43rd Aerospace Sciences Meeting and Exhibit Conference **AIAA-2005-0259**
10-14 January 2005, Reno, Nevada

TAMDAR Sensor Validation in 2003 AIRS II

Taumi. S. Daniels[*] and John J. Murray[†]
NASA Langley Research Center, Hampton, Virginia, 23681

Mark V. Anderson[‡],Daniel J. Mulally[§], Kristopher R. Jensen[**]
AirDat, LLC., Evergreen, Colorado, 80439

Cedric A. Grainger[††] and David J. Delene[‡‡]
University of North Dakota, Grand Forks, North Dakota, 58202

This study entails an assessment of TAMDAR in situ temperature, relative humidity and winds sensor data from seven flights of the UND Citation II. These data are undergoing rigorous assessment to determine their viability to significantly augment domestic Meteorological Data Communications Reporting System (MDCRS) and the international Aircraft Meteorological Data Reporting (AMDAR) system observational databases to improve the performance of regional and global numerical weather prediction models. NASA Langley Research Center participated in the Second Alliance Icing Research Study from November 17 to December 17, 2003. TAMDAR data taken during this period is compared with validation data from the UND Citation. The data indicate acceptable performance of the TAMDAR sensor when compared to measurements from the UND Citation research instruments.

I. INTRODUCTION

THE Tropospheric Airborne Meteorological Data Reporting (TAMDAR) sensor is designed to measure winds, temperature, humidity, turbulence and icing from regional commercial aircraft[1]. AirDat, LLC, developed the sensor under contract for NASA[2]. A system of TAMDAR sensors and data links on a sufficient number of aircraft would provide high temporal- and spatial-resolution wind and temperature data in the lower troposphere. Such a system has the potential to substantially improve weather forecasting. Moreover, the high-resolution humidity data produced by TAMDAR is unprecedented, and may provide substantial benefits. The meteorological community is keenly interested in additional observations of the lower troposphere and in particular moisture data as evidenced by the American Meteorological Society Statement[3].

The University of North Dakota (UND) Cessna Citation II and the NASA ER-2 participated from November 19 to December 14, 2003, a period of overlap between two separate field campaigns, the Second Alliance Icing Research Study (AIRS II). AIRS II flights were over Ottawa, Ontario and the Mirabel Airport outside Montreal, Quebec.

To support the campaign, it was necessary to identify suitable cases for targeting, provide information on the location of sensitive areas, and have the facilities to control each observing system at short notice. Early morning meteorological reports were used for daily aircraft routing. Additional information can be found on the websites[4,5].

As part of the development process, the TAMDAR sensor has been tested in various ground-based facilities and on different atmospheric research aircraft[6]. The subject of this report is validation of TAMDAR sensor using data other instruments installed on the UND Citation. Additional validation data came from GPS dropsondes (from the UND Citation). In addition, other data from two sounding instruments is used for comparison purposes.

[*] Project Manager, Electromagnetics and Sensors Branch, NASA, MS-473, Hampton, VA 23681
[†] Atmospheric Scientist, Chemistry and Dynamics Branch, NASA, MS-401B, Hampton, VA 23681
[‡] President, AirDat LLC, 30746-410 Bryant Dr., Evergreen, CO, 80439
[§] Vice President, AirDat LLC, 30746-410 Bryant Dr., Evergreen, CO, 80439
[**] Engineer, AirDat LLC, 30746-410 Bryant Dr., Evergreen, CO, 80439
[††] Professor, Department of Atmospheric Sciences, UND, Grand Forks, ND, 58202
[‡‡] Assistant Professor, Department of Atmospheric Sciences, UND, Grand Forks, ND, 58202

II. ALLIANCE ICING RESEARCH STUDY II

AIRS II objectives were to: a) develop techniques to remotely detect, diagnose and forecast hazardous winter conditions at airports, b) improve weather forecasts of aircraft icing conditions, c) improve characterization of the aircraft icing environment and d) improve our understanding of the icing process and its effect on aircraft[7,8].

In order to support the AIRS II operational objectives, data was collected to: a) investigate the conditions associated with supercooled large drop formation, b) determine conditions governing cloud glaciation, c) document the spatial distribution of ice crystals and supercooled water and the conditions under which they co-exist, and d) verify the response of remote sensors to various cloud particles, and determine how this can be exploited to remotely determine cloud composition.

III. AIRCRAFT INSTRUMENTATION

For the AIRS II flights, the three main aircraft, the NRC Convair 580, the NASA Twin Otter, and the NCAR C130 were joined by the UND Citation. Icing flight configurations typically consisted of the three main aircraft in flight patterns near the Mirabel site. Data from the three main aircraft are not presented here and are only mentioned for completeness. However, data from TAMDAR sensor and the UND Citation instruments is presented.

The UND Citation aircraft is instrumented for in-situ cloud physics research. For this field campaign the TAMDAR sensor package was installed on the fuselage near the ship's pitot probe. In addition, the aircraft was equipped to deploy NCAR GPS dropsondes.

The NASA ER-2 carried the NAST-I instrument. The temperature sounding data were retrieved from NAST-I infrared hyperspectral radiances[9]. NAST-I data were searched for the location where and time when the ER-2 and the Citation were collocated within a delta Latitude <= 0.05°, delta Longitude <=0.05°, and delta time <= 5 min. Mean values for temperature of NAST-I retrievals within the matching criteria are computed and reported as NAST-I temperature data.

The temperature accuracy for the TAMDAR sensor is ±1°C. To verify this value, a comparison to UND Citation Rosemount Model 102 Probe sensor data over the period of interest and also over the entire day's flight is made. The Rosemount sensor accuracy is 0.5°C. Both TAMDAR and Rosemount data are corrected for dynamic heating.

The TAMDAR sensor has two independent RH sensors, Honeywell HIH series thin film capacitive types. As both were reporting very similar values, only data from one is used for this comparison. The reported RH accuracy is +/- 5% for temperatures down to 0°C and below airspeed of Mach 0.4. Above Mach 0.4 the RH accuracy is +/- 10%. A lack of calibration data below 0°C forces an extrapolation of the available calibration data. While this is probably valid down to about -40°C, significant measurement differences will be apparent at the lower temperature extremes. With actual calibration data at the lower temperatures, the TAMDAR sensor values for relative humidity would be in line with the +/- 5% accuracy.

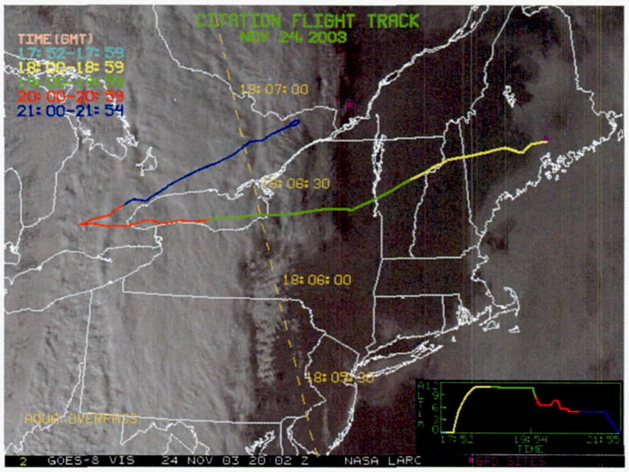

Figure 1. November 24, 2003 Flight Track.

To verify the TAMDAR RH values, a comparison to UND Citation relative humidity data is made. There were two sources of relative humidity data on the UND Citation, a tunable diode laser instrument and an EG&G dew point hygrometer. Unfortunately, post campaign data analysis revealed that both these instruments were miscalibrated. Another source of verification is GPS dropsonde data. The initial dropsonde values for relative humidity are often reported about 60-75 seconds after launch. The values used in this paper were converted to relative humidity with respect to ice using the Hyland and Wexler formulation[10].

The TAMDAR sensor computes wind speed and direction from measured airspeed, aircraft (UND Citation) magnetic heading, and GPS ground track. TAMDAR wind vector magnitude accuracy is +/-3.08 m/s (+/- 6 knots). To verify this value, a comparison to UND Citation nose probe sensor winds is made.

IV. CASE STUDIES

For each case study, a description of the flight configuration is followed by comparison data. TAMDAR data is validated against the UND Citation data and compared to sounding data from dropsondes (if available).

A. November 24, 2003 Case Study

On this date, the UND Citation flew an icing mission as shown in Fig. 1. A cold front was approaching the Mirabel area from the west that was expected to produce significant icing during the evening and early morning hours of the following day. The Citation was to position in Ottawa with the expectation of flying an early morning mission during the icing event on Tuesday, November 25. The Citation flew past Ottawa to penetrate the frontal zone and to measure the cloud microphysics before the system reached Ottawa. The aircraft took off from Bangor, ME at 1808 UTC and flew through the frontal zone to London, Ontario. Cloud microphysics data were collected at several temperature levels in the frontal system. Ice was detected at 2040 UTC and throughout the rest of the flight. The Citation then turned back to the east to pass through the frontal zone again and landed in Ottawa at 2155 UTC. The total flight time for the mission was 3.8 hours.

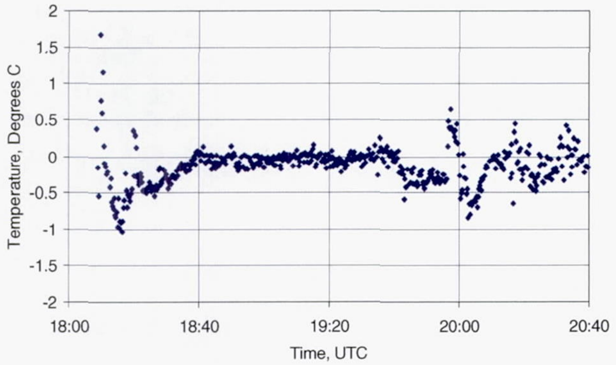

Figure 2. **Temperature Difference.**

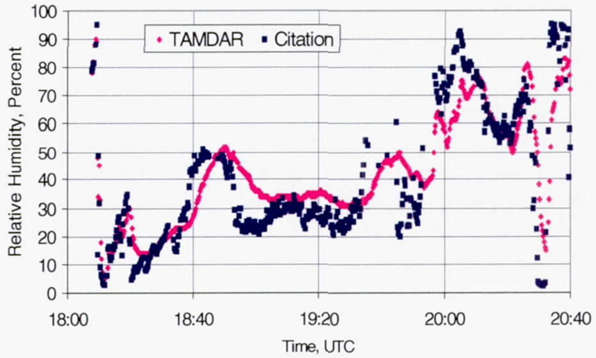

Figure 3. Relative Humidity Comparison.

2. Temperature

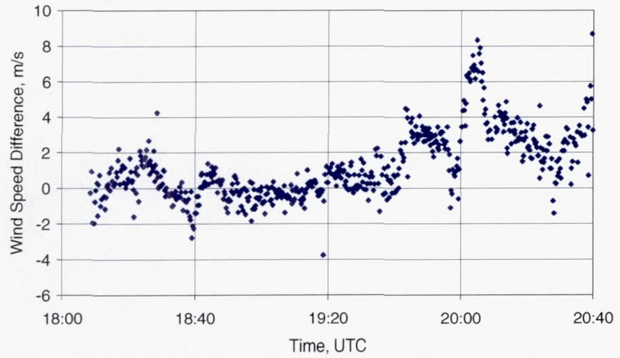

Figure 4. Wind Speed Difference.

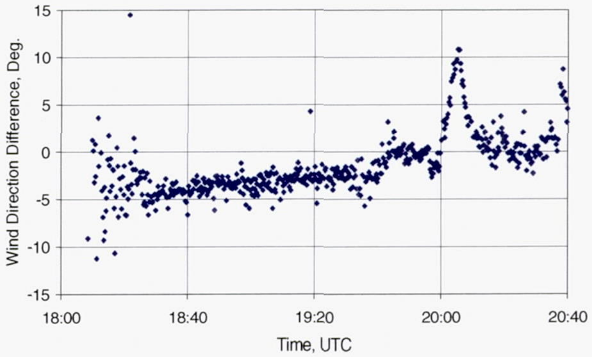

Figure 5. Wind Direction Difference.

Shown in Fig. 2 is a time-series plot of temperature comparison between the TAMDAR and UND Citation. Over the initial 2.5 hours of flight (excluding the icing portion after 2040 UTC), the mean difference is –0.13°C and the standard deviation is 0.26°C. A systematic deviation is seen in all the plots at 2000 UTC and is due to recovery from an icing event.

1. Relative Humidity

Shown in Fig. 3 is a time-series plot of relative humidity. Over the non-icing portion of the flight, the mean difference in relative humidity is –1.7% and the standard deviation is 12%.

2. Wind Speed

A time-series plot of computed wind speed differences is shown in Fig. 4. The mean difference is 1.2 m/s and the standard deviation is 1.9 m/s.

3. Wind Direction

Figure 5 is a time-series plot of wind direction differences. The mean difference is –1.2° and the standard deviation is 4.4°.

B. November 25, 2003 Case Study

As shown in Fig. 6., the UND Citation took off from Ottawa at 1506 UTC. The forecast was for the low clouds at Mirabel to last only a couple of hours, so the flight plan was adjusted to release dropsondes later and proceed back to Bangor with the hope of finding icing conditions farther to the east in northern Maine. Four dropsondes were released at FL370 in the training area with a spiral descent down to FL260. The aircraft headed back to Bangor at FL270 with the plan to change altitude when the Citation reached significant cloudiness. A very shallow low layer of broken stratocumulus was present that gradually cleared during the approach to Bangor. A small layer of glaciated altostratus well above FL270 (temperature -42 C) was observed, but nothing with any icing potential was seen to the east of the Bangor area, so the aircraft landed at Bangor at 1756 UTC. The total flight time for the mission was 2.5 hours.

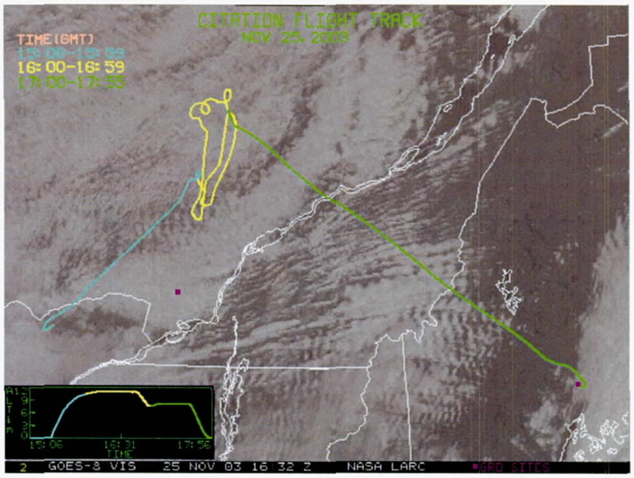

Figure 6. November 25, 2003 Flight Track.

1. Temperature

The plot shown in Fig. 7 is a time-series plot of temperature differences. The mean difference is 0.25°C and the standard deviation is 0.38°C.

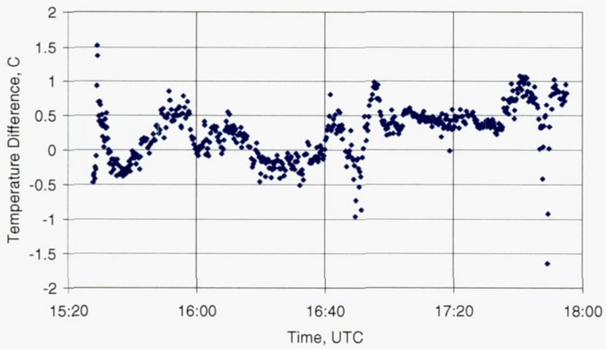

Figure 7. Temperature Difference.

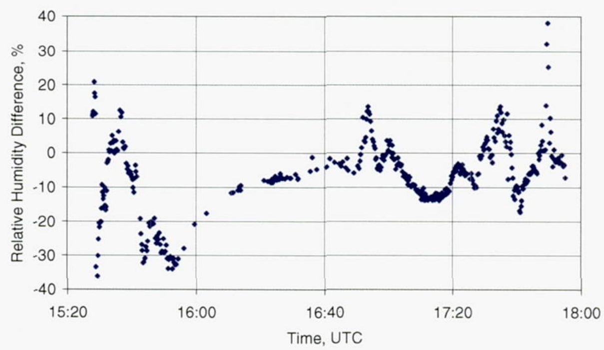

Figure 8. Relative Humidity Difference.

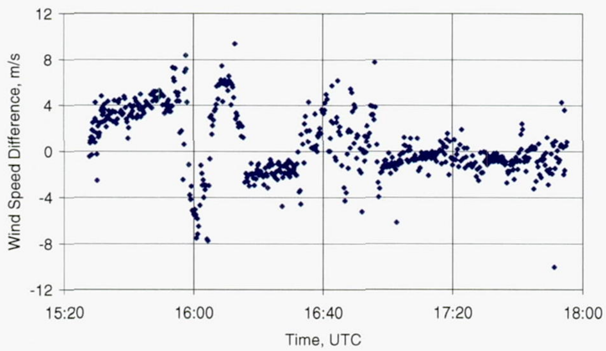

Figure 9. Wind Speed Difference.

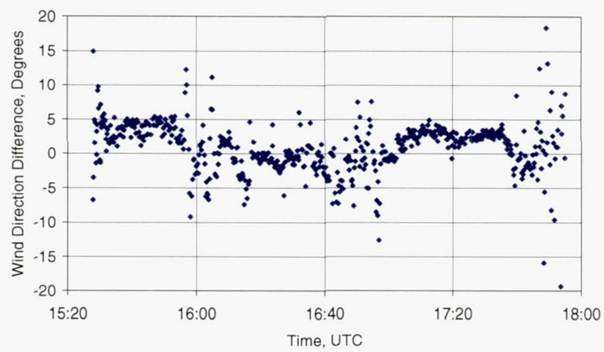

Figure 10. Wind Direction Difference.

2. Relative Humidity

Shown in Fig. 8 is a time-series plot of relative humidity differences. The mean difference in relative humidity is –4.9% and the standard deviation is 9.8%.

3. Wind Speed and Direction

A time-series plot of computed wind speed differences is shown in Fig. 9. The mean difference is -0.22 m/s and the standard deviation is 20 m/s. Figure 10 is a time-series plot of wind direction differences. The mean difference is 1.2° and the standard deviation is 9.2°.

C. November 30, 2003 Case Study

The Citation took off from Bangor at 1624 UTC, arriving over Mirabel at FL350 at about 1730 as shown in Fig. 11. A spiral descent was made over the runway intersection down to FL40. Clouds were not encountered until about FL72, where there was a layer about 1000 ft thick. The lower clouds had tops slightly above FL40, but variable. Several measurement passes were made along the runway at FL40 going in and out of cloud along the way. In cloud, the Citation encountered light to moderate rime ice and liquid water contents of 0.1 to 0.4 g/m3. This was followed by a missed approach over the runway from FL40. The cloud extended down to slightly below FL20. This was followed by passes at FL70 going west to east and missed approaches from FL70 over the runway going east to west. This profile was carried out several times In general, the liquid water content was higher in the upper cloud layer, with larger mean values of the droplet sizes. There were a few ice crystals in both layers, but the clouds were composed primarily of water droplets. The clouds were well characterized by the measurements in the horizontal as well as the vertical.

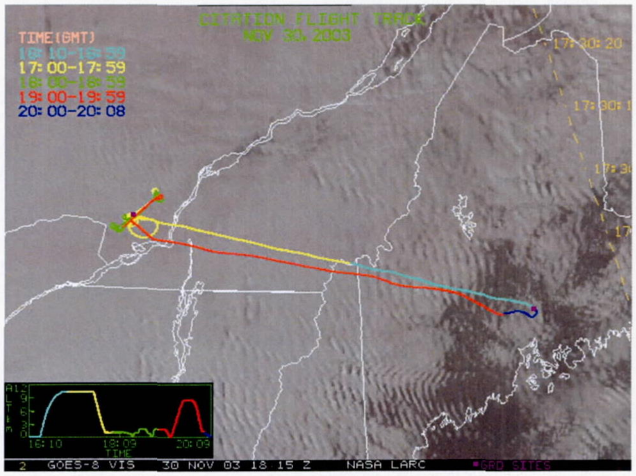

Figure 11. November 30, 2003 Flight Track.

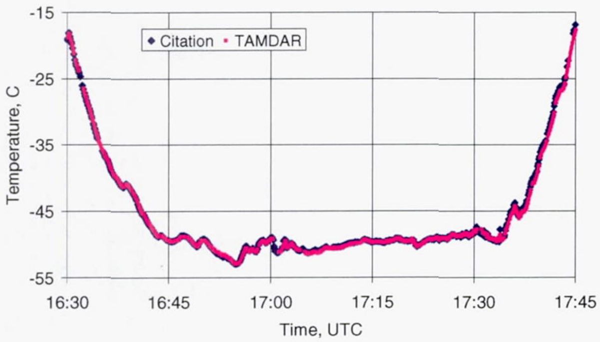

Figure 12. Temperature Comparison.

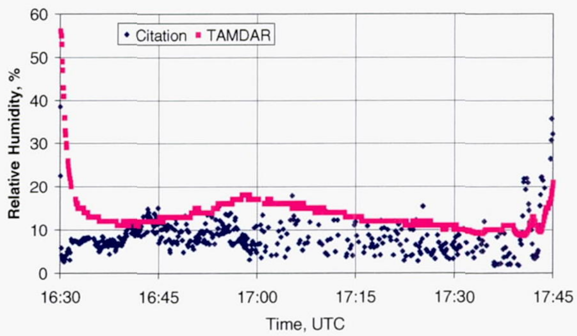

Figure 13. Relative Humidity Comparison.

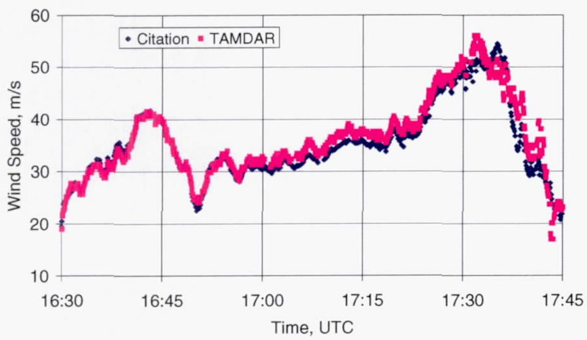

Figure 14. Wind Speed Comparison.

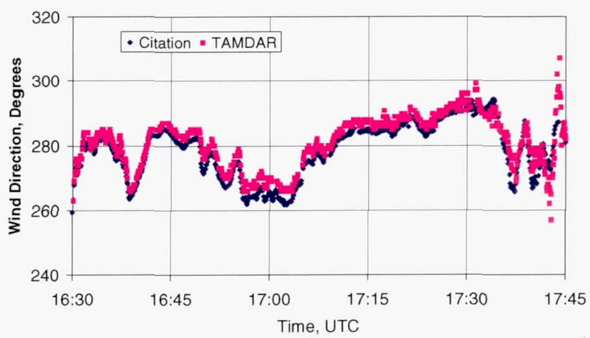

Figure 15. Wind Direction Comparison.

1. Temperature Comparison

The time-series plot shown in Fig. 12 is a comparison of temperature data from the initial 75 minutes of flight. The high rate turns and encounters with ice invalidate the TAMDAR data during different intervals during the remainder of the flight. While error statistics could be computed on individual segments, this initial segment that includes a take-off sounding and 60 minutes of cruise flight are sufficient for this comparison. A mean difference of –0.47°C and standard deviation of 1.8°C was computed from this segment.

2. Relative Humidity Comparison

Another time-series plot of data is shown in Fig. 13 for a comparison of relative humidity. The same time interval as describe above is used. The mean difference was –3.1% and the standard deviation was 6.7%.

3. Wind Speed and Direction Comparison

Shown in Fig. 14 is a time-series comparison of computed wind speed of the same 75-minute segment. The mean difference was –1.4 m/s and standard deviation was 10 m/s. A time-series plot of computed wind direction is shown in Fig. 15. For this segment, the mean difference is –1.5° and the standard deviation is 15°.

V. CONCLUSIONS

The intent of this paper is to use in-situ temperature, relative humidity, and winds aloft data from the UND Citation as a reference to compare all other measurements against. With the exception of the problems noted with the UND Citation relative humidity data, the reference data it provided proved to be highly valuable.

The data were collected in an extreme environment and yet the TAMDAR sensor maintained the desired accuracies. While not presented here, the TAMDAR data for the other parameters showed similarly acceptable performance. This field campaign was conducted prior to the completion of the TAMDAR sensor development phase. Results were used to help refine the sensor algorithms and improve the performance specifications.

In summary, the TAMDAR sensor performed very well over the entire period of the field campaign. The data from this new sensor compares favorably with the other instruments. The sensor should be able to collect the necessary data to significantly augment domestic Meteorological Data Communications Reporting System (MDCRS) and the international Aircraft Meteorological Data Reporting (AMDAR) system observational databases.

REFERENCES

[1]Daniels, T. S., "Tropospheric Airborne Meteorological Data Reporting (TAMDAR Sensor Development," 2002-02-153, SAE General Aviation Technology Conference and Exposition, April 16-18, 2002, Wichita, KS.

[2]Daniels, T. S., Tsoucalas, G., Anderson, M., Mulally, D., Moninger, W., Mamrosh, R., "Tropospheric Airborne Meteorological Data Reporting (TAMDAR) Sensor Development," *11th Conf. on Aviation, Range, and Aerospace Meteorology*, Hyannis, MA, American Meteorological Society.

[3]American Meteorological Society Council, "Support for Automated Observations from U.S. Commercial Aircraft," *Bulletin of the American Meteorological Society*, 84, 515—517, February 2003.

[4]Murray, J. J. and Nguyen, L. "NASA Langley ATReC & AIRS-II Satellite Page," [cited November 10, 2003], URL: http://www-angler.larc.nasa. gov/bangor/

[5]"Alliance Icing Research Study II Webpage," [cited November 19,2003], http://www.airs-icing.org/AIRS_II/AIRS_II.htm

[6]Daniels, T. S., Tsoucalas, G., Anderson, M., Mulally, D., Moninger, W., Mamrosh, R.,, ibid.

[7]Murray, J. J., Smith Sr, W., Daniels, T., Minnis, P., Kapitzke, M., Poellet, M., Avery, M., Revercomb, H., McGill, M, Myers, J., "Alliance Icing Research Study II, Science Plan Appendix E," [cited November 14, 2003], URL: http://www.airs-icing.org/AIRS_II/inside/AIRS_II.htm

[8]Hallet, J., Isaac, G., Politovich, M., Marcotte, D., Reehorst, A., Ryerson, C., "AIRS II Science Plan," [cited July 7, 2003], URL: http://www.airs-icing.org/AIRS_II/2003-07-07_AIRS_II_Science_Plan.pdf

[9]Zhou, D. K., Smith, W. L., Li, J., Howell, H. B., Cantwell, G. W., Larar, A. M., Knuteson, R. O., Tobin, D. C., Revercomb, H. E., and Mango, S. A., 2002: "Thermodynamic product retrieval methodology for NAST-I and validation," *Applied Optics*, 41, 6957–6967.

[10]Hyland, R. W. and Wexler, A., "Formulations for the Thermodynamic Properties of the saturated Phases of H2O from 173.15K to 473.15K," *ASHRAE Trans*, 89(2A), 500-519, 1983.