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Integrated Measurement and Modeling Characterization of Stratospheric Turbulence

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14. ABSTRACT The research goal of the AFOSR MURI Integrated Measurement and Modeling Characterization of Stratospheric Turbulence is to discover, understand, and characterize the spatiotemporal description of atmospheric turbulence and particulates above 80,000 ft (24 km), and the connection of these phenomena to meteorology at lower altitudes. A summary of the major accomplishments of the research include: - Atmospheric Measurements - Integrated payload with turbulence, particulate sensors; automated ground-station receivers; one-year multiple-site final campaign - Developed turbulence and particulate sensor calibration facilities; - Simulated fine-wire fly-through to verify experimental turbulence dissipation - Developed and deployed an automated distributed ground station receiver network - Conducted IOP campaigns to verify mountain wave turbulence source; field campaign support for BOLT-I, BOLT-II flight experiments - Conducted ground-based experiments to test and verify optical propagation models and fine-wire measurement theories - Atmospheric Simulations - Produced simulations scaled to represent mid-stratospheric turbulence inflow conditions for hypersonic simulations - Simulations verified potential mountain sources for turbulence for BOLT-I - Discovered "tubes & knots" as a ubiquitous source for strong turbulence throughout the atmosphere - Development of a strawman global forecast system in progress - Hypersonic Simulations - Verified boundary-layer amplification of disturbances from simulated intense mid-stratospheric turbulence event - Input-output analysis used to verify amplified disturbance frequencies - Verified supersonic particulates in the shock layer induce pressure disturbances in the hypersonic boundary layer					
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AFOSR MURI
Integrated Measurement and Modeling Characterization of
Stratospheric Turbulence

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Dale Lawrence, Andreas Muschinski, Gregory Rieker

14 December 2022

1 Executive Summary

1.1 MURI Research Statement: Goal and Objectives

Figure 1 shows a X-51A waverider scramjet engine demonstrator designed for airspeeds above Mach 6 and above 70,000-ft (21-km) altitude. The final of four test flights was completed on 1 May 2013, with the vehicle reaching an airspeed of approximately Mach 5.1, with a record-setting 210 seconds of airbreathing hypersonic flight (Rondeu & Jorris, 2013). At 80,000 ft (24 km) and Mach 5.1, atmospheric disturbance frequencies of 10 kHz to 1000 kHz correspond to spatial scales of 15 cm to 1.5 mm, respectively, and at Mach 7 and 24 km, the same disturbance frequency range corresponds to spatial scales of 21 cm to 2.1 mm. These spatiotemporal and disturbance frequency scales cover a range of interest to USAF for hypersonic flight.

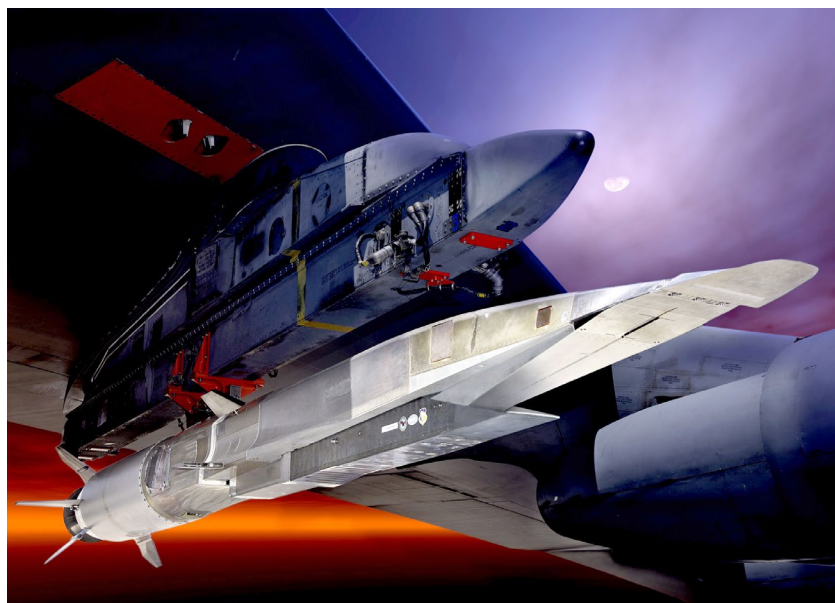


Figure 1 A X-51A Waverider, shown here under the wing of B-52 Stratofortress, demonstrated scramjet-powered acceleration to above Mach 5 and above 70,000 ft in 2013.[†]

The length scales correspond to freestream acoustic waves that pass through the bow shock wave of a hypersonic flight vehicle. However, realistic freestream disturbances due to atmospheric turbulence or suspended particulates are not acoustic waves, and their interaction with a hypersonic flow field is extremely complicated. Furthermore, turbulence is broadband and contains length scales down to the Kolmogorov scale when these disturbances interact with an oblique shock wave, producing a complicated array of acoustic, vertical, and entropy waves. These transmitted perturbations interact with the hypersonic flow field and may initiate boundary-layer instability modes, leading to boundary layer transition and the onset of turbulent flow. It is currently not known how freestream turbulent motion and particulates couple to a hypersonic flow field. Is there a critical level of turbulence that initiates transition? What is the range of scales required to couple with a given boundary-layer instability mode? Do small atmospheric particulates produce a sufficiently large disturbance to initiate the growth of instabilities? Which instabilities are more receptive to realistic atmospheric disturbances? Answering these questions is critical to predicting boundary-layer transition in hypersonic flight.

The research goal of the AFOSR MURI Integrated Measurement and Modeling Characterization of Stratospheric Turbulence is to discover, understand, and characterize the spatiotemporal description of atmospheric turbulence and particulates above 80,000 ft (24 km), and the connection of these phenomena to meteorology at lower altitudes.

1.2 MURI Year-5 Research Summary

The HYFLITS research team accepted an unprecedented multi-scale measurement, modeling, and simulation challenge. Our response to this challenge, highlighted in Figure 2, led us to develop new instruments and deployment strategies, and new modeling and simulations to measure and describe spatiotemporal conditions in the stratosphere.

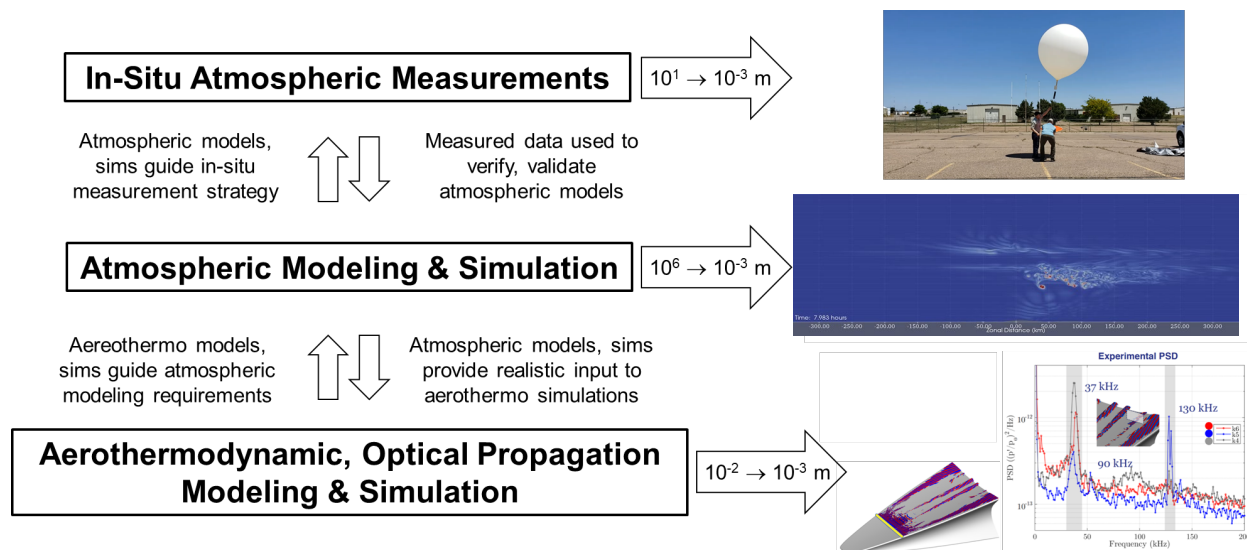


Figure 2 The HYFLITS multi-scale challenge illustrating the relevant spatial and temporal scales.

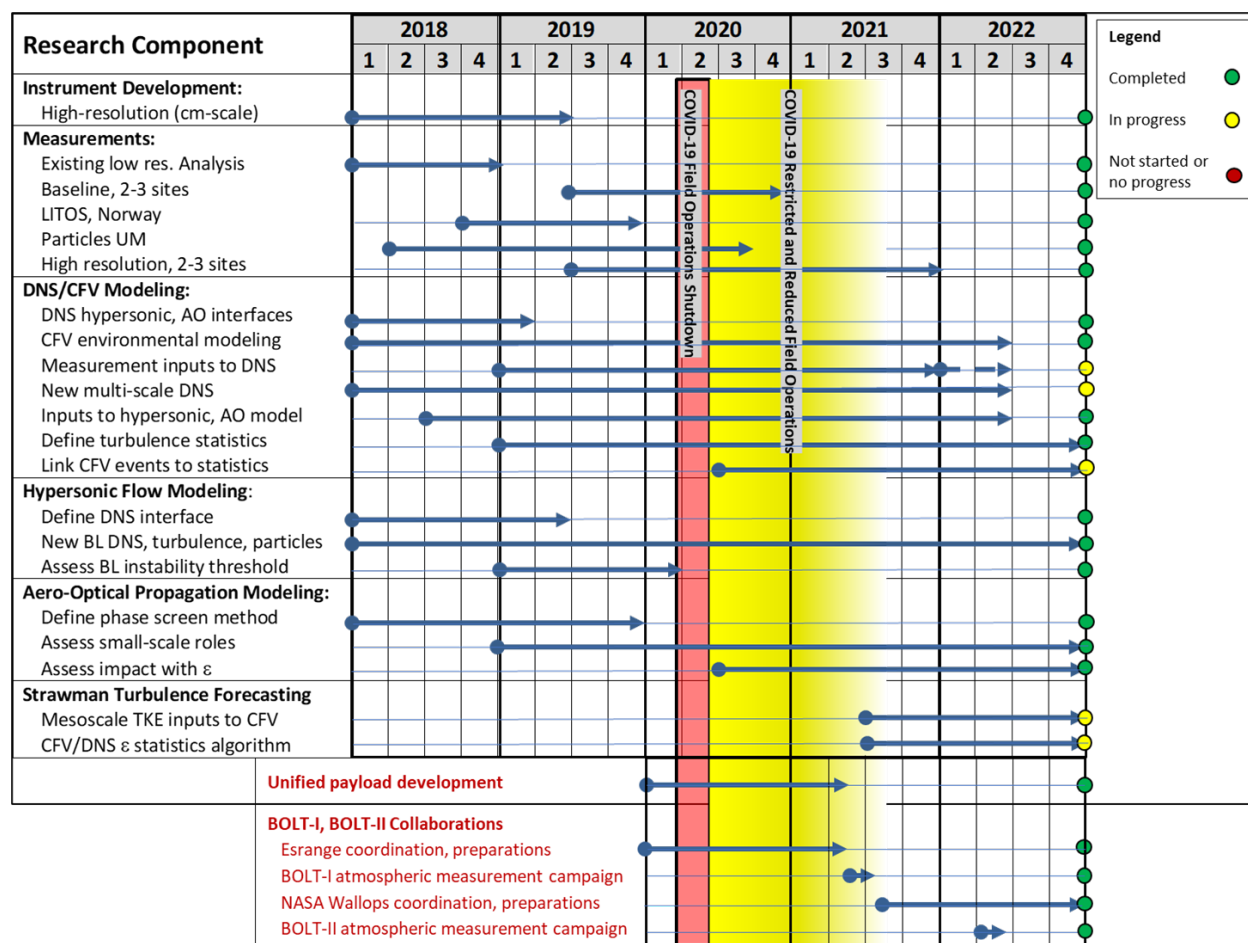
A summary of the major accomplishments of the HYFLITS research include:

- **Atmospheric Measurements**
 - Integrated payload with turbulence, particulate sensors; automated ground-station receivers; one-year multiple-site final campaign
 - Developed turbulence and particulate sensor calibration facilities;
 - Simulated fine-wire fly-through to verify experimental turbulence dissipation
 - Developed and deployed an automated distributed ground station receiver network
 - Conducted IOP campaigns to verify mountain wave turbulence source; field campaign support for BOLT-I, BOLT-II flight experiments
 - Conducted ground-based experiments to test and verify optical propagation models and fine-wire measurement theories
- **Atmospheric Simulations**
 - Produced simulations scaled to represent mid-stratospheric turbulence inflow conditions for hypersonic simulations
 - Simulations verified potential mountain sources for turbulence for BOLT-I
 - Discovered “tubes & knots” as a ubiquitous source for strong turbulence throughout the atmosphere
 - Development of a strawman global forecast system in progress
- **Hypersonic Simulations**
 - Verified boundary-layer amplification of disturbances from simulated intense mid-stratospheric turbulence event
 - Input-output analysis used to verify amplified disturbance frequencies
 - Verified supersonic particulates in the shock layer induce pressure disturbances in the hypersonic boundary layer

1.3 Year-5 Tasks and Project Completion

The MURI schedule is shown in Table 1. Progress on each task is described by the stoplight colors defined in the legend. There are no tasks for which there was no progress. Development of a robust, reliable, and low-cost method for balloon deployment and automated tracking, and turbulence and particulate sensing instruments into a common gondola, took a few extra months of testing at the CU, ERAU, and UMN sites. The integrated payload was not specifically proposed in the original proposal, but at the Year-2 Review in December 2019, it was agreed by the HYFLITS team and PO Ivett Leyva that an integrated measurement payload should be an objective prior to a sustained campaign of background measurements made at a regular cadence from the three launch sites. These instrument development and deployment challenges resulted in an approximate 6-mo delay for the start of routine balloon launches and data collection. The integrated payload was verified with flights a few weeks prior to the deployment to Esrange, Sweden to support the BOLT-I flight experiment.

Table 1 MURI schedule and final project status



Following the BOLT-I experiment, the MURI atmospheric measurement team received an additional 1.5-year grant for a measurement campaign to support the BOLT-II flight experiment at the Wallops Island Flight Facility in March 2022. As shown in Table 1, preparation and deployment for the flight tests overlapped with the final year of the MURI. The success of the BOLT-II atmospheric measurement campaign is described in the final report for that grant.

2 HYFLITS Research Team

2.1 Organization

The Co-PIs of the AFOSR MURI **HY**personic **FL**ight in the **T**urbulent **S**tratosphere (HYFLITS) research team are shown in Figure 3. Our team is grouped into four primary task areas: 1) **Stratospheric Measurements and Analysis** is focused in-situ technologies and strategies to collect stratospheric turbulence and particulate data. These data are analyzed to characterize conditions in the middle stratosphere; 2) **Atmospheric Modeling and Forecasting** is focused on creating high-fidelity, multi-scale atmospheric simulations covering synoptic-scale gravity waves to centimeter-scale turbulence. In-situ data are used to refine and tune the atmospheric models; 3) **Aerothermodynamics Modeling** is focused on the simulation of the hypersonic boundary layer and investigating how ambient turbulence and particulates drive instability and laminar-to-turbulent transition. In-situ turbulence and particulate measurements will be used to tune atmospheric simulations to provide realistic and accurate inflow conditions for flow simulations over air vehicles to investigate boundary-layer stability and laminar-to-turbulent flow transition; 4) **Optical Propagation Measurement, Modeling, and Simulations** will provide insight into how ambient stratospheric conditions impact optical propagation.

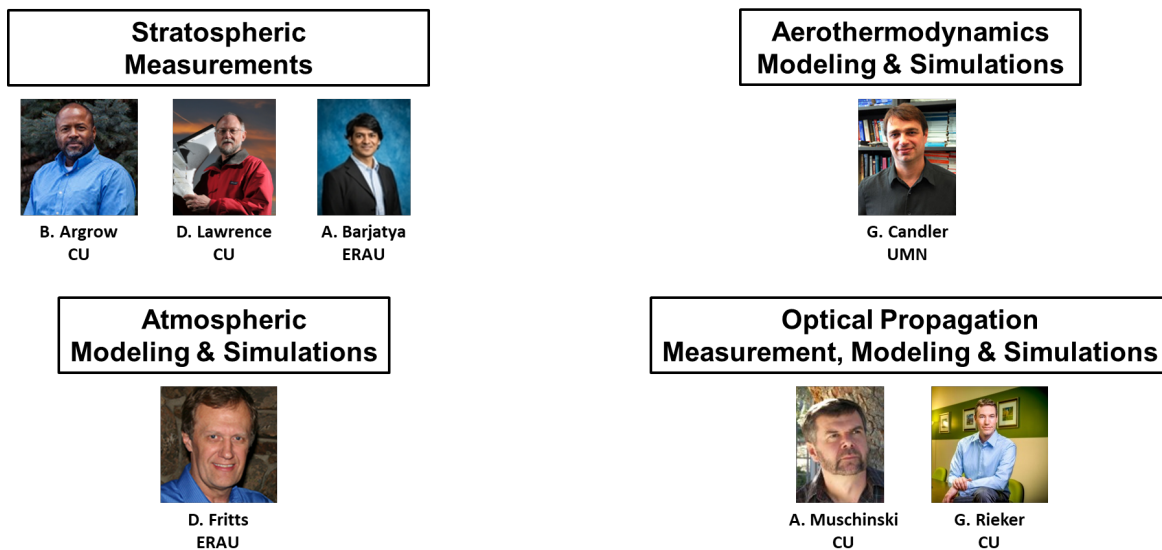


Figure 3 The HYFLITS MURI team and research areas, with PIs from the University of Colorado (CU), University of Minnesota (UMN), and Embry-Riddle Aeronautical University (ERAU).

MURI PI Brian Argrow is responsible for the organization of the overall team, and a co-investigator on the atmospheric measurement team. Co-PI David Fritts leads the ERAU atmospheric modeling and simulation team and is responsible for HYFLITS project coordination. This coordination includes guidance for the atmospheric measurements and optical-propagation teams for deployment locations and strategies based on atmospheric simulations and forecasts. Co-PI Dale Lawrence leads the atmospheric measurements team at CU and coordinates the measurement teams at ERAU and UMN led, respectively, by Co-PI Aroh Barjatya and Co-PI Graham Candler. Fritts' team is also responsible to provide high-resolution atmospheric simulations for Candler's UMN aerothermodynamics modeling team, and to the optical-propagation measurement and modeling team is led by Co-PI Andreas Muschinski CU.

3 Research Report

3.1 Stratospheric Measurements

The stratospheric turbulence measurement objectives of the HYFLITS project are:

- Conduct extensive, geographically distributed measurements of in-situ turbulence and background winds above 20 km altitude.
- Acquire measurements under normal and very strong meteorological forcing conditions.
- Combine in-situ turbulence measurements with geophysical modeling/simulation to guide specification of turbulence characteristics and spatiotemporal statistics as functions of the underlying meteorology.

The stratospheric particulate measurement objective of the HYFLITS project is:

- Characterize particulate sizes and concentrations coincident with turbulence measurements.

Progress toward these objectives is discussed in corresponding sections below. First, progress in balloon systems that support both turbulence and particulate measurements is discussed, followed by progress in the turbulence and particulate instruments separately.

3.1.1 Balloon Platform

The aim of turbulence-measurement effort is to develop measurement technology that can be deployed on low-cost weather balloons, and to lower the costs of deploying and recovering data from these platforms, such that a relatively large number (~100) of observations could be made per year. These observations would nominally be made at the three primary locations of the MURI team (Colorado, Florida, Minnesota), but other locations for campaigns of opportunity were also of interest. The BOLT-I experiment provided an ideal example of the latter, and plans are continuing to measure the local conditions that the BOLT-I vehicle will experience, as well as characterize the turbulence environment more widely in northern Sweden. See Sect. 5 for more detail on the HYFLITS/BOLT-I campaign.

Turbulence sensing requires measurements to be taken during a slow descent through the altitudes of interest, so that the sensors are not in the turbulent wake of the measurement system and supporting balloon. Figure 4 shows a typical altitude profile of the HYFLITS system, rising on a weather balloon at about 5 m/s, then partially venting the lifting gas (helium) to produce a slow descent (about 2 m/s). The balloon is typically cut away below the altitude range of interest to allow a faster descent of the payload through controlled airspace on a parachute. Note that the payload is lightweight enough to conform to an “unregulated” free balloon in the US, and to the “light” category of free balloons in the EU, greatly reducing the coordination needed with local air traffic control authorities.

Turbulence measurement technology was developed specifically for low-cost balloon platforms during the first year of the project, deriving from similar instruments developed at CU for small unmanned aircraft. This first-generation balloon instrument was flown during the second year of the project, but was refined to the second-generation design, shown in Figure 5, that was used during the third year of the project on flights from Colorado, Minnesota, and Florida. These avionics evolved into the current third-generation design that integrates the turbulence and particle instruments into a single, compact payload that is produced in one location for consistency and lower costs, and provided to MURI members in Colorado, Minnesota, and Florida in a ready-to-launch form. Figure 6 shows the third-generation integrated MURI payload with the insulating foam box removed.

Particulate concentration sensing in the integrated payload is based on a commercial Alphasense N3 optical particle counter (OPC) that has been modified to operate in the rarefied flow conditions in the Stratosphere. This sensor is operated by a custom interface board developed by the UMN that

communicates packetized OPC data to the main avionics board for subsequent storage or telemetry. A key problem with aspirating the optical sensor properly at high altitudes (low air density) was solved in this reporting period by using a centrifugal blower instead of the stock axial fan or a constant-displacement pump used on other high-altitude OPC systems. This is discussed in more detail in Section 3.1.4.

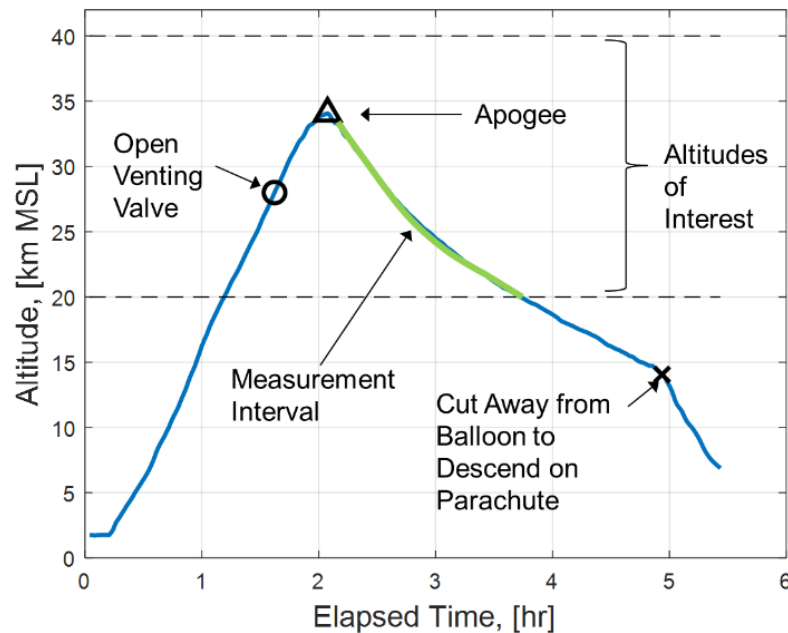


Figure 4 HYFLITS descending measurement strategy provides slow airspeed and no balloon wake for high-quality turbulence observations.

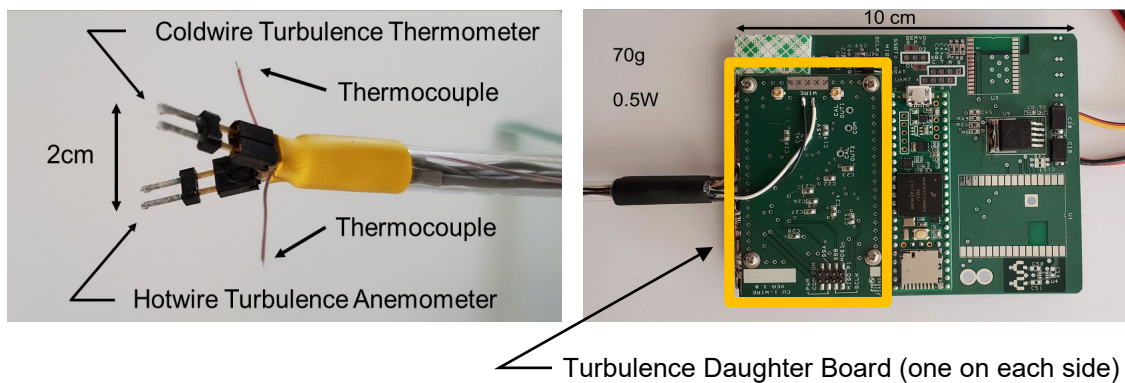


Figure 5 Second-generation custom HYFLITS turbulence instrument for hotwire anemometry and coldwire thermometry, along with supporting avionics for real time data telemetry.

Typical balloon deployments require several personnel. This makes even one launch per week problematic due to the variables of weather (to avoid or to target) combined with busy schedules, not to mention the costs of maintaining a large cadre of trained operators. Instead, work at CU has focused on enabling single-person balloon launches (Figure 7).

High-quality turbulence measurements cannot be made in the wake of the balloon, or at high airspeeds, so it is necessary for the payload (slung under the balloon) to make measurements during a slow descent; see Figure 4. Conventional two-balloon approaches, where one balloon is cut away at apogee, require more personnel to manage the balloons during launch, especially in winds. Instead, a low-cost and lightweight venting valve has been developed at CU (Figure 7), enabling a single-balloon flight train that can be handled by one person, as seen in Figure 8, shown just as the gondola is released, occurring about 6 seconds after the balloon was released by the same person.

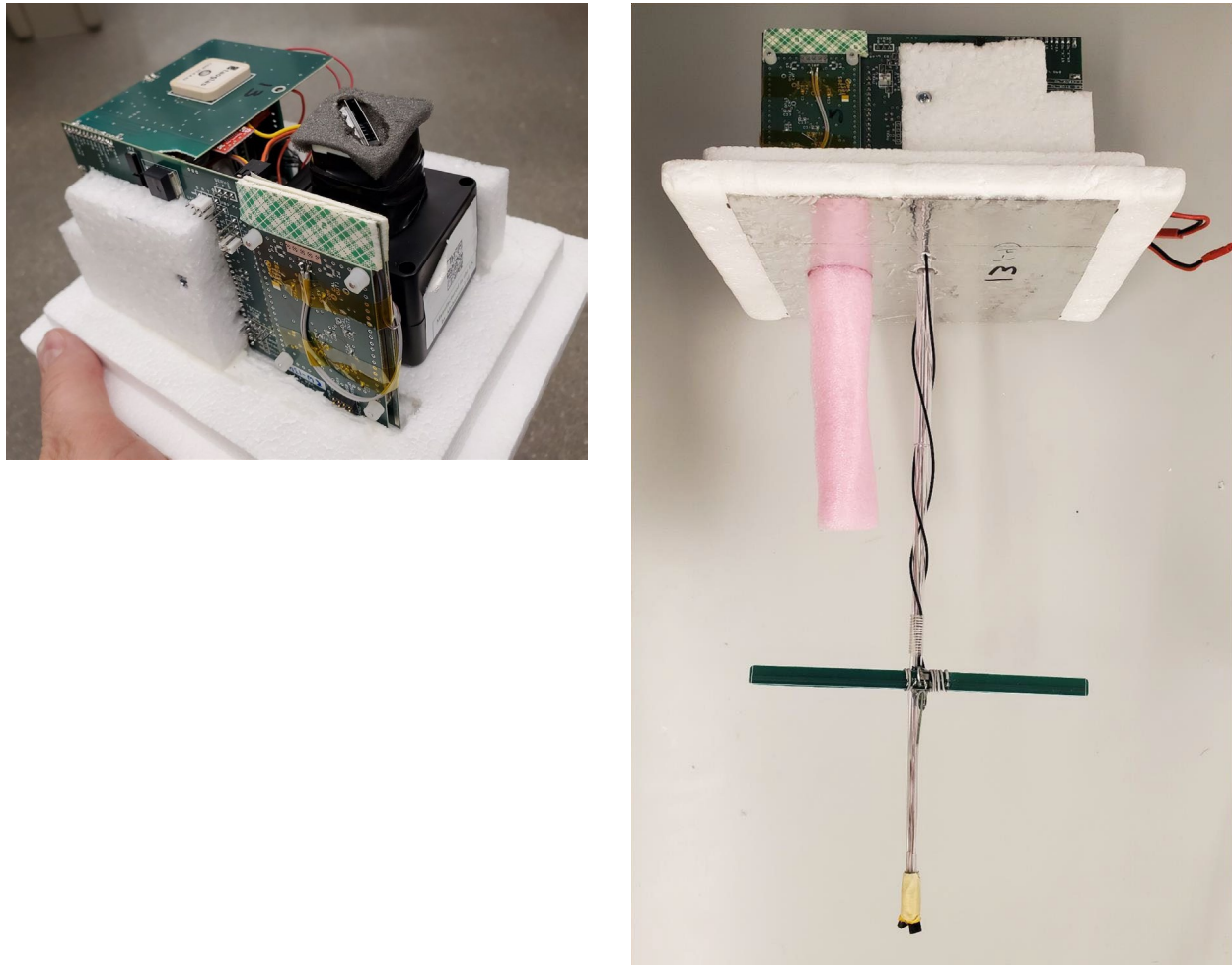


Figure 6 HYFLITS integrated turbulence and particle sensing payload avionics (left), along with the turbulence probe/telemetry antenna and particle inlet tube in the normal downward orientation for descending measurements of free-stream conditions (right).

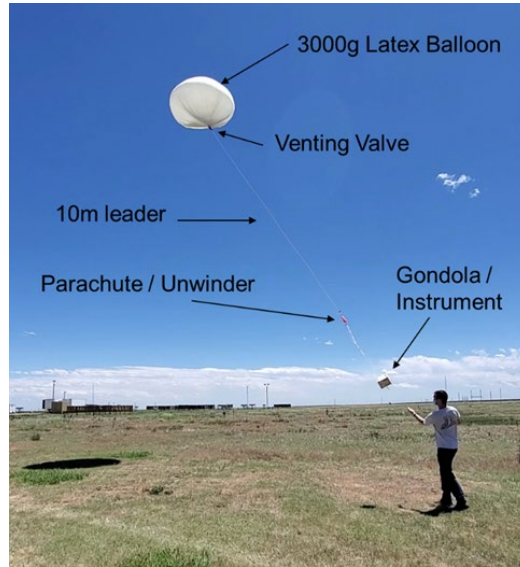


Figure 7 If the balloon can be filled indoors, a single-person launch is feasible even in gusty winds, greatly reducing the cost of balloon deployments. Outdoor filling, e.g. in cases where the launch must be mobile to target the measurement location based on predicted trajectory due to wind, require additional personnel to manage the balloon during filling.

Several advances were needed to reduce the cost of operations for the large number of observations planned. These advances are discussed briefly below.

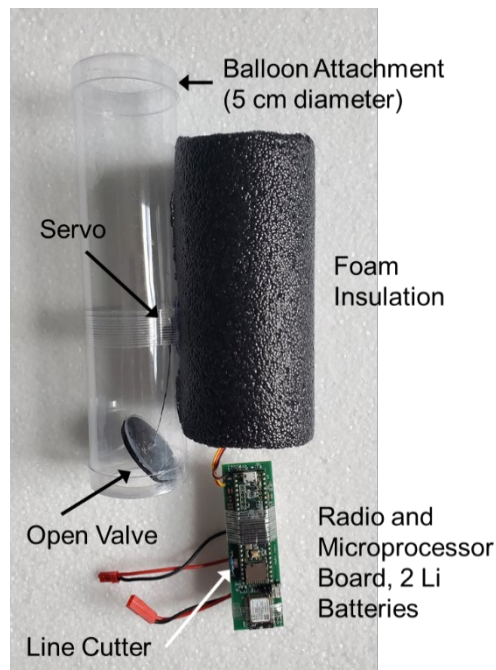


Figure 8 HYFLITS Lightweight, low cost venting valve at the balloon neck, linked by radio to the gondola.

In flight, the lifting gas is vented to stop the balloon's ascent at a desired apogee, and to provide a subsequent slow descent for wake-free measurements. A major challenge arose early in this work, where

the balloon sometimes does not expel enough lifting gas, even if the valve is left open, arresting the descent. This was traced to the inelastic properties of the latex balloon material, where strain past a critical threshold becomes unrecoverable. Through analysis of data from many flights, a critical strain limit of 2.9 was found, such that reliable descents (2-3 m/s) are produced by keeping balloon strain under this bound. Because the balloon expands with altitude, this enabled models to be developed that limit achievable apogees for descending measurements as a function of balloon size and payload mass. Figure 9 shows the resulting apogee limits for reliable descent after venting for descending measurements at 2 m/s as a function of balloon size and payload mass.

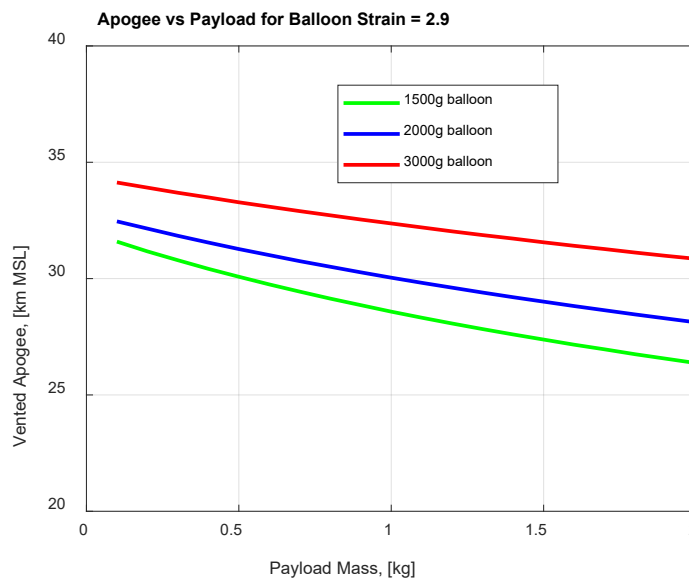


Figure 9 Apogee limits for reliable descent after venting, as a function of balloon size and payload mass.

A related problem is that predictions of vertical winds above 17 km are not available, e.g. from the Global Forecasting System models, and the prescribed apogee limits can be easily exceeded due to these updrafts if a fixed venting altitude threshold is used, resulting in widely scattered descent-rate statistics. This problem was solved by using a valve that can be opened and closed repeatedly, and a control law in flight that compares the current altitude-versus-vertical rate curve to a nominal one developed through analysis of many flights. The vent is opened if the balloon is above the nominal ascent rate, and the valve is closed if the balloon is below the nominal rate (see Figure 10), resulting in real-time reactions to vertical winds, and much more reliable limits on apogee, leading to significant reliability improvement in descent rates. See Figure 11.

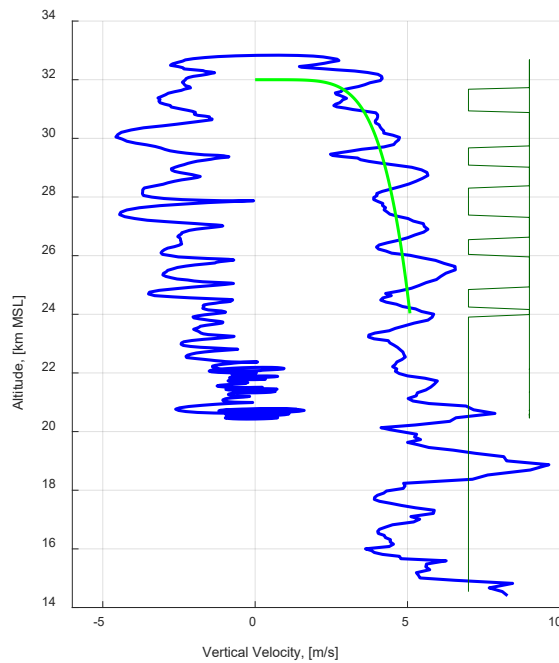


Figure 10 Balloon vertical velocity vs. altitude, showing how valve on-off behavior (dark green line) based on balloon velocity relative to the nominal target (light green line) can achieve reliable limits on apogee, even in the presence of extreme gravity wave activity.

The original single-person deployment approach had a short 2m tether between the instrument (in the gondola box) and the venting valve (in the balloon neck). Later analysis of the up-stream effects of the large balloon (about 6m in diameter at apogee) on turbulence measurements necessitated a longer tether. In turn, this required an unwinding mechanism to keep the tether short enough for one person to hold both balloon and gondola for launch but allow 10m tether lengths during descending measurements. A very low cost, low weight unwinder was developed for this purpose. This also required a radio link between the gondola and the venting valve, since direct wiring was no longer feasible at this length. A miniature version of the gondola avionics board was developed (shown in Figure 8) with a microcontroller to support this remote operation of the servo in the valve in the balloon neck. This board also supports measurements of the inside/outside pressure difference in the balloon, as well as inside/outside temperatures, intended to be used for more refined balloon performance modeling and prediction.

The final missing piece in low-cost operations is the large cost in traditional balloon operations incurred in chasing the balloon to recover the payload and its data. This is unavoidable if the instrument is of sufficiently high value, but this also prevents high-cadence measurements of the type desired for HYFLITS. In concert with low-cost expendable payloads, a long-range telemetry ability was developed, based on previous experience in over-ocean ballooning at ERAU (where payload recovery is generally impossible). The enables operation effort and cost to be focused on a few hours for preparation and launch, rather than entire days of effort to locate and recover payloads. The system developed at CU utilizes a custom switched-dipole antenna, that is concentric with the turbulence probe to avoid effects on the antenna pattern. See Figure 12. The pattern is also optimized for long-distance transmission from the balloon by design of a lightweight reflector, providing up to 5 dB of gain in directions needed most, and use of horizontal polarization to reduce interference from terrestrial radio antennas that are usually vertically polarized. A steerable high-gain antenna is used on the ground to receive these signals. This

system can receive data at a slant range up to 200km, enabling many more measurement scenarios while lowering the cost of each balloon deployment.

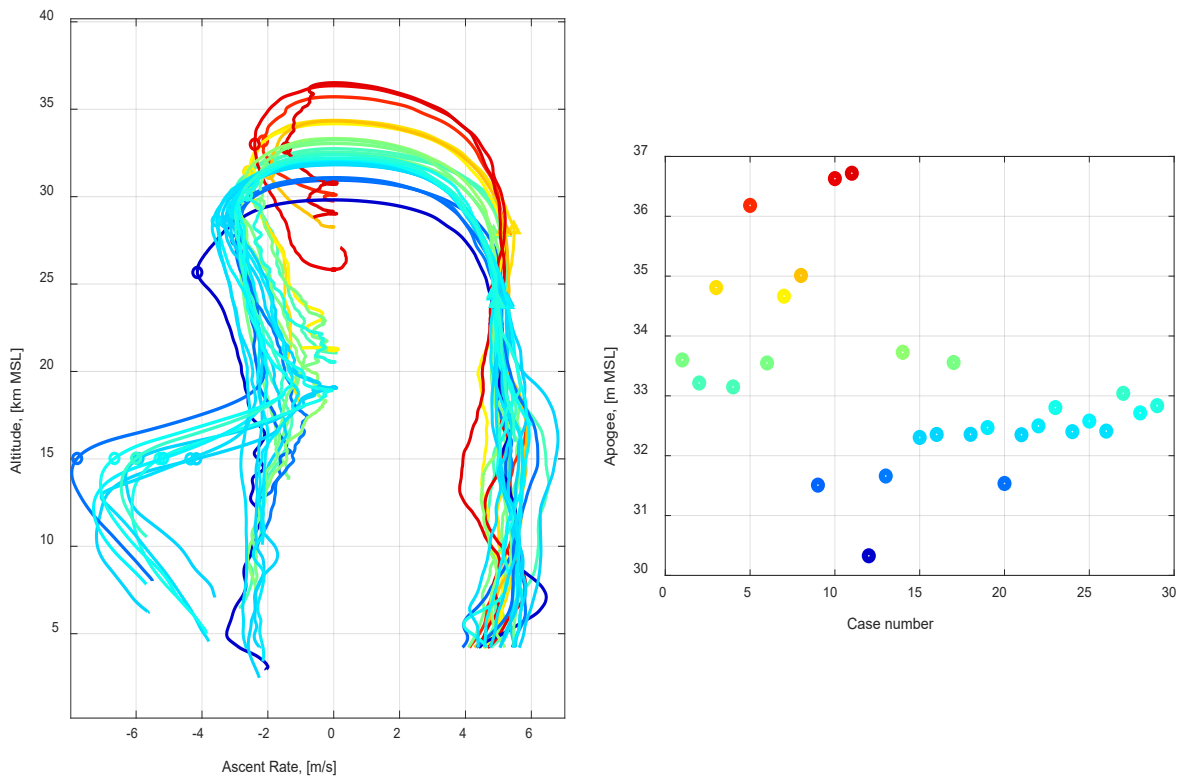


Figure 11 Flights without venting control (color coded by apogee, left). Achieved apogees showing large variation with fixed venting altitude (case numbers < 20), and significant reduction in variability using feedback on/off valve control (case numbers > 20).

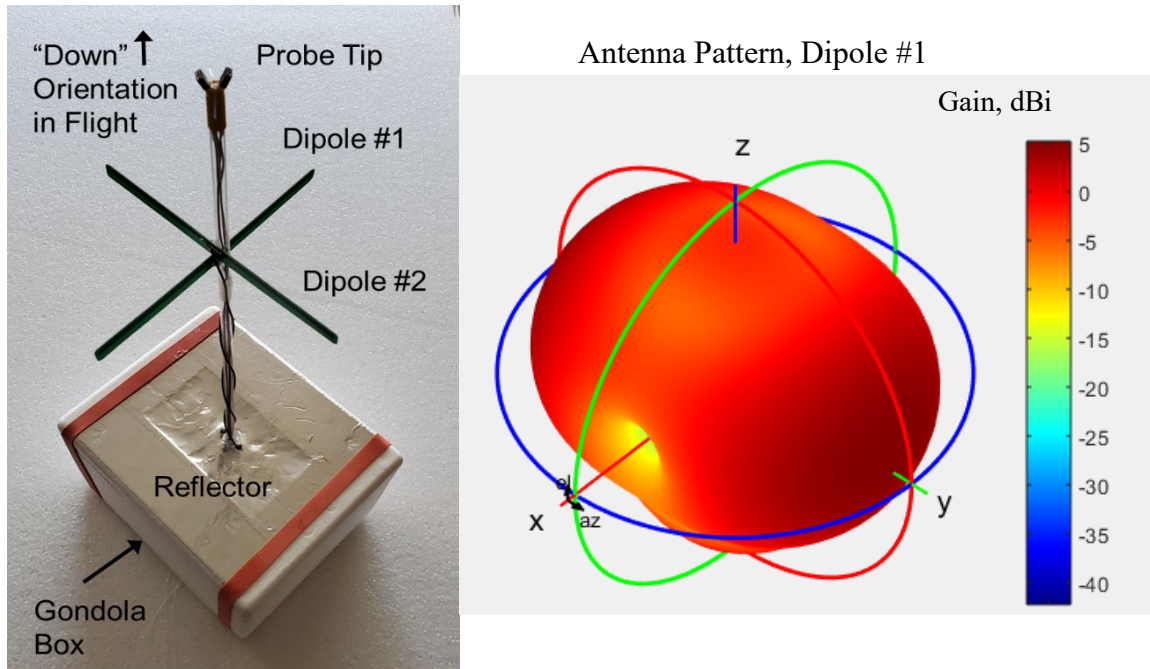


Figure 12 Custom switched dipole antenna design on the CU gondola provides enhanced gain in directions needed most, horizontal polarization, and no interaction with the concentric turbulence probes.

3.1.1.1 Acquire Measurements Under a Range of Forcing Conditions

Modeling efforts led by Dave Fritts (see Section 3.2) have shown that strong convective storm cells can generate gravity waves that propagate upward and outward into the stratosphere, and can subsequently break if the amplitudes are large enough to produce local potential temperature gradients that are negative, leading to instability. Turbulence arises from this unstable conversion into kinetic energy, and the resulting non-linear cascade of this energy to smaller scales. Coincidentally, one of the MURI researchers (Argrow) was involved in a large NSF-sponsored campaign called TORUS to study tornado genesis in supercell thunderstorms in the spring of 2019, involving significant resources for the prediction of supercell storms and personnel to place unmanned aircraft close to them. This was an ideal opportunity for the MURI team to deploy in cooperation with them to place high-altitude balloons in proximity to these storms to measure gravity wave forcing and resulting turbulence. This was also the first opportunity to fly the newly developed balloon-specific turbulence instrument, as well as the single-vented-balloon approach at CU.

A mobile balloon launch and tracking system was developed for the HYFLITS/TORUS campaign. Tracking was accomplished by comparing tracker and received balloon GPS coordinates and calculating the resulting geo-referenced azimuth and elevation angles to point the high-gain antenna at the balloon. This required the mobile tracker to be set up before each balloon launch with known reference angles that remain fixed throughout the flight. Although tracking locations were always chosen to stand-off from the targeted storm, and to avoid other storms, this location often became dangerous over the course of a 6 hour balloon flight, due to the genesis of other storms that would pass over this location. As a result, contact with many balloons was terminated by static discharge damage on the payload, and lightening danger to the personnel in the tracker sometimes required the tracker to be moved, causing loss of pointing references and subsequent loss of contact with the payload. Figure 13 shows one such case.

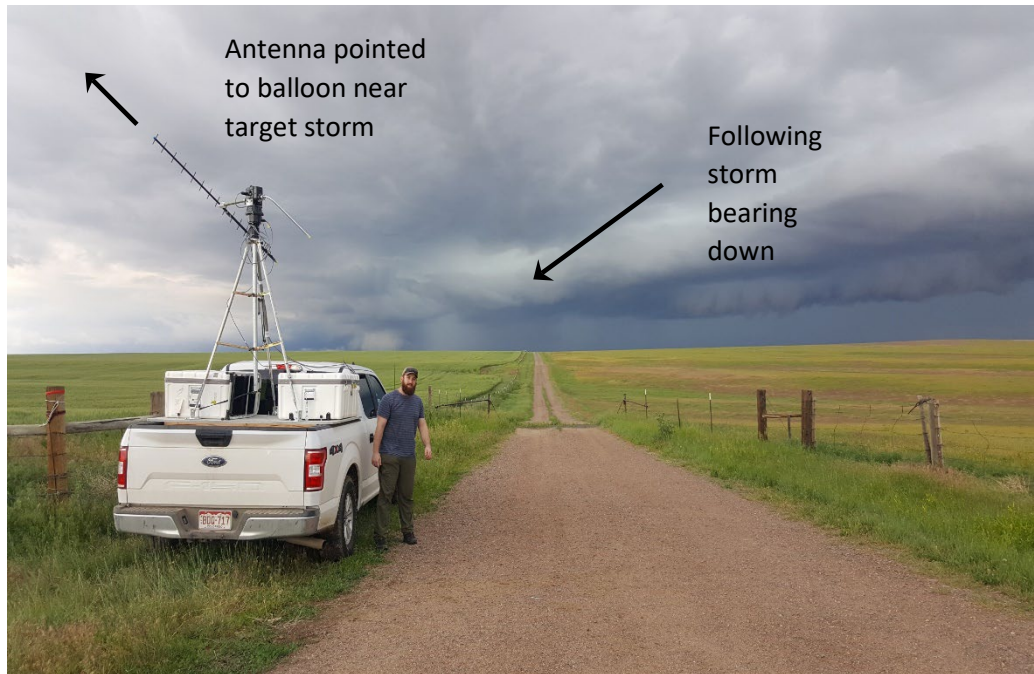


Figure 13 HYFLITS mobile balloon tracking used in the TORUS campaign. Contact with balloon was broken off due to lightening risk from the encroaching storm.

Overall, this mobile launch and tracking approach proved to be very difficult and very inefficient regarding data returned for the personnel time expended. This experience in year 2 of the project motivated the development of the Distributed Ground Receiving Station (DGRS) automated tracking system during year 3. This system returns data through the cell phone network to a cloud server, obviating travel and risk to personnel, provided that the DGRS location is within range of the balloon throughout its flight. The extended range of the telemetry system (discussed above) has enabled a single DGRS site to support many of the flight opportunities conducted in year 3, provided a suitable launch location is used. Figure 14 shows an installed DGRS station.

In year 4, five DGRS stations were installed: 3 in Colorado and 2 in Minnesota. These cover the expected measurement scenarios for launches from CU and from UMN. Launches from ERAU in Florida continue to be tracked using the existing stand-alone ground stations at the Daytona Beach airport.



Figure 14 Installed Distributed Ground Receiving Station (DGRS). These were used for the majority of the flights conducted in the post-COVID shutdown period.

Launch locations are constrained by the need to fill the balloon in a wind-protected shelter. Although the balloon can be filled inside a staked-down tarp virtually anywhere (as was done for the TORUS campaign), this tends to damage balloons, resulting in premature bursts and complete loss of descending measurement data. Better consistency is achieved by filling in a shed with a suitably high garage-door style opening, particularly on windy days that are often desirable targets for turbulence measurements. Most of the 30 flights in the post-COVID shutdown period of year 3 of the project were launched using either the NOAA filling shed at Marshall Mesa (5km south of Boulder) or using the jet engine test cell in the new Aerospace Engineering building on the CU campus in Boulder. A few recent flights have been launched from a similar large shed located in extreme western Colorado. This is about 250 km upstream of the DGRS station near Boulder, for windy periods in the winter that produce ideal conditions for generating mountain (gravity) waves that can propagate to very high altitudes.

Launch location is highly dependent on the particular target location for the descending measurements, and on the winds in which the balloon will be flying. Balloon trajectory predictions are invaluable for making launch location and launch time decisions. Although simulators are available for predicting balloon trajectories, these were developed for conventional balloon operations where a balloon rises until burst, then rapidly descends on a parachute for recovery. These do not provide useful predictions for the slow descending operations in HYFLITS, e.g., for deciding if a particular launch and tracking locations are suitable for a given potential launch opportunity. In year 3, a HYFLITS-specific simulator was developed that utilizes the unique vertical velocity profile of these flights, together with GFS models to predict flight paths. This predictor can also use measured GPS velocities on ascent to produce more accurate estimates on descent than a prediction based on coarse GFS models that may be up to 6 hours old. See Figure 15, and Section 3.1.2 for a more detailed discussion of this Balloon Trajectory Simulator (BTS).



Figure 15 HYFLITS Balloon Trajectory Simulator (BTS) showing ground track for an upstream launch in western Colorado, placing the descending measurements over the continental divide where the largest mountain wave activity is expected. Data is collected by the DGRS station at the center of the large circle.

The above developments have enabled a large number of measurements to be conducted. Figure 16 shows a record of 115 flights over year 4 of the HYFLITS project (calendar year 2021) and the last 5 months of year 3. Most of these flights (short bars in Figure 16) have single-instrument payloads. UMN has been developing and testing the optical particle counter instrument (OPC), and this is the instrument for most of their single-instrument flights. CU and ERAU have been developing the descending balloon technology and the turbulence instrument, and most of their single-instrument flights have provided turbulence measurements. The new integrated turbulence/particulate payloads (Figure 6, and flown in the tall-bar cases in Figure 16) were exclusively utilized in the BOLT I campaign at Esrange, Sweden, and are now being flown in the US locations at a cadence of about one per month.

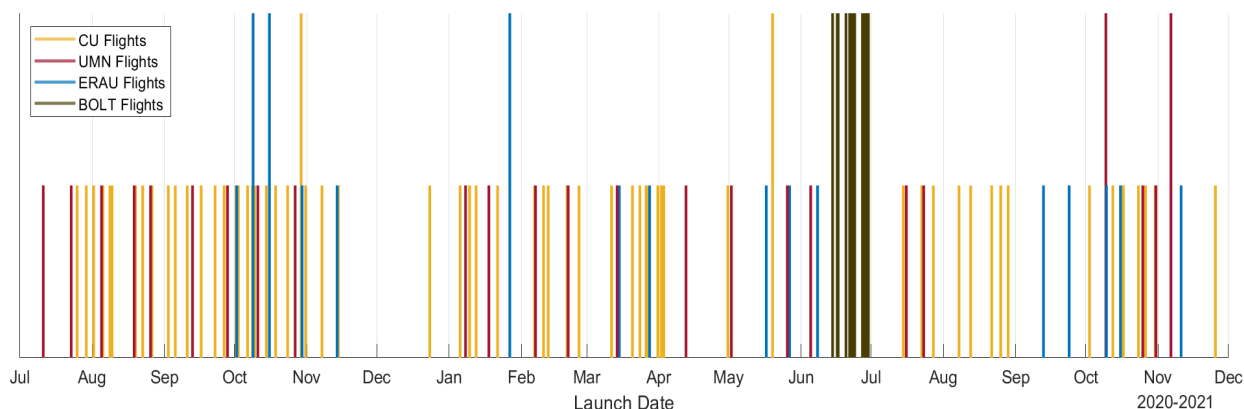


Figure 16 HYFLITS balloon-borne measurements over the last 18 months, encompassing year 4 of the project, color coded by launch location. Short bars indicate a single instrument flight: Particulates only for UMN, Turbulence only for CU and ERAU. Tall bars indicate an integrated payload containing both Particulate and Turbulence instruments. 115 flights are shown. A total of 160 flights have occurred in the HYFLITS project so far.

Figure 17 shows the descending legs of 85 of these flights (those with DGRS ground tracking, or from the BOLT I campaign). The beginning of this record shows initial experience with venting at various altitudes, resulting in several descents that were too slow, leading to the balloon strain modeling noted reach as high

as possible in the stratosphere, subject to reasonable reliability of making these measurements. This necessarily pushes the balloon material near its strain-failure limits. Accordingly, we would anticipate fewer premature burst failures, and faster descent rates, if lower apogees were targeted. earlier, and more consistent with apogees in the 32-33km range thereafter. Most of the BOLT I apogees were set at 28km to reduce downwind drift (making helicopter recovery of the payloads easier). The last few flights involved testing with a neck pump and with smaller balloons to reduce operations cost, and there are more altitude variations and attendant descent rate variations there. We have experienced a low rate (7/85) of premature balloon burst events over these flights, reflecting manufacturing inconsistencies in the balloons themselves in most cases. For HYFLITS, the goal was to reach as high as possible in the stratosphere, subject to reasonable reliability of making these measurements. This necessarily pushes the balloon material near its strain-failure limits. Accordingly, we would anticipate fewer premature burst failures, and faster descent rates, if lower apogees were targeted.

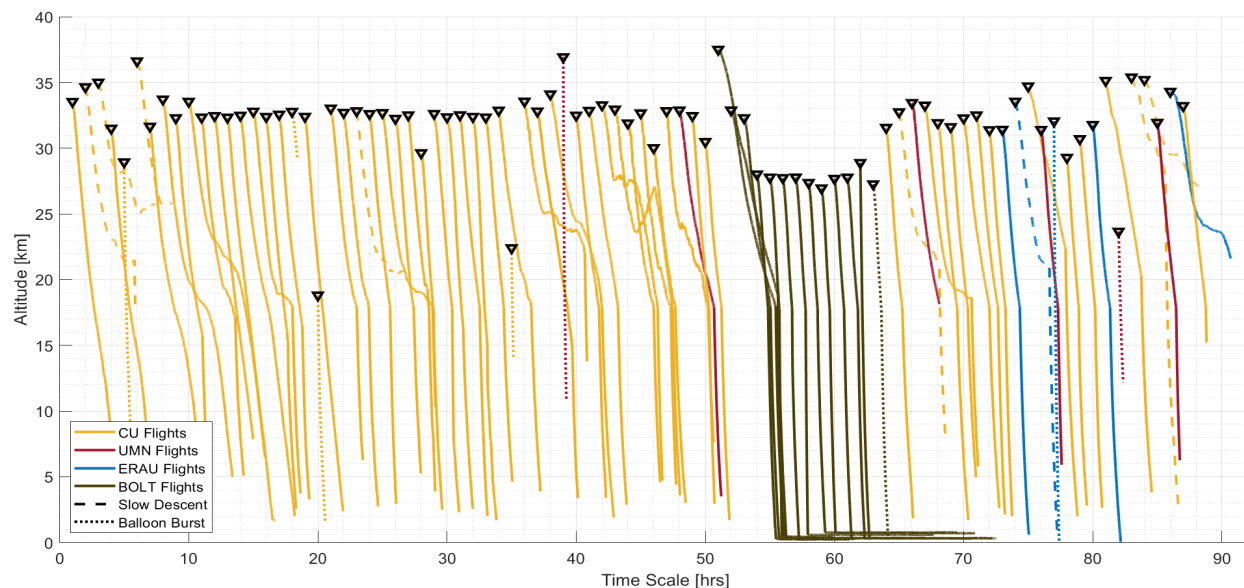


Figure 17 Descending segments of the HYFLITS measurement profiles corresponding to 85 of the flights in Figure 1.1-13, starting at apogee (triangles) until loss of signal. Dashed lines indicate cases where the descent slowed enough to cause some loss of turbulence data (8/85). Dotted lines indicate premature balloon burst resulting in no turbulence data (7/85). Note particulate measurements can be acquired on both ascent and descent.

Groundtracks for these flights are shown in the next few figures. Figure 18 shows the 62 flights conducted so far with the automated DGRS ground tracking systems. Two more of these were installed in year 4 of the project (Hartsel and Elizabeth), expanding our ability to make measurements east of the Rocky Mountains, as well as over the Continental Divide in the central mountains. In particular, mountain waves are produced by strong westerly winds, and measurements over the Divide can only be made if the balloons are launched upstream some 200km. A location in western Colorado (Collbran) was identified for this purpose, allowing payloads to be shipped there for launch locally, rather than traveling from Boulder for every such event. All these flights utilized telemetry for data recovery because physical recovery of the payloads is very difficult in the mountainous areas.

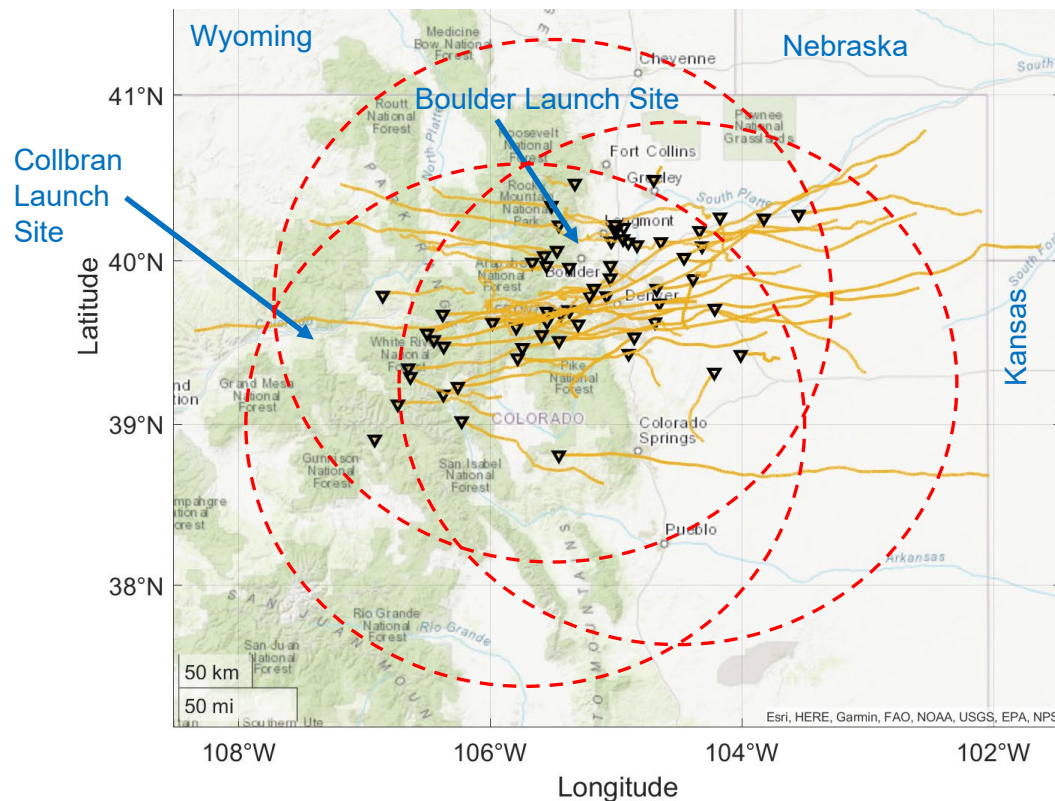


Figure 18 HYFLITS groundtracks from apogee (triangles) to loss of signal for the 62 flights conducted so far in Colorado using the DGRS tracking stations. Large circles indicate 200km reference range from the three DGRS stations (located at Hartsel, Elizabeth, and Arvada).

Figure 19 shows the recent launch activity from UMN in Minnesota. Operations there have focused on development and testing of the OPC instrument, that can make measurements during either the ascent or the descent of the balloon's trajectory. Accordingly, many of their earlier flights used the conventional approach of letting the balloon rise until burst. More recent flights have used the HYFLITS approach of venting before burst for slowly-descending measurements. Also, their operations have only recently used telemetry for data recovery, so many of their payloads had special purpose tracking devices (APRS HAM radio beacons and SPOT satellite trackers) to aid in their recovery after landing. This technology was also used in the BOLT I campaign in Sweden, since telemetry range was too small there using EU-approved radios. Recovery was also aided by choosing convenient launch locations given the wind forecast for that day, so UMN flights were often launched with a roving team that would also chase the balloon after launch for same-day recovery.

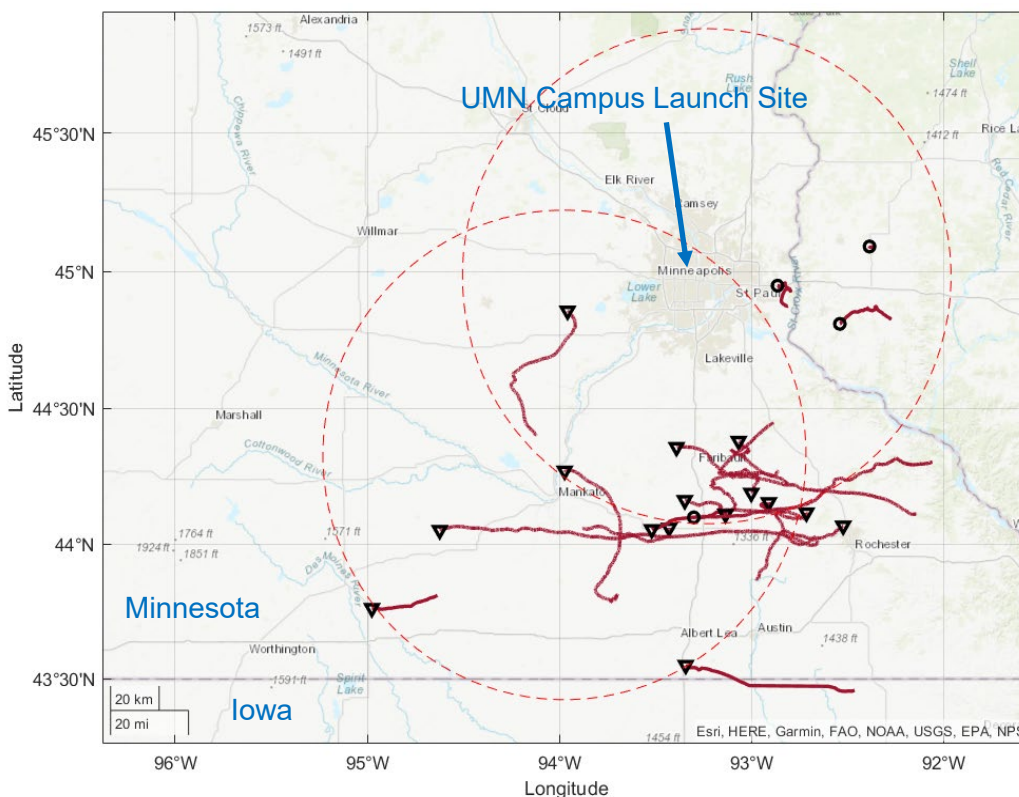


Figure 19 HYFLITS groundtracks for 19 launches in Minnesota. Triangles indicate ascent trajectories to balloon burst (OPC development flights). Circles indicate descending trajectories from apogee to loss of signal. Large circles indicate 200km reference range from the two DGRS tracking stations (located at the UMN campus and near Mankato, MN).

HYFLITS launches from ERAU on the Atlantic coast of Florida are shown in Figure 20. These follow the procedure used for many years at ERAU where balloons are prepared and launched from the roof of a building near the Daytona Beach airport. Tracking systems are also located there to retrieve telemetry data from the balloons, since recovery of payloads from the ocean or in swampy areas of Florida is not possible. Some of the early development flights occurred at ERAU where a two-balloon approach was used, cutting the first balloon away at apogee to allow a slow descent on the second balloon thereafter. While this is workable, it complicates the launch procedure, particularly in high winds, and results in a large shock at apogee when the first balloon is suddenly cut free, which can also cause the second balloon to burst.

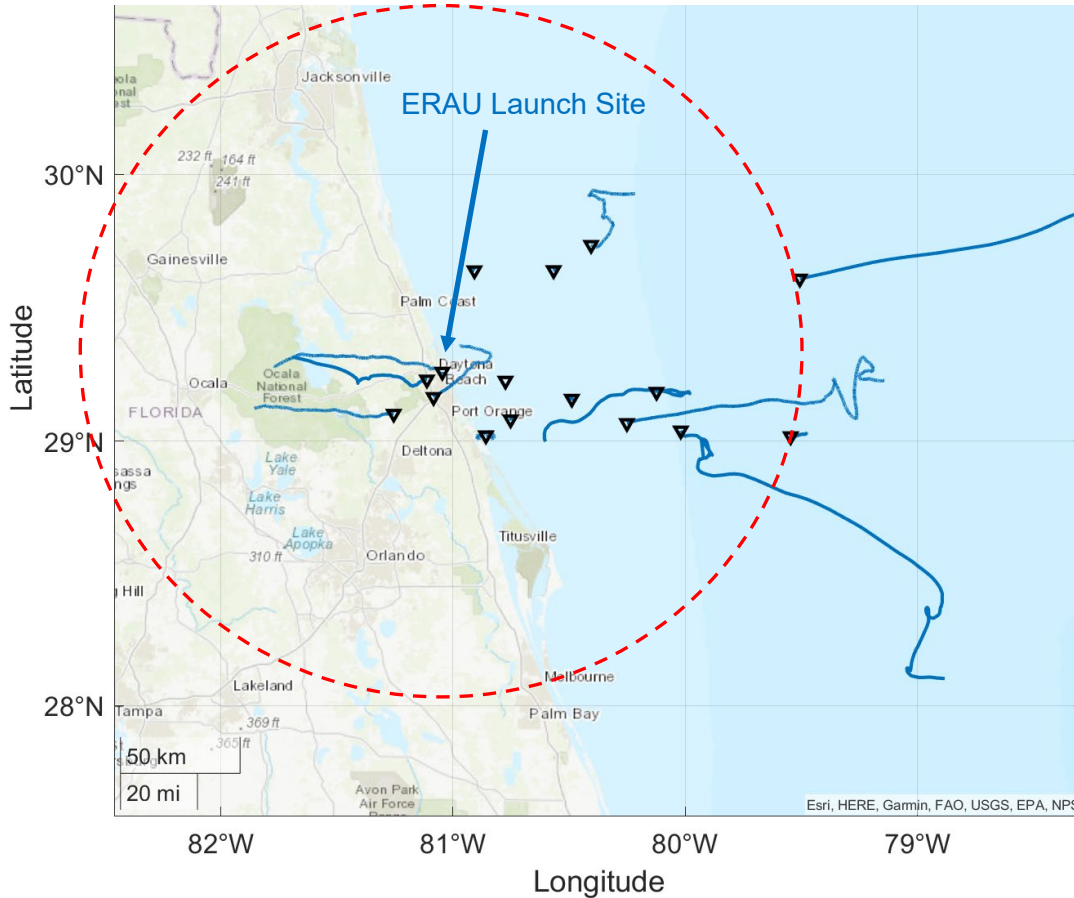


Figure 20 HYFLITS groundtracks for 16 launches in Florida. Triangles indicate descending trajectories from apogee to loss of signal. Large circle indicates 200km reference range from the ground tracking station located at the ERAU campus in Daytona Beach, FL.

3.1.2 Turbulence Instrument Progress

The HYFLITS turbulence instrument measures velocity and temperature fluctuations in the atmosphere as the balloon slowly descends from apogee at a nominal rate of 2 m/s. These fluctuations are stochastic but follow a characteristic cascade of variations from large scales (low wavenumbers) to small scales (high wavenumbers) according to the well-validated Kolmogorov “K41” theory [Kolmogorov, 1962], resulting in a so-called inertial range where spectral energy has a characteristic slope, decreasing with wavenumber. The overall level of this energy curve quantifies the intensity of turbulence. Since it is the turbulence intensity at various altitudes that is of primary interest, the HYFLITS instrument conducts the intensive spectral analysis on board, telemetering only 8 spectral averages of the 1000-point FFT from 1/3 decade frequency intervals from 1 to 500Hz resulting from each 1 second time record. This spectral averaging lowers the required data rate by a factor of 62.5, enabling the > 200km range radio link needed for many flights.

Spectral averages are then fit to the inertial range characteristic in post-flight analysis, and frequency is converted to wavenumber using estimates of the balloon mean airspeed. The results are then converted to kinetic energy dissipation rate ϵ (for velocity variations) and to temperature structure constant C_T^2 (for temperature variations).

Figure 21 shows the profiles of ϵ and C_T^2 for a recent “mountain wave” flight where very strong westerly winds extended from low altitudes up into the stratosphere. This generated strong gravity waves as the flow

encountered the main ridge of the Rocky Mountains at the continental divide, seen in the quasi-periodic vertical (downward) velocity variations in the right-most panel.

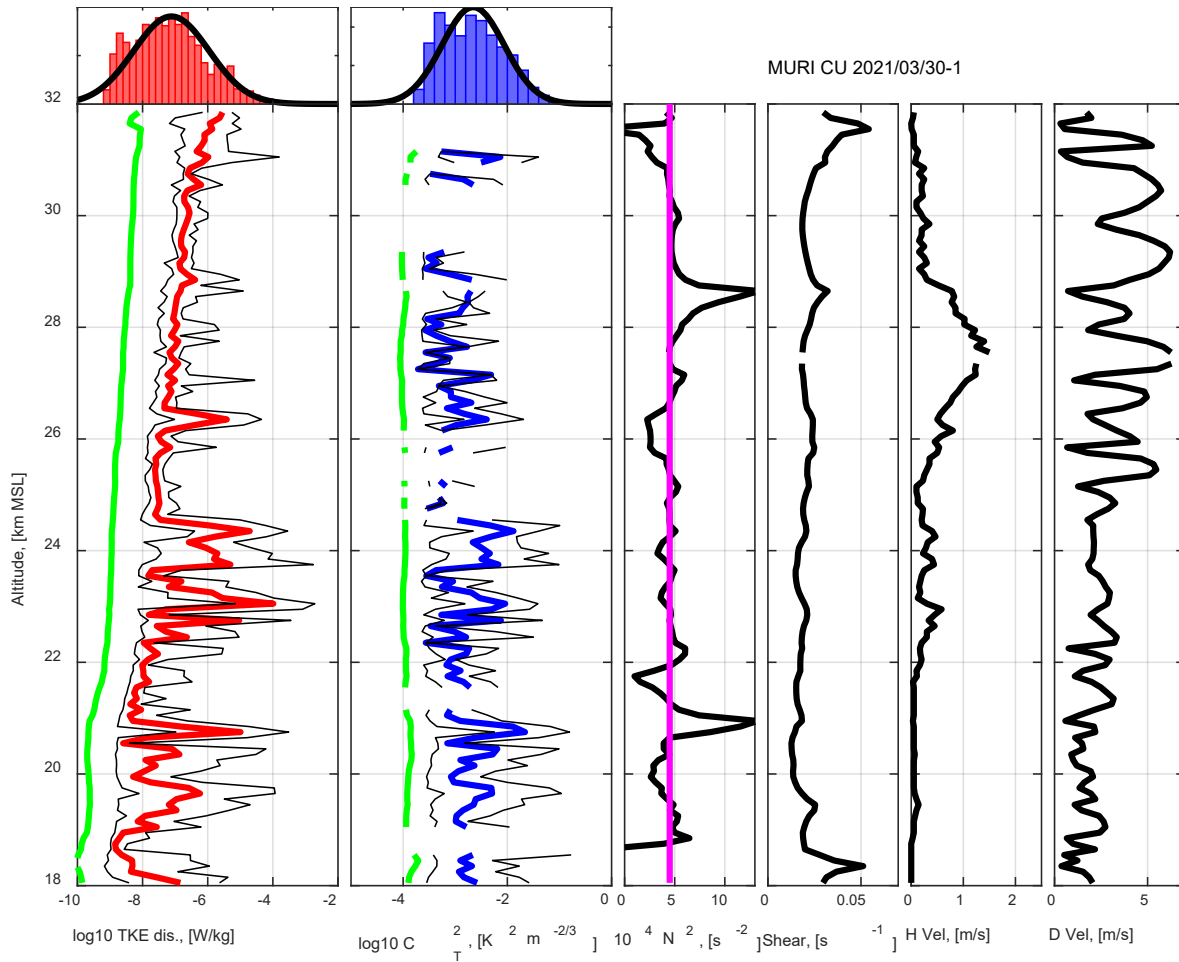


Figure 21 Current set of data products for the HYFLITS turbulence measurements includes vertical profiles of turbulent kinetic energy (TKE) dissipation rate ε , temperature structure parameter C_T^2 , Brunt-Vaisala frequency N^2 , horizontal wind shear, horizontal pendulation velocity, and GPS vertical (downward) velocity. For ε and C_T^2 the green line indicates noise floor, thick lines are the average over 100m vertical intervals, and the thin lines are min and max over these intervals.

Figure 22 shows a high-altitude WRF model, provided by subcontract to John Snook, showing predictions of the vertical velocity (red/blue colors) along with the potential temperature (numbers on contours) for the time slice corresponding to midway during the descent of the balloon (approximate trajectory through this region shown by the green line). Note the intense, short-period gravity waves propagating upward directly over the continental divide (the white outline at the bottom of the figure shows the topography of the mountains). These waves penetrated well into the stratosphere on this day – an unusual occurrence since they are often quashed by the highly stable conditions above about 20km, e.g., when the winds reverse direction at this altitude. Only when the winds are strongly westerly throughout the column do these waves reach the higher altitudes. We used the 3-day ahead prediction capability of this model to plan for an intensive observation period (IOP) for this day, launching 4 balloons in succession at about 1 hour cadence to provide measurements of the time evolution of this phenomenon.

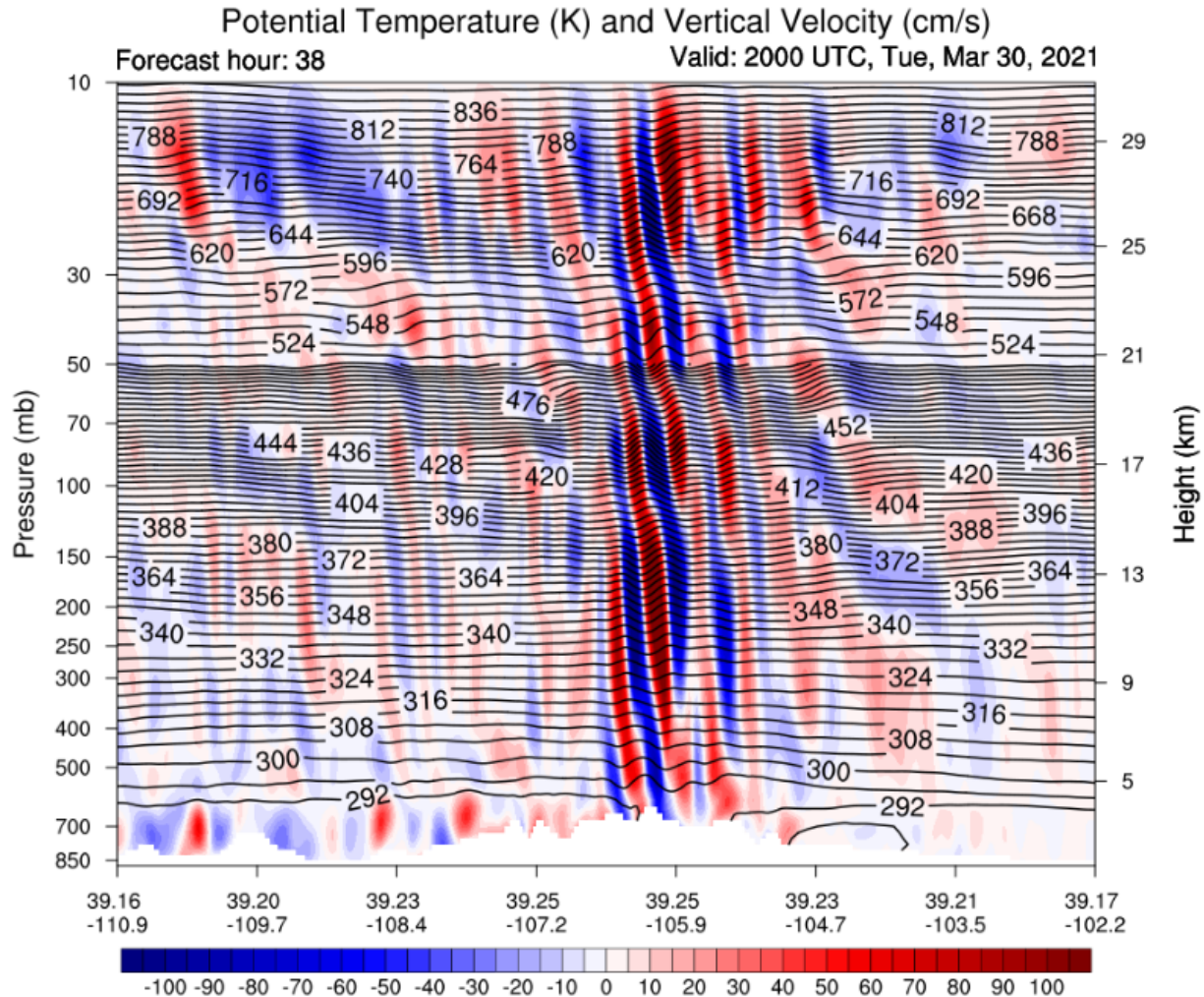


Figure 22 High-altitude WRF model over the Colorado mountains during an extreme mountain wave event on 3/30/2021. Color shading indicates vertical velocity in cm/sec., and numbers indicate potential temperature. The green line shows the approximate trajectory of a HYFLITS balloon during this event, where very strong, short-wavelength gravity waves propagate into the stratosphere, caused by strong westerly winds over the Continental Divide (white outline at the bottom of the plot).

Comparing Figure 21 and Figure 22, it is worth noting that the occurrence of the higher levels of turbulence (e.g., in the ε and C_T^2 plots below 25km) is *not* where the most intense gravity wave activity is occurring along the balloon trajectory (e.g., above 25km in the WRF model), as one might expect. This is where the DNS atmospheric modeling in the MURI is expected to provide a deeper understanding of the processes at work, so that turbulence instances and levels can be predicted more easily.

Currently, the MURI measurement team has archived the data from all flights to date, so it can be accessed on Google Drive. There is a detailed launch log corresponding to all the CU flights, describing the launch configuration and local conditions, with similar documents in preparation for the ERAU and UMN flights. All of the 85 DGRS tracked flights (to date) have the data processed to level 2, providing .mat files that have been quality-controlled and cleaned of anomalous data, and “quick looks” are provided for these flights consisting of the plots shown in Figure 23 below.

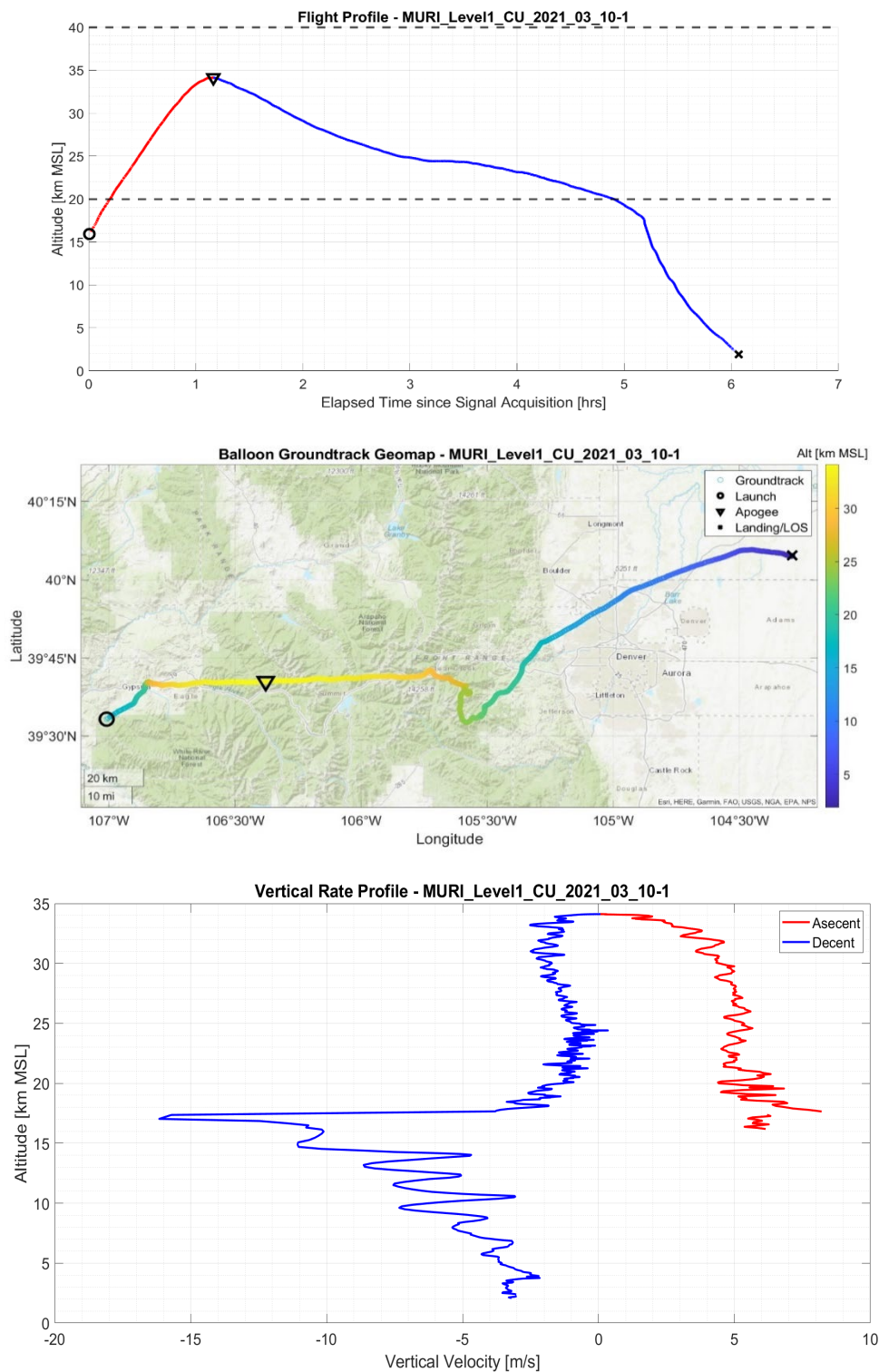


Figure 23 “Quick Look” plots available for all 85 DGRS-tracked HYFLITS measurements on Google Drive: Altitude vs. time (top), ground track (middle), and altitude vs vertical velocity (bottom).

Level 3 turbulence data products consist of the vertical profiles shown in Figure 21. Approximately 20 of the flights so far have data products at this level; the remaining flights continue to be processed. This database is just beginning to be analyzed to develop a more comprehensive understanding of the measurements and their dependence on forcing conditions, in concert with the high-resolution DNS modeling efforts in the program.

3.1.3 Turbulence Fine-Wire Instruments Calibration and Analysis

Proper calibration of the fine-wire anemometer at stratospheric conditions requires knowledge of the various physics that are taking place in the vicinity of the sensor during flight. Once identified and characterized, the effect on the resulting measurement can be understood and accounted for in the final analysis of the in-situ hot-wire measurements. The following subsections will address several of these processes and demonstrate how biases are corrected for if necessary.

3.1.3.1 Blockage Effects Due to Downstream Obstructions

With the critical measurement period occurring on the descent portion of the flight, the fine-wire sensors experience a relative velocity of roughly 3 m/s in the streamwise direction. At such low speeds, the flow blockage of the sensors has the potential to affect the state of the upstream fluid. As such, it is possible that the state of the fluid sensed by the instruments does not equal the freestream conditions. A breakdown of the flight configuration is shown in Figure 24 for reference. Two of the primary concerns are the mean and fluctuations of velocity incident to the wire.

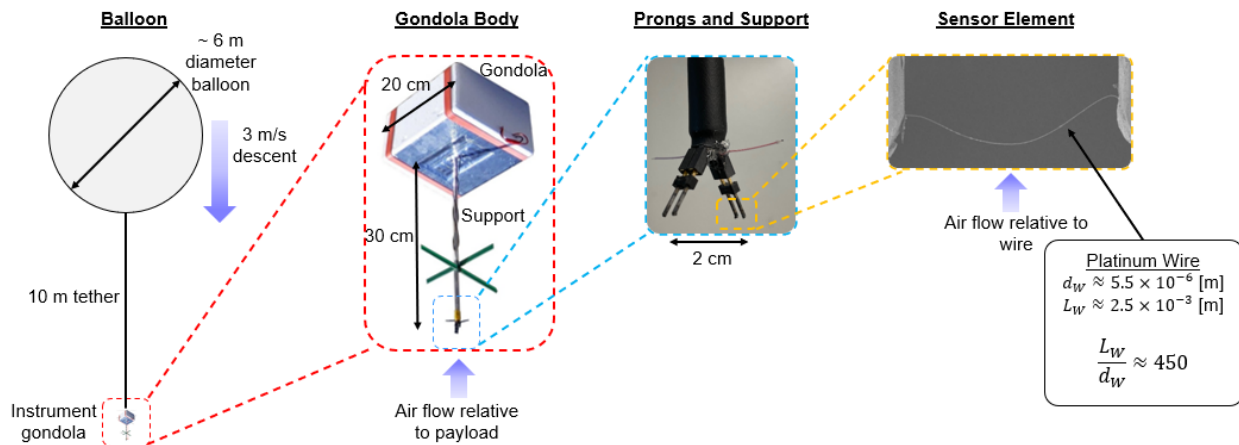


Figure 24 Breakdown of flight geometry

3.1.3.1.1 Effect on mean velocity at the wire

To investigate the effect of the downstream geometries on the mean flow velocity at the wire location, high fidelity numerical simulations are used. The commercially available finite-volume flow solver from Siemens, STAR-CCM+, is used to compute the steady, laminar, and incompressible flow solution for various geometries. The full 3D geometry is represented by a quarter section using planar symmetry conditions in the y and z directions to reduce the computational scale of the problem. In each simulation case, the solution is advanced at various levels of spatial refinement to ensure mesh convergence has been achieved. The mesh convergence criterion used is the average of the flow velocity along the region where the wire (not modeled) would be located, and the final mesh size is on the order of 2.6 million polyhedral cells. Each simulation is run until a residual convergence threshold of six decades below the starting residual is achieved. All computations were performed on a locally built and maintained desktop machine called Deneb/Arches HPC. The Deneb/Arches HPC features a dual boot (Windows or Linux) OS, a 32-core (Xeon) system, 128 Gb of RAM, and is primarily used for multi-thread code development in preparation for supercomputer production runs.

Referencing Figure 24, the simulation cases were run for both the gondola body with the prongs and support rod. An example of the computational domain is seen in Figure 25 and shows the use of two symmetry planes in the transverse direction.

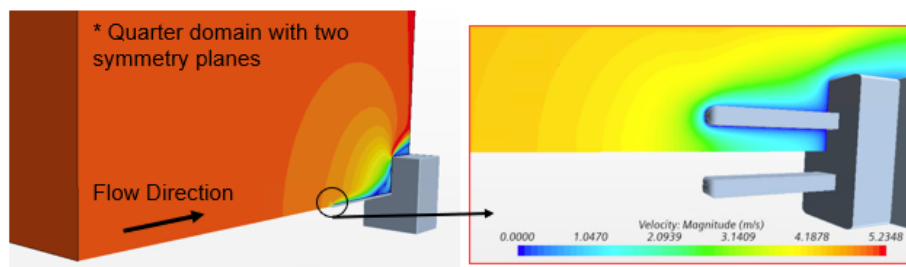


Figure 25 Mean flow velocity contours for the example case of 35 km at 3 m/s

From these results, the average velocity along the location of the wire is computed and plotted versus the freestream flow as shown in Figure 26. This process is repeated for 25, 30, and 35 km altitudes at freestream velocities of 1, 2, 3, 4, and 5 m/s. From the resulting velocity attenuation curve, the gondola + prongs/support case results in between 45 – 70% attenuation of the freestream velocity by the time it reaches the location of the fine wire sensor. This process was repeated for the case where only the gondola body was modeled, and the prongs/support were not included. The results of that study showed only ~ 5% attenuation, meaning that most of the blockage is due to the prongs/support geometry. Through these observations, the blockage effect of the balloon is arguably negligible and is not modeled.

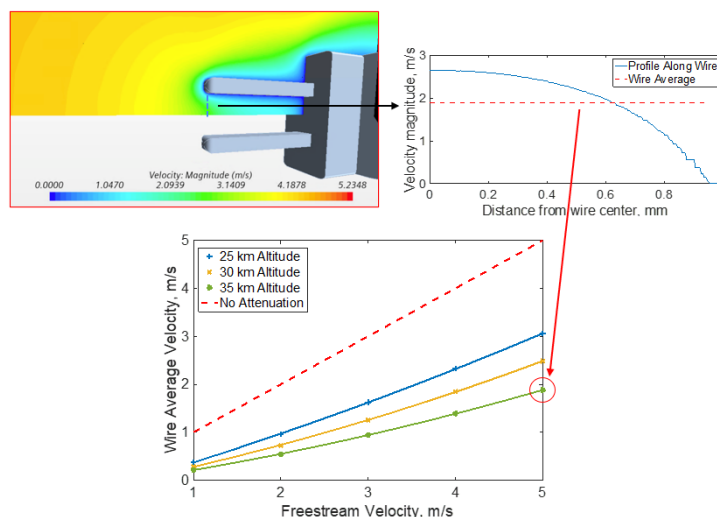


Figure 26 Example of computing points on the freestream velocity attenuation curve

3.1.3.1.2 Effect on velocity fluctuations at the wire

As mentioned previously, the downstream blockage not only has the potential to affect the mean flow velocity at the wire location, but also the velocity fluctuations as well. With the primary function of the fine-wire anemometer being to sense fluctuations in the freestream fluid, the blockage effect must be characterized and accounted for in the data post-processing if deemed necessary. In Berman (1972), the evolution of turbulence along the stagnation line towards a bluff body is investigated by measuring velocity fluctuations. It is shown that attenuation or amplification of the turbulence is dependent on the scale relative to the characteristic dimension of the bluff body. For turbulence scales larger than the body, the root mean squared (RMS) value of the streamwise component of velocity is attenuated. For scales smaller than the body, the turbulence is amplified due to vortex stretching until the region very near the body where it too is attenuated. A combination of these effects is observed when the turbulence scale is of the same order as

the bluff body. With the geometry outlined in Figure 27 having similarities to a bluff body, the turbulence statistics are predicted to vary according to Bearman (1972). To determine the magnitude of this effect and apply a correction to the in-situ measurements, a high-fidelity direct numerical simulation (DNS) of the incident turbulence is required for the specific geometry being used.

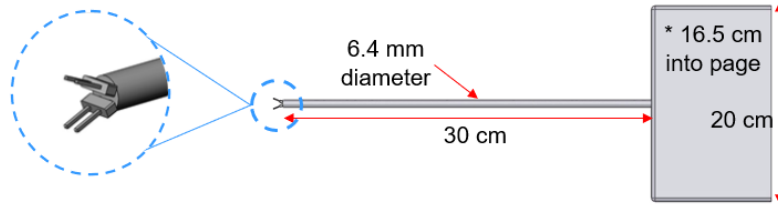


Figure 27 Gondola body, prongs, and support dimensions used in DNS domain.

A three-dimensional incompressible DNS of the turbulent field was conducted using the Parallel Hierarchic Adaptive Stabilized Transient Analysis (PHASTA) Navier-Stokes solver. PHASTA is a finite-element based flow solver that has been in development at University of Colorado and can be extended to massively parallel computations. All simulations were performed on the Rocky Mountain Advanced Computer Consortium (RMACC) Summit supercomputer due to the computational scale of the problem. Figure 28 shows the discretized domain that was used to separately investigate the effect of the gondola body and prongs/support on the turbulence along the stagnation line. The structured regions in each domain are composed of hexahedral elements and tetrahedral elements are used in the remainder of the domain.

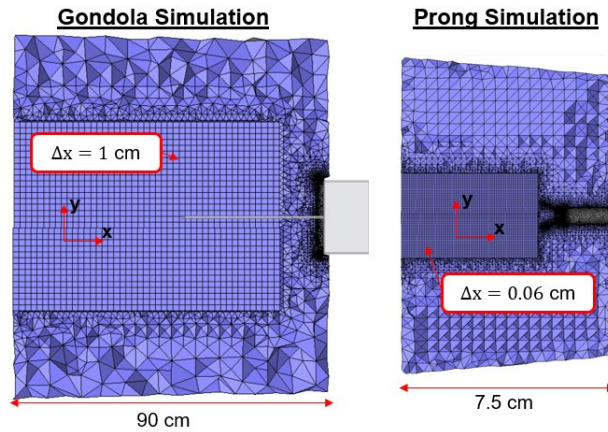


Figure 28 Gondola case domain (left) and prong case domain (right).

In order to simulate turbulence entering the inflow of the domain, a synthetic turbulence generator (STG), as described in Roseman (2021), was used to impose velocity fluctuations at the inflow plane of the domain in a time-varying manner. The parameters for the STG were tuned to replicate the power spectral density (PSD) levels observed from in-situ measurements. For all simulations, the STG was applied over the full inflow plane, although only the structured region has sufficient resolution to capture the full range of the turbulence spectrum. Figure 29 shows an example of the frequency-binned PSD plot obtained from in-situ measurements that was then used to tune the STG and create a field of velocity fluctuations at the inflow to the domain. For reference, for the $-5/3$ slope from the inertial range of the K41 theory is included in the middle plot of Figure 29.

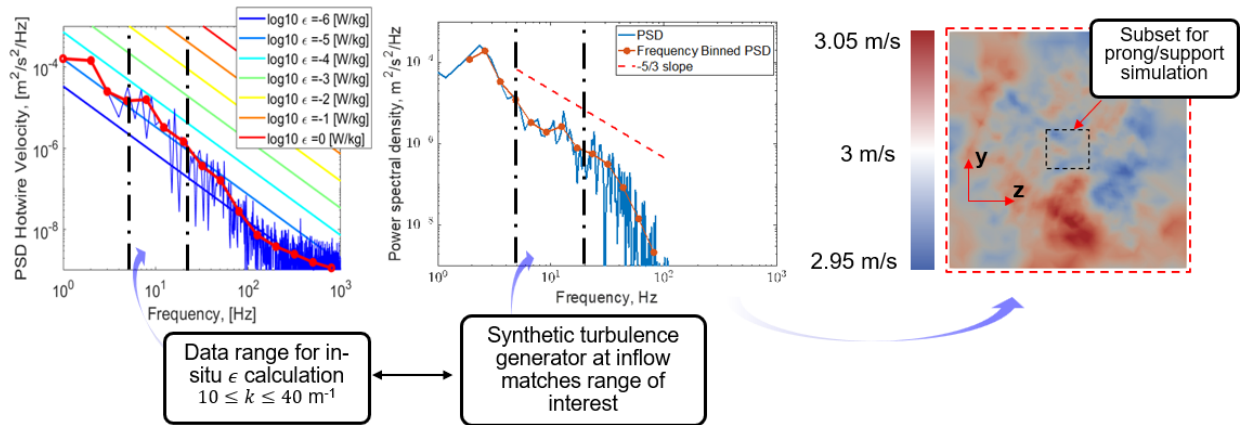


Figure 29 Use of in-situ measurement PSD (left) to tune STG spectrum (middle) and create inflow velocity fluctuations (right).

For the prongs/support case, two separate simulations were run. The first simulation was one in which the prongs/support were not included in the domain and the second simulation they were included. For each simulation, the spatial discretization was approximately the same, except in the region downstream of the structure mesh where the geometry was either absent or included. The case of no geometry present is primarily a method of establishing a baseline result that will characterize the effect of the spatial discretization and numerical scheme on the evolution of turbulence prior to inserting the downstream blockage. As the simulation is advanced in time, time histories of velocity are recorded at various stations along the stagnation line, as seen in Figure 30 for the prongs/support simulation case. The time history signals are detrended and windowed prior to computing the frequency-binned PSD at each location, as shown in Figure 31. Using the method outlined in Frehlich et al. (2003), the turbulent kinetic energy dissipation rate ϵ can be computed and is shown in the bottom plot of Figure 31. As shown, there is only a $1/10^{\text{th}}$ decade difference observed between the no prongs and with prongs simulations at the final station where the wire would be located. This magnitude of deviation is considered negligible in the overall calibration uncertainty and does not need to be corrected for.

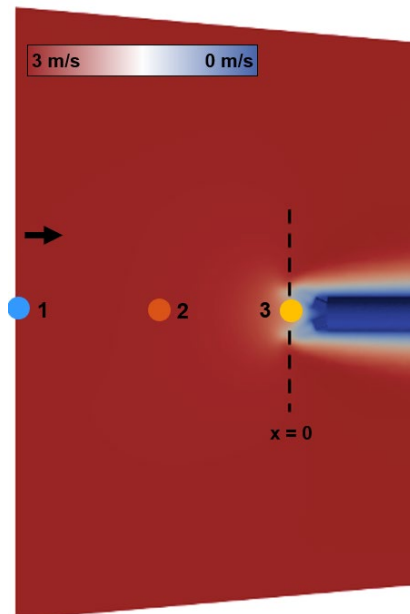


Figure 30 Prongs/support simulation domain with velocity contours for the 30 km altitude and 3 m/s velocity case.

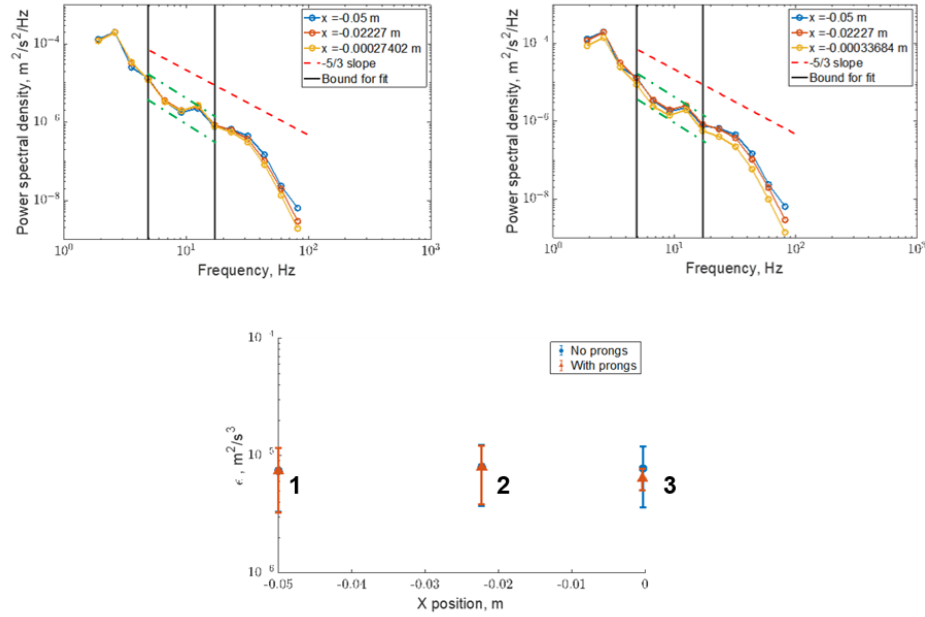


Figure 31 PSD plot for the case (left) without prongs/support and (right) with prongs/support. Computed values of ϵ (bottom) at the various stations along the stagnation line

Like the previous case, two separate simulations are performed for the case of the gondola domain. First in which the gondola body is removed and second in which it is included. Figure 32 shows the velocity contour field for the gondola domain with the points along the stagnation line identified. Using the same process as described previously, the value of ϵ at each point is computed and shown in Figure 33. Looking at the results for the case without the gondola, there is a decrease in ϵ along the points moving into the domain. This is likely attributed to a combination of natural and artificial dissipation due to fluid viscosity and insufficient spatial resolution, respectively. When looking at the case where the gondola is present, it is seen that at the third point the values of ϵ are nearly identical. With this observation, and the observation made previously in the case of the prongs/support domain, it can be said with confidence that the estimate of ϵ made from the in-situ measurements is not appreciably affected due to the downstream blockage posed by the system. Recalling that the simulations made thus far were only for the 30 km altitude at 3 m/s freestream velocity case, a more comprehensive sweep of the operating range will be conducted in the future.

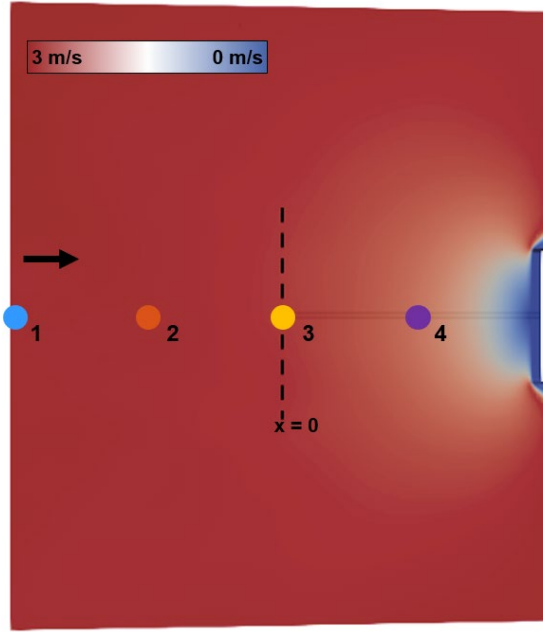


Figure 32 Gondola simulation domain with velocity contours for the 30 km altitude and 3 m/s velocity case.

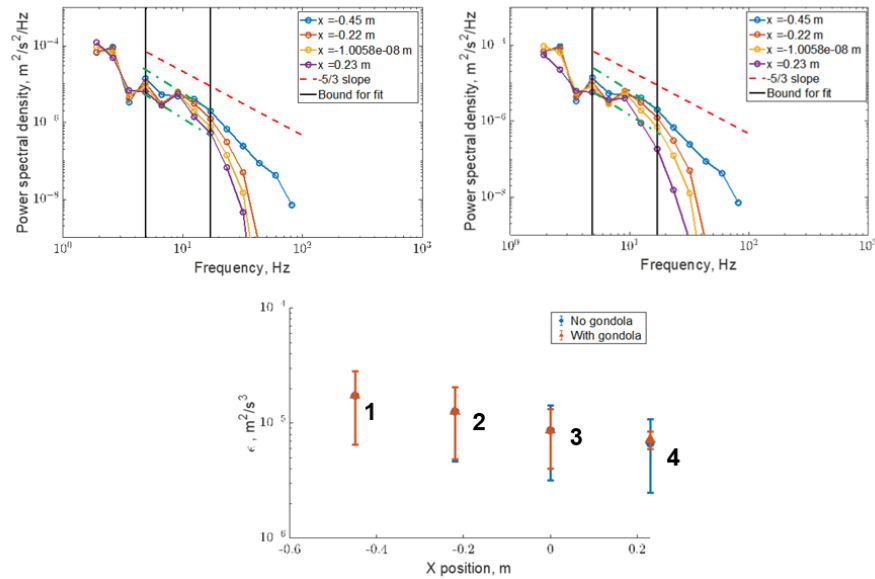


Figure 33 PSD plot for the case (left) without gondola and (right) with gondola. Computed values of ϵ (bottom) at the various stations along the stagnation line.

3.1.3.2 Finite-Length Wire Thermal Modeling

In Figure 34, an overview of the thermal system in the finite-length hot-wire system is shown and highlights the two primary means of thermal transport, conduction and convection. As seen in Eq. (1), the convective heat transfer coefficient, h , is calculated using the measured power loss Q from the wire, which is then used to determine the Nusselt number,

$$\text{Nu} = \frac{hL_w}{k_w} = \frac{QL_w}{k_w A_w (T_w - T_a)} \quad (1)$$

where A is the cross-sectional area, k is the thermal conductivity, T is the temperature, L is the segment length, and subscripts w and a denote the wire and ambient conditions, respectively. The relationship between Nu and velocity is expressed using empirically derived functions, an example from [23] being shown in the empirical Nu correlation function

$$Nu = A + B Re^n + C Kn^m + D Re^j Kn^j \quad (2)$$

where Kn is the Knudsen number, Re is the Reynolds number, and the remaining variables are empirically derived values that vary with the range of Kn and Re . Using the value of Nu from Eq. (1), Re can be calculated iteratively using Eq. (2). The velocity u is then obtained using Re , the diameter of the wire, and the kinematic viscosity air, with the thermodynamic properties of air evaluated at the film temperature, $T_f = (T_w - T_a)/2$.

Equations (1) and (2) are derived for wires of theoretically infinite length where end effects are nonexistent. For a finite-length wire, the temperature and velocity effects of the prongs can be addressed using a calibration facility. However, if a new empirical function is to be developed or the accuracy of a calibration facility is to be checked, the effects noted above must be accounted for. The following analysis focuses on quantifying the effect the prongs supporting the wire have on the temperature profile and power loss from a wire over the altitude conditions of interest.

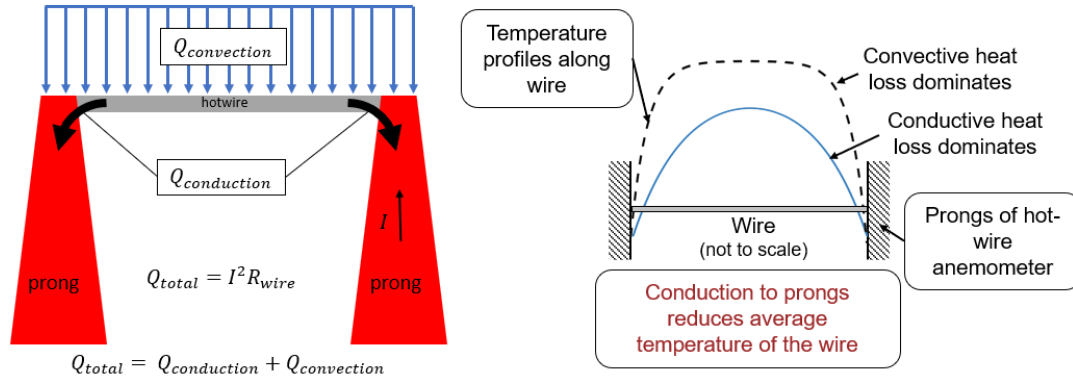


Figure 34 Description of (left) convection and conduction in finite-length hot-wire anemometer and (right) the resulting effect on the wire temperature profile.

3.1.3.2.1 Description of Thermal System

The partial differential equation governing the thermal response of a finite-length wire is

$$k_w A_w \frac{\partial^2 T_w}{\partial x^2} + \frac{I^2 \chi_w}{A_w} - \pi d_w h (T_w - T_a) - \rho_w c_w A_w \frac{\partial T_w}{\partial t} = 0 \quad (3)$$

The four terms are for internal thermal conduction, heat generation, forced convection, and heat storage, respectively. The variables in the four terms are electrical resistivity χ , electrical current I , wire diameter d , material density ρ , specific heat capacity of the material c , and those previously defined. Given the various inputs, Eq. (3) can be used to solve the unsteady thermal response of a resistively-heated material. The three-dimensional system of the probe is mapped to a one-dimensional thermal system that is then discretized into elements as shown in Figure 35. Note that the 3D geometry is a quarter section due to the symmetry planes being used. Material properties of the wire and prongs, assumed to be homogeneous, are set to that of platinum and phosphor-bronze, respectively.

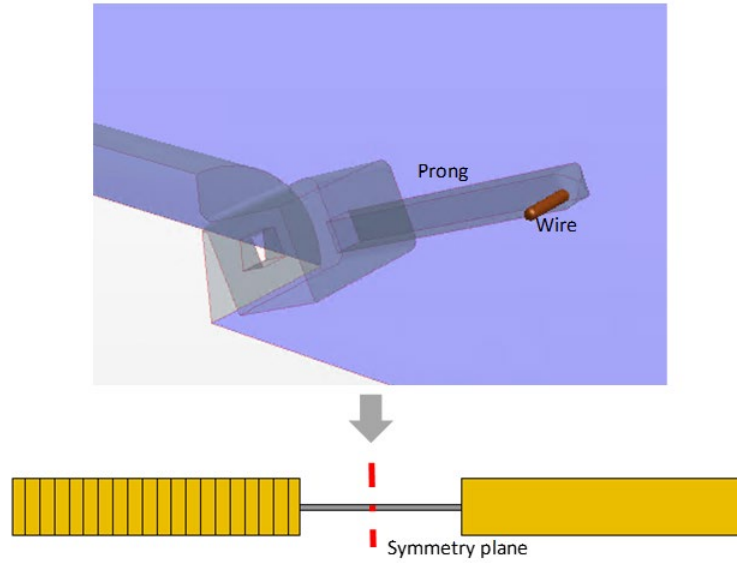


Figure 35 Mapping probe geometry to 1D system for use in thermal model.

3.1.3.2.2 Simulation of Wire Thermal Response

The finite-element (FE) description of the 1D thermal system described previously is solved using a MATLAB PDE solver, “pdepe”, until the system reaches steady state for a given excitation current and freestream flow conditions. This solution approach however is relatively slow and is not able to be used by the in-situ measurement system. An alternative approach, with slightly lower accuracy, is to use an analytical formulation to determine the temperature profile. Figure 36 shows the form of the analytical solution and the comparison with the FE method for temperature rise along the length of the wire. For the FE method, two approaches are simulated. The first being a constant velocity distributed across the wire and second a more realistic parabolic velocity profile, with an equivalent mean velocity, distributed across the wire. A comparison of axial power loss and thermal conductance between the analytical and FE methods is shown in Figure 37. The results show nearly identical predictions over the full altitude and velocity operating range. In terms of in-situ measurements, the analytical model can then be used on the flight computer to compensate for the axial power loss depending on the current altitude and descent rate of the balloon system. This ensures proper mapping from voltage to velocity by accounting for the fact that power is lost from the fine-wire system to the prongs due to axial conduction.

$$\begin{aligned}
 T_r &= \frac{\zeta^2}{\alpha [1 - \cosh(\eta x/L_w)/\cosh(\eta/2)]} \\
 \eta &= \sqrt{\frac{H_r - \alpha R_a I^2}{H_a}} & \zeta &= \sqrt{\frac{\alpha R_a I^2}{H_r - \alpha R_a I^2}} \\
 H_a &= \frac{k_w A_w}{L_w} \\
 H_r &= \pi k_f L_w \text{Nu}
 \end{aligned}$$

- **Assumes:**
- Steady State
- U is constant
- Nu is constant

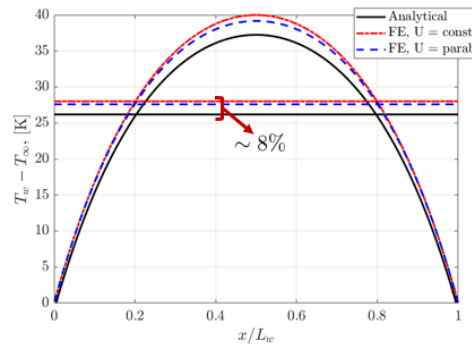


Figure 36 Description of (left) analytical solution formulation and (right) the comparison in temperature rise between the analytical formulation and the FE approach.

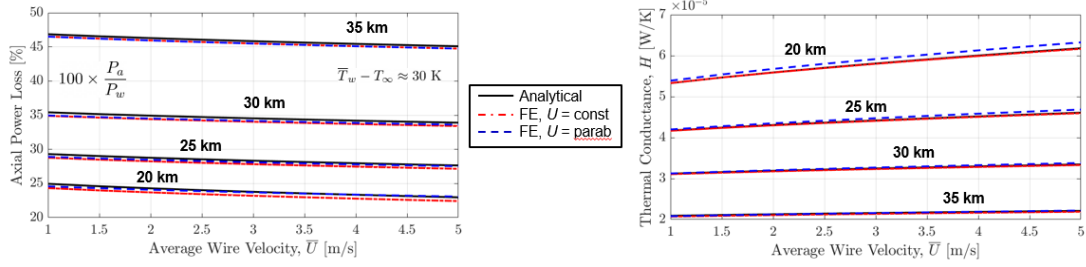


Figure 37 Summary of average (left) axial power loss from the wire and (right) thermal conductance of the wire.

3.1.3.3 Development of Nusselt vs Reynolds Heat Transfer Relations

A key aspect of the turbulence measurement system is the development of accurate models for fine-wire heat transfer in stratospheric conditions. The HYFLITS team is working to develop these models using both experiment and simulation. The status of each of these efforts are discussed below.

3.1.3.3.1 High-Altitude Calibration Tunnel (HiCaT) Update

The HiCaT has been developed under the HYFLITS project to experimentally calibrate and test finite-length fine-wire turbulence instruments in stratospheric conditions. Significant modifications and improvements to the tunnel have been made over this past year and are discussed below.

A thorough characterization of tunnel leak rate has been performed to validate that any potential errors caused by leakage are negligible for all pressure test points. Figure 38 shows leak rate data and the subsequent model. The model was then used to calculate the leak mass flow rate relative to the total mass flow rate in the tunnel. It was found that over the pressures and flow rates of interest, the leak mass rate is less than 2% of the total mass flow rate.

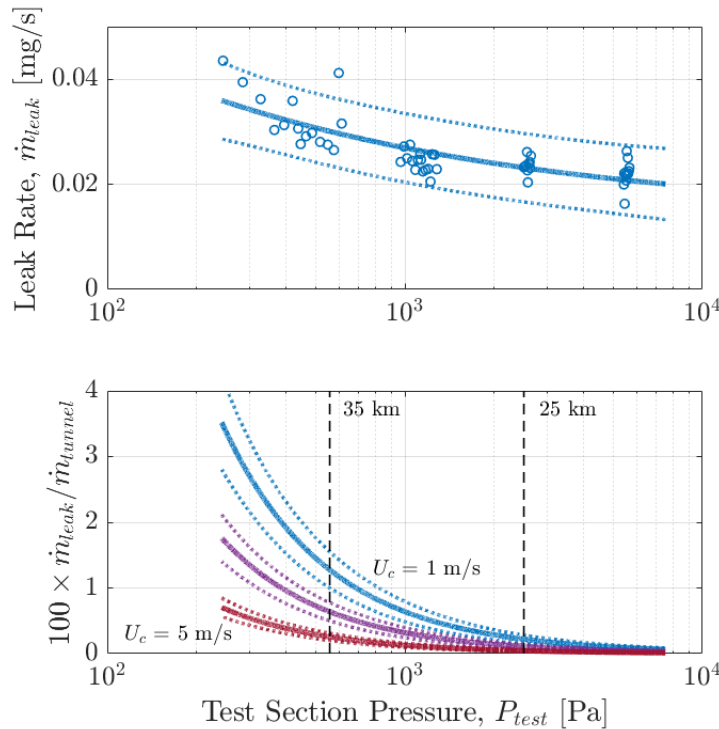


Figure 38 The top figure shows the model for the tunnel leak rate as a function of pressure and the respective data from which it was derived. The bottom figure shows a comparison of the leak rate model to the total mass flow rate

through the tunnel for centerline velocities of 1, 2, and 5 m/s. Dashed lines indicate 95% confidence bounds of the leak rate model.

Improved pressure control of the system has been achieved by using a stepper-motor to control the bleed valve that is downstream of the test section. The stepper motor allows for automated control of the tunnel pressure which has greatly reduced the amount of time it takes to perform a test by eliminating the need for manual adjustments. It has also improved test repeatability by enabling the system to track a desired pressure test point more accurately.

The critical orifice of the system was moved to the Alicat flow meters. The critical orifice separating the flow conditioning section from the flow development region has been removed. This was done to avoid the liquification of air in the flow conditioning section. Prior to this change, some air would liquify in the LN2 heat exchanger. Subsequent boiling of the liquified air would lead to unexpected and uncontrolled changes in system pressure. Moving the critical orifice to upstream of the heat exchanger means lower pressure air is passing through the heat exchanger. This reduces the boiling temperature of the air in the flow conditioning section of the tunnel to below the temperature of LN2.

It had been observed that significant blockage and flow distortion occurred in the original flow configuration (probe oriented perpendicular to the flow). To mitigate this blockage, a new L-shaped probe holder was purchased from Dantec Dynamics to move the probe further upstream. This new probe support orients the fine-wire probes such that the support prongs are parallel to the incoming flow rather than perpendicular to it. This orientation is also closer to the orientation of probes mounted on the balloon-borne payloads.

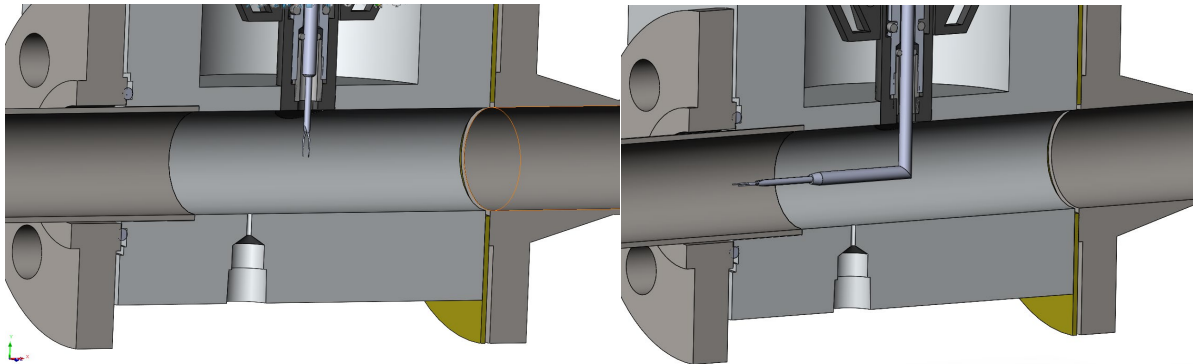


Figure 39 Left image shows original probe configuration which resulted in significant blockage and flow distortion. Right image shows the updated probe configuration with L-shaped probe holder.

The up-to-date schematic of the HiCaT is shown in Figure 40. Further developments of the HiCaT that are currently being pursued include:

- Characterization of the velocity profile using the new L-shaped probe holder
- Calculations of wire power loss from measured voltage for deriving models for wire heat transfer at various conditions
- Developments towards low temperature testing to include rapid system cooling and characterization of the temperature profile in the test section

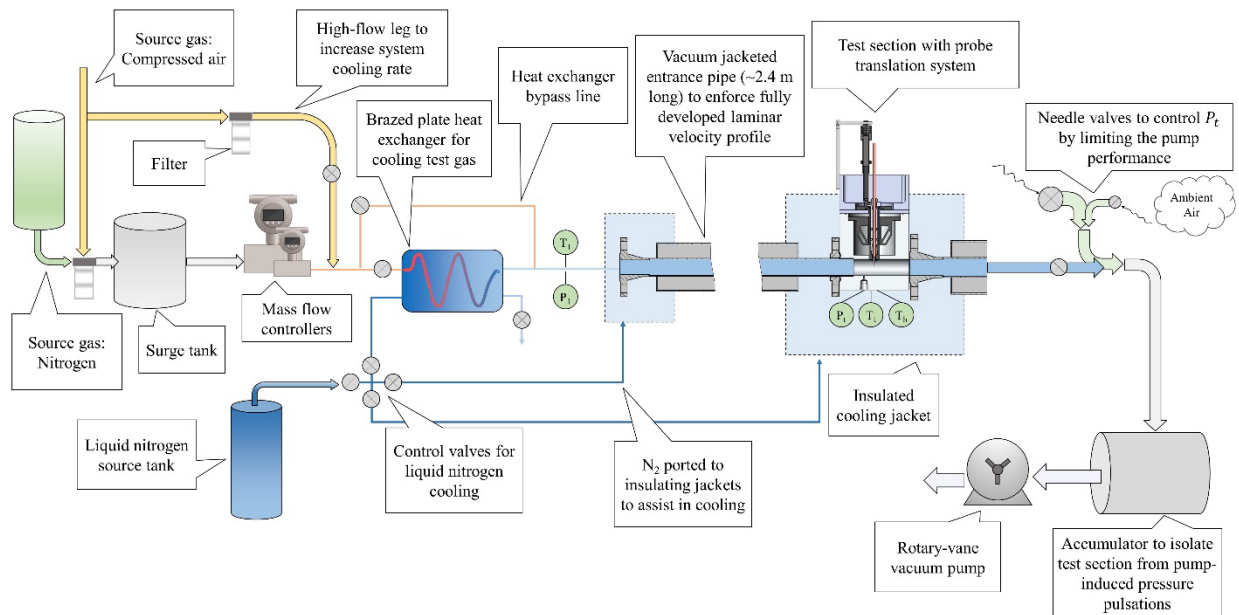


Figure 40 HiCaT system schematic.

3.1.3.3.2 Numerical Simulation of Fine-wire Heat Transfer

In addition to the high-altitude calibration tunnel (HiCaT) that is being developed at CU, numerical simulations are being used to investigate the flow around fine-wires at high-altitude conditions. This effort is being pursued to support the experimental work with HiCaT and to further explore the parameter space of these wires in rarefied conditions. At the altitudes of interest, the $5\text{-}\mu\text{m}$ diameter wires will experience Kn values between about 0.084 and 4.22. These conditions extend from the slip-flow to rarefied-flow regimes. The wire Re will range from about 0.0938 to 0.0037. A particle-based method is necessary for simulating the rarefied flow conditions around the wire. The Direct Simulation Monte Carlo (DSMC) method is currently being used to simulate these flows. Low-speed aerodynamic flows are challenging to simulate using this method because of the very large domains required and the low ratio of bulk flow speed to particle thermal speeds.

Much of the recent effort with respect to these DSMC simulations has been to improve result accuracy by mitigate the bias introduced by the finite size of the simulation domain. These efforts include performing extensive domain-size convergence studies and developing novel boundary condition methodologies for low-speed DSMC. To date, results have partially verified published data for fine-wire heat transfer in rarefied conditions. Simulations have also been used to explore the sensitivity of wire heat transfer with respect to surface accommodation coefficient, a parameter that can vary widely for small-scale engineering surfaces. These and other DSMC results are presented in a journal article published this past year (Roseman and Argrow 2021).

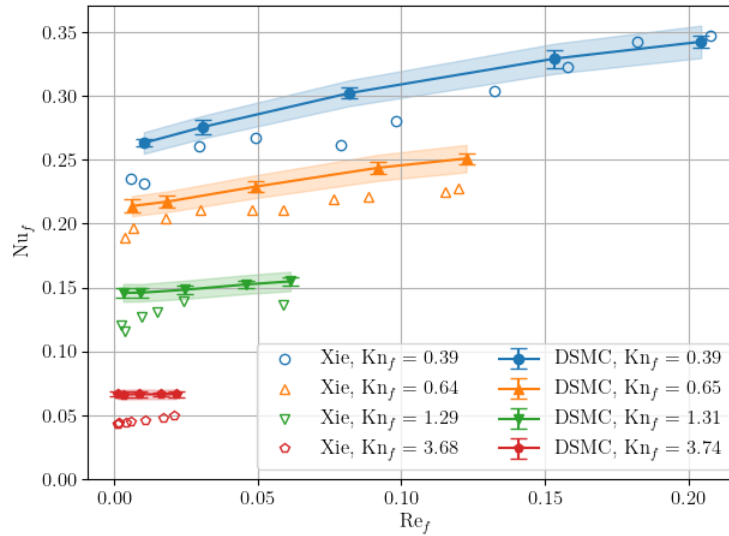


Figure 41 Comparison between DSMC results and published experimental data from Xie et al. (2017). Error bars indicate uncertainty in the DSMC results. Shaded regions around the simulation results indicate uncertainty in wire heat transfer due to a $\pm 10\%$ uncertainty in surface accommodation coefficient.

3.1.4 Particulate Instrument Progress

Commercial optical particle counters use a laser to illuminate particles in a flow chamber and measure the resulting optical intensity and pulse duration as the particles flow through the chamber. Although these sensors are designed with integral fans to pull air through the chamber at specified rates, these fans do not provide enough flow at the high altitudes (low atmospheric pressures) encountered in this project.

Initial attempts to increase the volumetric flow rate utilized a constant-displacement pump similar to that used on the more expensive LOAC instrument, that has been used in high-altitude balloon measurements before. This was not successful in flight experiments using the SPS-30 OPC sensor, nor the more capable Alphasense N3, however. No particle counts were obtained above about ?? altitude. These pumps produce relatively high pressures, but very small flow rates, so an alternative design that uses multiple pumps in parallel was evaluated. The case of 3 pumps provided flow rates closer to that specified for the N3 sensor, but was expensive, heavy, and required a large amount of battery power.

At this point a more detailed examination of the issues was carried out using various combinations of devices, including the constant-displacement pump above, axial fans (similar to those provided on the stock N3 sensor), and a centrifugal blower, tested in a vacuum chamber to replicate the low pressure conditions they would be operating under during HYFLITS measurements. Figure 42 shows the results of this evaluation.

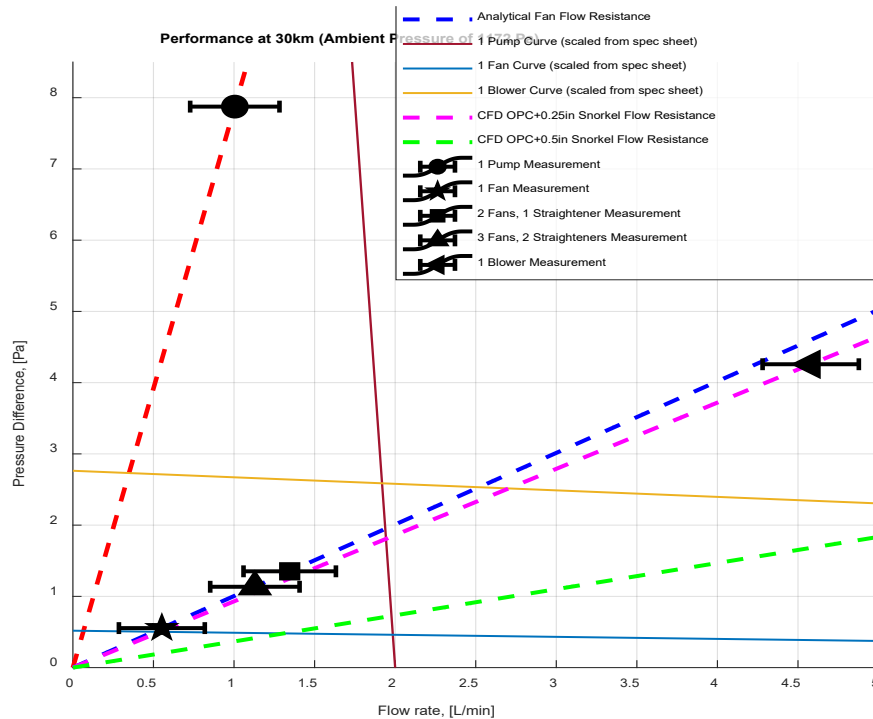


Figure 42 Pump curve measurements in a vacuum chamber at 30km equivalent altitude, comparing various types and arrangements of air movement devices.

As expected, the constant-displacement pump provided higher pressure, but low flow rates in these conditions, providing only about 1 L/min---well below the desired 5 L/m rate. On the other hand axial fans provide very little pressure and potentially high flow rate, but the flow resistance in the inlet and through the N3 sensor chamber could not be overcome with this small pressure rise, again providing a low flow rate (0.5 L/min for one fan) through the sensor. Here, an increase in the pressure can be achieved by placing fans in series, but even with three fans, this is not enough to produce more than 1.5 L/min. A single centrifugal blower turns out to be better suited to this application than multiple pumps or fans. This provided enough pressure to draw flow through the sensor at 4.5 L/m. It was also small, lightweight, consumed very little power, and was low cost, owing to its (designed) use in the newer thin laptop computers. Figure 43 shows how this commercial blower was fitted to the outlet of the N3 sensor using a custom 3-D printed adaptor, providing a simple, low-cost solution to the sensor aspiration problem at high altitudes. This sensor is oriented to pull air samples from the bottom of the gondola through an anti-static snorkel (see Figure 6) and this air flow is ejected through a slot in the top of the gondola box.

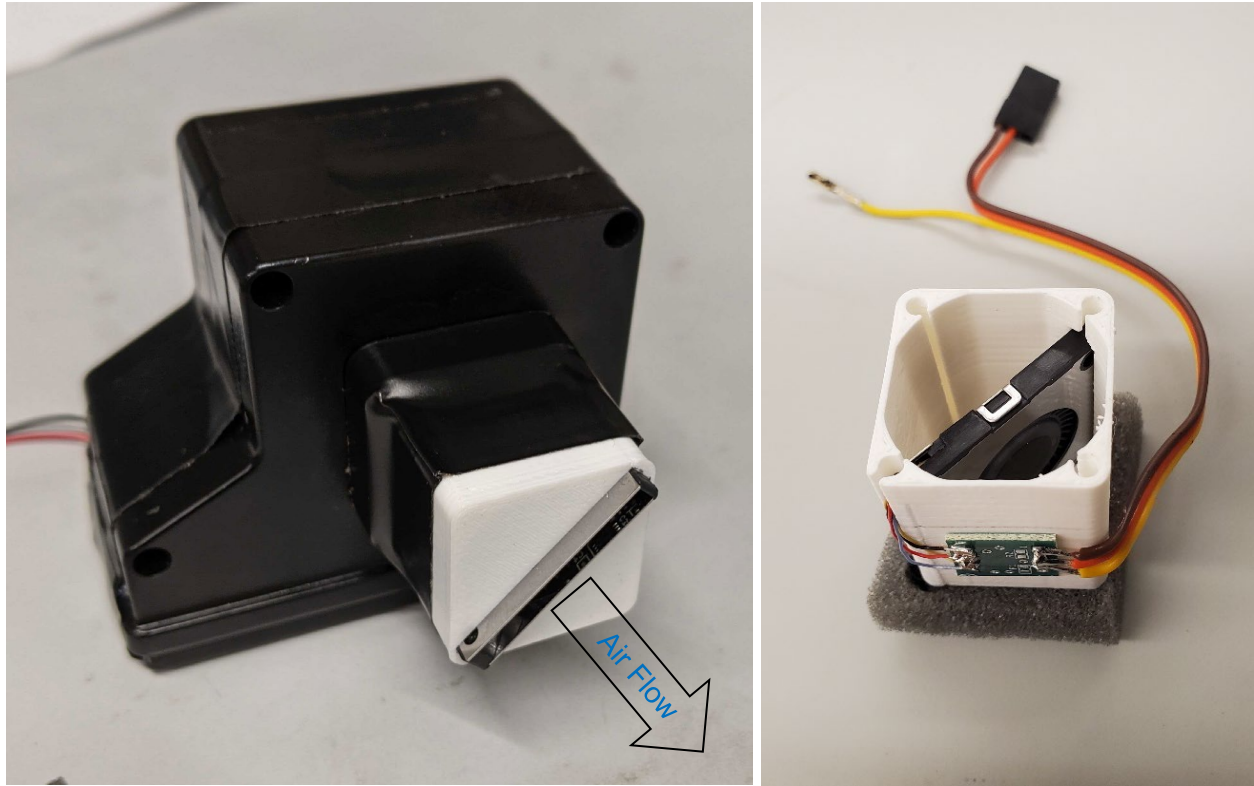


Figure 43 Commercial Alphasense N3 optical particle counter (black, left) with custom insert (white, right) using a lightweight, low-cost commercial centrifugal blower.

The UMN team has made significant progress in modifying and characterizing OPCs to understand their potential use in the stratosphere. Low-cost (<\$100) and mid-cost (<\$500) OPCs use fans to drive airflow through their laser-scattering chambers but these fans do not produce sufficient airflow in the rarefied environment of the stratosphere. Motivated by the pumped, high-cost (~\$10K) LOAC OPC which has been used effectively on stratospheric missions, these fans were removed and small rotary-vane pumps in parallel with one another were attached to OPCs using custom 3D printed sleeves that slide over the outlet of each OPC to maintain adequate airflow during flights (see Figure 43). Additionally, one or more centrifugal blowers were also attached to OPCs using custom 3D printed sleeves, and the effectiveness of the pumps and the centrifugal blowers in various pressure conditions were compared in-flight tests and calibration settings (see Figure 44).

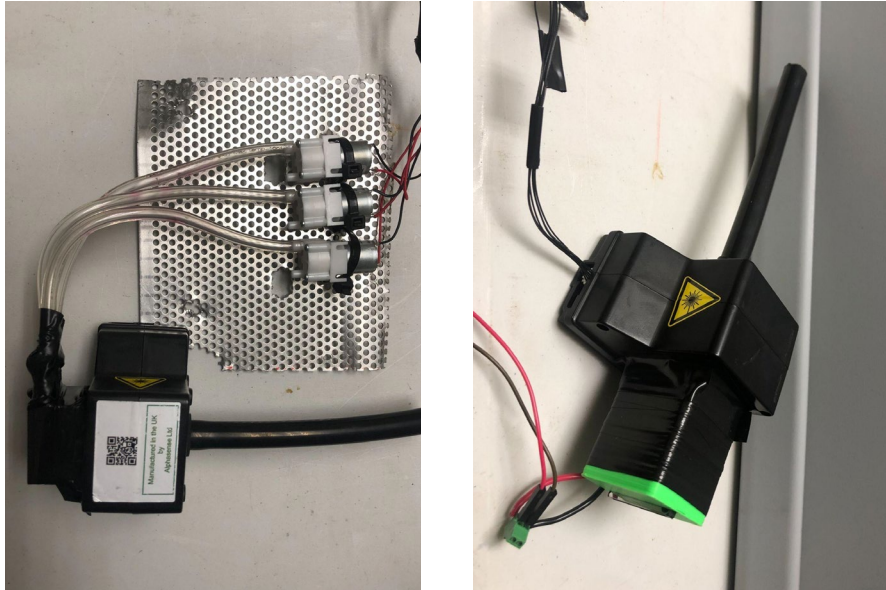


Figure 44 Modified OPCs - the Alphasense N3 with three rotary pumps in parallel (left) and one centrifugal blower (right) with 3D printed sleeves over the outlets of the devices that connect them to the pumps and blower respectively.

At the start of 2021, the two OPCs that remained under consideration for MURI flights, where cost is an issue since many missions are flown in the telemetry (no-recovery) mode, are the low-cost SPS30 and the mid-cost N3. The SPS30 had been most consistent in collecting data during stratospheric flights with the rotary-vane pumps, but the results at stratospheric altitudes were determined to be invalid. On the other hand, the N3 has shown better results during standard-condition ground calibration, and when connected to the centrifugal blowers, they have been able to collect adequate data at the desired MURI altitudes (above 20 km).

Figure 45 shows ascent data graphs from a July 2021 flight in Minnesota in which N3 OPC data with three rotary pumps in parallel powered at 6V and N3 OPC data with one centrifugal blower powered at 5V are compared. These voltages were chosen due to the maximum safe operating voltage for each option. The balloon burst at an altitude of 32 km, but the N3 OPC data with the rotary pumps dropped out at 29 km, whereas the data with the centrifugal blower was able to collect data for the smallest size bin up to burst. For the one-micron size bins and larger, neither system detected particles near 30 km. For this reason, the pumps were determined to not be powerful enough for the N3 OPC to detect particles at these altitudes. It is important to note that while the overall shape of the data from both OPCs is similar, there is a difference in magnitude between the rotary pumps and the centrifugal blower. This is due to how the N3 OPC measures the flow rate through the instrument and will be accounted for after calibration ground testing.

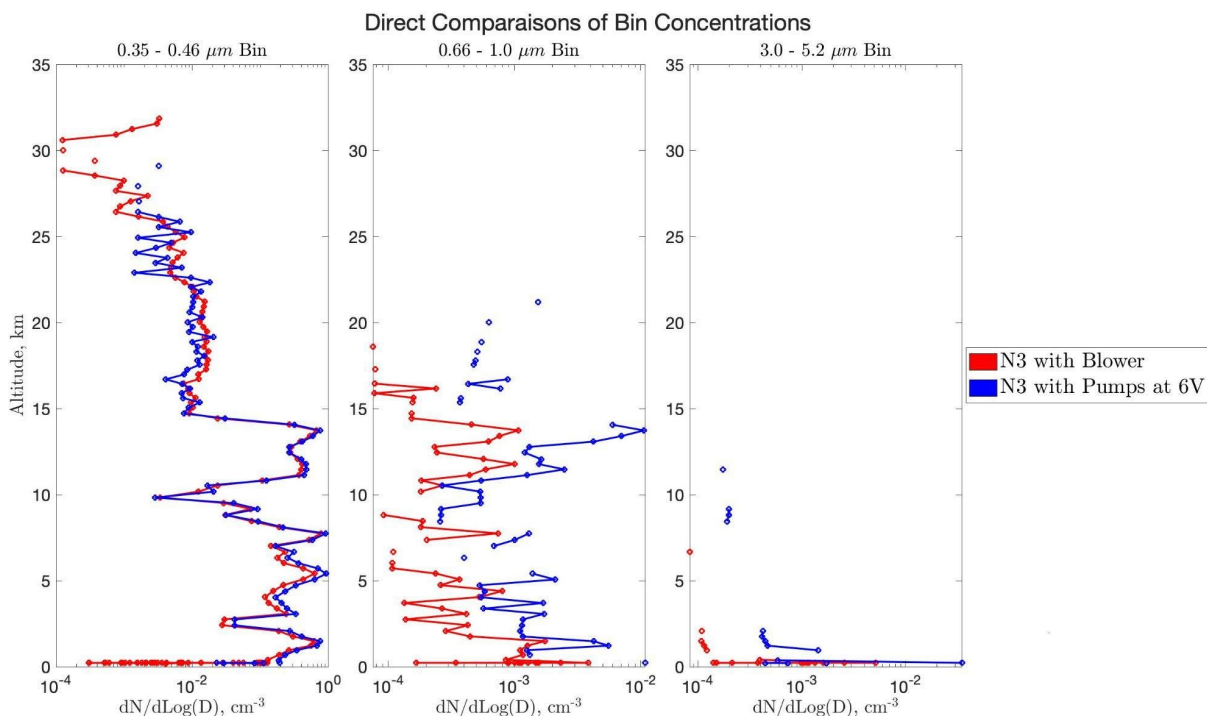


Figure 45 In-flight comparison of particle number concentration (normalized by bin width) measurements for the 0.3-0.5 micron bin (left), 0.66-1.0 micron bin (middle), and 3.0-5.6 micron bin (right) using the Alphasense N3 with three rotary pumps supplied with 6V (blue) and a centrifugal blower supplied with 5V (red). The measurements were all made during balloon ascent, not slow descent, on July 2, 2021.

Figure 46 shows N3 OPC data collected on a flight launched from Minnesota and suggests that particle data collected on the ascent and descent by parachute (faster than 5 m/s) are on the same order, including at altitudes of interest to the MURI project (above 20 km). This suggests that when ascending or descending, particle data collection is not sensitive to the orientation of the inlet, which was pointing down in this flight. Other flights in Minnesota carrying N3 OPCs with both up-facing and down-facing inlets taking data during ascent, slow descent (5 m/s or slower), and descent by parachute (faster than 5 m/s) suggest the same thing. Additionally, there has not been a significant difference seen in data with the centrifugal blower exhausting inside the payload box and with it exhausting outside the box. However, the final orientation of the N3 OPC inlet is down-facing with the centrifugal blower exhausting outside of the payload box.

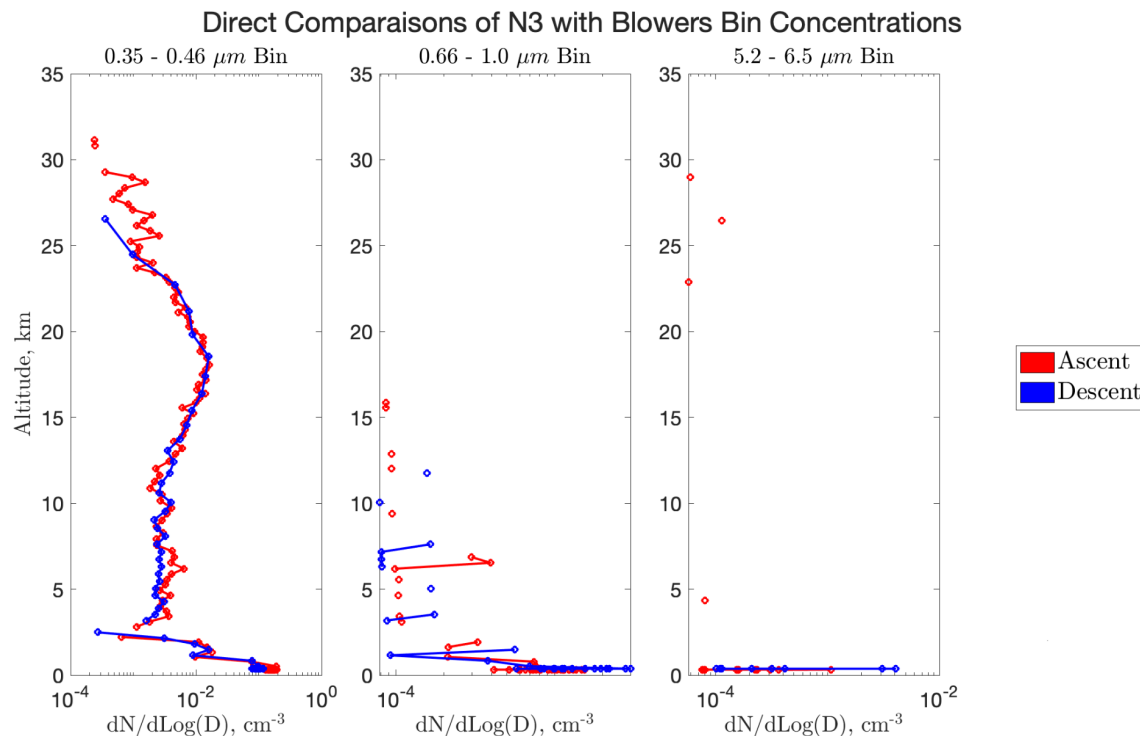


Figure 46 In-flight comparison of particle number concentration (normalized by bin width) measurements for the 0.3-0.5 micron bin (left), 0.66-1.0 micron bin (middle), and 3.0-5.6 micron bin (right) using the Alphasense N3 with a centrifugal blower during ascent and descent. The measurements were made during a balloon flight on Oct. 30, 2021.

However, the raw flight data from the N3 OPC cannot be taken at face value. Since the N3 OPC is designed to operate in ground-based environments, the instrument needs to be calibrated for stratospheric conditions. For this reason, a thermal-vacuum chamber has been developed in which OPCs can be placed and monitored under various conditions. By controlling the pressure, particle size, particle concentration, and temperature, a better understanding of how the N3 OPC operates under the extreme conditions of the stratosphere can be achieved.

To calibrate and characterize optical particle counters under standard (full atmospheric pressure/room temperature) conditions (see Figure 47), compressed air is first supplied through a HEPA filter to remove particles of the sizes measured by the sensor. Then a polystyrene latex solution is atomized to introduce particles of known size into the airflow. The particle-laden air is then passed through dryers to remove humidity, followed by a Krypton-85 (or Polonium-210) radioactive source in order to neutralize the particles electrically. The airflow is then split, with some passed to the sensor under test and some to a reference instrument. The volume flow rate through the system is adjusted and distributed between sensors to match the volume flow rates of each sensor, which are prescribed by their respective pumps.

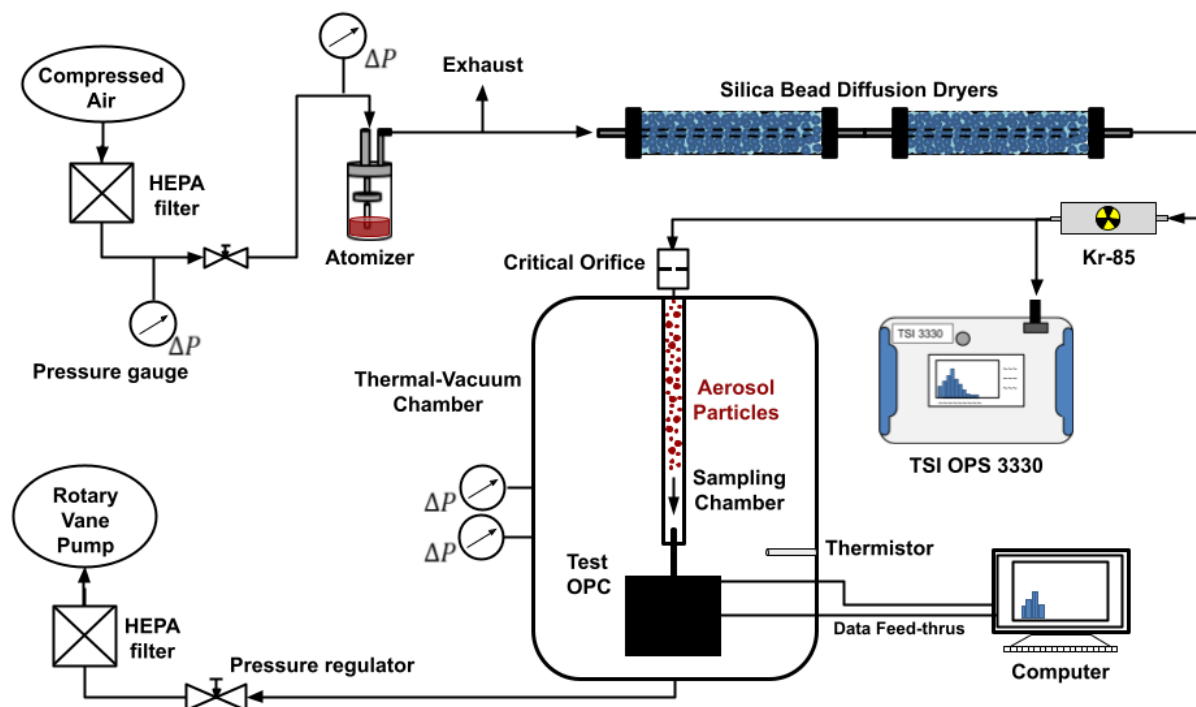


Figure 47 A schematic of the stratospheric particle calibration system.

This calibration system has been integrated into a thermal/vac chamber (see Figure 47 and Figure 48) so that particles of known size and concentration can be introduced into OPCs operating in extreme (stratospheric) conditions where the effects of low pressure and low temperature can be studied independently or at the same time. Pressure tests have been conducted for the N3 OPCs for sub-micron and micron-sized particles for pressures ranges equivalent to 24-37 km. Temperature and pressure will be monitored during balloon flights so OPC results can be correctly interpreted using a transfer function developed in the extreme-conditions calibration ground testing.



Figure 48 The thermal-vacuum calibration chamber mounted to its support structure. The image on the left shows the aerosol generation system on top of the chamber. The image on the right shows the pumping system on the bottom right of the image.

Figure 48 shows a photo of the actual thermal-vacuum chamber. Work is currently being done to characterize the velocity, temperature, and pressure fields via computational fluid dynamics. The initial calibration trials have shown that the peak particle sizes are captured well up to altitudes of about 30.5 km, after which the OPC data starts to be noticeably less than that of the reference instrument. At pressures corresponding to 36.6 km, there is very little data from the N3 OPC instruments. Additionally, tests comparing the variability of the N3 OPCs were done and found very little variability between individual instruments. This suggests that for each batch order of N3 OPCs, only a few instruments may need to be calibrated rather than individually calibrating the entire batch. Experiments to compare how temperature affects the data measurements have not been done, but there are plans to do so in the future. We anticipate the impact of stratospheric temperatures (modestly lower than standard conditions, in an absolute sense) will be much less than, and perhaps even negligible when compared to, the impact of stratospheric pressures (dramatically lower than standard conditions, in an absolute sense).

3.1.4.1 Progress in Integrating and Test-Flying MURI Payloads for US Flights and Ballooning Campaign in Support of BOLT-1 Rocket Launch

In previous years, the UMN team explored double-balloon flights as an option for achieving a show-descent phase of balloon flights. While this would allow for the flights to achieve a higher apogee, the UMN team struggled to accomplish reliable double-balloon flights. For this reason, single-balloon vented flights were determined the best choice going forward, and were used for the BOLT-1 campaign. Additionally, vented flights can be recovered if need be, as they were during the BOLT-1 campaign due to radio regulation issues in Europe that precluded the use of standard CU and ERAU telemetry. In support of the BOLT-1 Rocket Launch, the UMN team sent OPCs and their accompanying hardware to

the CU team for integration into payloads. Additionally, the UMN team remotely aided in tracking Sweden balloon flight in real-time. The OPC data that was collected from the recovered BOLT-1 payloads were analyzed by the UMN team. Figure 49 and Figure 50 show data from balloon flights on June 22, 2021, that were launched the same day as the BOLT-1 Rocket. The OPC data gathered in Sweden matches the expected results based on comparable OPC flights done by the UMN team. Furthermore, Figure GG depicts the ascent and slow descent data graphed on the same plot, illustrating how the ascent data and the slow descent data from the flight line up with one another, further supporting the claim that OPC data collected on ascent, slow descent, or parachute descent are all valid.

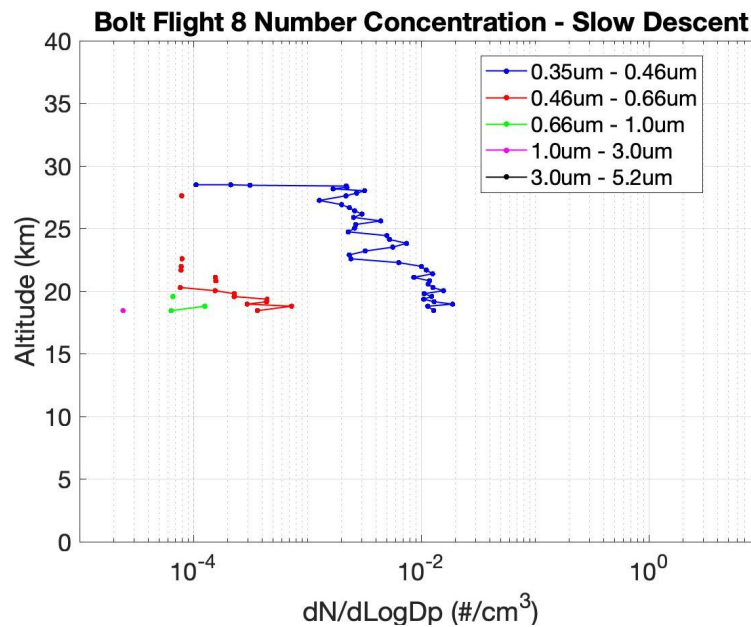


Figure 49 In-flight comparison of particle number concentration (normalized by bin width) measurements for the slow descent portion of the eighth balloon flight of the BOLT-1 campaign. The five smallest bin sizes of particles are graphed. The smallest bins receive data up to the peak altitude of approximately 29 km, matching what has been seen on other balloon flights.

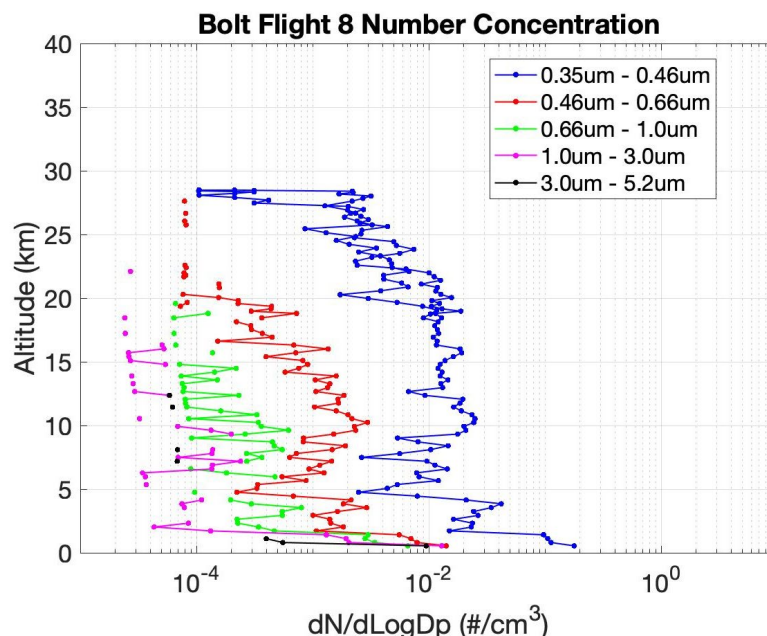


Figure 50 In-flight comparison of particle number concentration (normalized by bin width) measurements for the ascent and slow descent portions of the eighth balloon launch of the BOLT-1 campaign. The data for the five smallest bin sizes have been plotted on top of one another in the same color. The overall shape of the slow descent data lines up with the shape of the ascent data, suggesting that the OPC data collected upon ascent is as valid as the data collected on slow descent.

In accordance with the decision to conduct telemetry flights, and in preparation for the BOLT-2 campaign where no payload will be recovered, the UMN team has deployed two ground stations for use in non-recovered telemetry flights. One of these ground stations is located in St. Peter, MN, and the other is located on the UMN Minneapolis campus. With these stations, the UMN team launched six telemetry payloads between April and December of 2021, four of which were fully-integrated OPC and turbulence data payloads. Despite receiving data through the telemetry system, many of these payloads were recovered, which allowed the UMN team and the CU team to troubleshoot any issues that may have arisen on these flights. Additionally, “stand-alone” OPCs have continued to be flown on non-vented flights. In 2021, the UMN team has done twelve of these OPC-only flights, four of which were flown with the high-cost LOAC OPC for data comparison.

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3.2 Atmospheric Modeling and Simulations

3.2.1 Atmospheric Simulations and Project Coordination

HYFLITS Co-PI Dave Fritts both guides the HYFLITS Modeling Team and serves as Project Coordinator (PC), given the central roles atmospheric turbulence modeling plays in all aspects of the MURI research efforts. Specific HYFLITS Modeling Team roles include the following:

- Identify the major sources of local energy inputs into the stratosphere due to high-frequency gravity wave (GW) energy transport from these GW sources in the troposphere, and the conditions under which they arise;
- Identify the energy inputs into the stratosphere due to inertia-gravity wave (IGW) energy transport from sources at lower altitudes, and the conditions under which they play major roles;
- Guide specifications of modeling studies using the Complex Geometry Compressible Atmosphere Model (CGCAM) targeting idealized and realistic GW events in small and very large domains to identify the environmental factors lead to the strongest turbulence;
- Guide specifications of modeling studies using the Spectral Atmosphere Model (SAM) targeting idealized shear flow and GW breaking events enabling assessments of turbulence intensities and statistics for a range of expected environments;
- Identify the most likely sources of extreme stratospheric turbulence;
- Publication of multiple HYFLITS modeling results in peer-reviewed journals; and
- Design a strawman “Global Stratospheric Clear Air Turbulence (GSCAT)” forecasting methodology that can be implemented with current HYFLITS MURI modeling capabilities and global data assimilation (e.g., by the Naval Research Lab. NAVGEM and/or NEPTUNE models) of anticipated revolutionary, global measurements of stratospheric winds and temperatures (this design has been completed and is poised to proceed to development and implementation, if and when funding for such is obtained).

HYFLITS PC roles informed by our Modeling Team results to date include the following:

- Provide guidance to the HYFLITS Atmospheric Measurements team on the character and scales of the dynamics yielding the strongest stratospheric turbulence;
- Guide identification of the regions within various events likely to yield the strongest turbulence to be targeted by HYFLITS balloon measurements;
- Provide modeling guidance for HYFLITS turbulence measurements & instrument calibration;
- Provide turbulence fields for hypersonic boundary layer and optical propagation modeling;
- Provide modeling and turbulence source forecasting for BOLT-1 flight support;
- Anticipate flight support and/or “hindcast” modeling support for the BOLT-2 flight, as needed.

A review of our major research foci, ongoing support of MURI measurements, and MURI support of BOLT-1 are summarized in Section 1.1.2. A review of expected major sources of stratospheric turbulence that have motivated our modeling to date, and their importance, is provided in Section 1.1.3. Section 1.1.4 describes the HYFLITS DNS testbeds for hypersonic boundary layer modeling of instability transitions, evaluation of the HYFLITS in-situ sensors, and data enabling assessments of phase screens impacting aero-optical propagation. And a strawman “GSCAT” forecasting system is reviewed in Section 1.1.5.

3.2.2 Modeling Sources of Energy Transport and Turbulence Locations in the Stratosphere

The primary sources of strong stratospheric turbulence are mountain waves (MWs) over significant topography, convective gravity waves (CGWs) interacting with stratospheric wind shears, and large-scale wind shears enhanced by inertia-gravity waves leading to multi-scale Kelvin-Helmholtz instability (KHI) dynamics. All of these sources have been implicated in severe turbulence encounters by aircraft in the lower stratosphere and are expected to become more intense at higher altitudes. Examples of CGCAM and SAM modeling of these sources are shown in Figure 51.

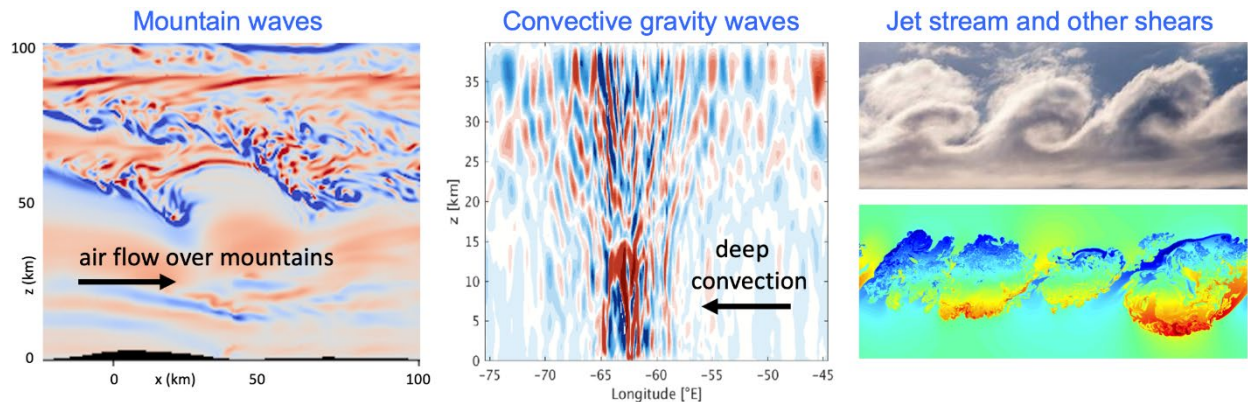


Figure 51 Illustrations of the major turbulence sources in the stratosphere. MWs are likely the strongest sources, but convective gravity wave generation and strong wind shears are also expected to pose significant risks, depending on characteristics, and particularly the wind shears of the underlying flows. All these sources are being explored with high-resolution CGCAM and SAM modeling by the HYFLITS MURI team at CU and ERAU.

The HYFLITS modeling team is performing MW turbulence simulations over Colorado, the Southern Andes, and elsewhere, all of which are known to have led to severe MW turbulence (see Figure 52) at lower altitudes, and an example of extreme responses over high terrain at other sites addressing MURI goals (see the left panel of Figure 51). MWs over Colorado are a particular focus of our MURI modeling and measurement efforts, given the proximity of the CU measurement team, the easy access to balloon launch and recovery sites, and the forecast skill that can be achieved combining local, high-resolution numerical weather prediction and very high-resolution modeling of turbulence sources by the HYFLITS team.

Figure 52 shows an example of a routine high-resolution WRF forecast extending out 3.5 days that is performed to enable the HYFLITS measurement and modeling teams to anticipate upcoming conditions that may be of interest and the high-resolution grid employed for our forecasting using CGCAM.

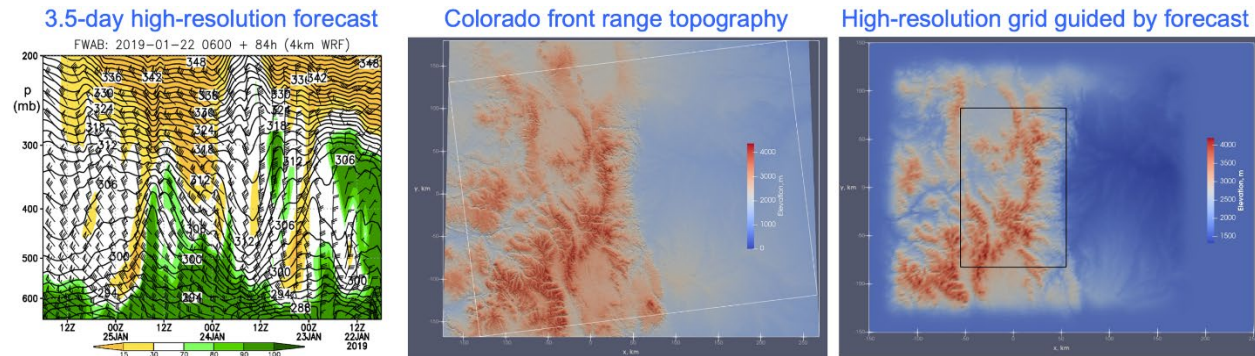


Figure 52 Example of a routine (daily) WRF 2-km forecast over Colorado (left) and the Colorado terrain and CGCAM domain configured to allow high-resolution turbulence forecasts (center, white rectangle) as needed, and the very-high-resolution central CGCAM domain (right, black).

When a candidate measurement target is identified, the HYFLITS team can initiate a further high-resolution Weather and Research Forecast (WRF) model simulation extending to ~31 km, and a corresponding CGCAM forecast achieving much higher resolution over and in the lee of the Rockies in order to more precisely guide the balloon measurement trajectory (Figure 52, right). An example of the expected turbulence locations in the lee of the Rockies at a 30-km altitude is shown in Figure 53.

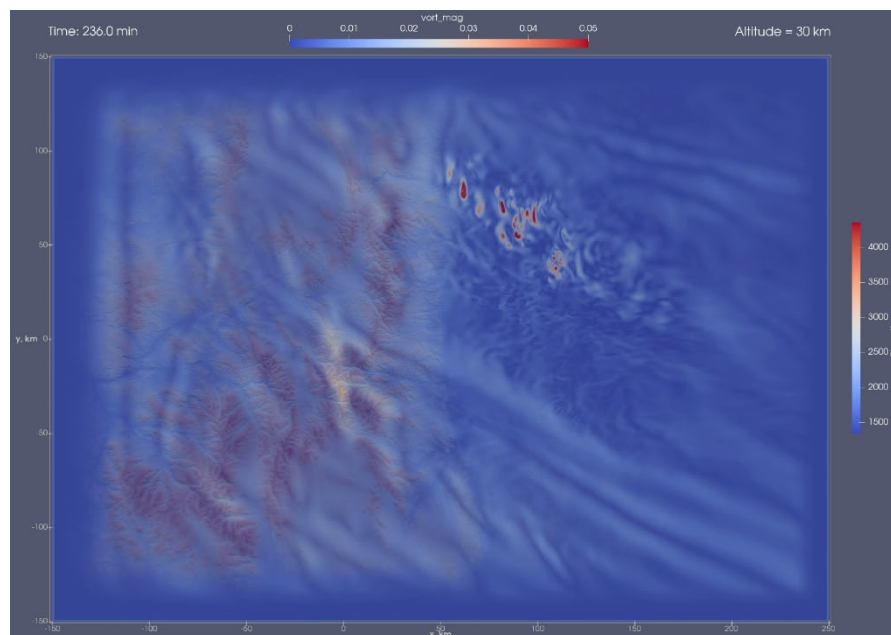


Figure 53 A previous CGCAM turbulence forecast over Colorado for 20 Feb. 2020 to guide balloon measurements. The vorticity revealing the strongest MW breaking is shown in red at ~4 hr after initiation of the CGCAM simulation. A similar CGCAM forecast of turbulence at 35 km in the vicinity of the BOLT-I launch site at Esrange, Sweden is shown for reference in Figure 54.

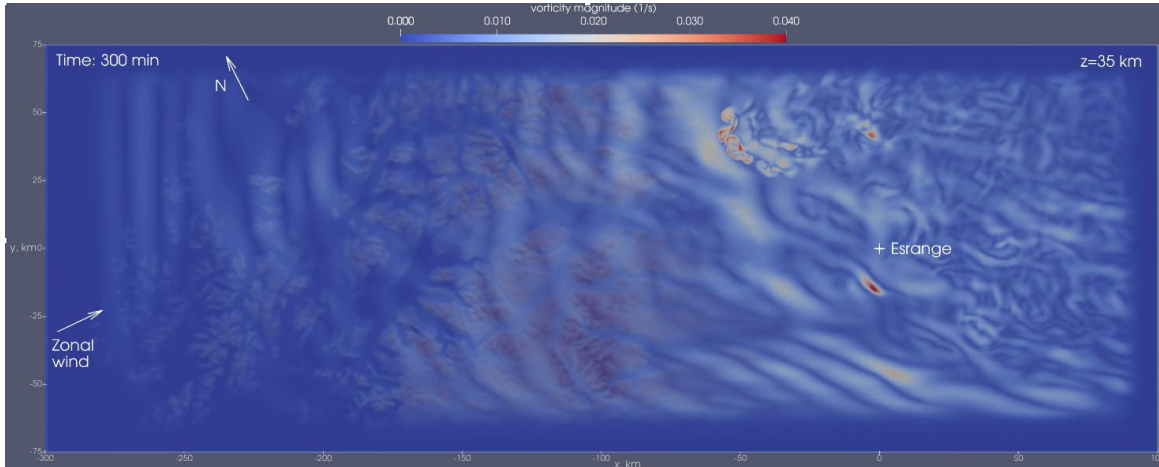


Figure 54 As in **Figure 53**, but over N. Sweden and Erange in Jan. 2017.

The HYFLITS MURI team has similar capabilities for forecasting and measuring stratospheric turbulence arising from convective gravity waves (CGWs) propagating into the middle stratosphere above deep convection. These forecasts are initialized with a NEXRAD rainfall rate source parameterization that allows CGCAM to reasonably replicate CGW fields seen by the AIRS instrument on the Aqua satellite in the middle and upper stratosphere. CGCAM has also been employed to explore the dependence of predicted regions of turbulence generation on the environments in which CGWs propagate throughout the stratosphere. Examples of the CGCAM forecast of CGWs throughout the stratosphere at two times for representative radiosonde winds and temperatures over Jacksonville, FL, in support of measurements by the HYFLITS ERAU measurement team are shown in Figure 55.

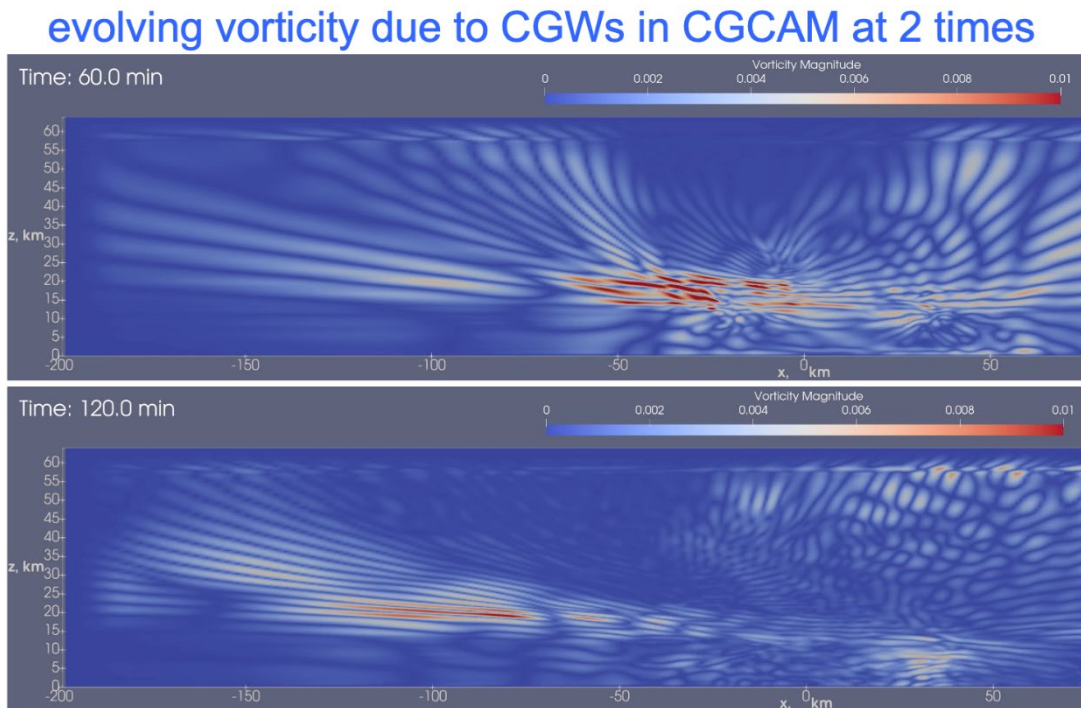


Figure 55 Example CGCAM simulation showing the CGW response 1 and 2 hr after convective initiation in an E-W domain extending to 65 km. Such simulations are performed for measured stratospheric fields supporting HYFLITS CGW measurements.

3.2.3 Modeling Turbulence Intensities for the Major Sources in the Stratosphere

KHI has been recognized as a widespread source of turbulence throughout the atmosphere for many years. Previous modeling studies of uniform KHI have anticipated turbulence intensities that are significantly smaller than are expected to accompany strong MW and CGW breaking. However, recent observations have revealed that new “multi-scale” KHI seen earlier in laboratory studies can also have dramatic consequences in the atmosphere. Hence, a significant HYFLITS modeling effort using both CGCAM and SAM is now addressing these dynamics and reveal that they can be competitive with strong MW and CGW breaking in turbulence intensities, and importantly, they may be much more widespread.

Large DoD High Performance Computing Modernization Program (HPCMP) supercomputing resources have allowed our modeling team to perform a series of “first-ever” simulations of the dynamics of multi-scale KHI, and the results have been dramatic. These reveal that initial KHI phase alignments arising from initial noise fields, or via perturbations by ubiquitous GWs, often exhibit phase kinks or mis-alignments that enable dramatically stronger and more rapid turbulence initiation and intensities than in the absence of these influences. The consequences are energy dissipation rates that can be up to ~ 5 times higher as turbulence transitions are initiated, and widespread influences of such enhancements relative to KHI in their absence. A simulation of these dynamics using SAM is shown with vertical and horizontal cross sections of the resulting energy dissipation rate, ε , at several times as the KH billows arise and exhibit turbulence transitions in the left and right panels of Figure 56 (Fritts et al., JGR, 2022).

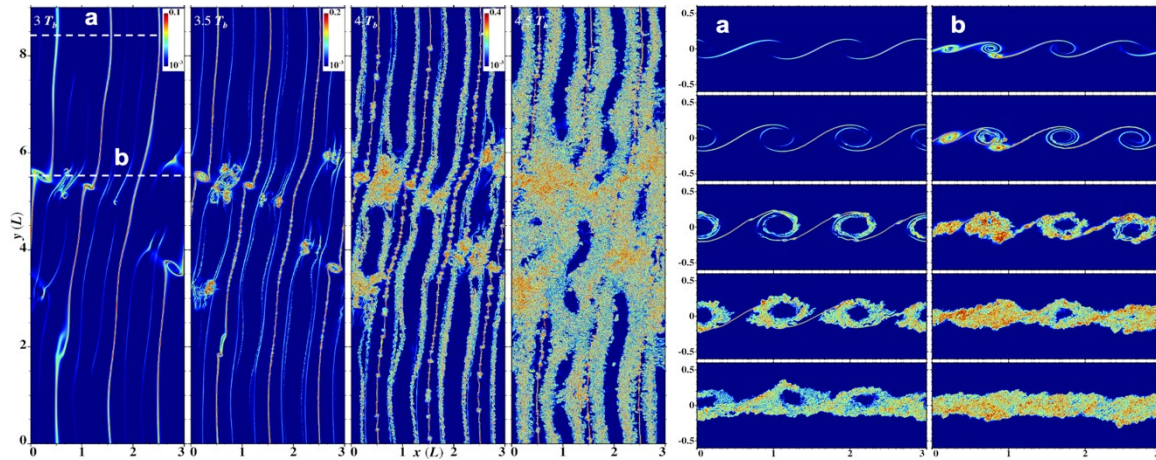


Figure 56 Horizontal (x, y) and vertical (x, z) cross sections (left and right) of SAM a multi-scale simulation of three KH billows shown in ε having mis-aligned cores that lead to enhanced turbulence transitions and intensities. The (x, z) sections at right, denoted a and b, are for the y -locations shown at left and ending at the same time.

These fields reveal that vortex “tubes and knots” (T&K) arise where KH billow cores are kinked or exhibit strongly variable phases, and that they yielded significantly earlier and enhanced ε where they occur.

A more aggressive example of these KHI T&K dynamics is shown in Figure 57. Both SAM and CGCAM simulations initiated with various small-amplitude white noise reveal a further form of strong T&K dynamics arising where a single KH billow core must link to two, or two must link to three. The details of these tube and knot dynamics are illustrated in a full SAM domain in Figure 57 and in a subset of a CGCAM simulation of these dynamics in Figure 58 and these reveal how and why large ε arises so quickly.

Additional idealized SAM simulations of MW breaking were also performed, and suggest that these various dynamics can all contribute strong stratospheric turbulence under suitable conditions at sufficiently large

spatial scales. For realistic KHI and MW scales, the modeling suggests that tube and knot dynamics can be competitive with MW and CGW breaking in terms of ε statistics, and that such KHI T&K events may be much more widespread than other sources of strong stratospheric turbulence, hence may pose a more pervasive influence on hypersonic-vehicle flight in the middle and upper stratosphere.

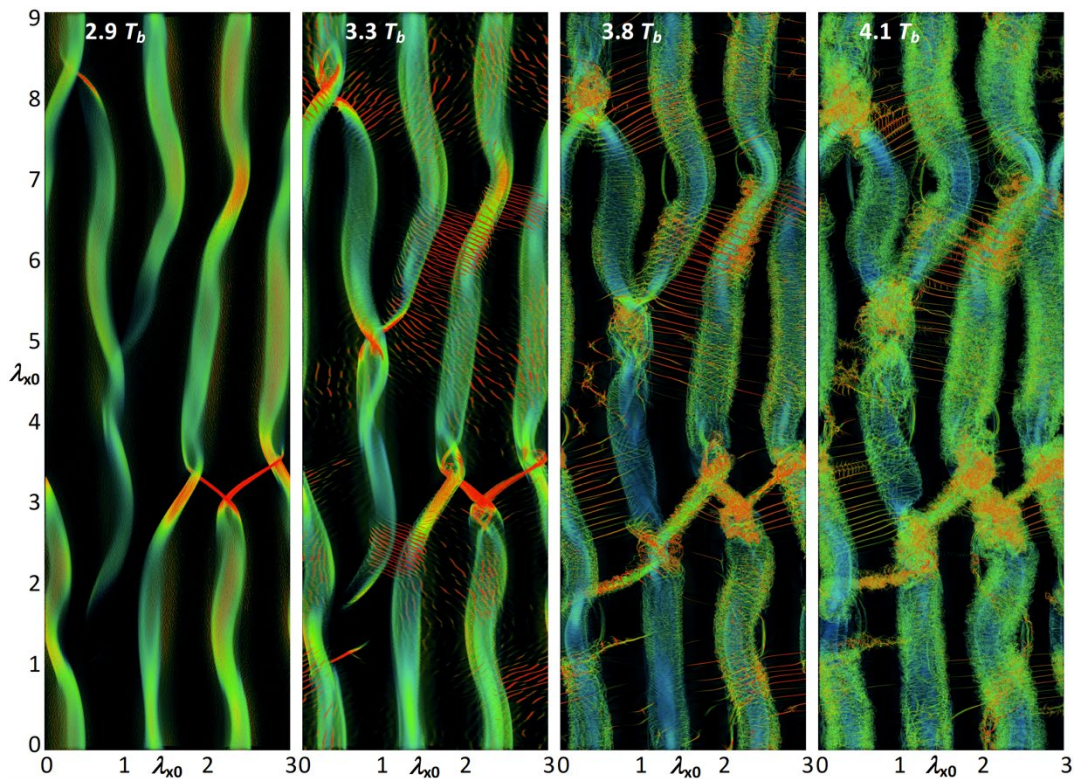


Figure 57 Horizontal (x,y) views of vorticity fields exhibiting KHI T&K dynamics similar to, but more energetic than, those seen in Figure 69. The strongest responses are seen to arise where the KH billows are mis-aligned along their axes. The evolution spans $1.2 T_b$, or ~ 2.5 min, and KH billow scales can be as large as ~ 3 -6 km in the stratosphere (Fritts et al., 2022, in preparation).

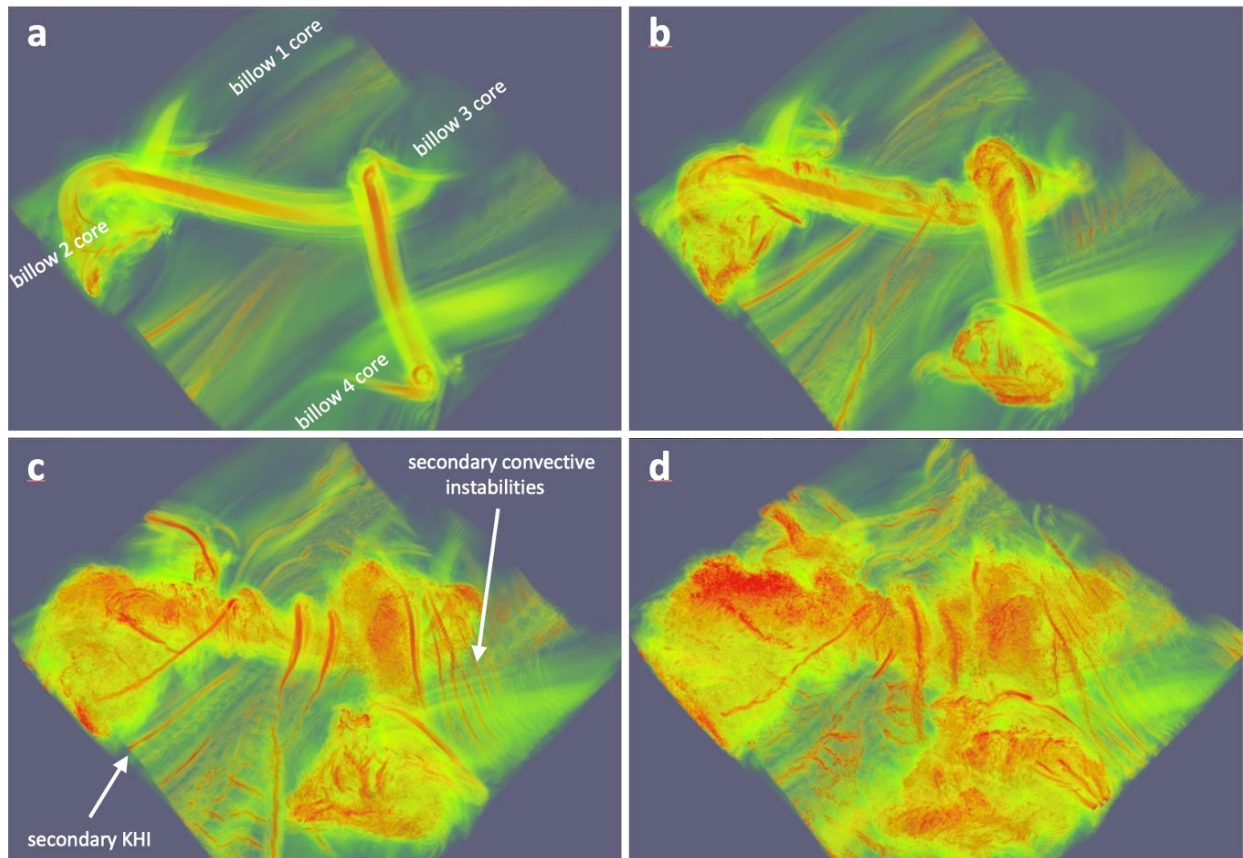


Figure 58 The dynamics of tubes and knots accompanying mis-aligned multi-scale KH billows in a CGCAM simulation spanning ~ 5 min in the stratosphere. The initially laminar tubes in panel (a) interact to form knots that then exhibit increasingly rapid and strong vortex interactions thereafter (see Fritts et al., 2021, JGR, for details).

3.2.4 HYFLITS Modeling of Stratified and Unstratified Turbulence Intensities as Inputs for Modeling Hypersonic Boundary Layer transitions, Evaluations of HYFLITS In-Situ Measurements, and Aero-Optical Propagation

The HYFLITS Modeling Team has performed very-high-resolution idealized and more realistic SAM modeling in order to assist in efforts requiring such modeling by other members of the HYFLITS team. These include the following:

- 1) both unstratified and stratified simulations of intense turbulence arising from intense, closely-spaced, orthogonal shears were provided to the UMN hypersonics modeling team as input flows for their exploration of boundary layer transitions; these flows were found to initiate ~ 200 kHz boundary layer instability transitions;
- 2) a high-resolution SAM DNS of idealized MW breaking was provided to the HYFLITS CU in-situ measurements team; these were judged to not have sufficient power at very small scales, so we are currently providing the same idealized stratified fields employed for the hypersonic boundary layer turbulence transition assessment; and
- 3) phase screens obtained by viewing vertically through one of our large, multi-scale KHI T&K simulations were provided to the HYFLITS Aero-Optical Propagation team to allow evaluation of the influences of these dynamics in those applications.

3.2.5 Design of a Global Stratospheric Clear Air Turbulence (GSCAT) Forecasting Model

A “strawman” design of a Global Stratospheric Clear Air Turbulence (GSCAT) Forecasting Model was proposed in the initial MURI HYFLITS proposal, and was identified as a key deliverable at the “kick-off” meeting by the initial Program Manager, Ivett Leyva. That high-priority “deliverable”, and significant model development efforts over the past year, have enabled coordinated efforts addressing the design and implementation of GSCAT in partnership with Naval Research Laboratory (NRL) colleagues who already perform the most advanced data assimilation extending to the highest altitudes within their NAVy Global Environment Model (NAVGEM) and the follow-on NRL NEPTUNE model. Such a “real-time” global forecasting model requires guidance of the evolving global atmosphere by global measurements of winds and temperatures by new satellite measurement capabilities, for which there is now specific, coordinated interest by NOAA, NASA, and the Air Force, and for which a lab-tested instrument prototype enabling such measurements from ~30-50 km, day and night, is now available. Such an effort also requires multiple modeling advances linking global to local scales, including the following (see **Figure 59** below):

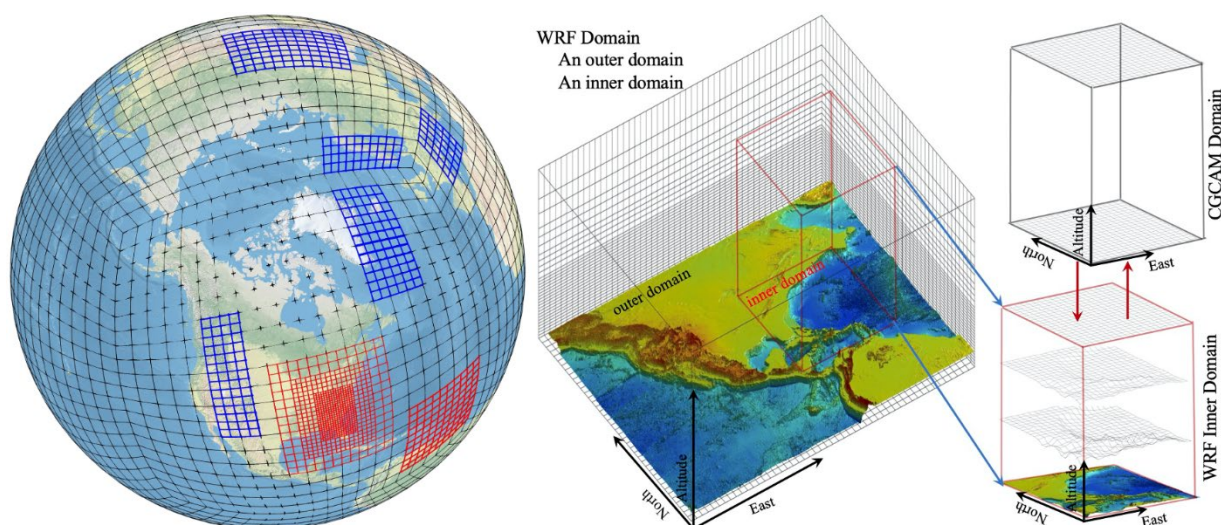


Figure 59 NAVGEM/NEPTUNE with multiple user-specified sub-domains (left). Shown at right is a combined WRF-CGCAM subdomain enabling descriptions of complex surface and forcing dynamics not included in CGCAM.

- 1) State-of-the-art global data assimilation (in place with NAVGEM, NEPTUNE, and elsewhere),
- 2) User-specified nesting capabilities (one-way required, two-way if desired) enabling embedded, very-high-resolution domains in all regions of interest,
- 3) Nested sub-domains describing evolving environments, energy inputs from below, and mesoscale dynamics providing statistical assessments of turbulence sources, locations, scales, and intensities, with time-dependent boundary conditions provided by NAVGEM or NEPTUNE.

The sub-domains will employ WRF in a nested configuration in the troposphere and lower stratosphere in order to capture moist dynamics and complex boundary-layer influences; WRF will serve as the lower boundary for CGCAM nested domains configured to enable multiple, high-resolution sub-domains describing various local responses, as required. CGCAM will allow multiple, adaptive, subdomains with adaptive mesh refinement, dependent of the local flow evolutions.

CGCAM and supporting SAM capabilities (describing representative turbulence statistics and intensities) will employ flexible and efficient domain decompositions and enabling utilization of very large numbers of HPCMP cores for “Near-Real-Time (NRT)” computing in a forecasting environment. For these GSCAT design purposes, we have recently expanded the CGCAM and SAM domain decomposition capabilities. Those for CGCAM now enable “block” decompositions for highly-optimized performance across ~10,000 to ~100,000 HPCMP cores (Figure 60 at top); those for SAM now enable “slab” and/or “pencil”

decomposition also enabling efficient scaling across ~10,000 to ~100,000 HPCMP cores (labeled “a” and “b” at lower left in Figure 60) required for global-scale, high-resolution GSCAT forecasting.

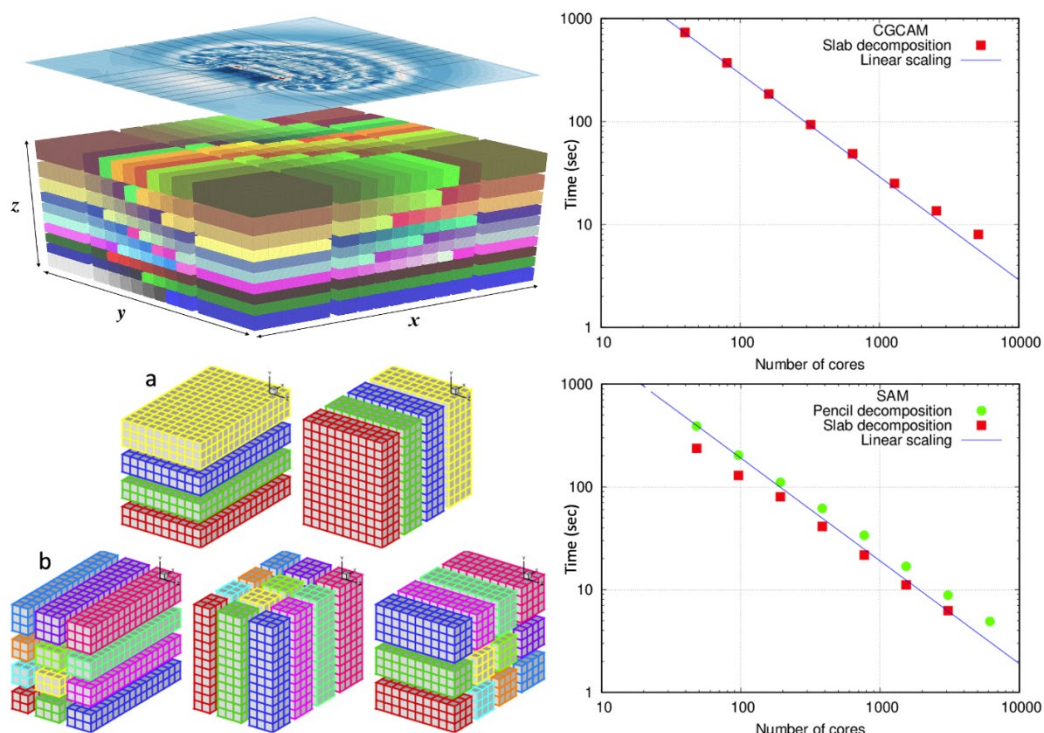


Figure 60 New CGCAM “block” decomposition (top, left) and SAM “slab” and/or “pencil” decomposition (bottom, left). Shown at right for each is an evaluation of scaling efficiency to ~10,000 cores for each model. The roughly linear scaling demonstrates that required to support GSCAT forecasting employing HPCMP capabilities.

3.3 Aerothermodynamic Simulations

In Year-4 the UMN Aerothermodynamics Modeling and Simulation team, led by Co-PI Graham Candler, continued the development of DNS simulation methods with realistic inflow conditions that represent stratospheric turbulence. This work involved several components that are required to obtain accurate DNS results. The key issues that were tackled in the past year are:

1. Development of a shock-fitting boundary condition to provide accurate bow shock wave location and post-shock conditions. This boundary condition is not yet complete, and its development is continuing during Year-5.
2. Full domain grid generation with carefully a tailored outer boundary for the blunt cone test cases being studied.
3. Development of a shock kinematic boundary condition (SKBC) for accurately passing free-stream perturbations through the shock wave. This boundary condition remains under development.
4. Running simulations and extracting relevant data to characterize the influence of free-stream turbulence on second-mode dominated transition.
5. A new Lagrangian particle tracking method developed the US3D code was used to simulate the effects of atmospheric particulates on a hypersonic boundary layer.

3.3.1 Freestream Turbulence Simulations

The overall goal of this aspect of the MURI is to accurately predict the effect of freestream turbulence on instability growth in hypersonic boundary layers on realistic flight configurations. A critical aspect of this challenge is to correctly pass disturbances through the strongly curved bow shock wave. During the past year, we have worked to improve how free-stream disturbances are passed through the shock wave. As discussed in the previous report and in our 2021 AIAA SciTech paper, the numerical method can introduce error into the flow field as disturbances pass through a strong shock wave. It was found that the grid must be perfectly aligned with the shock, and the grid lines running away from the shock must be normal to the shock wave in order to reduce the numerical error. If these criteria are met, good agreement between theory and CFD can be obtained with a sufficiently fine grid. Figure 61 illustrates the theoretical behavior of an entropy disturbance as it passes through an oblique shock wave and compares the present US3D simulations with theory. Three grids have been used, and the fine grid (64 grid points per wavelength, ppw) reproduces the theoretical results. We find that with careful tuning of the dissipation, it is possible to obtain accurate results on a grid with as few as 24 ppw. These results guided the design of computational grids for the DNS of free-stream turbulence interacting with the hypersonic flow fields.

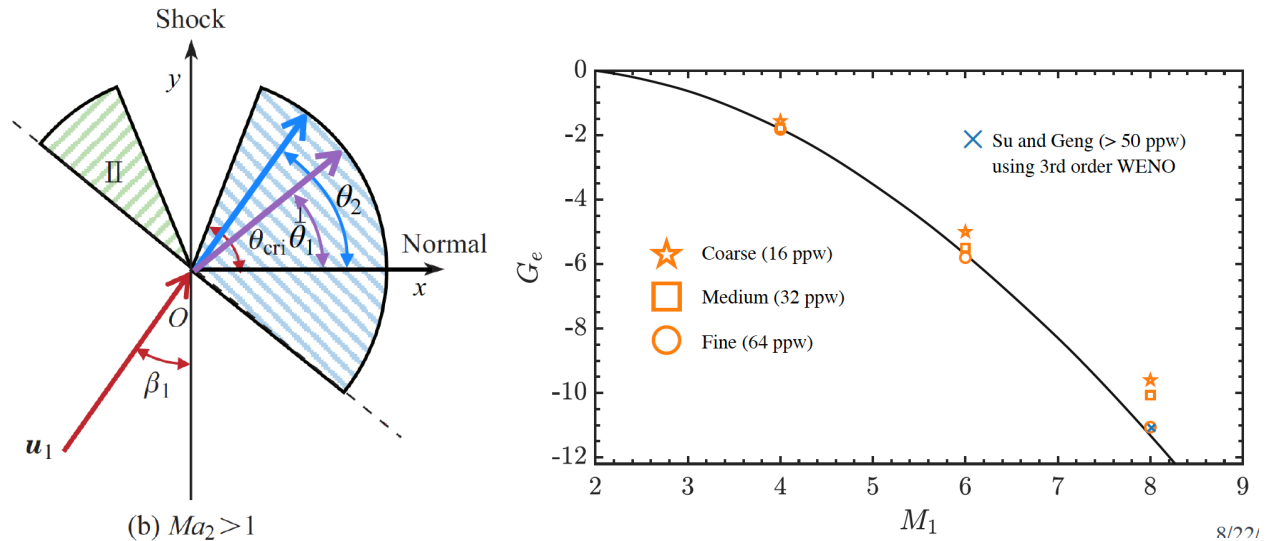


Figure 61 Left: Theory for the passage of a freestream disturbance through an oblique shock wave (from Su and Geng, 2017); Right: Entropy gain (Ge) as a function of free-stream Mach number computed with US3D vs. theory.

The simulations are using the high-fidelity DNS of atmospheric turbulence performed by the Fritts group. We have developed the ability to efficiently read in and interpolate the DNS data to provide free-stream conditions for the hypersonic flow simulations. In addition, the data are sampled so that a long non-periodic domain is used to provide the freestream conditions. The concept is to “fly” through the periodic box of turbulence at an angle so that the data record does not repeat; this allows a single DNS to provide as much as 1-km of representative freestream conditions for the hypersonic simulations.

Grid design and generation is a crucial aspect of accurate full vehicle simulations. As discussed above, the grid must be shock-aligned and there must be a sufficient number of grid elements to resolve the freestream waves. Furthermore, the wavelength of the waves changes as they pass through the shock; this increases the grid resolution requirements in the post-shock region of the computational domain. Generating a computational grid that satisfies all of these requirements is a very significant challenge and occupied much of Year-3 and Year-4. In addition, tuning the levels of dissipation required to capture the shock without damping out freestream disturbances is essential. Thus, optimizing the grid and the shock sensor has taken a great deal of time. This is now complete, and a final 500-million-element grid for one fourth of the

HIFiRE-1 blunt cone geometry has been generated and carefully shock aligned. Initial simulations have been run on this grid.

Preliminary simulation results indicate that freestream turbulence may activate boundary layer instability mechanisms and potentially lead to transition. Figure 62 shows a snapshot of the surface pressure perturbations near the end of the HIFiRE-1 blunt cone at Mach 10, 20 km altitude conditions. The regular streamwise-aligned perturbations are consistent with second-mode acoustic disturbances. This is expected because this flowfield is known to rapidly amplify these modes, based on linear stability theory. The wavelength near the trailing edge is approximately 3.4 mm, consistent with that predicted by theory. However, there remains a concern that these instabilities are initiated by numerical errors associated with how the numerical method processes the freestream turbulent perturbations, especially in the stagnation region where the shock is strong and highly curved. In this figure, note that the disturbances are intentionally damped near the trailing edge to prevent error from propagating into the domain from the outflow boundary condition.

Now, the question is: What is the source of the small-scale disturbances that activate these instabilities. Figure 63 plots a snapshot of the temperature disturbances in the nose region of the flowfield. Here, the radius of the spherical nose is 5 mm. Small-scale fluctuations are clearly present in this figure. These perturbations have a regularity that is associated with the grid. Even though the grid is aligned with bow shock, the small variations in the free-stream state due to wrinkling of the shock and the associated numerical error. Thus, we have not yet proven that turbulent motion and entropy spottiness in the atmosphere may initiate transition.

Therefore, we still have work to do. During Year-4, we have been developing a novel shock-fitting boundary condition that represents the bow shock as an interface – on the upstream side of the boundary condition is the freestream supersonic state, and on the downstream side is the post shock condition. The interface is moved until it reaches a steady-state condition that represents the exact location of the bow shock wave. This boundary condition is working in two dimensions, but we are still having surface geometry instabilities when running on realistic three-dimensional grids. We are continuing to develop the shock-fitting boundary condition in Year-5.

Once the exact steady-state shock wave position has been computed, we must contend with freestream fluctuations and their effect on the bow shock location. To accurately represent the effect of the fluctuations, we are working on an additional boundary condition that solves the time-dependent fluctuating shock jump conditions relative to the steady-state shock location. This boundary condition is also under development and will be made to be fully functional during Year-5. Therefore, we have made great progress in the assessment of freestream disturbances, but more work needs to be done. This will be accomplished during the next year.

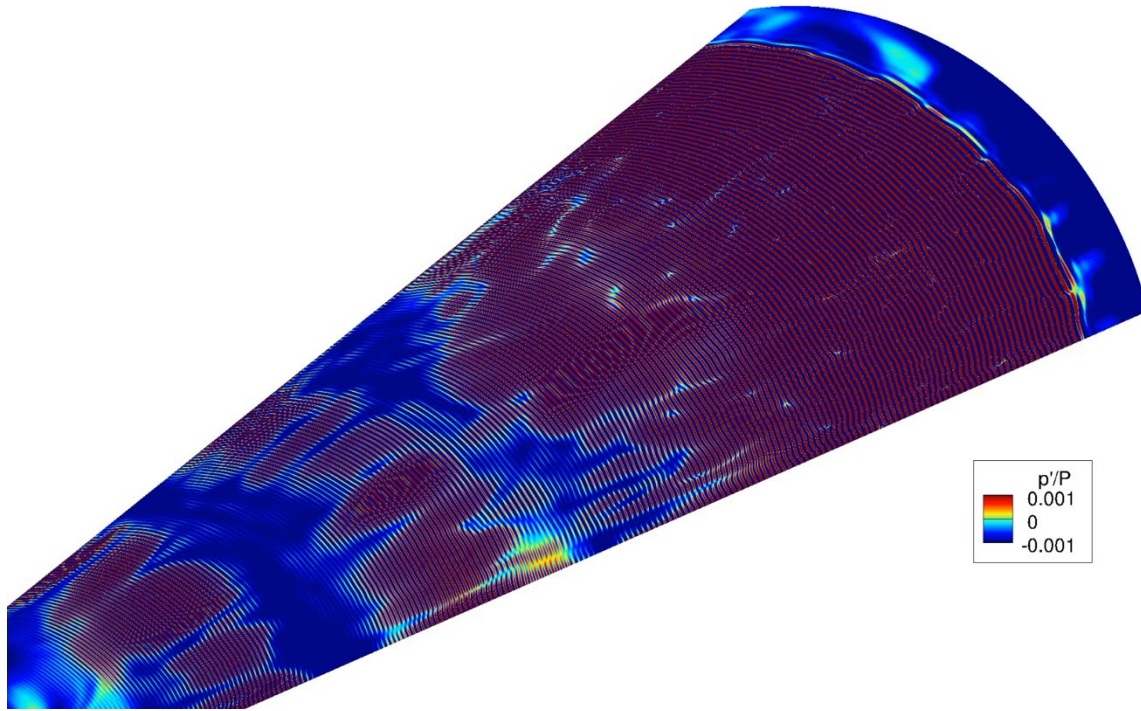


Figure 62 Surface pressure disturbances induced by free-stream turbulent motion on the HIFiRE-1 blunt cone at Mach 10 conditions. The dominant wavelength of the disturbances is approximately 3.4 mm, which corresponds to the most unstable wavelength for second-mode disturbances on this part of the cone frustum.

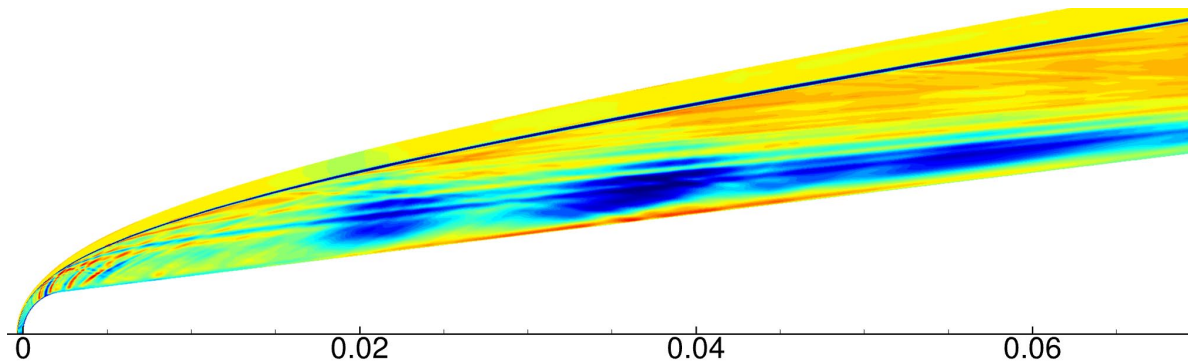


Figure 63 Temperature perturbations in the nose region of the 500 million element grid simulation of the HIFiRE-1 sphere-cone at Mach 10.

3.3.2 Freestream Particulate Simulations

In addition to the freestream turbulence DNS, the UMN group has been performing simulations of particulates interacting with the HIFiRE-1 blunt cone flowfield at conditions relevant to hypersonic flight. These simulations are using a newly-developed US3D plugin that tracks particulates through a flowfield. This Lagrangian particle tracking method includes drag and energy source terms for full coupling of the particulates and the flowfield. The implementation has been compared with previous simulations of a single particulate interacting with a boundary layer; excellent agreement has been obtained.

To date, we have only run simulations with an axisymmetric flow field; the grid is based on that used for the turbulence simulations discussed above. The full 500 million element three-dimensional simulations can in principle be run, but are extremely expensive. These will be completed during Year-5.

However, the axisymmetric simulations are interesting and may indicate that particulates can interact with the flow field and initiate transition when the boundary layer is receptive to second-mode disturbances. We use a particulate number density distribution that is consistent with the balloon measurements made in the atmosphere by the ballooning team. Figure 64 plots an instantaneous snapshot of pressure fluctuations due to the interaction of atmospheric particulates with the HIFiRE-1 flow field. In the center of the image, the effect of two particulates may be seen – one that has entered the shocklayer upstream and its bow shock has reflected off of the surface; behind the interaction are second-mode disturbances in the boundary layer are apparent. The second particulate has just entered the shocklayer and its bow shock has not yet interacted with the surface. In this image near the outflow there is the signature of second-mode boundary layer instabilities due to the passage of another particulate earlier in the simulation.

An interesting conclusion from these simulations is that the particulates do not need to actually impact the surface to introduce disturbances into the boundary layer. Submicron diameter particulates are deflected before they impact the surface, but the shock wave generated by their passage is sufficient to initiate second-mode disturbances. We need to perform full three-dimensional simulations to determine whether this effect is present under more realistic conditions.

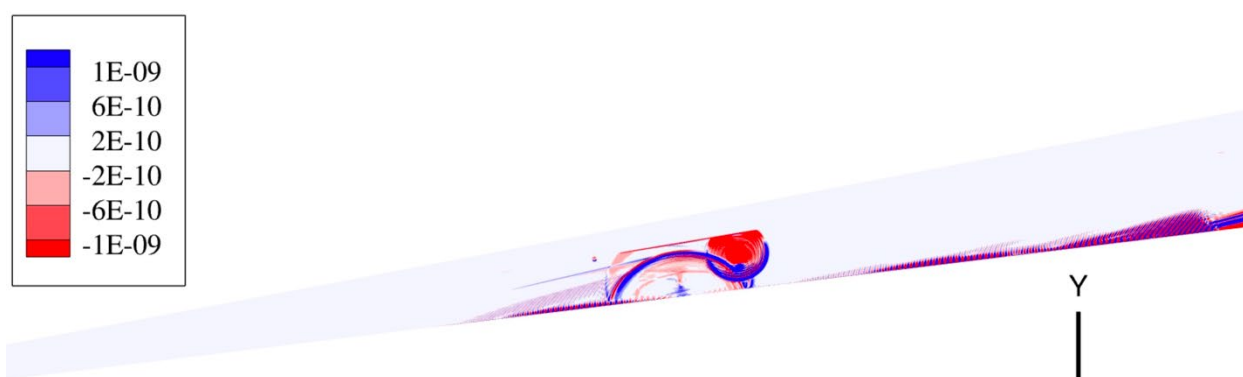


Figure 64 Instantaneous pressure fluctuations due to the passage of atmospheric particulates through the HIFiRE-1 flow field at Mach 10.

3.3.3 Next Steps for Aerothermodynamics Simulations

The main emphasis for the next several months will be on obtaining high accuracy simulations of turbulence interacting with a hypersonic flow field and running the full three-dimensional particulate interaction simulations. The most challenging issue remains the development of the shock-fitting boundary condition so that the exact steady-state, unperturbed flowfield can be obtained. Then, the time-dependent fluctuating shock boundary condition should be straight-forward to develop and implement. This will be the primary focus of the next several months of the project. When this is complete, we will be able to make detailed comparisons of turbulence and particulate interactions to assess their role in the onset of boundary layer transition.

3.4 Optical Propagation

Optical propagation through the turbulent atmosphere continues to be of interest for scientists and engineers in a wide range of areas, including terrestrial and extraterrestrial imaging and surveillance, atmospheric remote sensing, free-space optical communication, target acquisition, and directed-energy technology. Progress in any of these areas relies on the collaboration between theoreticians, instrument developers, observationalists, and computational physicists.

The Year-4 activities of the optical-propagation team, led by Co-PI Muschinski, can be divided into three categories:

1. Second-order statistics of turbulent phase screens with Gaussian and non-Gaussian increments
2. Analysis of fine-wire measurements of optical turbulence near the ground
3. Other activities.

3.4.1 Second-order statistics of turbulent phase screens with Gaussian and non-Gaussian increments

The material presented in this subsection has been taken directly from Muschinski (2021). The modern physics of optical wave propagation through turbulent media, pioneered by Tatarskii and coworkers in the 1950 and 1960 (Tatarskii, 1961, 1971), relies on Maxwell's electromagnetic field theory, the Obukhov-Corrsin theory (Obukhov, 1949; Corrsin, 1951) of fully developed, scalar turbulence, and the mathematics of stochastic processes and random fields (Yaglom, 1962). The starting point of Tatarskii's propagation theory is the scalar Helmholtz equation. By means of the geometrical-optics method and Rytov's "method of smooth perturbations," Tatarskii derived analytical and empirically testable predictions for a wide range of optical observables, such as the spectra and variances of irradiance fluctuations and angle-of-arrival fluctuations. It was clear that the geometrical-optics method cannot account for diffraction effects, and initially it was hoped that the Rytov method describes the interplay between refraction and diffraction accurately for most cases of practical relevance. After the discovery of the "saturation of scintillation" (Gracheva and Gurvich, 1965; Gracheva, 1967), however, the majority of researchers in the field have become aware that the Rytov method is reliable only if the irradiance fluctuations are small compared to the mean irradiance. This regime is usually referred to as the "weak-scattering regime" or "weak fluctuation regime". The theoretical and observational progress in the field since the 1970s has been documented in various standard texts and collections (e.g., Uscinski, 1977; Ishimaru, 1978; Strohbehn, 1978; Uscinski, 1986; Andreas, 1990; Tatarskii et al., 1993; Wheelon, 2001, 2003; Rytov et al., 1989; Andrews and Phillips, 2005; Korotkova, 2014).

An alternative approach to Tatarskii's methods is to represent turbulent layers as "phase screens" and to solve the problem of optical propagation through random phase screens by means of the Huygens-Fresnel principle. This method was pioneered by Booker, Ratcliffe and other radio scientists in the late 1940s and 1950s (Booker et al., 1950; Ratcliffe, 1956). In the 1960s, Goodman (1968) showed that the Huygens-Fresnel principle can be approximated as a 2D input-output relationship for an optical wave passing through a linear, shift-invariant optical system, such that the optical output field is the 2D spatial convolution of the optical input field and the optical system's 2D spatial impulse response function. Goodman's optical systems approach is the 2D equivalent to the standard theory of linear, time-invariant systems, or "LTI systems" (e.g., Lathi, 2005; Roberts, 2008). Goodman applied this concept first to deterministic optical systems Goodman (1968, 2017) and later to random optical systems, such as a slab of turbulent air through which light propagates (Goodman, 2015, 2020). In 1985, Booker, Ferguson and Vats Booker et al. (1985) analyzed, for the weak-scattering regime, the scintillation index σ_I^2 of a plane wave propagating through classical, fully developed turbulence. They showed that the values of σ_I^2 predicted by the Huygens-Fresnel principle and by the Rytov theory are equal to each other if the phase screen representing the distributed, 3D turbulence is placed half-way between the source (input) plane and the observation (output) plane. In recent decades, the system approach pioneered by Goodman has been widely used in imaging physics (Roggemann and Welsh, 1996; Kopeika, 1998) and computational optics (Martin and Flatté, 1988; Schmidt, 2010; Voelz, 2011). All these methods to analyze and predict optical wave propagation through turbulent media have in common that it is usually not the phase ϕ that matters but the phase *factor* ψ , where ψ is the complex exponential of the phase, $\psi = \exp(i\phi)$. Nevertheless, most theoretical and observational research has been done on the basis of phase statistics rather than phase-*factor* statistics.

In Muschinski (2021), we analyzed the covariance function, the structure function, and the 2D spectrum of the phase *factor* for four different types of random, 2D phase screens $\phi(\mathbf{x})$. Each of these phase screens is characterized by a power-law phase structure function (with exponents $\gamma = 5/3$ or $\gamma = 2$) and a model for the probability density function of the spatial phase *increments* (either Gaussian or Laplacian). Our main results are as follows:

1. The second-order phase-*factor* statistics (in contrast to the second-order phase statistics) are all “well-behaved”. In particular, the phase-*factor* statistics show no singularities at $r = 0$, $r \rightarrow \infty$, $\kappa = 0$, and $\kappa \rightarrow \infty$ if the underlying phase structure function follows a power law with exponents $\gamma = 5/3$ or $\gamma = 2$.
2. We have defined a phase coherence length, r_c , which for the turbulent case, $\gamma = 5/3$, is physically equivalent to Fried’s coherence length, r_0 , except for the numerical factor $\frac{r_0}{r_c} = 6.88^{3/5} = 3.18$. We show that both r_c and r_0 are pure phase-screen statistics based on optical path-length (“eikonal”) fluctuations. Both r_c and r_0 are unaffected by any assumptions or approximations regarding the propagation after passing through the phase screen.
3. We have formulated the second-order phase-*factor* structure function as an infinite sum of second- and higher-order (of even order) phase structure functions. For $r \ll r_c$, we find $D_\psi(r) \approx D_\phi(r)$. For $r \gg r_c$, however, $D_\psi(r)$ saturates to the universal value 2 while $D_\phi(r)$ increases without bound.
4. For turbulent ($\gamma = 5/3$) phase screens, at high wavenumbers ($\kappa \gg r_c^{-1}$) the dimensionless phase-*factor* spectra $f_\psi(K)$ (where $K = \kappa r_c$ is a dimensionless wavenumber) for Gaussian and Laplacian phase increments converge to the same power law, $f_\psi(K) = 0.45 K^{-11/3}$. The only parameter that affects this result is $\gamma = 5/3$.
5. Independently, we have retrieved the $K \gg 1$ asymptote of the normalized phase-*factor* spectrum $f_\psi(K)$ from Tatarskii’s (1961) relationships for the phase structure function, $F_\phi(\kappa) = 2\pi k^2 L \times C_n^2 \kappa^{-11/3}$ and $D_\phi(r) = 2.91 k^2 L C_n^2 r^{5/3}$, and we find the same power law and the same coefficient, $f_\psi(K) = 0.45 K^{-11/3}$; see Figure 65.
6. For phase screens with quadratic ($\gamma = 2$) phase structure functions, $f_\psi(K)$ drops exponentially for $K \gg 1$, more rapidly for Gaussian than for Laplacian phase increments.
7. At low wavenumbers ($K \ll 1$), all four ψ spectra become flat, which is consistent with the fact that ψ becomes uncorrelated for $r \gg r_c$.
8. At intermediate wavenumbers, $K \sim 1$, each of the four non-dimensionalized phase-*factor* spectra $f_\psi(K)$ shows a “bump,” in the turbulent case ($\gamma = 5/3$) exceeding the high-wavenumber asymptote $f_\psi(K) = 0.45 K^{-11/3}$ by a factor of up to 2.8 for Gaussian phase increments and a factor of up to 2.2 for Laplacian phase increments.

As we have shown (Muschinski, 2021), the second-order phase-*factor* (ψ) statistics (covariance function, structure function, and 2D spectrum) exhibit a rich variety of phase-screen characteristics that are not as directly, or not at all, captured by means of second-order phase (ϕ) statistics characterizing the same phase screen. There are two obvious advantages of characterizing phase screens by means of ψ statistics rather than ϕ statistics. First, the second-order ψ statistics account for the probability density $p_\alpha(\alpha)$ of the phase *increments* α while the second-order ϕ statistics are invariant with respect to the functional form of $p_\alpha(\alpha)$; second, the second-order ψ statistics account explicitly for effects resulting from a finite phase coherence length r_c while the second-order ϕ statistics are simply the second-order path-length (eikonal) statistics rescaled with the constant factor k^2 , where k is the optical wavenumber.

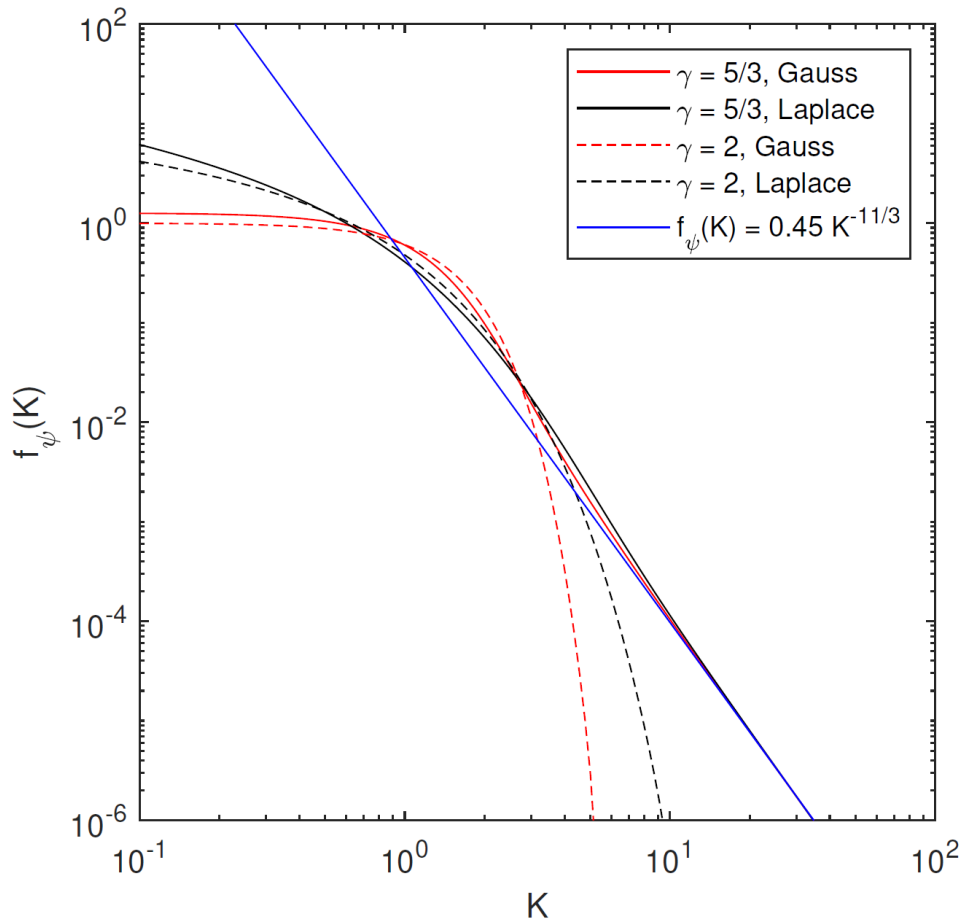


Figure 65 Theoretical results for the non-dimensionalized phase-factor spectra $f_{\psi}(K)$ of the four types of random phase screens analyzed in Muschinski (2021). The fifth spectrum (blue) is the classical phase spectrum given by Tatarskii (1961).

3.4.2 Analysis of fine-wire measurements of optical turbulence near the ground

The material presented in this subsection has been taken from a manuscript (Muschinski and Wagner, 2021) that we submitted, in December 2021, for publication in an upcoming Special Issue of *Waves in Random and Complex Media*, in honor of Valeryan Tatarskii.

In the evening of 15 September 2020, we collected temperature measurements by means of an array of three fine-wire sensors (labeled FW5, FW7, and FW8), which we attached to a microphone stand. The stand was mounted in a car and extended through the sunroof 1.0 m above the roof line, angled forward somewhat, while the sensor mounting was adjusted to be horizontal, with sensors FW7 and FW8 spaced 5 cm above and below the mount, respectively, in front, facing into the wind. Sensor FW5 was placed at the same height as FW7, 10 cm directly behind FW7. The car's roof line was 1.5 m above the ground, such that the sensors were approximately 2.5 m above ground level (AGL).

Recording began at 2238 MDT and lasted less than 1 h. We divided the data into 13 “runs,” referred to as Run 408 through Run 420. Thus far, we have analyzed only Run 411. Run 411 began at 2247 MDT and lasted 3 min 12 s. During Run 411, the car was driven at a speed of about 20 m/s.

We found that our fine-wire thermometer system is capable of collecting high-quality measurements of turbulent temperature fluctuations in the open atmosphere. Even though the $0.64\text{-}\mu\text{m}$ -diameter platinum fine wires are extremely delicate, our three sensors did not break when exposed to a true air speed of about 20 m/s over the course of several tens of minutes.

The active length of the wires is less than 1 mm, which is small compared to 5 mm, the smallest value of the inner scale l_0 observed during Run 411. Therefore, the measured temperature fluctuations are not affected by spatial filtering due to the finite size of the sensors. The wires' response times are so short that temporal filtering plays no role either. The noise level of the entire system is so low that the spectrum can be measured well into the viscous-diffusive range. (The uncorrelated rms value of the noise in the temperature signal over a bandwidth of 10 kHz is about 1 mK.)

We found that the delay between signals measured with a pair of longitudinally spaced sensors (we used a spacing of 10 cm) can be used for reliably measuring the true air speed (the speed of the air relative to the sensor) if the platform moves fast compared to the wind speed relative to the ground.

The temperature structure function $D_{\theta\theta}(r)$ and the frequency spectrum $S_{\theta\theta}(f)$ estimated from the measured temperature fluctuations are consistent with the predictions of the classical Obukhov-Corrsin theory; see Figure 66 and Figure 67. We determined the power-law exponent α of $D_{\theta\theta}(r)$ from observed values of the ratio $D_{\theta\theta}(r_2)/D_{\theta\theta}(r_1)$, where we chose $r_1 = 5$ cm and $r_2 = 10$ cm. We estimated α for each 5-s interval and found $\alpha = 0.63 \pm 0.06$, which is consistent with the theoretically predicted value $2/3 \approx 0.67$.

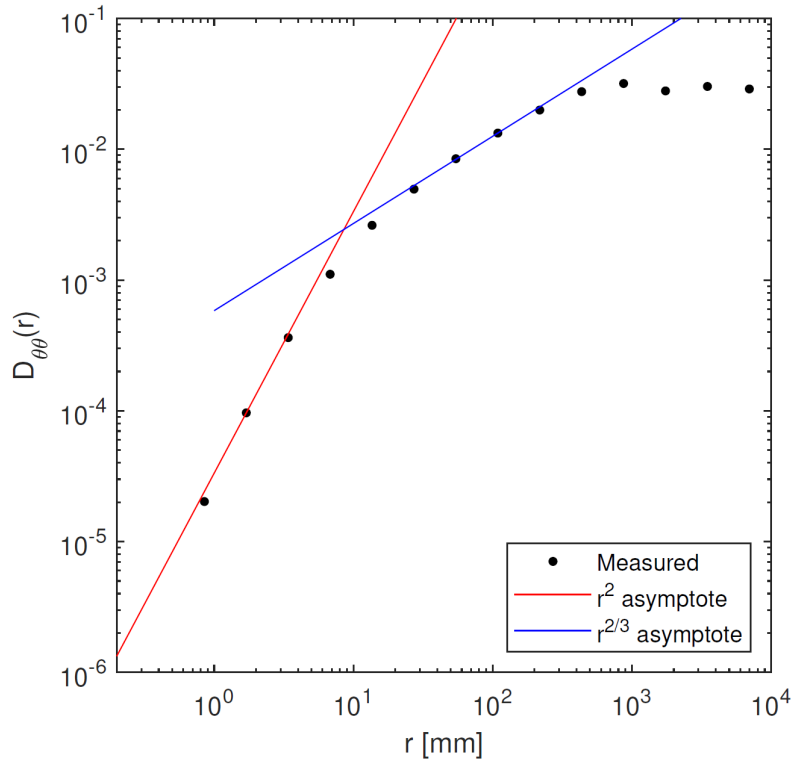


Figure 66 Temperature structure function $D_{\theta\theta}(r)$ estimated from a single 5-s long segment of the FW7 signal. The measured structure function follows an r^2 power for small r and an $r^{2/3}$ power law for intermediate r , as predicted by the Obukhov-Corrsin theory. The two asymptotes intersect at $r = l_0$, where l_0 is, per definition, the inner scale.

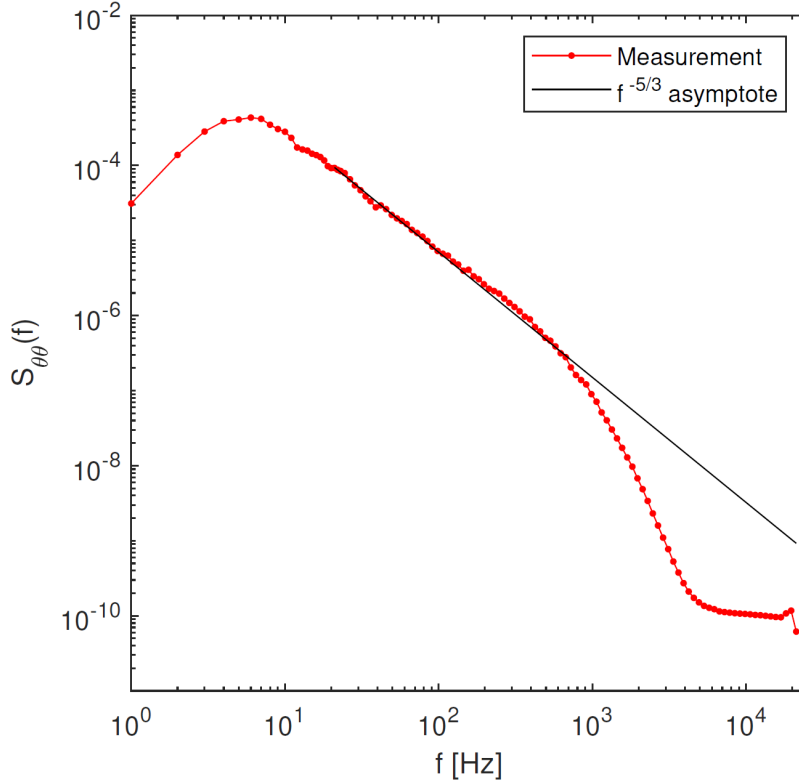


Figure 67 Temperature frequency spectrum $S_{\theta\theta}(f)$ estimated from the entire 192-s long FW7 signal. At frequencies between about 10 Hz and 100 Hz, the measured spectrum follows the $f^{-5/3}$ power law predicted for the inertial-convective subrange. Above 100 Hz, the measured spectral density slightly exceeds the value predicted by the $f^{-5/3}$ asymptote, indicating the “Hill bump”. Above about 1000 Hz, the observed $S_{\theta\theta}(f)$ drops dramatically, indicating the transition into the viscous-diffusive range. (At 20 m/s, 1000 Hz corresponds to a length scale of 20 mm, which is on the order of the inner scale, as expected.)

3.4.3 Other activities

During the reporting period, we made progress also in two other areas: first, we continued to analyze measurements collected during the 2019 Table Mountain Experiment (Caldwell et al., 2020), which we conducted in the summer of 2019 at the Table Mountain Test Facility between Boulder and Lyons, CO; second, we began to analyze optical phase screens that we computationally generated from DNS output data.

For the continued analysis of the Table Mountain Experiment observations, we focused on the in-situ measurements (ultrasonic anemometer-thermometers, quartz-crystal barometers) and on collocated sequences of images (60 frames per second) of a checkerboard pattern placed 140 m away from a 14-inch telescope equipped with a digital camera. While the optical observations were episodic (several one-hour long sequences), the in-situ measurements were collected quasi-continuously during more than two months. The combined dataset is of high quality, and we are using it to test (1) the usefulness of the Monin-Obukhov similarity theory for the prediction of optical turbulence in the atmospheric surface layer and (2) to test hypotheses and models for estimating refractive-index statistics (including the refractive-index structure parameter, C_n^2 , and the inner and outer scales of turbulent temperature fluctuations) from differential image-motion measurements.

We began to analyze turbulent phase screens that we constructed from 3D temperature fields generated by means of the direct numerical simulations (DNS) by Co-PI David Fritts and his colleagues. Of particular interest is to find out whether the spatial increments of those phase screens have Gaussian or non-Gaussian probability densities. As shown in Figure 68, the histograms of the phase increments are better represented by a two-sided exponential (Laplacian), rather than a Gaussian function; see also Muschinski (2021) and the summary in the subsection above.

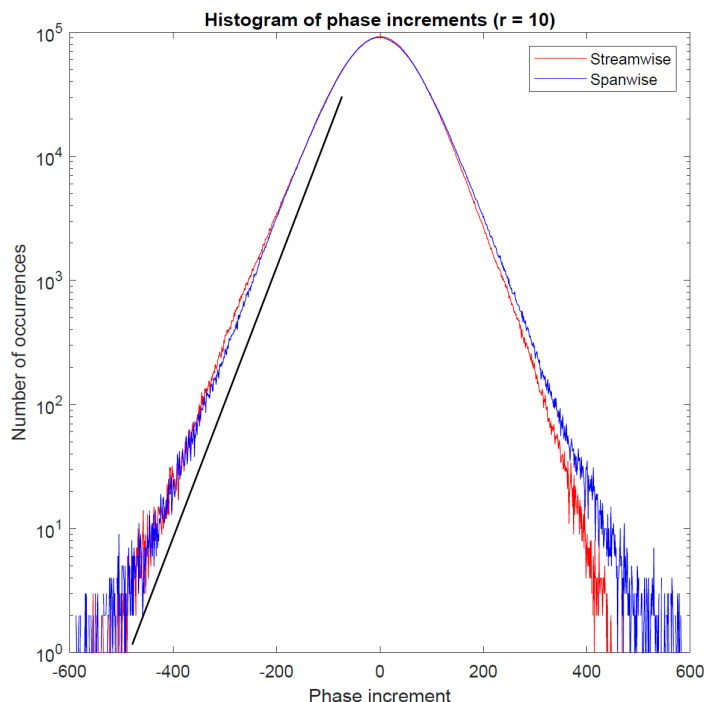


Figure 68 Histograms of the streamwise (red) and spanwise (blue) phase increments of a DNS-generated, turbulent phase screen for a spatial separation of 10 grid points. The data follow an exponential function indicated by the straight line (black), which shows that the “tails” of the histograms of the phase increments are two-sided exponential (Laplacian), rather than Gaussian.

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4 HYFLITS – BOLT-I Joint Campaign

4.1 Overview

In January 2020, PO Leyva proposed a joint deployment collaboration for the BOLT-I flight experiment, that was originally scheduled for May-June 2020 at Esrange Space Center in Sweden. Some details of the initial discussions of deployment preparations and subsequent tasks are discussed in Sect. 3.2. Most of these discussions occurred with weekly, one-hour videoconferences that included PO Ivett Leyva; Marcus Hoerschgen-Eggers, DLR; and the HYFLITS Stratospheric Measurements team, that, in addition to the Co-PIs, includes Minnesota Space Grant Associate Director James Flaten at UMN, and IRISS Engineering Manager Steve Borenstein at CU. Co-PI and MURI Project Coordinator David Fritts was also an occasional participant, to provide high-resolution atmospheric simulations and scientific advice. On 15 July 2020, BOLT-I PI Bradley Wheaton briefed the HYFLITS team on the BOLT-I project.

4.1.1 Application of the Balloon Trajectory Simulator (BTS)

In addition to the original ERAU balloon trajectory simulation and GUI developed by Co-PI Barjatya, a new balloon trajectory simulation (BTS) was developed at CU. The initial purpose of CU BTS was to assist in planning balloon launches from the Western Slope of Colorado for mountain wave measurements. As described below, the BTS was later used to analyze balloon trajectories near the Esrange, Sweden rocket test site that might intersect the BOLT-I trajectory.

To solve trajectories from a particular launch location, a targeting feature was developed for the BTS. This feature solves a trajectory such that the balloon passes through a particular location in space and time. When performing a targeting trajectory, the simulation results given an estimated launch location and time that would carry the balloon to the desired target point. This feature was highly applicable when planning for the BOLT research campaign. The goal of the balloon campaign during BOLT-I is to characterize as much

as possible the atmosphere through which the BOLT-I test vehicle is flying. This requires launching balloons from a location that will result in the balloons passing near (in space and time) the BOLT-I rocket. The uncertainty in the atmospheric predictions mean that highly accurate targeting is impossible, but batches of these target simulations for different times throughout the year have helped to inform the HYFLITS team of approximately where in the region balloons should be launched from in order that they measure the atmosphere as close as possible to the BOLT-I rocket. Figure 69 shows a demonstration of the targeting feature of BTS. Results such as these informed the team that, especially during winter months, it will likely be appropriate to launch from somewhere in Norway, rather than near the Esrange Space Center, where the BOLT-I rocket will be launched.

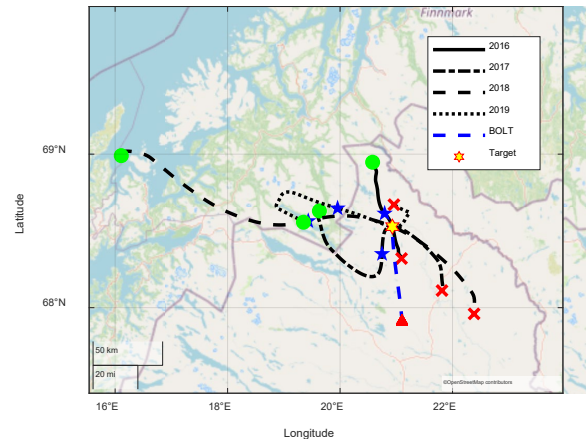


Figure 69 Predicted trajectories that were targeted to intercept the flight path of the BOLT-I rocket.

The Andøya Space Center in Norway was identified as a potential location for launching balloons for the HYFLITS – BOLT-I joint campaign. To understand seasonal and year-to-year variability, large numbers of BTS predictions were made using archived GFS data. Typical results of these simulations can be seen in Figure 70. During the winter months (February results are shown), winds are strong from west to east. At this time of year, it is likely appropriate to launch from Norway to target the BOLT-I flight path.

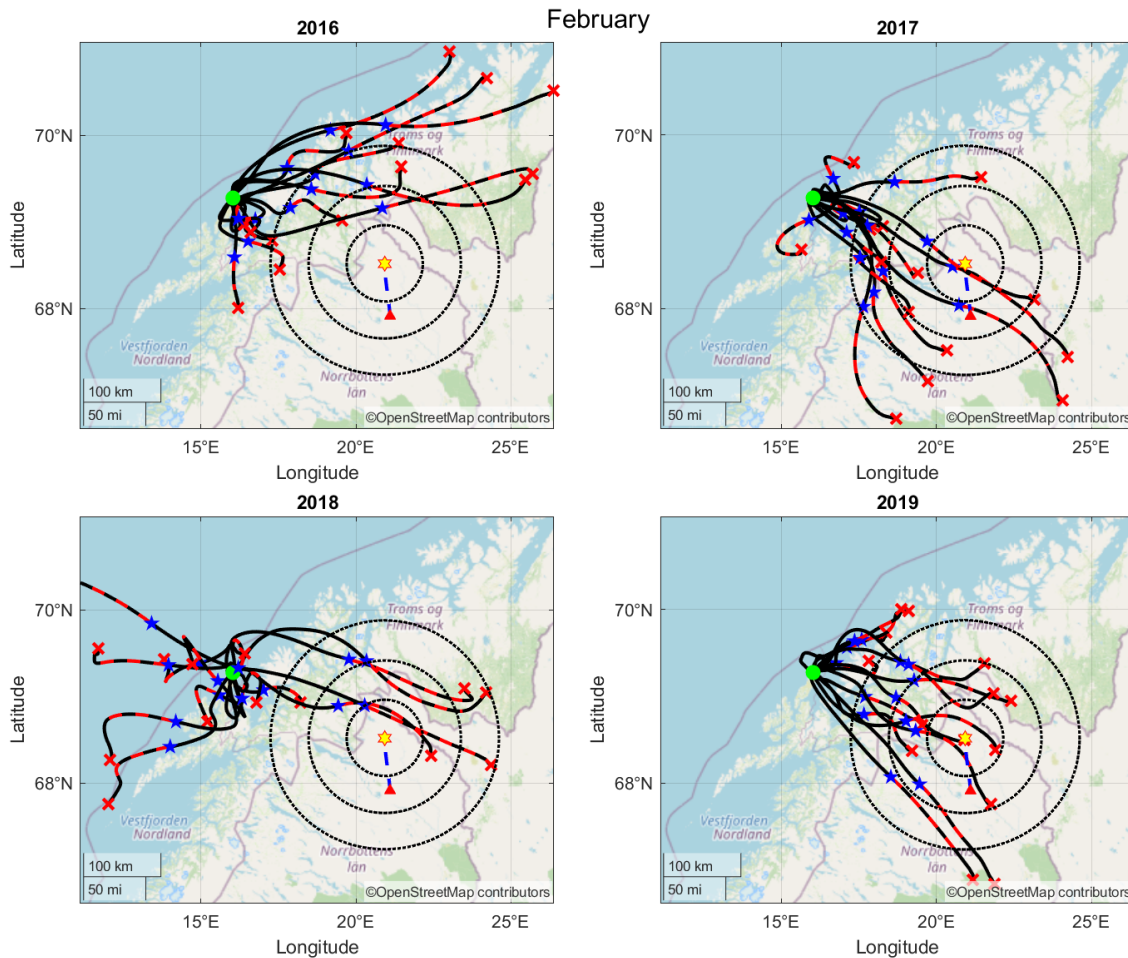


Figure 70 BTS predictions using archived GFS data for the month of February. Launch location is Andøya Space Center in Norway. The red triangle and yellow star mark the launch site and predicted landing site of the BOLT-I rocket. Circles are 50, 100, and 150 km radii from the BOLT-I landing.

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