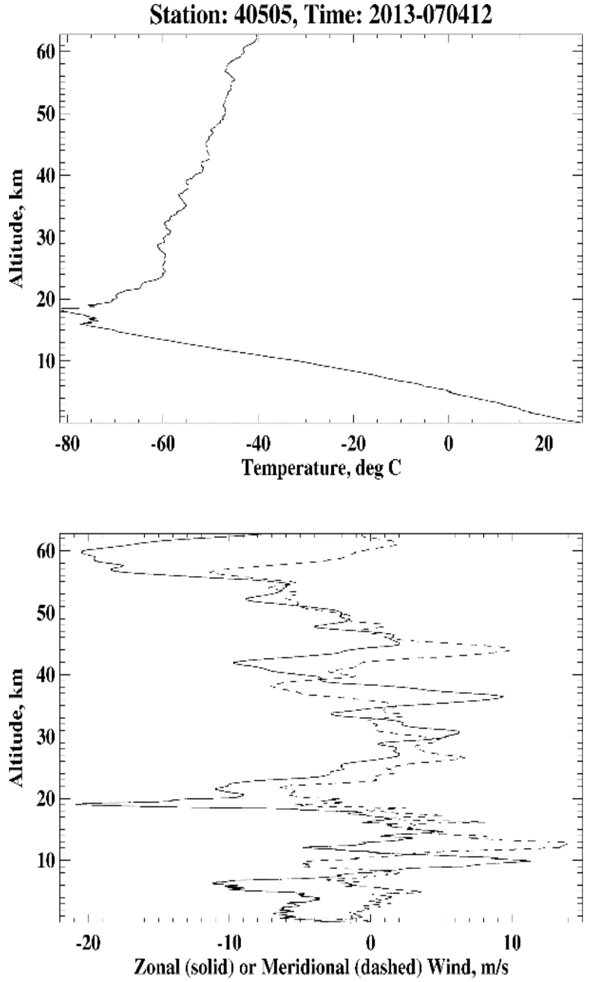


Figure 2. Temperatures and horizontal winds measured by a radiosonde over Truk (7.5N, 152E) that reached >60 km.

Our approach to quantifying turbulence sources and characteristics will involve merging state-of-the-art measurements and modeling to identify the major GW and instability dynamics and environments accounting for turbulence characteristics in the stratosphere. These efforts will include the following:

1. extensive, geographically distributed, measurements of turbulence and its background to above 120,000 ft under normal and very strong meteorological forcing conditions;
2. modeling of GW responses to specific source types and the environmental influences that dictate the instabilities driving turbulence in the stratosphere;
3. modeling the GW and instability dynamics accounting for specific turbulence responses;
4. use of turbulence measurements and modeling to guide specification of turbulence characteristics and spatiotemporal statistics as functions of the underlying meteorology.

2.2. Particle measurements

The stratosphere is populated by liquid and solid particles ranging from sub-micron scales to particles of over 100 μm. These particles can be present at concentrations of over one particle per cubic centimeter, but measurements show wide variations with height, local events such as sand storms, and latitude, for example. The origins of these aerosols vary considerably. Many natural and anthropogenic particles (e.g., sulfates, soot, minerals, etc.) with complex chemistry are found in the troposphere. In the stratosphere, liquid aerosols originate from the condensation of gases released during volcanic eruptions and sources, including rocket motor exhaust. In addition to liquid aerosols, solid particles have been detected in the lower and middle stratosphere. Stratospheric soot particles mainly originate from biomass combustion and anthropogenic activities. Aerosols from micrometeorites and cosmic dust are also present in the stratosphere due to an approximate daily flux of about 110 (±55) metric tons into the atmosphere. The stable stratification of the stratosphere, and the layering accompanying multi-scale instability and turbulence dynamics (Fritts et al. 2016a), may result in bands of particles and cause them to persist for relatively long times.

There have been speculations in the literature (e.g., Bushnell 1990; Fedorov 2013; Pugach et al. 2016) that the particles present in the stratosphere may be sufficient to cause laminar-turbulent transition. Measurements and flow visualizations in ground-based wind tunnels have shown that small (~10 μm-scale) particles can significantly disturb a hypersonic flow. Thus, if they are present in sufficient concentrations, particles could be the dominant mechanism that promotes transition. Our measurements will characterize particle concentrations and size distributions at altitudes relevant to hypersonic flight.

2.3. Aero-optical propagation

In the 1950s and 1960s, Tatarskii integrated Maxwell's electromagnetic field theory, first-principle fluid mechanics, the Kolmogorov-Obukhov theory of fully developed turbulence (Kolmogorov 1941; Obukhov 1949), and the mathematics of stochastic processes and random fields (Yaglom 1952, 1962) into a unified, statistical theory of electromagnetic wave propagation through turbulent media (Tatarskii 1961, 1971). Tatarskii's theory remains the physical and mathematical basis for progress in a wide range of science and engineering disciplines involving optical propagation through the turbulent atmosphere, such as optical remote sensing, optical imaging and surveillance, directed-energy technology, free-space optical communication, and adaptive optics.

Tatarskii's assumptions and approximations include the time-harmonicity and quasi-stationarity of electromagnetic fields, the validity of the Markov approximation with respect to the propagation direction, Taylor's frozen-turbulence hypothesis, the (local) homogeneity and isotropy of turbulence, the existence of a wide inertial-convective subrange of turbulence, and the smallness of the turbulent refractive-index fluctuations compared to unity. The discovery of phenomena not addressed in Tatarskii's original theory (such as "strong-scattering" effects, inner-scale effects, the "Hill bump", refractive-index "sheets", and so-called "non-Kolmogorov" turbulence) have opened new research avenues and have stimulated an explosive growth of the literature in the field since the 1970s (e.g., Uscinski 1977; Strohbehn 1978; Ishimaru 1978; Rytov et al. 1989; Atlas 1990; Tatarskii et al. 1993; Wheelon 2001, 2003; Andrews and Phillips 2005; Sasiela 2007; Korotkova 2014; McKechnie 2016).

The performance metrics of free-space optical communication systems are functionals of the spatiotemporal statistics of optical refractive-index fluctuations (e.g., Zhu and Kahn 2002). Key statistics are the local 3D refractive-index spectrum $\Phi(\boldsymbol{\kappa})$ and its variability ("intermittency") on larger spatial and temporal scales. The classical model is the so-called "Kolmogorov spectrum" $\Phi(\kappa)=0.033C_n^2\kappa^{-11/3}$ (Tatarskii 1961, p. 48), which assumes locally homogeneous and isotropic, fully developed, stationary turbulence and ignores effects due to a finite inner scale, l_0. A more general model that takes inner-scale effects into account is $\Phi(\kappa)=0.033C_n^2\kappa^{-11/3}h(\kappa l_0)$, and various models of the "tail function" $h(\kappa l_0)$ have been suggested over the years, beginning with

Tatarskii's (1961) cut-off model and Tatarskii's (1971) Gaussian model. Muschinski (2015) evaluated Tatarskii's and more recent models and found that most of the more recent models are inconsistent with the scalar transport equation, that is, inconsistent with first-principle fluid mechanics. Muschinski and de Bruyn Kops (2015) estimated $h(\kappa l_0)$ from 3D turbulent fields generated by a 4096^3 grid-point DNS of isotropic turbulence, and they found excellent agreement with $h(\kappa l_0)$ predicted by the semi-empirical Hill (1978) model of scalar turbulence.

There is substantial uncertainty of C_n^2 as a function of height z and of the variability of $C_n^2(z)$ with time of day and year, with geographic location, and with the meteorological situation. Many researchers rely still on the outdated Hufnagel-Valley model (Andrews and Phillips 2005, p. 481), which does not account for variability with time, geographic location, and the meteorological situation.

In recent years, the number of studies on effects of "non-Kolmogorov turbulence" on free-space optical communication has rapidly increased; see, e.g., Toselli and Korotkova (2015) and references therein. For the most part, however, these models are *ad hoc*, and it is unclear to what extent they are consistent with first-principle fluid mechanics. An extreme case of non-Kolmogorov turbulence is an atmosphere populated by horizontally elongated temperature "sheets" (Dalaudier et al. 1994; Muschinski and Wode 1998). Recently, Muschinski (2016) has used geometrical optics and the Rytov approximation to theoretically investigate the scintillation index of a plane wave propagating horizontally through an atmosphere characterized by randomly undulating sheets, where the vertical fine-structure was modelled according to Phillips (1971).

2.4. Laminar-turbulent transition in hypersonic boundary layers

When the boundary layer on a hypersonic vehicle transitions from a laminar to a turbulent state, the heat transfer rate increases by a factor of between 3 and 8. This can have important implications on the design and operability of a hypersonic flight vehicle. Thus, it is critical to understand and predict how transition occurs under flight conditions in the upper atmosphere. In recent years, it has become possible to apply mechanism-based approaches to predict transition and this has greatly improved the fidelity of transition predictions relative to ad hoc correlations. However, all of the present transition prediction methods compute the amplification of particular instability modes relative to assumed background amplitudes. Marineau et al. have shown that using measurements of the free-stream disturbance levels, it is possible to greatly improve the predictions of stability theory for wind-tunnel experiments. However, this observation raises the question: what are the sources of atmospheric disturbances and how do they drive transition to turbulence at realistic flight conditions? We seek to answer this question using detailed balloon-based measurements, theory and simulations of atmospheric turbulence, and large-scale simulations of the interaction of disturbances with candidate hypersonic flow fields.

In 1990, Bushnell postulated four possible sources of disturbances in flight: atmospheric fluctuations, suspended particles, electrostatic discharges, and acoustic radiation from the flight vehicle. More recently, Pugach et al. (2016) estimated the role of atmospheric turbulence and particles on initiating transition for hypersonic flight vehicles. These studies indicate that free-stream turbulence is likely to dominate in the lower part of the hypersonic flight corridor (below about 20 km or 76 kft). Both postulate that particles may dominate at higher altitudes. However, the turbulence theory used by Pugach et al. to scale the turbulent motion to relevant length scales is out of date and is known to be erroneous. Also, the analysis relies on limited particle concentration and size distribution measurements, and the approach used for predicting how particles promote transition is approximate at best.

This MURI project will greatly improve the fidelity of the previous analyses and will quantify the role of atmospheric turbulence and particles on laminar-turbulent transition. The detailed measurements of turbulent motion as well as particle concentration and morphology in the upper atmosphere will establish a statistical basis for the dominant free stream disturbances in hypersonic flight.

3. Research Plan & Expected Results

3.1. Stratospheric Measurements

3.1.1 turbulence measurement requirements

Measurements of 2D (and preferably 3D) winds and temperatures (or densities) are needed to define both the larger-scale GW and mean environment that drives instability and turbulence events and the associated turbulence scales, characteristics, and intensities to ~120,000 ft with high spatial resolution. The need for very-small-scale sensitivity is due to the potential for very strong, local turbulence to extend to scales of ~1 mm in the stratosphere that may impact hypersonic-vehicle boundary layers. Expected peak turbulence intensities imply Kolmogorov microscales of η~1-10 mm at altitudes above ~60,000 ft. An example of a turbulence spectrum from the LITOS hot-wire wind instrument (8 kHz sampling, see **Figure 3**) from measurements at ~34,000 ft suggests an inner scale l_0=5.7η~5.7 mm and ε ~0.05 W/kg (assuming a Heisenberg model spectral fit). Much larger ε would be required to achieve similar l_0 at higher altitudes, but such conditions are expected for larger temperature variances and regions of active overturning, as seen in Figure 1. Importantly, the results in Figure 3 imply a LITOS ability to define l_0 ~1 mm or smaller for larger ε.

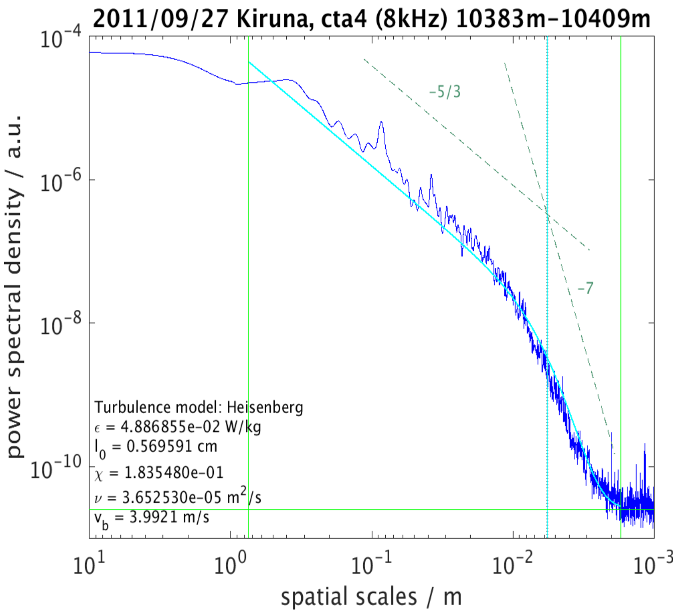


Figure 3. A LITOS turbulence spectrum obtained over an interval of 26 m at a 10.4-km altitude showing the ability to resolve spatial scales capturing an inner scale l_0 ~5.7 mm under moderate turbulence conditions.

3.1.2 low-resolution GW measurements

High-resolution data are not needed to define stratospheric GW scales and variances, as these can be determined well by standard radiosondes using 1-s sampling (e.g., see Figure 1). There are ~90 stations in the US, each launching 2 soundings daily for an average of ~7 years, hence ~500,000 soundings. We have these data, and will employ them to examine the correlations of stratospheric GW variances with GW source strengths, e.g., air flow over topography, the convective index, CAPE, or a measure of jet stream imbalance. Examples of good correlations of CAPE and lowest 1-km winds with vertical velocity variances (all normalized) for intervals of ~20 days in the stratosphere over FL and CO, respectively, are shown in **Figure 4**. These reveal that large stratospheric variances implying large GW energy fluxes are often closely related to strong tropospheric GW forcing by topography and convection.

Employing these data will remove the need to use large resources for routine soundings and to allow us to perform more high-resolution measurements to more fully explore the range of turbulence responses to the identified major GW sources at lower altitudes in various stratospheric wind and stability environments.

3.1.3 high-resolution turbulence measurements

High-resolution measurements are required to characterize stratospheric turbulence intensities, event scales, and statistics for multiple reasons, including:

1) we require guidance on the highest turbulence intensities and smallest scales expected to impact hypersonic boundary-layer flows and aero-optical propagation,
2) we must assess whether strong turbulence is highly correlated with strong GW forcing, or whether there are events for which this cannot be the explanation,
3) we require guidance on turbulence statistics and the environments in which they occur as inputs to our parallel, high-resolution modeling of GW-driven instability and turbulence events because turbulence intermittency makes it very unlikely that any one or several measurement profiles will capture the peak intensities accompanying any single event (Fritts et al. 2016c), and
4) measurement guidance for our modeling efforts is also needed to allow extrapolation of our predictions of turbulence intensities, statistics, and hypersonic-vehicle impacts to higher altitudes that are of interest to the Air Force, but cannot be measured directly.

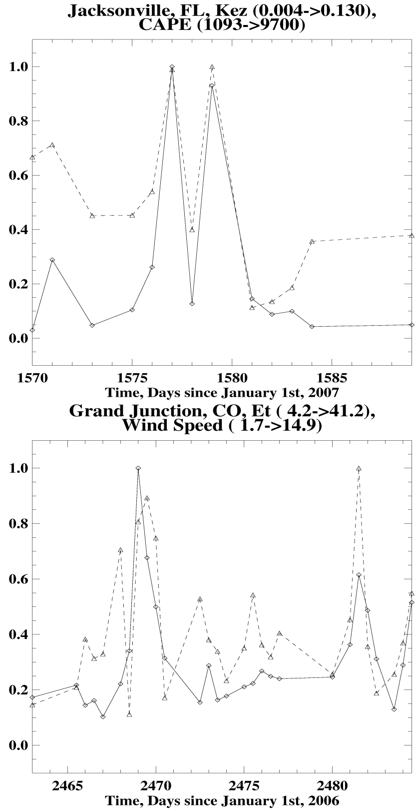


Figure 4. Correlations of GW topographic and convective source proxies and stratospheric variances over FL and CO (details in text).

Routine turbulence measurements: A small portion of our high-resolution measurements (perhaps 10 balloons each over CO and FL during Years 2-4) will be used for routine sampling in order to correlate mean turbulence statistics with measures of GW source strengths at lower altitudes and the GW variances in the stratosphere during each measurement. This will extend what can be done with the low-resolution radiosonde assessment discussed in Sec. 3.1.1 and provide additional guidance for turbulence estimates at times when GW forcing and/or stratospheric temperature and velocity variances are not large.

Intensive Observing Period (IOP) turbulence measurements: The majority of our high-resolution measurements will occur during focused IOPs when strong GW forcing (especially topographic and convective) is anticipated to yield strong GWs, instabilities, and turbulence in the middle and upper stratosphere based on available weather forecasts and current observations. These IOPs will occur at three sites: 1) in Norway together with colleagues at IAP, 2) in CO by the CU balloon/instrument teams, and 3) in FL by the ERAU balloon/instrument teams.

Initial IOPs employing multiple LITOS, and likely new high-resolution CU, instruments will be performed at the Andoya Space Center and the adjacent ALOMAR observatory (andoyaspace.no) because of the major beneficial ground-based measurement capabilities at this site – and the ~15-year collaboration at this site between IAP and MURI Co-PI Dave Fritts, who operates a U.S.-funded sodium resonance lidar at ALOMAR. The relevant instruments will include the IAP MAARSY radar that images the 3D wind field from near the surface into the lower stratosphere, the IAP Rayleigh lidar that measures winds and temperatures at altitudes of ~98,000-250,000 ft, and new versions of the LITOS and standard balloon instruments flown previously in the BEXUS balloon program. These high-resolution *in-situ* measurements will include flights of multiple successive LITOS and CU *in-situ* instruments spanning ~5-10 hr in an environment defined continuously in time and altitude by ground-based measurements. Importantly, this will enable definition of the temporal character of the GW fields contributing to local instabilities and turbulence in the stratosphere, thus providing a very comprehensive characterization of these events and their associated turbulence as guidance for our related modeling studies (see below).

More extensive IOPs beginning in Year 2 will address topographic, convective, and frontal GW forcing of turbulence events in the stratosphere over CO and FL with more advanced, high-resolution and lower-cost balloon instrumentation. Unlike in Norway, we expect these IOPs to include balloon measurements that are more distributed spatially and temporally, in order to examine the 4D variability of the stratospheric turbulence responses to specific expected turbulence sources and to quantify the evolving intermittency and statistics of strong turbulence throughout these events.

We anticipate performing ~20-40 IOPs overall, with 2-3 IOPs in Norway and ~3-6 IOPs each in CO and FL from Years 2-4 of our MURI program, each employing ~3-6 balloons, so a total of ~160 high-resolution IOP balloon launches. We expect these to quantify the range of variability of the stratospheric GW and turbulence fields, and to provide the best possible guidance for our parallel modeling efforts, the development of turbulence statistics, and their contributions to predictive capabilities based on lower atmosphere weather.

A baseline balloon flight is shown in **Figure 5**. The strategy is to make primary measurements during a slow descent to provide wake-free high-resolution turbulence data. A fast rise through class A airspace (7.5 m/s) limits downwind drift before the minimum altitude of interest is reached (20 km). The balloon is vented at that point to produce a slower ascent (5 m/s) so that (lower resolution) measurements can be obtained up to the predicted burst altitude (about 40 km). Just before that, the balloon is vented again to produce a 2 m/s descent. The measurement period ends at 20 km on the descent, where the balloon is again vented to produce a fast descent (7.5 m/s) through class A airspace to the ground. This results in a measurement time between 20 km and 40 km altitudes (including both ascent and descent) of about 4 hours. Assuming a typical 15 m/s prevailing wind, nominal downwind drift is approximately 250 km.

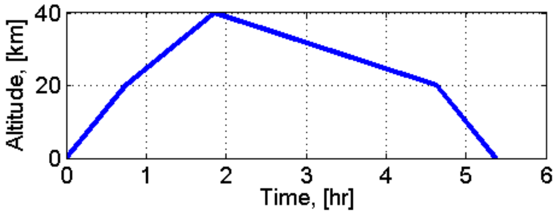


Figure 5. Baseline altitude profile for small balloons that provides wake-free turbulence measurements on a slow descent from 40 to 20 km.

All three universities (CU, ERAU, UM) have extensive experience in scientific ballooning, and altitudes of 30km (100,000 ft) are common. The target altitude of 40km is more difficult. Altitude records from the amateur radio community [arhab.org] show over 30 balloons at this scale reaching 40 km, with 60 reaching 37 km (120,000 ft). Models from the ballooning community, e.g. [highaltitudescience.com] indicate that these upper reaches are likely to be attained using relatively large balloons and relatively small payload masses. This reduces the expansion of the balloon, enabling higher altitudes before burst. We have established a baseline approach using these models to reach 40km with a 3 kg balloon and a 1 kg total payload mass, requiring approximately 7.4 m^3 of He lifting gas at launch.

3.1.4 analyses of balloon measurements of GWs and turbulence

The motion field in the stratosphere is composed of mean motions, planetary waves (**PWs**), IGWs, higher-frequency GWs that contribute large energy fluxes into the stratosphere, and the instabilities and turbulence that account for energy dissipation. Of these, mean and PW motions contribute very little to strong wind shears, hence very little to the generation of turbulence. IGWs often contribute strong shears and a tendency for slow, weaker instabilities and turbulence (e.g., Figure 2). But only higher-frequency GWs contribute the energy fluxes needed to account for strong stratospheric instability dynamics (e.g., Figure 1) and turbulence. The implications are that strong stratospheric turbulence will almost always accompany strong local GW forcing at lower altitudes. IGWs nevertheless often define the environments in which strong turbulence occurs, hence to the character, scales, and intensities of strong turbulence events. These dynamics imply two requirements for balloon analyses supporting our need to characterize, understand, and predict stratospheric turbulence:

1) ***we must differentiate between the "background GW spectrum" composed of IGWs that have propagated nearly horizontally from very distant sources and the "local GW spectrum" that is due to sources within ~100-200 km of the balloon location, and***
2) ***we must provide guidance on the multi-scale interactions involving the background IGWs and the local GWs forced at lower altitudes for our CFV and DNS modeling of the dependence of strong turbulence event character and intensities on GW forcing.***

Importantly, the existing U.S. radiosonde data set with 1-s sampling, and our planned high-resolution measurements, described in Sections 3.1.2 and 3.1.3 above will allow us to address both these needs in a comprehensive manner.

Low-resolution turbulence data from balloons: Analyses of ~500,000 standard radiosondes at ~90 U.S. stations (sampled at 1-s/~5-m resolution) will address item 1 above in a quantitative manner. Higher-frequency GWs and IGWs have very different ratios of horizontal and vertical velocities that will allow a clear distinction between these motions in individual radiosonde profiles. IGWs have periods of hours and very small *w'* because their motions are nearly horizontal. Thus, the IGW "background" field will be characterized by temperature and horizontal velocity measurements, as shown in Figure 2, as these readily reveal the IGW vertical scales, amplitudes, and shears.

Higher-frequency GWs arising from local sources (within ~100-200 km of the balloon location) will be characterized by their vertical velocities (i.e., variations in the balloon rise rates), given that these GWs dominate the energy fluxes, $<p'w'>$ (where *p'* and *w'* are the pressure and vertical velocity perturbations and <> denote a spatial average). Together, these assessments will allow a clear identification of, and distinction between, the GWs providing the major energy inputs to the stratosphere, and the IGWs imposing the environment that defines the character of the MSD driving instability ands turbulence events.

High-resolution turbulence data from balloons: Data from ~200 balloons sampling at 8-10 kHz will characterize turbulence to the inner scale or smaller to altitudes of ~115,000-125,000 ft. These simultaneous measurements of small-scale turbulence within the larger-scale GW and instability structures will enable us to relate the turbulence events, scales, and intensities to the larger-scale flows. Repeated soundings from the same sites during IOPs will provide guidance on the temporal evolution of the larger-scale GW dynamics driving the turbulence events and the turbulence responses. These analyses will allow us to identify the flow of energy from the larger GWs to the smaller turbulence scales, and provide guidance for parallel modeling studies that will further quantify these dynamics (see modeling discussion below).

3.1.5 particle measurement requirements

High-altitude particle measurements have been made with many different devices, most of which required the use of large payload balloons or high-altitude aircraft because the sensors are large and heavy (e.g., Reitmyer et al. 2014). Recently, a sensor that counts and determines the size distribution of atmospheric particles has been developed by a team of French researchers (Renard et al. 2015). We propose to use their Light Optical Aerosol Counter (**LOAC**) to characterize particles in the stratosphere. The LOAC combines laser measurements at two scattering angles to determine the particle size and morphology. A schematic of the LOAC sensor is shown in Figure 6. For balloon-based measurements, the aerosols are drawn into the optical chamber; a small pump provides this flux. Photodiodes measure the scattered light at the two measuring angles. On-board electronics process the data and provide a stream of particle size and concentration data. The entire sensor and housing has a mass of about 1 kg.

The LOAC sensor was designed to detect irregular aerosol particles like those found in ambient air. It uses a statistical approach for the size and concentration measurements, requiring careful calibration with known particle sizes and concentrations. Renard et al. (2015) provide detailed information about the instrument calibration.

The LOAC instrument has been used to make many measurements on a variety of flight platforms, including UAVs, low-altitude balloons, and long-duration stratospheric balloons. Renard et al. (2015) document these test flights and provide examples of LOAC data. For example, **Figure 6** shows particle size and concentration distributions obtained during a meteorological balloon flight in France during August 2013. At this time, there was a severe sand storm in the Sahara Desert, as can be seen from the high tropospheric concentrations. Small-scale particles are detected up to the highest altitude of the flight, with interesting high-concentration bands at several altitudes. We propose to make this type of balloon measurement to statistically characterize the stratospheric particle concentration and size distribution.

In addition to the LOAC, we propose to develop and validate much less expensive particle sensors based on commercially available dust sensors. During the summer of 2016, a four-person team of UMN undergraduates made preliminary balloon-based measurements using two types of low-cost sensors; one did not operate at low temperature, but the other provided promising data up to 75 kft (Amphenol SM-PWM-01C). We propose to continue this development and rigorously calibrate both the LOAC and the low-cost sensor. The LOAC has been extensively tested by its developers; however, we propose to verify its performance prior to use. Particles used for particle image velocimetry (PIV) seeding will provide a relevant surrogate for stratospheric particles. The low-cost sensor will also be calibrated with the same techniques.

The proposed measurements to characterize the upper atmosphere will be implemented through a series of sensor development and design steps, test flights on local weather balloons, sensor validation, and final instrument suite design, until we have developed a reliable particle measurement system; this will take approximately two years with the students doing most of the work over the summers. The proposed data collection will be conducted in two modes: during balloon ascent at approximately 5 m/s, and during balloon float mode at approximately constant altitude. Critical elements of the sensor design involve eliminating balloon wake effects and establishing an accurate three-dimensional track of the sensor suite and balloon. We propose to use the LOAC and low-cost sensor(s) in tandem to provide complementary data.

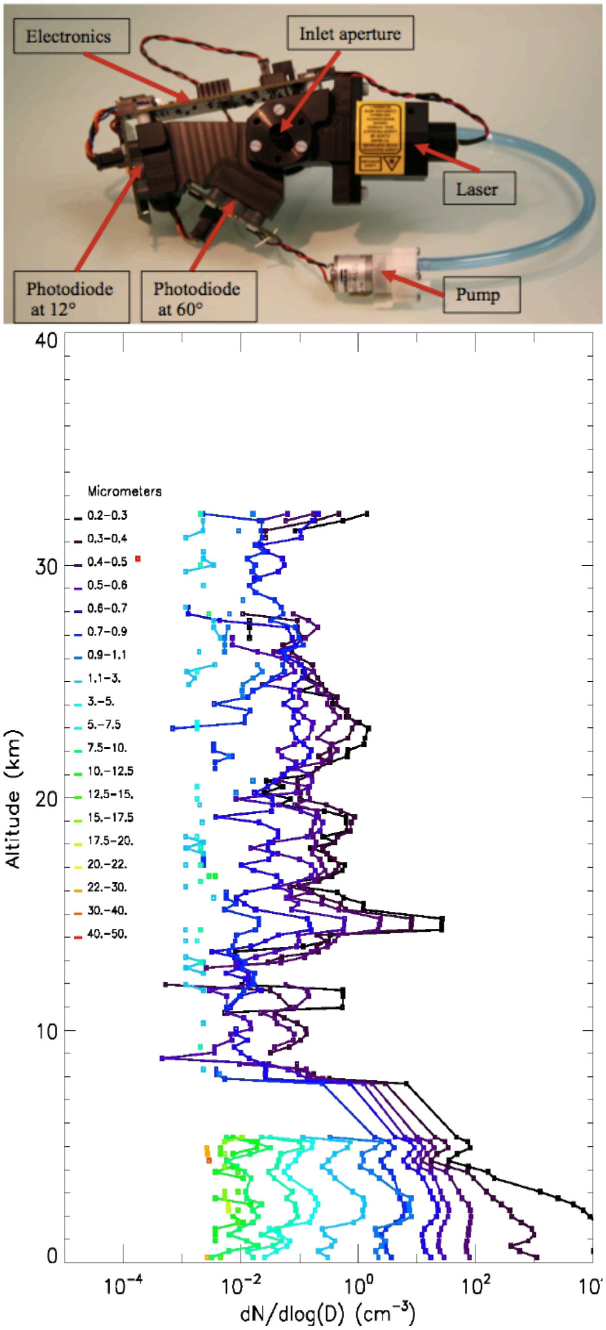


Figure 6. The MeteoModem Inc. Light Optical Aerosol Counter (LOAC) device (top) and Particle concentrations up to 32 km altitude taken by the LOAC flight of a meteorological balloon from Ile du Levant, France, on August 4, 2013 (bottom). (After Renard et al. 2015).

3.1.6. instrument and payload development for stratospheric turbulence measurements

The balloon-borne CU turbulence instrument will be an upgrade to an existing multi-wire sensor designed for measurements of turbulent velocity and temperature fluctuations onboard a small UAV (Lawrence and Balsley 2013; Fritts et al. 2016a; see **Figure 7**). This uses 5 μm diameter Pt wires with a custom electronics module for signal amplification and high-resolution A/D conversion, developed by Co-PI Lawrence. Constant-voltage excitation is used for both hotwire (velocity) and coldwire (temperature) measurements, with a bandwidth limited by the wire thermal time constant of 0.3 ms (at 15 m/s flow rate, 1.6 km altitude). Assuming continuum flow, the measurement bandwidth of this system at 2 m/s and 32 km altitude would reduce by a factor of about 24 to only 20 Hz, for a turbulence scale size resolution of 0.1 m at the nominal 2 m/s, descent rate on a balloon. The proposed upgrade to this instrument focuses on increasing bandwidth by a factor of 100 to achieve 1-mm scale size resolution, and survival in the low temperature environment at high altitudes. The standard approach of electronic feedback to maintain constant wire temperature (Fingerson and Freymuth 1996) will be used for the hotwire to increase bandwidth. The coldwire cannot use this technique directly, due to the large ambient temperature variation, but a derivative of the method will be developed using a complementary filter to enforce constant power control at low frequencies (maintaining the coldwire regime), and a constant temperature control at higher frequencies where the turbulent temperature fluctuations will be measured via the excitation variation needed to maintain constant wire temperature. Insulation and active heating will be used to maintain electronics temperatures within component limits at high altitudes. This system will be developed and tested in the first year of the project, led by Co-PI Lawrence.

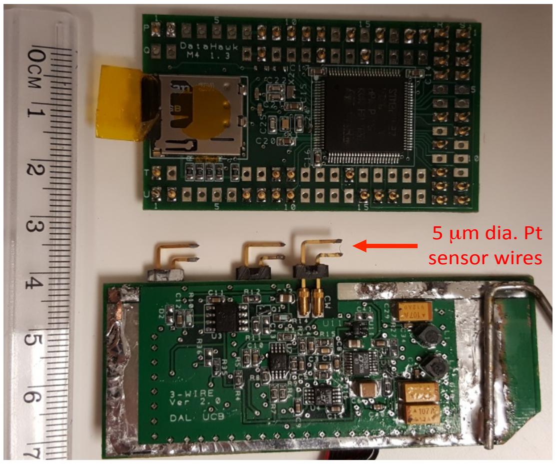


Figure 7. Existing fine-wire velocity and temperature sensor (bottom), developed at CU, will be upgraded for higher bandwidth. Shown with a custom microcontroller board (top) to be used for data handling in the balloon payload. Each weighs 10 g.

The turbulent wake of an ascending balloon will be avoided by a strategy of active venting at the top of the altitude range, as discussed earlier.. Venting will be altitude controlled by the same custom avionics system that handles the turbulence data, using a simple actuated flap valve in the balloon neck. This capability will also be developed and tested in the first year of the project. If variable balloon quality results in unpredictable burst altitude, a more conventional "rise-until-burst" strategy could be used, together with a long payload tether to reduce the wake effects of turbulence measurement during the ascent. Although we intend to fly as "exempt" free balloons under FAR Part 101, we intend to communicate with local FAA air traffic control authorities during all balloon operations.

Although a fast balloon ascent is planned, the slow descent will produce downwind drift that could be as much as 400 km from the launch site. This raises challenges in recovering the data. On-board Storage would necessitate recovery of the payload, significantly raising the cost of field campaigns (in Colorado) or making recovery prohibitive (in Florida). Real time data communication is therefore preferred. Telemetering raw data will require about 100 k bits/sec data rates to be sustained. This appears possible using commercial radios with maximum allowed power in the ISM bands (900 MHz or 2.4 GHz), together with high gain tracking antennas on the ground. To maintain line-of-sight at the low elevation angles this long slant range implies, we anticipate launching at an up-wind location and acquiring telemetry from a separate down-wind site. In Colorado, measurement of mountain wave influences on stratospheric turbulence will require launches from the Western slope, with ground station tracking and data downlink from locations on the Eastern plains. In Florida, launches will generally occur from the Gulf coast, with the tracking system located on the Atlantic coast. A secondary strategy will also be pursued, where turbulence data will be processed on-board to extract spectral parameters. This highly compressed information could then be routed through a low-data rate Iridium satellite link directly to an e-mail account, obviating ground station hardware and personnel costs. This could serve as a backup for the high-rate direct downlink initially, and may evolve into the primary data link as experience with the operations and data quality grows.

Disposable payloads will require a low-cost system, including instrument, avionics, balloon, and lifting gas. Inexpensive Latex balloons have reached altitudes of 44 km, but this requires lightweight payloads (~1 kg), a large volume (2-3 kg balloon), and an under-filled condition at launch. Total flight system cost is estimated at approximately $2000, bringing some 200 flights within scope of the measurement program. Key components in maintaining low cost are the use of commercial off-the-shelf components wherever possible, and the use of undergraduate students-in-training to perform system assemblyand payload integration, under supervision of faculty and graduate students on the project team. Co-PI Barjatya will lead the balloon telemetry and payload development efforts.

Calibration of the turbulence instrument will be challenging due to the wide range of temperatures and pressures encountered, and the high altitude transition from a continuum to a free molecular flow regime. Accordingly, we intend to outfit a small thermal vacuum chamber with an internal (recirculating) jet to provide representative temperature, pressure, and flow characteristics for instrument calibration over the expected range of conditions. Based on the 1976 Standard Atmosphere, the Knudsen number Kn for a 5-μm diameter wire at 24 km and 40 km is 0.35 (slip-flow regime) and 4.22 (transition regime), respectively. Several references (Antonia et al. 1981; LaRue et al. 1981; Comte-Bellot 1976) discuss the importance of a Knudsen-number correction to the standard continuum-based correlation equations, that accounts for the finite jump in velocity and temperature at the air-surface boundary that begins with the onset of the slip boundary condition for $Kn > 0.1$ (Collis and Williams 1959). PI Argrow will lead the instrument calibration efforts.

3.2. Atmospheric modeling

Our team is performing the highest-resolution DNS and large-eddy simulations (LES) of geophysical multi-scale GW, instability, and turbulence dynamics of relevance to this MURI. Importantly, these capabilities have a long history of applications for the DoD, specifically for the Air Force Airborne Laser (**ABL**) and HEL-JTO programs, the MDA High Altitude Airship (**HAA**) program, and the Navy Wakes program. These capabilities include two models, the CFV code developed by Tom Lund that describes GW responses to various sources, including strong multi-scale interaction dynamics extending into the MLT and the Werne/NWRA "Triple" code that has performed the majority of previous DoD applications and is best able to describe turbulence event characterization and statistics extending to very small spatial scales.

3.2.1. Compressible finite-volume code modeling of GW propagation and instabilities

Our CFV code solves the compressible Navier-Stokes equations using a numerical scheme that exactly conserves energy, apart from specified dissipation. It has recently been configured to address GW generation by convection and resolved topography and GW propagation through and interactions with variable backgrounds in large domains extending to high altitudes. A stretched mesh allows for very high spatial resolution where it is needed to assess instability dynamics at small spatial scales.

Given previous simulations of GW forcing by deep convection and topography, and their interactions with structured flows at higher altitudes, we anticipate that our CFV code will allow us to describe GW and instability responses to various meteorological forcing at lower altitudes, thus characterizing the fraction of initial GW energy able to reach the stratosphere, and the instability types and scales expected to define local turbulence characteristics. An example of the CFV code description of the encounter of convective GWs with strong wind shears at higher altitudes performed in a computational domain extending 3000x3000 km horizontally is shown in **Figure 8**. The CFV stretched grid enables description of GW instability dynamics, including resolution of the detailed initial instability dynamics at a resolution of ~100 m (and much better in applications to the stratosphere) where this is needed, and yet maintain high computational efficiency due to lower resolution elsewhere (Lund and Fritts 2016).

Our MURI research will employ the CFV code for the following efforts:

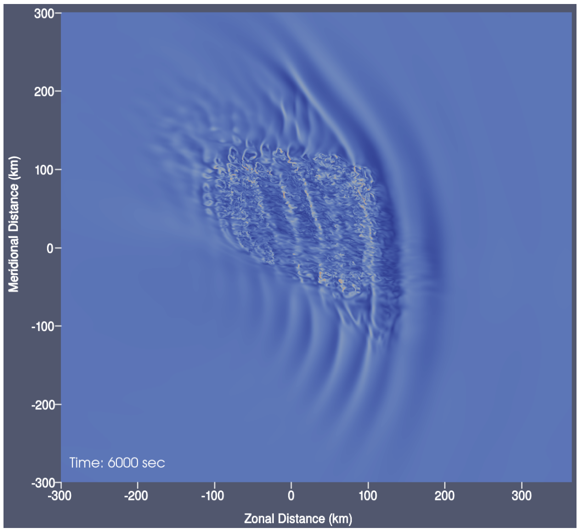


Figure 8. Vorticity magnitude in a horizontal plane showing breaking convective GWs in a strong wind shear. The ~600x600-km field shown is the central portion of a 3000x3000x200-km CFV simulation (Lund and Fritts 2016).

1) exploration of the sensitivity of GW propagation and instabilities throughout the stratosphere as functions of source type, GW amplitudes, and stratospheric IGW fields,
2) simulations of stratospheric responses for our measurement IOPs to assess the modeled energy inputs and scales that best agree with the IOP balloon measurements, and
3) definition of the environments for high-resolution Triple code MSD simulations for comparisons with measurements and as guidance for the development of turbulence statistics.

The CFV code will use NCEP/WRF and Navy COAMPS model outputs (see below) for initial conditions over CO and GOES IR indices to estimate convective GW forcing over FL. In all cases, stratospheric winds will be specified by our own balloon measurements in order to ensure optimal descriptions of the MSD arising from these flows and their influences on the instability forms and scales driving turbulence events.

3.2.2. Spectral DNS modeling of GWs, instabilities, and turbulence

The pseudo-spectral Triple code is highly efficient and can be configured to address a wide range of flows including superposed GW MSD. As noted above, it has performed very-high-resolution (and high Reynolds number) DNS of turbulence in support of multiple DoD programs. It is also the only code to date that has proven able to describe the formation of sheet-and-layer (S&L) structures and their associated turbulence events that have recently been observed at many altitudes (Fritts et al., 2016a, c).

The Triple code will be the major modeling workhorse for the following MURI applications:

1) confirmation and prediction of turbulence event types, scales, intensities, and statistics using our MURI stratospheric balloon observations and CFV GW source and propagation simulations as guidance for initial conditions,
2) comparison with, and interpretation of, our high-resolution balloon measurements to identify the major MSD contributors to stratospheric turbulence,
3) extrapolation of the MURI turbulence measurements to define the turbulence statistics, especially the widths of the turbulence intensity distributions (typically ~log-normal) and the magnitudes of the intensity extrema for each turbulence event class,
4) use of Triple code turbulence fields (guided by measurements) as inputs to hypersonic boundary-layer modeling to explore sensitivity to turbulence scales extending to ~1 mm,
5) use of Triple code turbulence fields (guided by balloon and frequency-comb laser measurements) to evaluate impacts on aero-optical propagation, including phase-screen and Fourier-optic assessments extending to ~1-mm spatial scales.

As noted above, the Triple code has recently been applied to the interpretation of instability and turbulence dynamics observed in the lower troposphere with MURI Co-PI Dale Lawrence (Fritts et al. 2016a), at ~80-90 km with colleagues at IAP (Fritts et al., 2016c), and more recently for comparisons of turbulence scales and energy dissipation rates by LITOS in the stratosphere also with our MURI colleagues at IAP. These applications have revealed that the DNS are able to describe multiple instability types that closely resemble those revealed in atmospheric observations, and turbulence energy dissipation rates that agree reasonably with observations. Equally as important, they yield ε magnitudes that agree well with observed values when scaled to the observed larger-scale dynamics. Importantly, the Triple code vertical domain dimension can vary from ~10 m to ~5-10 km, depending on the large-scale mean and GW fields.

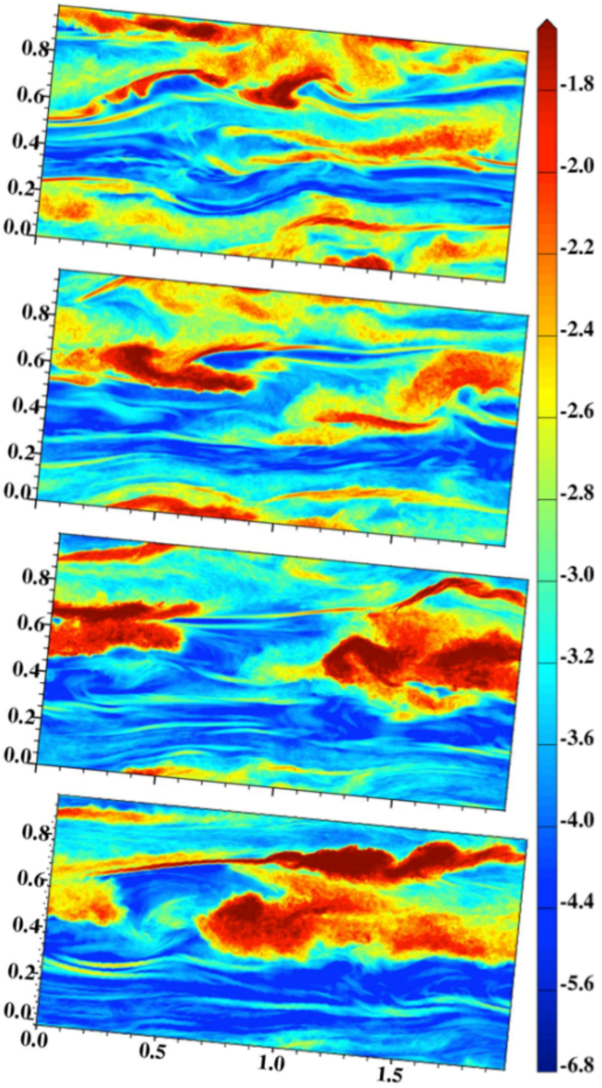


Figure 9. Vertical cross sections of non-dimensional $\log_{10}\varepsilon$ from the DNS described by Fritts et al. (2016a) at 4 times spaced by 1 buoyancy period showing GW breaking & KHI at small scales.

Given our various applications to date, we expect our spectral modeling capabilities to enable quantitative comparisons with observations of stratospheric turbulence events and the ability to develop statistics of turbulence characteristics with guidance by our MURI *in-situ* stratospheric measurements. Examples of the instability and turbulence structures arising in such an MSD DNS are shown with non-dimensional $\log_{10}\varepsilon$ at four times in **Figure 9**. These DNS exhibit both the layering of the dynamical and turbulence fields observed in LITOS high-resolution stratospheric measurements and the major instability types (e.g., GW breaking, Kelvin-Helmholtz instability, **KHI**, and intrusions) that we expect to account for the majority of turbulence events in the middle and upper stratosphere. These fields suggest very significant variability in turbulence intensities at closely-spaced locations. Examples of the probability distribution functions (**PDFs**) of non-dimensional $\log_{10}\varepsilon$ are shown at nearby horizontal layers at 10 horizontal locations in **Figure 10** near the domain center in the lower panel of Figure 9. These reveal variability in turbulence intensities exceeding 3 decades over small spatial scales. ***Importantly, the highest 1% of ε values are typically another decade larger than the mean ε, and 30-100 times larger than the median ε, in each sub-volume of an MSD DNS*** (Fritts et al., 2016c).

Together, the Triple and CFV codes will enable optimal guidance for predictions of GW instability dynamics and the resulting turbulence scales, intensities, and intermittency based on observed forcing conditions in the troposphere, our MURI measurements, and the observed (or predicted) GW environments. We expect to perform an extensive suite (many 10's) of such CFV and spectral DNS simulations, both enabling analyses of observations during specific IOPs where the initial conditions are well documented, and for cases where the sources are not specifically defined, but for which we have guidance from representative stratospheric measurements of the underlying GW field defining the local environment.

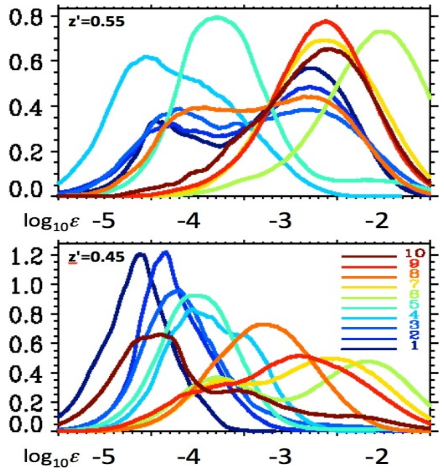


Figure 10. log$_{10}\varepsilon$ PDFs from the last panel of Figure 9 at z'=0.45 & 0.55 (see details in text).

The Triple and CFV codes will also provide 3D GW and turbulence volumes as inputs for assessments of 1) hypersonic boundary layer stability and 2) aero-optical propagation responses to realistic turbulence density perturbations at the smallest and largest scales relevant for each application. The former application will require only the spectral DNS code defining smaller-scale dynamics that span the expected inertial range of turbulence in the stratosphere at high Reynolds numbers. The latter need will be addressed by computing phase screens and supporting Fourier-optic assessments (see below) for multiple representative spectral DNS and CFV simulations over smaller and larger path lengths, respectively, depending on the scales and turbulence intensities observed in our measurements and typical path lengths for anticipated hypersonic vehicle applications.

3.2.3. WRF and Navy COAMPS models

The Weather Research and Forecasting (**WRF**) model will also be used to specify initial conditions for the CFV code for all IOPs performed over CO. This model is run continuously using NCEP initialization in support of various CO modeling interests by Dr. John Snook of Colorado Mountain College (**CMC**). This model has performed extremely well in anticipating GWs arising from various sources during the 2014 DEEPWAVE airborne measurement program over New Zealand, especially in applications to MW breaking at various altitudes in the stratosphere, depending on forcing and propagation conditions.

The Coupled Ocean/Atmosphere Mesoscale Prediction System (**COAMPS**) is the Navy operational mesoscale model. If Navy resources allow, we intend to collaborate with Dr. Jim Doyle (Naval Research Lab, Monterey) in using COAMPS to specify initial conditions for our CFV code for IOPs that may be of specific interest to NRL at no cost to the Air Force. Dr. Doyle will seek to secure funding for these efforts, given significant Navy interests in improving and evaluating COAMPS capabilities extending into the stratosphere and above.

3.3. Aerothermodynamics modeling

3.3.1. Simulations of particle / hypersonic boundary layer interactions

The interaction of atmospheric particles with a hypersonic boundary layer will be studied with a combination of advanced simulation codes and stability theory. This problem is complicated by the fact that the typical mean free path in the hypersonic shock layer is typically of the same order of magnitude as the expected particle sizes. This is illustrated in **Figure 11**; this plots the estimated mean free path in the stagnation region as a function of flight Mach number and altitude. The mean free path will vary considerably throughout the flow, depending on the local density and temperature. Clearly, non-continuum or rarefied flow effects will be present and must be included in the analysis. Therefore, we propose to use a hybrid Direct Simulation Monte Carlo (**DSMC**) / CFD approach that is under development at UMN. The method uses the DSMC method in regions of rarefied flow effects, and CFD where the continuum approximation is valid. This will provide an accurate representation of how atmospheric particles interact with and disturb a hypersonic boundary layer.

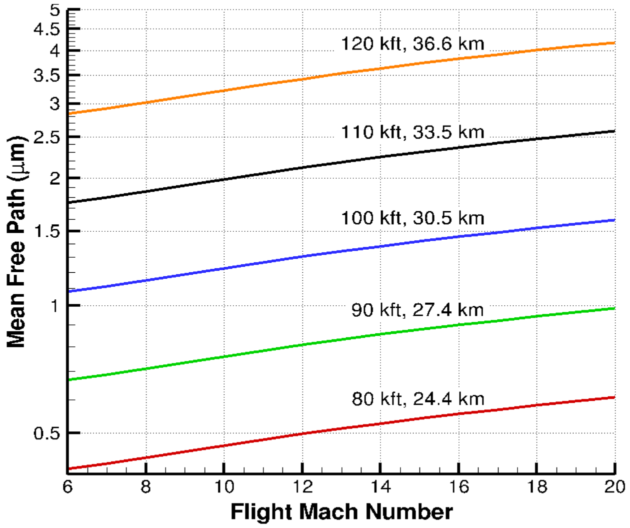


Figure 11. Approximate mean free path in the stagnation region of a hypersonic vehicle as a function of Mach number and altitude.

The simulations will be used to characterize the boundary layer disturbance as a function of the particle size and interaction location, flight conditions, and vehicle scale. These impulses will be used as input to DNS and stability theory to study the boundary layer receptivity. The ultimate goal is to determine whether a particle of a given size can cause a hypersonic boundary layer to transition to turbulence.

Presumably, a single particle will have a transient effect on the boundary layer; when it leaves the critical region of the shock layer, the boundary layer is expected to relaminarize. Thus, there is expected to be a critical number density of particles that results in persistent transitional flow – this level will be determined by DNS. Particle / boundary layer simulations will be performed and the time history of the transition event will be related to the particle transit time.

3.3.2. Simulations of free-stream turbulence interacting with a hypersonic boundary layer

A second key component of the research is to study how the free-stream turbulent motion is processed by the shock wave, and then interacts with the boundary layer and potentially causes transition. We propose to use the turbulence fields generated by the atmospheric turbulence modeling group as an inflow boundary condition for the DNS of a hypersonic vehicle. We propose to use the HIFiRE-1 blunt-cone and the HIFiRE-5 2:1 elliptical cone configurations as open-literature candidate vehicles for this study. The higher-speed Re-Entry F experiment may also have relevance for this study.Most hypersonic boundary layers are primarily susceptible to acoustic disturbances that are trapped in the subsonic part of the boundary layer (the Mack second-mode instability). Certain frequencies absorb energy from the mean flow and are preferentially amplified.

We have shown that with sixth-order accurate, low-dissipation numerical methods it is possible to accurately predict how acoustic waves interact with the stagnation region flow around pitot pressure probes (Chaudhry and Candler 2016). These direct numerical simulations show that there is a resonance phenomenon at certain frequencies due to the constructive interference between reflected and transmitted acoustic waves. These frequencies are significantly amplified by this interaction, while others are damped. Initial comparisons with experimental data qualitatively confirm these results.

We propose to use this capability to simulate the interaction of relevant scales of turbulent motion with the hypersonic flow field; in particular, we will determine how the stagnation region amplifies or damps these modes. Ultimately, we need to characterize how the turbulence is processed and what perturbations it provides to the boundary layer. These perturbations will be used as input to stability theory DNS to quantify the receptivity of the boundary layer to atmospheric turbulence. Ultimately, this study will connect the atmospheric state to the background noise level to provide an amplitude-based instability growth and transition approach for hypersonic flight systems (similar to the approach developed by Marineau et al. for hypersonic ground test facilities).

3.4. Aero-optical propagation

The main goal of the MURI aero-optical propagation research is to test and improve statistical models of optical turbulence (i.e., of the spatiotemporal statistics of small-scale temperature fluctuations) through theoretical analysis, computer simulations, and observations.

3.4.1. Computer simulations: combining DNS with split-step Fourier optics

Simulating long-range optical propagation through the stably stratified atmosphere is a major challenge because there is a wide range of length scales (about five orders of magnitude, from 1 mm to 100 km) that must be accounted for. We will use DNS-generated temperature fields in 3D wave-number space to calculate 2D phase screens. These phase screens are the result of the multi-scale, turbulent stirring of temperature fluctuations by turbulent velocity fluctuations and are expected to be more realistic than phase screens generated by filtering 2D fields of Gaussian-distributed white noise with a model spectrum (Gbur 2014). The DNS-generated phase screens will be used in a split-step Fourier optics algorithm to solve the Helmholtz equation for a set of canonical optical waves (e.g., plane waves, spherical waves, Gaussian beam waves). Because DNS can only address real stratospheric Reynolds numbers (*Re*) in very small volumes, they can either describe the GWs, instabilities, and turbulence to scales ~2 decades above the Kolmogorov length *h*, or they can include scales to ~*h*, but ignore the GWs providing the energy sources of turbulence. Both will be employed for the Fourier optics simulations. Where we wish to resolve scales to ~*h*, however, separate DNS of the larger-scale dynamics can be added to include GW and instability scales extending to several tens of kilometers. For efficiency, these studies will be performed as DNS post-processing on the DoD supercomputers.

3.4.2. Analysis of in situ measurements of optical turbulence in the stratosphere

We will use Co-PI Lawrence's in situ measurements of turbulent temperature and velocity fluctuations in the stratosphere to test and improve models of optical turbulence and of non-turbulent sheets. In particular, these measurements provide insight into the larger-scale variability (intermittency) of the statistics of small-scale turbulence and sheets.

3.4.3 Optical field observations with near-ground propagation paths

It is beyond the scope of this MURI to perform optical propagation experiments in the stratosphere. Rather, the team proposes to leverage newly built, state-of-the-art ground-based instrumentation based on Nobel prize winning frequency comb laser technology for low-cost assessments of the hypotheses and assumptions associated with the theoretical high altitude aero-optical propagation studies and stratospheric phase screen computations.

A frequency comb is a mode-locked laser that is carefully controlled such that the pulse timing, and carrier frequency and phase is nearly constant over long periods of time. Two frequency combs can be phase-locked to one another to create a system that is capable of very precise differential phase measurements. Here, we plan to directly measure optical phase variations on time scales from milliseconds to tens of minutes (correspond to turbulence length scales from millimeters to kilometers) using a first-of-a-kind mobile dual frequency comb spectrometer.

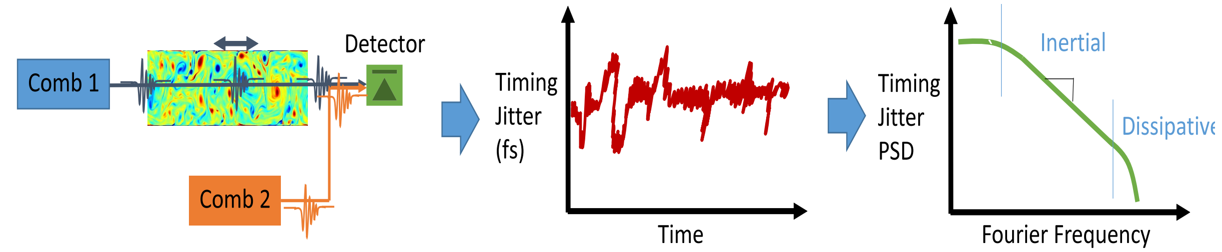


Figure 12. Turbulence measurements based on frequency comb laser optical sampling of turbulence-induced pulse jitter.

The atmospheric phase variation can be measured two ways with the frequency comb setup – either by measuring the carrier phase variation or by measuring the timing jitter of the incoming pulses (Giorgetta, Rieker et al. 2015). The carrier phase variation measurement is similar to continuous-wave laser interferometry, and is subject to ambiguity (2p phase slips), particularly if the laser signal is momentarily lost (which is likely under conditions of strong turbulence). The timing jitter method instead takes advantage of the extremely precise pulse timing of the two combs. The concept is illustrated in **Figure 12**. The turbulence-induced phase variations along the path are also manifest as small variations in the time-of-flight of the laser pulses. The incoming pulses from the turbulent path are optically sampled through interference with the second frequency comb, enabling pulse jitter measurements down to femtosecond levels (Sinclair et al, 2014). The stability of the frequency comb pulse rates, particularly when referenced to a stable oscillator, mean that phase measurements can continue despite prolonged dropouts of the laser light across the turbulent path.

Figure 13. Mobile laboratory for the proposed low-cost aero-optic propagation and phase screen assessments.

The mobile frequency comb spectrometer is contained in the mobile laboratory shown in **Figure 13**. The frequency comb light can be transmitted up to 2 km using a telescope mounted on a motorized gimbal atop the laboratory (inset). The mobile laboratory is located at Table Mountain test site, 8 miles north of Boulder, CO, surrounded by several square miles of flat terrain. The frequency comb spectrometer will be complemented by Co-PI Muschinski's optical turbulence measurements by means of ultrasound anemometer-thermometers and digital cameras attached to 14-inch telescopes (Cheon et al. 2007; Tichkule and Muschinski 2012).

4. Expected Impacts on USAF Capabilities

Our proposed research will resolve significant operational issues concerning hypersonic vehicle aerothermodynamics, boundary layer stability, and aero-optical propagation. Turbulence measurements and modeling will quantify its spatiotemporal statistics and the dependence of stratospheric turbulence on underlying meteorology to a degree not possible before. Measurements will also characterize particle concentrations in the middle and upper stratosphere. Applications of these results for hypersonic boundary layer modeling, aero-optical propagation assessments, and linkages from meteorology to stratospheric turbulence statistics will yield the following expected outcomes addressing US Air Force capabilities:

1. Quantify the roles of atmospheric turbulence and particle concentrations on laminar-turbulent transition for hypersonic flight conditions.
2. Rigorously connect the atmospheric turbulence state to the disturbance forcing amplitude of relevant boundary layer instability mechanisms.
3. Understand how atmospheric particles interact with a hypersonic flow field and promote instability growth and transition to turbulence.
4. Quantify the impacts of stratospheric turbulence spatiotemporal statistics and larger-scale coherent refractive index fluctuations on long-distance aero-optical propagation.
5. Provide a "strawman" stratospheric turbulence forecasting scheme accounting for variable environments and energy inputs from meteorology at lower altitudes.

5. Research Training Plan

STRATO-HY provides a unique opportunity for collaboration in multidisciplinary education and research. In addition to high-quality graduate research programs, each university is a member of one of the 52 consortia supported in all 50 states through the NASA National Space Grant College and Fellowship Program, also known as the Space Grant Program (**SGP**). High-altitude ballooning has long been used as an SGP activity to engage undergraduate students in lessons related to the development and deployment of "sub-orbital" payloads. Our proposed Stratospheric Turbulence Experiment and Analysis Program (**STEAP**, see **Figure 14**) will enlist the SGP at each university to support instrument development and assembly, and experimental-balloon campaigns during each IOP. CU will educate and train 4 PhD-candidate research assistants (**RAs**), two in in-situ turbulence measurements, and one each in aero-optics and modeling of turbulence sources and dynamics. The CU Integrated Remote & In Situ Sensing Program (**IRISS**) will support 3 undergraduate research apprentices at no cost to the MURI, to assist in assembling stratospheric measurement payloads and to support IOP deployments. UM will educate and train 2 PhD candidate RAs in the area of hypersonic aerothermodynamics, with 3 undergraduates supporting the assembly and deployment of UM high-altitude balloon payloads. ERAU will educate and train 2 PhD-candidate RAs in GW and turbulence modeling, 2 MS RAs, and multiple undergraduates participating in the various IOPs.

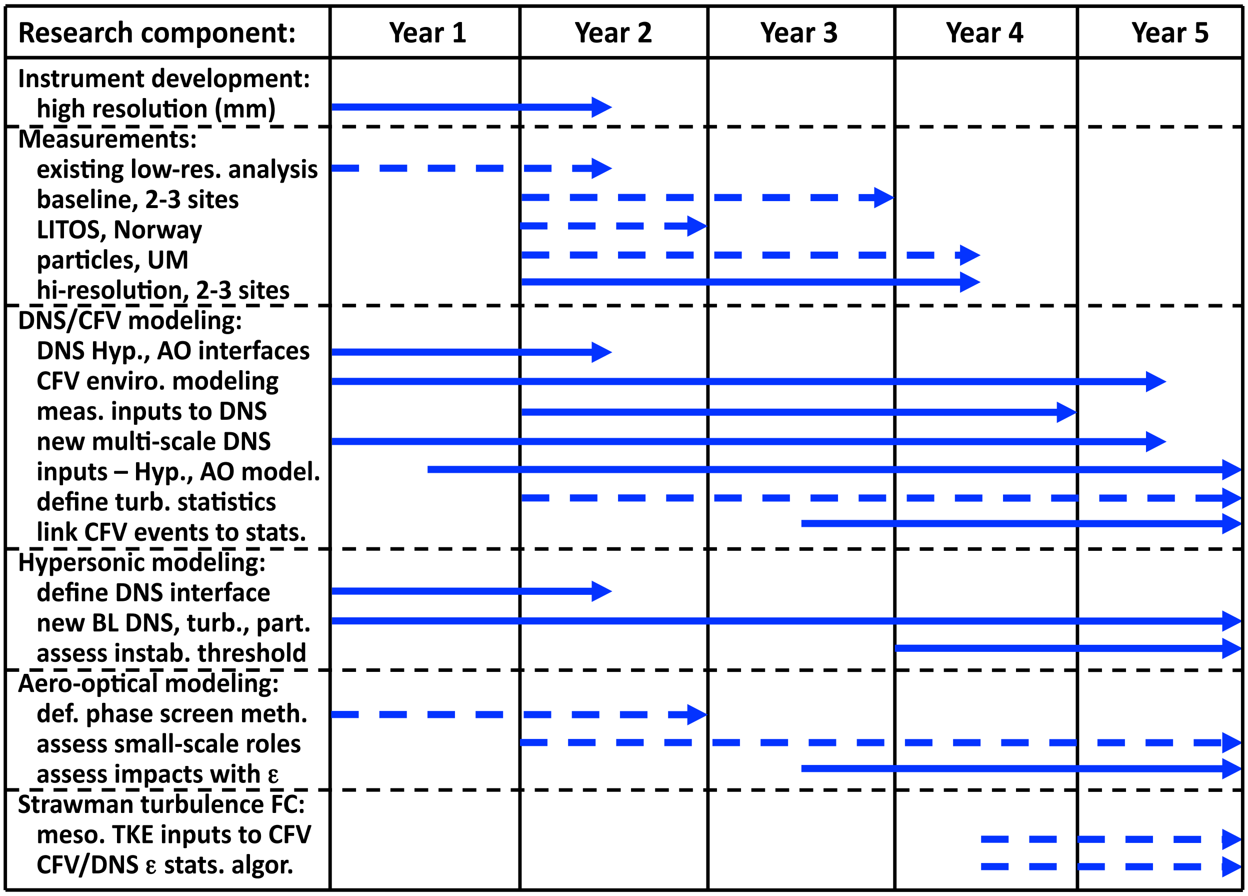
Figure 14. Colorado SGP undergraduates conducting a high-altitude balloon launch in northeast Colorado, Aug. 2016.

6. Project Schedule, Milestones, and Deliverables

6.1. Project tasks and schedule

Table 2 lists our project tasks and expected timelines. Solid arrow indicate more extensive efforts; dashed arrows indicate less extensive efforts (and costs).

Table 2. MURI Tasks and Schedule.



6.2. Milestones and target dates (chronological completion dates)

1. Complete high-resolution instrument development	Dec. 2018
2. Complete low-resolution balloon analysis	Dec. 2018
3. Complete interfaces of DNS turbulence simulations for hypersonic and aero-optical applications	Dec. 2018
4. Complete initial high-resolution LITOS measurements	June 2019
5. Complete phase screen methodologies for DNS	June 2019
6. Complete baseline measurements defining background variability	June 2020
7. Complete particle measurements	Dec. 2020
8. Complete high-resolution IOP measurements	Dec. 2020
9. Complete measurement inputs to DNS modeling	June 2021
10. Complete CFV environ. modeling describing GW sources/coupling	Dec. 2021
11. Complete multi-scale DNS supporting turbulence statistics determinations	Dec. 2021
12. Complete DNS and CFV inputs to hypersonics and aero-optical modeling	June 2022
13. Complete definition of turbulence statistics, linkages to CFV events	June 2022
14. Complete hypersonics boundary layer modeling	June 2022
15. Complete assessment of hypersonics instability threshold	June 2022
16. Complete assessment of roles of small turbulence scales for aero-optics	June 2022
17. Complete assessment of variable aero-optics influences with variable ε	June 2022
18. Complete mesoscale (GW) total kinetic energy inputs to CFV component	June 2022
19. Complete CFV and DNS descriptions of ε statistics algorithms	June 2022

6.3. Deliverables and dissemination of results

We will use traditional means of disseminating research results through conference presentations and journal publications. The annual AIAA SciTech conference and the various annual American Geophysical Union and American Meteorological Society conferences are all venues for regular and special and/or invited papers and sessions. The MURI project will also be featured through a website managed by the CU IRISS program. Undergraduate students supporting the experimental high-altitude balloon campaigns at each of our universities will be encouraged to share their experiences through a blog maintained on the MURI website.

A specific deliverable will be a "strawman" global stratospheric turbulence forecasting framework employing the methodologies and understanding of the stratospheric turbulence sources and statistics developed under this research.

7. Management Approach

Qualifications of the Principal Investigator: Professor Brian Argrow (University of Colorado/Dept. Aerospace Engineering Sciences) will serve as PI, responsible for overall project coordination and point-of-contact with the Research Topic Chief. PI Argrow possesses extensive experience as a researcher, educator, and manager. As a *researcher*, he has published over 100 papers on high-speed aerodynamics, dense and rarefied gasdynamics, transition-regime entry flows, and in-situ atmospheric sensing with unmanned aircraft. He is an AIAA Fellow and he received the USAF Distinguished Citizen Award for service on the USAF Scientific Advisory Board. He currently serves on the Aeronautics and Space Engineering Board of the National Academies of Science, Engineering, and Medicine. His faculty appointment requires research, teaching and service commitments. His current awards include 4-mo CY effort with 1.5-mo CY effort in pending awards. As a *manager*, he is founding and current Director of the CU Grand Challenges Integrated Remote & In Situ Sensing Program (IRISS), and the founding Director (emeritus) of the Research and Engineering Center for Unmanned Vehicles (RECUV). As an *educator* he is former Associate Dean for Education (2007-2012), and his numerous education/teaching awards include the W.M. Keck Foundation Excellence in Engineering Education Award. **IRISS Administrative Manager Laura Clayton** will coordinate communication with the Co-PIs and their research groups to manage subaward commitments, schedule meetings, assist with travel, and ensure that reports are properly prepared and submitted. Ms. Clayton's experience includes extensive grants management services as the Research & Communications Officer for the Columbia University Medical Center (CUMC) Herbert Irving Comprehensive Cancer Center, and Project Officer for the CUMC Sponsored Projects Administration.

MURI Steering Committee: The MURI Steering Committee (SC), shown in **Table 3** consists of the PI (Chair) and the five Co-PIs, with names designated in bold font, leading the major research thrusts sub-topics.

Table 3. Steering Committee.

Steering Committee: Chair B. Argrow				
GW / turbulence modeling/simulation & project coord.	Hypersonics modeling & simulation	In-situ turbulence & particulate measurements	Aero-optical analysis	Balloon payloads & telemetry
D. Fritts	**G. Candler**	**D. Lawrence**	**A. Muschinski**	**A. Barjatya**

Co-PIs will coordinate activities in the designated research thrusts and each is responsible for communicating engineering and scientific progress to the MURI team. Each Co-PI is an established leader for the research-thrust topic, and in most instances has already established collaborations with other team members.

Dave Fritts will serve as Project Coordinator and GW/turbulence Modeling Lead responsible for measurement guidance, inputs to hypersonics & aero-optical modeling, "strawman" turbulence forecast scheme design. Fritts has led turbulence modeling efforts for the USAF Airborne Laser, Navy Wakes, and MDA High-Altitude Airship programs. Co-PI Fritts has initiated and led multiple international ground-based and airborne research programs addressing GW and turbulence dynamics (see CV). He has written several major review papers, and his "h" and "i10" citation indices are 61 and 212. He supports PhD students, but has no teaching salary, and is appointed as an ERAU faculty researcher; he currently has 8.2-mo CY effort in current research awards and 5.7-mo CY in pending awards.

Graham Candler will serve as Hypersonics Lead, responsible for hypersonics modeling of vehicle boundary layer stability. Co-PI Candler is a world leader in the aerothermodynamics of high-speed and hypersonic flows. He led the development of the US3D CFD code for hypersonic flow simulations and the STABL suite of codes for hypersonic boundary layer stability analysis. His faculty appointment requires research, teaching and service commitments; current research includes 3.5-month CY effort and 2.75-month CY effort in pending proposals.

Dale Lawrence will serve as Instrument Lead, responsible for instrument/payload development, integration, and analysis. Co-PI Lawrence collected the first high-fidelity turbulence measurements in the atmospheric boundary layer from a small unmanned aircraft system with hot- and cold-wire sensors built in-house. His faculty appointment requires research, teaching and service commitments; current research includes 2.5-month CY effort and 3.75-month CY effort in pending awards.

Andreas Muschinski will serve as Aero-Optics Lead, responsible for theoretical, computational, and observational aspects of aero-optical propagation. Co-PI Muschinski is a widely published international expert on the theoretical and applied aspects of atmospheric turbulence and electromagnetic wave propagation through the turbulent atmosphere. He will be appointed as a CU faculty researcher; he currently has 3.87 mo CY in current research awards and 8.77 mo CY in pending awards.

Aroh Barjatya will serve as Balloon Technology Lead, responsible for balloon-payload integration and telemetry. Co-PI Barajatya has led the instrument development on multiple NASA sounding rockets and CubeSats. His faculty appointment requires research, teaching and service commitments. He currently serves as the program coordinator for Engineering Physics program and his current research includes 1-month CY effort and 6-month CY effort in pending awards.

The SC chair will schedule **bi-monthly Technical Exchange Meetings (TEMs)** in year-1, transitioning to quarterly TEMs in year-2 and out-years as the research programs are established with clear paths to achieve project objectives. The TEMs will facilitate research coordination, presentation and publication preparation, and timely report submissions.

Institutional Subawards: CU will lead the proposed effort with partners from Embry-Riddle Aeronautical University (ERAU) and the University of Minnesota (UM). PI Argrow will lead overall subaward coordination. Co-PIs Lawrence and Muschinski will guide and oversee and coordinate the research in the respective research thrust areas that they are designated to lead.

MURI research efforts at ERAU will be guided by ERAU PI and Project Coordinator Dave Fritts. Co-PI Fritts will guide and oversee the ERAU modeling involving the following:

1) CFV code simulations addressing the transport of energy into the stratosphere by GWs arising from various sources in multiple representative meteorological environments,
2) spectral DNS of turbulence events for extrapolation of turbulence measurements to event-based statistics, and as inputs to hypersonic boundary layer and aero-optical modeling, &
3) development of a "strawman" turbulence forecasting scheme employing these results.

ERAU Co-PI, Aroh Barjatya, will guide the ERAU payload development in coordination with Dale Lawrence at CU, and will oversee measurement testing and IOP measurements in Florida.

MURI research efforts at UM will be guided by UM PI Graham Candler. Co-PI Candler will guide and oversee the UM in-situ measurements campaigns and hypersonic-vehicle simulations

Facilities: ***CU facilities*** include laboratories for custom miniature electronics design/fabrication, and for micron-scale turbulence sensor element fabrication (800-ft^2). An analog and digital electronics test laboratory (600-ft^2) and a full-scale machine shop (1600-ft^2) are also available to support the proposed instrument developments. Instrument calibration will be carried out in a local NCAR environmental chamber, upgraded to include an interior recirculating jet. Balloon payload assembly is supported by the 1600-ft^2 Space Grant Laboratory, that has launched some 400 scientific high-altitude balloons since 1989. The 1500-ft^2 Systems Integration Laboratory will also be used to support the assembly of the large number of balloon payloads planned for this project. For balloon launches and telemetry, a 15-passenger van and a 5-passenger SUV are available, each customized with distributed internal power and equipped for VHF communications, to support mobile and nomadic deployments. Three additional vehicles have been purchased by IRISS and will be in service by the MURI start date.

ERAU Facilities include 1400-ft^2 Space and Atmospheric Instrumentation Laboratory (sail.erau.edu), which is split in three parts. One part has mechanical hardware building capability with metal lathe, drill press, hardtop benches for assembly, a spin table, etc. The second part has an ESD safe zone with two electronics workbenches for doing surface mount assembly and testing. The third and final past has five desks and workstations for students, as well as a conference table setup with a projector and camera for internet based conferences. The lab has access to the multitude of University owned vans that can be used for field launches. The ERAU modelling effort will be conducted in Experimental and Computational Laboratory for Atmospheric and Ionospheric Research (400-ft^2) and the Space Physics Research Laboratory (800-ft^2). Resources include iMac workstations and eight server-class Intel Xeon systems with 160 total Xeon E5 cores and 480 total Xeon Phi MIC cores, rack-mounted, with UPS backup power, >50TB RAID storage, 768GB RAM, Infiniband networking, and access to Intel Fortran and MATLAB for computation and data analysis.

UM Facilities include a 6720-core AMD Bulldozer cluster and a 1960-core Magny-Cours cluster within the Aerospace Engineering and Mechanics Department. We will also apply for time at the University of Minnesota Supercomputing Institute, which typically allocates several million node hours for use by the Candler research group. In addition, workstations and large-scale disk arrays will be made available for use on this project.

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University of Colorado
Boulder

Terri Fiez, Vice Chancellor for Research & Innovation Terri.Fiez@colorado.edu
Research & Innovation Office
330 Regent Administrative Center, 99 UCB t 303 492-2890
Boulder, CO 80309-0099 f 303 492-5777

November 11, 2016

Brian M. Argrow
Professor, Dept. Aerospace Engineering Sciences
Director, CU Grand Challenges Integrated Remote & In Situ Sensing Program (IRISS)
University of Colorado Boulder
Boulder, CO 80309

Re: IRISS support for the AFOSR MURI: Stratospheric Turbulence/Particle Measurements and Models for Air Force Hypersonics.

Dear Brian:

I enthusiastically support your leadership as the PI of the AFOSR MURI: *Stratospheric Turbulence/Particle Measurements and Models for Air Force Hypersonics*. I also support your pledge, as IRISS Director, to provide opportunities for 3-4 IRISS undergraduate research assistants to assist in the preparation of balloon payloads and deployment over the course of the project, and to provide logistical support with the purchase of mesoscale weather forecasting services from John Snook, LLC in years 1-3 of the project.

The vision of the CU Grand Challenges IRISS initiative is to employ aerospace mobility to bridge the sensing column between the ground and space, and to provide unique education and research experiences for our students. This vision is being realized with IRISS support of the *in-situ* stratospheric sensing proposed by your multi-university MURI team.

Sincerely,

Terri Fiez

Terri Fiez
Vice Chancellor for Research and Innovation
Research & Innovation Office
University of Colorado Boulder

LEIBNIZ-INSTITUT FÜR ATMOSPHÄRENPHYSIK
AN DER UNIVERSITÄT ROSTOCK
KÜHLUNGSBORN

Prof. Dr. F.-J. Lübken

IAP

– Inst. für Atmosphärenphysik, Schloss-Str. 6, 18225 Kühlungsborn –

Schloss-Str. 6
D-18225 Ostseebad
Kühlungsborn, Germany
Telefon: +49(38293) 68 - 100
Telefax: +49(38293) 68 - 50
E-mail : luebken@iap-kborn.de

Dr. Dave Fritts
Adjoint Professor
Embry-Riddle Aeronautical University

U. S. A.

July 28, 2016

Dear Dave,

I am writing to express our enthusiasm for collaborating with you and your MURI team in performing new balloon flights to explore the variability of stratospheric turbulence, if you receive Air Force MURI funding for such studies. As you know well, we at IAP are actively pursuing similar studies, including improvements in the LITOS measurement capabilities and our current calibration of LITOS measurements using your numerical simulations of turbulence fields.

Our initial LITOS flights on the BEXUS balloons revealed very significant variability in stratospheric turbulence, and we intend to expand these measurements in the future. Your suggestions of turbulence climatologies and focused multi-balloon studies for strong meteorological forcing conditions fit well with our own interests. We also have a desire to reach the highest possible altitudes, and your suggested long-duration balloon applications are also of interest.

I wish you good luck with your MURI proposal efforts, and will be eager to collaborate in these studies if your team receives funding.

Sincerely,

Franz-Josef

Curriculum Vitae

Brian M. Argrow

(a) Professional Preparation

University of Oklahoma	Norman, OK	Aerospace Engineering	BS	1983
University of Oklahoma	Norman, OK	Mechanical Engineering	MS	1986
University of Oklahoma	Norman, OK	Aerospace Engineering	PhD	1989

(b) Appointments

2015 – pres	***Founding Director***, *Integrated Remote & In Situ Sensing Initiative (IRISS), at CU Boulder*. With the Earth Lab Initiative IRISS will implement the CU Boulder Grand Challenge "Our Space. Our Future."
2004 – 2012	***Founding Director,*** *Research and Engineering Center for Unmanned Vehicles, at CU Boulder* A university/government/industry partnership dedicated to the development and application of unmanned vehicle systems.
2007 – 2012	***Associate Dean for Education,*** *College of Engineering and Applied Science, at CU Boulder*, Provided vision and leadership for advancing the College at the forefront of engineering education, including curriculum modernization, student programs, enhanced-learning initiatives, and program assessment.
2006 – 2012	***Alfred and Betty Look Professor of Engineering***, *U. of Colorado Boulder*
2006 – pres	***Professor***, *Aerospace Engineering Sciences, U. of Colorado Boulder*
2001 – 2004	***Associate Chair***, *Aerospace Engineering Sciences, U. of Colorado Boulder* Led re-design of the AES senior projects courses, the final major revision for the AES Curriculum 2000. Created the annual AES Curriculum and Teaching Workshop.
1999 – 2006	***Associate Professor,*** *Aerospace Engineering Sciences, U. of Colorado Boulder* Named a 2000 President's Teaching Scholar, with lifetime guild appointment.
1992 – 1999	***Assistant Professor,*** *Aerospace Engineering Sciences, U. of Colorado Boulder* Co-led AES Curriculum 2000 development and implementation; introduced the Proactive Teaching and Learning model adopted for classroom teaching.
Sum 1992	***AFOSR Summer Faculty Researcher,*** *Wright Lab, Wright-Patterson AFB, OH*
1989 – 1992	***Assistant Professor,*** *Aerospace and Mechanical Engineering, U. of Oklahoma*
1986 – 1989	***Instructor,*** *Aerospace & Mechanical Engineering, U. of Oklahoma*
1983 – 1986	***NSF Graduate Fellow,*** *Aerospace Engineering Program, Aerospace and Mechanical Engineering Department, U. of Oklahoma*
1983 – 1984	***GEM Graduate Fellow,*** *Aerospace Engineering Program, Aerospace and Mechanical Engineering Department, U. of Oklahoma*

(c) Publications

Recent and relevant to project

1. Elston, J., Argrow, B., Stachura, M., Weibel, D., Lawrence, D., and Pope, D., "Overview of Small Fixed-Wing Unmanned Aircraft for Meteorological Sampling, *Journal of Oceanic and Atmospheric Technology*, Vol. 32, 1, pp. 97-115, doi: 10.1175/JTECH-D-13-00236.1 (2015).
2. Roadman, J., Elston, J., Argrow, B., and Frew, E., "Mission Performance of the Tempest Unmanned Aircraft System in Supercell Storms," *Journal of Aircraft*, Vol. 49, No. 6, pp. 1821-1830 (2012)
3. Houston, A.L., Argrow, B., Elston, J., Lahowetz, J., Frew, E.W., and Kennedy, P. C., "The Collaborative Colorado–Nebraska Unmanned Aircraft System Experiment," *Bulletin of the American Meteorological Society*, Vol. 93, No. 1, pp. 39-54 (2012).
4. Elston, J., Argrow, B., Frew, E., Houston, A., and Straka, J., "Evaluation of Unmanned Aircraft Systems for Severe Storm Sampling using Hardware-in-the-Loop Simulations," *Journal of Aerospace Computing, Information, and Communication*, Vol. 8, No. 9, pp. 269-294 (2011).

5. Elston, J., Roadman, J., Stachura, M., Argrow, B., Houston, A., and Frew, E., “The Tempest Unmanned Aircraft System for In Situ Observations of Tornadic Supercells: Design and VORTEX2 Flight Results,” *Journal of Field Robotics,* Vol. 28, No. 4, pp. 461-483 (2011).

<u>Selected other recent publications</u>

1. Frew, E.W., Argrow, B., Houston, A., and Weiss, C., “Toward an Autonomous Airborne Scientist for Studying Severe Local Storms,” AIAA Aviation Conference,” Washingtion, DC., Jun 2016. (Invited)
2. Laurence, R.J., Argrow, B., Frew, E.W., “Development of Wind Sensing from Small UAS with Distributed Pressure Sensors,” AIAA Aviation Conference, Washingtion, DC., Jun 2016. (Invited)
3. Elston, J., Argrow, B., Stachura, M, “Covariance Analysis of Sensors for Wind Field Estimation by Small Unmanned Aircraft,” AIAA SciTech Conference, Kissimmee, FL, Jan 2015.
4. Laurence III, R.J., Elston, J.S., and Argrow, B., “A Low-Cost System for Wind Field Estimation Through Sensor Networks and Aircraft Design,” AIAA SciTech Conference, Kissimmee, FL, Jan 2015.
5. Laurence III, R., Nichols, T., Elston, J., and Argrow, B., “Validation of Supercell Wind and Thermodynamic Measurements from the Tempest UAS and a Mobile Mesonet,” Proceedings of the AUVSI Unmanned Systems 2014 Conference, Orlando, FL, May 2014.

(d) Recent Synergistic Activities

- Fellow of the American Institute of Aeronautics and Astronautics (elected Jan 2016)
- Panel Organizer/Moderator, Integrated Remote & In Situ Sensing (IRISS) Initiative, CU’s “Our Space. Our Future.” Grand Challenges Event, Denver Museum of Nature and Science, Denver, CO (Sep 2015)
- Panel Organizer/Moderator, Small UAS in the Academic Setting, NASA UAS Traffic Management (UTM) Convention, NASA Ames Research Center, Moffett Field, CA (July 2015)
- Panel Organizer/Moderator, UAS Policy Issues, International Society for Atmospheric Research Using Remotely Piloted Aircraft (ISARRA), University of Oklahoma, Norman, OK, 2015 (May 2015)
- ISARRA 2015 Organizing Committee (May 2015)

Dale A. Lawrence

Current Position

Professor, Aerospace Engineering Sciences, University of Colorado

Professional Preparation

Cornell University	Ithaca, NY	Electrical Engineering	Ph.D., 1985
Cornell University	Ithaca, NY	Electrical Engineering	M.S., 1982
Colorado State University	Ft. Collins, CO	Electrical Engineering	B.S., 1980

Appointments

6/11 – present	Professor, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, CO.
8/95 – 6/11	Associate Professor, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, CO.
8/91 -- 8/95	Assistant Professor, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, CO.
8/88 -- 8/91	Assistant Professor, Department of Electrical and Computer Engineering, University of Cincinnati, Cincinnati, OH.
6/85 -- 8/88	Staff Engineer, Martin Marietta Astronautics Group, Denver, CO.

Research Expertise Specific to this Proposal

Over the past 15 years, research has focused on unmanned aerial vehicles for scientific applications. The goal has been to develop technology that can greatly expand the precision and reach of atmospheric measurements, while lowering the cost of the vehicles and their operation. The approach is centered on the design of small low-cost, rugged, safe-to-operate vehicles that can be launched and landed virtually anywhere. Advances include gust-insensitive aerodynamics, crash-tolerant structures, and compact packaging for transport. This is coupled with custom-designed avionics hardware and software that provides a flexible interface for a variety of sensor interfaces, as well as highly autonomous control that supports field deployments by non-experts and multiple vehicle measurement schemes. A custom fine-wire turbulence sensor has also been developed that is low-cost, lightweight, and low power, suitable for small vehicles, such as the DataHawk UAS mentioned above, and small balloon payloads as proposed here. It currently has cm-scale resolution, and will be upgraded using bandwidth-increasing feedback control for both hotwire and coldwire sensors to achieve mm-scale measurements. The existing avionics system also provides a modular basis for the proposed balloon venting control, and sensor data acquisition, storage, and telemetry. Since these systems have been developed in house, they provide a great deal of initial capability, yet can be easily modified as needed.

Publications Closely Related to the Proposed Effort

D. Fritts, L.Wang, M. Geller, **D. Lawrence**, J. Werne, and B. Balsley, “Numerical Modeling of Multi-Scale Dynamics at a High Reynolds Number: Instabilities, Turbulence, and an Assessment of Ozmidov and Thorpe Scales”, *J. Atmospheric Sciences*, Vol. 73, No. 2, 2015, pp. 555-578. DOI: 10.1175/JAS-D-14-0343.1.

D. Weibel and **D. Lawrence**, “Small Unmanned Aerial System Attitude Estimation for Flight in Wind”, AIAA J. Guidance, Control, and Dynamics, Vol. 38, No. 7, 2015, pp. 1300-1305.

A. Bradley, S. Palo, G. LoDolce, D. Weibel, and **D. Lawrence**, “Air Deployed Micro Buoy measurement of temperatures in the marginal ice zone upper ocean during the MIZOPEX campaign”, J. Atmospheric And Oceanic Technology, Vol. 32, No. 5, pp. 1058–1070, 2015. DOI: http://dx.doi.org/10.1175/JTECH-D-14-00209.1

J. Elston, B. Argrow, M. Stachura, D. Weibel , **D. Lawrence**, and D. Pope, “Overview of Small Fixed-Wing Aircraft for Meteorological Sampling”, J. Atmospheric And Oceanic Technology, Vol. 32, Jan., 2015, pp. 97-115. DOI: 10.1175/JTECH-D-13-00236.

D. A. Lawrence and B. B. Balsley, “High-Resolution Atmospheric Sensing of Multiple Atmospheric Variables using the DataHawk Small Airborne Measurement System”, *J. Atmosphere And Ocean Technology*, Vol. **30**, 2352–2366, Oct, 2013, doi: http://dx.doi.org/10.1175/JTECH-D-12-00089.1

B. B. Balsley, **D. A. Lawrence**, “Fine-Scale Characteristics of Temperature, Wind, and Turbulence in the Lower Atmosphere (0–1,300 m) Over the South Peruvian Coast’’, *Boundary-Layer Meteorology*, Vol. 147, No. 1, pp. 165-178, April, 2013, DOI: 10.1007/s10546-012-9774x.

H. Fernando, et al, “The MATERHORN: Unraveling the Intricacies of Mountain Weather”, Bulletin American Meteorologiocal Society, Nov., 2015, pp, 1945-1967.

D. A. Lawrence and B. B. Balsley, “Design of a Low-Cost UAS for High-Resolution Atmospheric Sensing”, Proc. AIAA Infotech@Aerospace conference, Boston, MA, Aug., 2013. D. Wiebel and **D. Lawrence**, "Evaluation of Longitudinal Control Algorithms for Small Unmanned Aerial Systems for Robustness to Throttle Saturation and Wind Disturbances", Proc. AIAA Guidance, Navigation, and Control Conf., August, 2013. AIAA 2013-4864. DOI: 10.2514/6.2013-4864.

W. Pisano and **D. Lawrence**, ``Control Limitations of Small Unmanned Aerial Vehicles in Turbulent Environments", *Proc. AIAA Guidance, Navigation and Control Conference*, Chicago, IL , Aug., 2009, AIAA-2009-5909.

J. Elston, E. W. Frew, **D. Lawrence**, P. Gray, and B. Argrow, ``Net-Centric Communication and Control for a Heterogeneous Unmanned Aircraft System", *J. Intelligent and Robotic Systems*, Vol. 56, pp. 199-232, 2009.

Synergistic Activities

- PI on 13 federally funded research grants totaling $3.8M. Co-PI on another 17 grants totaling $2.9M.
- Founding member of the BYU/CU Center for Unmanned Aerial Vehicles, an NSF IUCRC.
- Founding member, Research and Engineering Center for Unmanned Vehicles (RECUV) at the University of Colorado, an interdisciplinary center focused on unmanned vehicles for atmospheric science, disaster mitigation, and homeland security.
- Collaborator on the ONR/ARO MATERHORN project for atmospheric dynamics over mountainous terrain.
- Program Committee, Civilian Applications of Unmanned Aircraft Systems, Sept. 2007.
- Developer of the DataHawk small unmanned aerial system and miniaturized turbulence sensors for atmospheric measurements, that has been deployed in field campaigns in CO, KS, UT, AK, Peru and Japan, supported by funding from ARO, ONR, DOE and NSF.

Biographical Sketch: Andreas Muschinski

Professional Preparation

Techn. Univ. Braunschweig, Germany	Physics	Dipl.-Phys. 1990
Univ. Hannover, Germany	Meteorology	Dr. rer. nat. 1992
Univ. Hannover, Germany	Meteorology	Habilitation 1998

Appointments

2011–present	Senior Research Scientist, NorthWest Research Associates (NWRA), Inc., CoRA office, Boulder, CO
2004–2011	Professor (2008–2011), Jerome M. Paros Endowed Professor in Measurement Sciences (2007–2010), and Associate Professor (2004–2008), Dept. of Electrical and Computer Engineering, University of Massachusetts, Amherst, MA
1998–2004	CIRES Research Scientist III (1999-2004) and CIRES Research Scientist II (1998-1999), University of Colorado and NOAA Environmental Technology Laboratory, Boulder, CO
1992–1998	Wissenschaftlicher Assistent C1 (1992-1998) and Wissenschaftlicher Mitarbeiter BAT IIa (1990-1992), Institut für Meteorologie und Klimatologie, Universität Hannover, Germany
1996–2006	Visiting scientist appointments at NCAR/ATD, Boulder, CO (12/1996–11/1997); DLR/IPA, Oberpfaffenhofen, Germany (5/2002–8/2002); NCAR/MMM, Boulder, CO (6/2005); DLR/IPA (6/2006–8/2006).

Publications most closely related to the proposed project

1. Muschinski, A., 2016: Optical propagation through non-overturning, undulating temperature sheets. *J. Opt. Soc. Am. A*, **32**, 793-800.

2. Muschinski, A., 2015: Temperature variance dissipation equation and its relevance for optical turbulence modeling. *J. Opt. Soc. Am. A*, **32**, 2195-2200.

3. Muschinski, A., and S. M. de Bruyn Kops, 2015: Investigation of Hill's optical turbulence model by means of direct numerical simulation. *J. Opt. Soc. Am. A*, **32**, 2423-2430.

4. Tichkule, S., and A. Muschinski, 2014: Effects of wind-driven telescope vibrations on measurements of turbulent angle-of-arrival fluctuations. *Appl. Optics*, **53**, 4651-4660.

5. Tichkule, S., and A. Muschinski, 2012: Optical anemometry based on the temporal cross-correlation of angle-of-arrival fluctuations obtained from spatially separated light sources. *Appl. Optics*, **51**, 5272-5282.

6. Cheon, Y., V. Hohreiter, M. Behn, and A. Muschinski, 2007: Angle-of-arrival anemometry by means of a large-aperture Schmidt-Cassegrain telescope equipped with a CCD camera. *J. Opt. Soc. Am. A*, **24**, 3478-3492.

Other significant publications

1. Cheon, Y., and A. Muschinski, 2007: Closed-form approximations for the angle-of-arrival variance of plane and spherical waves propagating through homogeneous and isotropic turbulence. *J. Opt. Soc. Am. A*, **24**, 415-422.
2. Muschinski, A., R. G. Frehlich, and B. B. Balsley, 2004: Small-scale and large-scale intermittency in the nocturnal boundary layer and residual layer. *J. Fluid Mech.*, **515**, 319-351.
3. Muschinski, A., 1996: A similarity theory of locally homogeneous and isotropic turbulence generated by a Smagorinsky-type LES. *J. Fluid Mech.*, **325**, 239-260.
4. Muschinski, A., P. P. Sullivan, D. B. Wuertz, R. J. Hill, S. A. Cohn, D. H. Lenschow, and R. J. Doviak, 1999: First synthesis of wind-profiler signals on the basis of large-eddy simulation data. *Radio Sci.*, **34**, 1437-1453.
5. Muschinski, A., and C. Wode, 1998: First in situ evidence for co-existing sub-meter temperature and humidity sheets in the lower free troposphere. *J. Atmos. Sci.*, **55**, 2893-2906.
6. Muschinski, A., R. Frehlich, M. Jensen, R. Hugo, F. Eaton, and B. Balsley, 2001: Fine-scale measurements of turbulence in the lower troposphere: an intercomparison between a kite- and balloon-borne, and a helicopter-borne measurement system. *Boundary-Layer Meteorol.*, **98**, 219-250.
7. Muschinski, A., 2004: Local and global statistics of clear-air Doppler radar signals. *Radio Sci.*, **39**, doi:10.1029/2003RS002908.

Synergistic activities

Dr. Muschinski has 24 years of post-doctoral research and teaching experience in geophysics, boundary-layer meteorology, wave propagation physics, and turbulence physics. — As single PI or lead PI he has raised approximately $5M in research support from Federal sponsors (NSF and DoD). — He has served as a reviewer for 36 archival technical journals. — He has served on program committees for numerous scientific conferences and workshops and has organized or co-organized several national and international field experiments.

Collaborators during the last 48 months:

S. de Bruyn Kops (UMass Amherst, MA), P. Chilson (OU Norman, OK), P. Diamessis (Cornell, Ithaca, NY), A. J. Gasiewski (CU Boulder, CO), P. Klein (OU Norman, OK), S. Oncley (NCAR, Boulder, CO), J. Riley (UW Seattle, WA), J. Wilczak (NOAA/ESRL, Boulder, CO), D. Voelz (NMSU, Las Cruces, NM), D. Wolfe (NOAA/ESRL, Boulder, CO).

Graduate and post-graduate advisees:

J. Ayvazian, J. Bange, M. Behn, Y. Cheon, N. Eike, O. Danne, M. Heinke, V. Hohreiter, R. Hollmann, K. Hu, S. Kern, B. Klocke, S. Pearse, L. Root, M. Schlueter, H. Siebert, M. Steffen, G. Subramanian, S. Tichkule, B. Wehner, C. Wode.

Graduate and post-graduate advisors:

Peter Weidelt (deceased), TU Braunschweig, Germany (Dipl.-Phys. advisor); Rainer Roth (deceased), Univ. Hannover, Germany (Ph.D. advisor and habilitation advisor).

Aroh Barjatya

Professional Preparation:

Ph.D., Electrical Engineering, Utah State University, 2007
M.S., Electrical Engineering, Utah State University, 2003

Appointments:

Tenured Associate Professor, Physical Sciences, Embry-Riddle Aero Univ., 2013-Present
Tenure-Track Assistant Professor, Physical Sciences, Embry-Riddle Aero Univ., 2007-2013

Dr. Barjatya is a tenured Associate Professor within the Physical Sciences Department at Embry-Riddle Aeronautical University in Daytona Beach, FL. He is the program coordinator of Engineering Physics program, where he has started the Spacecraft Instrumentation area of concentration six years ago. In addition to myriad physics and basic electronics courses, he also teaches once-a-year course on Spacecraft Systems Engineering that involves case studies of small satellites. Furthermore, he also advises student teams pursuing senior year capstone projects involving small satellites; as well student clubs interested in small satellite and related engineering technologies.

For the past decade, Dr. Barjatya has been involved with design, calibration and data analysis efforts for Langmuir probes, impedance probes, and E-field probes for several NASA sounding rocket campaigns (21.117, 29.036, 29.037, 36.218, 46.009, 46.010) as well as two German rocket missions: WADIS-1 and WADIS-2. He has also analyzed the data from Floating Potential Measurement Unit aboard the International Space Station. He was also the Co-I on the NSF DICE CubeSat mission that carried fixed bias Langmuir probes.

Recent Relevant Publications:

Robert M. AlbarranII and Aroh Barjatya. "Plasma Density Analysis of CubeSat Wakes in the Earth's Ionosphere", Journal of Spacecraft and Rockets, Vol. 53, No. 3 (2016), pp. 393-400.

C.S. Fish, C.M. Swenson, G. Crowley, A. Barjatya, T. Neilsen, et al (2014), Design, development, implementation, and on orbit performance of the Dynamic Ionosphere CubeSat Experiment , Space Science Reviews, 2014, Volume 181, Issue 1-4, pp 61-120

Bekkeng T.A., A. Barjatya, U.P. Hoppe and M. Friedrich (2013), Payload charging events in the mesosphere and their impact on Langmuir type electric probes, *Annales Geophysicae,* 31, 187-196, doi:10.5194/angeo-31-187-2013

Steigies, C.T. and A. Barjatya (2012), Contamination effects on fixed bias Langmuir probes, *Rev Sci Instrum,* 83(11):113502. doi: 10.1063/1.4764582.

Barjatya, A., C.M. Swenson, D.C. Thompson, and K.H. Wright Jr. (2009), Invited Article (Journal Cover) : Data analysis of the Floating Potential Measurement Unit aboard the International Space Station, *Rev. Sci. Instr.,* 80, 4, pp. 041301-041301-11

Synergistic Activities:

Session Chair: *Science on a Shoestring: New Frontiers in Space Weather Observations I and II*, AGU Fall Meeting, San Francisco, 2013
Member of American Geophysical Union (AGU)

Member of Institute of Electronics and Electrical Engineers (IEEE)

Reviewer of articles submitted to Journal of Geophysical Research, Geophysical Research Letters, Annales Geophysicae, Journal of Atmospheric and Solar-Terrestrial Physics, Reviews of Scientific Instruments

Reviewer of proposals submitted to NASA and the NSF
Public outreach to newspapers and local media. Visits to local schools and science fairs. Talks to the public about small satellite technology and NASA sounding rockets.

Graduate Advisor: Dr. Charles M. Swenson, Utah State University.

Thesis Advisor:

Jorn Mumme (DLR, Germany), Robert Albarran (PhD Student at ERAU), Adam Blake (NSROC Wallops), Zachary Laurencio (current student), Michael Arsenault (current student), Forrest Gasdia (current student)
Total Graduate Students: 5

David C. Fritts

Position: Adjoint Professor of Space & Atmospheric Research
Embry-Riddle Aeronautical University, Daytona Beach, Florida
Physical address: GATS
3360 Mitchell Lane, Boulder, CO 80301
Contact information: 720-274-4747; dave@gats-inc.com

Professional preparation:

Carleton College	BA	Physics	1971
University of Illinois	MS, PhD	Physics	1973, 1977
Postdoctoral Fellow	NCAR Adv. Studies Program		1977-1978
Postdoctoral Fellow	NOAA/ERL		1978-1979

Appointments:

Research Scientist	Physical Dynamics, Inc.	1979-1982
Assist./Assoc./Professor	Geophys. Inst., Univ. of Alaska	1982-1991
Research Professor	LASP/ECE, Univ. of Colorado	1991-1997
Adjunct Professor	CU Physics, Aerospace Eng.	1997-present
Founder, Sr. Res. Scientist	NorthWest Res. Assoc./CoRA	1997-2012
Office founder, Sr. Res. Sci.	GATS Inc./Boulder	2012-present
Adjunct Professor	Embry-Riddle Aeronautical Univ.	beginning July 2016

Service, collaborative activities, and recognition:

Dave has served as associate editor for the Journal of Atmospheric Sciences and the Journal of Geophysical Research, president of the Int'l. Commission on the Middle Atmosphere (ICMA) within IAMAS, chairman of the Middle Atmosphere Program Comm. on Upward Coupling of Wave Energy, member of the National Academy of Sciences Committee on Solar-Terrestrial Relations, and member of various scientific and advisory panels. Dave initiated and/or guided multiple national and international measurement and modeling research programs (including measurements on 6 continents) with funding from NASA, NSF, the Army Research Office (ARO), the Air Force Office of Scientific Research (AFOSR), the Office of Naval Research (ONR), and the Missile Defense Agency (MDA). He installed radar or lidar instruments in Hawaii, Rarotonga, Antarctica, Norway, and S. America, helped design and carry out the NASA TIMED satellite mission that launched in December 2001 and is still flying, coordinated multiple journal special issues (MacWAVE, MAC/EPSILON, CADRE, DYSMER, CASES-99, SpreadFEX, DEEPWAVE), and wrote the major reviews of gravity wave and instability dynamics in the stratosphere and mesosphere beginning in 1984. Finally, Dave has been listed as a member of "most highly cited researchers" (upper 0.5%) by ISIHighlyCited beginning in 2003.

Research expertise specific to this proposal:

Modeling, theoretical, and observational studies of atmospheric dynamics, especially gravity waves, instability processes, and turbulence, including advanced modeling using of multiple supercomputers and observations using radar, lidar, airglow, balloon, rocket, aircraft, and satellite instruments and data analyses, and field programs on 6 continents. Specific efforts guided by Dave for NASA or DoD programs of relevance to this proposal include the following:

1. Turbulence modeling for the ***Air Force Airborne Laser (ABL) program;***
2. Wake evolution and turbulence modeling for the ***ONR Wakes program***;
3. Turbulence forecast model development for the ***MDA High-Altitude Airship program***;

4. Performance of the ***PMC-Turbo long-duration balloon (LDB) experiment*** with NASA funding to measure and model turbulence arising from gravity wave instabilities at high altitudes (planned circumpolar LDB flight around Antarctica in austral summer 2017-18).

Dave has also written a number of the major reviews of gravity wave and instability dynamics spanning 30 years: Fritts (1984, 1989), Fritts and Rastogi (1985), Fritts and Alexander (2003).

Reviews of gravity wave and instability dynamics:

Fritts, D. C., 1984: Gravity wave saturation in the middle atmosphere: A review of theory and observations, Rev. Geophys. Space Phys., 22, 275-308.

Fritts, D. C., 1989: A review of gravity wave saturation processes, effects, and variability in the middle atmosphere, Pure Appl. Geophys., 130, 343-371.

Fritts, D. C., and M. J. Alexander, 2003: Gravity wave dynamics and effects in the middle atmosphere, Rev. Geophys., 41, doi: 10.1029/2001/RG000106.

Fritts, D. C., and P. K. Rastogi, 1985: Convective and dynamical instabilities due to gravity wave motions in the lower and middle atmosphere: Theory and observations, Radio Sci., 20, 1247-1277.

Other publications on gravity waves, instabilities and turbulence related to this proposal:

Fritts, D. C., and G. D. Nastrom, 1992: Sources of mesoscale variability of gravity waves, II: Frontal, convective, and jet stream excitation, J. Atmos. Sci., 49, 111-127.

Fritts, D. C., L. Wang, M. A. Geller, D. A. Lawrence, J. Werne, and B. B. Balsley, 2015a: Numerical Modeling of Multi-Scale Dynamics at a High Reynolds Number: Instabilities, Turbulence, and an Assessment of Ozmidov and Thorpe Scales, J. Atmos. Sci., doi: 10.1175/JAS-D-14-0343.1.

Fritts, D. C., L. Wang, and J. Werne, 2009: Gravity wave - fine structure interactions: A reservoir of small-scale and large-scale turbulence energy, Geophys. Res. Lett., 36, L19805, doi:10.1029/2009GL039501.

Fritts, D. C., L. Wang, and J. Werne, 2013: Gravity Wave – Fine Structure Interactions, Part 1: Energy dissipation evolutions, statistics, and implications, J. Atmos. Sci., 70(12), 3710-3734, doi: 10.1175/JAS-D-13-055.1.

Fritts, D. C., L. Wang, J. Werne, T. Lund, and K. Wan, 2009: Gravity wave instability dynamics at high Reynolds numbers, 1: Wave field evolution at large amplitudes and high frequencies, J. Atmos. Sci., 66, 1126-1148, doi:10.1175/2008JAS2726.1.

Fritts, D. C., L. Wang, J. Werne, T. Lund, and K. Wan, 2009: Gravity wave instability dynamics at high Reynolds numbers, 2: Turbulence evolution, structure, and anisotropy, J. Atmos. Sci., 66, 1149-1171, doi:10.1175/2008JAS2727.1.

Fritts, D. C., and L. Wang, 2013: Gravity Wave – Fine Structure Interactions, Part 2: Energy dissipation evolutions, statistics, and implications, J. Atmos. Sci., 70(12), 3735-3755, doi: 10.1175/JAS-D-13-059.1.

Fritts, D. C., L. Wang, G. Baumgarten, A. D. Miller, M. A. Geller, G. Jones, M. Limon, D. Chapman, J. Didier, C. B. Kjellstrand, D. Araujo, S. Hillbrand, A. Korotkov, G. Tucker, and J. Vinokurov, 2016: High-Resolution Observations and Modeling of Turbulence Sources, Structures, and Intensities in the Upper Mesosphere, J. Atmos. Solar-Terres. Phys., submitted.

Fritts, D. C., L. Wang, M. A. Geller, D. A. Lawrence, J. Werne, and B. B. Balsley, 2015a: Numerical Modeling of Multi-Scale Dynamics at a High Reynolds Number: Instabilities, Turbulence, and an Assessment of Ozmidov and Thorpe Scales, J. Atmos. Sci., doi: 10.1175/JAS-D-14-0343.1.

Fritts, D. C., L. Wang, and J. Werne, 2009: Gravity wave - fine structure interactions: A reservoir of small-scale and large-scale turbulence energy, Geophys. Res. Lett., 36, L19805, doi:10.1029/2009GL039501.

Fritts, D. C., L. Wang, and J. Werne, 2013: Gravity Wave – Fine Structure Interactions, Part 1: Energy dissipation evolutions, statistics, and implications, J. Atmos. Sci., 70(12), 3710-3734, doi: 10.1175/JAS-D-13-055.1.

Fritts, D. C., J. A. Werne, 2000: Turbulence dynamics due to gravity waves in the lower and middle atmosphere, AGU Monograph, Atmospheric Science Across the Stratopause, 143-159.

Nastrom, G. D., and D. C. Fritts, 1992: Sources of mesoscale variability of gravity waves, I: Topographic excitation, J. Atmos. Sci., 49, 101-110.

Graham V. Candler

Current Position:

McKnight Presidential and Russell J. Penrose Professor of Aerospace Engineering & Mechanics, University of Minnesota

Education:

Doctor of Philosophy, June 1988, Aeronautics & Astronautics, Stanford University
Master of Science, June 1985, Aeronautics & Astronautics, Stanford University
Bachelor of Engineering (Honors), Nov. 1984, Mechanical Engineering, McGill University

Professional Experience:

1999-	Professor, Aerospace Engineering & Mechanics, University of Minnesota
1994-1999	Associate Prof., Aerospace Engineering & Mechanics, University of Minnesota
1992-1994	Assistant Prof., Aerospace Engineering & Mechanics, University of Minnesota
1989-1992	Assistant Prof., Mechanical & Aerospace Engineering, NC State University
1988-1989	Aerospace Engineer, NASA Ames Research Center
1988-1989	Visiting Professor, Aeronautics & Astronautics, Stanford University

Honors and Awards:

Ballhaus Prize for Best Ph.D. Thesis, Stanford University Aeronautics & Astronautics, 1998
AIAA Award for Best Paper in Thermophysics, 1990 and 2001
George Taylor Distinguished Research Award, University of Minnesota, 2002
Distinguished McKnight University Professor, University of Minnesota, 2004
AIAA Outstanding Paper Award in Aerodynamic Measurement and Ground Testing, 2006
AIAA Thermophysics Award, 2007
Fellow of the American Institute of Aeronautics and Astronautics (AIAA), 2008
National Security Science and Engineering Faculty Fellowship, 2009
McKnight Presidential Professor, University of Minnesota, 2009
Russell J. Penrose Professor, University of Minnesota, 2012
AIAA Fluid Dynamics Award, 2012

Relevant Experience:

Graham Candler's current research interests include computational fluid dynamics of compressible flows, CFD algorithm development, aerothermodynamics, and high temperature gas dynamics. His current research projects include the direct numerical simulations of transitional hypersonic flows and shock-boundary layer interactions, development of advanced chemical kinetics models for high-temperature flows, modeling approaches for high-speed combustion flows, subgrid-scale modeling for large-eddy simulations of variable-density turbulence, and the application of advanced boundary layer stability methods. He is the author or co-author of over two hundred and fifty journal and conference papers on these topics, and he led the development of the NASA DPLR and US3D computational fluid dynamics codes for the simulation of aerothermodynamics and high-enthalpy nonequilibrium flows.

Selected Relevant Publications:

Alba, C., H. Johnson, M. Bartkowicz, G.V. Candler, and K. Berger, “Boundary-Layer Stability Calculations for the HIFiRE-1 Transition Experiment,” *J. Spacecraft and Rockets*, Vol. 45, No. 6, pp. 1125-1133, Nov.-Dec. 2008.

Subbareddy, P., and G.V. Candler, "A Fully-Discrete, Kinetic Energy Consistent Finite Volume Scheme for Compressible Flows," *J. Computational Physics*, Vol. 228, pp. 1347-1364, Mar. 2009.

Peterson, D., and G.V. Candler, "Hybrid RANS/LES of Normal Injection into a Supersonic Crossflow," *J. Propulsion and Power*, Vol. 26, No. 3, pp. 533-544, Mar. 2010.

Peterson, D., and G.V. Candler, "Numerical Simulations of Mixing for Normal and Low-Angled Injection into a Mach 2 Crossflow," *AIAA Journal*, Vol. 49, No. 12, pp. 2792-2804, Dec. 2011.

Barnhardt, M., and G.V. Candler, "Detached Eddy Simulation of the Reentry-F Flight Experiment," *J. Spacecraft and Rockets*, Vol. 49, pp. 691-699, 2012.

Candler, G.V., P. Subbareddy, and I. Nompelis, "A Decoupled Implicit Method for Aerothermodynamics and Reacting Flows," *AIAA Journal*, Vol. 51, No. 5, pp. 1245-1254, May. 2013.

Gronvall, J.E., H. Johnson, and G.V. Candler, "Boundary Layer Stability Analysis of the High Enthalpy Shock Tunnel Transition Experiments," *J. Spacecraft and Rockets*, Vol. 51, No. 2, pp. 455-467, Mar.-Apr. 2014.

Subbareddy, P.K., M. Bartkowicz, and G.V. Candler, "Numerical Simulations of Roughness Induced Instability in the Purdue Mach 6 Wind Tunnel," *J. Fluid Mechanics*, Vol. 748, pp. 848-878, 2014.

Wagnild, R., and G.V. Candler, "Computational Analysis of Acoustic Damping in High Enthalpy Environments," *AIAA Journal*, Vol. 52, No. 11, pp. 2615-2618, 2014.

Candler, G.V., P.K. Subbareddy, and J.M. Brock, "Advances in Computational Fluid Dynamics Methods for Hypersonic Flows," *J. Spacecraft and Rockets*, Vol. 52, No. 1, pp. 17-28, Jan.-Feb. 2015.

Candler, G.V., "Rate-Dependent Energetic Processes in Hypersonic Flows," *Progress in Aerospace Sciences*, Vol. 72, No. 1, pp. 37-48, Jan. 2015.

Brock, J.M., P. Subbareddy, and G.V. Candler, "Detached Eddy Simulations of Hypersonic Capsule Wake Flow," *AIAA Journal*, Vol. 53, No. 1, pp. 70-80, Jan. 2015.

Schwing, A., and G.V. Candler, "Validation of DES for Capsule Aerodynamics using 05-CA Wind Tunnel Test Data," *J. Spacecraft and Rockets*, Vol. 52, No. 2, Mar.-Apr. 2015.

Candler, G.V., P.K. Subbareddy, and I. Nompelis, "CFD Methods for Hypersonic Flows and Aerothermodynamics," Ed. E. Josyula, *Progress in Astronautics and Aeronautics*, Vol. 247, pp. 203-237, AIAA, 2015.

Candler, G.V., H.B. Johnson, I. Nompelis, V.M. Gidzak, P.K. Subbareddy, and M. Barnhardt, "Development of the US3D Code for Advanced Compressible and Reacting Flow Simulations," AIAA 2015-1893, Jan. 2015.

Dinzl, D.J., and G.V. Candler, "Direct Numerical Simulation of Crossflow Instability Excited by Microscale Roughness on HIFiRE-5," AIAA 2016-0353, Jan. 2016.

Chaudhry, R.S., and G.V. Candler, "Recovery of Freestream Acoustic Disturbances from Stagnation Pressure Spectrum in Hypersonic Flow," AIAA-2016-2059, Jan. 2016.

I. PROPOSED BUDGET DETAILS: University of Colorado, Boulder

Institution:	The Regents of the University of Colorado 572 UCB Boulder, CO 80309	Title:	Stratospheric Turbulence/Particle Measurements and Models for Air Force Hypersonics
Principal Investigator:	Brian Argrow	Duration:	06/01/2017-05/31/2022
Co-Principal Investigator(s):	Dale Lawrence Andreas Muschinski		

A. Salaries and Wages

	Notes	Year 1	Year 2	Year 3	Option 1	Option 2	Total
PI: Brian Argrow	*Task 6: Project Coordination*						
100% time, 1 months, AY	*All Years: 1 Month Effort*	16,062	16,544	17,040	17,551	18,078	85,275
Co-PI: Dale Lawrence	*Tasks 1, 2: Measurements/Analysis*						
100% time, 2 months, AY	*All Years: 2 Months Effort*	29,354	30,235	31,142	32,076	33,038	155,845
Co-PI: Andreas Muschinski	*Task 3: AeroOptics*						
100% time, 2 months, CY	*All Years: 2 Months Effort*	30,333	31,243	32,181	33,146	34,140	161,043
Senior Personnel: Greg Rieker	*Task 3: AeroOptics*						
100% time, 0 months, AY	*Y2-5: 1 Month Effort*	0	10,966	11,295	11,634	11,983	45,878
CU PREP: Postdoc	*Task 3: AeroOptics*						
100% time, 0 months, CY	*Y2-5: 1 Month Effort*	0	7,296	7,515	7,740	7,972	30,523
Senior Personnel: Thomas Lund	*Task 5: Turbulence Modelling*						
100% time, 3 months, CY	*All Years: 3 Months Effort*	28,750	29,613	30,501	31,416	32,358	152,638
Senior Personnel: Christopher Koehler	*Task 1: Measurements*						
100% time, 0 months, CY	*Y2-3: 1 Month Effort*	0	14,544	14,980	0	0	29,524
Graduate Research Assistant: Pre Comps	*Task 3: AeroOptics*						
50% time, 0 months, AY	*Pre-comp Y2*	0	21,446	0	0	0	21,446
100% time, 0 months, Summer		0	14,369	0	0	0	14,369
Graduate Research Assistant: Pre Comps	*Tasks 1, 2: Measurements/Analysis*						
50% time, 9 months, AY	*Pre-comp Y1-2*	20,925	21,553	0	0	0	42,478
100% time, 3 months, Summer		13,950	14,369	0	0	0	28,319
Graduate Research Assistant: Pre Comps	*Tasks 1, 2: Measurements/Analysis*						
50% time, 9 months, AY	*Pre-comp Y1-2*	20,925	21,553	0	0	0	42,478
100% time, 3 months, Summer		13,950	14,369	0	0	0	28,319
Graduate Research Assistant: Pre Comps	*Task 5: Turbulence Modelling*						
50% time, 9 months, AY	*Pre-comp Y1-2*	20,822	21,446	0	0	0	42,268
100% time, 3 months, Summer		13,950	14,369	0	0	0	28,319
Graduate Research Assistant-Post Doc	*Task 3: AeroOptics*						
50% time, 0 months, AY	*Post-comp Y3-5*	0	0	22,906	23,593	24,301	70,800
100% time, 0 months, Summer		0	0	15,271	15,729	16,201	47,201
Graduate Research Assistant-post doc	*Tasks 1, 2: Measurements/Analysis*						
50% time, 0 months, AY	*Post-comp Y3-4*	0	0	23,154	23,849	0	47,003

100% time, 0 months, Summer					0	0	15,436	15,899	0	31,335
Graduate Research Assistant-post doc	*Tasks 1, 2: Measurements/Analysis*									
50% time, 0 months, AY	*Post-comp Y3-5*				0	0	23,154	23,849	24,564	71,567
100% time, 0 months, Summer					0	0	15,436	15,899	16,376	47,711
Graduate Research Assistant-post doc	*Task 5: Turbulence Modelling*									
50% time, 0 months, AY	*Post-comp Y3-5*				0	0	22,906	23,593	24,301	70,800
100% time, 0 months, Summer					0	0	15,271	15,729	16,201	47,201
Total Salaries and Wages					209,021	283,915	298,188	291,703	259,513	1,342,340
B. Fringe Benefits				***Rate***						
PI: Brian Argrow				*30.60%*	4,915	5,265	5,640	6,041	6,472	28,333
Co-PI: Dale Lawrence				*30.60%*	8,982	9,622	10,307	11,041	11,827	51,779
Co-PI: Andreas Muschinski				*37.70%*	11,436	12,250	13,122	14,056	15,057	65,921
Senior Personnel: Greg Rieker				*30.60%*	0	3,490	3,738	4,005	4,290	15,523
CU PREP: Postdoc				*37.70%*	0	2,861	3,064	3,282	3,516	12,723
Senior Personnel: Thomas Lund				*37.70%*	10,839	11,611	12,437	13,323	14,271	62,481
Senior Personnel: Christopher Koehler				*37.70%*	0	5,702	6,108	0	0	11,810
Graduate Research Assistant: Pre Comps				*13.70%*	0	5,103	0	0	0	5,103
Graduate Research Assistant: Pre Comps				*13.70%*	4,778	5,118	0	0	0	9,896
Graduate Research Assistant: Pre Comps				*13.70%*	4,778	5,118	0	0	0	9,896
Graduate Research Assistant: Pre Comps				*13.70%*	4,764	5,103	0	0	0	9,867
Graduate Research Assistant-Post Doc				*13.70%*	0	0	5,657	6,060	6,491	18,208
Graduate Research Assistant-post doc				*13.70%*	0	0	5,718	6,125	0	11,843
Graduate Research Assistant-post doc				*13.70%*	0	0	5,718	6,125	6,561	18,404
Graduate Research Assistant-post doc				*13.70%*	0	0	5,657	6,060	6,491	18,208
Total Fringe Benefits					50,492	71,243	77,166	76,118	74,976	349,995
Total Salaries and Wages and Fringe Benefits					259,513	355,158	375,354	367,821	334,489	1,692,335
C. Permanent Equipment										
Flight Hardware					20,700	70,380	78,660	18,630	18,630	207,000
CU instrument development					30,000	0	0	0	0	30,000
Cu Ground station hardware					0	5,000	0	0	0	5,000
Total Permanent Equipment					50,700	75,380	78,660	18,630	18,630	242,000
D. Travel										
Domestic	*Cost*	*No. Days*	*No. People*	*No. Trips*						
Program review and professional conferences: AIAA SciTech Grapevine, TX										
Airfare	*$425*		*2*	*9*	7,650	7,650	7,650	7,650	7,650	38,250
Lodging	*$152*	*5*	*2*	*9*	13,680	13,680	13,680	13,680	13,680	68,400
Per diem	*$59*	*5*	*2*	*9*	5,310	5,310	5,310	5,310	5,310	26,550

Ground Transportation	*$100*		*2*	*9*	1,800	1,800	1,800	1,800	1,800	9,000
Conference Registration	*$1,000*		*2*	*8*	16,000	16,000	16,000	16,000	16,000	80,000
**estimates taken from gsa.gov and Southwest.com 10.7.2016										
Field campaign										
Lodging					0	3,600	3,600	600	600	8,400
Per diem					250	1,690	1,930	365	365	4,600
Field campaign										
Mileage	*Cost*	*No. Miles*	*No. People*	*No. Trips*						
Trips to launch site					1,000	3,100	3,450	850	850	9,250
				Subtotal Domestic Travel	*45,690*	*52,830*	*53,420*	*46,255*	*46,255*	*244,450*
International	*Cost*	*No. Days*	*No. People*	*No. Trips*						
International Conference										
Airfare					0	0	0	0	0	0
Lodging					0	0	0	0	0	0
Per diem					0	0	0	0	0	0
Ground Transportation					0	0	0	0	0	0
Conference Registration					0	0	0	0	0	0
Description	*Cost*	*No. Days*	*No. People*	*No. Trips*						
Airfare					0	0	0	0	0	0
Lodging					0	0	0	0	0	0
Per diem					0	0	0	0	0	0
Ground Transportation					0	0	0	0	0	0
Conference Registration					0	0	0	0	0	0
				Subtotal International Travel	*0*	*0*	*0*	*0*	*0*	*0*
Total Travel					45,690	52,830	53,420	46,255	46,255	244,450
F. Other Direct Costs										
Materials and Supplies										
Small equipment					2,000	2,000	2,000	2,000	2,000	10,000
Publications					0	24,000	24,000	27,000	27,000	102,000
Subcontracts										
Subcontractor 1-UM		*Direct Costs*			190,025	186,759	196,602	201,591	206,730	981,707
		Indirect Costs			73,280	76,740	84,919	87,105	89,357	411,401
Subcontractor 2-ERAU-Fritts		*Direct Costs*			255,827	254,691	260,730	266,951	273,358	1,311,557
		Indirect Costs			54,983	54,721	56,110	57,541	59,015	282,370
Subcontractor 3 -ERAU 2		*Direct Costs*			144,408	147,563	148,736	81,143	71,590	593,440
		Indirect Costs			53,219	54,411	54,737	25,052	20,605	208,024
Other Direct Costs										
Tuition remission		*7,047*		*0*	42,282	58,067	59,809	61,604	47,589	269,351
Total Other Direct Costs					816,024	858,952	887,643	809,987	797,244	4,169,850

G. Total Direct Costs		**1,171,927**	**1,342,320**	**1,395,077**	**1,242,693**	**1,196,618**	**6,348,635**
Total Direct Costs less Sub Indirects		990,445	1,156,448	1,199,311	1,072,995	1,027,641	5,446,840
H. Indirect Costs							
On Campus: MTDC Base							
Predetermined for 7/1/14-6/30/15:	53.00%						
Predetermined for the period 7/1/15-6/30/16:	53.50%						
Predetermined for the period 7/1/16-6/30/18:	54.00%						
Provisional thereafter per HHS agreement dated 5/13/16.		206,390	234,354	245,578	239,261	221,262	1,146,845
I. Total Costs		1,378,317	1,576,674	1,640,655	1,481,954	1,417,880	7,495,480
			Base Period Total:	*4,595,646*	*Option Total:*	*2,899,834*	
Total Amount Requested:		**$7,495,480**					

Inflation Rates	*FY 17*
Salaries	*3.00%*
Fringe Benefits	*4.00%*
Tuition	*3.00%*
Other Costs	*1.80%*

Task I: In-Situ Turbulence and Particle Measurements

Personnel Costs: Lawrence, GRA2-3 (Y1: Y2-3 25%: Y4-5: 75%); Koehler (Y2-3)

Non-Personnel Costs: All permanent equipment; travel: field campaign (100%); conferences (33% distributed to reflect Lawrence effort)

Subcontracts: UM: 15%; ERAU1: 0% ERAU2: 100%

	Year 1	**Year 2**	**Year 3**	**Option 1**	**Option 2**	**Total**
Labor: PI/Co-PI Salaries	29,354	7,559	7,786	24,057	24,779	93,535
Labor: Other Personnel	0	14,544	14,980	0	0	29,524
Labor: GRAs	69,750	17,961	19,295	59,622	30,705	197,333
Fringe	18,538	10,667	11,544	17,468	13,791	72,008
Travel	16,063	12,093	12,683	12,925	12,925	66,689
Permanent Equipment	50,700	75,380	78,660	18,630	18,630	242,000
Subcontracts	237,123	241,499	245,701	149,499	136,608	1,010,430
Other: Tuition	28,188	7,258	7,476	23,102	11,897	77,921
Indirect Costs	85,703	33,925	35,796	61,599	44,388	261,411
Total for Task 1	**535,419**	**420,886**	**433,921**	**366,902**	**293,723**	**2,050,851**

Task 2: Data Analysis

Personnel Costs:	Lawrence, GRA2-3 (Y2-3 75%: Y4-5: 25%)
Non-Personnel Costs:	Travel: conferences (33%)
Subcontracts:	UM: 0%; ERAU1: 10% ERAU2: 0%

	Year 1	Year 2	Year 3	Option 1	Option 2	Total
Labor: PI/Co-PI Salaries	0	22,676	23,357	8,019	8,260	62,312
Labor: Other Personnel	0	0	0	0	0	0
Labor: GRAs	0	53,883	57,885	19,874	10,235	141,877
Fringe	0	14,894	16,307	5,823	4,597	41,621
Travel	0	11,110	11,110	3,703	3,703	29,626
Subcontracts	31,081	30,941	31,684	32,449	33,237	159,392
Other: Tuition	0	21,775	22,428	7,701	3,966	55,870
Indirect Costs	0	55,384	58,676	20,206	14,469	148,735
Total for Task 2	**31,081**	**210,663**	**221,447**	**97,775**	**78,467**	**639,433**

Task 3: Aero-Optical Measurements and Analysis

Personnel Costs:	Muschinski (100% Y1-5); Rieker (100% Y2-5); GRA1 (100% Y2-5); Postdoc (10%; Y2-5)
Non-Personnel Costs:	Travel: conferences (33%)
Subcontracts:	UM: 0%; ERAU1: 10% ERAU2: 0%

	Year 1	Year 2	Year 3	Option 1	Option 2	Total
Labor: PI/Co-PI Salaries	30,333	31,243	32,181	33,146	34,140	161,043
Labor: Other Personnel	0	18,262	18,810	19,374	19,955	76,401
Labor: GRAs	0	35,815	38,177	39,322	40,502	153,816
Fringe	11,436	23,704	25,581	27,403	29,354	117,478
Travel	14,813	14,813	14,813	14,813	14,813	74,065
Subcontracts	31,081	30,941	31,684	32,449	33,237	159,392
Other: Tuition	0	14,517	14,952	15,401	15,863	60,733
Indirect Costs	30,554	66,872	69,963	72,391	74,933	314,713
Total for Task 3	**118,217**	**236,167**	**246,161**	**254,299**	**262,797**	**1,117,641**

Task 4: Transition Modelling

Subcontracts: UM: 85%; ERAU1: 0% ERAU2: 0%

	Year 1	Year 2	Year 3	Option 1	Option 2	Total
Subcontracts	223,809	223,974	239,293	245,392	251,674	1,184,142
Indirect Costs	13,500	0	0	0	0	13,500
Total for Task 4	**237,309**	**223,974**	**239,293**	**245,392**	**251,674**	**1,197,642**

Task 5: Gravity Wave and Large-Scale Turbulence Simulations, and Small-Scale Turbulence Simulations

Personnel Costs: Lund (Y1-5; 100%); GRA4 (Y1-5; 100%)

Non-Personnel Costs: Travel: conferences (33%)

Subcontracts: UM: 0%; ERAU1: 70% ERAU2: 0%

	Year 1	Year 2	Year 3	Option 1	Option 2	Total
Labor: Other Personnel	28,750	29,613	30,501	31,416	32,358	152,638
Labor: GRAs	34,772	35,815	38,177	39,322	40,502	188,588
Fringe	15,603	16,714	18,094	19,383	20,762	90,556
Travel	14,813	14,813	14,813	14,813	14,813	74,065
Subcontracts	217,567	216,588	221,788	227,144	232,661	1,115,748
Other: Tuition	14,094	14,517	14,952	15,401	15,863	74,827
Indirect Costs	64,229	52,356	54,856	56,664	58,555	286,660
Total for Task 5	**389,828**	**380,416**	**393,181**	**404,143**	**415,514**	**1,983,082**

Task 6: Project Coordination

Personnel Costs: Argrow (Y1-5; 100%)

Non-Personnel Costs: Supplies; Publications

Subcontracts: UM: 0%; ERAU1: 10% ERAU2: 0%

	Year 1	Year 2	Year 3	Option 1	Option 2	Total
Labor: PI/Co-PI Salaries	16,062	16,544	17,040	17,551	18,078	85,275
Fringe	4,915	5,265	5,640	6,041	6,472	28,333
Materials and Supplies	2,000	2,000	2,000	2,000	2,000	10,000

Publications	0	24,000	24,000	27,000	27,000	102,000
Subcontracts	31,081	30,941	31,684	32,449	33,237	159,392
Indirect Costs	12,410	25,817	26,287	28,400	28,917	121,831
Total for Task 6	**66,468**	**104,567**	**106,651**	**113,441**	**115,704**	**506,831**

Summary of Costs by Task

	Year 1	**Year 2**	**Year 3**	**Option 1**	**Option 2**	**Total**
Task I: In-Situ Turbulence and Particle Measurements	535,419	420,886	433,921	366,902	293,723	2,050,851
Task 2: Data Analysis	31,081	210,663	221,447	97,775	78,467	639,433
Task 3: Aero-Optical Measurements and Analysis	118,217	236,167	246,161	254,299	262,797	1,117,641
Task 4: Transition Modelling	237,309	223,974	239,293	245,392	251,674	1,197,642
Task 5: Gravity Wave and Large-Scale Turbulence Simulations, and Small-Scale Turbulence Si	389,828	380,416	393,181	404,143	415,514	1,983,082
Task 6: Project Coordination	66,468	104,567	106,651	113,441	115,704	506,831
Total Request:	**1,378,322**	**1,576,673**	**1,640,654**	**1,481,952**	**1,417,879**	**7,495,480**

Ia. PROPOSED BUDGET JUSTIFICATION: University of Colorado, Boulder

A. PERSONNEL

Salaries for all named personnel are based upon current University of Colorado Boulder (CU-Boulder) academic and staff salary scales. All personnel budget calculations include salary range adjustments and merit increases as applicable for each year of support in accordance with University policy. Salaries are calculated with an anticipated 3% annual increase throughout the project.

Principal Investigator/Co-PIs

- **Brian Argrow** (Principal Investigator; 100% effort, 1 Summer Month): Dr. Argrow will be responsible for the overall coordination of the project and will contribute to the Stratospheric Measurements task.
- **Dale Lawrence** (Co-PI, Task 1-2 Lead; 100% effort, 2 Summer Months): Dr. Lawrence is the Stratospheric Measurements lead on the project and will oversee personnel efforts for balloon campaigns and data analysis.
- **Andreas Muschinski** (Co-PI, Task 3 Lead; 16.67% Calendar Year effort): Dr. Muschinski is the Aero-Optical Measurements lead and will oversee personnel efforts and analysis.

Other Personnel

- **Greg Rieker** (100% effort, 1 Summer Month Y2-5): Dr. Rieker will assist in performing the aero-optical measurements and analysis
- **Christopher Koehler** (100% effort, 1 Summer Month Y2-3): Dr. Koehler is the Director of the Colorado Space Grant Consortium and will coordinate balloon deployments
- **Thomas Lund** (25% Calendar Year effort): Dr. Lund will oversee large-scale gravity wave and turbulence simulations
- **CU PREP Postdoc** (TBD; 8.33% Calendar Year effort): The postdoc will support the Aero-Optical measurements task.

Graduate Students

Graduate student support is based on the current University rate with an anticipated annual increase of 3% throughout the project.

- **GRA1&5**, (Pre-Comprehensive Review, Y2; Post Comprehensive Review Y3-5)
  - Support Aero-Optical Measurements
  - Y2-5: 3 summer months at 100%, 9 months AY at 50%
- **GRA2&6**, (Pre-Comprehensive Review, Y1-2; Post Comprehensive Review Y3-4)
  - Support Turbulence and Particle Measurements and Data Analysis
  - Y1-4: 3 summer months at 100%, 9 months AY at 50%
- **GRA3&7**, (Pre-Comprehensive Review, Y1-2; Post Comprehensive Review Y3-5)
  - Support Turbulence and Particle Measurements and Data Analysis Y2-5: 3 summer months at 100%, 9 months AY at 50%
- **GRA4&8**, (Pre-Comprehensive Review, Y2; Post Comprehensive Review Y3-5)

- Support Gravity Wave and Large-Scale Turbulence Simulations, and Small-Scale Turbulence Simulations
- Y2-5: 3 summer months at 100%, 9 months AY at 50%

FRINGE BENEFITS

Fringe benefits are calculated on requested salary per the University's federally negotiated Indirect Cost Rate Agreement with the Department of Health and Human Services (DHHS). The rate used for the PI and other faculty members is 30.6%; the rate used for non-faculty research personnel is 37.7%; the rate used for graduate research assistants is 13.7%, and the rate used for hourly employees is 1.2%.

EQUIPMENT

Equipment funds are requested as below:

Year 1: CU Instrument Development	Calibration instrument designed to work inside an existing NCAR environmental chamber	$10,000
	Reference sensors for jet temperature, humidity, and flow rate	$10,000
	and two prototype iterations of an upgraded stratospheric turbulence instrument	$10,000
Year 1-5: Flight Hardware	200 copies of this finalized instrument for field measurements	$160,000
	100 copies of the high altitude balloon systems to carry instruments	$47,000
Year 2: CU Ground Station Hardware	Station for tracking balloons and downlinking flight data	$5,000

Total equipment requested: $242,000

TRAVEL

Domestic

Travel funds are requested for eight conference trips per year for the CU team of 4 faculty/senior personnel and 4 students, plus one trip per year (for two people) for project reporting to AFOSR program managers.

Travel charges were based on the cost of attending the 2017 AIAA SciTech conference in Grapevine, TX.

Cost category	**Rate**	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Total**
Airfare	$425/person/trip	$7,650	$7,650	$7,650	$7,650	$7,650	$38,250
Lodging (4 nights)	$152/night	$13,680	$13,680	$13,680	$13,680	$13,680	$68,400
Meals & incidental expenses (5 days)	$59/day	$5,310	$5,310	$5,310	$5,310	$5,310	$26,550
Ground transportation	$100/person/trip	$1,800	$1,800	$1,800	$1,800	$1,800	$9,000
Registration fees	$1000/person	$16,000	$16,000	$16,000	$16,000	$16,000	$80,000
Total		$44,440	$44,440	$44,440	$44,440	$44,440	$222,200

Field Campaigns
Travel is also budgeted to support the field campaigns. Two types are planned.

1. Single Balloon Launch ($5,000): 40 launches @ $125/launch:
    a. $100 mileage for one person to travel to site to operate the ground station (estimated to be within 200 miles of CU @ $.50/mile)
    b. $25 per diem for a half day of travel.
2. Intensive Observational Period: 15 launches @ $1150/launch
    a. $350 mileage for four people to travel to 2 separate sites for launching and tracking (700 miles @ $.50/mile)
    b. $600 for hotel for one night for 4 people ($150/person/night/launch)
    c. $200 per diem ($50/person)

Total: $22,250

OTHER DIRECT COSTS

Materials and Supplies: $2,000 per year is requested for Y1-5 for project-specific supplies to support fabrication, launch projects.

Publication Costs: $24,000 is requested in Y2-3 and $27,000 in Y4-5 for publications related to technical findings.

Subawards:

Subaward 1: University of Minnesota ($1,393,108 Total, Y1-5)

Dr. Candler will participate in measurements and lead the Transition Modelling task throughout all years, as outlined in the Budget Proposal Document.

Subaward 2: Embry-Riddle Aeronautical University ($1,593,927 Total, Y1-5)

Dr. Fritts will provide input and leadership for all tasks and lead the Turbulence modelling throughout all years, as outlined in the Budget Proposal Document.

Subaward 3: Embry-Riddle Aeronautical University ($801,464 Total, Y1-5)

Dr. Barjatya will lead the measurements team at Embry-Riddle for all years, as outlined in the Budget Proposal Document.

Tuition: Graduate student tuition is requested in accordance with University policy. The rate used for GRA tuition remission is the resident rate and includes a 3% annual increase throughout the project.

INDIRECT COSTS

Indirect costs are charged according to the University's federally negotiated rate agreement. The indirect cost rate for on-campus research is 53% of Modified Total Direct Cost (MTDC), predetermined for the period 7/1/14 - 6/30/15, 53.5% of MTDC, predetermined for the period

7/1/15 - 6/30/16; 54% MTDC, predetermined for the period 7/1/16 - 6/30/18; provisional thereafter per HHS agreement dated 05/13/2016.

INFLATION RATES

The University of Colorado’s current budget planning parameters include an annual inflation factor of 3% for salaries of investigators, post-doctoral researchers, graduate research assistant, and hourly students. Tuition is estimated to increase 3% per year, fringe benefits are estimated to increase 4% per year, and other direct costs such as travel, can be inflated at 1.8% per year (inflation of other direct costs is optional).

II. PROPOSED BUDGET DETAILS: University of Minnesota

	Period 1	Period 2	Period 3	Period 4	Period 5	TOTAL
Salaries	**126,961**	**129,963**	**123,592**	**123,120**	**122,634**	**626,270**
G. Candler 1.0 mos	23,427	24,130	24,854	25,600	26,368	124,379
J. Flatten 1.0 mos	9,151	9,426	9,709	10,000	10,300	48,586
Post Doc Assoc.	19,883	19,672	9,992	6,112	2,116	57,775
3 Undergraduates	22,500	23,175	23,870	24,586	25,324	119,455
2 Graduate RA 50% 9 mos Acad	39,000	40,170	41,375	42,616	43,894	207,055
2 Graduate RA 50% 3 mos Summer	13,000	13,390	13,792	14,206	14,632	69,020
Benefits	**53,673**	**55,122**	**54,710**	**55,512**	**56,337**	**275,354**
PI @ 33.7%	10,979	11,309	11,648	11,998	12,358	58,292
Post Doc Assoc. @ 20.1%	3996	3954	2008	1229	425	11,612
Graduate RA						
-Health @17.6%	6,864	7,070	7,282	7,500	7,725	36,441
-Tuition @ $18.94/hr	29,546	30,432	31,345	32,285	33,254	156,862
-Summer Benefits @ 17.6%	2,288	2,357	2,427	2,500	2,575	12,147
Subtotal Salaries and Benefits	**180,634**	**185,085**	**178,302**	**178,632**	**178,971**	**901,624**
Travel	**5,000**	**5,000**	**8,000**	**8,000**	**8,000**	**34,000**
- Domestic	5,000	5,000	8,000	8,000	8,000	34,000
Other Direct Costs	**28,300**	**20,300**	**22,300**	**22,300**	**22,300**	**115,500**
- Computer Services	2,300	2,300	2,300	2,300	2,300	11,500
-balloon flights	4,000	4,000	12,000	12,000	12,000	44,000
-equipment	22,000	14,000	8,000	8,000	8,000	60,000
Total Direct Costs	**213,934**	**210,385**	**208,602**	**208,932**	**209,271**	**1,051,124**
Modified Total Direct Costs	162,388	165,953	169,257	168,647	168,017	834,262
Indirect Costs	86,066	89,615	91,398	91,068	90,729	448,876
Total Budget	**300,000**	**300,000**	**300,000**	**300,000**	**300,000**	**1,500,000**

IIa. PROPOSED BUDGET JUSTIFICATION: University of Minnesota

Salary
G. Candler PI – 1.0 mos per year
J. Flaten CoPI – 1.0 mos per year
2 Graduate Students –50% time 12 mos per year
3 Undergraduate Students - hourly

Fringe Benefits
PI @ 33.7%
Graduate Student
- Benefits @ 16.9% 06/01/17 – 06/31/17 ;17.6% 07/01/17 – 05/31/22
- Tuition @ $18.94/hr

Travel

Travel funds have been budgeted to cover the cost of travel for Candler and Flaten to an annual review for the project, and for the two graduate students to attend an annual technical conference. In the final three years, additional travel funds are budgeted for Flaten and one student to travel to a remote site to help set up additional balloon flights.

Equipment
A major uncertainty involves the purchase of the MeteoModem LOAC particle sensor. We plan to buy one ground unit with software (13,000 Euros, or $14,300) in the first year, along with one flight unit and radiosonde (5500 Euros, or $6050). In subsequent years, we expect to have to purchase 2 additional flight units per year because we expect to lose some flight units. We have also budgeted additional equipment funds for the development of alternative particle sensors and their calibration, as well as the calibration of the LOAC flight units.

Other Direct Costs

- Computer Services: Specialized computer and networking services need for the computation portion of the research project.

- Balloon Flights: For the proposed local weather balloon flights, we have budgeted $1000 per flight, which includes the balloon, helium fill gas, transportation to the launch site, and other expendables. From past experience this is a reasonable cost estimate.

Indirect Costs:

- Modified total direct costs shall exclude equipment, capital expenditures, charges for patient care, student tuition remission, rental costs of off-site facilities, scholarships, and fellowships as well as portion of each subgrant and subcontract in excess of $25,000.

7/1/2015-6/30/2017: 52% MTDC
7/1/2017-6/30/2018: 53% MTDC
7/1/2018-6/30/2019: 54% MTDC
7/1/2019-6/30/2021: (provisional) Use same rates and conditions as those cited for fiscal year ending June 30,2019

III. PROPOSED BUDGET DETAILS: ERAU (Fritts)

Budget Justification
Integrated Measurement and Modeling Characterization of Stratospheric Turbulence
PI: David Fritts, PhD

Direct Labor	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Total**
Senior Salaries						
PI: David Fritts: 25% FTE	$ 63,786	$ 65,700	$ 67,671	$ 69,701	$ 71,792	$ 338,650
Senior Personnel: Research Associate: 33% FTE	$ 29,300	$ 30,179	$ 31,084	$ 32,017	$ 32,977	$ 155,556
PhD student: 2x, Starting at $25,000 in year 1	$ 50,000	$ 51,500	$ 53,045	$ 54,636	$ 56,275	$ 265,457
Postdoc: 55% at $60,000 in year 1	$ 33,000	$ 33,990	$ 35,010	$ 36,060	$ 37,142	$ 175,201
Salary subtotal	**$ 176,086**	**$ 181,369**	**$ 186,810**	**$ 192,414**	**$ 198,186**	**$ 934,864**
						$ -
David Fritts fringe: 7.75%	$ 4,943	$ 5,092	$ 5,244	$ 5,402	$ 5,564	$ 26,245
Research Associate fringe: 7.75%	$ 2,271	$ 2,339	$ 2,409	$ 2,481	$ 2,556	$ 12,056
.22% PhD Student fringe	$ 110	$ 113	$ 117	$ 120	$ 124	$ 584
36.5% Postdoc fringe	$ 12,045	$ 12,406	$ 12,779	$ 13,162	$ 13,557	$ 63,949
Fringe subtotal	**$ 19,369**	**$ 19,950**	**$ 20,549**	**$ 21,165**	**$ 21,800**	**$ 102,834**
Total personnel cost	**$ 195,455**	**$ 201,319**	**$ 207,358**	**$ 213,579**	**$ 219,986**	**$ 1,037,698**
Domestic Travel & Meetings						
Collaboration travel from ERAU to Boulder, Colorado, two trips for one week a year is requested: Rental car at $55/ day; $132/ hotel a night; $59 per diem; $550 airfare; and $75 misc. fees and ground transportation.	$ 4,694	$ 4,694	$ 4,694	$ 4,694	$ 4,694	$ 23,470
Collaboration travel from Boulder, Colorado to ERAU in Daytona Beach, FL, two trips for one week a year is requested: Rental car at $55/ day; $100/ hotel a night; $51 per diem; $550 airfare; and $75 misc. fees and ground transportation.	$ 4,134	$ 4,134	$ 4,134	$ 4,134	$ 4,134	$ 20,670
Scholarly conference travel is requested for four trips at 1 week a year: $220/ hotel a night; $69 per diem; $550 airfare; $520 in conference fees and $100 misc. fees and ground transportation.	$ 12,772	$ 12,772	$ 12,772	$ 12,772	$ 12,772	$ 63,860
Materials and Supplies						
Non-capital Laptops and Harddrives for remote Postdoc/Students work	$ 12,000	$ -	$ -	$ -	$ -	$ 12,000
Publication Costs						
$10,000-15,000 a year is requested for publication costs	$ 10,000	$ 15,000	$ 15,000	$ 15,000	$ 15,000	$ 70,000
PhD Tuition						
2x PhD tuition at $8,386 a year	$ 16,772	$ 16,772	$ 16,772	$ 16,772	$ 16,772	$ 83,860
Subtotal Direct Operational Costs	**$ 60,372**	**$ 53,372**	**$ 53,372**	**$ 53,372**	**$ 53,372**	**$ 273,860**
Indirect Costs Federally negotiated 23% MTDC off-campus rate (less PhD tuition)	**$ 54,983**	**$ 54,721**	**$ 56,110**	**$ 57,541**	**$ 59,015**	**$ 282,370**
TOTAL BUDGET REQUEST	**$ 310,810**	**$ 309,412**	**$ 316,841**	**$ 324,492**	**$ 332,373**	**$ 1,593,928**

IVa. PROPOSED BUDGET JUSTIFICATION: ERAU (Barjatya)

ERAU Budget Justification Narrative - Fritts

This proposal seeks support at the Co-PI institution for a proposal titled “Integrated Measurement and Modeling Characterization of Stratospheric Turbulence.”

The justification of the specific budget categories follows below.

Salaries:

1. **Key personnel.** PI, Dr. Dave Fritts; support includes 3 months annually for his role as MURI Project Coordinator and modeling oversight. Year 2 through 5 include a 3% salary increase for anticipated wage increases.
2. **Student/Postdoc/Research Associate support** will include the following:
   a. two PhD students for 5 years at an individual initial annual stipend of $25,000,
   b. a 55% time Postdoc skilled in advanced dynamics modeling initially at $33,000, and
   c. a 33% Research Associate having extensive experience with our advanced CFV and DNS codes at $29,300 annually.
3. All salaries increase at 3% in Years 2-5 for anticipated inflation.

Benefits:
FY 2016 fringe benefits have been included. Faculty summer benefits are calculated to be 16.35% and 35.7% is for academic salary, which includes social security, group health insurance, workman’s compensation, retirement, unemployment compensation and tuition waivers. Summer fringe benefits rates are lower since they do not include group health insurance or tuition waiver benefits as these are paid for over the nine month period during academic salary. Student wages include fringe benefits at 0.22% for workman’s compensation. Actuals are applied at costing, and a detail list is available upon request.

Direct Costs:

1. **Travel and Meetings.** Only travel necessary and directly related to the project has been included in the proposal. Per ERAU policies, employees will use the Federal GSA CONUS rates for travel within the Continental U.S. and OCONUS rates determined by the US Department of State for foreign travel.

   Domestic Collaboration Travel:
   Years 1-5: Two trips of one week each from ERAU to Boulder, and two trips from Boulder to ERAU for collaborations on modeling efforts.

   Domestic Conference Travel:
   Years 1-5: Four trips of one week each from conference participation, anticipating both American Geophysical Union and American Meteorological Society meetings.

2. **Publications.** Funds are requested for publications each year: 4 each at $2,500 in Year 1, and 6 each in Years 2-5.

3. **Materials and Supplies:** Non-capital laptops and hard drives for remote student/postdoc work: $12,000 in Year 1 only.

4. **PhD tuition.** Two PhD students at $8,386 each per year, Years 1-5.

Indirect Costs:
ERAU's 43.5% Modified Total Direct Cost (MTDC), federally negotiated, on-campus rate is applied to the proposal. This agreement for ERAU has been negotiated with the Department of Health and Human Services, Federal Cognizant Agency. The agreement is in effect from January 31, 2014 to June 30, 2017 for predetermined rates and June 30, 2018 for provisional rates. The distribution base for indirect costs is as defined in the Office of Management and Budget (OMB) Circular A-21, consisting of all salaries and wages, fringe benefits, materials and supplies, services, travel, and subgrants and subcontracts up to the first $25,000 of each subgrant or subcontract, regardless of the period covered by the subgrant or subcontract. Equipment, capital expenditures, charges for patient care and **tuition remission**, rental costs (for facilities), scholarships, and fellowships are also excluded from modified total direct costs. A copy of the agreement is available upon request.

IV. PROPOSED BUDGET DETAILS: ERAU (Barjatya)

Budget Justification
Integrated Measurement and Modeling Characterization of Stratospheric Turbulence
Dr. Aroh Barjatya

Direct Labor	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Total**
Senior Salaries						
Co-PI: 1.0 months summer salary annually	$ 10,030	$ 10,331	$ 10,641	$ 10,960	$ 11,289	$ 53,251
Co-PI: 0.9 academic months per year (1 course release)	$ 9,298	$ 9,577	$ 9,864	$ 10,160	$ 10,465	$ 49,364
Other Salaries						
Undergraduate hourly salaries	$ 10,000	$ 15,000	$ 15,000	$ 8,000	$ -	$ 48,000
Master's student annual stipend of $15,000	$ 15,000	$ 15,000	$ 15,000	$ 15,000	$ 15,000	$ 75,000
	$ 44,328	**$ 49,908**	**$ 50,505**	**$ 44,120**	**$ 36,754**	**$ 225,615**
Fringe Benefits						
16.35% Summer salary fringe	$ 1,640	$ 1,689	$ 1,740	$ 1,792	$ 1,846	$ 8,707
35.7% Academic salary fringe	$ 3,319	$ 3,419	$ 3,521	$ 3,627	$ 3,736	$ 17,623
.22% Student fringe	$ 55	$ 66	$ 66	$ 51	$ 33	$ 271
	$ 5,014	**$ 5,174**	**$ 5,327**	**$ 5,470**	**$ 5,615**	**$ 26,600**
Subtotal Labor	**$ 49,342**	**$ 55,082**	**$ 55,832**	**$ 49,590**	**$ 42,369**	**$ 252,215**
Domestic Travel & Meetings						
Travel: Local, domestic and foreign travel are requested as broken down in the budget narrative.	$ 8,000	$ 15,000	$ 15,000	$ 8,000	$ 5,000	$ 51,000
Materials and supplies: No capital items	$ 65,000	$ 55,000	$ 55,000	$ -	$ -	$ 175,000
Master's Tuition: 15 credits a year	$ 22,066	$ 22,481	$ 22,904	$ 23,553	$ 24,221	$ 115,225
	$ 95,066	**$ 92,481**	**$ 92,904**	**$ 31,553**	**$ 29,221**	**$ 341,225**
Indirect Costs - 43.5% MTDC On-campus	**$ 53,219**	**$ 54,411**	**$ 54,737**	**$ 25,052**	**$ 20,605**	**$ 208,024**
	$ 197,627	**$ 201,974**	**$ 203,473**	**$ 106,194**	**$ 92,195**	**$ 801,464**

IVa. PROPOSED BUDGET JUSTIFICATION: ERAU (Barjatya)

ERAU Budget Justification Narrative - Barjatya

This proposal seeks support at the Co-PI institution for a proposal titled "Integrated Measurement and Modeling Characterization of Stratospheric Turbulence."

The justification of the specific budget categories follows below.

Salaries:

1. **Key personnel.** Co-PI, Dr. Aroh Barjatya, support includes 1.0 summer months and 0.9 academic months annually. Year 2 through 5 includes a 3% salary increase for anticipated wage increases.
2. **Student support.** Two undergraduate students are requested at hourly pay for up to $10,000 in year 1, $15,000 in years 2-3, and $8,000 in year 4. One master's student is requested to be supported at $5,000 stipends, one each for fall, spring and summer semesters annually, for a total of $15,000 a year annually.

Benefits:

FY 2016 fringe benefits have been included. Faculty summer benefits are calculated to be 16.35% and 35.7% is for academic salary, which includes social security, group health insurance, workman's compensation, retirement, unemployment compensation and tuition waivers. Summer fringe benefits rates are lower since they do not include group health insurance or tuition waiver benefits as these are paid for over the nine month period during academic salary. Student wages include fringe benefits at 0.22% for workman's compensation. Actuals are applied at costing, and a detail list is available upon request.

Direct Costs:

1. **Travel and Meetings.** Only travel necessary and directly related to the project has been included in the proposal. Per ERAU policies, employees will use the Federal GSA CONUS rates for travel within the Continental U.S. and OCONUS rates determined by the US Department of State for foreign travel.

   Domestic Travel:
   Year 1 and 4: $8,000; Research and collaboration: Mileage travel is requested at .54 cents a mile for up to 1,000 miles for the Co-PI and team to travel throughout FL for off-site balloon launches for a total of $540 a year. Note that we plan on launching downwind of the ground station to increase the balloon contact time. Up to four of these trips for two nights are requested at a total of $1,472: $105/ hotel, $69 per diem, and $20 for miscellaneous transportation costs, for a cumulative total of $2,012. **Scholarly conference travel:** $200/day lodging, $69/day per diem, $500 airfare, $500 conference fee and $110 misc. expenses for 2 people at 7 days = $5,988 a year.

   Year 2 and 3: $2,380; Research and collaboration: Mileage travel is requested at .54 cents a mile for up to 1,000 miles for the Co-PI and team to travel throughout FL for off-site balloon launches for a total of $540 a year. Note that we plan on launching downwind of the ground station to increase the balloon contact time. Up to five of these trips for two nights are requested at a total of $1,840: $105/ hotel, $69 per diem, and $20 for miscellaneous transportation costs equals $1,840, for a cumulative total of $2,380.

Year 5: $5,000; Research and collaboration: Mileage travel is requested at .54 cents a mile for up to 1,000 miles for the Co-PI and team to travel throughout FL for off-site balloon launches for a total of $540 a year. Note that we plan on launching downwind of the ground station to increase the balloon contact time. Up to four of these trips for two nights are requested at a total of $1,472: $105/ hotel, $69 per diem, and $20 for miscellaneous transportation costs, for a cumulative total of $2,012. **Scholarly conference travel:** $200/day lodging, $69/day per diem, $500 airfare, $500 conference fee and $110 misc. expenses for 1 people at 7 days = $2,988 a year.

Foreign Travel:
$12,620 in years 2 and 3, for a total of $25,240 in foreign travel.
Norway Year 2 and 3: $145/day lodging, $125/day per diem, $2,760 airfare, $310 misc. expenses for 2 people at 12 days = $12,620 a year. The Intense Observing Period launches will be held near Andoya, Norway.

2. **General Materials and Supplies.** General supplies are requested in years 1 and 2 for $65,000 and $55,000 in year 3. These general supplies will cover balloons, helium, radio, antenna, command and data handling board, and standard environmental sensors for upto 180 launches during the course of the entire program. It also includes testing and development costs for the balloon platform which will be conducted in the first year of the program to achieve maximum balloon altitude.

3. **Master's Student Tuition.** Tuition is requested for 15 credits a year.

Indirect Costs:

ERAU's 43.5% Modified Total Direct Cost (MTDC), federally negotiated, on-campus rate is applied to the proposal. This agreement for ERAU has been negotiated with the Department of Health and Human Services, Federal Cognizant Agency. The agreement is in effect from January 31, 2014 to June 30, 2017 for predetermined rates and June 30, 2018 for provisional rates. The distribution base for indirect costs is as defined in the Office of Management and Budget (OMB) Circular A-21, consisting of all salaries and wages, fringe benefits, materials and supplies, services, travel, and subgrants and subcontracts up to the first $25,000 of each subgrant or subcontract, regardless of the period covered by the subgrant or subcontract. Equipment, capital expenditures, charges for patient care and **tuition remission**, rental costs (for facilities), scholarships, and fellowships are also excluded from modified total direct costs. A copy of the agreement is available upon request.

Contracts & Grants

Proposal Title Integrated Mesaurement and Modeling Characterization of Stratosperic Tubulence

Proposal Number and/or Date 16-10-0009

Representation Regarding an Unpaid Delinquent Tax Liability or a Felony Conviction under Any Federal Law – DoD Appropriations

(1) The applicant represents that it is ___ is not__X_a corporation that has any unpaid Federal tax liability that has been assessed, for which all judicial and administrative remedies have been exhausted or have lapsed, and that is not being paid in timely manner pursuant to an agreement with the authority responsible for collecting the tax liability.

(2) The applicant represents that it is__ is not _X_a corporation that was convicted of a felony criminal violation under any Federal law within the preceding 24 months.

NOTE: If an applicant responds in the affirmative to either of the above representations, the applicant is ineligible to receive an award unless a Federal agency suspension and debarment official (SDO) has considered suspension or debarment and determined that further action is not required to protect the Government's interests. The applicant therefore should provide information about its tax liability or conviction to the agency's SDO as soon as it can do so, to facilitate completion of the required consideration before award decisions are made.

Representation Regarding the Prohibition on Using Funds under Grants and Cooperative Agreements with Entities that Require Certain Internal Confidentiality Agreements

By submission of its proposal or application, the applicant represents that it does not require any of its employees, contractors, or subrecipients seeking to report fraud, waste, or abuse to sign or comply with internal confidentiality agreements or statements prohibiting or otherwise restricting those employees, contractors, or subrecipients from lawfully reporting that waste, fraud, or abuse to a designated investigative or law enforcement representative of a Federal department or agency authorized to receive such information. Note that, as applicable, the bases for this representation are the prohibition(s) as follow:

a. Section 743 of the Financial Services and General Government Appropriation Act, 2015 (Division E of the Consolidated and Further Continuing Appropriations Act, 2015, Pub. L. 113-235)
b. Section 101(a) of the Continuing Appropriation Act, 2016 (Pub. L. 114-53) and any subsequent FY2016 appropriations act that extends to FY2016 the same restrictions as are contained in section 743 of Division E, title VII of the Consolidated and Further Continuing Appropriations Act, 2015 (Pub L. 113-235)
c. Any successor provision of law on making funds available through grants and cooperative agreements to entities with certain internal confidentiality agreements or statements

The prohibitions stated above do not contravene requirements applicable to Standard Form 312, Form 4414, or any other form issued by a Federal department or agency governing the nondisclosure of classified information.

(1) The applicant represents that it is ___ is not_X__ a corporation that has any unpaid Federal tax liability that has been assessed, for which all judicial and administrative remedies have been exhausted or have lapsed, and that is not being paid in timely manner pursuant to an agreement with the authority responsible for collecting the tax liability

(2) The applicant represents that it is__ is not _X_a corporation that was convicted of a felony criminal violation under any Federal law within the preceding 24 months.