5.1 INNOVATIVE PROCEDURES FOR THE PERFORMANCE AUDITING OF RADAR WIND AND RASS PROFILERS

Robert A. Baxter *
Parsons Engineering Science
Pasadena, California

1. INTRODUCTION

With the increased use of radar wind profiler, sodar and Radio Acoustic Sounding Systems (RASS) for measurement of upper air wind and temperature profiles comes a need for practical methods to verify their operation. Whether for air pollution studies or general meteorological observation programs, any type of measurement program must include operational practices that verify the overall data collection and processing systems. This will assure the collected data is useable for the intended purpose and will provide the appropriate documentation to back up the claims of data accuracy.

The verification of instrument operation is generally in the form of system and performance audits. The system audit evaluates the overall setup and operational procedures of the data collection and processing system while the performance audit assesses the ability of the instrument to collect valid data. The performance audit methods include the use of an independent observational system to collect data and compare measurements to the on-site profiling system.

The above referenced upper air systems are remote sensors that use Doppler shift technologies to measure air movement. Initially, the use of such an instrument for regulatory monitoring often required the reproving of the technology through extensive comparisons with other measurement devices, such as tethersondes or rawinsondes. Within the last decade, the use of the remote sensors has grown and become more accepted, and the need to "reprove" the technology has shifted to a more logical verification that the instrument is working properly. Recent guidance released by the USEPA (EPA 2000, 1995) has provided guidelines for the needed verifications and audit procedures that are appropriate for these instruments.

Suggested methods within the EPA guidance still require comparison measurements to be made to assure the system being audited is functioning properly. However, because of the relatively high cost of traditional comparison methods, this requirement is sometimes ignored, or the availability of cost-effective systems and methods for auditing is simply not known. The listed methods in the EPA guidance leave open the option for innovative and cost-effective technologies to collect the needed data, providing the new technologies achieve the goals of the audit.

* *Corresponding author address:* Robert A. Baxter, Parsons Engineering Science, Inc. 100 West Walnut Street, Pasadena, CA 91124; e-mail: rabaxter@earthlink.net

This paper discusses the audit process and means for auditing radar wind profilers and RASS systems. Several innovative methods and systems are presented and results from audits performed using these methods are discussed. The underlying goals and practical limitations of the audit technologies are then presented.

2. QUALITY ASSURANCE AUDIT PROCEDURES

Radar wind profiler and RASS systems use an indirect method to measure the profiles of temperature and winds. This presents a unique challenge to the quality assurance process to verify the measurements being made appropriately represent the atmosphere being measured. The procedures used in the audit process incorporate various system and performance checks that verify the system setup and assess the reasonableness of the data collected. The system checks verify the antenna alignment and level, RASS source level, and appropriate cable wiring. The performance checks then evaluate the reasonableness of the data collected.

The reasonableness is assessed by review of the data for internal meteorological consistency and then by comparison to an independent means of measuring the meteorological variables. This independent means for traditional sensors (cup and vane, or thermal measurement) is performed by either simulated atmosphere or by collocated measurement. Since there is no direct means of placing the radar based systems in a controlled atmosphere, this assessment must be performed using collocated measurements. To perform this comparison it must be understood that the analyses are not intended to assess the accuracy of the remote sensor system, but instead to gain confidence that the system is operating properly and the data collected are reasonable.

There are various methods that can be used for the collection of the comparison data. The data may come from tall towers, sodars, radiosondes, tethersondes, or other balloon or kite borne systems. The intent is to collect enough data so that an assessment of reasonableness can be made. It is not required that the comparison data be of greater resolution or accuracy than the remote sensor, only that the data have adequate quality to make the assessment.

The quantitative assessment of the reasonableness is performed using measures of "systematic difference" and "operational comparability", as described in ASTM, 1984. The comparability for the purpose of these assessments is the root-mean-square (rms) of the series of differences between the two measurement methods. This statistic provides a combined measure of both precision and bias, and will express how well the two systems agree.

Using the ASTM notation, the systematic difference is defined as:

$$d = \frac{1}{n}\sum (P_{a,i} - P_{b,i}) \qquad (1)$$

where

n = number of observations

$P_{a,i}$ = i th observation of the sensor being evaluated

$P_{b,i}$ = i th observation of the "reference" instrument

The operational comparability (or root-mean-square error) is defined as

$$c = \sqrt{\frac{1}{n}\sum (P_{a,i} - P_{b,i})^2} \qquad (2)$$

Results from the comparisons are interpreted against evaluation criteria to assess whether the comparisons are reasonable. Typical criteria for the comparisons are provided in Table 1. Comparison results in excess of the criteria do not necessarily mean that the remote sensor data are invalid. In making the assessment it is important to understand the reasons for the differences. Reasons may include unusual meteorological conditions, differences due to sampling techniques and data reduction procedures, or problems or limitations in one or both instruments. Both the reasons for, and the magnitude of, the differences as well as the anticipated uses of the data need to be considered in determining whether the observed differences are significant.

Table 1. Typical audit criteria.

Variable	Systematic Difference	Operational Comparability
u, v*	±1 ms^{-1}	2 ms^{-1}
Wind speed**	±1 ms^{-1}	2 ms^{-1}
Wind direction**	±10°	30°
RASS temperature	±1°C	1.5°C

* The u and v components are calculated along the antenna beams

** The wind speed and wind direction criteria apply to data when the wind speeds are greater than 2 to 3 ms^{-1}

Given this intent for the comparisons above, there is significant latitude for the incorporation of new and different technologies for the reasonableness assessment. The primary criterion in selecting the method is to assure the accuracy, and any limitations in its use, is appropriately understood.

3. WIND ASSESSMENT PROCEDURES

Regardless of the method selected to perform comparisons, the comparison and interpretation of the data is key in the successful application of any approach. Radar wind profilers (and sodars) have two basic antenna systems. The first includes individual antennas for each axis where the pointing direction and antenna elevation, or zenith, angle can be measured. The second is a phased array antenna where the beam directions and elevation angles are steered electronically. The beam direction in the first type can be verified visually. However, for practical reasons, the phasing and steering in the second type cannot be measured in the field. The primary purpose of the wind comparisons is to evaluate this steering by comparison methods.

In performing the comparisons it is important to process the comparison data in a manner similar to the data collection and display of the radar or sodar data. This includes averaging the observations into "range gates" similar to that provided by the remote sensor. Additionally, processing the data to provide the winds along each of the antenna radials provides antenna specific information to more easily assess any potential problems that may be caused by phasing or antenna related problems. Once data are in these formats then significant differences between the data sets will become more obvious when the statistical comparisons are made and differences evaluated.

Given the analysis methods above and the overall goal to determine if the winds measured by the profiling system are reasonable, collection of data using a variety of methods is possible. To minimize costs, yet still achieve this goal, simple single theodolite pilot balloons (pibals) may be released. While it is recognized that the assumptions for ascent rate, and the "snapshot" nature of the measurements could easily produce diverging comparison data sets, the overall goal of identifying if there are any gross errors in the wind profiler measurements can be achieved. This is especially true if multiple launches are made and periods of rapidly changing meteorological conditions are avoided.

The use of pibals helps to assess if the wind data from the radar have any serious problems with the beam steering that could not be determined from review of the data alone.

4. TEMPERATURE ASSESSMENT PROCEDURES

Similar to the wind assessment procedures above, the temperature assessment procedures include the volume averaging of the collected comparison data into range gates to match those of the RASS system. Additionally, the comparison method must measure the variables required to calculate virtual temperature, as this is the value that is provided by the RASS system. To measure virtual temperature requires dry bulb temperature, moisture and pressure. This is best performed using a simple temperature and relative humidity type sonde.

Comparisons of the data sets are then performed using several soundings and comparing the results for systematic differences and comparability.

5. WIND ASSESSMENT USING SIMPLE PIBALS

Figure 1 shows comparisons made using the pibal technique during an audit in July 2001. The site location was in the Owens Valley of California. The radar was operated in a mode to collect vertical wind data in two range gate intervals, approximately 200 meters and 400 meters. The displayed data merges the two modes.

The pibal launches covered three meteorological patterns. The morning launch around 0830 had persistent northerly winds up to about 1500 meters where the wind shifted to the northeast. Both the balloon and radar derived winds matched reasonably well. By 1300 a more than 90° wind shift occurred and afternoon heating and thermal activity dominated the period. The two balloon launches at about 1400 showed more significant differences in speed and direction when compared to the radar data. During the period of significant thermal activity the balloon ascent can be affected by thermal plumes that may make the "snapshot" profile substantially different from the hourly consensus profile derived by the radar. The thermal activity can also affect the radar data, but over the one hour consensus period the effect is somewhat reduced. By 1600 when the thermal activity was diminishing the radar and balloon data matched reasonably close.

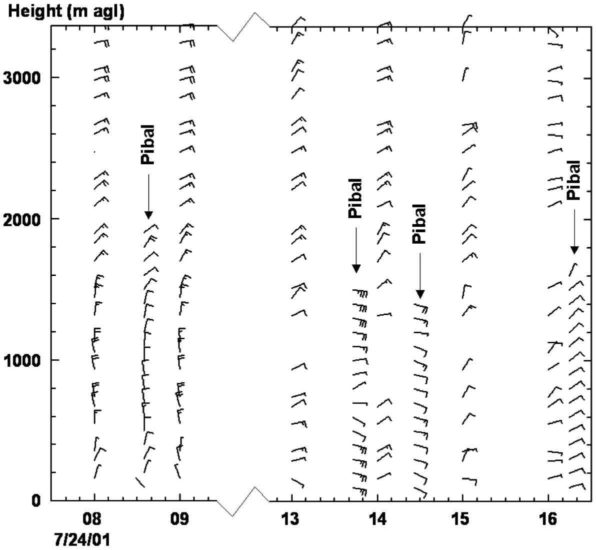

Figure 1. Comparison of pibal and radar wind profiler wind soundings.

6. WIND AND TEMPERATURE ASSESSMENTS USING A KITE BORNE SONDE

Different field conditions will sometimes define which audit method can be used. For example, if surface winds are in excess of 5 ms^{-1}, then use of a tethered balloon borne measurement system may not be practical. However, a tethered kite system, which includes a simple temperature and relative humidity sonde, provides the measure of both winds and temperature for comparison to the radar wind profiler and RASS systems.

In March 2001 an audit was performed on the radar wind profiler and RASS system described above. Surface wind speeds during the afternoon were in excess of 10 ms^{-1} precluding the use of any tethered balloon borne system for wind or temperature measurement. Instead, a Tala kite system, originally intended for wind energy type research, was used as a measurement platform for a prototype sonde package. The instrument package consisted of a temperature and relative humidity data logger, manufactured by Onset Computer Corporation (Onset). The data logger was encased in a Styrofoam package and vents provided for aspiration of the temperature and relative humidity sensors. The sonde was suspended on the kite line between the kite and the reel. Soundings were performed downwind of the radar/RASS system using the calibrated line length indicator and elevation angle of the kite to determine the altitude. Several soundings were performed to collect both the variables for calculating virtual temperature, and the winds.

When using a kite sonde, the winds are calculated from the observed azimuth angle to the kite and the measured pull of the kite on the line. The line pull was measured on a calibrated spring scale mounted on the line assembly. This scale was calibrated using known weights to simulate the pull on the line. Measurements of azimuth angle and pull generated wind speed were taken at one minute intervals and averaged over the same sample interval as the wind profiler. The one-minute data were volume averaged over the range gates in the wind profiler to produce comparable time and space averaged data.

Temperature and moisture variables were logged on the Onset data logger and the altitude of the sonde was calculated as described earlier. The altitude measurement variables were documented at one-minute intervals as the wind data were collected. The temperature variables were collected at two-second intervals and averaged to match the range gates in the RASS. Virtual temperature was then calculated using the measured variables and surface pressure.

Under the observed conditions the kite sonde was flown to it's maximum achievable altitude of about 250 meters. This altitude cap was defined by the ability of the sled type kite to produce enough lift to carry the kite, line and sonde package. While the maximum altitude achieved only overlapped several range gates in the wind profiler and RASS system, the soundings provided enough data to verify the radar system was producing reasonable data. Figure 2 shows some typical data from the wind soundings while Figure 3 shows temperature sounding data. Excellent comparison results were obtained from both the wind and temperature data obtained from the kite sonde.

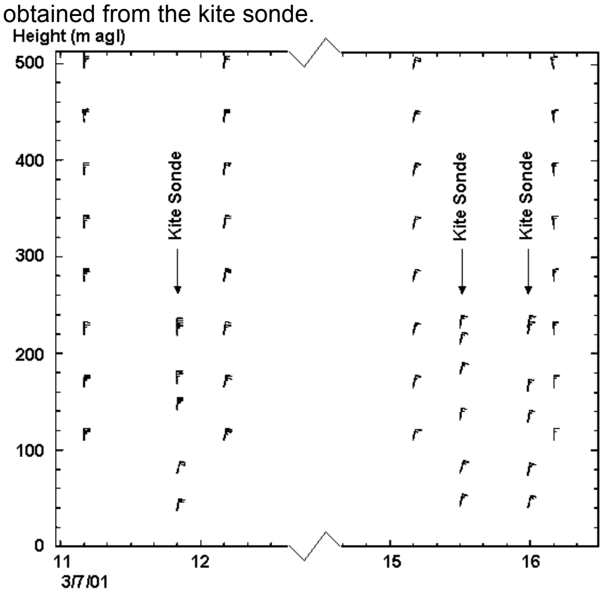

Figure 2. Comparison of kite sonde and radar wind profiler wind soundings.

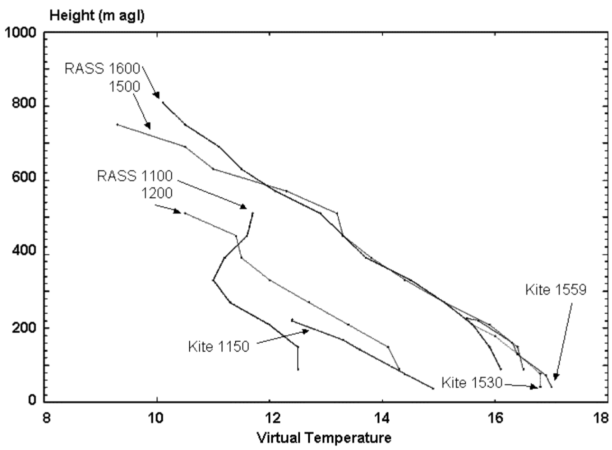

Figure 3. Comparison of kite sonde virtual temperature and RASS sounding data.

7. TEMPERATURE ASSESSMENTS USING A BALLOON BORNE SONDE

During periods when winds are relatively light (less than 3-5 ms^{-1}), a sonde package can be lifted by a helium filled balloon or array of balloons. During the March 2001 audits a new sonde package was tested that consisted of the same Onset temperature/relative humidity data logger as the kite sonde. A Global Positioning System (GPS) receiver was placed in a compartment below the meteorological sensors and used to collect time-stamped altitude data. These data were subsequently merged with the 2-second data stream of temperature and relative humidity data. This package was raised and lowered using the kite system reel with a digital line length counter. The elevation angle to the balloon package and length of the line were used to verify the accuracy and appropriateness of the GPS derived altitudes.

Software was developed to process the sonde data and allow time averaging of each of the measured variables. The algorithms allowed looking forward and backward in time to account for the different response times of the temperature and relative humidity sensors. Additionally, the averaging help to minimize errors introduced by the limited resolution of the temperature/relative humidity data logger. Since the data logging capabilities are limited to eight bits of resolution (one part in 256), the resulting temperature resolution is about 0.5 C in the temperature range of interest.

During the July 2001 audits, a modification was made to this sonde package, adding a pressure sensor in place of the GPS receiver. The pressure was recorded on the spare voltage channel on the Onset logger. This placed all needed variables in the same data stream, removing the need to merge the two different data sets. Again, due to the resolution limitations of the data logger (8-bits), averaging was needed of the resulting data to recover the needed pressure-altitude resolution of the sonde.

The temperature sonde package was initially used during the March 2001 audit. Soundings during the morning hours had relatively good results, but as the day progressed and the solar heating of the sonde increased, a bias appeared in the sonde virtual temperatures being measured. It was suspected that airflow rate through the sonde was not adequate to overcome the solar heating of the package.

To increase the ventilation rate in the sonde, flow deflectors were then placed on the sonde to help channel airflow through the sonde during the ascent and decent operations. Additionally, for the July audit, the manual method of raising and lowering the sonde was replaced by a winch system to provide continuous movement during the soundings.

Figure 4 shows a typical comparison made during the July 2001 audits after the flow deflectors were installed on the sonde. These measurements also used the pressure-altitude, as measured on the data logger channel. The temperature/RH sonde was the same one used in the March audits and the apparent bias seen during those audits was not present in the July data. By placing the flow deflectors on the sonde the potential problem with solar heating was minimized. As can be seen in the figure, the RASS reflected significant heating from 1000 to 1100. Temperatures measured from the RASS compared well with the sonde. Figure 5 shows the sonde with the pressure sensor installed in the lower left. Prior to the use of the pressure sensor, the GPS unit was placed into the lower compartment. The data logger with the temperature sensor can be seen in the upper chamber of the sonde. The kite sonde uses the same type styrafoam casing, but has only the chamber for the temperature/relative humidity data logger.

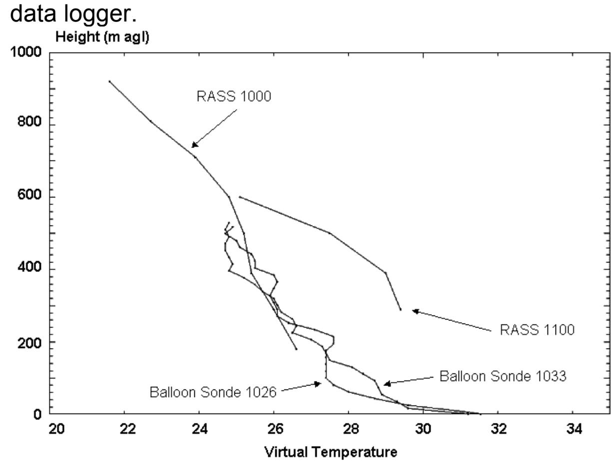

Figure 4. Comparison of balloon sonde and RASS measurements of virtual temperature.

8. LIMITATIONS OF THE EVALUATED METHODS

The presented methods above clearly show the value of inexpensive and innovative techniques to minimize equipment costs when performing audits of remote profiling systems. However, the methods are not without limitations, as discussed below.

Local flight regulations -- While the launch of balloons for just wind measurements has few restrictions, the ability to fly tethered balloons above about 150 meters may present problems. FAA regulations impose restrictions on flight areas and altitudes that must be adhered too when flying tethered balloons and kites. This may hamper or prohibit operations in some locations. For the audits discussed in this paper the area of operation was near

Owens Dry Lake, in a region of air space used by China Lake Naval Weapons Center and Edwards Air Force Base. Coordination prior to each of the audits allowed the limited use of the tethered system to altitudes of about 800 meters during daylight hours. Use of the system elsewhere will require similar coordination with the users and regulators of the air space penetrated by the sounding system.

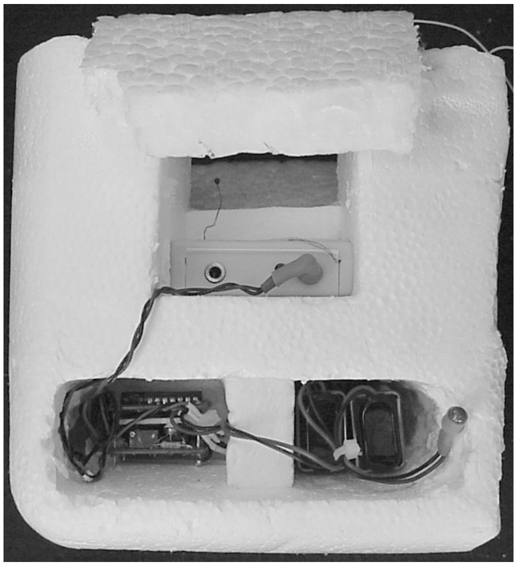

Figure 5. Sonde for measurement of temperature, relative humidity and pressure.

Accuracy and Resolution -- The use of simple pibal measurements have their own inherent inaccuracies. These are recognized and the use of such data should incorporate these limitations in the analysis. When performing the analysis it is key to recognize the purpose of the comparisons as a reasonableness check and not an accuracy check of the radar system. In this sense the check is more qualitative than quantitative to determine if there are any gross errors such as cables being swapped that may not be noticed during the data review process. Such was the case during an audit performed during the summer of 2000 where wind directions differed between the radar and pibal data by 90 to 180 degrees. The comparison data is shown in Figure 6. It was subsequently determined that a cable had been wired incorrectly to the phased array antenna. The stand alone data initially looked reasonable, but when compared with the independent pibal measurements, the inconsistencies were identified.

The calculated profiles for virtual temperature also have inherent limitations related to the resolution of the data collected. These limitations are somewhat mitigated by the averaging techniques employed, but for soundings of limited altitude coverage the averaging may not fully recover the true temperature profile in near isothermal conditions.

Potential interference with measurements -- Not discussed above, but of concern in the technique, is what effect the presence of an object in the sky has on the measurements made by the remote sensor. Earlier systems were found to be very sensitive to any moving objects that could produce reflections from the radar signal. This is why special "bird algorithms" have been developed to minimize bird migration interference on the radar data. The use of a tethered balloon or kite package for measurements has the potential for interference. However, experience gained during the last several years of auditing has shown the interference to temperature measurements to be minimal and to wind measurements it is much reduced from the earliest versions of the radars. In any case, the data should be carefully scrutinized to identify any instance when the audit device may be influencing the measurements made by the radar being audited.

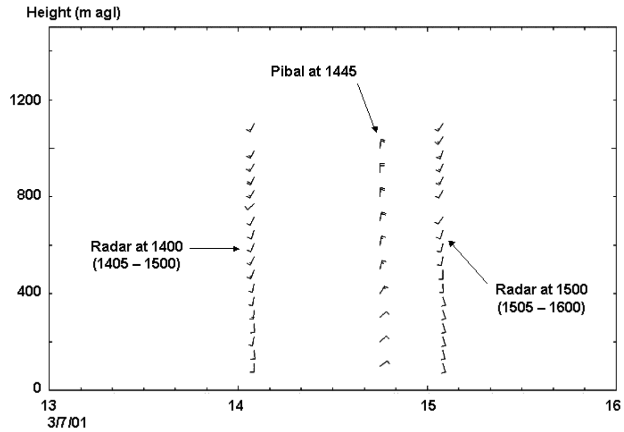

Figure 6. Comparison of pibal and radar data where the radar cabling to the antennas was incorrect.

Temporal errors in measurements -- Measurements made by the radar system incorporate inherent time averaging in the data over the period of consensus. These data can be significantly different from the "snapshot" measurements made by free flight or tethered balloon soundings. These differences must be recognized when interpreting the comparison results. A typical example of this temporal averaging issue is shown in Figure 7. This balloon sounding was performed during the peak of solar insolation. During the sounding the three-balloon package used to lift the sonde was observed to be significantly "shaken" in the upper portions of the sounding. At first it was thought that the line may have broken, as it became very taught and then slack. The three balloons were visually observed to spread apart then come back together in significant turbulence. The resulting sounding showed almost a two-degree increase in temperature over a 100-meter layer at an altitude of about 600 meters. This layer was not reflected in any of the other time-adjacent balloon soundings. The cause of this disturbance was most likely an ascending thermal plume caused by the daytime heating of the desert surface. While the sounding clearly represented the atmosphere, comparisons to the RASS data taken at nearly the same time showed significant differences due to a small time scale event. Interestingly enough, when the RASS data were vertical velocity corrected the comparison significantly improved. The radar data showed vertical winds during the RASS sampling period on the order of 1.5 ms^{-1}. Figure 8 shows the same balloon sonde data compared to the vertical velocity corrected RASS values. The profiles at 1100 and 1300 are changed slightly, but the greatest improvement is with the 1200 sounding. Additionally, the vertical velocity corrected data achieved one more range gate of data.

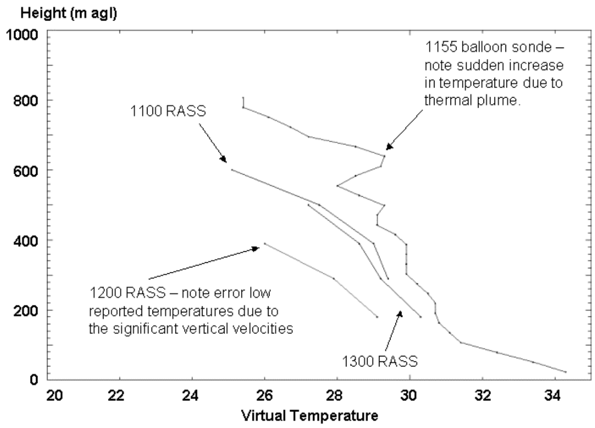

Figure 7. Balloon sonde and non-vertical velocity corrected RASS data showing the effect of a thermal plume on the measurements.

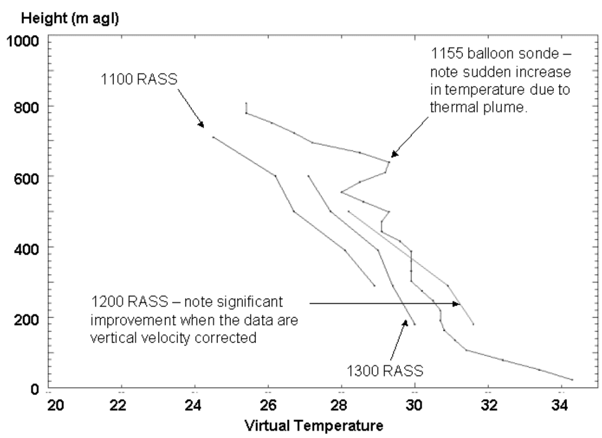

Figure 8. Balloon sonde and vertical velocity corrected RASS data showing the effect of a thermal plume on the measurements.

9. CONCLUSIONS

This paper presented some simple innovative methods and techniques for auditing radar wind profiler and RASS systems that merge existing methods with new technologies. The presented methods allow the collection of needed data to assess the performance of radar and RASS systems using relatively inexpensive sensors. The affordability of these techniques, along with the proper understanding of their limitations, can make the verification of radar and RASS performance relatively straightforward. Incorporation of the audit methods into the overall data collection efforts can then provide more documentation to help support the quality of the data collected. For some types of measurements this independent assessment is needed to fulfill the quality assurance requirements imposed by the USEPA guidance (USEPA 2000).

While the development of the above techniques were for use in auditing, the methods are applicable to a variety of boundary layer studies. Given the rapid drop in prices for GPS systems, the systems' ability to log spatial position, and the inexpensive cost of the Onset data loggers, sounding packages can be deployed in a very cost effective manner in many simultaneous locations. This type of system is reusable and an unlimited number of units can be flown in close proximity without frequency interference concerns associated with radio transmitting type sondes. The primary concern, as mentioned above, is air space and the associated coordination and limitations imposed by the tethered balloon systems.

Work is continuing on development of additional applications and improved sensors. The existing systems are being used as part of audit programs to verify radar and RASS as well as sodar performance, and the use is being expanded into other types of atmospheric research.

10. REFERENCES

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