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14. ABSTRACT

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Simultaneous Balloon Launches to Investigate Wake Effects on Thermosonde Results

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Simultaneous Balloon Launches to Investigate Wake Effects on Thermosonde Results

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Abstract

The thermosonde is a balloon borne instrument used by the Air Force and other organizations to measure optical turbulence in the atmosphere. A continuing uncertainty has been the effect of the balloon wake on the output of the instrument. Previous attempts to compare the results from a descending instrument to those of a nominal thermosonde have proven difficult and inconclusive. Over the years, the length of the line connecting the thermosonde to the balloon was lengthened until it did not seem to change the results. Since those results were never documented, a study was performed to determine the effect of different line lengths. Simultaneous launches were made with different length lines, and the impact on the thermosonde output was determined. While this experiment provided additional information about the effect of balloon wake, definitive quantification of the wake effects was not possible.

Nomenclature

C_n^2 = Index of refraction structure constant ($m^{-2/3}$)
C_T^2 = Temperature structure constant ($K^2m^{-2/3}$)
d = Horizontal distance: wake to balloon CL (m)
D = Balloon diameter (m)
h = Line length: balloon to payload (m)
P = Pressure (Pa)
S = Horizontal wind shear (s^{-1})
T = Absolute temperature (K)
V_a = Vertical velocity (ms^{-1})

Introduction

Meteorologists have been monitoring the atmosphere with balloon-borne radiosonde instruments for decades. It has been known for some time that a rising balloon leaves behind a wake that can affect turbulence measurements. Barat[1] and coworkers caution experimenters that wake problems are more likely in low shear conditions. They derive the following expression for distance, d, between the wake centerline and point a distance ***h*** directly below the balloon, assumed to be the payload position, given a constant shear, ***S***, and a constant rise rate, V_a:

$$d = {Sh^2}/{2V_a} \qquad (1)$$

They also give the criterion, that if the diameter of the balloon velocity disturbance wake is assumed to be twice the balloon diameter, ***D***, (considered conservative for h/D ~ 20) than the possibility of payload interaction with the wake is very low if ***d > 2D***. Using this criterion, they discount high turbulence readings when ***d*** is less than ***2D***, and one can determine the minimum shear for acceptable data:

$$S_{\min} = 4V_aD/h^2 \qquad (2)$$

Tiefenau and Gebbeken discovered that the temperatures measured below a rising meteorological balloon were higher than those measured below a descending parachute during the day, and that the situation was reversed at night[2]. They performed thorough thermodynamic and heat transfer analyses of the system and developed the thermal properties of the wake. Their balloons were filled with hydrogen, which has a specific heat ratio that is nearly the same as air. Except for adiabatic and super-adiabatic atmospheres, rare above the surface layer, the balloon gas always cools faster than the surrounding atmosphere. This is especially true in the stratosphere. The colder balloon gas cools the balloon skin, which then cools the air flowing over the balloon. At night, the thermal wake flowing behind the balloon above the surface layer is always cooler than the surrounding air. In the daytime, the radiant heat flux from the sun exceeds the rate of heat absorption by the expanding hydrogen, thereby producing a wake that is warmer than the surrounding air.

AFRL thermosondes are carried aloft by balloons filled with helium instead of hydrogen. Helium, with a specific heat ratio that is larger than air, will always cool faster than hydrogen, and will result in nighttime wake temperatures that are even cooler than those produced by a hydrogen filled balloon.

Since 1971, optical turbulence research has been conducted using the Thermosonde[3,4], which ascends into the atmosphere attached to radiosondes. While there have been concerns of contamination of radiosonde data from the balloon wake, the concern is even more intense for the Thermosonde[5]. The Thermosonde uses two very fine wire resistance probes to measure the temperature difference across a 1m horizontal distance, performs a 4 to 8 second running average of that difference, and transmits the value back to the ground station along with the meteorological data from the radiosonde. As the thermosonde developed, researchers began making the line to the balloon longer and

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longer until the results did not seem to be sensitive to increasing length. This was not performed in any systematic way and results were never reported.

Since ascending balloons leave a wake behind them, and it is hard to imagine that the payload does not occasionally enter the wake region, there are concerns as to the impact of the wake on the results. There have been attempts to make the measurements in descending flight to avoid the wake problem. Early attempts with a small parachute did not work well. Increasing atmospheric density causes the parachutes to decrease in velocity as they descend, and there is a concern about pendular motion under a small parachute. In 1999, there were attempts to descend with an under-inflated balloon, but that experiment failed because of extreme sensitivity of descent velocity to the amount of balloon under-inflation.

In 1999 two experiments were proposed to obtain temperature fluctuation data without the presence of a wake. One proposal was to instrument a ring that is large enough to be outside of the balloon wake. It has been difficult to get sufficient stiffness in the ring while keeping the total weight within FAA guidelines for an uncontrolled balloon. That effort has come to fruition this year[6]. A second proposal was to use a large, research balloon to carry a large array of temperature sensors aloft, and acquire data during the controlled descent[7,8] portion of the flight. This "Microturbulence" experiment had the goal of measuring multiple structure functions from 10m down to centimeters, which were used to determine the characteristics of the fluctuating temperature structure functions[9]. A Thermosonde was mounted in the center of the structure pointing down to serve the dual purpose of measuring C_n^2 using a traditional instrument and collecting coincident meteorological data. An additional benefit was that this experiment might provide thermosonde data in a wake-free configuration. By flying normal Thermosondes at times near the Microturbulence descent, there would be a basis for comparing nominal ascents to wake free conditions. While the amount of suitable descending data was limited, a comparison showed that the ascending thermosonde had a larger number of small turbulence spikes in the troposphere, which only contributed less than 2% to the integrated C_n^2 in the region[10]. Unfortunately, a reliable comparison could not be made in the stratosphere because of apparent flow interference.

In that study, a methodology was developed to study the wake interference problem. The thermosonde output was first examined so that each turbulence layer or "spike" was analyzed to determine the maximum turbulence value in the spike. Both C_T^2 and C_n^2 were used as strength parameters. The spike statistics were put into a database that could be queried for different altitude bands in the flight. The resulting spike "heights" or magnitudes were then put into histograms of spike height.

Following the lead of Tiefenau and Gebbeken, the wake problem was further investigated in an experimental and theoretical study of balloon wake temperatures[11]. Theoretical and experimental studies showed that the temperature difference between balloon skin and air temperature was about 6 times worse in the stratosphere than in the troposphere, as shown in Figure 1. Encounters with the wake in the stratosphere could be detected with fast acting "micro-bead" temperature sensor. The smaller wake temperature difference in the troposphere proved too weak to be detected by the sensors. Based on limited data in predominantly low turbulence conditions, wake encounters were seen to become more prevalent in conditions when the overall turbulence level was low as shown in Figure 2. This is probably because lower turbulence was usually seen in lower shear conditions.

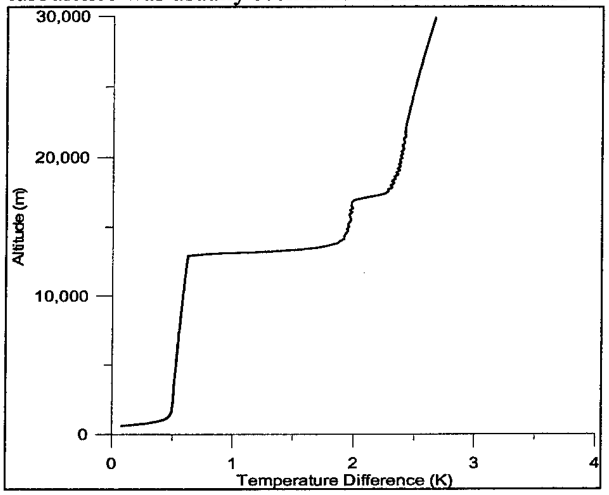

Figure 1. Difference between balloon skin temperature and atmospheric temperature for a atmospheric with a tropopause region extending from 13km to 17km[11].

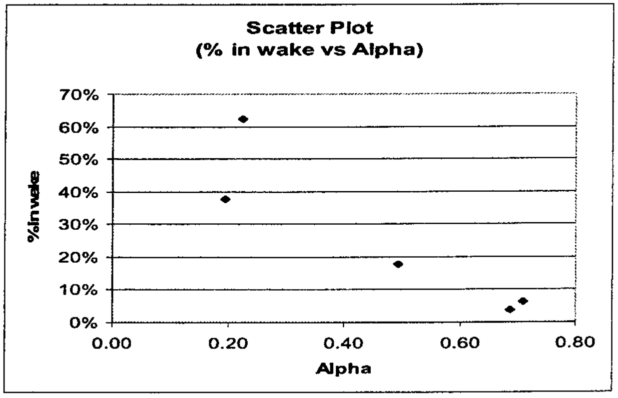

Figure 2. Scatter plot of the percent of the integrated C_n^2 profile contaminated by the wake vs. Alpha, the ratio of the integrated C_n^2 column to Clear 1, for the five flights with analyzable data.

This paper reports efforts to further investigate the wake problem through systematic variation of line length. As discussed above, Barat *et al* suggested a minimum shear criterion for avoiding wake encounters. That criterion was applied three different line lengths in Figure 3, along with a plot of the shear deduced from the wind profile of a rather low-shear atmospheric condition (from HMNSP014). The solid smooth line going through the highly variable shear profile is for the standard line length of 110m. The dashed line closer to the y-axis if for 160m, and the dashed line further away from the y-axis is for 30m. For this flight condition, there might be several times that the shear would be below minimum for the standard line, while the 160m line would result in the shear being above minimum for most of the flight, and the 30m line would result in the payload being in the wake for most – if not all of the flight. Note that as the balloon rises, the diameter increases, which causes the minimum shear value to increase.

Several nearly simultaneous thermosonde launches were made with different line lengths to compare the results.

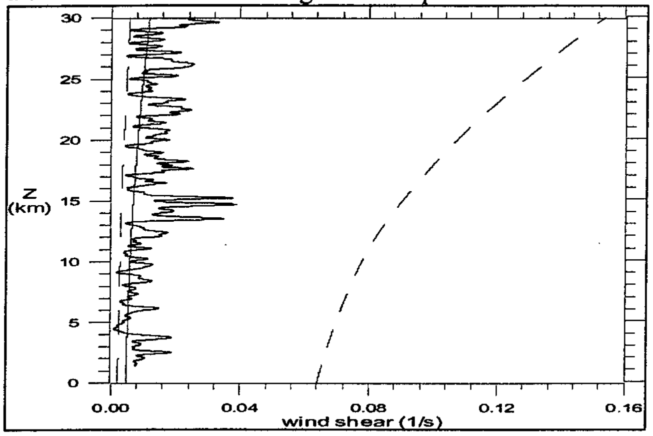

Figure 3. Minimum shear values for 160m (left dashed), 110m (solid) and 30m (right dashed) line lengths for a typical rising balloon. The highly variable actual shear profile for a fairly low-shear flight (HMNSP014) is also shown.

The Experiments

In 2001, AFRL/VSBL acquired a second Väisälä ground station, which presented the opportunity to receive data from two Väisälä equipped thermosondes at the same time. Beginning in April 2001, a series of thermosonde flights began at Hanscom AFB, MA to investigate the effect of line length on the output of the instrument. For each test, two balloon-borne thermosondes were launched within minutes of each other. Both balloons carried thermosondes attached to radiosondes of basically the same configuration, except that the line to the balloon was the standard 110m for one instrument and a different length for the other. In May 2001, two pair of flights were conducted in the lee of Mt. Washington, in Bartlett, NH. These flights, which all had the standard 110m-line length, served as a control for dual launch experiments. In March 2002, one dual launch was flown at Vandenberg AFB. Finally, in May 2003, a pair was flown at Holloman AFB, with one having a line length of 160m, and the other had a length of 110m. The flight dates, line lengths and launch times are listed in Table 1.

Table 1. Listing of dual flights.

Place	Flight #	Date	Time LT	Line (m)
Hanscom AFB, MA	HA1SP002	4/29/01	19:39	110
Hanscom AFB, MA	HA2SP002	4/29/01	19:41	30
Hanscom AFB, MA	HA1SP004	4/30/01	19:45	110
Hanscom AFB, MA	HA2SP004	4/30/01	19:46	10
Hanscom AFB, MA	HA1SP005	5/10/01	20:01	110
Hanscom AFB, MA	HA2SP005	5/10/01	20:02	10
Bartlett, NH	NH_1	5/31/01	21:08	110
Bartlett, NH	NH_2	5/31/01	21:09	110
Bartlett, NH	NH_3	5/31/01	23:00	110
Bartlett, NH	NH_4	5/31/01	23:05	110
Vandenberg AFB, CA	VANWN009	3/01/02	18:01	110
Vandenberg AFB, CA	VANWN010	3/01/02	18:03	30
Holloman, NM	HMNSP014	5/28/03	20:02	160
Holloman, NM	HMNSP015	5/28/03	20:05	110

Analysis and Results

Spike Histogram Analysis

Following technique described in an earlier paper (Ref. 10), the effect of the wake was first examined by comparing histograms of the magnitude of the local maxima in the C_T^2 profiles, referred to spike sizes. In Reference 10, there was an apparent trend toward the wake causing a higher number of lower magnitude spikes in the troposphere and causing a higher number of larger magnitude spikes in the stratosphere. This logic complimented the results of the thermal analysis discussed in Reference 11. In that study, it was determined that the difference between balloon temperature and air temperature was greatest in the stratosphere, thereby producing the stronger wake thermal turbulence in that region. Following that logic, we expected to see similar trends with the shorter line causing more spikes than the longer line, and that the wake induced spikes would be of lower magnitudes in the troposphere and of higher magnitudes in the stratosphere. This trend is still apparent in the long – short line tests, but is seen to be a guide or trend rather than a hard and fast rule.

Take, for instance the result of two pairs of runs shown in Figures 4 and 5. Flights HA1SP002 with a 110m line and HA2SP002 with a 30m line, are shown in Figure 4 on the left side of the page. The longer line flight of this pair exhibited a large number of smaller spikes, which I would have associated with tropospheric wake encounters. Uncharacteristically, the smaller spikes persist right up through the stratosphere, which indicates that they could actually be the result of circuit noise. The shorter line does not seem to show any aberrations in the lower 12km, but larger spikes become prevalent, especially in the 18 to 24km altitude range. As we move into the final altitude range, 24 to 30km, the longer line begins to exhibit an increase in the larger spike sizes which is probably an increase in the number of wake encounters as the balloon diameter creates an even larger wake region.

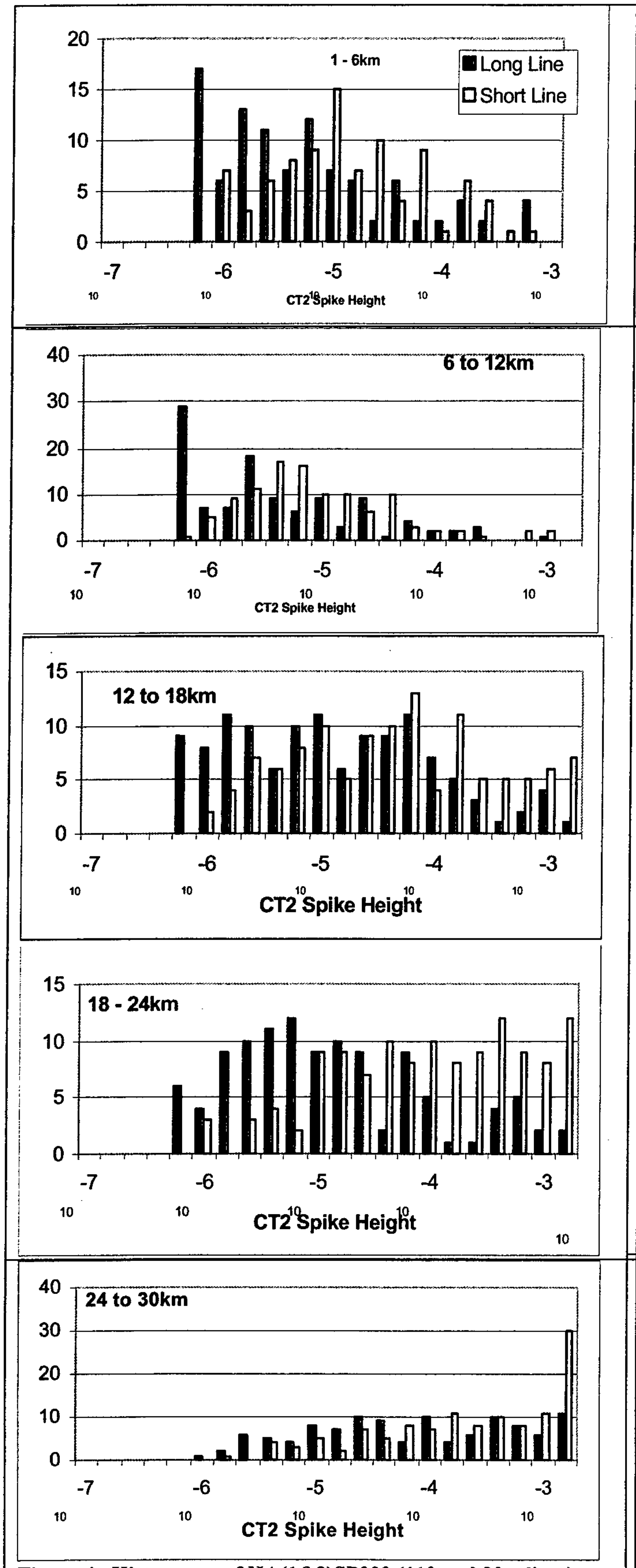

Figure 4. Histograms of HA(1&2)SP002 (110 and 30m lines)

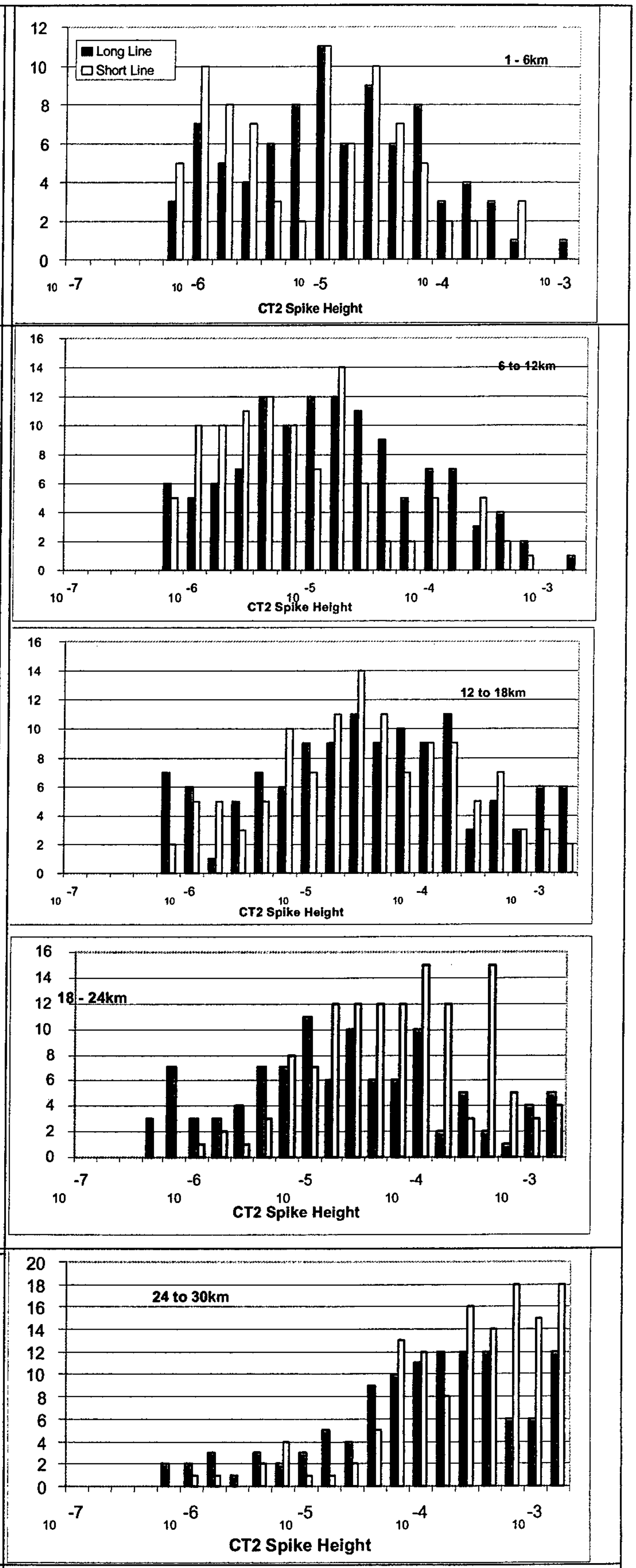

Figure 5. Histograms of HAXSP004 (110m and 10m)

Flights HA1SP004 and HA2SP004, shown in Figure 5, had line lengths of 110m and 10m respectively, and exhibited results that are closer to the expected response. The shorter line had more small spikes in the troposphere and more of the larger magnitude spikes in the stratosphere. Again, even the long line exhibits more of the larger magnitude spike activity in the final altitude range, probably due to wake encounters.

Mean values of C_T^2 and C_n^2 for 1km altitude bins

To put these results into better perspective, we examined the dual flights with arithmetic mean values of C_T^2 for each km of the flight. These results are shown in Figures 6 and 7. These results more closely follow the expected result in that the shorter line exhibits more average temperature turbulence than the longer lines. While there were more small spikes for the longer line flight, they did not seriously affect the integrated value of the turbulence.

An even better perspective is to rank the results in terms of their effect on optical performance. Optical performance is generally expressed by different weighted integrals of the C_n^2, the structure constant of the fluctuations of index of refraction (See Appendix of Ref. 11). Again, I have used the arithmetic mean over 1km bin sizes, which represent integrations with a weighting factor of 1. The results of these two runs are shown in Figures 8 and 9. Since C_n^2 is obtained from C_T^2 by multiplication with a factor that includes P^2/T^4, the exponentially decreasing atmospheric pressure rapidly decreases the impact of any aberrations of C_T^2 at higher altitudes. This probably explains why the apparent increase in the number of wake encounters above 25km was not noted earlier.

While the earlier trend of higher values of turbulence being associated with shorter lines is evident in these arithmetic averages, some of the altitude bins have the opposite results. The nature of these flights is such that it is very difficult to make any statement about the cause of these anomalous results. While it could have been caused by more wake encounters by the longer line in those regions, or it might be that the instrument was in a more turbulent region. Even thought many of these pairs were launched within seconds of each other, slightly different ascent rates result in differences in the trajectory loci that increase over time.

The 1km mean C_T^2 and C_n^2 for the Vandenberg AFB flights are shown in Figures 10 and 11. This pair generally exhibit closer to the expected result of the shorter line showing more turbulence and that the effect gets worse as the balloon approaches the higher altitudes; however there are exceptions.

A final comparison of interest is the resent Holloman pair, HMNSU014 and HMNSU015. The C_T^2 bins are shown in Figure 12, the C_n^2 bins are in Figure 13. This pair had line lengths of 160m and 110m. Theoretically the 160m line is only half as likely to encounter a wake as the 110m. While the mean turbulence values are lower for the 160m than the 110m results overall, sometimes the longer line values are higher than the shorter, and sometimes the shorter line are much worse than the longer line, especially at the higher altitudes when wake encounters are more prevalent. As shown in Figure 3, the winds were so low for these flights that shears were below minimum many times for the 110m line, and wake encounters may have dominated these generally lower turbulence levels.

The two pairs of flights in Bartlett, NH were a "control" for the dual flight methodology. For these flights, the line lengths for each pair were the standard 110m. This particular campaign had very high turbulence levels, especially at the lower altitudes, as shown in Figures 14, 15, 16 and 17. The jet stream was right over the region, and the launch site was directly in the lee of Mt. Washington. The shear levels were high during a lot of the flights, as shown in Figure 18. In spite of these conditions, the C_T^2 levels for the flight pairs are reasonably similar. The low altitude turbulence was so severe for these flights, that I have also provided semi-log plots of C_T^2 so that the low altitude values do not overwhelm the high altitude values. No two altitudes have equal values, and some vary more than others, but the general agreement is not bad. The mean variance of C_T^2 was 50% for the first pair and 37% for the second pair. There was only a slight bias in the pairs: the first pair had a mean difference of less than 2% of average C_T^2, the second pair had less than 0.02%.

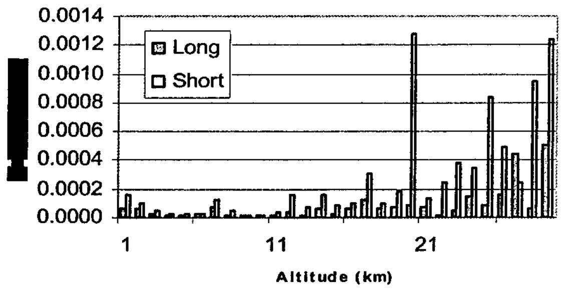

Figure 6. Arithmetic mean values of C_T^2 for 1km bin sizes for Flights HA1SP002 and HA2SP002. Bins are labeled by the value at the minimum altitude of the bin.

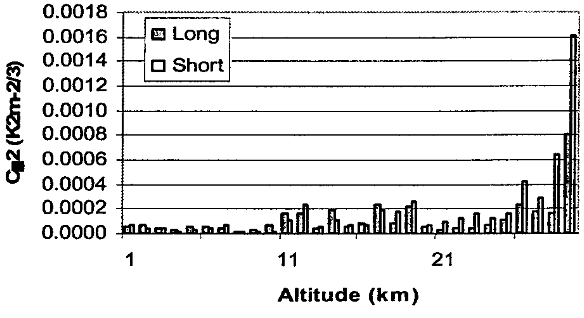

Figure 7. Arithmetic mean values of C_T^2 for 1km bin sizes for flights HAXSP004.

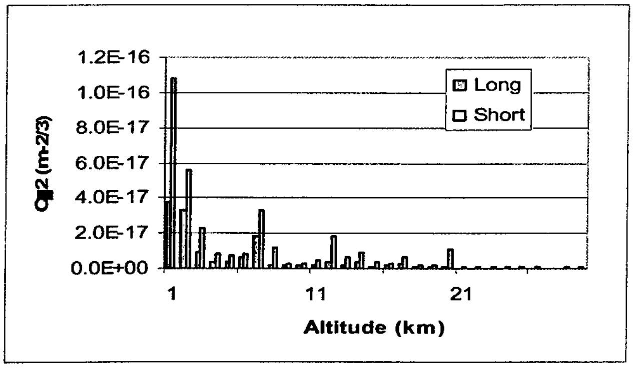

Figure 8. Arithmetic mean values of C_n^2 for 1km bin sizes for flights HAXSP02.

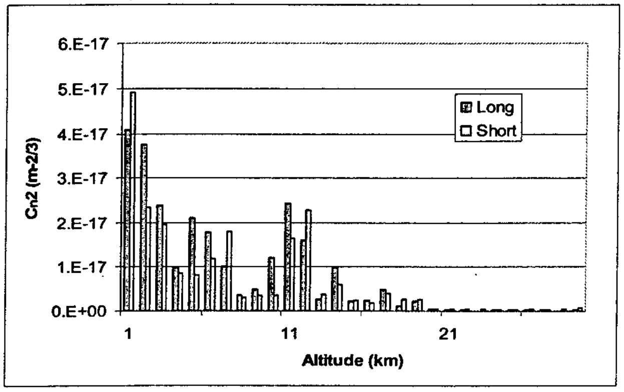

Figure 9. Arithmetic mean values of C_n^2 for 1km bin sizes for flights HAXSP04.

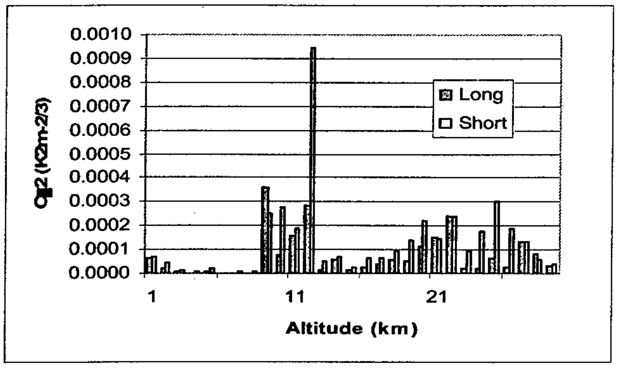

Figure 10. Arithmetic mean values of C_T^2 for 1km bin sizes for flights VANWN009 and VANWN010.

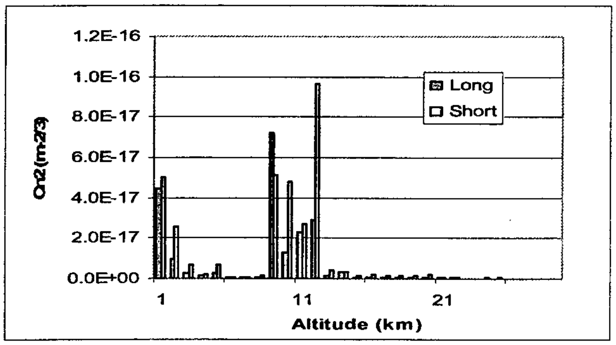

Figure 11. Arithmetic mean values of C_n^2 for 1km bins for flights VANWN009 and VANWN010

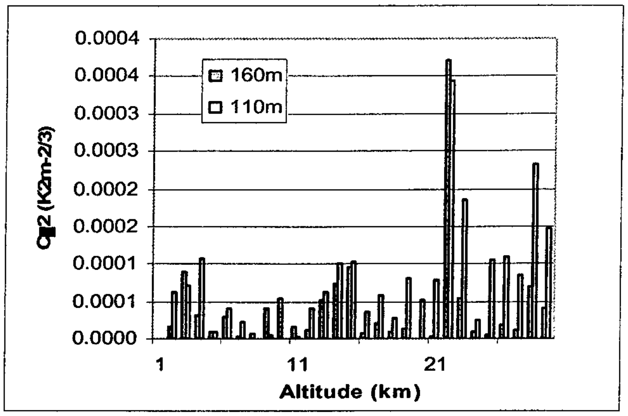

Figure 12. Arithmetic Mean values of C_T^2 for 1km bins for flights HMNSP014 and 015.

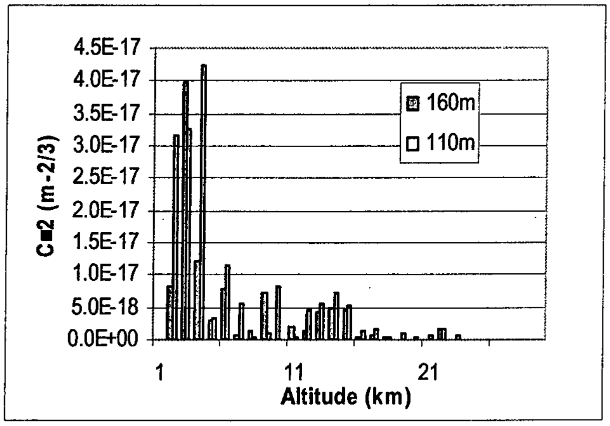

Figure 13. Arithmetic mean values of C_n^2 for 1km bins for flights HMNSP014 and 015.

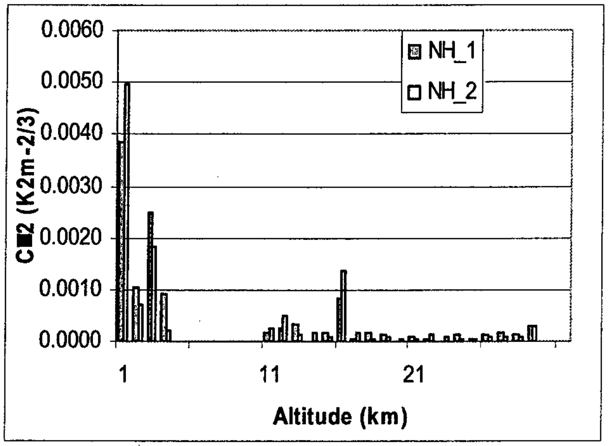

Figure 14. Mean values of C_T^2 for 1km bins for flights NH_1 and NH_2

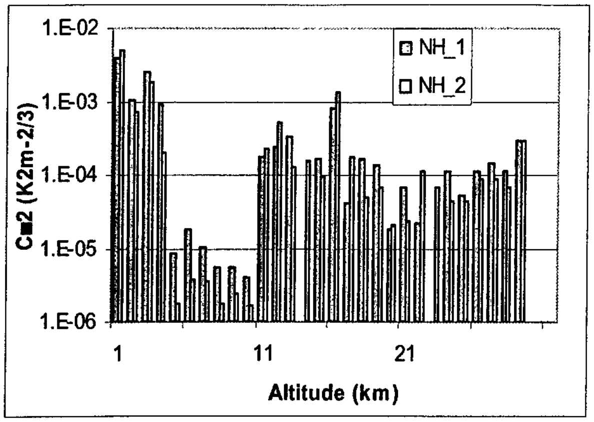

Figure 15. Mean values of C_T^2 on a log scale for 1km bins for flights NH_1 and NH_2. (Note NH_1 had transmission drop-outs at 14 and 23km.)

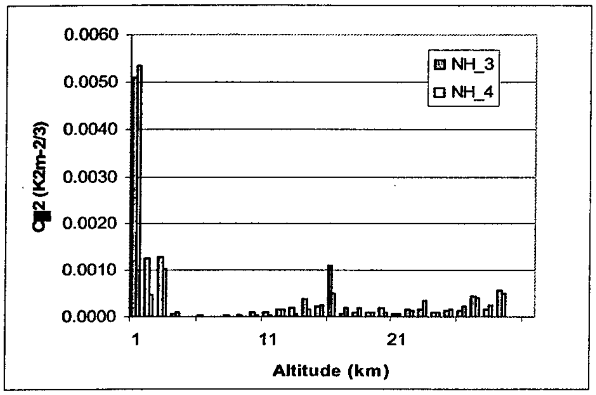

Figure 16. Mean values of C_T^2 for 1km bins for flights NH_3 and NH_4

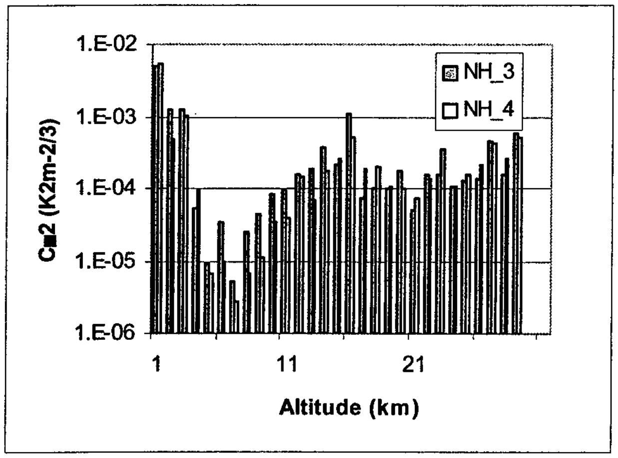

Figure 17. Mean values of C_T^2 on a log scale for 1km bins for flights NH_3 and NH_4

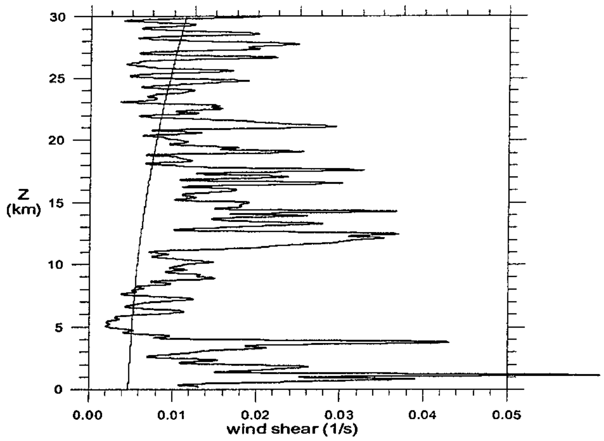

Figure 18. Shear for NH_1 and NH_2 and the smooth minimum shear line for 110m-line length

Conclusions

By launching two essentially identical thermosondes only minutes apart with different line lengths, AFRL/VSBL attempted to quantify the effect of line length and balloon wake on thermosonde output. Five pairs had different line lengths, and two pairs had identical line lengths. While the experiments reinforced conventional wisdom about wake encounter tendencies and the effect of the wake on the results, no definitive quantification of wake encounters was possible. The tendencies are 1) that shorter line lengths appear to have more wake encounters, 2) more wake encounters appear to occur at high altitudes when the balloon is at its largest diameter, and 3) more wake encounters appear in lower shear conditions. Another tendency that is born out is that wake encounters in the troposphere result in smaller thermal perturbations than encounters in the stratosphere due to the difference between air temperature and balloon skin temperature.

The above tendencies do not appear to be hard and fast rules. There are instances in every flight where certain altitudes will show more turbulence with the longer line than with the shorter. The use of different line lengths to attempt to quantify the effect of balloon wake on thermosonde results does not appear to be a definitive by itself. It proved impossible to determine the cause of differences seen in the output of a pair of essentially identical thermosondes with different line lengths to the balloon. The problem is that there was no method to insure that both thermosondes had gone through the same atmosphere. Even two balloons that are launched at the same time will not go through the same atmosphere since it is impossible to insure identical ascent rates through the atmosphere, as seen in the New Hampshire data. It should also be mentioned that atmospheric turbulence is a random statistical process of many length scales, and that a transit with even a perfect turbulence sensor is only a single realization of the process that is not expected to be identical to a different transit.

Hopefully someone will make a successful flight with one of the wake avoiding platforms. Perhaps the ring experiment or a stable descending thermosonde configuration will provide the vehicle to further investigate the wake problem. To date, the cold regions detected by the sensitive "micro-bead" thermal detectors proved the best way to identify a wake encounter in the stratosphere[11]. While the analysis was tedious, it did provide evidence of a wake encounter by the "signature" drop in potential temperature. A combination of micro-bead sensors and different line lengths would provide more information than we have at this time, but will still leave uncertainties.

Acknowledgement

The authors acknowledge the invaluable assistance of the many people who made these results possible. We especially appreciate the work of our thermosonde engineer, Kris Robinson, and thermosonde technician, George Clement. In addition, we thank the many other people involved in a balloon launch. These include the personnel at the balloon launch facility at Holloman AFB, NM, and the GroundWinds Lidar crew at the University of New Hampshire. We also acknowledge the valuable support and advice of our Branch Chief and Principal Investigator, Dr. Robert R. Beland.

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