Data Package Report for Honeywell Atmospheric Winds Campaign for Space (HAWCS)

Authors: ***Patrick Conry, Jeffrey VanKerkhove, Erik Horak, and Matthew ArchMiller***

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1. Executive Summary

The Honeywell Atmospheric Winds Campaign for Space accomplished a first-of-its-kind atmospheric measurements with multiple HALAS lidar systems and radiosondes spanning from the lower troposphere into the stratosphere. The campaign was designed and executed in partnership with multiple government collaborators and achieved the goal of coordinating data collection from multiple systems within a region of southern California, maximizing the co-location and temporal extent of observations with the available resources. During a 2.5-week period in Spring 2025, the newest generation HALAS airborne system operated during three overnight flights coincident with measurements from a ground-based HALAS system and radiosonde launches across multiple sites. Overall, 47 radiosonde datasets, 26 HALAS airborne datasets, and 14 HALAS ground-based datasets were collected, delivered to NOAA, and evaluated by Honeywell. Preliminary results presented in this report demonstrate the HALAS systems performed well based on mean absolute differences from radiosondes, being on the order of mid-point requirements for 3D winds uncertainty from NOAA's Broad Agency Announcement Table 2 which were <5 m/s and <10° for wind speed and wind direction, respectively. Despite challenges of fog impacting HALAS ground system's availability and airborne HALAS system's laser anomalies degrading its performance, the amount and quality of data enabled the campaign to accomplish its objectives of providing a rich dataset for evaluation of the technology and modeling studies performed by NOAA DEEVA to understand the potential impact of HALAS systems on Earth observations and numerical weather prediction.

2. Campaign Overview

2.1 Introduction

Planning for the Honeywell Atmospheric Winds Campaign for Space (HAWCS) commenced in 2022 with the program kickoff and was formalized ahead of the Mid-Year Meeting in Q1 of 2024. The campaign aimed to collect large datasets to enable NOAA to evaluate the HALAS (High Altitude LiDAR Atmospheric Sensing) technology. Two key priorities of the campaign design were: 1) to spatiotemporally coincide measurements from multiple HALAS systems and other atmospheric sensors (e.g., radiosondes) as closely as possible for ease of comparisons, and 2) to span multiple operational data assimilation cycles (i.e., 0Z, 6Z, 12Z, and 18Z) with the data collection window. These priorities then influenced the design and execution of the campaign as described in the following subsections.

2.2 Campaign Location

The region selected for the campaign was Southern California because of the relatively high concentration of HALAS systems deployed there during the 2024-2025 period. The airborne HALAS system (HALAS-airborne or HALAS-AB) system was being integrated and tested on the aircraft at Edwards Air Force Bases (EAFB), and one of the ground-based HALAS (HALAS-ground) systems known as Serial Number 4 (SN4) was based at Vandenberg Space Force Base (VSFB). The experimental design exploited the proximity of these locations to minimize the times and distances HALAS-AB would be in transit from takeoff to the location where secondary ground-based measurements were being taken. Both EAFB and VSFB meteorological groups had capability of launching their own radiosondes, and Honeywell added to this by launching additional radiosondes from VSFB and the San Joaquin Valley National Weather Service office in Hanford, CA (HNWS) through collaborative efforts. The latter was selected due to its location approximately equidistant from VSFB and EAFB. Figure 1 shows the approximate ground locations of all equipment used during the campaign within the region of operations in Southern California.

Figure 1: Locations of equipment supporting HAWCS within region of Southern California. Background map imagery ©Google Earth.

2.3 Campaign Equipment

The ground-based and airborne HALAS systems and their underpinning lidar technology were described previously in the HAWCS Instrument Report. In addition to the HALAS technology, radiosondes were launched from multiple sites during HAWCS flights to obtain reference measurements for comparisons. These radiosondes along with the HALAS systems would thoroughly document the atmosphere's evolution in the region between 0 UTC and 12 UTC standard soundings when the HAWCS flights were approximately scheduled.

At VSFB and HNWS Honeywell personnel launched radiosondes using an InterMet (iMet) 3050A antenna / receiver and iMet-4 Radiosondes. At VSFB, radiosondes were set to transmit at 404-405 MHz to deconflict with frequencies used by VSFB Weather Squadron on launches at 0 UTC and 12 UTC with Vaisala RS41-SGP sondes. At HNWS 402-403 MHz radiosonde frequencies were utilized to avoid overlap with VSFB. For EAFB, radiosondes were released by NASA Armstrong Flight Research Center (AFRC) personnel using a Vaisala system and RS-41 SGP sondes. All HAWCS radiosondes were lifted with 1000-gram balloons that could reach altitudes >32 km beyond the typical maximum altitudes achieved by HALAS systems for wind data products to ensure full coverage for comparisons. Helium was the balloon lifting gas, and parachutes were attached to the radiosondes for safety.

The SN4 HALAS-ground system was operated atop Tranquillon Mountain before and during the HAWCS flights when atmospheric conditions permitted (i.e., little to no fog or precipitation). Figure 2 shows the SN4 system deployed in its Tranquillon Mountain location at VSFB with Pacific Ocean in the background during favorable clear-sky conditions. The HALAS-ground system utilized its typical scanning strategy of scanning 12 LOS at different azimuth angles for 5 minutes each over the course of a ~1 hour data collection. This strategy enables derivation of spatially and temporally averaged wind vectors vertically resolved for the region of the atmosphere above the HALAS-ground system.

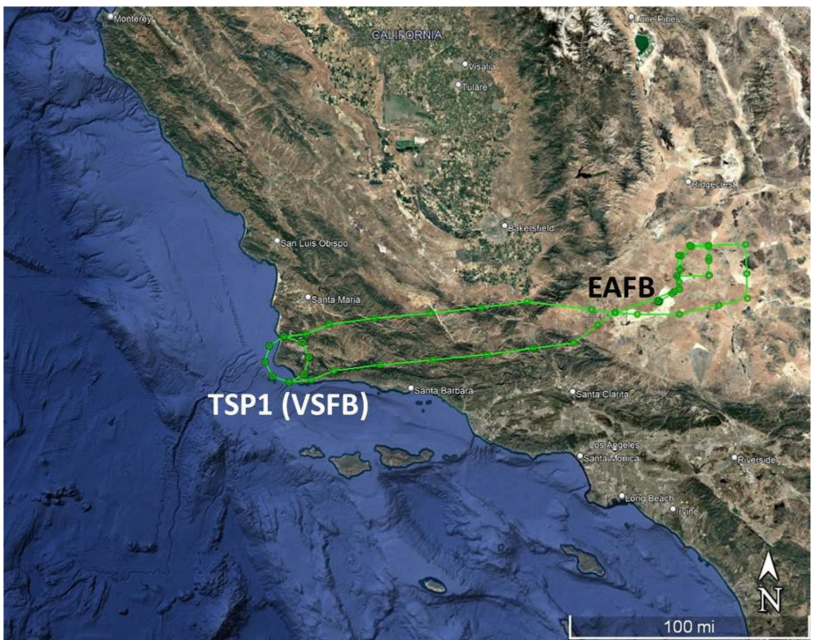
Figure 2: SN4 HALAS-ground system deployed for scanning at the VSFB location atop Tranquillon Mountain used during HAWCS

The HALAS-AB system is integrated into an unmanned aircraft operated by NASA AFRC. As part of the HAWCS campaign, the aircraft flew from EAFB to various locations, referred to as Test Support Points (TSPs), over the course of 3 separate flights. At each TSP, the aircraft flew in a circular pattern with a near-constant bank angle for approximately 1 hour, providing a diversity of lines-of-sight used for deriving wind vectors in the same manner as the HALAS-ground system for the region above the TSP. A summary of these TSPs is provided in Table 1, with a description of the plans for each flight provided in the next section.

2.4 Flight Plans

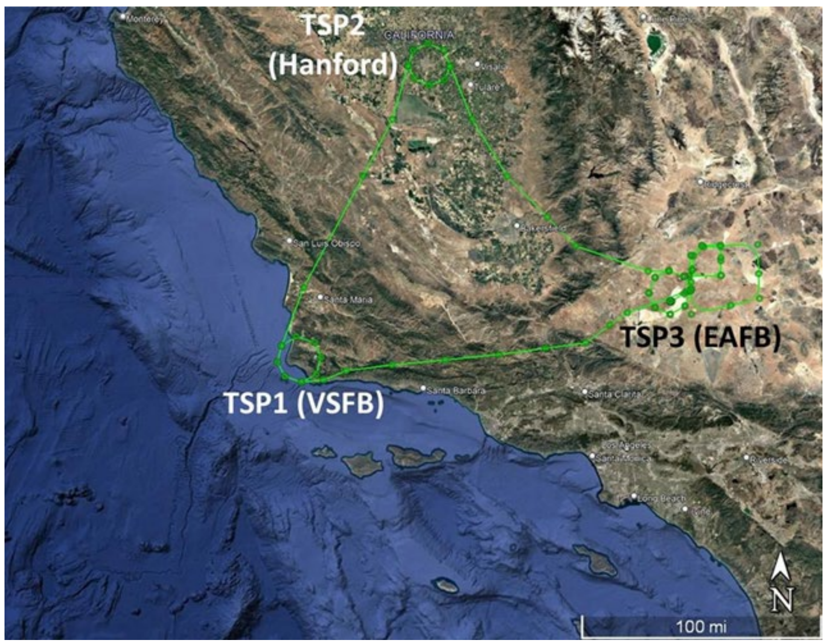
All HAWCS flights were planned to occur overnight to maximize airspace availability with estimated takeoff times at 18:00 PDT (01:00 UTC) and landing times at 06:00 PDT (13:00 UTC) for a total flight time of 12 hours. For Flight 1, shown in Figure 3, the flight plan involved the aircraft flying from EAFB to a single TSP over VSFB, collecting sky data for approximately 10 hours before flying back to EAFB. While HALAS-AB is taking data above VSFB, the ground-based HALAS system based at VSFB would be collecting data simultaneously (weather permitting). Additionally, numerous radiosondes including periodic launches by the HALAS team and routine launches at 00:00 and 12:00 UTC by the NWS would also provide atmospheric data for comparison to the HALAS systems and use in modeling.

Figure 3: Flight Plan for Flight 1. Background map imagery ©Google Earth.



The Flight 2 plan, shown in Figure 4, involved flying from EAFB to TSP 1 (over VSFB) and collecting data there for ~1 hour. After TSP1, the aircraft would fly to TSP2 (over Hanford, CA) and collect another 1 hour of data before proceeding to TSP 3 (over EAFB) and collecting an additional 1 hour of data. The aircraft would repeat this flight pattern for the remainder of the 10-hour flight duration, excluding takeoff and landing. In addition to the ground-based HALAS system collecting data at VSFB, the HALAS team would periodically launch radiosondes at VSFB and Hanford, and AFRC personnel will launch radiosondes from EAFB.

Figure 4: Flight Plan for Flight 2. Background map imagery ©Google Earth.



For Flight 3, as shown in Figure 5, the aircraft would again take off from EAFB and proceed to collect data at 5 different TSPs along a southwesterly trajectory. The first TSP was over EAFB and TSPs 2 and 3 were between EAFB and VSFB. Flight 3 would bypass VSFB to avoid airspace scheduling restrictions before proceeding to the last 2 TSPs over the Pacific Ocean. On the return leg back to EAFB, the aircraft would return at TSP3 before landing. As with the previous 2 flights, the estimated test duration is 10 hours. Additionally, the ground-based HALAS system would collect data at VSFB, the HALAS team would periodically launch radiosondes at VSFB, and AFRC personnel would launch radiosondes near EAFB.

Figure 5: Flight Plan for Flight 3. Background map imagery ©Google Earth.

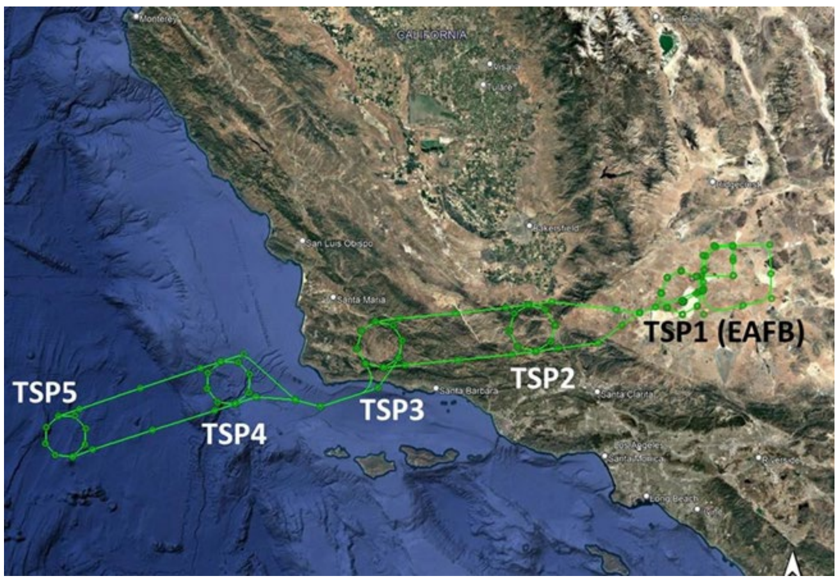


Table 1: List of TSPs for all HAWCS flights

Flight	TSP	Location	Altitude Range
1	1	34.5822°N, -120.5625°E (VSFB, CA)	51-52 kft
2	1	34.5822°N, -120.5625°E (VSFB, CA)	52-53 kft
2	2	36.3167°N, -119.6277°E (Hanford, CA)	52-53 kft
2	3	34.97°N, -117.89°E (EAFB, CA)	52-53 kft
3	1	34.97°N, -117.89°E (EAFB, CA)	52-53 kft
3	2	34.77°N, -118.99°E (Frazier Mountain, CA)	52-53 kft
3	3	34.66°N, -120.08°E (Santa Ynez, CA)	52-53 kft
3	4	34.4430°N, -121.1549°E (Pacific Ocean)	52-53 kft
3	5	34.1104°N, -122.30973611°E (Pacific Ocean)	52-53 kft

2.5 Pre-HAWCS Flights and Calibration

After completing the ground calibration of the HALAS-AB system, a test flight was performed prior to the HAWCS flights to ensure system readiness. This test flight was performed on the EAFB range and involved flying between two test TSPs there.

This test flight served several important functions: 1) to fully test HALAS functionality during flight, 2) to prove out data analysis functionality, 3) to assess data quality, and 4) to perform any calibration required for accurate atmospheric data product retrievals. The flight was comprised of an initial takeoff from EAFB, a transit north to TSP locations, circling around TSP1 for ~40 min, moving to and then circling around TSP2 for ~30 min, returning to and circling around TSP1 again for ~40 min, transitioning again to circle around TSP2 for ~40 min, and finally landing at EAFB.

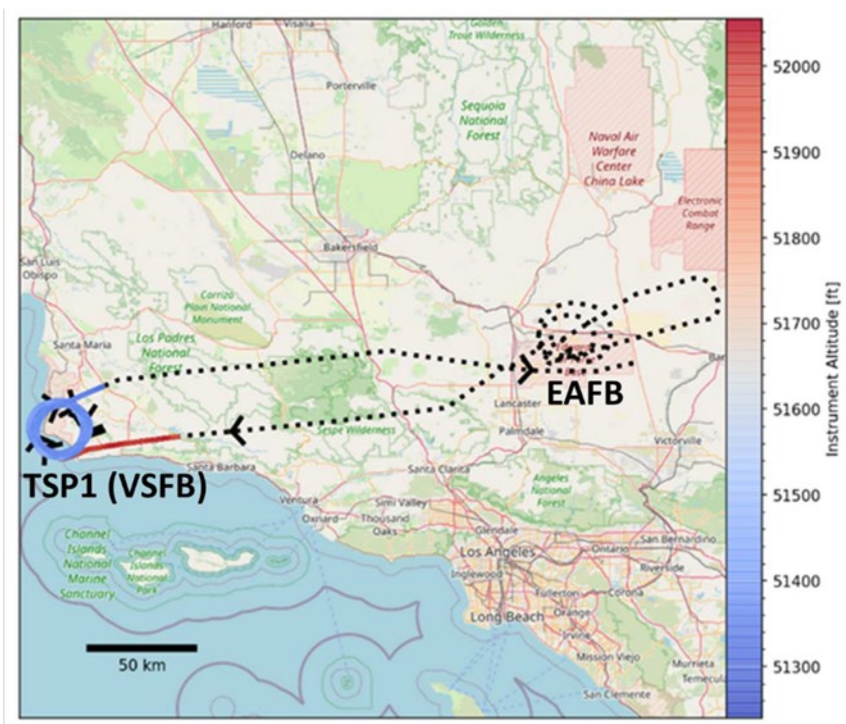
This test flight was the first successful demonstration of the HALAS-AB system during flight. This flight also served to discover issues and determine system performance. This included uncovering an intermittent aircraft communication issue during circular flight patterns around a TSP, issues surrounding Laser Clearinghouse (LCH) lockouts around TSP points, and a need for a new temperature calibration of the HALAS science equipment. A corrective action of resetting the ground communication antennas by the aircraft operators substantially improved the communication issues, this flight found an improved LCH-uptime by increasing the flight pattern radius from 6.0 NM to 7.5 NM, and a new temperature calibration was performed for the HALAS science equipment using the flight data and the co-temporal, co-localized radiosonde launched for this test flight by AFRC personnel.

Lastly, the impact of the known laser stability and power issues was determined during this flight test. The laser instability observed during flights is related to the vibrational environment during flight. This laser instability was found to be influenced by both the aircraft sources and internal HALAS-AB sources including the thermal system's pump and the inertial navigation system. This instability led to ~80-90% reduction in useable laser shots. The laser power issues are related to lower output power of the laser itself by ~50%. Taken together, the expected HALAS-AB laser performance was at ~5-10% of nominal. These issues would limit data collection to nighttime operations with minimal solar background, increase necessary data collection times to ~1 hour data collections (from the 20-minute collections planned nominally), and reduce the maximum range of the detected data products. Additionally, changes to the data analysis algorithms were needed to compensate for the sparse data collected. Remedying the core laser issues unfortunately was not possible in the timeline of the HAWCS missions but is planned to be done later in 2025.

3. Flight 1 Results

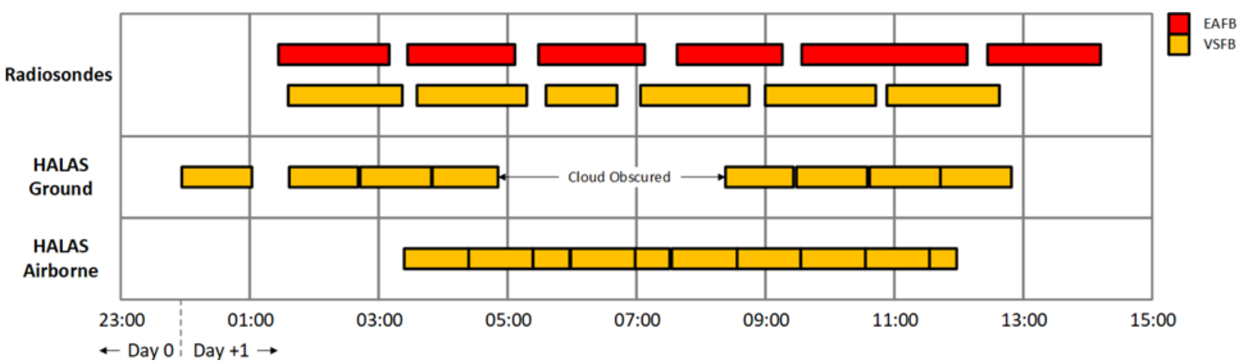
Flight 1 occurred from roughly 02:00 UTC to 13:00 UTC due to takeoff being delayed 1 hour for aircraft mechanical issues. Figure 6 shows the flight path of the aircraft during Flight 1. The aircraft had an instrument altitude around 52 kft during the approach to the TSP over Vandenberg. However, the altitude was reduced due to differences between the GPS altitude from the Honeywell internal navigation sensor and the pressure altitude from the aircraft altimeter. This difference results from atmospheric conditions that induce local deviations of the pressure-altitude relationship assumed by the aircraft, creating a mismatch between pressure flight levels of the aircraft and the true GPS flight level. This mismatch is important due to the LCH deconfliction calculations relying on GPS altitude, ultimately resulting in LCH lockouts. Additionally, the flight radius was reduced from 7.5 NM to 6 NM, due to an abnormally high number of position-based LCH lockouts (only about 40% open windows), contrasting the lessons learned from the test flight. This change helped with the number of LCH open windows, but there was still a consistent lockout on the west side of the loop while crossing the coast, resulting in a laser prohibition of approximately 30 seconds over an 8-minute loop. These LCH lockouts reduced performance and understanding the optimal flight plan to maximize system performance is ongoing.

Figure 6: Airborne HALAS system's (HALAS-AB) flight path for HAWCS Flight 1.



HALAS-AB entered the TSP at ~03:30 UTC and recorded for ~8.5 hours shown in Figure 7. At the end of the data collection, a laser interrupt necessitated a reset of the laser and science equipment just prior to the end of the mission. After the hardware recovery, only ~3 min of data was able to be collected prior to leaving the TSP and returning to base. This data was omitted from analysis. Additionally, two communications failures stopped data collection for short periods of time truncating some datasets. This analyses in the data package consist of 10 datasets, approximately 1 hour each shown in Figure 7 and listed in Table A1 in the Appendix.

Figure 7: Atmospheric data collection timeline for HAWCS Flight 1.



Co-localized HALAS-ground atmospheric profiles were recorded from Tranquillon Mountain. Co-temporal HALAS-ground measurements were performed as much as possible with data collection started prior to the arrival of the aircraft and continuing until after the aircraft initiated a return to base as shown in Figure 7. Unfortunately, a roughly 3.5-hour gap in HALAS-ground collection is evident due to the onset of a fog layer. The analyses in the data package consist of 8 datasets, each ~1 hour in length as shown in Figure 7 and listed in Table A2 in the Appendix.

Radiosondes were launched from EAFB and VSFB to match the time on station by HALAS-AB, with 6 radiosondes launched from each location. The timeline of each radiosonde is shown in Figure 7 and listed in Table A3 in the appendix.

This first flight of the HALAS-AB system above a HALAS-ground system enabled first-of-its-kind intercomparisons of both HALAS system's results with radiosondes released from a proximate location. Examples of these comparisons are shown in Figure 8 and Figure 9 below demonstrating strong agreement for data products available from HALAS-AB. Note that humidity data product from HALAS-AB was omitted due to very low values at the available altitudes which caused low SNR and high random uncertainty.

The HALAS-AB data has relatively limited altitude range for all data products, in part due to the lower laser power, both through design and poor laser performance. It is expected that for a fully functional laser, the HALAS-AB system will have a substantially larger altitude range. In addition to this limitation, a thermal issue was identified due to the long duration of this flight. The temperature of the spectrograph was found to drop below operational thresholds due to the cold environment at the flight altitude. This occurred in part due to the desire to improve laser stability by reducing the pump speeds in the environmental control system. The lower pump speed reduced the vibrational impacts on the laser, improving performance, but the lower pump speed reduced heat distribution capabilities allowing the spectrograph temperature to dip below operational conditions. To combat this, the atmospheric temperature profile (measured by the spectrograph) was calibrated twice during the flight to ensure the atmospheric temperature profile bias was minimized.

Figure 8: Comparisons of HALAS-airborne (HALAS-AB, green), HALAS-ground (orange), and radiosondes (blue) for near-coincident time periods around 09:00 UTC during Flight 1

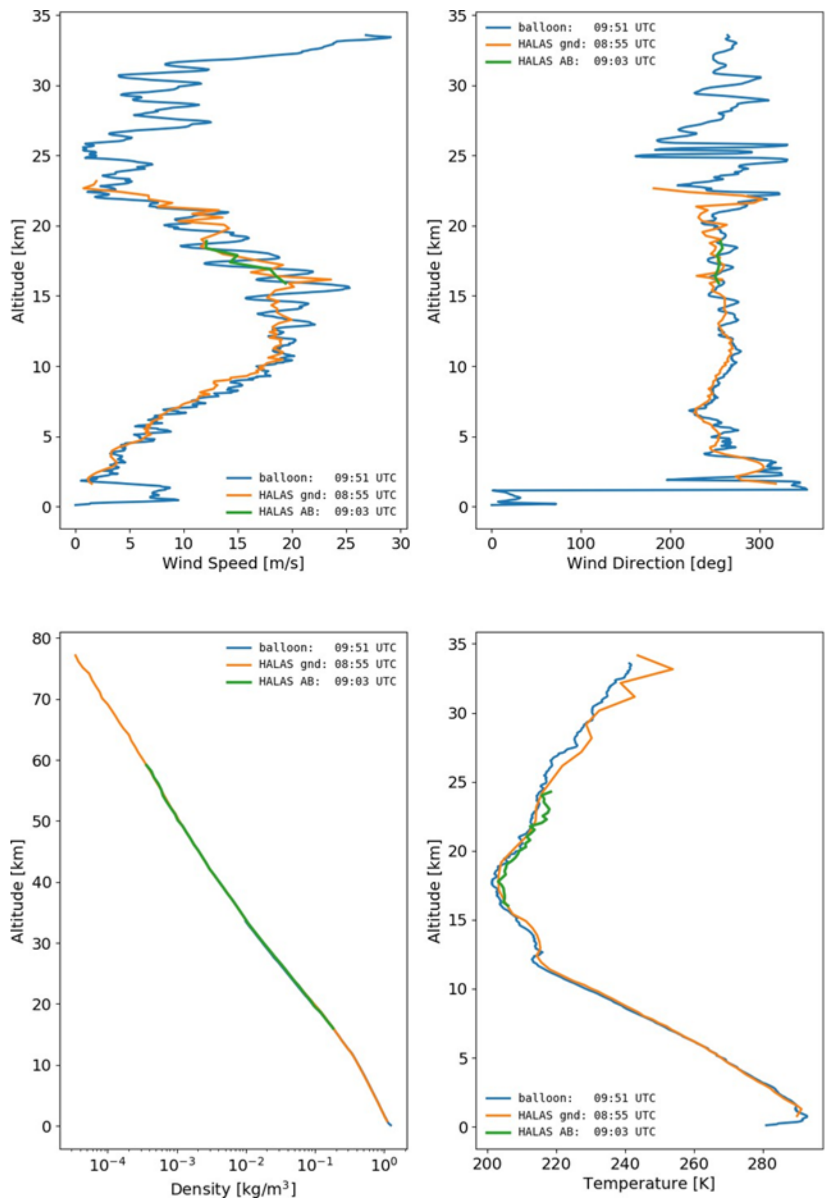
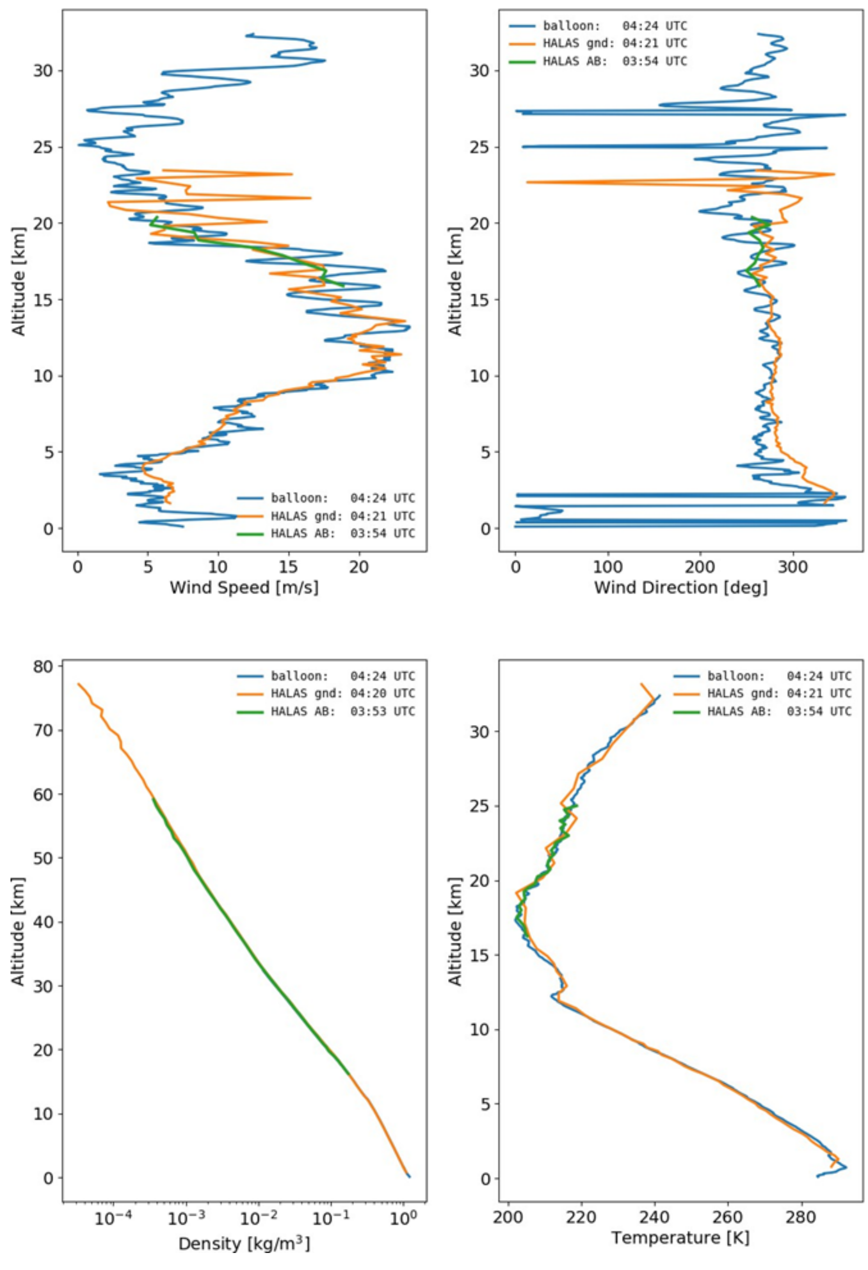


Figure 9: Comparisons of HALAS-airborne (HALAS-AB, green), HALAS-ground (orange), and radiosondes (blue) for near-coincident time periods around 04:00 UTC during Flight 1



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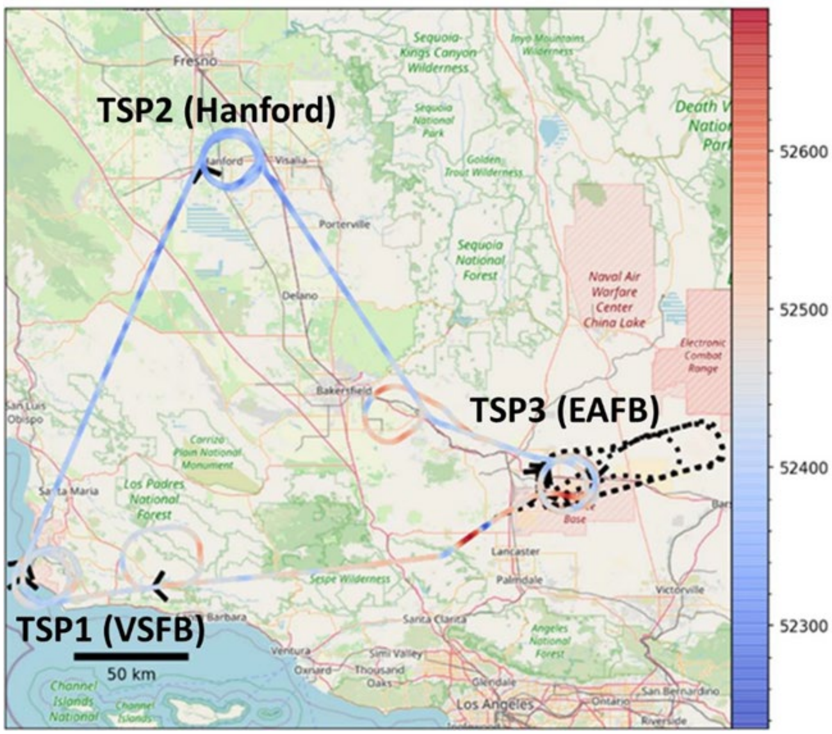
4. Flight 2 Results

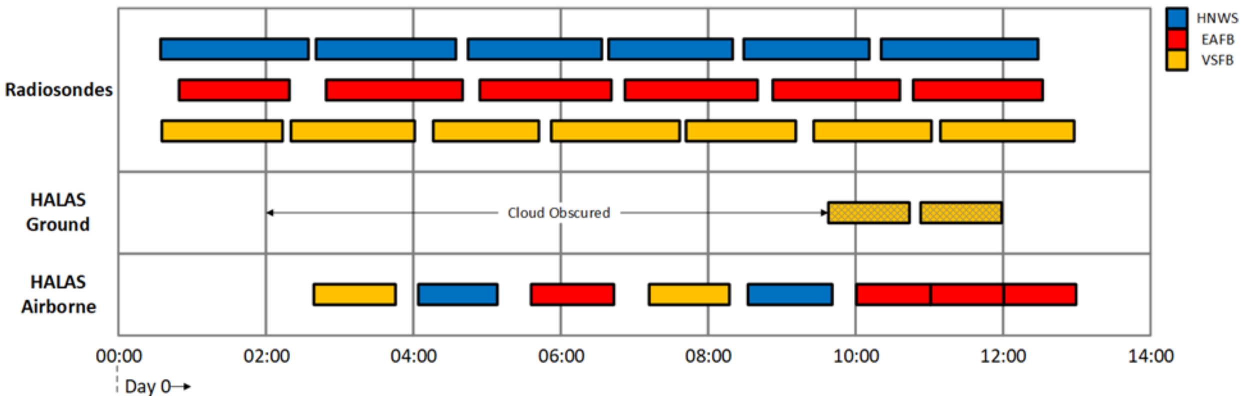
Flight 2 occurred from roughly 01:00 UTC to 13:00 UTC. Sequentially, Flight 2 occurred after Flight 3 due to logistical considerations in the week leading up to the flight, but the numbering was not switched from the original numbering due to its pervasiveness in the planning documentation used by collaborators to avoid confusion. Figure 10 shows the flight path of the aircraft during Flight 2. Flight 2 primarily followed the intended Flight Plan. The loop prior to TSP1 was because VSFB ATC denied the aircraft entry into their airspace due to a miscommunication at that time. Likewise, the loop near Bakersfield was a holding pattern as the aircraft did not yet have proper authorization to enter EAFB airspace

Figure 10: Airborne HALAS system's (HALAS-AB) flight path for HAWCS Flight 2.



The aircraft was able to complete the circuit twice, collecting data at each TSP for about 1 hour each time. It was decided to stay at TSP3 longer instead of proceeding to TSP1 for a third circuit, since TSP1 was in an ALTRV which closed at 12:00UTC. As a result, the final data collection event at TSP3 was nearly 3 hours instead of 1 hour. Altogether, HALAS-AB was able to record ~8 hours of data spread across the three TSPs, with two 1-hour datasets at both VSFB and HNWS and four 1-hour datasets at EAFB. The analyses in the data package consist of these 8 datasets shown in Figure 11 and listed in Table A4 in the appendix.

Figure 11: Atmospheric data collection timeline for HAWCS Flight 2.

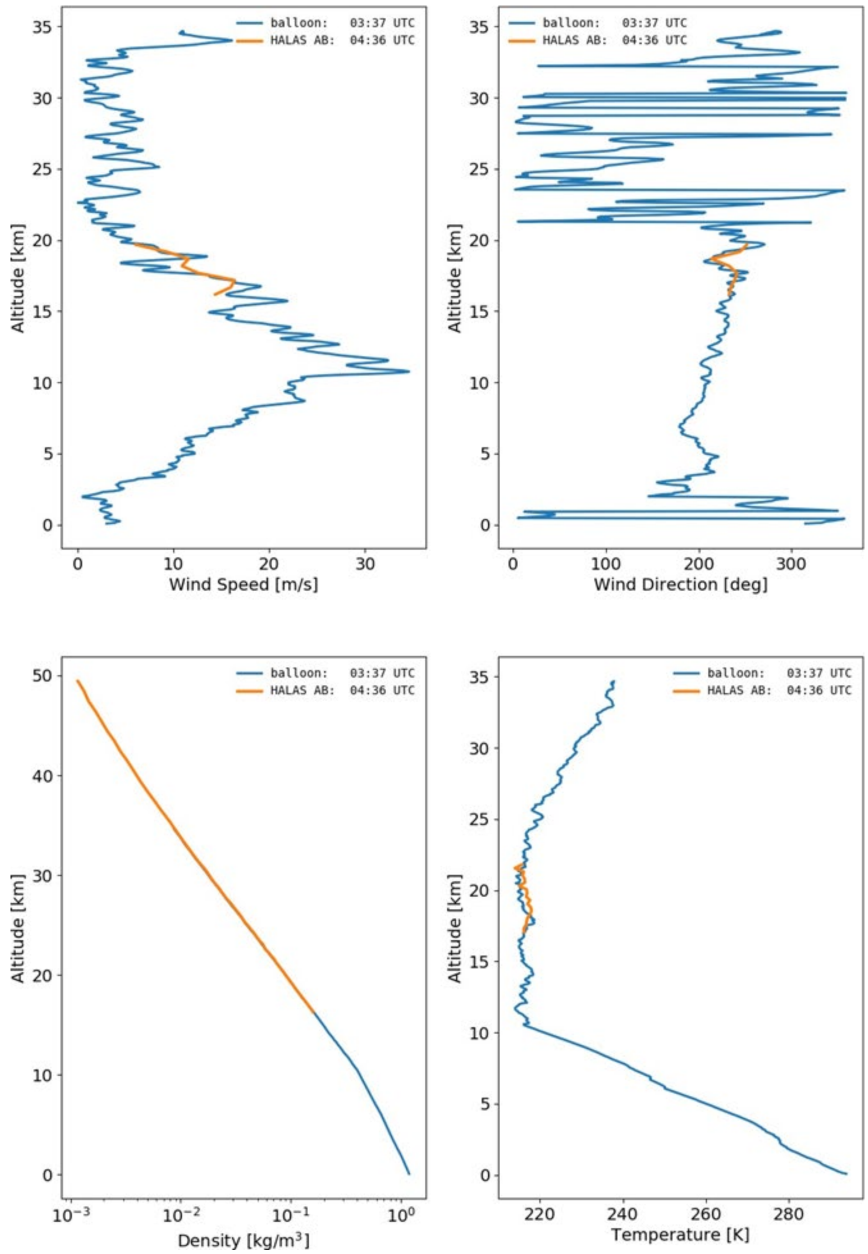


HALAS-ground atmospheric profiles were again recorded from VSFB. Unfortunately, a low cloud layer impeded any wind-data collection. At the end of Flight 2 some low-altitude temperature, humidity, and density data were retrieved in these conditions. The analyses in the data package consist of 2 limited datasets (i.e., no wind), each ~1 hour in length as shown in Figure 11 and listed in Table A5 in the Appendix.

Radiosondes were launched from EAFB, VSFB, and HNWS to match the time on station by HALAS-AB, with 6 radiosondes launched from each location. The timeline of each radiosonde is shown in Figure 11 and listed in Table A6 in the appendix.

Only meaningful comparisons between HALAS-AB and the radiosondes were available due to the obscuring clouds with the HALAS-ground system. An example of this comparison is shown in Figure 12. Although the HALAS-AB data only has limited altitude range it does show good agreement with the co-located, co-temporal radiosonde. This limited range stems from the higher pump speed of the environmental control system. This environmental setting adjustment was made in an effort to mitigate the thermal instability observed in Flight 1 but resulted in a higher degree of laser instability thereby reducing system performance.

Figure 12: Comparisons of HALAS-airborne (HALAS-AB, orange) and radiosondes (blue) around 04:00 UTC during Flight 2.



5. Flight 3 Results

Flight 3 occurred from roughly 18:00 PDT to 06:00 PDT. Figure 13 shows the flight path of the aircraft during Flight 3. The aircraft stayed at TSP1 much longer than anticipated due to a communications issue which prevented it from proceeding to TSP2. By the time the issue was resolved, the aircraft skipped TSP2 and proceeded directly to TSP3 to maintain the schedule. After collecting data at TSPs 3, 4, and 5, the aircraft proceeded back to TSP3 to collect another hour of data before returning to base. Altogether, HALAS-AB was able to record >8 hours of data spread across five 1-hour datasets at TSP1, no datasets at TSP2, two ~1-hour datasets at TSP3, one 1-hour dataset at TSP4, and one <1-hour dataset at TSP5. The analyses in the data package consist of these 8 datasets as shown in Figure 14 and listed in Table A7 in the Appendix.

Figure 13: Airborne HALAS system's (HALAS-AB) flight path for HAWCS Flight 3.

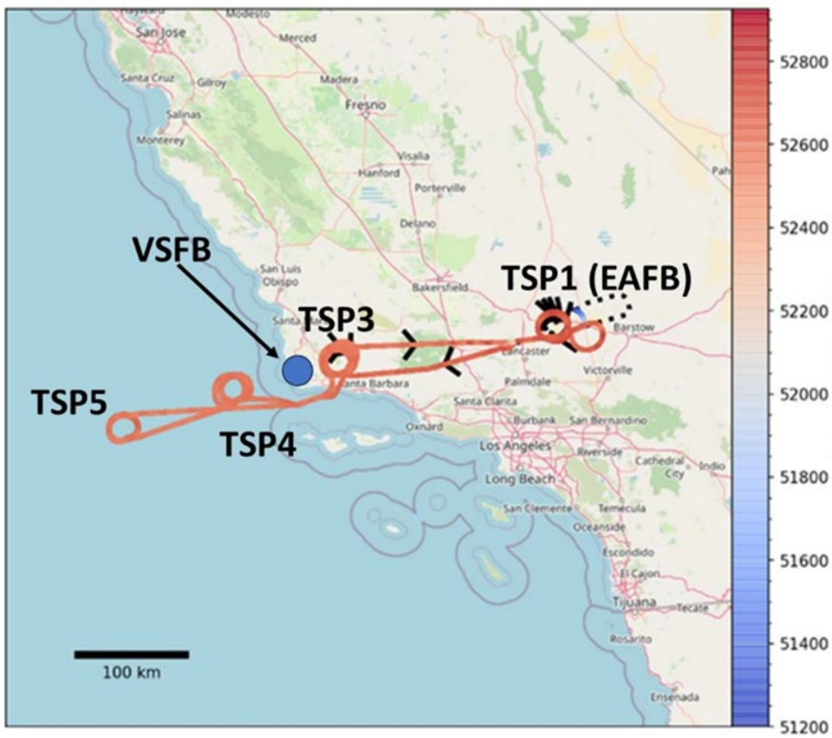
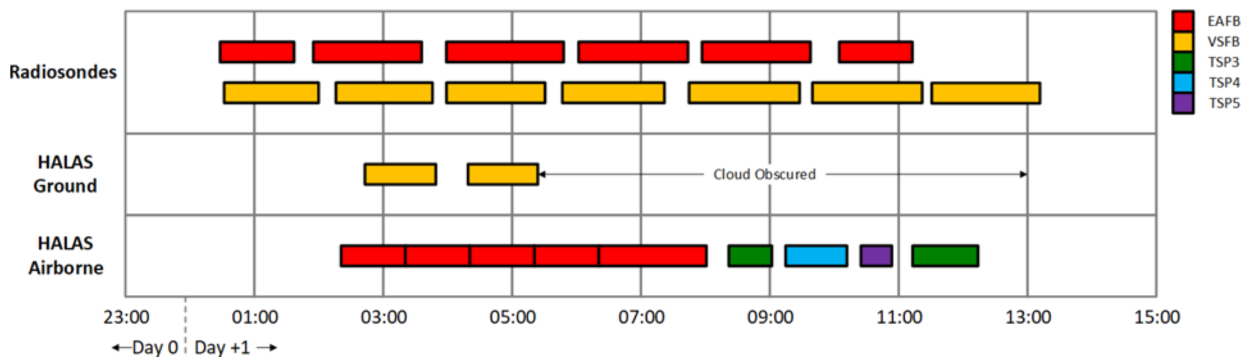


Figure 14: Atmospheric data collection timeline for HAWCS Flight 3.

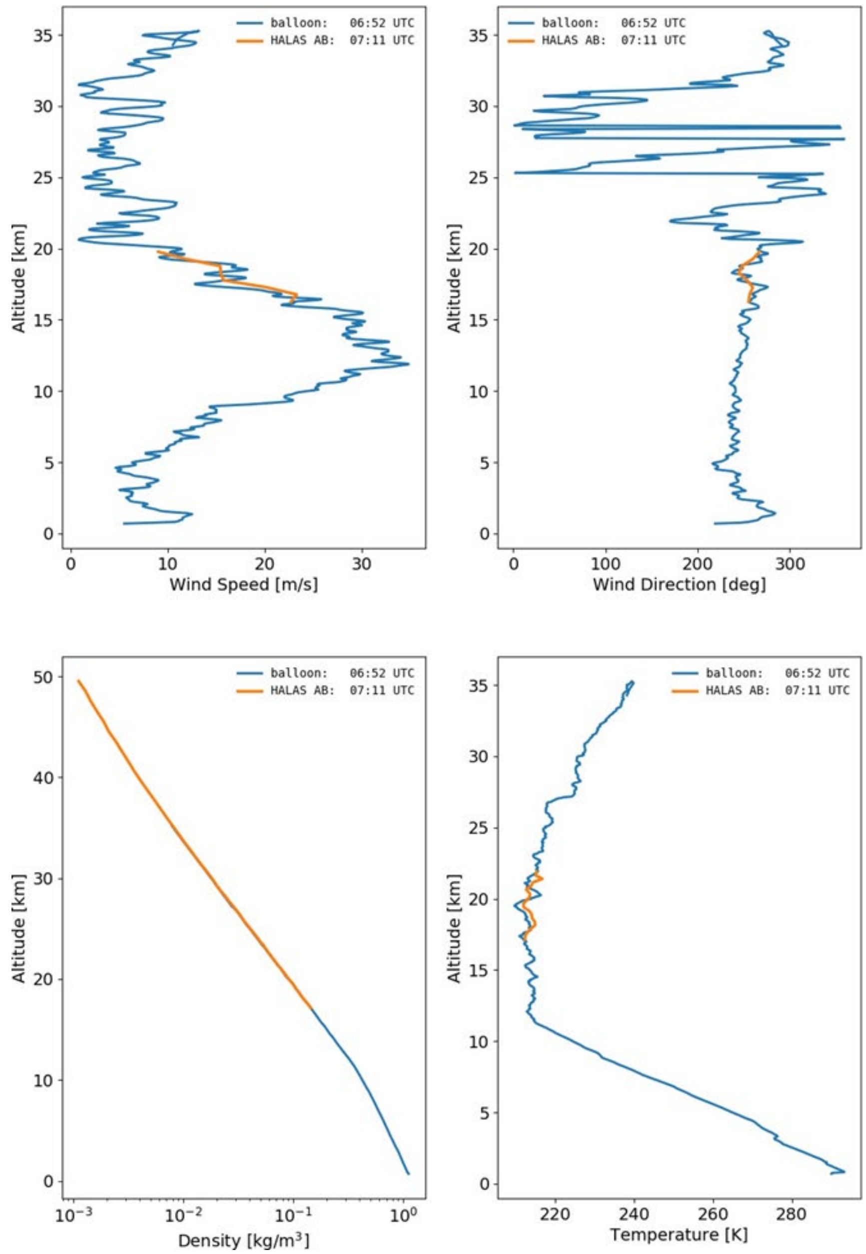


As in Flight 2, the HALAS-ground system measurements were limited due to fog and were only accomplished at the beginning of Flight 3. The analyses in the data package consist of 2 datasets, each ~1 hour in length as shown in Figure 14 and listed in Table A8 in the Appendix.

Radiosondes were launched from EAFB and VSFB to match the time on station by HALAS-AB, with 6 and 7 radiosondes launched from the locations respectively. The timeline of each radiosonde is shown in Figure 14 and listed in Table A9 in the Appendix.

Only meaningful comparisons between HALAS-AB and the radiosondes were available due to the obscuring fog with the HALAS-ground system. An example of this comparison is shown in Figure 12 and Figure 15. Importantly, these comparisons are only available at TSP1 and TSP3 where the HALAS-AB system was flying around radiosonde launch locations. Although the HALAS-AB data only has limited altitude range it does show good agreement with the co-located, co-temporal radiosonde. This limited range, like in Flight 2, stems from the higher pump speed of the environmental control system causing a higher degree of laser instability and reducing system performance.

Figure 15: Comparisons of HALAS-airborne (HALAS-AB, orange) and radiosondes (blue) around 07:00 UTC during Flight 3.



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6. Campaign Performance

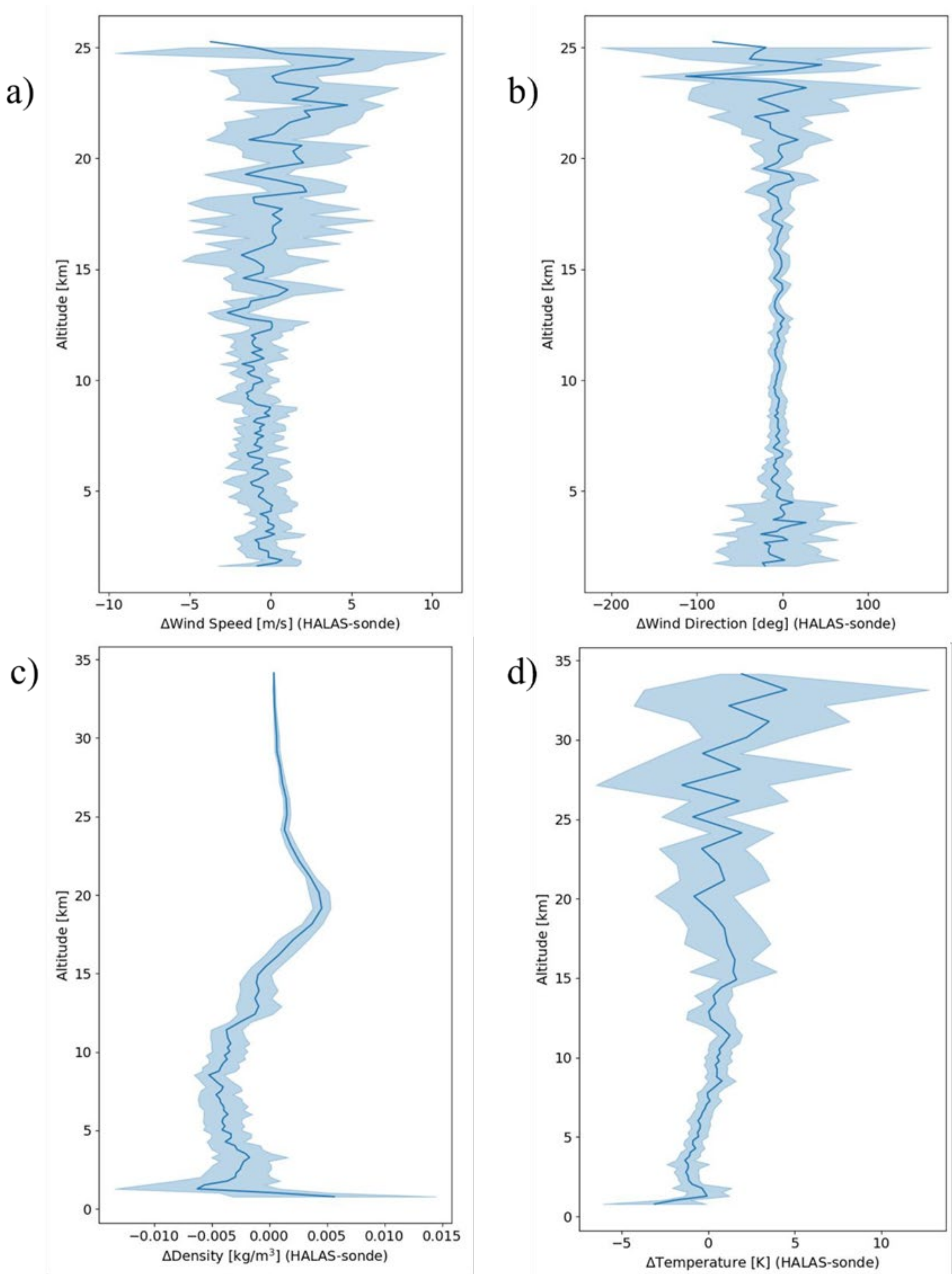
6.1 Methodology

HAWCS accomplished a series of measurements from HALAS-AB and HALAS-ground systems that can be statistically compared to the radiosondes released during HAWCS. The methodology used to compare HALAS datasets to radiosondes utilized automated selection of the most appropriate radiosonde launched from the site nearest SN4 (i.e., VSFB sounding site) or HALAS- AB's TSP. The radiosonde with the maximum temporal overlap with the HALAS dataset time range was selected for comparison (see Table A1-Table A9). In the case where no radiosonde overlapped with the HALAS data, the radiosonde with the minimum temporal difference, up to two hours, from the time range of HALAS data collection was selected for comparison. In some cases, the same radiosonde was used for more than one comparison if it was selected based on the above criterion.

6.2 HALAS-Ground Performance

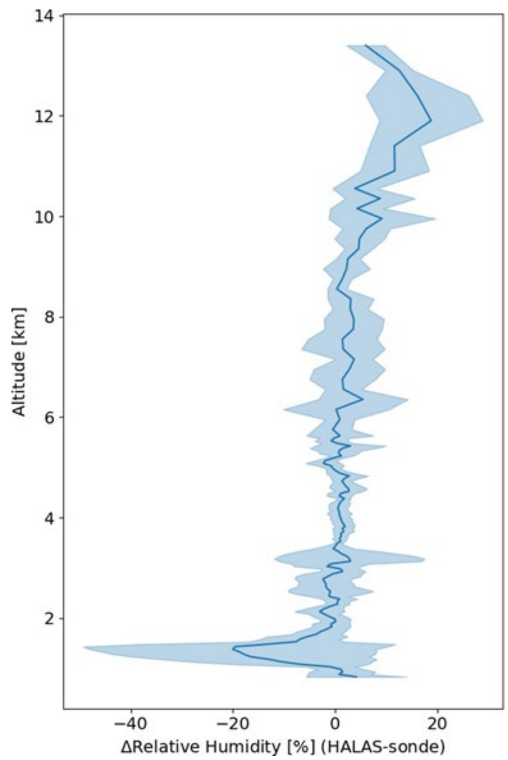
The HALAS ground system measurements during Flight 1 and with limited input from Flight 3 measurements were compared to radiosondes by calculating statistics such as the average difference between HALAS-ground and iMet radiosondes released from VSFB. The differences for winds, density, and temperature are shown in Figure 16. Even though there are clear differences between the measurements, these differences do not indicate either is necessarily incorrect. Due to the time differences allowed between measurements of up to 2 hours and the radiosonde launch location being separated by 19 km from SN4's location on Tranquillon Mountain, some differences may be attributed to spatiotemporal variability naturally present within the atmosphere. Moreover, the HALAS-ground measurements represent an average value over ~1 hour, but the radiosonde measurements are collected at a frequency of 1 Hz.

Figure 16: Plot of differences between HALAS-ground and radiosondes across all flights for key atmospheric parameters



The cumulative relative humidity difference across all datasets is plotted in Figure 17 indicating a dry bias in HALAS-ground near the surface is a good indication of the potential influence of spatiotemporal variability in the atmosphere. While a detector issue at closer ranges was not conclusively ruled out, the low altitude differences are likely more related to the strong heterogeneity in moisture layers near a mountainous coast particularly during the campaign nights which were marked by intermittent fog. The topographic differences between SN4 atop a mountain and the radiosonde launch location in a flat area near the VSFB airfield could be a contributing factor to the differences.

Figure 17: Relative humidity difference between HALAS-ground and radiosondes.



In addition to the figures illustrating the trends in comparisons between HALAS-ground and radiosondes, the quantitative statistics of SN4's performance during the campaign are documented in Table 2 for wind speed and direction averaged over a selection of altitude intervals. The mean signed differences presented in Table 2 are vertically averaged from profiles presented in Figure 16 and indicate any consistent biases between the different measurement systems (e.g., the HALAS-ground system's dry bias evident in lowermost altitudes of Figure 17). These mean signed differences, or mean biases, were relatively small and inconsistent for wind speed, <1 m/s below 20 km, but for wind direction there is a consistent, albeit small, bias of ~5° in the negative or counterclockwise direction which may warrant reinvestigation of the pointing calibration.

The mean absolute difference (MAD) in Table 2 is a better measure of the overall statistical dispersion between the two datasets. While a portion of the MAD is likely related to spatiotemporal variability within the atmosphere as discussed above, if the radiosondes are assumed to be the truth source, the MAD will provide some gauge of the uncertainty of HALAS-ground measurements. Therefore, one can compare these

MAD values for wind speed and direction to the requirements described in the Broad Agency Announcement (BAA) Table 2 (see Appendix Table A10). For wind speed, the MAD value would meet the maximum uncertainty requirement from BAA (2 m/s) for altitudes <15 km and the mid-point requirement (5 m/s) for all altitudes measured (up to ~25 km). The wind direction MAD values meet either minimum or mid-point BAA requirements for 5-15 km (approximately the minimum requirements vertical extent of mid-troposphere to just above tropopause from BAA). Above and below this range, wind direction MAD values would not meet any BAA requirements, but the higher MAD values at altitudes <5 km and >20 km are likely related to the relatively low wind speeds (<5-10 m/s) found at these altitudes (e.g., Figure 8). Wind direction uncertainty is highly dependent on background wind speed with higher uncertainty values at lower wind speeds. Overall, the statistical investigation of the differences in winds measured by the radiosondes and HALAS-ground system reveals that HALAS-ground performed well, but the statistical significance of this result was somewhat impeded by the low number of measurements available from Flights 2 and 3 due to fog. The figures and statistics presented in this subsection were limited to 12-14 HALAS-ground datasets depending on the data product.

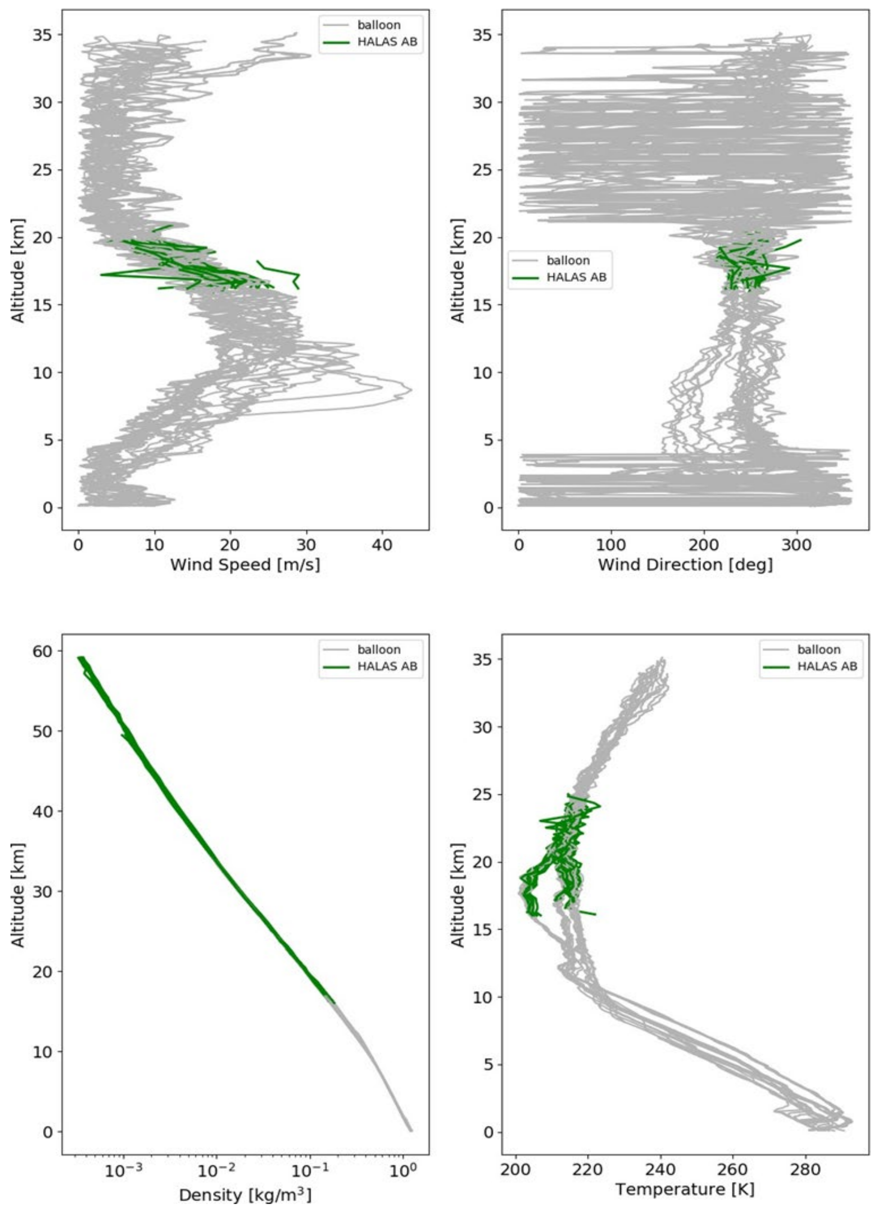
Table 2: Mean Difference and Mean Absolute Difference between HALAS-ground and Radiosondes for 2D winds.

Altitude Range	Mean Signed Difference		Mean Absolute Difference	
	Wind speed (m/s)	*Wind Direction (°)*	*Wind speed (m/s)*	*Wind Direction (°)*
0-5 km	-0.2	-5	1.2	35
5-10 km	-0.8	-6	1.3	11
10-15 km	-0.8	-5	1.5	8
15-20 km	0.1	-5	2.6	14
>20 km	1.6	-10	3.2	51

6.3 HALAS-AB Performance

The HALAS-AB collected 8-9 datasets per flight for a larger dataset for statistical comparisons. A comparison between the HALAS-AB and radiosondes for all flights is shown in Figure 18. Wind speed and direction measurements from HALAS-AB generally range from 16-20 km in altitude. Density measurements extend up the 60 km for particularly good datasets and temperature measurements extend up to 25 km. Figure 18 also shows three distinct temperature trends in the lower stratosphere across each of the flights, captured by HALAS-AB and the radiosondes.

Figure 18: Comparisons of HALAS-AB (green) and radiosondes (grey) for all flights and sites during the HAWCS campaign.



To assess HALAS-AB performance, comparisons between HALAS-AB and radiosondes are performed over the course of the 3 flights at 3 different sites: VSFB, EAFB, and HNWS. Over the course of these 3 flights, there were 15 HALAS-AB datasets from TSPs in the vicinity of VSFB. There were 9 total HALAS-AB datasets over EAFB (during Flights 2 and 3) and only 2 sets over HNWS (during Flight 2). At VSFB and HNWS, iMet-4 radiosondes were launched by the Honeywell team while Vaisala RS41-SGP radiosondes were launched by AFRC personnel at EAFB. Routine radiosondes are also launched by the NWS at VSFB, as well as other stations surrounding the HAWCS test sites including San Diego, Las Vegas, and Oakland. However, this analysis only uses the radiosondes launched locally by Honeywell and AFRC personnel to ensure the best possible time coincidence between the HALAS systems and radiosondes. These results are shown in Figure 19, Figure 20, and Figure 21 for VSFB, EAFB, and HNWS, respectively.

Figure 19: Plot of differences between HALAS-AB and radiosonde measurements near VSFB across all 3 flights.

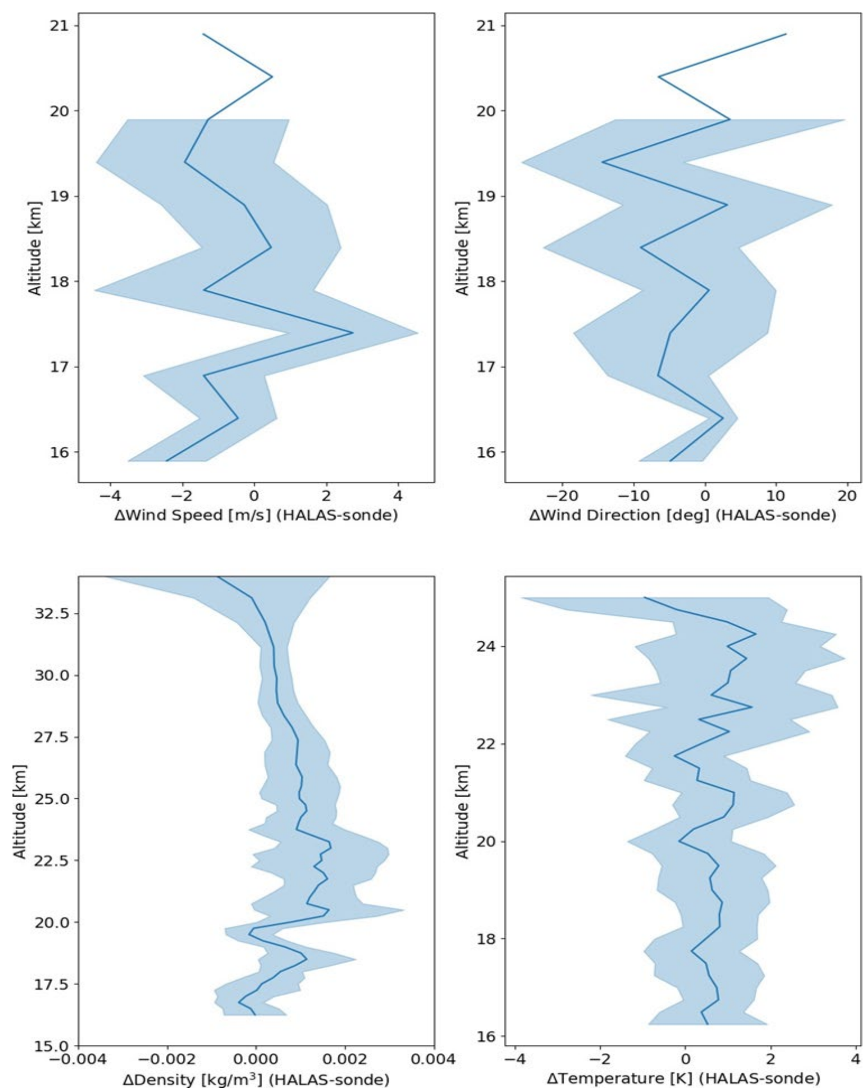


Figure 20: Plot of differences between HALAS-AB and radiosonde measurements near EAFB during Flights 2 and 3.

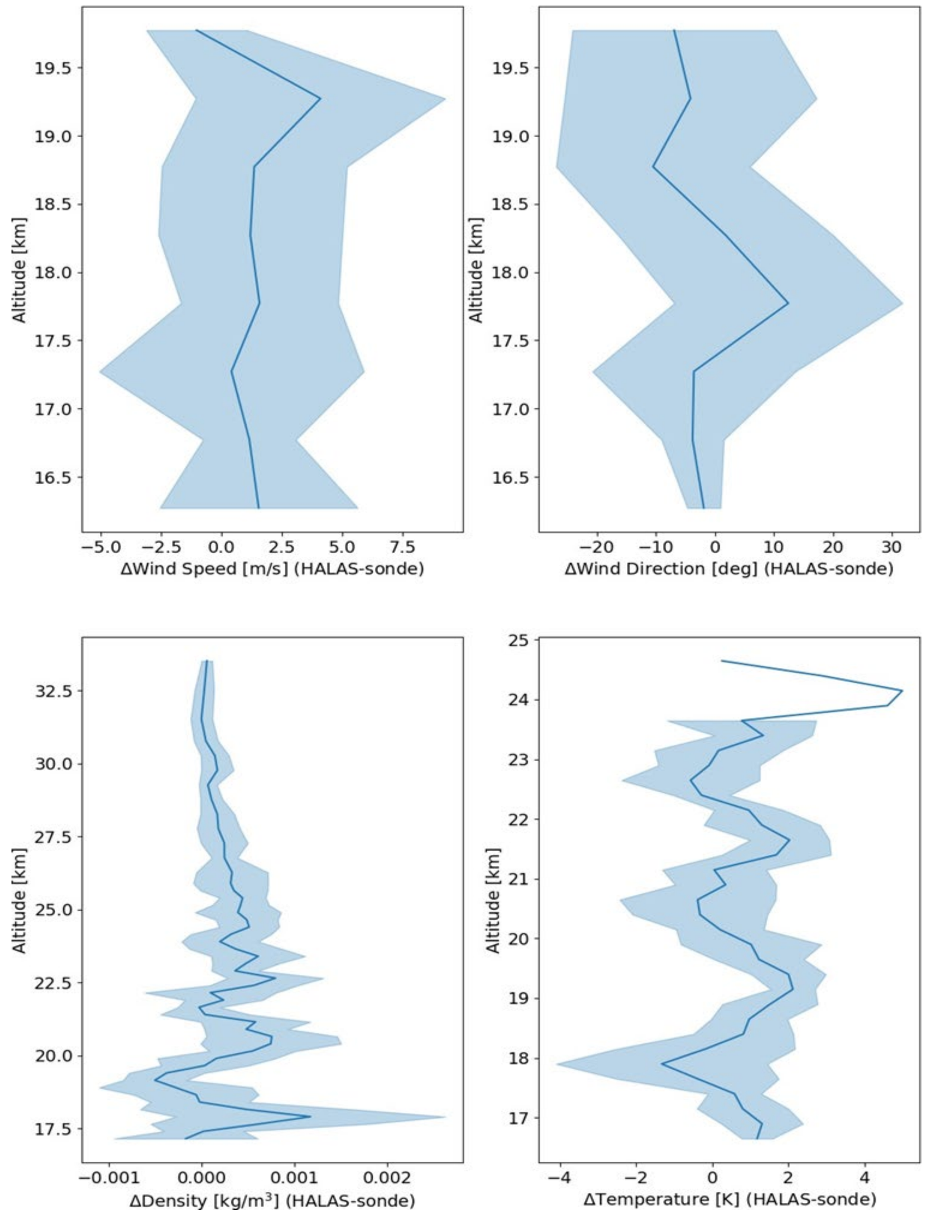
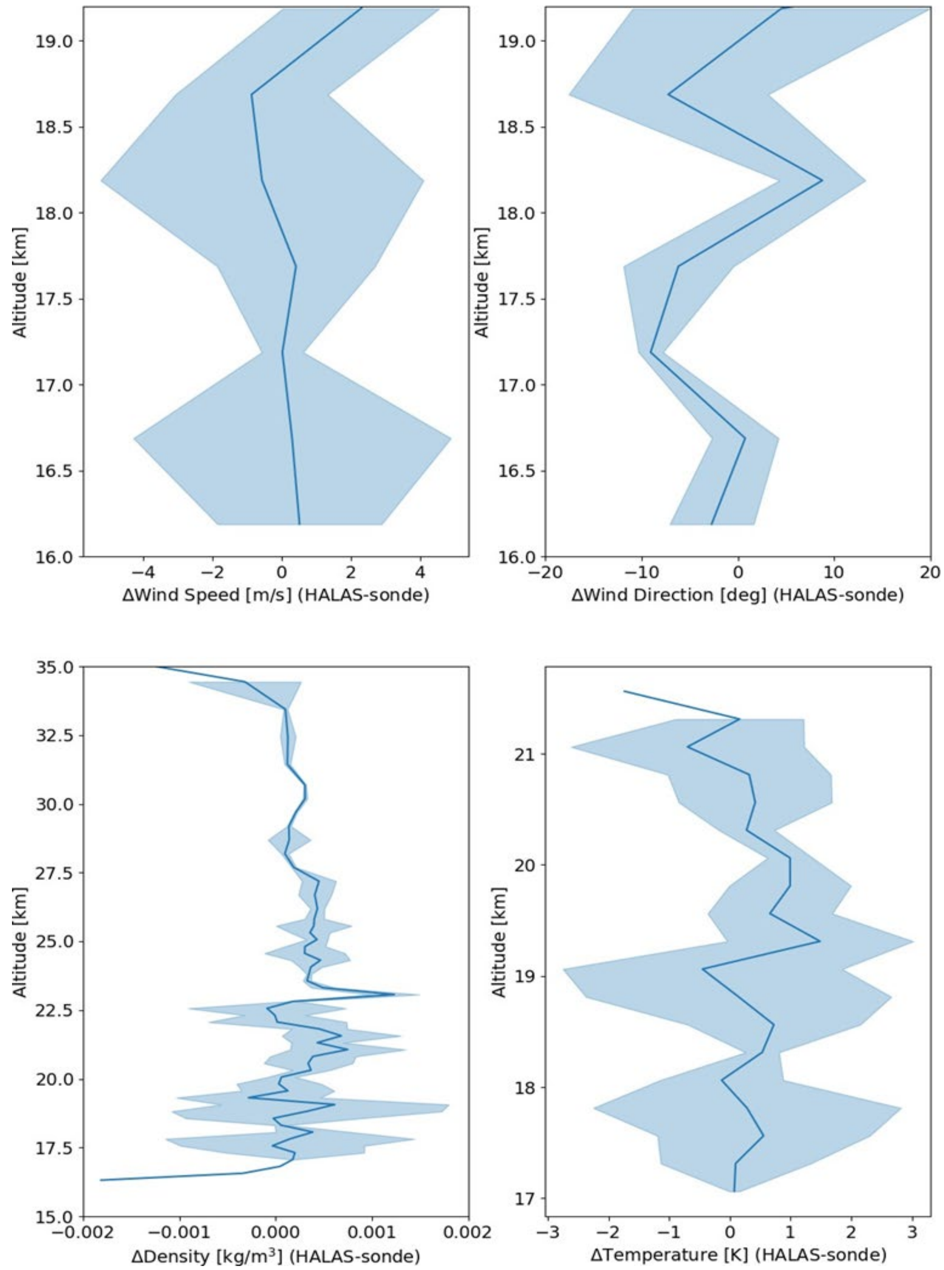


Figure 21: . Plot of differences between HALAS-AB and radiosonde measurements near HNWS during Flight 2.



A summary of the wind statistical comparison for each site is provided in Table 3. For each site, the mean bias and mean absolute difference are vertically averaged over the entire altitude range of the HALAS-AB wind measurements. The values for all these sites are calculated as the weighted mean across the individual sites. For the VSFB comparison, the 15 HALAS-AB sets include TSPs directly over VSFB as well as the TSPs over the Pacific Ocean during Flight 3. The furthest of these sets is taken at TSP 5, which is more than 150 km southwest of VSFB. When TSP 4 and 5 from Flight 3 are omitted from the statistical comparison, there is only a slight change in the difference values, as shown in Table 3. There is a relatively small, altitude-varying mean signed difference for wind speed (<2 m/s) and direction (<5°) for each of the individual sites. For all sites combined, the difference is smaller, with an overall mean bias of 0.2 m/s for wind speed and -2° for wind direction. If the MAD value were considered as a proxy for uncertainty, HALAS wind speed would achieve the minimum and mid-point uncertainty requirements from BAA (10 m/s and 5 m/s, respectively), being slightly too large to satisfy the maximum uncertainty requirement (2 m/s). For wind direction, the MAD value for each site meets the minimum uncertainty requirement (15°) and the MAD value for all sites combined also meets the mid-point requirement (10°).

Table 3: Mean Difference and Mean Absolute Difference between HALAS-AB and Radiosondes for 2D winds.

Site	Mean Signed Difference		Mean Absolute Difference	
	Wind speed (m/s)	*Wind Direction (°)*	*Wind speed (m/s)*	*Wind Direction (°)*
VSFB (15 sets)	-0.4	-3	2.0	9
VSFB, no TSP4 & 5 (13 sets)	-0.4	-4	2.1	10
EAFB (9 sets)	1.2	-1	2.7	11
HNWS (2 sets)	0.5	2	2.1	10
All Sites (26 sets)	0.2	-2	2.3	10

A summary of the statistical comparison between HALAS-AB and radiosondes for density and temperature is provided in Table 4. For density, there is a small bias which varies slightly with altitude. For reference, a 0.002 kg/m3 difference between HALAS-AB and the radiosonde at 20km corresponds to a roughly 2% difference in density. At the lowest altitudes, the density bias might be attributed to detector saturation in the HALAS-AB measurements, while biases above 20km might be due to how aerosols are handled in the HALAS-AB analysis. For temperature, there is a small bias, related to the thermal issue discussed in Section 3.0.

Table 4: Mean Difference and Mean Absolute Difference between HALAS-AB and Radiosondes for density and temperature.

Site	Mean Signed Difference		Mean Absolute Difference	
	Density (g/m^3)	*Temperature (°K)*	*Density (g/m^3)*	*Temperature (°K)*
VSFB (15 sets)	0.6	0.6	1.2	1.2
VSFB, no TSP4 & 5 (13 sets)	0.6	0.7	1.3	1.2
EAFB (9 sets)	0.3	0.7	0.4	1.5
HNWS (2 sets)	-0.6	0.3	1.2	1.0
All Sites (26 sets)	0.3	0.6	0.9	1.3

As with the statistical investigation of HALAS-ground, the comparison of wind speed and direction measured by the radiosondes and HALAS-AB system reveals that HALAS-AB also performed well. While HALAS-AB was not adversely affected by fog, as was experienced by HALAS-ground during Flights 2 and 3, laser and detector instabilities due to the vibrational and thermal environment on the aircraft (as discussed in Sections 2.5 and 3.0) reduced performance, limiting the overall range of wind measurements.

7. Acknowledgements

This project was funded by NOAA/NESDIS/SAE Joint Venture Partnerships. Campaign equipment and flight hours provided by TRMC and HSST. VSFB Weather Squadron and HNWS provided Honeywell access to facilities and limited on-site resources for radiosonde operations. AFRC funded by TRMC and HSST launched radiosondes in support of HAWCS. Many Honeywell employees contributed to the data collection. The authors express gratitude to all those in government and Honeywell who made this campaign possible.

8. Acronyms

Acronym	Description
AFRC	Armstrong Flight Research Center
ALTRV	Altitude Reservation
ATC	Air Traffic Control
BAA	Broad Agency Announcement
EAFB	Edwards Air Force Base
HALAS-AB	HALAS-Airborne
HAWCS	Honeywell Atmospheric Winds Campaign for Space
HNWS	San Joaquin Valley National Weather Service office in Hanford, California
LCH	Laser Clearinghouse
LOS	Line of Sight
MAD	Mean Absolute Difference
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
PDT	Pacific Daylight Time

Acronym	Description
SNR	Signal-to-Noise Ratio
TSP	Test Support Point
UTC	Coordinated Universal Time
UV	Ultraviolet
VSFB	Vandenberg Space Force Base
2D	Two-Dimensional
3D	Three-Dimensional

9. Appendix

9.1 Flight 1 Dataset Information

Table A1: HALAS Airborne data sets from Flight 1.

Location	HALAS Airborne Data set	Data Set Time Range (UTC)	Data Set Duration (HH:MM)
TSP1 (VSFB)	Set 1	03:24-04:24	01:00
	Set 2	04:24-05:24	01:00
	Set 3	05:24-05:58	00:34
	Set 4	05:59-06:59	01:00
	Set 5	06:59-07:31	00:32
	Set 6	07:33-08:33	01:00
	Set 7	08:33-09:33	01:00
	Set 8	09:33-10:33	01:00
	Set 9	10:33-11:33	01:00
	Set 10	11:33-11:58	00:25

Table A2: HALAS-ground data sets around Flight 1.

Location	HALAS-ground Dataset id	Data Set Time Range (UTC)	Data Set Duration (HH:MM)
VSFB	HALAS-ground Set 1	23:57- 01:02	1:05
	HALAS-ground Set 2	01:37-02:41	1:04
	HALAS-ground Set 3	02:43-03:49	1:06
	HALAS-ground Set 4	03:50-04:51	1:01
	HALAS-ground Set 5	08:23-09:26	1:03
	HALAS-ground Set 6	09:29-10:35	1:06
	HALAS-ground Set 7	10:37-11:43	1:06
	HALAS-ground Set 8	11:43-12:49	1:06

Table A3: Radiosondes launched around Flight 1.

Location	Sonde Type	Radiosonde id	Data Set Time Range (UTC)	Data Set Duration (HH:MM)
VSFB	iMet-4	VSFB Radiosonde Set 1	01:40 – 03:20	1:40
		VSFB Radiosonde Set 2	01:36 – 3:22	1:46
		VSFB Radiosonde Set 3	03:36 – 05:18	1:42
		VSFB Radiosonde Set 4	05:36 – 06:42	1:06
		VSFB Radiosonde Set 5	07:04 – 08:45	1:41

9.2 Flight 2 Dataset Information

Table A4: HALAS Airborne data sets during Flight 2.

Location	HALAS Airborne Data set	Data Set Time Range (UTC)	Data Set Duration (HH:MM)
TSP1 (VSFB)	Set 20	02:40-03:45	01:05
TSP2 (Hanford)	Set 21	04:04-05:08	01:04
TSP3 (EAFB)	Set 22	05:36-06:43	01:07
TSP1 (VSFB)	Set 23	07:12-08:17	01:05
TSP2 (Hanford)	Set 24	08:33-09:41	01:08
TSP3 (EAFB)	Set 25	10:01-11:01	01:00
	Set 26	11:01-12:01	01:00
	Set 27	12:01-13:00	00:59

Table A5: HALAS-ground data sets around Flight 2.

Location	HALAS-ground Dataset id	Data Set Time Range (UTC)	Data Set Duration (HH:MM)
VSFB	HALAS-ground Set 9	09:38-10:44	1:06
	HALAS-ground Set 10	10:53-11:59	1:06

Table A6: Radiosondes launched around Flight 2

Location	Sonde Type	Radiosonde id	Data Set Time Range (UTC)	Data Set Duration (HH:MM)
VSFB	iMet-4	VSFB Radiosonde Set 20	00:35 – 02:13	1:38
		VSFB Radiosonde Set 21	02:20 – 04:01	1:41
		VSFB Radiosonde Set 22	04:16 – 05:42	1:26
		VSFB Radiosonde Set 23	05:52 – 07:37	1:45
		VSFB Radiosonde Set 24	07:42 – 09:11	1:29
		VSFB Radiosonde Set 25	09:26 – 11:02	1:36
		VSFB Radiosonde Set 26	11:09 – 12:58	1:49
EAFB		EAFB Radiosonde Set 13	00:49 – 02:19	1:30

Location	Sonde Type	Radiosonde id	Data Set Time Range (UTC)	Data Set Duration (HH:MM)
	Vaisala RS41-SGP	EAFB Radiosonde Set 14	02:49 – 04:40	1:51
		EAFB Radiosonde Set 15	04:54 – 06:41	1:47
		EAFB Radiosonde Set 16	06:52 – 08:40	1:48
		EAFB Radiosonde Set 17	08:52 – 10:36	1:44
		EAFB Radiosonde Set 18	10:47 – 12:32	1:45
HNWS	Vaisala RS41-SGP	HNWS Radiosonde Set 1	03:39 – 05:25	1:46
		HNWS Radiosonde Set 2	00:34 – 02:34	2:00
		HNWS Radiosonde Set 3	04:44 – 06:33	1:49
		HNWS Radiosonde Set 4	06:39 – 08:20	1:41
		HNWS Radiosonde Set 5	08:29 – 10:11	1:42
		HNWS Radiosonde Set 6	10:21 – 12:29	2:08
		HNWS Radiosonde Set 7	02:41 – 04:34	1:53

9.3 Flight 3 Dataset Information

Table A7: HALAS Airborne data sets during Flight 3.

Location	HALAS Airborne Data Set	Data Set Time Range (UTC)	Data Set Duration (HH:MM)
TSP1 (EAFB)	Set 11	02:21-03:21	01:00
	Set 12	03:21-04:21	01:00
	Set 13	04:21-05:21	01:00
	Set 14	05:21-06:21	01:00
	Set 15	06:21-08:01	01:40
TSP3 (East of VSFB)	Set 16	08:22-09:02	00:40
TSP4 (West of VSFB)	Set 17	09:15-10:12	00:57
TSP5 (Pacific Ocean)	Set 18	10:25-10:54	00:29
TSP3 (East of VSFB)	Set 19	11:13-12:14	01:01

Table A8: HALAS-ground data sets around Flight 3.

Location	HALAS-ground Dataset id	Data Set Time Range (UTC)	Data Set Duration (HH:MM)
VSFB	VSFB Radiosonde Set 8	22:39 – 23:44	1:05
	VSFB Radiosonde Set 9	00:00 – 01:05	1:05
	VSFB Radiosonde Set 10	02:43 – 03:49	1:06
	VSFB Radiosonde Set 11	04:19 – 05:24	1:05

Table A9: Radiosondes launched around Flight 3

Location	Sonde Type	Radiosonde id	Data Set Time Range (UTC)	Data Set Duration (HH:MM)
VSFB	iMet-4	VSFB Radiosonde Set 12	01:21 – 03:02	1:41
		VSFB Radiosonde Set 13	00:32 – 02:00	1:28
		VSFB Radiosonde Set 14	02:16 – 03:46	1:30
		VSFB Radiosonde Set 15	03:59 – 05:31	1:32
		VSFB Radiosonde Set 16	05:47 – 07:22	1:35
		VSFB Radiosonde Set 17	07:45 – 09:28	1:43
		VSFB Radiosonde Set 18	09:40 – 11:22	1:42
		VSFB Radiosonde Set 19	11:31 – 13:12	1:41
EAFB	Vaisala RS41-SGP	EAFB Radiosonde Set 7	00:28 – 01:37	1:09
		EAFB Radiosonde Set 8	01:55 – 03:36	1:41
		EAFB Radiosonde Set 9	03:59 – 05:48	1:49
		EAFB Radiosonde Set 10	06:02 – 07:44	1:42
		EAFB Radiosonde Set 11	07:57 – 09:38	1:41
		EAFB Radiosonde Set 12	10:05 – 11:13	1:08

9.4 BAA Table 2

Table A10: Trade ranges for 3D Wind Measurements from Broad Agency Announcement

Attribute	Minimum	Mid-Point	Maximum
Minimum Coverage Area	Close to global, if possible, regional gaps acceptable	Global	Global
Update Rate[1]	24 hrs	6 hrs	3 hrs
Latency[2]	165 min	60 min	30 min
Horizontal Resolution (nadir)	400 km	40 km	15 km
Vertical Resolution	4 km	2 km	0.5 km
Uncertainty: Direction	±15°	±10°	±5°
Uncertainty: Speed	10 m s^{-1}	5 m s^{-1}	2 m s^{-1} or 10%
Vertical Extent	Mid-troposphere to just above tropopause	Surface to just above tropopause	Surface to Stratopause

[1]Update rate is the time interval between successive collections of data from the same geographical point on, or above, the surface of the earth.

[2]Data Latency is defined as the period from the time of observation of all requisite data by the satellite until the data product produced from those date is available to the user at the distribution system.