Bleed-Air Sensing: Wireless Sensor Networks in Mock-up Cabin

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16. Abstract

The semi-enclosed and pressurized nature of the aircraft cabin results in a highly dynamic environment. The dynamic conditions establish spatiotemporal dependent environmental characteristics. Characterization of aircraft cabin environmental and bleed-air conditions have traditionally been done with stand-alone measurement systems which, by their very nature, cannot provide the necessary sensor coverage in such an environment. In an effort to provide better tools for bleed-air and aircraft cabin environmental monitoring, research is being done to implement a wireless sensor network (WSN) for bleed-air and cabin environmental monitoring.

This report presents the results of initial testing done to verify the feasibility of a prototype WSN system developed by Boise State University for bleed-air and environmental monitoring. The environmental measurement tests were carried out within a mock-up Boeing 767 cabin developed by Kansas State University in an effort to simulate the conditions found within aircraft cabins. The test results indicate that the developed wireless sensor network may be used to effectively detect general environmental contaminant levels throughout the aircraft cabin. Moreover, the performance of the system indicates that the monitoring system may be applied to bleed-air sensing once an effective bleed-air contamination sensor is selected.

17. Key Words	18. Distribution Statement
Aircraft cabin, environmental monitoring, wireless sensor network	

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Introduction

On August 2nd 2011, Boise State University deployed its Fusion wireless sensor network within Kansas State University's Boeing 767 mock-up cabin section to verify the feasibility of capturing measurements of highly dynamic environmental conditions present in airliner cabins utilizing wireless sensor networks. The sensor network consisted of 12 wireless sensor units and a base station. Each wireless sensor unit was configured to measure four environmental conditions: CO_2, temperature, humidity, and atmospheric pressure. This set of sensors was used to show that wireless sensor network can be used to monitor bleed-air and general cabin environmental variables. The WSN system is designed to allow a wide range of different sensors to be incorporated into the system (as the particular application requires). The 12 sensor units were uniformly distributed across the cabin such that each seating section had sensor modules located at 100" intervals down the length of the cabin. This configuration resulted in a 76" spacing laterally between modules. The modules were placed on the top of the seatbacks to provide proximity to seated passenger head level. Figure 1 shows a diagram of the sensor module locations within the cabin section.

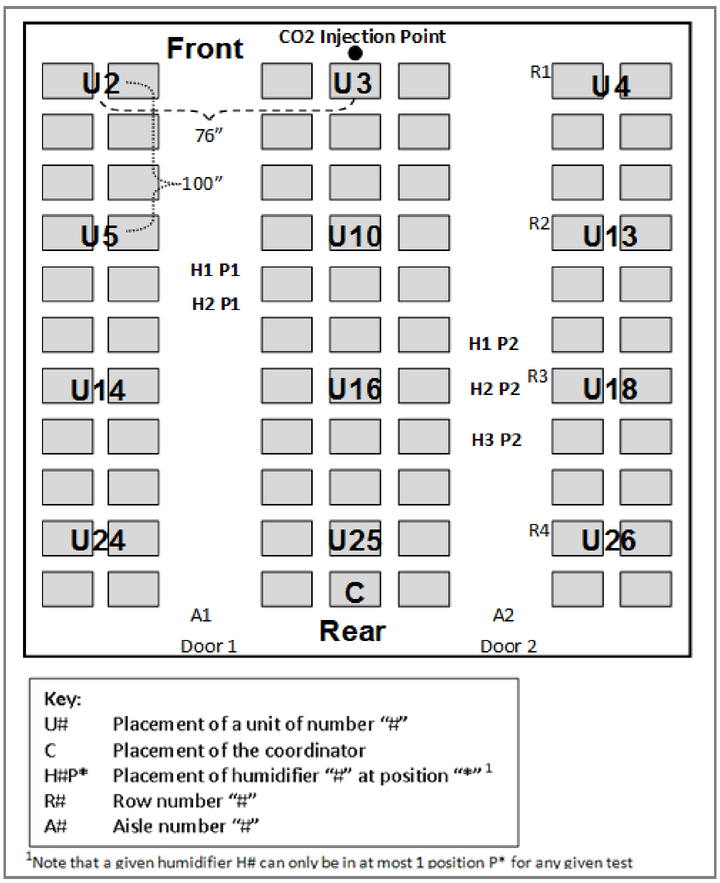

Figure 1: Cabin Layout and Test Configuration

Two test series were performed. The first test series (Series 1) primarily tested humidity dispersion and provided a basic test of the system. During Series 1, humidifiers were located in two different areas within the cabin (P1 and P2 in Figure 1). The other three environmental parameters (CO_2, temperature, and pressure) were also acquired during the humidity testing. The second test series (Series 2) primarily tested CO_2 dispersion through the cabin. Unlike the humidity sources used in Series 1, the CO_2 injection point remained fixed across all test runs as the CO_2 injection point was not adjustable in the cabin system.

Test Series 1

Series 1 was composed of five humidity cycles. Two cycles were done in position P1, and three cycles were done in position P2, as shown in Figure 1. For the first two cycles, two humidifiers were placed at P1 while the remaining three runs were conducted with three humidifiers at P2. Figure 2 shows the humidity changes over the first two humidity runs in Series 1.

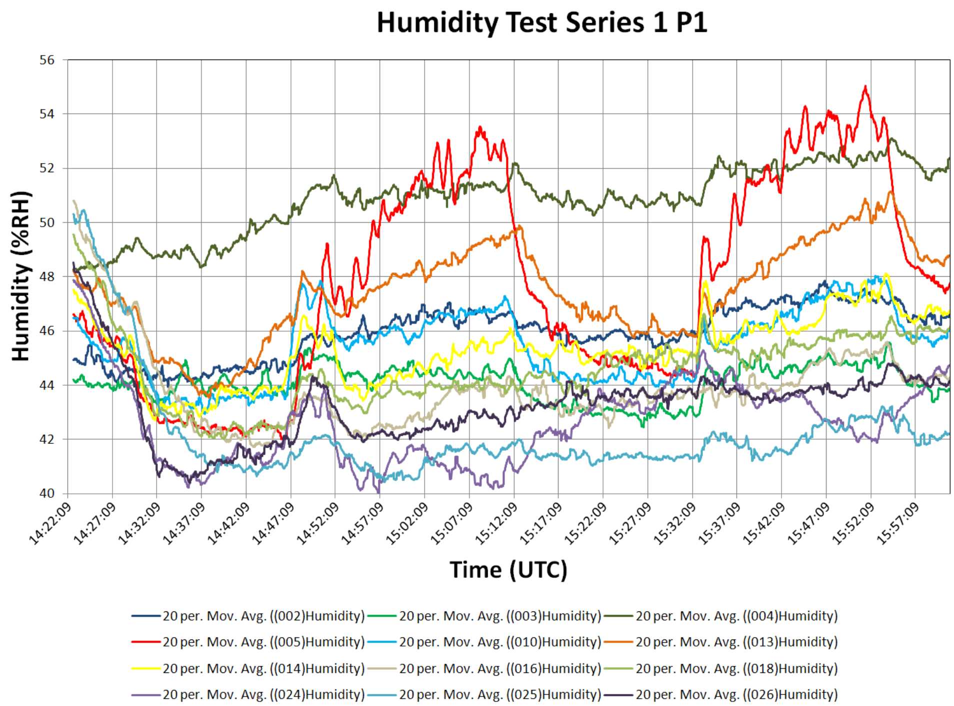

Figure 2: Humidity Test Series 1 P1

As seen in Figure 2, the sensor units responded to the changing humidity. The units in row 2 (U5, U10, and U13) and U2 showed strong humidity perturbations, while the remaining units did not change significantly from the baseline. The humidity sensor behavior on U4 seems to indicate some humidity saturation. U4 humidity remained well above the baseline and did not track closely with humidity reduction cycles as compared with other humidity sensors in the group.

The last three runs of Series 1 are shown in Figure 3. With the additional humidifier at P2 it was possible to generate an increased humidity perturbation. This is evident in the peak humidity measurements which exceeded 60%, whereas the first two runs at P1 did not exceed 55%.

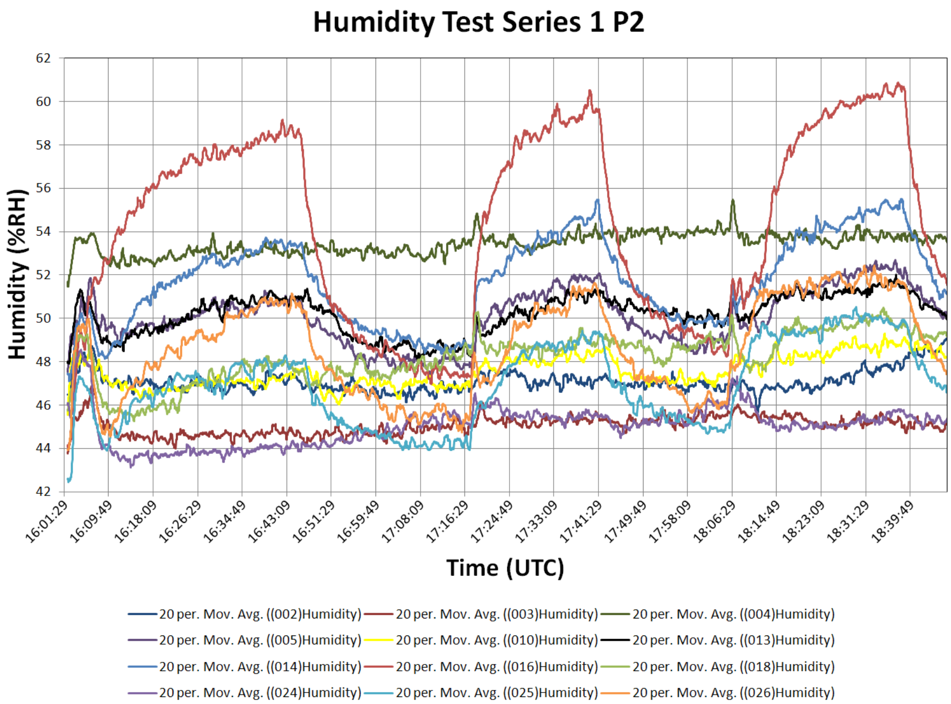

Figure 3: Humidity Test Series 1 P2

With the increased volume of humidified air being generated at P2, a larger portion of the sensor modules showed measureable changes in humidity. Units located in rows 2 (U5, U10, and U13), 3 (U14, U16, and U18), and 4 (U25 and U26; excluding U24) showed increased humidity during each run, with units U14, U16, and U26 showing the largest increase.

The complete timeline of the Series 1 tests is shown in Table 1.

Table 1: Test Series 1 Timeline

Time	Event	Description
14:22:08	Start of Series 1	All units connected to network by this time. We experienced some issue with connecting units 4 and 13. They connected to the network (indicated by the solid blue Zigbit LED), but never sent identifiers or data. To get them to connect, we had to move them closer to the coordinator, let them connect, and then replace them in the proper spots.
XX:XX:XX	Setup	Two occupants opened door 1 and set up a humidifier in position H1P0. Humidifier was turned on.
14:30:00	Door Closed	Door 1 closed.
14:46:00	Start of Run 1	Door 1 opened and 2 occupants set up two humidifiers in positions H1P1 and H2P1. Both Humidifiers were turned on. H1P0 was removed.
14:50:00	Door Closed	Door 1 closed.
15:10:30	End of Run 1	Door 1 opened and humidifiers turned off.
15:11:00	Door Closed	Door 1 closed.
15:32:00	Start of Run 2	Door 1 opened, one occupant entered and turned on humidifiers.
15:33:00	Door Closed	Door 1 closed.
15:53:00	End of Run 2	Door 1 opened, one occupant entered and turned off humidifiers.
15:53:30	Door Closed	Door 1 closed.

16:01:30	Start of Run 3	Doors 1 and 2 opened, four occupants set up three humidifiers in position P2.
16:06:00	Door Closed	Doors 1 and 2 closed.
16:45:35	End of Run 3	All humidifiers turned off. (No occupants, humidifier power unplugged)
17:17:30	Start of Run 4	Door 2 opened, one occupant entered and turned on humidifiers.
17:17:40	Door Closed	Door 2 closed.
17:41:00	End of Run 4	All humidifiers turned off. (No occupants, humidifier power unplugged)
18:05:30	Start of Run 5	Door 2 opened, one occupant entered and turned on humidifiers
18:05:40	Door Closed	Door 2 closed.
18:38:00	End of Run 5	All humidifiers turned off. (No occupants, humidifier power unplugged)

Figure 4, Figure 5, and Figure 6 show the CO_2, temperature, and pressure respectively over the Series 1 test runs.

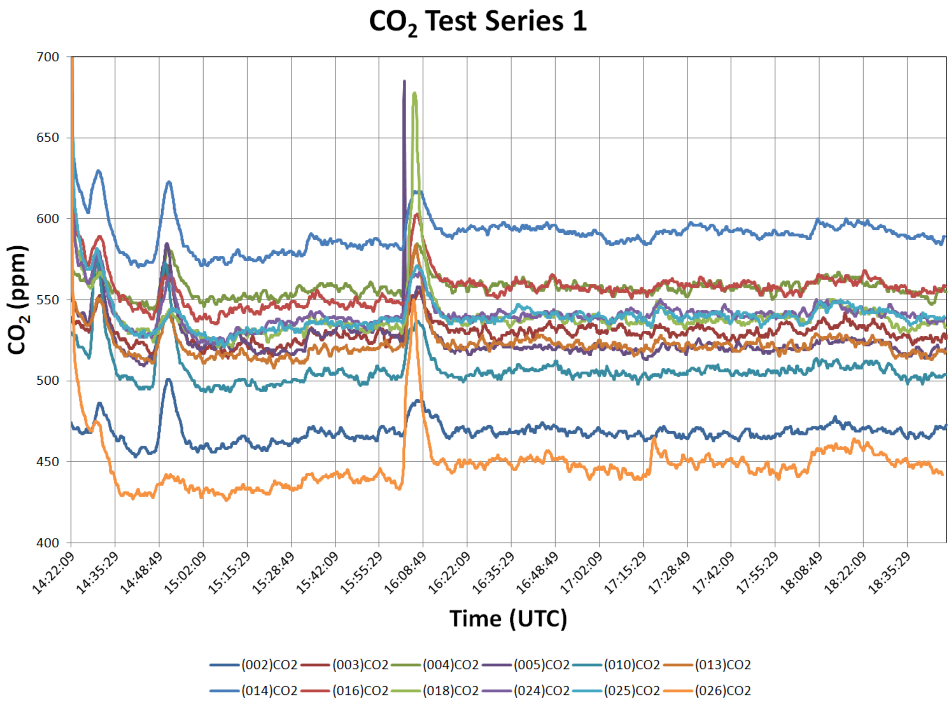

Figure 4: CO2 Measurements during Series 1 Tests

In Figure 4, a peak in CO_2 corresponds with the time during which four occupants placed humidifiers within the cabin. Figure 4 also shows that there was a maximum of approximately a 150 ppm spread among sensor nodes, with most sensors within a 50 ppm spread. Units U26 and U2 read low whereas U14 reads high. The CO_2 sensor used on the sensor nodes provides accuracy of ±75 ppm or ± 10%, whichever is greater. In this case we see that the sensors are behaving within specification as we expect that the cabin at that time to be uniform.

Figure 5 shows the temperature variation within the cabin. We see the temperature variation is nearly the inverse of the humidity variations at nodes where humidity changed significantly. This is more clearly shown in Figure 7 which shows the temperature and humidity at U16.

For reference, Figure 6 shows the atmospheric pressure during Test Series 1. During the testing day we saw a general trend of decreasing pressure.

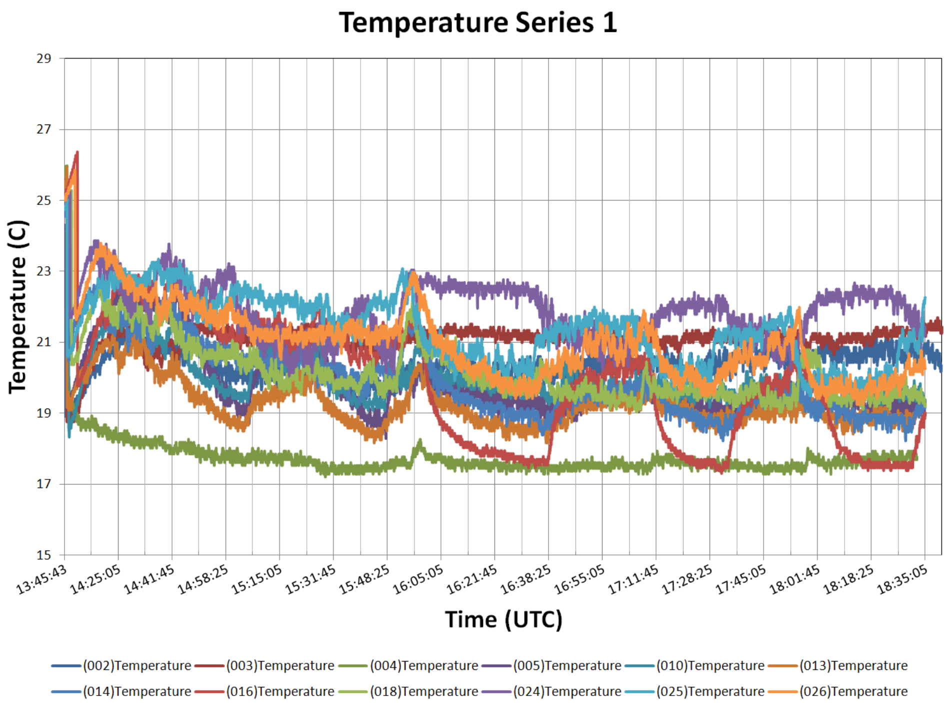

Figure 5: Temperature Test Series 1

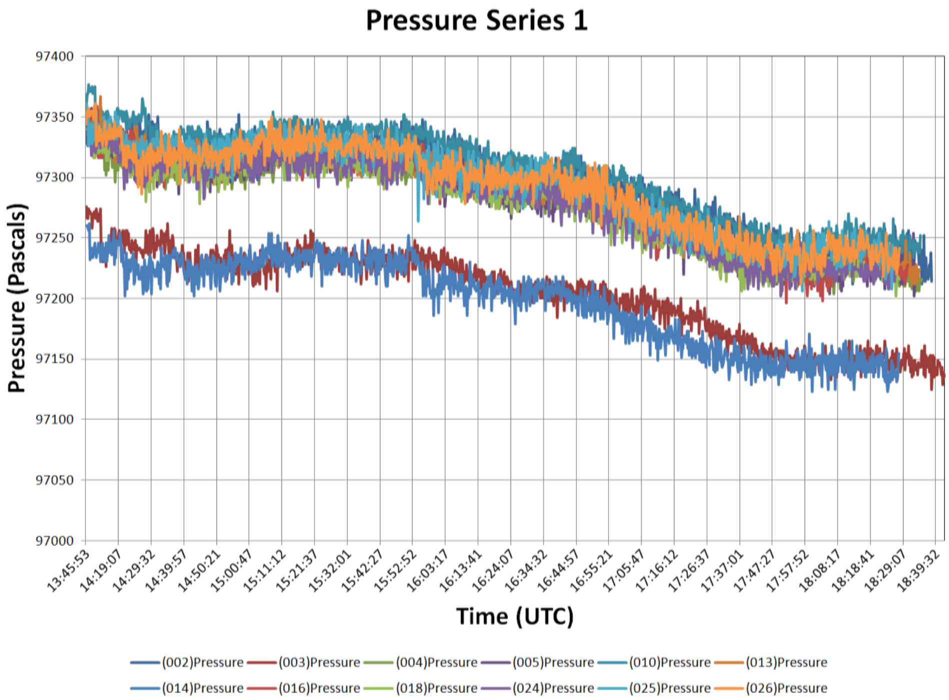

Figure 6: Pressure Test Series 1

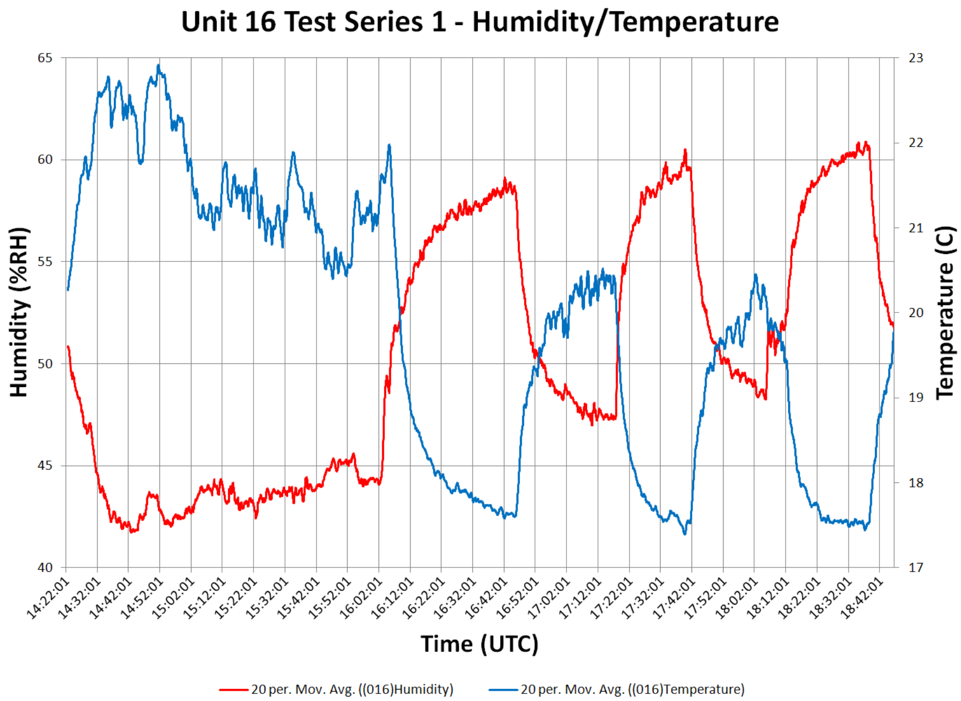

Figure 7: Humidity/Temperature Relationship

Test Series 2

Test Series 2 was composed of four test runs. During the first two runs only CO_2 was flowed into the cabin. For runs three and four CO_2 was flowed, passenger dummy heaters remained on, and humidifiers were cycled. Table 2 shows the experimental timeline.

Table 2: Test Series 2 Timeline

Time	Event	Description
18:55:00	Start of Test Series 2	All units power cycled. Note: Turning the CO_2 on and off does not require any doors to open in the cabin.
UU:UU:UU	Node reset	CO_2 was flowed but Unit 3 had to be reset because it stopped sending data.
19:05:00	Started Run 1	Flowed CO_2
19:28:00	Stopped Run 1	Stopped CO_2
19:43:20	Started Run 2	Flowed CO_2
20:08:00	Stopped Run 2	Stopped CO_2
20:12:00	Started Heaters	Passenger dummy heaters started
20:22:00	Started Run 3	One occupant entered and started humidifiers.
20:22:10	Closed Door	Closed door 2. Started CO_2.
20:57:00	Stopped Run 3	All humidifiers turned off and CO_2 stopped.
21:13:00	Started Run 4	Door 2 opened, humidifiers started.
21:13:10	Door Closed	Door 2 closed. CO_2 started.
21:37:00	Stopped Run 4	All humidifiers turned off and CO_2 stopped

As seen in Figure 8, CO_2 concentrations were well distributed through the cabin. As the CO_2 was flowed into the front of the cabin, we see the highest concentration of CO_2 nearest the front of the cabin, tapering off toward the rear of the cabin. From Figure 8, we see that the last two runs which included humidity and temperature variations, U2 showed a significantly higher concentration of CO_2 than the other tests. Which effect (increased heat or humidity) may have caused this reaction is not clear.

As illustrated in Figure 10 and Figure 11, increasing humidity resulted in a decreasing temperature on nodes where humidity was significantly increased. Figure 10 also clearly shows the time at which the passenger dummy heaters were turned on.

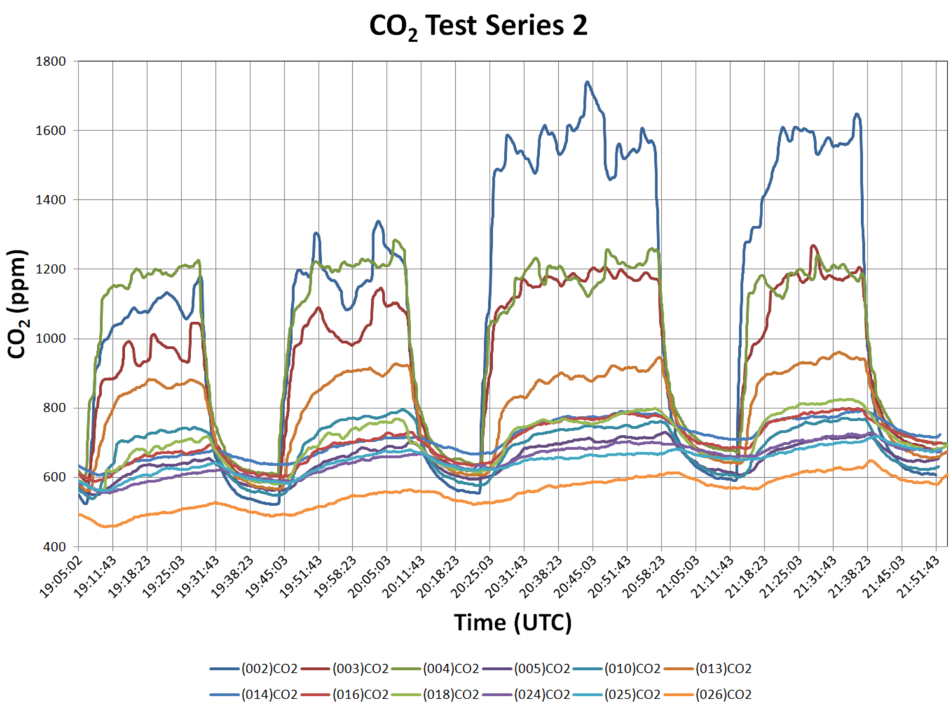

Figure 8: CO_2 Test Series 2

Figure 9 shows a contour plot of the CO_2 distribution to better visualize the CO_2 distribution.

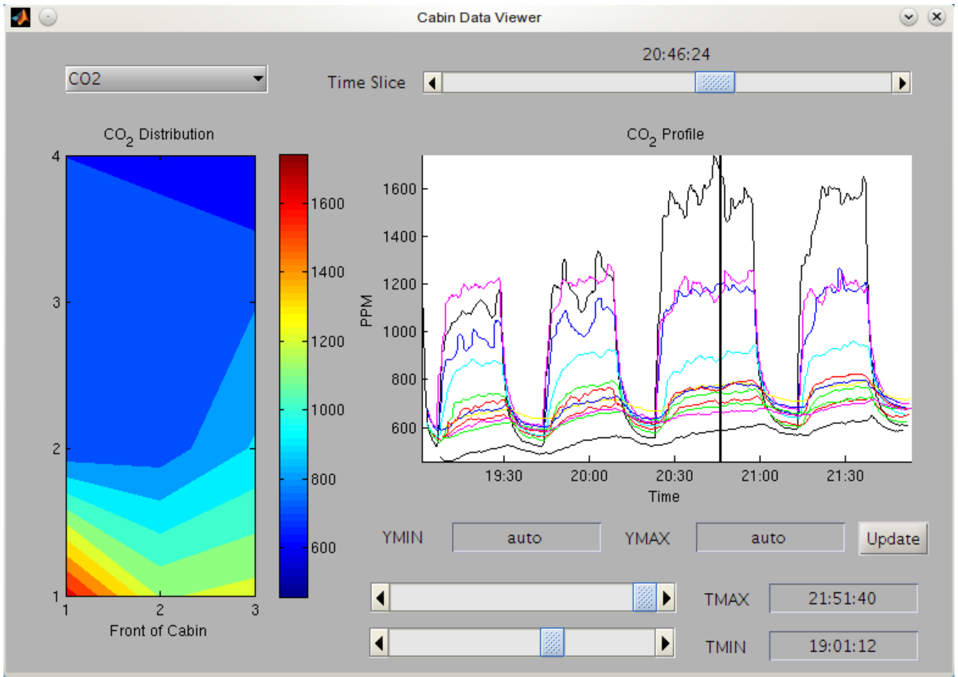

Figure 9: CO_2 Distribution

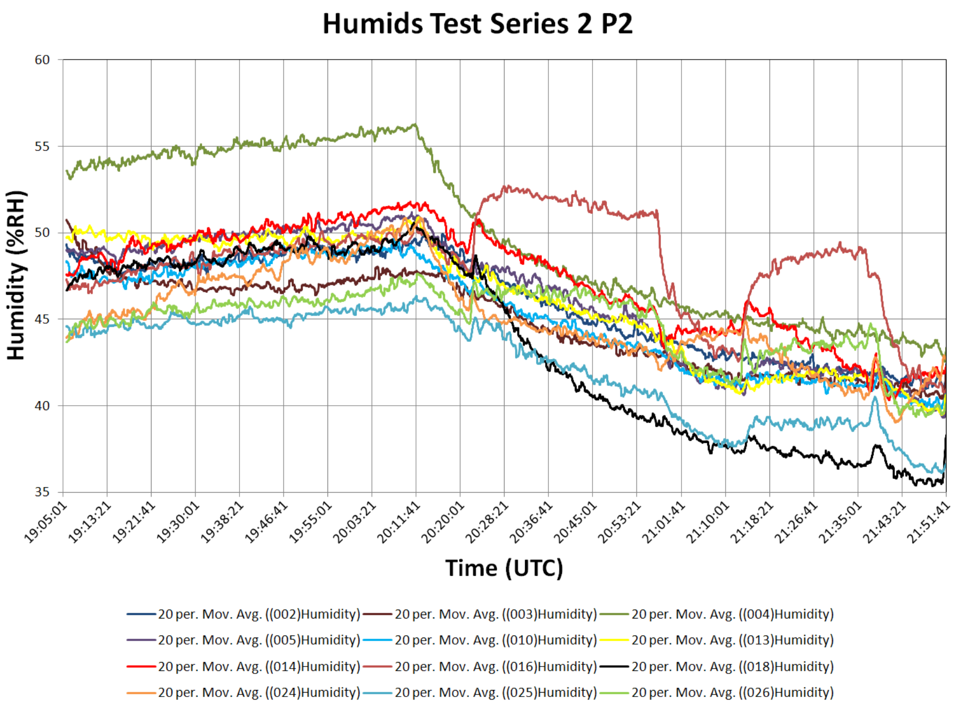

Figure 10: Humidity Test Series 2 (P2)

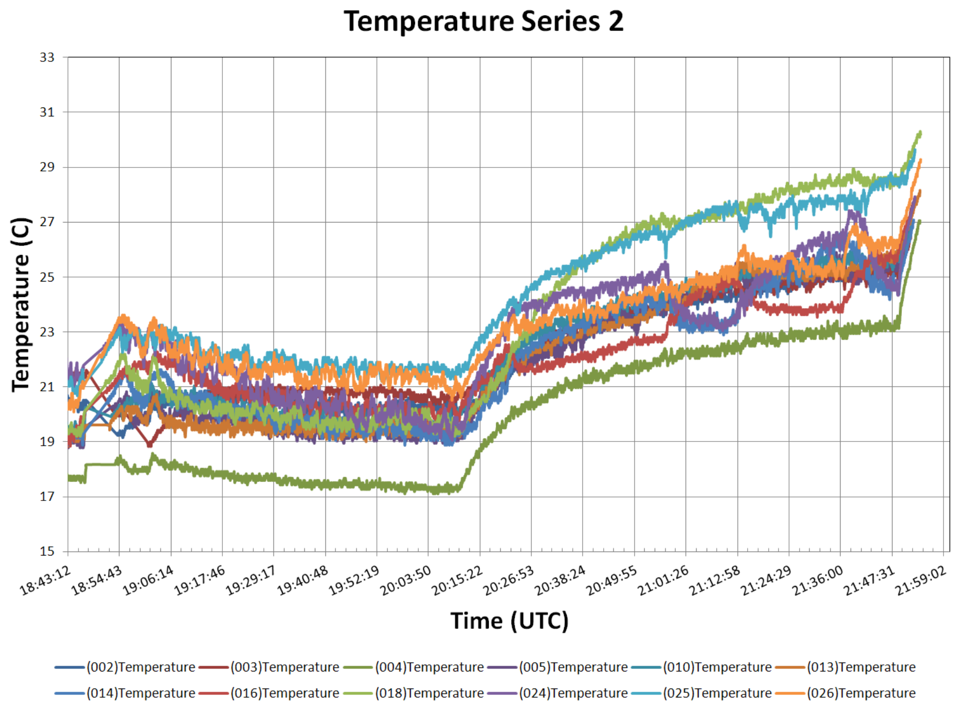

Figure 11: Temperature Series 2

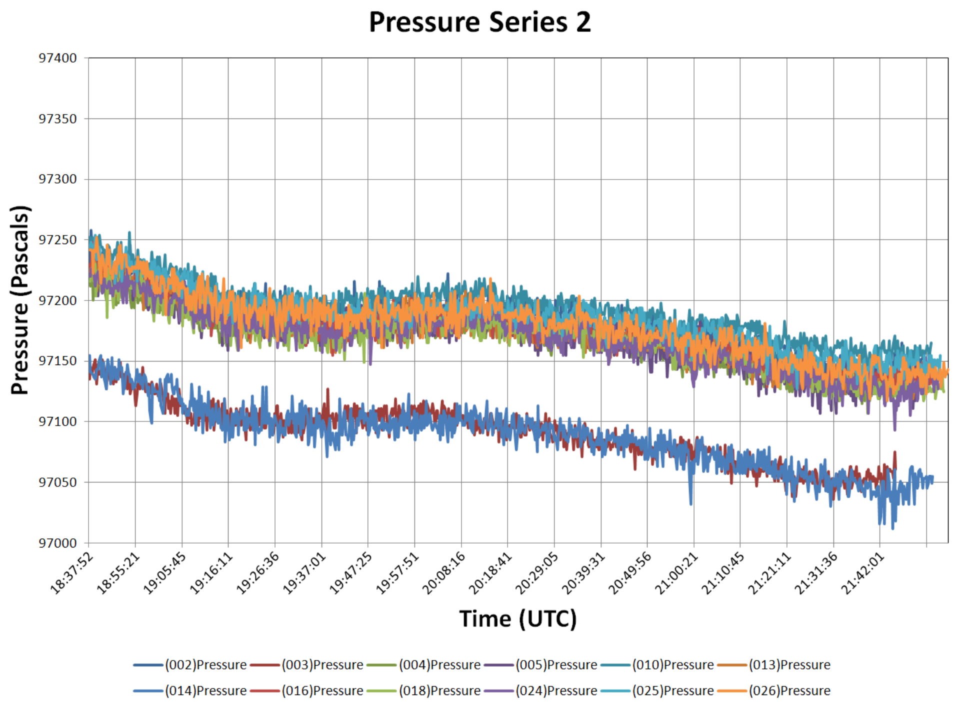

Figure 12: Pressure Series 2

Figure 12 shows that, as with Test Series 1, atmospheric pressure continued to drop during Test Series 2.

Summary Data

Finally, in Figure 13, Figure 14, Figure 15, and Figure 16, we see the overall responses across both test series.

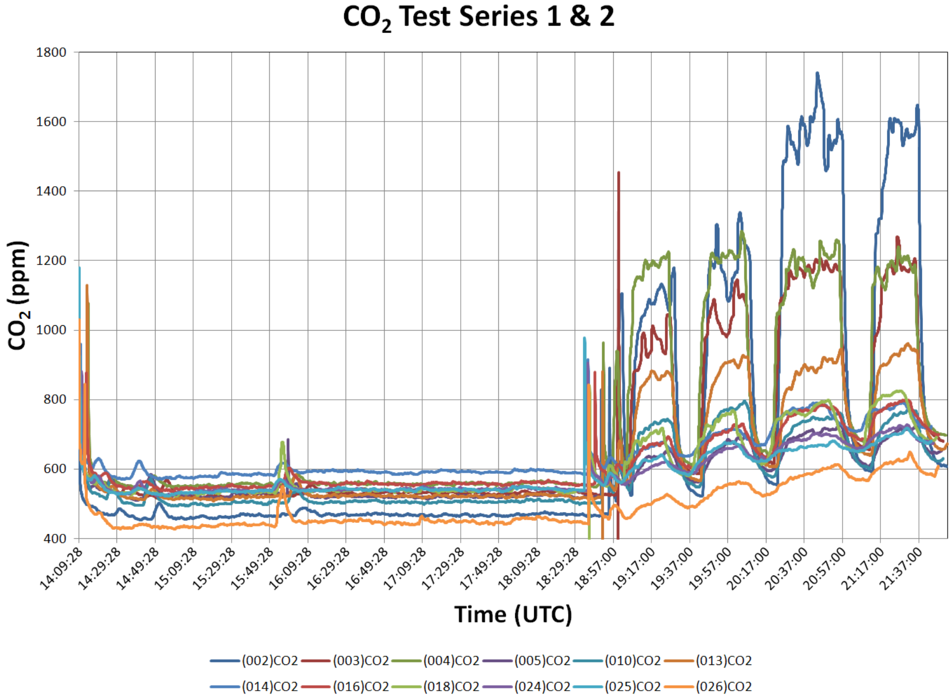

Figure 13: CO2 Test Series 1 and 2

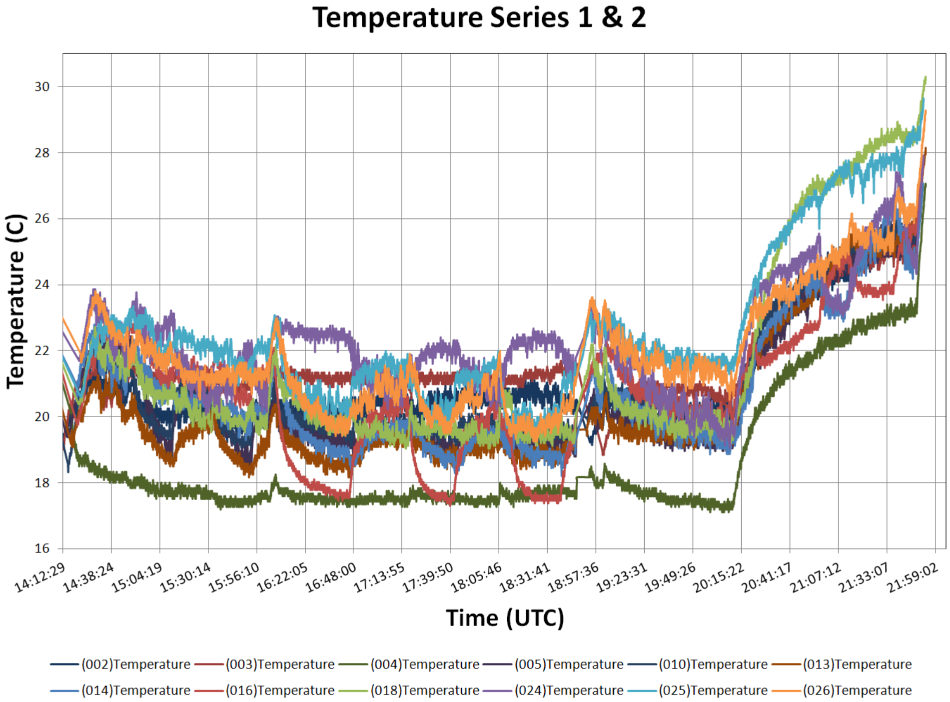

Figure 14: Temperature Test Series 1 and 2

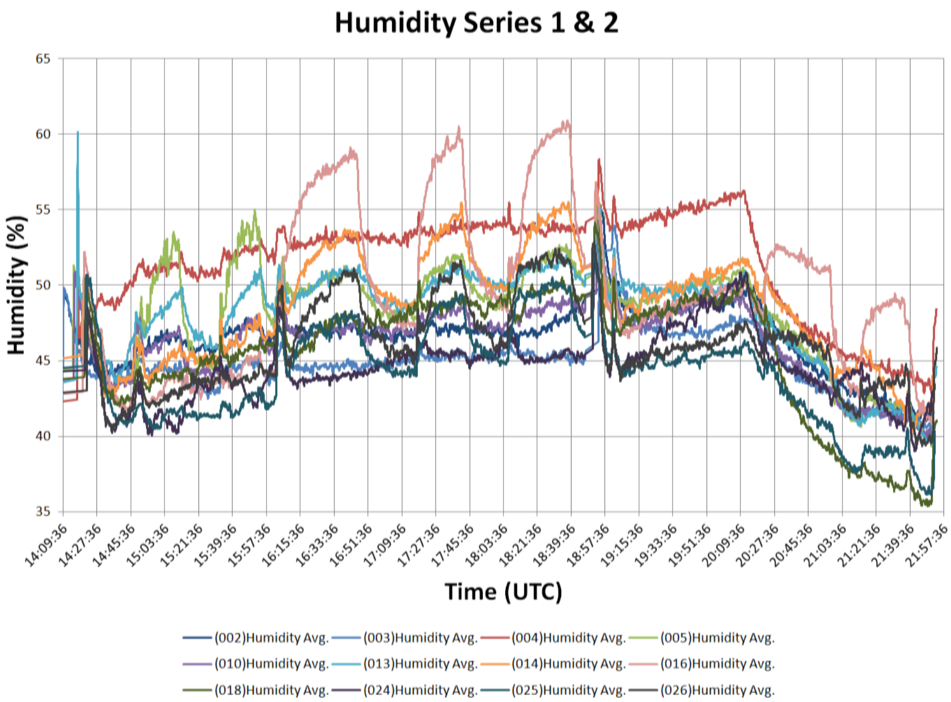

Figure 15: Humidity Test Series 1 and 2

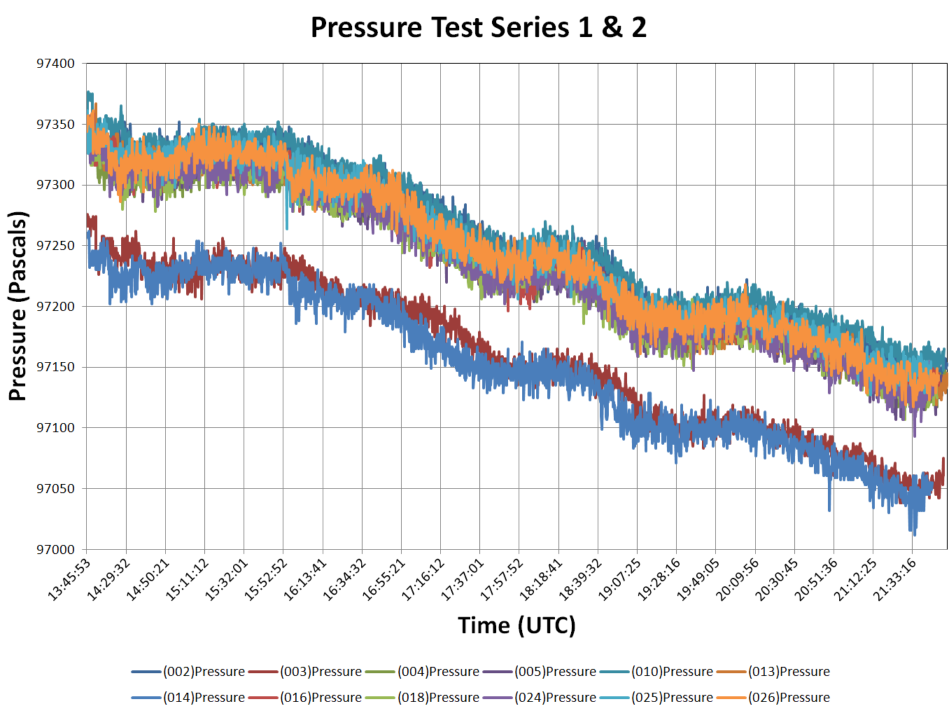

Figure 16: Pressure Test Series 1 and 2

Conclusion

In previous research, baseline data was collected in the aircraft cabin using single-point measurement systems. This new system can be used to characterize bleed-air and monitor the way contaminants distribute throughout an aircraft cabin. The system performance results indicate that with appropriate sensors, the wireless sensor network may be used to localize where a contaminant has been introduced into the cabin. We believe contaminant localization will enable differentiation of bleed-air sourced and other cabin sourced contaminants introduced into the aircraft cabin. Wireless sensor networks can provide the necessary coverage and cooperation to effectively monitor the aircraft cabin environment. This new high-performance wireless data acquisition system (in prototype state) may be used to meet the needs of aircraft bleed-air and environmental monitoring. A prototype of this new system has been tested in a Boeing 767 mock-up cabin. A few issues related to the initial wireless network formation were discovered. However, as was illustrated by the presented data, the Fusion wireless sensor network was shown capable of monitoring multiple environmental variables, and providing real-time, correlated data. Certainly, the Fusion network provides a new tool that will improve our ability to characterize highly dynamic environmental systems.