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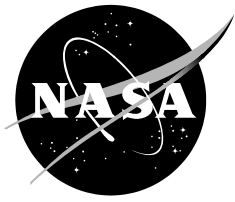
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ABSTRACT

A comparison study by the National Aeronautics and Space Administration Dryden Flight Research Center (Edwards, California) and the Naval Post Graduate School Center for Interdisciplinary Remotely-Piloted Aircraft Studies (Marina, California) was conducted to show the advantages of an airborne wind profiling light detection and ranging (lidar) system in reducing drift uncertainty along a reentry vehicle descent trajectory. This effort was in support of the once planned Orion Crew Exploration Vehicle ground landing. A Twin Otter Doppler Wind Lidar was flown on multiple flights along the approximate ground track of each ascending weather balloon launched from the Marina Municipal Airport (Marina, California). The airborne lidar used was a 5-mJ, 2-micron infrared laser with a 10-cm telescope and a two-axis scanner. Each lidar wind profile contains data for an altitude range between the surface and flight altitude of 2.7 km, processed on board every 20 s. In comparison, a typical weather balloon would traverse that same altitude range with a similar data set available in approximately 15 to 20 min. These tests were conducted on November 15 and 16, 2007. Results show a best-case absolute difference of 0.18 m/s (0.35 kn) in speed and 1 deg in direction.

NOMENCLATURE

CEV	Crew Exploration Vehicle
CIRPAS	Center for Interdisciplinary Remotely-Piloted Aircraft Studies
DFRC	Dryden Flight Research Center
DWL	Doppler Wind Lidar
lidar	light detection and ranging
NASA	National Aeronautics and Space Administration
Z	Zulu time (Greenwich Mean Time)

INTRODUCTION

The overall objective of this study was to determine the accuracy and benefits of airborne lidar wind measurements for potential ground landings of the Orion Crew Exploration Vehicle (CEV). Though the CEV program was the source of funding for this effort, these results can be applied towards any future program that has a rapid update wind profile requirement. The National Aeronautics and Space Administration (NASA) Dryden Flight Research Center (DFRC) (Edwards, California) and the Naval Postgraduate School, Center for Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS) (Marina, California) participated in this effort. Testing was conducted on November 15 and 16, 2007 at the Marina Municipal Airport (Marina, California) at a flight altitude of 2.7 km. Predictions for airdrop landings are easily and unfavorably affected by winds, and the problem becomes exaggerated when the vehicle returns from higher altitudes by the integration of small uncertainties over the large altitude range. Two primary solutions were formulated to address this uncertainty. One could determine the integrated wind profile at the landing site in order to predict the amount of vehicle drift under chute from the desired landing location. The other solution, based on the wind, is to back out an atmospheric entry point and a trajectory that will bring the vehicle to the desired location (bull's eye). There were various methods attempted for analysis, with the resulting best approach being an average of all the lidar profiles associated with the balloon ascent period. This method shows the least difference between balloon and lidar. The advantages for using an airborne lidar as a wind measurement sensor include geographically fixed site monitoring, continuous profiling, and reduced time for creating a profile. Several disadvantages exist including laser

output power limitations (for ranging), cloud layer presence that interrupts beam propagation, and lack of aerosols for signal returns. Initial mission weather requirements for the Crew Exploration Vehicle ground landing demanded rapid and reliable updates from the lidar as obtained from the balloon at a fixed location.

SYSTEMS DESCRIPTIONS

The two instrument systems used were radiosondes and a Doppler lidar. Radiosondes are routinely used all over the world, while lidar is not as widely known.

Radiosonde

Radiosondes contain instruments for direct in-situ measurements of ambient air temperature, humidity, and pressure typically to altitudes of approximately 30 km (ref. 1). For this balloon test, a Vaisala Inc. (Helsinki, Finland) DigiCORA® III Sounding System and the RS92 GPS radiosonde packages were suspended from an 800 g latex balloon (ref. 2). The balloon system transmits thermodynamic data (temperature, pressure, and relative humidity) every two seconds. Winds are calculated by integrating the position coordinates, provided by real-time code correlated differential GPS, over time. Balloons are inflated to climb at approximately 300 m/min (1,000 ft/min). Kalman and notch filtering is performed in order to minimize tracking noise and the effects of the pendulum motion of the sonde, and is suspended approximately 30 m below the balloon (ref. 3). A balloon to 15 km and 20 km would require approximately 50 min and 70 min for ascent, respectively, plus about 15-25 min for processing and delivery. According to the vendor's literature, wind measurements have an uncertainty of 0.15 m/s (0.29 kn).

Lidar

The CIRPAS Twin Otter (de Havilland Canada, now Viking Air, Victoria, British Columbia) Doppler Wind Lidar (DWL) is a 5-mJ, 2-micron infrared airborne Doppler lidar used to investigate sensitivities of local scale wind fields, fine scale model validation, interpretation of space-based DWL data, and the calibration or validation for other lidars (ref. 4). The principle of pulsed lidar measurement of wind and aerosols is the use of optical heterodyne (coherent) detection, in which laser pulses are transmitted into the atmosphere and scattered off of naturally-occurring small dust particles (aerosols) entrained in the ambient flow field (ref. 5). The lidar system has an external two-axis focal length scanner. The scanner allows the beam to be pointed within a 60-deg azimuth arc in the forward position and a plus or minus 120-deg elevation arc with 0 pointing horizontal. The lidar scanner is mounted in a side door of the aircraft, which allows scanning upward as well as downward. The aircraft is an unpressurized Navy Twin Otter with a cruise speed of 95-160 kn (ref. 4). The lidar processing software produces an altitude increment file every 50 m from ground level to the flight altitude of 2.7 km for non-vertical scanning. The data rate is 80 samples per second, which is then averaged over 20 s for a single wind profile. This would amount to a rate of 3 profiles per minute, but due to the time the instrument needs to process the data, the time between each 20-s sample varies by about 1-2 s. The lidar has demonstrated a 10-min profile retrieval and 5-min processing and delivery, regardless of altitude range.

PROCEDURES AND CONDITIONS

A precise comparison of the two instruments (radiosonde and lidar) requires obtaining valid data, and knowing when certain data is corrupt and not reliable for analysis. Having good data allows for a firm understanding of the atmosphere and confidence in the results.

Test Description

Two days of measurements were conducted in order to obtain data for the lidar and radiosonde wind velocity comparison. As mentioned above, the dates of the comparison were November 15 and 16, 2007, with flights at 1800 Z, 2000 Z, and 2200 Z time on the 15th, and at 1800 Z and 2000 Z time on the 16th.

The method used to plan the aircraft's flight path was intended to encompass the balloon path through its ascent, which was expected to be a southeast drift based on the November 16, 2007, 1200 Z Oakland, California upper air wind analysis. Figures 1 through 3 show that the balloon and aircraft sampled the atmosphere from different locations. While the aircraft was a fixed ground track, the balloon moved toward the southeast, as expected. For this test, the balloon only reached 30 km. It is possible, under the right conditions, for a balloon ascending to 15 or 20 km to drift down wind many tens of kilometers.
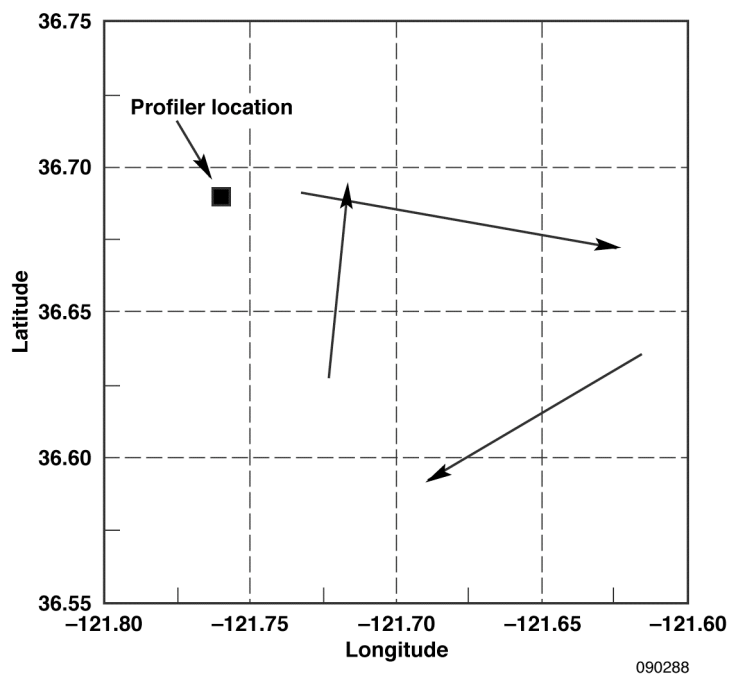

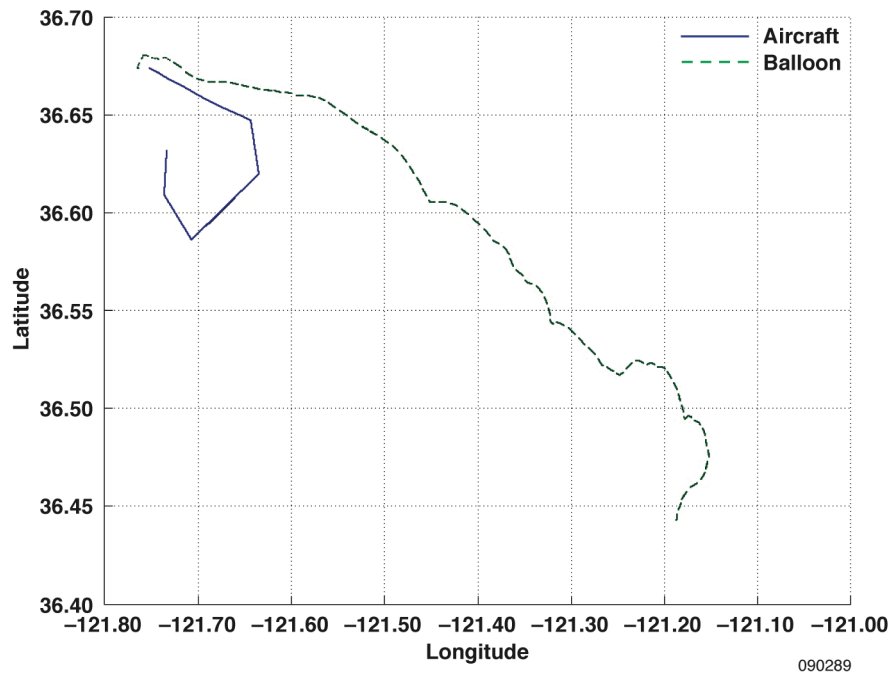Figure 1. Proposed path of aircraft during 2000 Z run.

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Figure 2. Path of aircraft and balloon on November 16, 2007 for 1800 Z.
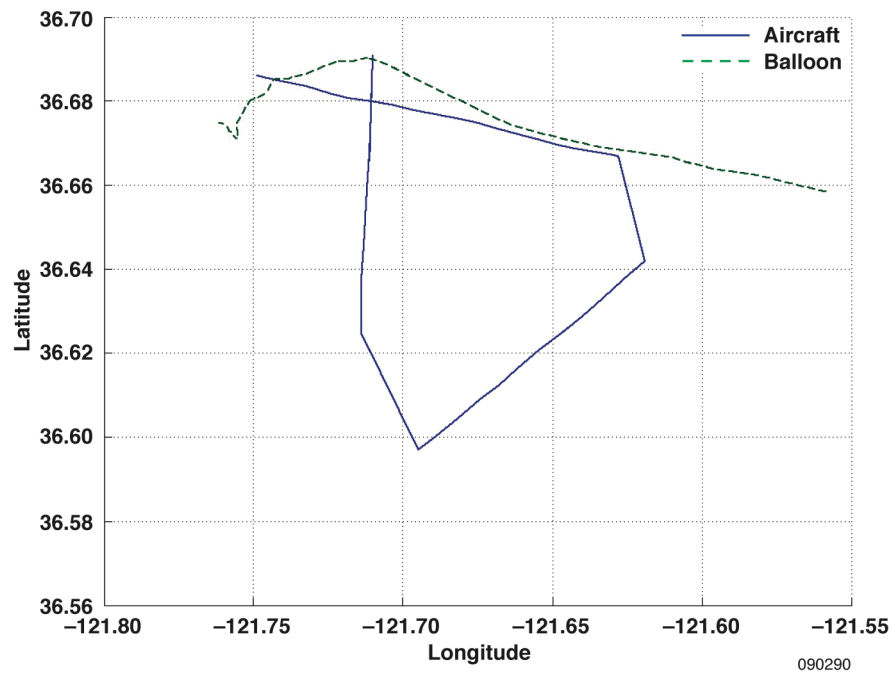

Figure 3. Path of aircraft and balloon on November 16, 2007 for 2000 Z.

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Atmospheric Conditions

Aerosols in the atmosphere are required in order to obtain a return from the lidar. Based on discussions with the CIRPAS lidar operators, aerosol densities were determined to be lower than optimum for November 15, 2007. Weather conditions, such as clouds, also play a role in the clarity of the lidar data. Dense clouds would not allow for the signal to return with an accurate picture of the winds within the layer. The table below lists the conditions for the test days.

Table 1. Weather conditions for November 15, 2007 at 1600 Z, 1800 Z, and 2000 Z.

November 15, 2007	1600 Z	1800 Z	2000 Z
Wind direction	East	Calm	Calm
Wind speed	2.5-5 m/s (5-10 kn)	<1.28 m/s (<2.5 kn)	<1.28 m/s (<2.5 kn)
Sky cover	Overcast near 400 m (1,312 ft)	Clear	Clear with a few high cirrus to the east

Table 2. Weather conditions for November 16, 2007 at 1600 Z, 1800 Z, and 2000 Z.

November 16, 2007	1600 Z	1800 Z	2000 Z
Wind direction	Southeast	Southwest	Southwest
Wind speed	2.5 m/s (5 kn)	2.5 m/s (5 kn)	2.5 m/s (5 kn)
Sky cover	Overcast near 900 m (3,000 ft)	Overcast near 900 m (3,000 ft)	Overcast near 900 m (3,000 ft)

Instrument Issues

There were some initial problems with both the balloon system and the airborne lidar on November 15, 2007. One of the ground telemetry antenna cables for the balloon system had a broken connection, which resulted in the sonde losing signal within seconds of balloon release, once the distance from the antenna increased. The lidar team also experienced technical issues with the lidar during calibration in flight and was unable to obtain an acceptable returned signal. Overall, confidence for the November 15 data return was rated very low and therefore, for the purposes of this study, no data from November 15 will be used. By morning of November 16, both the balloon antenna break and the lidar calibration problem were resolved. Therefore 60 percent of our validating data was lost.

Data Analysis

In order to compare compatible data, all altitudes (balloon and lidar) were converted to geometric height. This conversion results in matching height increments for both the balloon and the lidar data. During a lidar calibration for a following CIRPAS project, it was determined that an error in the lidar processing accounted for the derived altitude being approximately 100 m too high. In a previous lidar and sonde comparison study (ref. 3), it was determined that a 25 m, too low, offset exists between the effective wind response altitude of the balloon and sonde system, and the thermodynamically derived geometric altitude. Accounting for all the offsets, a 75-m correction is subtracted from each lidar profile (fig. 4).

Figure 4. Correction for lidar calibration and balloon offset of effective wind (not to scale).

As a first approach, the November 16, 2007, 1800 Z balloon versus uncorrected lidar height profiles for wind speed and direction are shown in figures 5 and 6. These data represent all the lidar profiles associated with the test time during the balloon ascent. Upon further inspection, the 75-m altitude offset is observed in figure 5 (wind speed) between 1.5 and 2.0 km in altitude. In addition, figures 5 and 6 also show the high uncertainty in the comparison from lidar signal interaction with the thin low clouds. The instrument was unable to acquire consistently usable returns through the cloud layer. Therefore, in most of the returns, the first useful wind observation from the lidar is near 900 m above ground level.
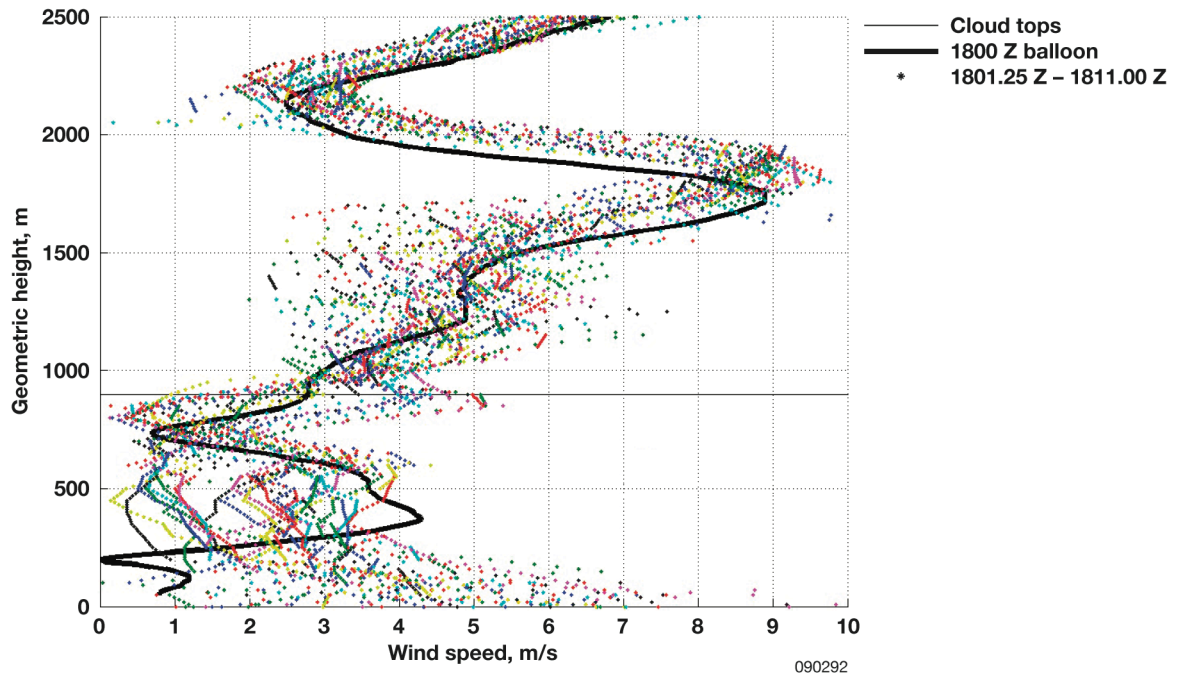
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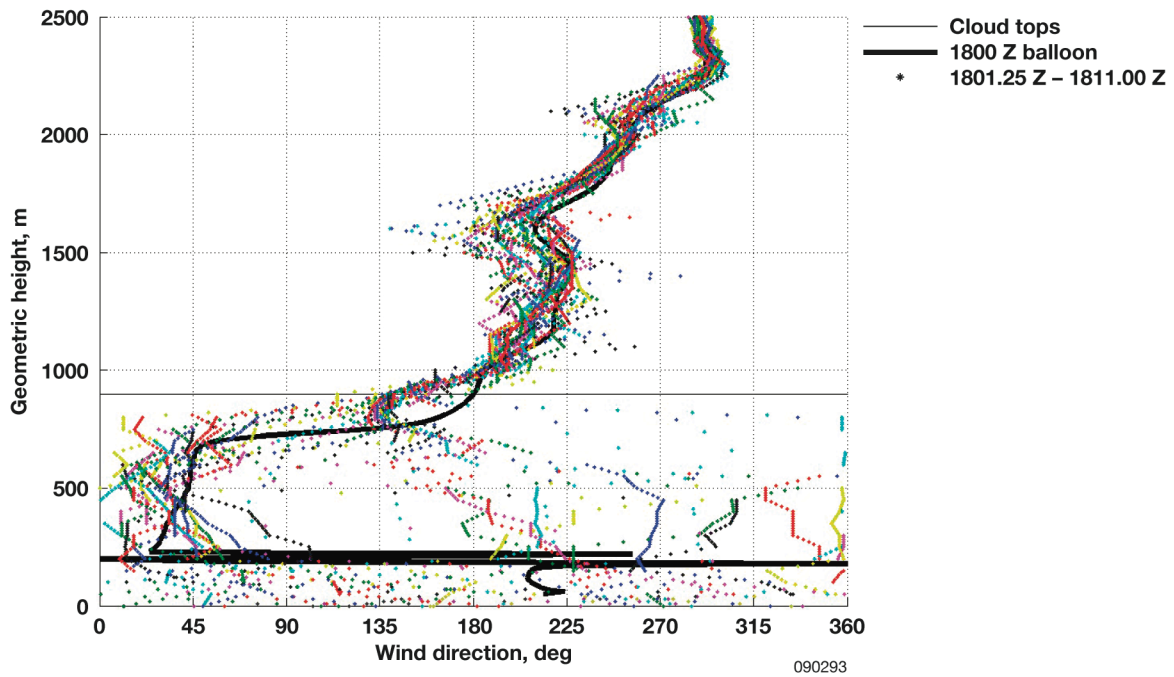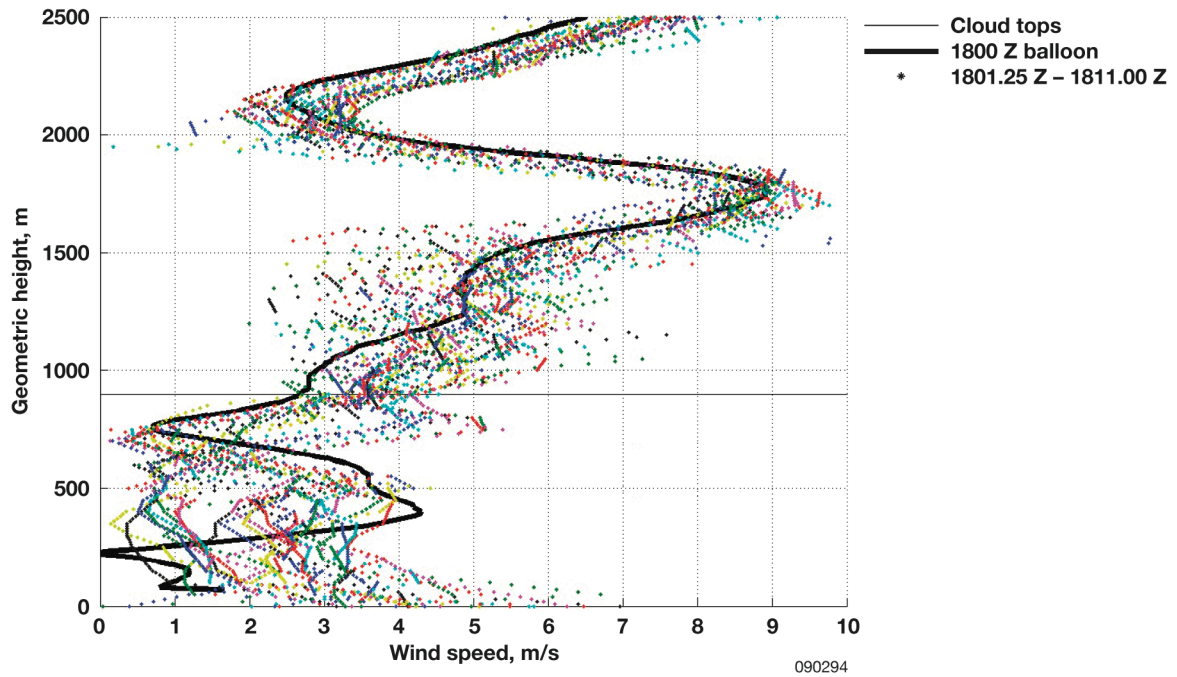Figure 5. Uncorrected lidar wind speed profiles for 1800 Z.

Figure 6. Uncorrected lidar wind direction profiles for 1800 Z.

To correct the data so that each represents the actual geometric altitude, an offset value based on previous analysis and calibration must be applied. These corrected profiles are shown in figures 7 and 8 for November 16 at 1800 Z and in figures 9 and 10 for November 16 at 2000 Z. Figures 7 through 10 better portray how well the lidar profiles compare to the balloon, and upon initial review, the comparison seems to be a good fit to the data. In figures 7 and 8, between 1.0 km and 1.5 km altitude, additional noise due to lack of aerosols is shown. In some cases, depending on power, there are not enough aerosols present to effectively scatter the transmitted energy.

Figure 7. Corrected lidar wind speed profiles for 1800 Z.

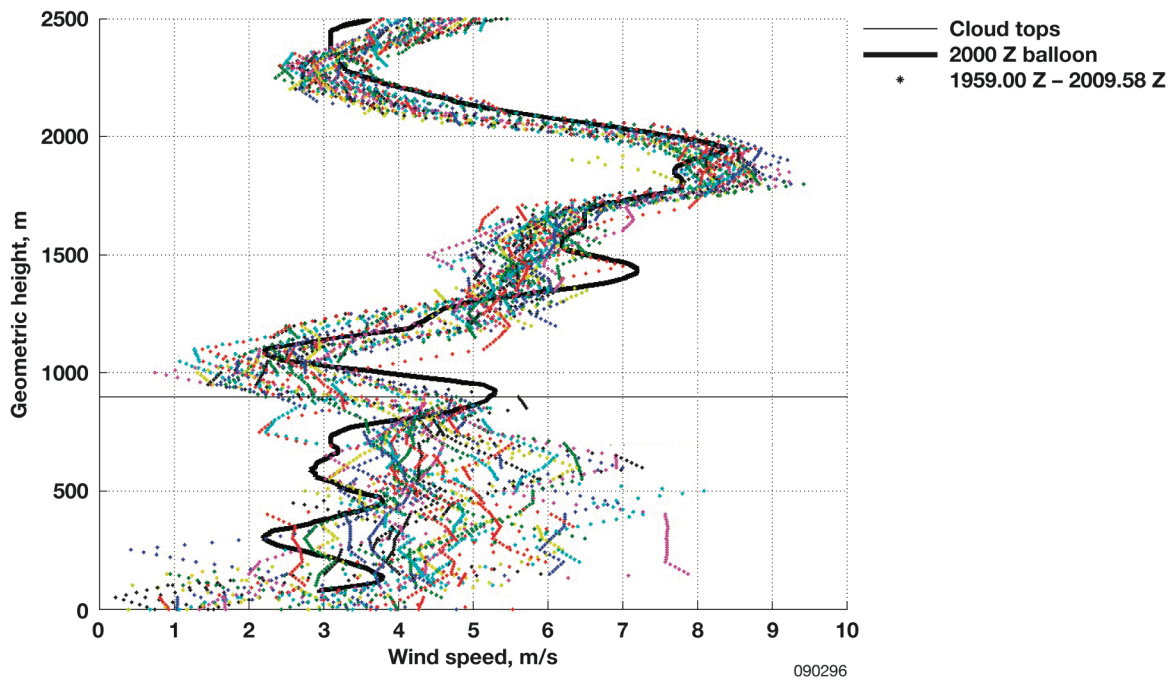Figure 8. Corrected lidar wind direction profiles for 1800 Z.

Figure 9. Corrected lidar wind speed profiles for 2000 Z.
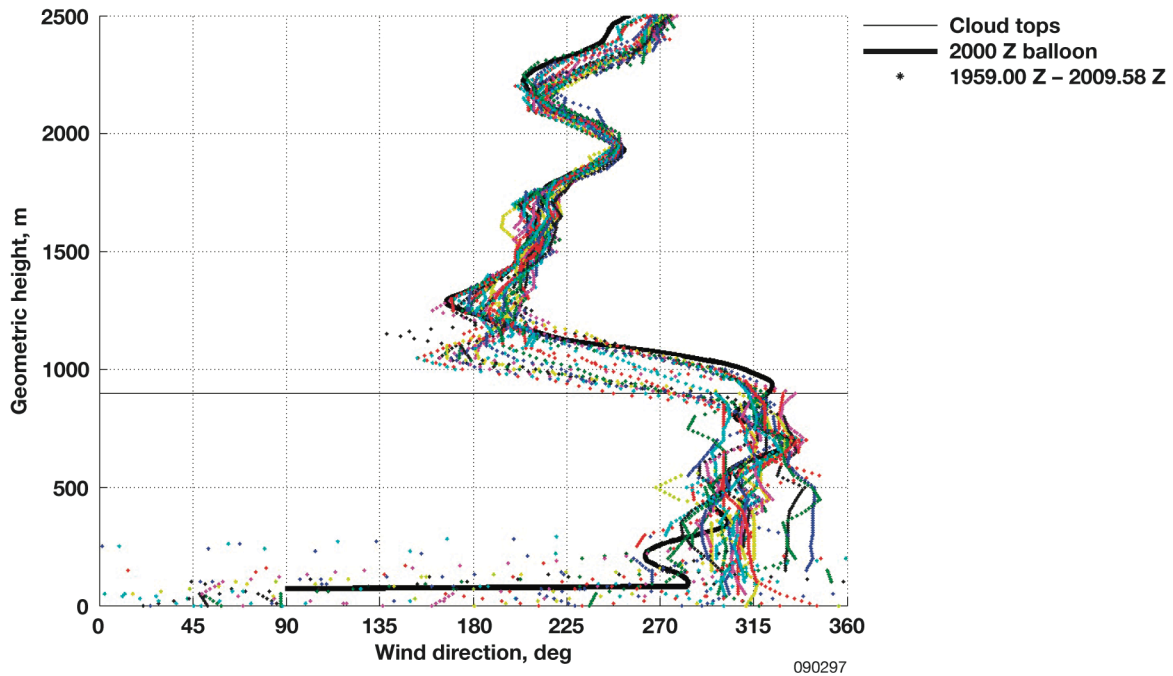
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Figure 10. Corrected lidar wind direction profiles for 2000 Z.

The 1800 Z run consists of 24 profiles in an 11-min period, for a rate of 2.18 profiles per minute, and the 2000 Z run consists of 25 profiles in a 10-min period, for a rate of 2.5 profiles per minute. Although all of this data is good, the high number of lidar profiles becomes a little cumbersome for analysis, especially if the balloon ascent is 20 km instead of 3.0 km. In order to get the best operational usage of the profiles, the data is averaged into fewer profiles, which also allows for a clearer understanding of the winds within the time frame of the balloon ascent. Therefore, approximately every 8-sample profiles were averaged to produce a new and cleaner profile of 5 groupings. The numbers of groupings were dependent on the total number of samples. For November 16, 2007, there are 24 and 25 samples for the 1800 Z and 2000 Z cases, respectively. These groups consist of an overlapping 8-sample average with the second average beginning with the 5th sample (i.e. profile one begins at sample one, profile two begins at sample five, profile three begins at sample nine, etc.). By averaging in an overlapping interval, the data appears to converge closer to the balloon profiles. Figures 11 through 14 illustrate this convergence as compared with the unvaried data. These figures show cohesiveness between all the lidar average profiles, with only a few outliers within the grouping. The wind speed and direction difference between the balloon and each overlapping average profile are displayed in figures 15 through 18. The greatest differences in figures 15 through 18 are 3.5 m/s (6.8 kn) in speed, and 283 deg in direction for 1800 Z, and 3.35 m/s (6.5 kn) and 176 deg for 2000 Z. Excluding the data from the surface to 900 m due to the cloud layers discussed previously, the largest difference is 2.0 m/s (3.8 kn), and 47 deg for 1800 Z, and 3.35 m/s (6.5 kn) and 120 deg for 2000 Z.
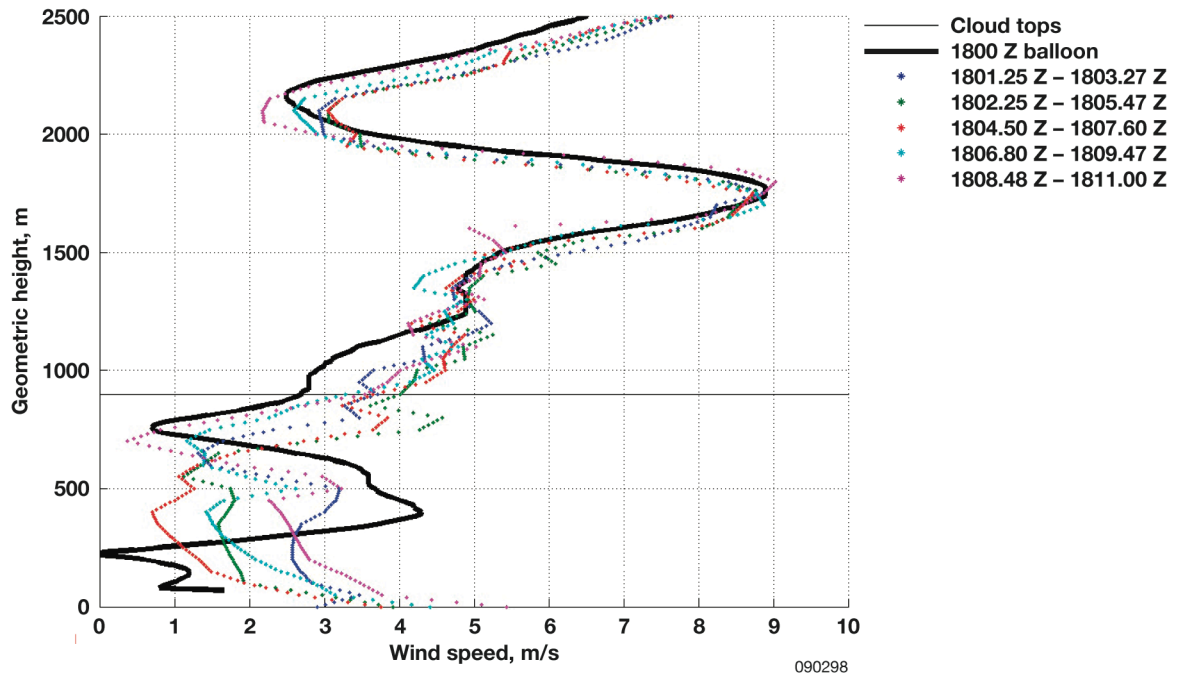
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Figure 11. Five overlapping lidar interval average wind speed with height correction for 1800 Z.
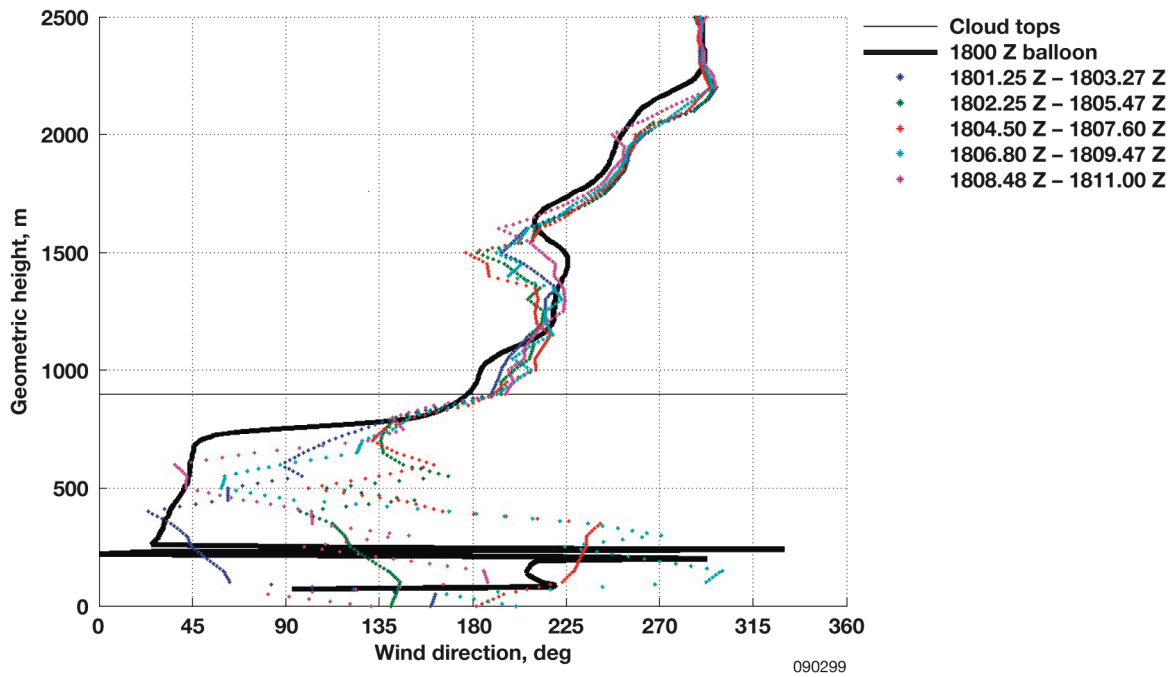

Figure 12. Five overlapping lidar interval average wind direction with height correction for 1800 Z.
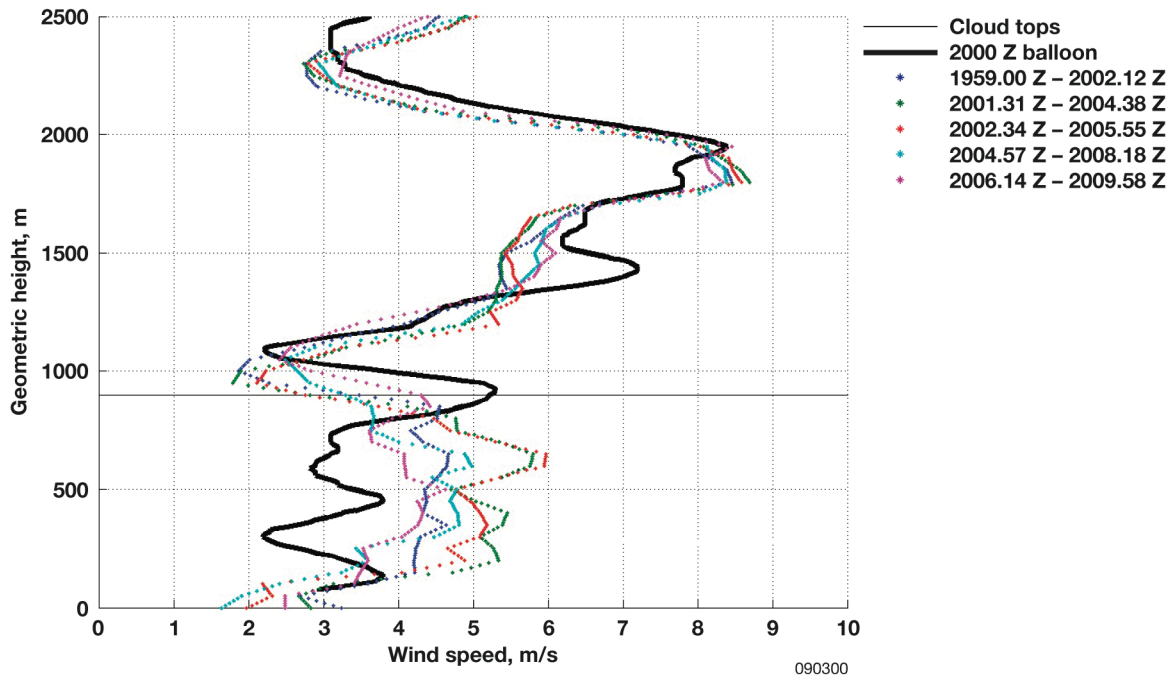
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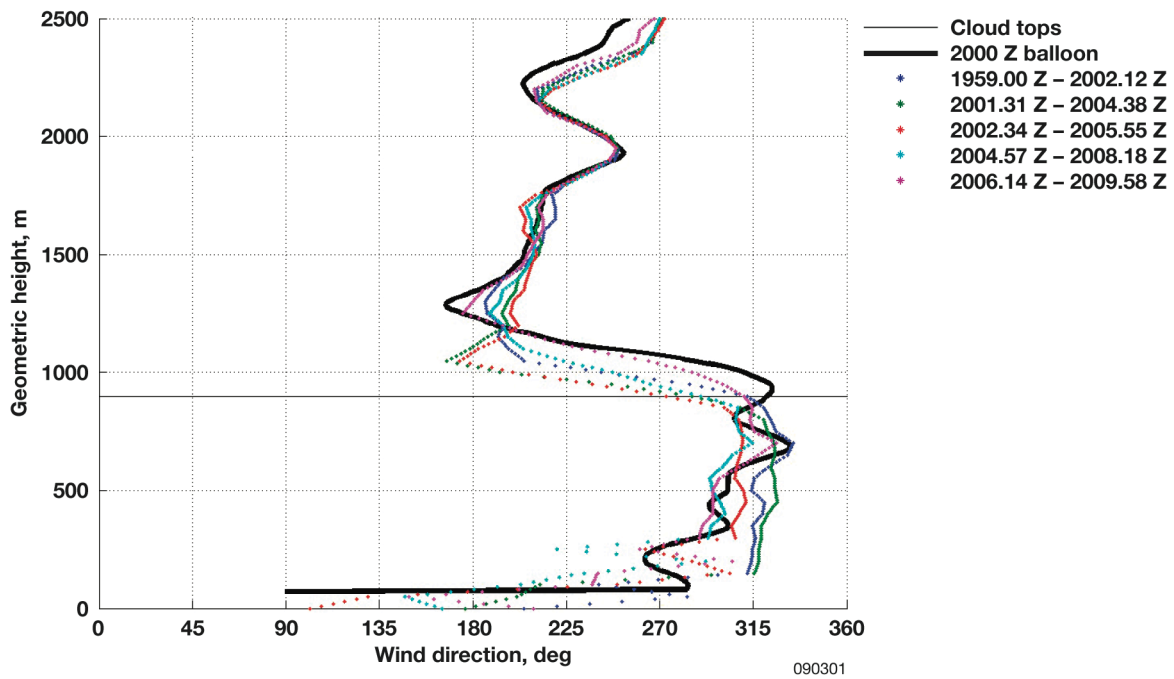Figure 13. Five overlapping lidar interval average wind speed with height correction for 2000 Z.

Figure 14. Five overlapping lidar interval average wind direction with height correction for 2000 Z.
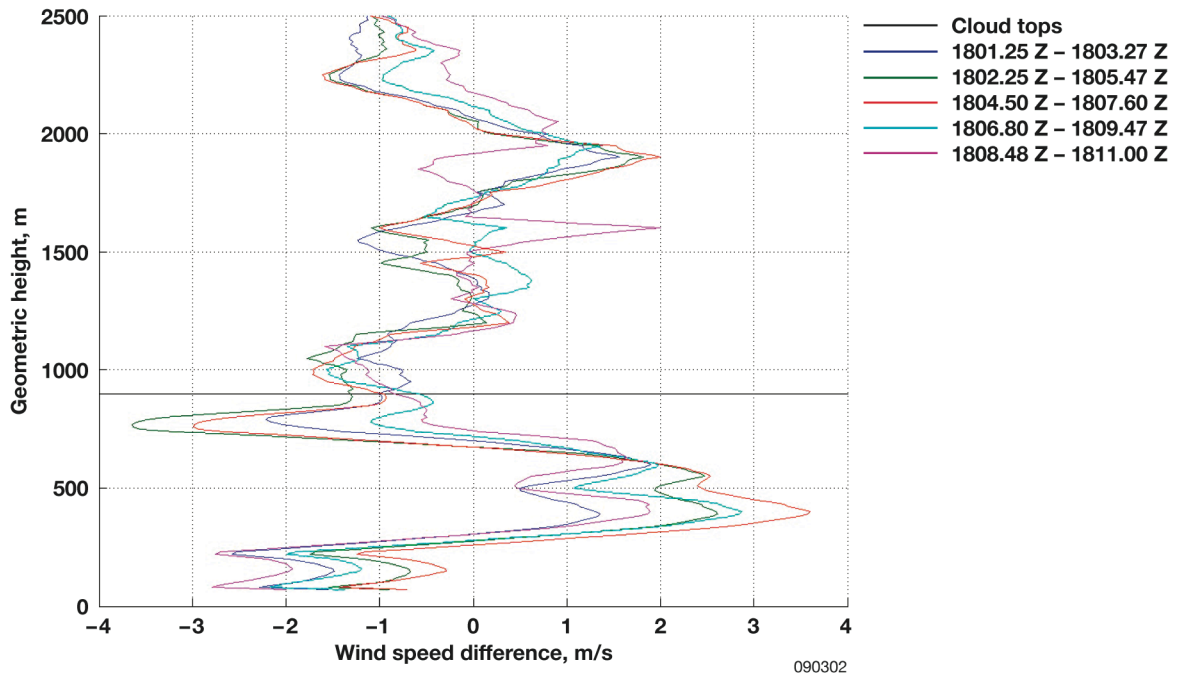
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Figure 15. Difference in wind speed of overlapping average of lidar to balloon for 1800 Z.
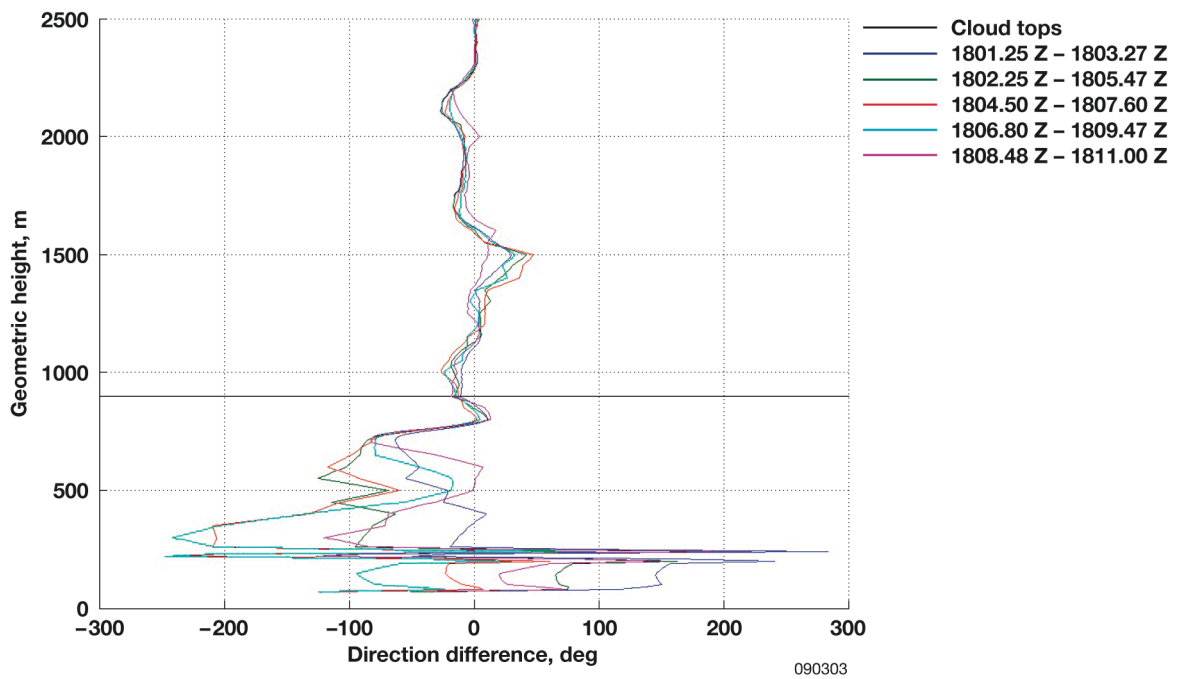

Figure 16. Difference in wind direction of overlapping average of lidar to balloon for 1800 Z.
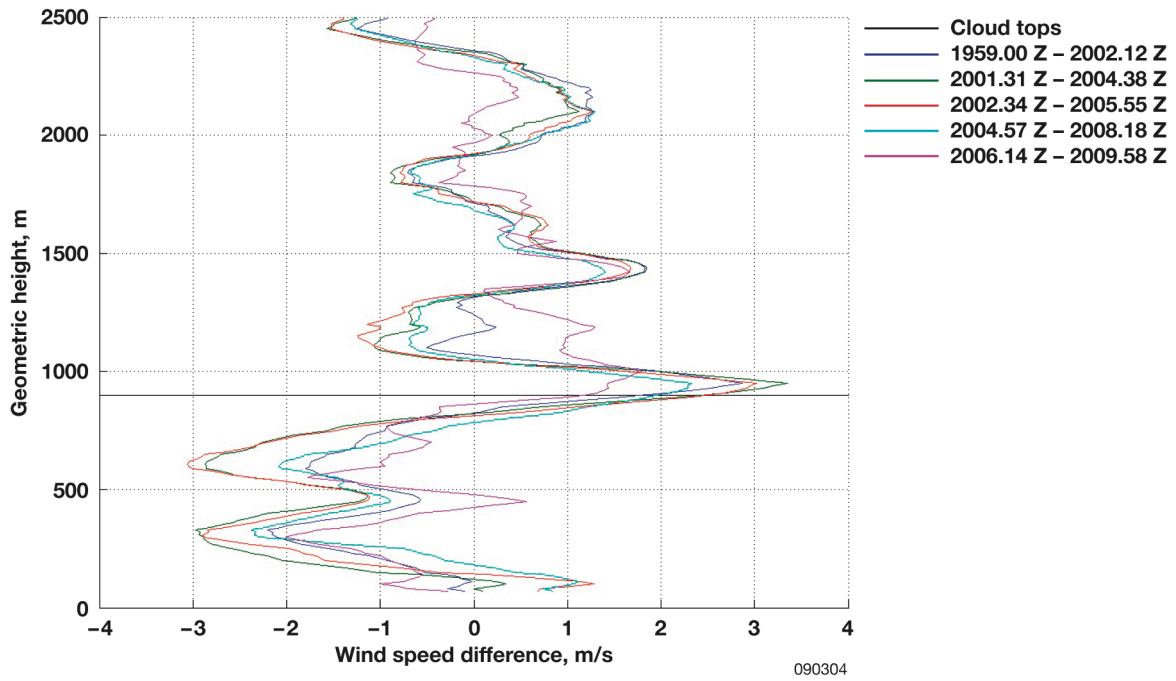
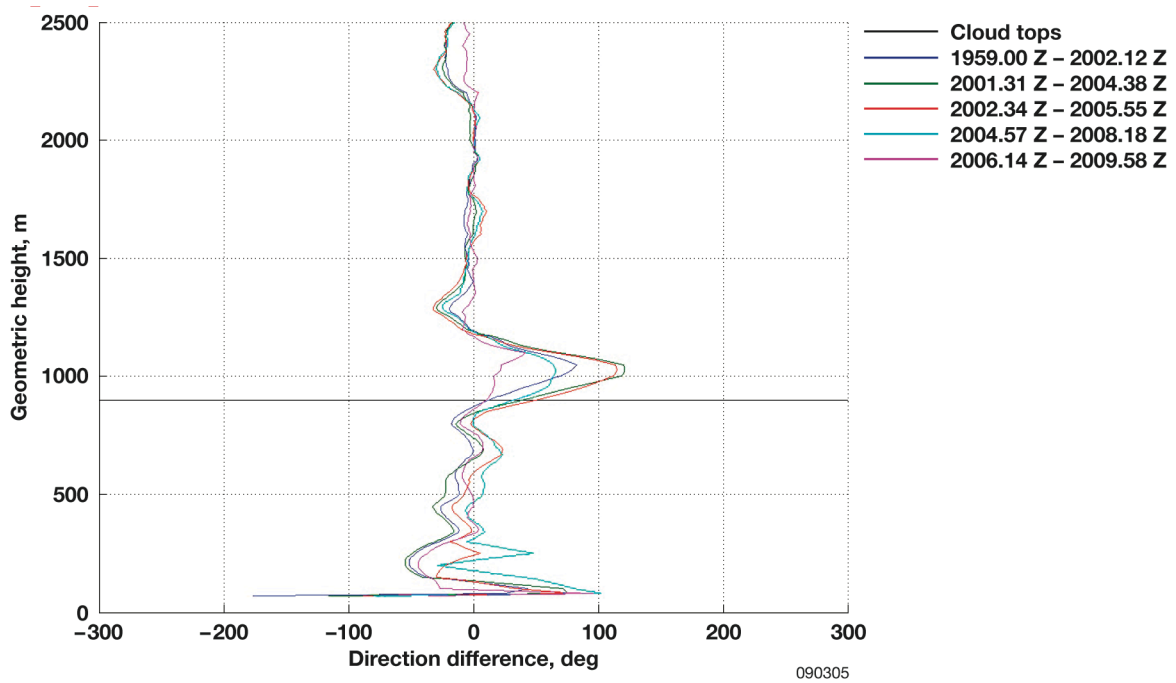Figure 17. Difference in wind speed of overlapping average of lidar to balloon for 2000 Z.

Figure 18. Difference in wind direction of overlapping average of lidar to balloon for 2000 Z.

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An alternative and probably the best approach to analyzing the data was accomplished by averaging all the 20-s sample profiles associated with the balloon ascent interval into one profile and then comparing this profile with the balloon; these comparisons are shown in figures 19 through 22. This method clearly gives the best results between the two methods. Further evaluation of the differences demonstrates that averaging every sample together reduces the uncertainties and smoothes out the high noise. For example, in figures 23 through 26, the magnitudes of the differences are observably smaller than the difference between the 8-sample profiles in figures 15 through 18. The greatest differences, as depicted in figures 23 through 26, are 2.89 m/s (5.6 kn) and 298 deg for 1800 Z, and 2.56 m/s (4.9 kn) and 233 deg for 2000 Z. Excluding low-level cloud layers, the greatest differences are 2.89 m/s (5.6 kn) and 76.3 deg for 1800 Z, and 1.65 m/s (3.2 kn) and 22 deg for 2000 Z. Some differences between the two methods are shown in tables 3 and 4 for 1800 Z, and tables 5 and 6 for 2000 Z. These limited test results indicated a standard deviation wind velocity and direction differences of 0.71 m/s (1.3 kn) and 7.17 deg for 1800 Z, and 0.70 m/s (1.3 kn) and 6.79 deg, outside of the cloud layer (tables 7 and 8).
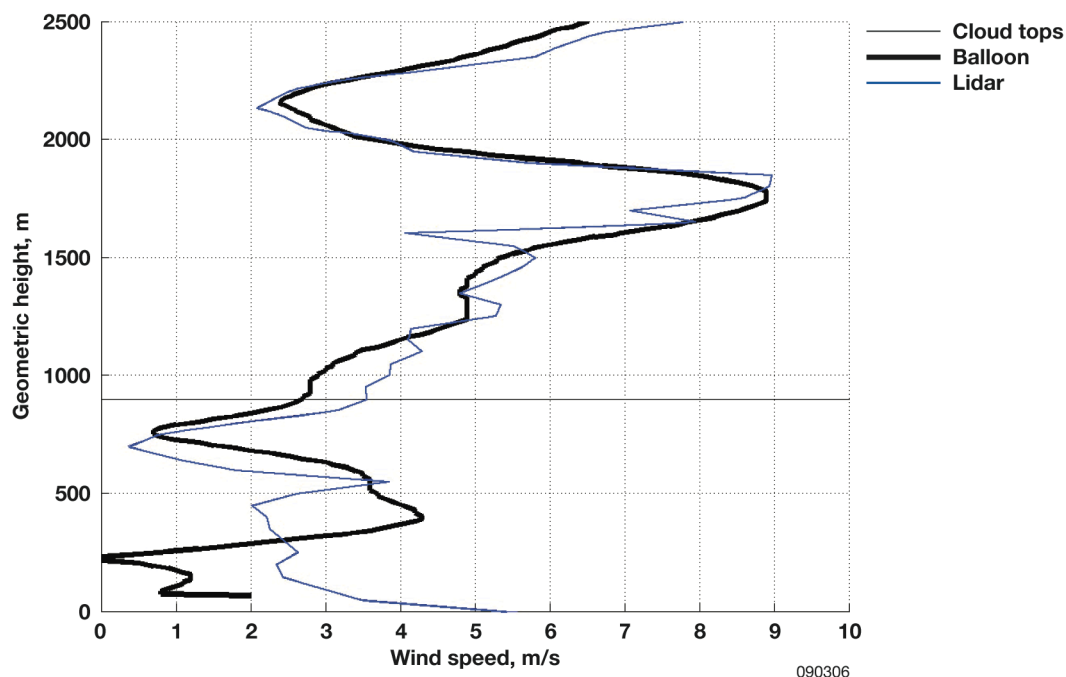

Figure 19. 10-min average of wind speed corrected lidar profiles compared to balloon for 1800 Z.
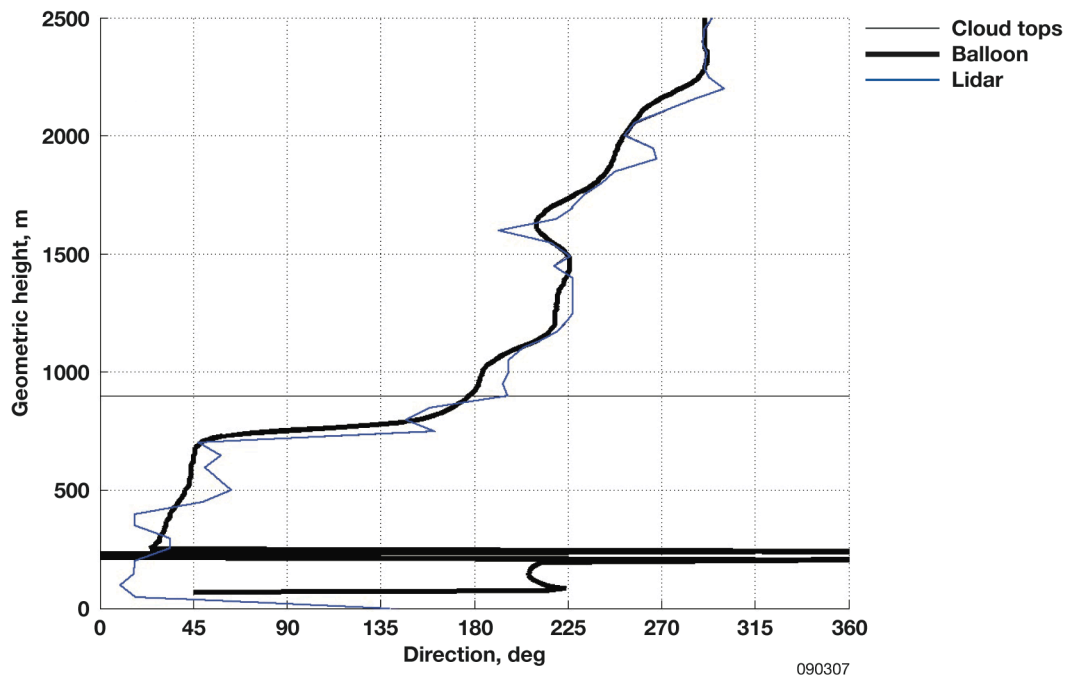
Figure 20. 10-min average of wind direction corrected lidar profiles compared to balloon for 1800 Z.
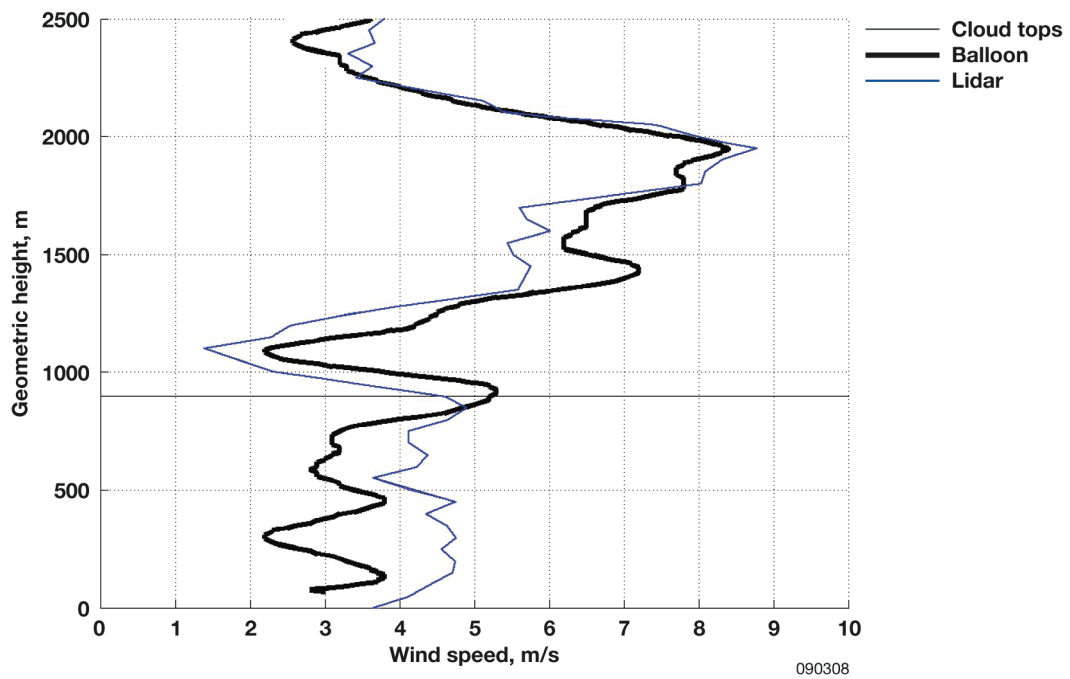

Figure 21. 10-min average of wind speed corrected lidar profiles compared to balloon for 2000 Z.
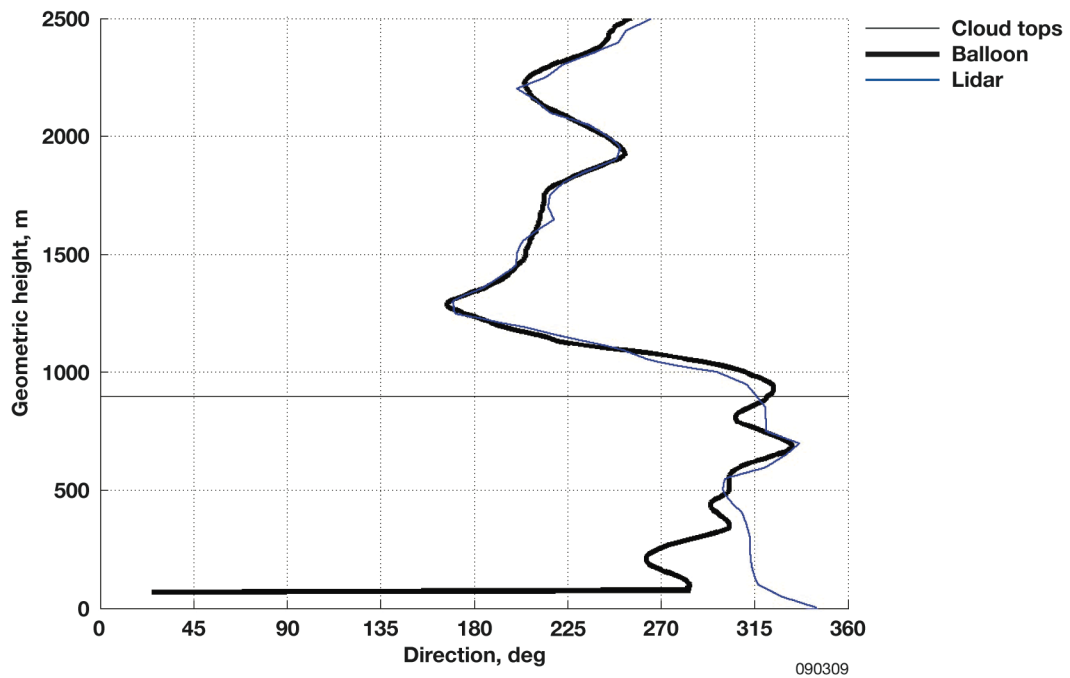
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Figure 22. 10-min average of wind direction corrected lidar profiles compared to balloon for 2000 Z.

Figure 23. Difference in 10-min average corrected wind speed lidar to balloon for 1800 Z.

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Figure 24. Difference in 10-min average corrected wind direction lidar to balloon for 1800 Z.
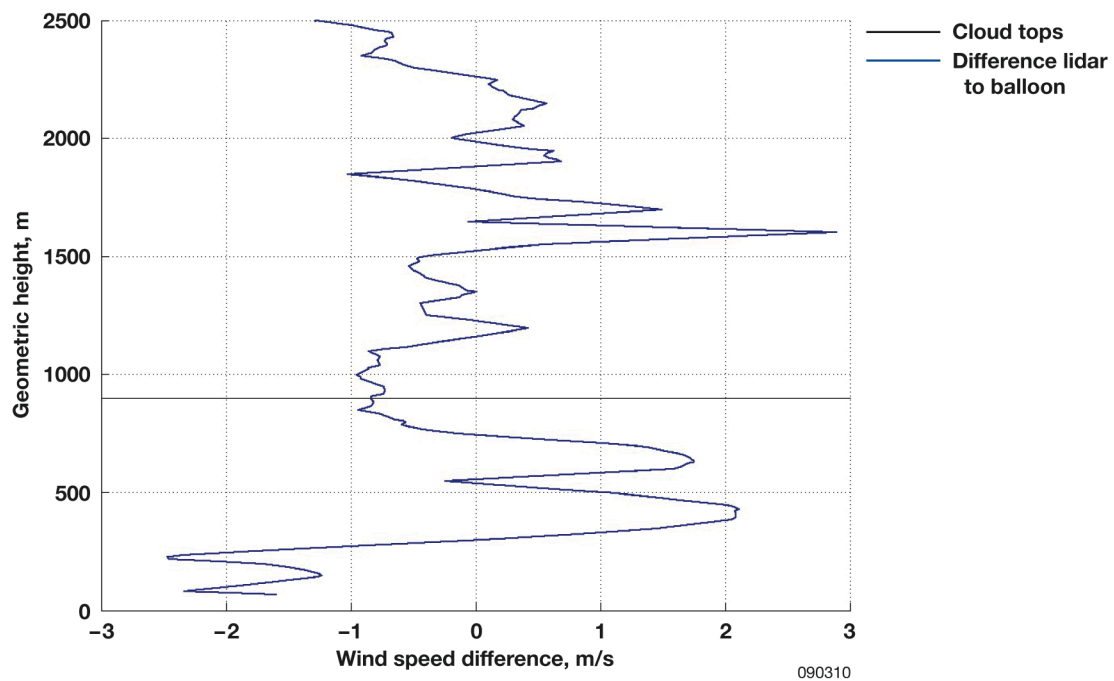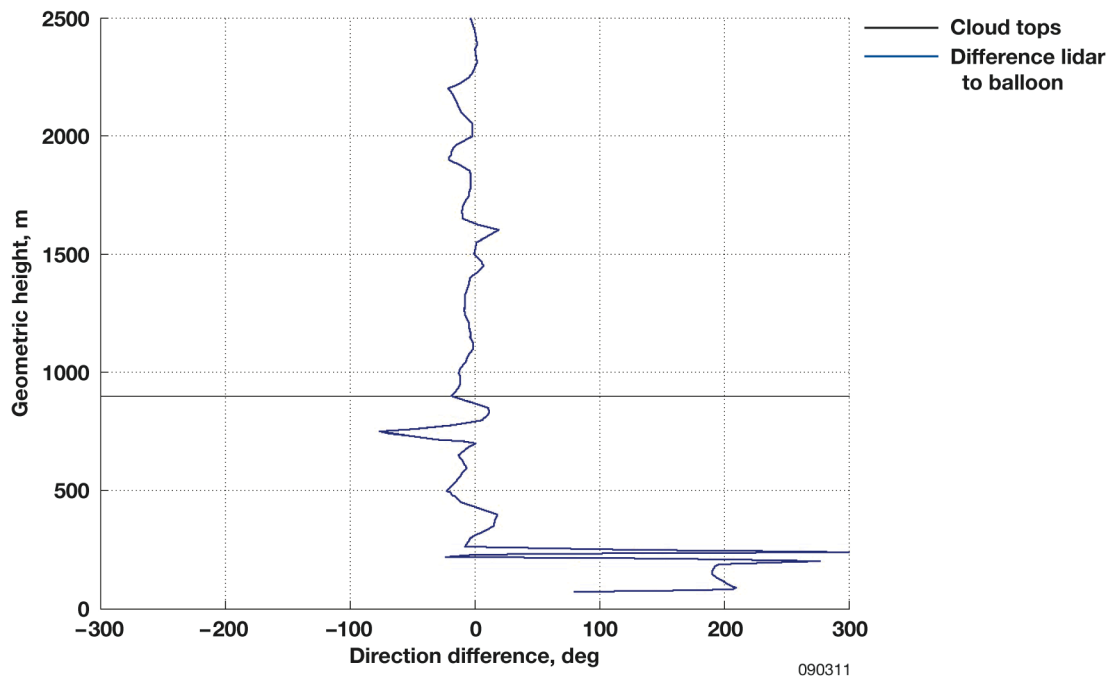

Figure 25. Difference in 10-min average corrected wind speed lidar to balloon for 2000 Z.

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Figure 26. Difference in 10-min average corrected wind direction lidar to balloon for 2000 Z.

Table 3. Speed (m/s) of absolute differences for overlapping average and combined average at 1800 Z.

Altitude, m	Time, Z					
	1801.25-1803.27	1802.25-1805.47	1804.50-1807.06	1806.08-1809.47	1808.48-1811.00	Combined average
500	0.49	1.95	2.39	1.07	0.47	1.09
1000	0.76	1.34	1.71	1.57	1.11	0.91
1500	0.92	0.49	0.35	0.03	0.06	0.44
2000	0.67	0.19	0.24	0.76	0.78	0.18
2500	1.13	1.09	1.11	0.91	0.98	1.30

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Table 4. Direction (deg) of absolute differences for overlapping average and combined average at 1800 Z.

Altitude, m	Time, Z					
	1801.25-1803.27	1802.25-1805.47	1804.50-1807.06	1806.08-1809.47	1808.48-1811.00	Combined average
500	21	68	59	18	1	22
1000	9	16	26	23	13	12
1500	30	42	47	33	11	0
2000	11	8	6	9	4	1
2500	2	4	3	1	1	3

Table 5. Speed (m/s) of absolute differences for overlapping average and combined average at 2000 Z.

Altitude, m	Time, Z					
	1959.00-2002.12	2001.31-2004.38	2002.34-2005.55	2004.57-2008.19	2006.14-2009.58	Combined average
500	0.94	1.29	1.35	1.36	0.59	0.71
1000	1.97	1.93	1.60	1.19	1.79	1.52
1500	1.10	1.17	1.12	0.73	0.47	1.03
2000	0.71	0.27	0.59	0.72	0.19	0.22
2500	0.90	1.25	1.40	1.28	0.44	0.19

Table 6. Direction (deg) of absolute differences for overlapping average and combined average at 2000 Z.

Altitude, m	Time, Z					
	1959.00-2002.12	2001.31-2004.38	2002.34-2005.55	2004.57-2008.19	2006.14-2009.58	Combined average
500	23	30	15	2	0	3
1000	69	118	112	64	16	14
1500	4	6	5	4	3	4
2000	1	2	0	0	0	0
2500	16	16	17	14	7	10

Table 7. Average difference and standard deviation for combined profile at 1800 Z.

	Average direction, deg	Average speed, m/s	Standard deviation direction, deg	Standard deviation speed, m/s
Entire profile	7.89	0.02	54.000	1.00
Excluding cloud layer	5.22	0.08	7.170	0.71

Table 8. Average difference and standard deviation for combined profile at 2000 Z.

	Average direction, deg	Average speed, m/s	Standard deviation direction, deg	Standard deviation speed, m/s
Entire profile	6.26	0.11	19.800	0.99
Excluding cloud layer	0.03	0.41	6.790	0.70

CONCLUSION

Radiosonde balloons have long been the accepted method for determining upper level winds. The use of an airborne lidar can provide significant advantages as a wind measurement sensor over traditional balloons. During the limited testing, the lidar-aircraft system demonstrated station-keeping capability over a theoretical landing site for rapid profiling. More importantly, this activity showed lidars can significantly reduce the amount of time in obtaining a usable wind profile. This particular test showed that viable profiles could be generated about once every 20 s. However, to further increase accuracy, additional single lidar profiles should be incorporated into the average. A balloon to 15 km would require approximately 50 min for ascent, plus about 15 min for processing and delivery. The lidar has demonstrated a 10-min profile retrieval and 5-min processing and delivery, regardless of altitude range. Through this current method, while the balloon could provide one profile, the lidar could produce at least five. Even so, a 10-min sample of between 20 and 25 lidar sweeps virtually reproduce the balloon-measured wind profile, excluding the low cloud layer. These results produced overall mean differences of 0.02 m/s (0.04 kn) and 0.41 m/s (0.79 kn) in speed, and 5.33 deg and 0.03 deg in direction with the standard deviations of 0.71 m/s (1.3 kn) and 0.70 m/s (1.3 kn) in speed, and 7.17 deg and 6.79 deg for the 1800 Z and 2000 Z profiles, respectively. These early results provide encouragement that wind profiling via lidars can be accomplished in a much shorter time, with comparable results, and without drifting that occurs with traditional balloons. While these few samples are encouraging, additional tests (multiple balloon comparisons) should be conducted to refine the process and improve the statistics. Also, these tests should be performed with an airborne laser having more power, a shorter wavelength, and flown at higher altitudes.

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14. ABSTRACT

A comparison study by the National Aeronautics and Space Administration Dryden Flight Research Center (Edwards, California) and the Naval Post Graduate School Center for Interdisciplinary Remotely-Piloted Aircraft Studies (Marina, California) was conducted to show the advantages of an airborne wind profiling light detection and ranging (lidar) system in reducing drift uncertainty along a reentry vehicle descent trajectory. This effort was in support of the once planned Orion Crew Exploration Vehicle ground landing. A Twin Otter Doppler Wind Lidar was flown on multiple flights along the approximate ground track of each ascending weather balloon launched from the Marina Municipal Airport (Marina, California). The airborne lidar used was a 5-mJ, 2-micron infrared laser with a 10-cm telescope and a two-axis scanner. Each lidar wind profile contains data for an altitude range between the surface and flight altitude of 2.7 km, processed on board every 20 s. In comparison, a typical weather balloon would traverse that same altitude range with a similar data set available in approximately 15 to 20 min. These tests were conducted on November 15 and 16, 2007. Results show a best-case absolute difference of 0.18 m/s (0.35 knots) in speed and 1 degree in direction.

15. SUBJECT TERMS
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