Feb 26th, 11:00 AM

Enhancing suborbital science through better understanding of wind effects

Pedro Llanos  
*Embry-Riddle Aeronautical University - Daytona Beach, llanosp@erau.edu*

Diane Howard  
*University of Texas at Austin*

Follow this and additional works at: [https://commons.erau.edu/stm](https://commons.erau.edu/stm)

Part of the Aviation and Space Education Commons, Educational Technology Commons, Operational Research Commons, and the Space Vehicles Commons

[https://commons.erau.edu/stm/2019/presentations/25](https://commons.erau.edu/stm/2019/presentations/25)

This Event is brought to you for free and open access by the Conferences at Scholarly Commons. It has been accepted for inclusion in Space Traffic Management Conference by an authorized administrator of Scholarly Commons. For more information, please contact commons@erau.edu.
Enhancing suborbital science through better understanding of wind effects

Pedro Llanos,1 and Diane Howard2

Embry-Riddle Aeronautical University, Daytona Beach, Florida, 32114, USA

This paper highlights the importance of understanding some key factors, such as winds effects, trajectory and vehicle parameters variations in order to streamline the space vehicle operations and enhance science in the upper mesosphere at about 85 km. Understanding these effects is crucial to refine current space operations and establish more robust procedures. These procedures will involve training new space operators to conduct and coordinate space operations in class E above FL600 airspace within the Air Traffic Organization (ATO).

Space vehicles such as Space Ship Two can spend up to 6 minutes in class E airspace above FL600 after launch. Most of this time is dedicated for science data collection in microgravity and maximizing the science is a key priority. Typical suborbital trajectories cut through the noctilucent cloud layer in the mesosphere region from about 260,000 feet to 280,000 feet during the ascent and descent. This space activity falls within the D-layer of the ionosphere (50-90 km). In each of these segments, the space vehicle spends about 10 seconds in the region of interest, totaling about 20 seconds of total in-situ uninterrupted science in the mesosphere.

This study illustrates some examples of suborbital trajectories that can enhance the scientific research performed in this region. The altitude of these trajectories can be targeted in order to provide continuous data collection that can last for about 100 seconds, and could be enhanced by current ground based technologies prior to launch. Suborbital flights usually operate under visual flight rules (VFR) and in Special Use Airspace (SUA) in the vicinity of a designated spaceport. For example, Blue Origin’s New Shepard has a vertical space transition corridor (STC) with about two miles between the launch and landing locations in West Texas Launch Site, that is, a very well defined corridor given that it is a vertical takeoff vertical landing (VTVL) space activity. However, Virgin Galactic SS2 or XCOR Lynx vehicles have similar flight profiles with STC that can vary up to 60-75 miles in range. These last two require more refined operations with air traffic control since these vehicles have an air launched takeoff and horizontal take off, and spend a good portion of their flights within the National Air Space (NAS), especially during descent. Typical suborbital flights go through the mesosphere in a few seconds, yet most of the science to be collected is in this region. Extending science operations in the upper mesosphere will imply having a slight different trajectory and therefore a different STC where the vehicle will spend more time in that particular layer of the atmosphere.

Thus, we believe these science requirements should be coordinated with space operators and air traffic controllers to increase the success of the mission. Although there is no current technology yet that can track these space vehicles real-time from the ground, it is important to streamline such operations, to refine and establish more mature space vehicle operations. Embry-Riddle Aeronautical University has successfully flown some ADS-B equipment on balloons (140,000 feet) and aboard NASA’s WB57 aircraft (60,000 feet), and current collaborative efforts are being carried to test these technologies as prospective commercial tools to seamlessly track future high-speed vehicles. Given that suborbital flights can be mission dependent, we will have to ensure that these technologies enable tracking and telemetry of the space vehicle to ground space and traffic operators, since longer point-to-

1 Assistant Professor, Spaceflight Operations at Applied Aviation Sciences, AIAA member.
2 Assistant Professor, Spaceflight Operations at Applied Aviation Sciences.
point suborbital flights may have ranges beyond the range of the FAA ground receiver network. Thus, additional network nodes and marine operations may be required to fulfill such space activities.

Nomenclature

AHA = Automated Hazard Areas
ATC = Air Traffic Control
ATO = Air Traffic Organization
CMEs = Coronal Mass Ejections
GCRs = Galactic Cosmic Rays
HTHL = Horizontal Takeoff Horizontal Landing
NAS = National Airspace System
MEO = Main Engine Cut Off
MET = Mission Elapsed Time
SS2 = Virgin Galactic’s SpaceShipTwo
SAC = Scientist Astronaut Candidate
SFPs = Space Flight Participants
STC = Space Transition Corridor
STM = Space Traffic Management
sRLV = suborbital Reusable Launch Vehicle
SSFS = Suborbital Space Flight Simulator
WK2 = White Knight Two

I. Introduction

The suborbital reusable vehicles market supports a wide variety of activities such as basic and applied research, which comprises about 10% of the entire market. Aerospace technology test and demonstration, education, satellite deployment, media and personal relations accounts for another 10% of the suborbital market. Two other markets, the remote sensing and point-to-point transportation, are considered prospective activities for the suborbital market but not in the near future. However, commercial human spaceflight accounts for the other 80% of the suborbital market, and private companies, such as Virgin Galactic and Blue Origin’s New Shepard Crew Capsule 2.0, are planning to conduct their first commercial human flights by the end of 2019-2020. The first commercial cargo flown aboard Blue Origin’s New Shepard was on December 12th 2018; Embry-Riddle Aeronautical University (ERAU) launched its first suborbital payload on this flight.

In particular, simulations using flight profiles based upon space vehicles such as the stagnated XCOR Lynx and the on-going SpaceShipTwo (SS2) will help enhance our understanding from the modeling perspective using our current tools in the SSFS. Although XCOR Lynx was decommissioned in 2017, use of its flight profile in research simulations remains of value. This research increases understanding of the mesosphere and provides useful data about gravity waves, tides, oscillations, and noctilucent clouds imagery and tomography. These research findings could unravel some of the most intrinsic questions still to be answered about the noctilucent clouds micro-features and gravity waves, and unstable dynamics (eg. Kelvin-Helmholtz instabilities created by gravity waves) in the mesosphere region at about 80 to 86 km in altitude. Carbon monoxide (abundant above 80 km) and nitrogen oxides are thought to contribute to the heating of
the troposphere and the cooling of the mesosphere and thermosphere. The effect of these molecules on the F2 layer (a critical layer for communications in the ionosphere) and on the gravity wave activity near the mesopause is still not clear. According to the National Oceanic and Atmospheric (NOAA), carbon dioxide has increased from about 350 parts per million in 2003 to about 400 parts per million (ppm) in 2015. These carbon dioxide increases are thought to be a factor of the thermosphere changing in response to climate change. As of 2018, carbon dioxide is above 408 ppm.

Winds must be accounted for to increase the precision of the position and velocity state vector of the vehicle and assess any possible dispersion at breakup during the ascent trajectory or the descent segment of the trajectory. If the vehicle disintegrates during the ascent trajectory, then the effects of winds are needed to identify the descending debris pieces during the impact location, which will help with the debris risk analysis. In our simulations, wind magnitude (not direction) was considered. The atmosphere is also modeled in our simulations, such as the density as a function of altitude, speed of sound as a function of altitude, and temperature as a function of altitude. The vehicle characteristics, such as the mass, thrust and specific impulse (Isp), were also modeled as functions of altitude. Our simulations also account for the variation of gravity with altitude, but it does not take into account the Earth flattening factor or the gravitational harmonic constants (J2, J3, J4). These last parameters of the gravity model can be neglected due to short suborbital flight durations. These parameters will be more significant on future point-to-point transportation suborbital flights with longer flight durations.

II. Methodology

Collecting science data from the noctilucent clouds will enable scientists to characterize the roles of gravity waves and instability dynamics in the mixing and transport processes of the upper atmosphere. Characterizing the geometry of the noctilucent cloud particles will enhance our understanding of the growth of these particles and the sublimation processes. Maximizing the science data collection will facilitate data analysis and interpretation. In this paper, we will show that this data collection can be uninterrupted if the suborbital trajectory is designed properly and targeted at the right altitude. Trajectories could be designed to have the vehicle flying through the mesosphere (80 km - 90 km) so it would be constantly taking measurements (blue trajectory in Figure 4a) for over a minute instead of taking some samples during ascent for about 10 to 12 seconds and waiting for 2-3 minutes before the next sample is obtained (green trajectory in Figure 4a). Scientists, engineers and technologists are encouraging the enhancement of science in the mesospheric region using various techniques to enhance wind measurements, such as the sodium lidar technology targeting from about 75 to 95 km in altitude, the 142 GHz radiometer for continuous wind measurements to target 30-79 km altitudes and the OH and O2 simultaneous measurements targeting altitudes between 70 and 94 km. The sodium lidar ground based observations is a promising technique that could provide very high resolution data about this region of the atmosphere in question of minutes. This means that these suborbital flights could rely on this technology to leverage their suborbital operations in the mesosphere by providing new temperature conditions, and speed of the particles moving which can be related to the wind conditions. Given that these research platform can provide about 4-5 minutes in microgravity, every second in this region matters to enhance science.

According to publicly available information, SpaceShipTwo will have two pilots and up to 6 space flight participants. The cabin atmosphere will be pressurized to 8.000 ft altitude or lower with re-circulated atmospheric air (21% O2).
1. **Horizontal air-launched takeoff:** The projected flight profile begins with a horizontal takeoff underneath the carrier aircraft "WhiteKnightTwo" with a flight to approximately 50,000 ft where SpaceShipTwo will be launched.

2. **Boost phase:** The boost phase will be 70 sec long and will have a maximum peak of 3.8 g (longest duration in +Gx with a brief spike in +Gz). Speeds will be Mach 1 at 8 sec and Mach 3 at 30 sec. Maximum speed will be 2600 mph.

3. **Microgravity:** The 0 g coast phase will last approximately 4 minutes and will reach an apogee of 361,000 ft.

4. **Coast phase:** During the coast phase, space flight participants (but not the flight crewmembers) will be out of the seats and able to freely move around the 12 ft x 7.5 ft (3.7 m x 2.3 m) cabin.

5. **Deceleration phase:** The deceleration phase will have a maximum peak of 6 g, but the seats will recline to convert most of the forces to +Gx for the space flight participants. However, the flight crewmembers will experience most of the deceleration forces in the +Gz axis. The wings rotate to a feather position to increase stability and drag for entry.

6. **Glide phase:** At 80,000 ft, the glide phase will begin with a return to an unpowered horizontal runway landing that will occur after a glide of 25 min.

---

**Figure 1. SpaceShip Two vehicle.**

The information is based on estimates from the SpaceShipOne flights with extrapolation to SpaceShipTwo. Until test flights of SpaceShipTwo are much further along, the exact parameters will not be known.
In our simulation, we used preliminary parameters shown in Table 1. SpaceShipTwo’s crew cabin is 3.7 m (12 ft) long and 2.3 m (7.5 ft) in diameter. The wing span is 8.2 m (27 ft), the length is 18 m (60 ft) and the tail height is 4.6 m (15 ft).

A nominal trajectory is one that is not affected by external perturbing influences\(^4\) (e.g., winds) other than atmospheric drag and gravity. Understanding these effects is relevant for planning the nominal trajectory during the nominal flight and to further analyze the vehicle performance variations and other external forces that cause deviations from this nominal trajectory (reference trajectory). Some of these performance error parameters are variations in thrust, thrust misalignment, specific impulse, and weight, variation in firing times of the RCS for science adjustments, fuel flow rates, and winds. Similar parameters\(^6\) that can generate dispersions on suborbital launch vehicles are thrust misalignment, fin misalignment, nozzle erosion and distortion, separation dispersion (boost carriage), and variation in launch velocity caused by wind effects. Our study only focuses on the ascent segment of the trajectory and not on the reentry or gliding segments of the descent of the trajectory. Our analysis includes, to the best of our knowledge, the vehicles characteristics, such as the specific impulse, fuel burning time, fuel mass, take off wheel mass, payload mass, and empty mass (see Table 1). The characteristics\(^15,16\) of the XCOR Lynx and SS2 are displayed in the table:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lynx</th>
<th>SS2 (SSFS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m_{TOW}) (kg)</td>
<td>4,654</td>
<td>12,587</td>
</tr>
<tr>
<td>(m_{fuel}) (kg)</td>
<td>2,322</td>
<td>5,500</td>
</tr>
<tr>
<td>(m_{empty}) (kg)</td>
<td>2,087</td>
<td>4,536</td>
</tr>
<tr>
<td>(m_{payload}) (kg)</td>
<td>245</td>
<td>1,020</td>
</tr>
<tr>
<td>(I_{sp}) (s)</td>
<td>360</td>
<td>184</td>
</tr>
<tr>
<td>(t_b) (s)</td>
<td>180</td>
<td>60</td>
</tr>
<tr>
<td>(z_0) (m)</td>
<td>1</td>
<td>14,000</td>
</tr>
</tbody>
</table>

The trajectory of the suborbital vehicle trajectory for the XCOR Lynx and the Scaled Composites Mode 339 SpaceShipTwo can be simulated using the following equations of motion explained in this section. The initial state vector of the vehicle is given by:

\[
\vec{X}_0 = \begin{bmatrix} V_0 \gamma_0 \ x_{downrange,0} \ h_0 \ v_{D0} \ v_{G0} \ \psi_0 \ x_0 \ y_0 \ z_0 \end{bmatrix}
\]

where \(V_0\) is the initial velocity of the vehicle, \(\gamma_0\) is the flight path angle, \(x_{downrange,0}\) is the downrange, \(h_0\) is the initial altitude, \(v_{D0}\) is the initial velocity loss due to drag, \(v_{G0}\) is the initial velocity loss due to gravity, \(\psi_0\) is the initial heading angle, \(x_0\) is the initial position in the x-direction, \(y_0\) is the initial position in the y-direction and \(z_0\) is the initial position in the z-direction. The flight path angle is the angle between the velocity vector and the local horizontal plane. The flight path angle is positive when the velocity vector points above the local horizon. The heading angle (between -180\(^\circ\) to +180\(^\circ\)), indicates the direction of the velocity component projected on the local horizontal plane with respect to the local vector pointing north towards the east\(^12\).
To simulate these suborbital trajectories we included the ARDC Model Atmosphere from 1956 as a representation of the atmosphere. This model provides the variation of pressure, temperature and density with altitude. This model was also compared with an exponential model for some of these suborbital trajectories.

![Temperature variation with altitude 0-85 km](image1)

![Average Windspeed Profile from Ground to Mesosphere (85 km)](image2)

**Figure 2.** (a) Temperature variation up to 85 km. Wind speeds (average and maximum) up to 85 km.

Although this model was used in our MATLAB simulations, there are other higher fidelity atmospheric models, such as the Mass-Spectrometer-Incoherent-Scatter (MSIS) and Jacchia atmospheric density models that could be used for more precise orbit determination and propagation\(^{17}\). While the MSIS model can be used for high altitudes up to about 500 km in low earth orbit, the Jacchia model could be used solely for altitudes up to about 90 km, which is the region of interest in our particular study. In particular the MSIS-86 model refers to the upper part of the COSPAR International Reference Atmosphere (CIRA) 1986 and is publicly available\(^{18}\) as a MATLAB routine. However, the inclusion of any of these two models can be considered in future research, and is not addressed in our study.

The air temperature varies from 288 K at sea level to about 197 K in the 85-km region of the mesosphere (see Figure 2a). The average air temperature between 0 and 85 km is about 242 K. The ratio of specific heats (adiabatic constant) is 1.4. The diatomic gas constant is 287.04 J/kg/K. The altitude is calculated with the density, \(\rho\), and the equation:

\[
\rho = \rho_0 e^{-\frac{z}{H_{\text{scale}}}}
\]

where we assumed the atmospheric density at the Earth’s surface, \(\rho_0 = 1.225 \text{ kg/m}^3\) and the scale height, \(H_{\text{scale}} = 8,434 \text{ m at sea level. The unit of altitude, } z, \text{ is meters.}

Our suborbital model also included the wind speed at different altitudes since it will affect the rate of altitude with time and therefore the maximum apogee distance achieved which will be different from the desired altitude.

Similar to the launch of a rocket, a wind weighting analysis (FAA, 1998) should be conducted to predict the wind effect on a launch vehicle during the different flight phases, such as ascent,
coast phase, descent, and parachute recovery (if applicable). Our study focuses on the effect of winds up to 85 km (Figure 2b), the mesosphere region. In a real-life scenario, we would have to input the real-time weather to better assess the wind effects on these suborbital trajectories. The intent of this work is to enhance trajectory-based planning as a collaborative effort to streamline seamless airspace operations. Most of these space vehicles, although not rockets, behave for the most part of the ascent as a rocket with a high pitch angle of about 75-80 degrees. Wind effects should not be underestimated, as they are one of the most significant dispersion factors on the launch vehicle which can affect the predicted trajectory. The researcher could use a higher fidelity wind model, such as the U.S. Naval Research Laboratory Horizontal Wind Model HWM07 or any of its predecessors HWM93/90/87 to obtain a more refined solution. This model, which provides zonal and meridional wind information from the ground up to about 500 km, is publicly available by MathWorks. The Lynx flight profile is assumed to have several phases:

1. **Horizontal takeoff Horizontal landing (HTHL):** The projected flight profile begins with a horizontal takeoff from a conventional runway.
2. **Climb phase:** After takeoff, the vehicle throttles up to 100% to build speed to an attitude of about 75-85 degrees.
3. **Main Engine Cut Off (MECO):** Vehicle will burn all fuel at about 180,000 ft after 3 minutes of flight or higher depending on initial weight conditions. Mach number is near 3 at this point.
4. **Parabolic Flight and Data Acquisition Phase:** Vehicle during ascent conducts pitch maneuvers to prepare payload instrumentation for first set of in-situ measurements to be conducted in the ascent portion of the trajectory.
5. **Ascending through the Noctilucent Cloud Layer:** Vehicle starts data collection during ascent. This phase lasts about 20-30 seconds.
6. **Apogee:** Pilot can adjust the nose of the vehicle to point in the desired direction without changing the flight path.
7. **Descent:** Conduct second set of measurements and the vehicle penetrates through the noctilucent cloud layer.
8. **Reentry:** Configure the re-entry attitude. This segment is not addressed in this study.

The XCOR Lynx vehicle starts with a horizontal take off (no vertical launch as most rockets) and horizontal landing (HTHL). These simulations will only deal with the horizontal take off to the apogee part of the trajectory. Soon after takeoff, the Lynx will start a gravity turn maneuver before starting its ascent at about 75-85 degrees before reaching apogee. SpaceShipTwo (SS2) was deployed from its mother ship the White Knight Two (WK2) at about 14,000 m and then it will start its ascent at about 75-85 degrees before reaching apogee. The vehicle starts with a gravity turn when it reaches the desired altitude for the gravity turn, h\text{turn}. The gravity turn is one parameter that will dictate how the vehicle will achieve one or another flight profile. We can think of the gravity turn point as an inflexion point in the trajectory of the vehicle. The vehicle trajectory will be modeled according to the general equations of motion (1)-(6). We will consider that the vehicle is a point mass, m, under the influence of a gravity field.
\[
\begin{align*}
\frac{dv}{dt} &= \frac{T \cdot \cos(\alpha) - D}{m} - g \cdot \sin(\gamma) - \frac{D}{m} - g \cdot \sin(\gamma) \\
\frac{dy}{dt} &= \frac{T \cdot \sin(\alpha) + L}{m \cdot (V + V_{wind})} - \frac{1}{V + V_{wind}} \cdot \left( g = \frac{(V + V_{wind})^2}{R_e + z} \right) \cdot \cos(\gamma) \\
&\approx \frac{m \cdot (V + V_{wind})}{m \cdot (V + V_{wind})} - \frac{1}{V + V_{wind}} \cdot \left( g = \frac{(V + V_{wind})^2}{R_e + z} \right) \cdot \cos(\gamma) \\
\frac{dx_{range}}{dt} &= -\frac{R_e}{R_e + z} \cdot (V + V_{wind}) \cdot \cos(\gamma) + \omega Re \cdot \sin(\gamma)
\end{align*}
\]

where \( T \) is the thrust generated by the propulsion system onboard of the vehicle, \( D \) is the drag, \( \alpha \) is the angle of attack or angle between the flight path angle and the pitch angle, \( g \) is the gravity that changes with altitude, and \( m \) is the mass of the vehicle that also changes with time. The maximum rotation of the earth was assumed to be \( \omega_{earth}R_{earth} \) or about 0.465 km/s. This rotation is affected by the flight path angle of the vehicle. The Earth rotation was included in this analysis, yet their effects on sub-orbital flight is negligible\(^{11} \). The equation for the change of velocity of the vehicle was simplified by assuming that the angle of attack, \( \alpha \), between the velocity vector and the thrust is a small angle and therefore we can assume its effect is negligible during the ascent part of the trajectory. Also, the flight path angle, \( \gamma \), between the velocity vector and the local horizon of the vehicle is assumed to be near 75 degrees during ascent in our simulation (this value changes slightly when pilot flew the simulator). In our SSFS simulations, the suborbital flights horizontal takeoff were conducted from the Daytona Beach International airport, thus the variation in latitude of these flights is negligible since the flights are mostly due east with barely any change in the latitude of the flight. Therefore, the second term in the seventh equation of (1)

\[
(V + V_{wind}) \cdot \cos(\gamma) \cdot \cos(\psi) \cdot \tan(\phi) \approx 0
\]

can be neglected in the our analytical simulations simulated in MATLAB. This term could also be neglected for suborbital flights that are due north as long as this flights are short flights where the variation in latitude is negligible. In our study we are dealing with suborbital flights of about 4-5 minutes during the ascent trajectory. For longer suborbital flights or perhaps point-to-point transportation, this term should not be neglected, and therefore an additional equation
would need to be integrated to obtain a more refined flight trajectory. In addition, the next set of equations are required when integrating the equations above:

\[ T = \dot{m} U_e = \dot{m} (I_{sp} \cdot g_e) \]  \hspace{1cm} (2)

\[ g(z) = g_e \left( 1 + \frac{z}{R_e} \right)^2 \]  \hspace{1cm} (3)

\[ m(t) = m_{TOW} - \dot{m} \cdot t \]  \hspace{1cm} (4)

\[ m_{TOW} = m_{empty} + m_{payload} + m_{propellant} \]  \hspace{1cm} (5)

\[ \dot{m} = \frac{m_{propellant}}{t_{burn}} \]  \hspace{1cm} (6)

\[ L = \frac{1}{2} \cdot C_L \cdot A \cdot (V + V_{wind})^2 \]  \hspace{1cm} (7)

\[ D = \frac{1}{2} \cdot C_D \cdot A \cdot (V + V_{wind})^2 \]  \hspace{1cm} (8)

where \( m_{TOW} \) is the mass of the vehicle at the start of the flight (takeoff weight), \( I_{sp} \) is the specific impulse, \( g_e = 9.80665 \text{ m/s}^2 \) and the Earth’s radius, \( R_e \), is assumed to be 6,378.136 km. The lift force and the drag force depend on the lift and drag coefficients, respectively. Both lift and drag forces depend on the cross section area, \( A \), and the velocity, \( V \), of the vehicle. The equations of motion depicted by equations (1)-(8) were used to simulate the suborbital flight trajectory of the vehicle. From the density of the atmosphere, we can obtain the velocity of sound:

\[ V_{sound} = \sqrt{\gamma_{gas} \cdot T \cdot R_{gas}} \]

where \( \gamma_{gas} \) is the adiabatic constant of the gas of the atmosphere, \( T \) is the temperature of the atmosphere in Kelvin and \( R_{gas} \) is the diatomic gas constant, 287.04 J/(kg·K). Figure 3 shows the profile of the speed of sound in the atmosphere from the ground to 100 km-altitude.

![Speed of Sound in Earth's Atmosphere](image)

**Figure 3. Variation of speed of sound up to 100 km.**
III. Results

This section is dedicated to analyzing the effects of several perturbations on the ascent portion of suborbital trajectories for XCOR Lynx vehicle Mark II. These perturbations can be associated to atmospheric perturbations, such as winds in the atmosphere up to 100 km. These trajectories were simulated using the mathematical model explained earlier and these perturbations were included in the model. Also, a sensitivity analysis was conducted on various trajectory parameters and launch vehicle parameters to assess the trajectory performance due to a single parameter variation while keeping the rest of parameters constant. A suborbital trajectory was simulated based on this new variation and compared with a baseline trajectory.

Figure 4. Examples of simulated trajectories for Lynx during the ascent portion of the trajectory. (a) Comparison of Lynx trajectories simulated for wind effects the ARDC atmospheric model. (b) Single Lynx trajectory. (c) Simulated Lynx trajectories with longer science windows. (d) Simulated Lynx trajectories with extended science operations under various wind effects.

In addition to the simulated suborbital trajectories for XCOR Lynx, the SSFS was used to fly eight trajectories with XCOR Lynx platform. These trajectories were compared with ten
suborbital trajectories flown in the SS2 by three different pilots.

Figure 4a displays examples of simulated suborbital trajectories using equations (1) to (8). We used two atmospheric models, the exponential atmospheric density model and the ARDC atmospheric 1956 model, and simulated suborbital trajectories for comparison purposes. The burning time was assumed to be 180 seconds as indicated in Figure 4a. These two trajectories (magenta and green, respectively) show a very good agreement, the science data collection in the mesosphere lasts for about 10 seconds during ascent and another 10 seconds during descent. The vehicle has to wait near two minutes to obtain in-situ measurements between science data measurement locations.

This figure also shows another two suborbital trajectories (brown and blue) where the Lynx spends about 60 to 90 seconds in the mesosphere region to maximize the science data collection. In this case, the Lynx does not exit the mesosphere region and can continuously collect science data during this timeframe. Since in our case, we are targeting the mesosphere, the vehicle is desired to spend the most amount of time in this region. Given that the vehicle would need to be navigated to pin-point at the noctilucent clouds, the orientation of the vehicle (flight path angle) near apogee would need to be maneuvered. In the simulator, the mission specialist gives directions to the pilot as to what part of the mesosphere to study, and therefore, the orientation of the vehicle can quickly change.

However, in our simulations, these maneuvers are less defined due to the lack of instructions. In our simulations, we assumed that since the flight path angle of 75 degrees remains constant during the ascent part of the suborbital flight and before the end of the burning time. After this time domain, the flight path angle changes with time because the angle of attack varies as the vehicles coasts from MECO to apogee. In fact, the angle of attack is between 0 degrees and 1 degree for most of the trajectory until the burn time, and after that, the vehicle’s angle of attack starts being more significant. Thus, this angle cannot be neglected after the burn time and it is considered into the equations of motion (Equation 1). When the vehicle is past MECO and approaching apogee it shows again stable behavior in the angle of attack before it starts getting less stable during descent (Figure 6). Our results in Figure 4 indicate we can find suborbital trajectories that can maximize their data collection in the mesosphere when the angle of attack is near zero, the flight path angle is near 90 degrees, and when minimizing the lift of the vehicle when it is flying in this region of interest.

Figure 4b illustrates part of a single suborbital trajectory from the gravity turn point to apogee. Figure 4c shows the comparison of another two suborbital trajectories (green, and red with wind effects of +50 m/s) were included in the simulation. Both trajectories display similar trajectories, yet the red trajectory affected by winds behaves slightly different than the reference trajectory. These trajectories also suggest longer times conducting microgravity science in the mesosphere. Figure 4d depicts another set of trajectories (blue includes variable maximum wind speeds and black includes variable average wind speeds) with very similar profiles and longer science data collection times, similar to Figure 4c. In these simulations, we considered the wind magnitude as a function of altitude, and not the wind direction.

Sensitivity Analysis

In this section, we conducted a first order sensitivity analysis of various vehicle parameters, such as the pitch angle, payload mass, fuel mass, specific impulse, burn time and gravity turn. The
goal is to illustrate the relation of these parameters to the performance of the suborbital trajectory for a specific space vehicle. Our sensitivity analysis was based on perturbing the various vehicle (fuel mass, payload mass, specific impulse) and trajectory parameters (pitch angle and gravity turn) one at a time. After each parameter has been varied, a baseline trajectory was computed, and the suborbital trajectory performance was analyzed based on the perturbed value while maintaining the other parameters constant, then compared with the baseline trajectory with that parameter unchanged. The research commenced in 2015 before the XCOR Lynx was decommissioned. Subsequent to the Lynx’s retirement, we transitioned to SS2. However, we believe the Lynx remains a good tool for academic and operational research and for comparison purposes in our work in our SSFS. The same model is used for both the XCOR Lynx and SS2 using X-plane software. The only variables we have changed are the input vehicle parameters.

Figure 5a displays several ascent trajectories for the XCOR Lynx vehicle. The trajectories in green were simulated with a pitch angle of 75 degrees with a difference of 10 seconds in the burning time. By changing the burning time, we change the mass flow rate and therefore the thrust. The lower the burning time, the higher the mass flow rate, and the higher the thrust, which translates into a higher altitude for a 170 seconds burn. Rockets have variations in the mass flow rate of about 3%. In our example, we reduced the burning time from 180 seconds to 170 seconds, which is higher than a 3% or near 6%. The difference in apogee between these two trajectories is about 10 km. A 3% error in the mass flow rate would yield a trajectory (not plotted) between both trajectories depicted in green in Figure 5a, with an error variation of about 5 km in apogee. In these simulations, we assumed that the mass flow rate is constant through the ascent of the suborbital trajectory. Another observation can be made about the payload capability for the four main suborbital trajectories simulated in Figure 5a.

The first suborbital trajectory (T\textsubscript{burn} of 180 seconds and pitch angle of 75 degrees) can carry a payload mass of 245 kg to an altitude of 85.2 km. The second trajectory (also in green) with T\textsubscript{burn} of 170 seconds and pitch angle of 75 degrees can carry the same payload of 245 kg to a higher orbit of 92.8 km. This suggests that if the vehicle is to target the mesosphere at about 85.8 km with 10 seconds lower burning time, the vehicle could carry 490 kg of payload to this altitude.
Similarly, we compare the trajectories in blue in Figure 5a. The first trajectory ($T_{burn}$ of 180 seconds and pitch angle of 77 degrees) brings a payload mass of 245 kg to 102.4 km. The vehicle provides sufficient performance to penetrate through the noctilucent cloud layers during ascent and descent. Changing the pitch angle of the vehicle from 75 degrees to 77 degrees brings the trajectory higher to over 100 km (blue trajectory), and reducing even the burning time brings this same trajectory to near 113 km. Since there may not be a need to go this high for this science mission, the vehicle trajectory could be optimized to target lower altitudes, yet increasing the payload capability from 245 kg to 453 kg. For these trajectories with a specific impulse of 360 seconds, we slightly varied the specific impulse above and below 360 seconds for each condition, for which the results showed different apogee heights as indicated by the trajectories in orange. Small changes in the specific impulse seems to affect more trajectories with lower pitch angle than high pitch angle. All the cases analyzed in Figure 5a were simulated with a pitch angle of 75 degrees unless otherwise stated on the graph. Several observations can be made based on the information displayed in Figure 5. In this particular scenario, one of the scientific main goals was to bring the space vehicle to the mesosphere region near 80-90 km to conduct in-situ measurements of the noctilucent clouds. The first observation is that higher apogee trajectories (100 km - 115 km above mentioned) suggests a potential for increasing payload to the region of the mesosphere by accounting for a steeper pitch angle and larger mass flow rate (lower burn time). The second observation is that we can place the same payload into a higher suborbital orbit, which will take much less energy to boost it to a higher orbit (low earth orbit).

Figure 5b illustrates various ascent trajectories when varying the payload mass, fuel mass and gravity turn parameters. Initially, we assumed the vehicle has a fuel mass of 2,363 kg, payload mass of 245 kg, and performs the gravity turn at 7,500 m (black baseline trajectory since it targets the mesosphere) for a constant (simulation) pitch angle of 75 degrees. All the cases analyzed in Figure 5b were simulated with this pitch angle unless otherwise stated on the graph. Similarly, all the cases analyzed in Figure 5b assumed a gravity turn at 7,500 m unless otherwise stated in the graph. The pitch angle is assumed to be constant but this angle is never constant when flown the same trajectory in the SSFS as illustrated in Figure 6. The vehicle reaches about 85.2 km. A reduction of the fuel mass of about 1.5% brings the vehicle to a very similar ascent trajectory (magenta) to the baseline trajectory. Reducing the payload mass to 50%, the vehicle reaches a slightly higher apogee about 10 seconds earlier (green) than the baseline trajectory. When the vehicle performs the gravity turn at 7,000 m, it reaches an altitude of 75.7 km, and if the gravity turn is conducted at 8,000 m, the vehicle reaches an altitude of 96.5 km (11 km higher than baseline trajectory). Finally, when reducing the mass of the payload to 50% and increasing the pitch angle, the vehicle reaches an altitude of 104.7 km (orange trajectory), which is about 20 km higher than the baseline trajectory.

Gravity turn of the vehicle can be adjusted and optimized to deliver a payload to a specific region above or below in the mesosphere as illustrated in Figure 5b. Lower gravity turn than the baseline suggests the vehicle will miss reaching the mesosphere and will only be able to monitor the sub-layer of the noctilucent clouds in the mesosphere, not being able to obtain in-situ measurements of this cloud layers. Higher gravity turn than the baseline suggests the vehicle will penetrate the layer during the ascent, and will have to wait a few minutes before is able to continue a second set of in-situ measurements. However, when the vehicle is above the noctilucent clouds, the vehicle orientation can be adjusted to maximize the data collection. For example, the vehicle pitch could be adjusted manually by the pilot so that the payload would see the limb of the
noctilucent cloud layer up through penetration of the cloud layers on the descent portion of the trajectory.
Figure 6. XCOR Lynx profiles of some of the vehicle parameters for a single trajectory. a. Range. b. Drag coefficient. c. Lift coefficient. d. Lift-to-Drag (L/D) ratio. e. Mach number. f. Velocity components. g. Angle of attack. h. L/D as a function of Mach number. i. Flight path angle during ascent flight. j. Flight path angle for two single suborbital trajectories.

In our MATLAB simulation, we assumed a constant drag coefficient of 0.096785 which is an average value from obtained from a flown simulated trajectory in the SSFS as displayed in Figure 6b. Also, although the average value from the lift coefficient is 0.0334694 for the same flown trajectory, in our simulations we assumed this value to be zero for simplicity. Including the average of the lift coefficient, would yield the vehicle to reach slightly higher altitudes. The vehicle spends a significant amount of time during ascent at a climb angle of 75 degrees for which we assumed a zero-lift. Since the XCOR Lynx is a horizontal take off, it takes about one minute for the vehicle to reach a stable pitch angle of 75 degrees (or similar angle) after takeoff. When flying the SSFS, the pitch angle is manipulated by the pilot who is able to maintain a steady angle of about 80-85 degrees for about 2 minutes during ascent before this angle starts decreasing during the coast phase (see Figure 6i and Figure 6j). Figure 6 depicts all parameters as a function of time starting at 60
seconds, the time where the gravity turn takes place. In the SSFS, the simulated range achieved by the Lynx vehicle at 305 seconds mission elapsed time (MET) was 104 km as shown in Figure 6a.

During ascent the vehicle goes through the mesosphere at about 80 degrees flight path angle (Figure 6i). When the vehicle reaches apogee, the flight path angle is zero for a few seconds (see Figure 6i), and the pilot can orient the vehicle by pitching the nose down to monitor the noctilucent cloud layer from above at about 110 km for this particular trajectory. The flight path angle can be used to enhance science data collection since it allows the crew to obtain multiple views of these clouds from different angles, which can give us more details about the various size of ice particles that make up the cloud layer, and reveal mixture of chemicals that prompt the formation of these clouds and the environment in which these clouds are generated. When the vehicle goes through the mesosphere during the descent, its flight path angle is about -65 degrees, the pilot is able to sustain this angle for over a minute before he starts pitching up and start the glide.

Figure 7 depicts the vehicle space transition corridors (STCs). The hazard volume is 15 nautical miles ahead and behind the vehicle, 5 nautical miles to the right and left of the vehicle and 5,000 feet above and below the vehicle. Depending on the type of flight profile and phase of the ascent/descent, these parameters will need to be modified to evolve with the flight. This hazard volume will change dynamically during the flight due to different angles of attack. The discretized reference trajectory is plotted in black inside the corridors.

In the future, the HTHL sRLVs will be flown across several scenarios using the SSFS at ERAU. One of the scenarios will be the Nominal Launch and Landing Scenario. The sRLV takes off from Midland, Texas, and makes a nominal ascent and descent using a space transition corridor (STC) trajectory deconfliction separation method described in the FAA’s Space Vehicle Operations Concept of Operations. In the climb to 60,000 feet and during the return from 60,000 feet to landing, ATC separates commercial aircraft from the sRLV using separation standards of 15 nautical miles (NM) front and back, 5 NM lateral and 5,000 feet vertical and below (hereafter referred to as the ‘hazard volume’ depicted in Figure 7).

The Lynx trajectories flown with the SSFS reached 110 to 112 km, which are slightly higher than the expected altitude for this vehicle (103-107 km). The reason for this is because the pilot who has conducted over 100 suborbital flights, was very proficient in keeping a very steady pitch angle of near 85 degrees instead of 80 degrees for most of the eight flights. This slight deviation in the pitch angle brought the vehicle to a higher suborbital trajectory. Not every pilot who flies the sim has the same level of proficiency and therefore, this can cause the target altitude to vary, which could affect the payload delivery point near apogee resulting in a lower orbit.
Figure 7 (a). Example of flight corridors (color map) during the ascent discretized trajectory (in black) for Lynx. (a) XYZ projection. (b) XY projection. (c) XZ projection. (d) YZ projection.

The suborbital trajectories illustrated in Figure 8 were flown by three different pilots (each pilot has flown near 90 flights in the SSFS) with the SS2 platform and illustrates the vehicle reaches lower altitudes of about 100 to 105 km than the Lynx vehicle. These results suggest that deviations in the Lynx vehicle were larger since the vehicle starts lower in the atmosphere and it is more sensitive to accumulative error in the flight path since it follows a horizontal takeoff, and these errors begin to accumulate early in the flight. On the other hand, the SS2 vehicle is released from underneath the carrier aircraft WhiteKnightTwo and after about 50 seconds, it pulls up to start the ascent. These trajectories (Figure 8) were closer to each other. Also, both of these set of trajectories included some input wind parameters in the X-plane software that runs the simulator. These winds were assumed to be of 5.75 miles per hour with shear direction of 10 degrees and no turbulence.
Figure 8. Comparison of XCOR Lynx and SpaceShipTwo flight profiles

Figure 9. Comparison of XCOR Lynx and SpaceShipTwo flight profiles
These conditions were applied throughout the entire trajectory for the low altitude wind layer (2,000 mean sea level), mid altitude wind layer (8,000 mean sea level) and the high altitude wind layer (18,000 mean sea level). Higher winds can be assumed in the simulator but pilots have much more difficulty in maintaining a constant pitch angle of the vehicle.

Small variations in the pitch angle can result in variations in the angle of attack (see Figure 9) that the pilot would need to adjust for in order to keep the vehicle along the reference baseline trajectory.

Suborbital trajectories are mission dependent. During the last two years, ERAU have hosted Scientists Astronauts Candidates (SACs) as part of the Polar Suborbital Science in the Upper Mesosphere (PoSSUM) program to educate scientists, engineers, faculty and students in various aspects of the noctilucent clouds. Since 2015, SACs trained in the SSFS with procedures and checklists for various research platforms. Initially, the XCOR Lynx was used but soon transition to the SS2 vehicle since the Lynx vehicle was decommissioned in 2016. With either of these platforms SACs followed a certain flight profile that was targeted at above 100 to 110 km (see Figure 10).

Figure 10. Illustration of elevation angle for a XCOR Lynx suborbital trajectory.
These trajectories provide the SAC with about 10 seconds of data during ascent and 10 seconds during descent as they cross the noctilucent cloud layer, this data is interrupted. Our study suggests that this specific mission could be flown in order to enhance science and obtain continuous monitoring data while flying through this cloud layer located between 80-90 km. Figure 10a illustrates a diagram with the noctilucent layer (in blue) placed at 83.5 km as seen by an observer on the ground (black line). The diagram shows these noctilucent clouds could be visible at about 100 km along the horizontal distance from the observer, beyond this point this cloud layer is obscured and cannot be seen (red circles).

The black box in Figure 10b is a zoom of Figure 10a and depicts the elevation angle\(^{22}\) of the cloud layer at about 138 km horizontal range (dashed line) and 116 km horizontal range (dot dashed line) as seen from the observer on the ground. These elevation angle will vary depending on the type of flight profile flown by the pilot since some trajectories will have longer horizontal ranges than other. Figure 10c show an example of the elevation map profile for a single trajectory of the Lynx vehicle from ground to apogee assuming this path targets the cloud layer located at a horizontal distance of 138 km.

**IV. Summary and Future Work**

Establishing novel space operation procedures\(^{23}\) is key to establish business and research cases that justify the cost of access and these require coordination of space traffic with more traditional aviation usage of national air space. These operating procedures will involve training new space operators to conduct and coordinate space operations in class E above FL600 airspace. Over the past decade suborbital flights by several commercial launch providers have been tested from the technology perspective. A strong argument can be made for tailoring future flights to increase the science gathered during the precious 4-5 minutes in microgravity. Current costs for such suborbital flights range about $250,000, which means every second is very valuable for scientific purpose, since every second is valued at about $833 assuming we can use all 5 minutes in microgravity. Unless there is a vehicle that targets this region of interest to maximize science, we are talking about 30 seconds only of actual in-situ data collection. This means that each second would be valued at about one order of magnitude higher or about $8,333.

Ground based technologies, such as sodium lidar, can provide real-time high accuracy of the conditions in the upper atmosphere, which ultimately will benefit suborbital operations since we will know a more refined timeframe where to launch a suborbital flight to meet scientific requirements. Clearly, the additional inclusion of higher fidelity models of the atmosphere will need to be considered to streamline the space operations during ascent, and descent when the vehicle is above FL600 for over 5 minutes for XCOR Lynx and SpaceShipTwo (see Figure 9). Note that for the XCOR Lynx, the vehicle clears the FL600 after 90 seconds to about 2 minutes depending on the mission profile and pilot maneuvering the vehicle. Then, the Lynx vehicle reenters the NAS 8 to 9 minutes after takeoff. As for the SpaceShipTwo, the vehicle takes about one minute to clear the FL600 during ascent, spends about 5 minutes in the FL600 before reentering the NAS. These timeframes vary from vehicle to vehicle, yet it is feasible through may pilot flown simulations to refine the vehicle path (space vehicle tracking is not available yet) to streamline and integrate automated hazard areas (AHA) into air traffic management tools. These procedures should also include other training materials, such as the proficiency of pilots to train...
and fly simulators mimicking various types of vehicles, the type of science mission (mission time of flight and altitude targeting), the frequency of operations, and the location of the spaceports. These ATO Space Vehicle Operations are identified as high-level gaps in the development and validation of such operations among the fine functional categories in the roadmap to organize and track ATO activities for integrating commercial space operations into the NAS: airspace, procedures and standards, ATO space vehicle planning, ATO space vehicle operations, training, policy and regulations, systems and capabilities, safety and integration and planning.

Day of launch weather hazards (clouds, thunderstorms, etc) details are not accurately forecast down to the minute due to the lack of precision in weather forecasts. Weather travels so forecasts need data from distant parts of the Earth. While the FAA says they recognize the need for uncertainty in forecasts, nothing has been done to utilize the uncertainties in decision making processes for ATC. Short-term forecast models of 2 to 3 hours or several tens of minutes would be possible with connections between site regional sensors and national weather sensors to provide high accuracy of wind speed, direction and timing of shifts. This more accurate data will be used as weather initial conditions (usually imperfect) input to improve weather models. These refined models would be used to increase safety and separation from other traffic and potential hazards during the various phases of the spaceflight operations. For example, upper level winds are not only important for terrestrial aviation support for forecasting shear and turbulence, but even more critical for supporting suborbital launches. Besides winds, thunderstorm and convection, aircraft/spacecraft icing ceiling, and excessive winds are of critical importance for spaceflight operations. Day of launch weather hazards (clouds, thunderstorms, etc) details are not accurately forecast down to the minute due to the lack of precision in weather forecasts. Weather travels so forecasts need data from distant parts of the Earth. While the FAA says they recognize the need for uncertainty in forecasts, nothing has been done to utilize the uncertainties in decision making processes for ATC. Short-term forecast models of 2 to 3 hours or several tens of minutes would be possible with connections between site regional sensors and national weather sensors to provide high accuracy of wind speed, direction and timing of shifts. This more accurate data will be used as weather initial conditions (usually imperfect) input to improve weather models. These refined models would be used to increase safety and separation from other traffic and potential hazards during the various phases of the spaceflight operations. For example, upper level winds are not only important for terrestrial aviation support for forecasting shear and turbulence, but even more critical for supporting suborbital launches. Besides winds, thunderstorm and convection, aircraft/spacecraft icing ceiling, and excessive winds are of critical importance for spaceflight operations. 

Our SSFS and MCC at ERAU generates suborbital flights. These flights launches do not have incorporated yet real weather data into a single scenario. Our group is working on including real-time weather data feeds from satellite radar, and numerical models and space weather information from the National Weather Service Space Weather Center. This console in the MCC could be utilized in conjunction by both spaceflight operations and meteorology students to make the final launch criteria decision which will be clearly communicated to the launch operations officer of several agencies, such as Kennedy Space Center and Cape Canaveral Air Force. This data can then coordinated between ATC and STC to monitor the STCs for both departure and arrival. For example, students will be able to run several scenarios so that real weather data can be incorporated into a single space vehicle, which can be locked into the SSFS and MCC lab.

Understanding the variations of parameters and their sensitivities is crucial for better understanding the trajectory analysis. Our work mainly focuses on the ascent portion of the suborbital trajectory, which is the portion of the trajectory that would affect payload delivery from suborbital space to orbit. Range management and assessment of the vehicle descent trajectory will be dictated by the knowledge of its ascent trajectory, and whether the space vehicle can land safely at the same spaceport or nearby airport when enhancing the science operations in the mesosphere. Sensitivity analysis of some parameters and their behavior are linked to certain areas in the trajectory optimization, such as propulsion, aerodynamics, thermodynamics, heat transfer and orbital mechanics. Although our results are not optimized, they can be used to provide good insight as to how to enhance in-situ science in the upper mesosphere and improve payload weight to reach orbit from various points along the ascent suborbital trajectory and near apogee of a launch vehicle. Then, we can determine the optimal point to perform the maneuver that will maximize the payload.
weight delivered into orbit. Ultimately, we can estimate the time for the payload deployment from the launch vehicle along the suborbital path into orbit.

In future work, we will study how a payload can be delivered into orbit (for example conducted with the research platform Lynx Mark III in the SSFS) using two different navigation approaches:

1) Using a single deterministic maneuver a few seconds before apogee and at apogee (eg., $T_{\text{apogee}}$ -30 seconds, $T_{\text{apogee}}$ -20 seconds, $T_{\text{apogee}}$ -10 seconds, $T_{\text{apogee}}$ -5 seconds, $T_{\text{apogee}}$). This first $\Delta V$ (change in velocity) is conducted to propel the payload from the suborbital trajectory to a higher energy orbit. Then, a second deterministic maneuver would be required to be conducted at the target orbit for each of the above scenarios. This second $\Delta V$ would be needed to circularize the payload into orbit assuming the payload has enough fuel.

2) Using continuous low thrust between the release point along the suborbital trajectory and the target orbit.

Radiation modeling is not included in the current configuration of our SSFS software. Space flight participants (SFPs) are not expected to be exposed to unsafe\(^3\) doses of ionizing radiation unless in the case of a sudden change in solar activity (as happened during the Columbia reentry in February 1 2013 with several high-peaks CMEs of 400 km/s and 800 km/s in less than a minute). The radiation exposure to the SFPs on a suborbital flight is less than that for a long duration airline flight. However, high energetic particles, such as solar particle events (SPEs with tens of MeV to $\sim$ 100 MeV) but mainly galactic cosmic rays (GCRs) can still penetrate the atmosphere and generate a cascade of subsequent particles, such as the backscattered neutrons, which will be particles affecting SFPs to suborbital radiation exposure. ERAU flew a payload\(^{28}\) aboard NASA WB-57 aircraft with our payload onboard, we were able to measure certain radiation levels for a steady flight during the 2-3 hours of cruise at FL600. One of our objectives in flying this particular payload was to better understand current radiation levels at FL600 using a very high energy calibration sensor, NASA’s TimePix radiation detector, previously flown aboard NASA’s EFT-1 to count photons and other high energy particles.

Weather effects on suborbital flights will depend on many factors: suborbital flight profile (altitude), mission duration, solar cycle, solar activity, geomagnetic conditions, vehicle shielding, latitude and longitude. Addressing these space weather effects is critical to prevent having SFPs develop possible cataracts, skin damage, central nervous system damage and impaired immune system. It is estimated that a 30-minute suborbital flight can yield on the order of 10 µSv/hour. The region of interest for suborbital flights is up to 100 km. The region from the surface to 40 km is comprised dominantly by secondary particles from scattering GCRs. These particles peak near 20 km and the dose increases with altitude. The region from 40 km to 100 km, which is still not well characterized with respect to the latitude, is comprised mainly of unscattered GCRs and also increase with altitude.

For suborbital (and short-duration orbital missions), the most significant (although minor) risk is cancer. Suborbital flights launched at high latitude sites (55 to 65 degrees) or during peak of storm can yield radiation levels of about 0.2 to 1 mSv. For suborbital flights, solar storm exposure is below background GCRs for latitudes less than 45 degrees. The radiation exposure for suborbital flights ranges from about 0.34 to 2.4 µSv, which is much less that cross-country commercial airline flights (25 µSv). Still, exposure to significant levels of radiation will increase the probability of cancer. If spaceflight participants are to fly in these regions to maximize science operations, we need to know more about the radiation levels in this region.
Acknowledgments

This research was partially supported by the Applied Aviation Science Department at Embry-Riddle Aeronautical University. This research was conducted in the Suborbital Space Flight Simulator Laboratory in the College of Aviation. We would like to thank Professor Emeritus Dr. Frederick Mosher and Dr. Michael Hickey for their valuable input through private communications about the atmospheric model, and Dr. Richard Snow for his help with editing the paper.

References