GreenCube II

Multiple Balloon Measurements of Gravity Waves in the Skies Above New Hampshire

SEAN CURREY '11

This paper details the experimental method and results of the GreenCube II mission, a student-driven research program at Dartmouth College. The objective of the mission was to use multiple-point high altitude sounding balloon measurements to characterize the gravity wave structure over New Hampshire's Mt. Washington. Each payload collected GPS and temperature data. The results were compared to a numerical simulation to verify that the perturbations measured were a product of gravity wave action. Although the measurements appear accurate, the simulation is not yet accurate enough to verify the presence of gravity waves.

Introduction

The GreenCube project stems from Dartmouth physics professor Kristina Lynch's interest in small, autonomous science payloads for multipayload auroral sounding rockets, and from Professor Robyn Millan's interest in small, CubeSat-like orbiters for future science missions. The goals of the GreenCube project are to maintain a scientifically interesting, student-driven balloon-borne CubeSat program in the Dartmouth Physics Department, to incorporate new design features into small payloads for LCAS-class auroral sounding rocket proposals by Professor Lynch, and, on a longer timescale, to incorporate designs into future plans for small spacecraft for orbital science missions (1).

Unlike the preceding two GreenCube missions, which verified the feasibility of using small payloads to collect data from the atmosphere, GreenCube II was designed as an actual science mission to collect measurements on atmospheric gravity waves – movements of air perpetuated by a gravitational restoring force. Gravity waves are invisible to the naked eye but play a major role in the transfer of energy from the lower to the middle and upper atmosphere. Understanding gravity waves may one day allow us to more accurately predict the weather or conditions in the upper atmosphere. However, because of their inherent invisibility, gravity waves are difficult to measure.

Image courtesy of Max Fagin.

Members of the GreenCube II team prepare for launch at Mt. Washington Airport in Whitefield, New Hampshire.

Terrain-generated gravity waves are divided into two categories: mountain waves and lee waves. Both types are formed when wind blowing over the Earth's surface is obstructed by a terrain feature, such as Mt. Washington in New Hampshire. Air is forced up and over this feature, which in turn forces the air above it up, and so on. These waves are referred to as mountain waves. As the wind settles on the opposite side of the feature, it oscillates up and down as it settles. The waves generated here are called lee waves, due to the fact that they are generated on the leeward side of the mountain (2).

The goal of GreenCube II was to use multiple-point measurements to analyze the structure of mountain waves. After examining occultations measured by the GPS satellites, the team determined that Mt. Washington was a likely source of mountain waves. The team assumed that the atmospheric density changes indicative of occulations were caused by gravity waves.

Objectives

The objective of the GreenCube II mission was to successfully launch two sounding balloons spaced in such a manner that the flight paths could be compared to measure the wave structure above Mt. Washington. The balloons were to fly over Mt. Washington and burst between 80,000 and 90,000 ft and then descend to a location at which they could be recovered. After launch, the data collected was used to determine the size of the wave structure over Mt. Washington and how the structure changed with time. The data collected was also compared with the Taylor-Goldstein equation to verify that the perturbations seen by the payloads were in fact generated by gravity waves.

Experiment

Equipment description

The two GreenCube payloads contained a GPS to record its position and five thermistors to record local atmospheric temperatures. The payloads recorded GPS data every five seconds and temperature data every 10 seconds, and send this information to the ground team via radio. The payloads were attached to high altitude sounding balloons. In addition to the GreenCube payloads, each balloon also carried a commercial camcorder on its lower secondary payload (designed to carry an emergency locator transmit-

Fig. 1: One of the two GreenCube payloads flown.

ter). These cameras captured HD video of the Earth from the balloon altitudes, including images of cloud formations which bore the signs of atmospheric gravity waves.

Flight description

Two adjacent GreenCubes were launched from Mt. Washington Airport. The balloons reached an altitude of approximately 90,000 feet before bursting. The payloads then descended via parachute and were retrieved using the real-time GPS track received through the ham radio system. The balloons flew over the Presidential Range and were recovered in Maine. The flight time was approximately two hours.

GPS data was transmitted to the ground crew in real time over the course of the flight. GPS position vectors and timestamps were recorded and transmitted every five seconds, as shown in Fig. 1. The balloons ascended in a roughly linear fashion. After the balloon burst at the flight apogee, the balloons descended in a roughly exponential profile. As the atmosphere becomes denser at lower altitude, the parachute created more drag, lowering the ascent rate. Both balloons burst between 25 and 28 km in altitude, well within the preflight prediction of 80,000 to 90,000 feet.

The velocity of the balloon was derived from the recorded position and time data by dividing the distance between GPS position coordinates by the time delay between them (usually 5 seconds). In this manner, both the speed of the payload and its heading were calculated horizontal velocity profiles, as shown in Fig. 2. The team made an important assumption that the velocity of the payload at any given moment is the same as the wind speed, i.e. the payload accelerates nearly instantaneously with the wind. The payload profiles look almost identical, indicating that they ascended through similar atmospheric features. As the balloons approach 5 km in altitude they enter the jet stream and accelerate very rapidly. After achieving about 15 km in altitude the balloons begin to slow down. The many small-scale fluctuations seen in these horizontal velocity profiles could be caused by gravity waves.

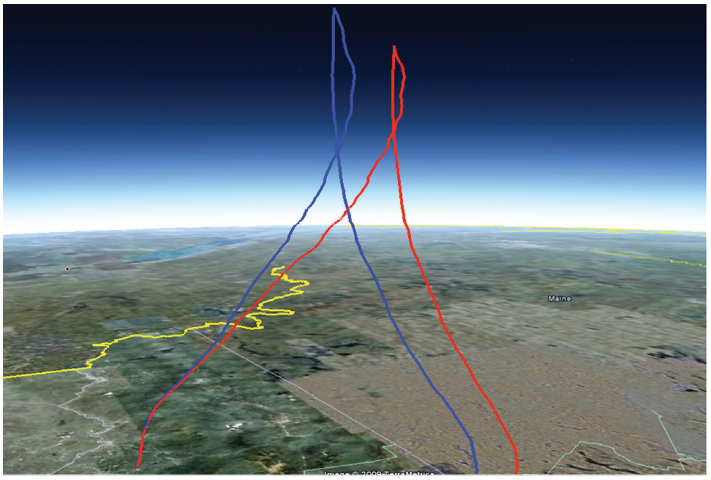

Fig. 2: The above graph is a plot of all position coordinates for both payloads created using Google Earth. The blue trajectory belongs to the first balloon launched (Payload 1) and the red belongs to the second balloon launched (Payload 2). Payload 2 was launched 90 seconds after Payload 1.

GPS data

To start our gravity wave analysis we transformed our velocity data into components. A look at the compass heading of the balloon over the course of its ascent shows that the balloon oscillated in direction around a 120 degree heading. Therefore, we designed a new coordinate system that better reflected the direction of the balloon, in which the “along” velocity shows movement in the direction of the prevailing winds, and the “across” velocity registers movement perpendicular to the prevailing winds. When the new coordinate system is applied, the oscillations are more pronounced and the heading changes are more apparent. The fluctuations in horizontal velocity are strongest perpendicular to the balloon’s path.

Temperature data

Also flown aboard the payloads were five thermistors which recorded temperature data. Data from the thermistors was transmitted approximately every 10 seconds. Before analyzing the temperature data, the data from all five thermistors was averaged so that one tem-

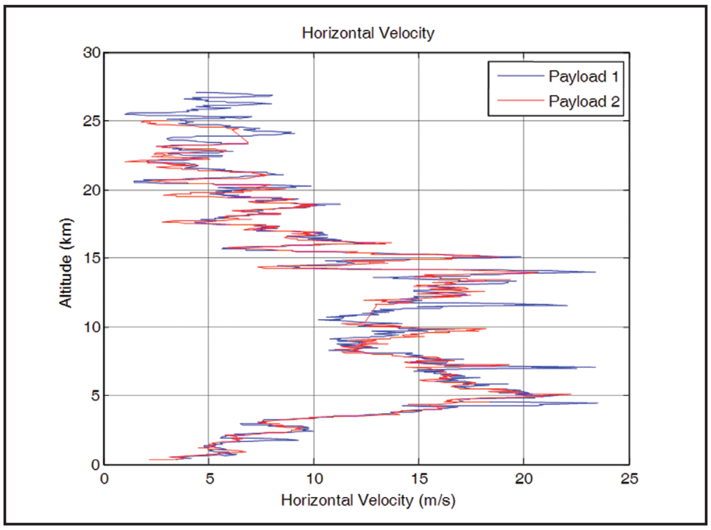

Fig. 3: The graph above shows the horizontal velocity profiles of both payloads as they ascended to apogee. The overall velocity curves are permeated by small perturbations in horizontal velocity.

perature profile was derived from each payload. The data was also converted into potential temperature to follow convention. Potential temperature is defined as the temperature of a volume of gas adiabatically changed from its initial pressure to a standard reference pressure (3).

$$\theta = T\left(\frac{P_0}{P}\right)^{R/cp}$$

The standard pressure used was 1000 millibars. Because the GPS data and temperature data were handled by two different systems, they therefore were reported at different rates. The time stamps sent out on each radio transmission represented times corresponding to the GPS data but not necessarily the temperature data. The temperature data was splined with the GPS data regarding when and at what altitude the temperature data was recorded.

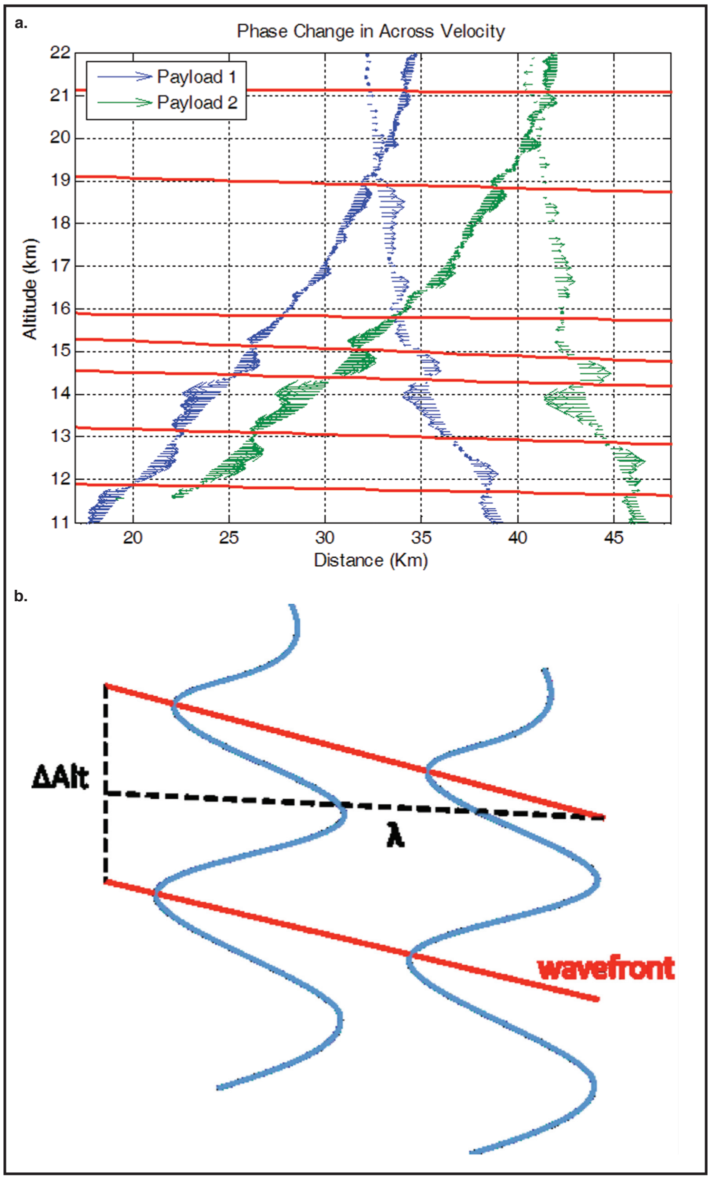

Fig. 4: 4a is a quiver plot showing the “across” (perpendicular to prevailing winds) component of payload velocity plotted along payload trajectory. The red lines connect atmospheric features detected by payload 1 with corresponding features detected by payload 2. Note that the lines are not perfectly horizontal, suggesting that the two payloads encountered the same features at slightly different altitudes. 4b shows a clearer example of the concept.

Results

Combining the position and velocity data on a quiver graph allows for a glimpse into two slices of the atmospheric velocity vector field above Mt. Washington (Fig. 4a). At first glance, the velocity vector profiles look very similar. Features appear identical across lines of equal altitude, therefore there are no obvious time or range dependence. However, a closer look shows very faint changes along lines of equal altitude. For example, along the 14 km altitude contour, a peak in the cross component velocity can clearly be seen just above the contour on both payloads as they ascent through this area. However, when payload 1 descends the peak occurs exactly on the contour, and payload 2’s peak occurs below this contour. The change in altitude of this atmospheric feature is indicative of either a change with respect to time or distance of this feature.

We can use this phase change to measure the horizontal wavelength of this feature. The change in altitude of two vertically propagating wave structures can be used to calculate the horizontal wavelength of the structure as shown in Fig. 4b. Because the horizontal wavelength is proportional to the change in altitude, the peak to peak change in altitude of one full vertical wavelength can be used to calculate the horizontal wavelength.

$$\lambda = \frac{\Delta altitude}{slope\ of\ red\ line}$$

In Fig. 4a, we plotted lines connecting similar features. Rather than connecting peaks, however, we chose to connect the nodes together. The nodes represent a change in the across velocity from southeast to northwest. The lines with the greatest slope are located between 13 to 16 km in altitude. These lines describe the atmospheric fea-

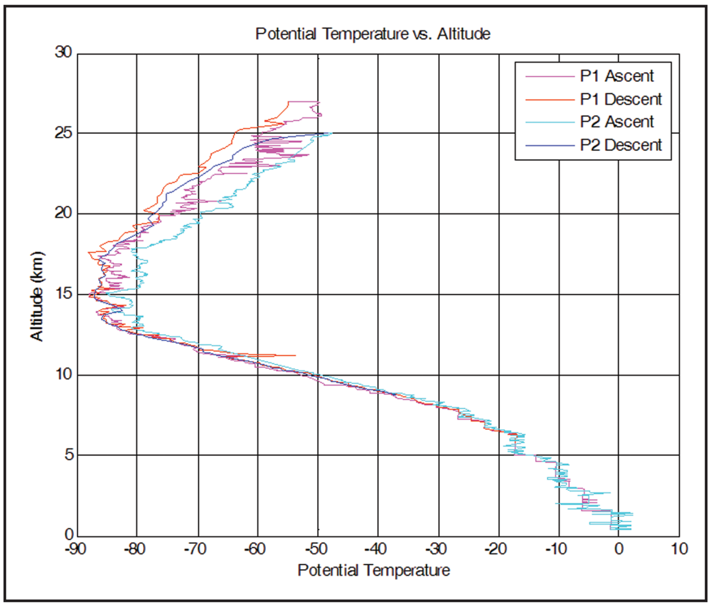

Fig. 5: Average potential temperature for each payload plotted against altitude.

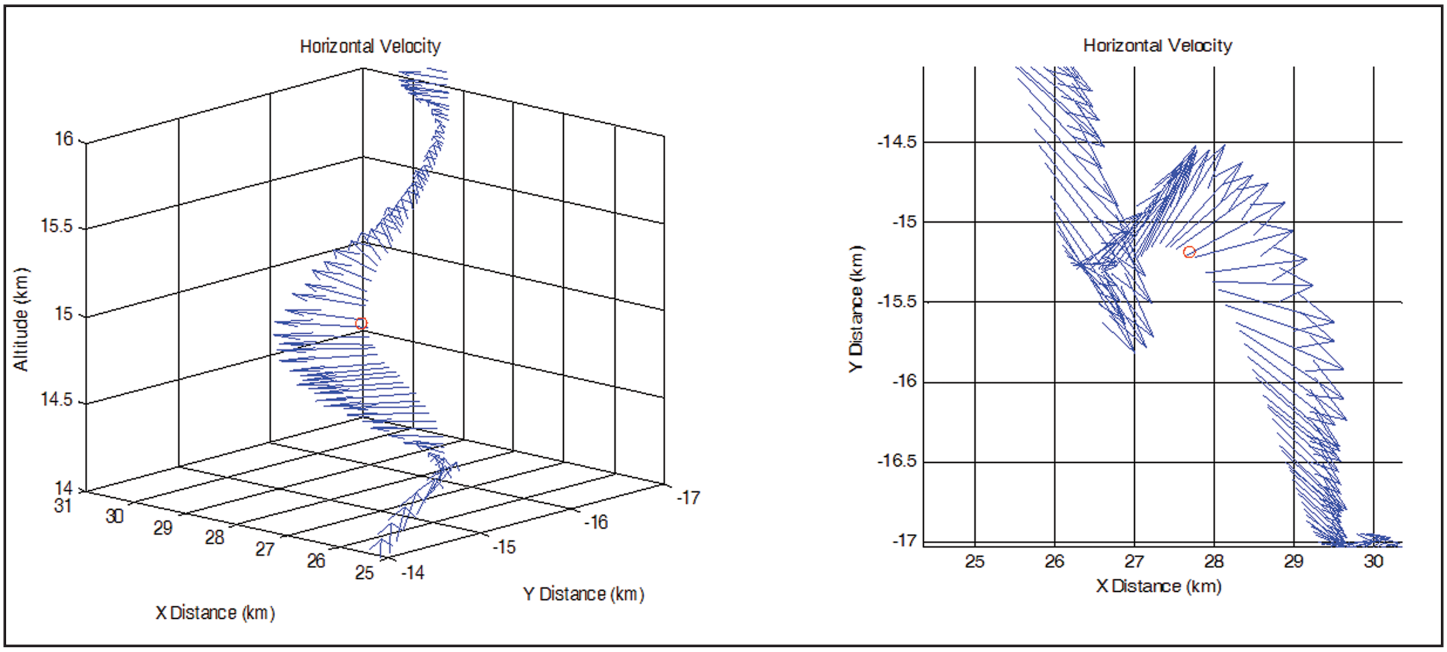

Fig. 6: Shear layers. As the balloons ascend through various sections of the atmosphere the horizontal velocity suddenly changes. The figures above show this phenomenon. The left figure shows the payload ascending through the Tropopause at 15km. The path is shown at the vector bases, and the magnitude of the vector describes the velocity. The right figure shows a bird's eye view of this graph. The balloon hits the shear layer and its path is directed in the +x-direction.

tures with the greatest change. The phase change becomes zero at increased altitudes. The line around 14.5 km had the greatest slope at -17.36 m per km distance. The peak to peak vertical wavelength of payload 1's ascent measured 1.3 km. Therefore, the minimum horizontal wavelength we observed was 76.5 km. The balloons themselves only collected reliable data above 10 km and less than 40 km. Therefore, the structure is so large that horizontal distance is a negligible factor in determining the "across velocity."

Starting at 15 km altitude the balloon makes repeated fan-like patterns in which the balloon sharply changed direction and then gradually returned to its normal heading. The largest of such fluctuations occurs at 15 km, corresponding with the Tropopause and therefore the largest change in temperature. The Tropopause is the boundary region between the Troposphere and Stratosphere, and is characterized by a local minimum in temperature (4). The other prominent sharp accelerations occur at 17.8 and 20.5 km, which are the same regions that correspond to the second and third largest changes in temperature. This could be indicative of an atmospheric shear layer, an area of the atmosphere where the velocity of the wind is vastly different from the layers above and below it. This sudden change in velocity of the gas would change the balloon's heading and cause it to record a very different temperature. To conclude, the large changes in temperature and velocity occur together, and indicate that the payload is passing through a discontinuous shear layer.

Simulation

Although the perturbations in velocity and temperature seen by the balloons were indeed measurable, we cannot say with any certainty that they were caused by gravity waves. Therefore, we created a numerical simulation that predicts the perturbations in vertical velocity the balloon should have experienced while flying over Mt. Washington.

The mountain was modeled as a Gaussian function with a height and width representative of the actual size of Mt. Washington. The incoming horizontal wind velocity was generated by smoothing the velocity data obtained by Payload 1 during its ascent. The simulation then solved the Taylor-Goldstein equation using inverse Fourier transforms (2).

$$w_1(x, z) = \frac{1}{\pi}\Re\int_0^\infty \hat{w}(-k,0)\,e^{-i(kx+mz)}\,dk$$

The results are shown in Fig. 8. The colored lines in this figure represent the streamlines on the velocity field over

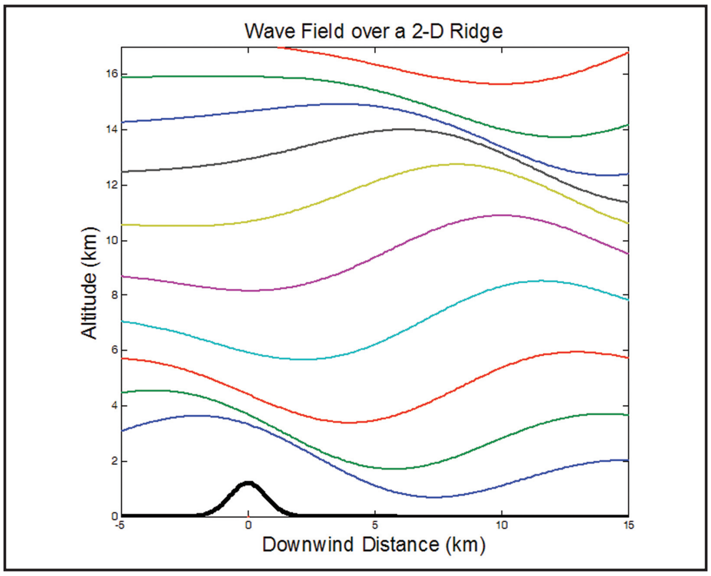

Fig. 7: A numerical simulation illustrating the formation of mountain waves. Incoming air from the left is forced over the terrain feature, sending velocity perturbations propagating forwards in distance and upwards in velocity.

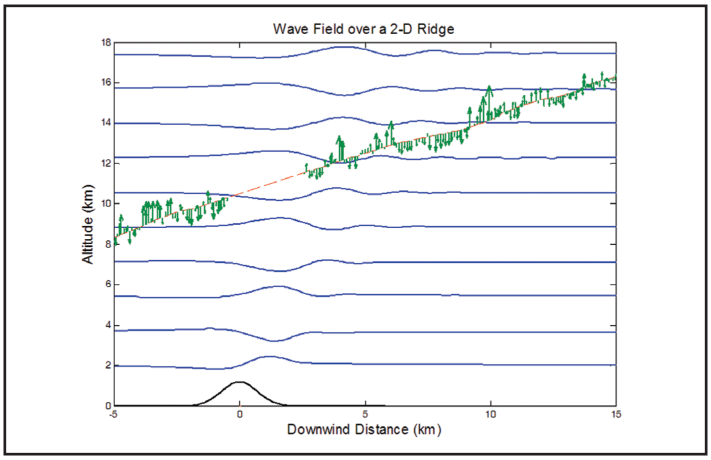

Fig. 8: Payload 2's vertical velocity perturbations and flight path are plotted over the simulated mountain waves created by Mt. Washington.

the mountain. The trajectory of payload 2 was plotted over this field, along with the perturbations in horizontal velocity.

Fig. 9 shows the expected amplitudes of the vertical velocity as a function of downstream distance, versus the actual amplitudes seen by payload 2. This figure shows that the model closely guesses the amplitude or perturbations inside the region affected by mountain waves. However, there are also large perturbations seen by payload 2 outside this region.

Does this indicate that the balloon's perturbations were not caused by gravity waves? Not necessarily. This model only predicts perturbations in vertical velocity, which as stated earlier is difficult to measure with a sounding balloon due to buoyancy concerns. Creating a model that predicts horizontal perturbations might yield better results. Additionally, this is only a two-dimensional model, with a very simple contour representing Mt. Washington. In reality, the Mt. Washington ridgeline is shaped like an integral sign, which might force air over the mountain in a manner rather different from the straight ridgeline model used in this simulation. Lastly, the terrain around Mt. Washington is corrugated, which could account for the large perturbations seen far downstream of the mountain. A more high-fidelity simulation is needed to test these sources of error.

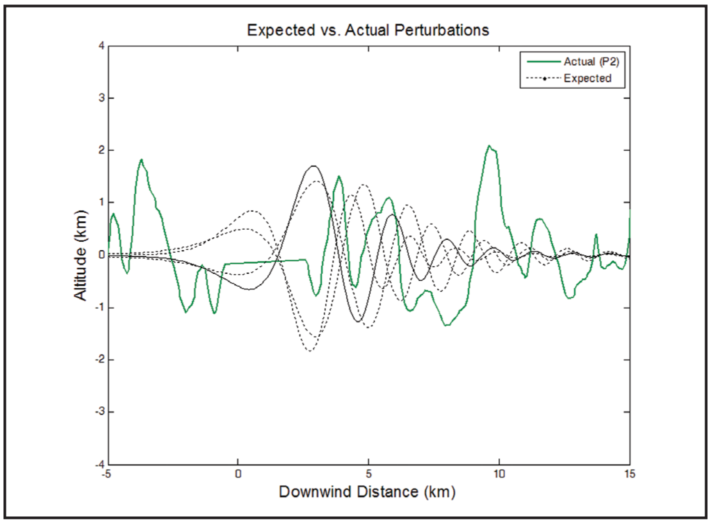

Fig. 9: The expected vertical velocity perturbations (black) are plotted with the actual perturbations seen by Payload 2 (green). Because the green line is not fully contained in the black line, we know that there must be other sources of velocity perturbations besides mountain waves.

Conclusion

The GreenCube II mission was successful in collecting multiple-point measurements over the course of its two hour flight. The GPS and temperature data from the payloads was received in real-time and translates into accurate temperature and flight profiles. This data was used to estimate the structure of the gravity wave system over Mt. Washington. Although as the simulation shows, it is still difficult to tell whether these perturbations are caused by gravity waves, or instead by another phenomenon, such as atmospheric shear layers. A higher fidelity simulation is needed to verify this.

Nomenclature

θ = potential temperature [˚C, K]
P = Pressure [millibars]
P_o = Reference Pressure [millibars]
C_p = specific heat capacity [J/Kg K]
R = gas constant [J/mol K]
T = Temperature [C, K]
λ = wavelength [m]
m_{red} = slope [dimensionless]
w_1 = perturbation velocity (vertical)
x = position (x-direction) [m]
z = position (z-direction) [m]
w = Fourier transform of perturbation functions
k = wavenumber in x-direction
m = wavenumber in z-direction

References

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