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5.6 Correction of Aircraft Flux Valve Based Heading for Two-Dimensional Winds Aloft Calculations Using Weather Model Comparisons

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1 Overview

Dramatic differences exist in the quality of wind data provided by aircraft with different heading systems. The authors have devised a method to correct for inaccuracies associated with flux valve heading systems that can significantly improve the quality of wind measurements from previously poorly performing aircraft. Originally, one set of flux valve (flux gate) equipped aircraft delivered data with an RMS wind vector disagreement relative to weather models of 10.8 knots (kn); after application of the method described herein, the disagreement between the aircraft wind data and models was reduced to 8.4 kn.

2 Introduction to the TAMDAR Sensor Network

The TAMDAR (Tropospheric Airborne Meteorological Data Reporting) Sensor is an airborne atmospheric instrument developed by AirDat in cooperation with NASA (Figure 1). TAMDAR is a novel approach for an aircraft mounted, in-situ, atmospheric measurement system that combines the measurement capabilities of temperature, turbulence, icing, relative humidity (RH), pressure altitude, GPS height (above mean sea level), and winds into one sensor. Each observation includes the associated time, latitude, and longitude. It has proven effective for measuring atmospheric parameters not only in the lower troposphere, but also at altitudes up to 40,000 feet flown by jet aircraft.

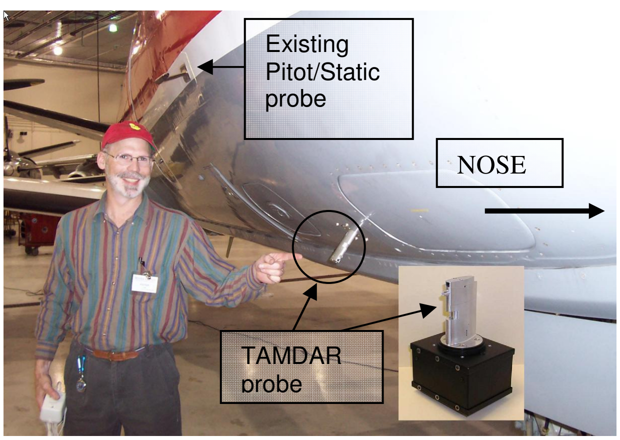

Figure 1. The TAMDAR Sensor on a SAAB-340

TAMDAR has been addressing the need for atmospheric data in the lower troposphere since spring of 2005 when the Mesaba SAAB340 turbo prop fleet of 64 airplanes was equipped. This fleet provides data from the greater Great Lakes region. The PenAir SAAB-340 fleet was subsequently equipped in June of 2007 and provides valuable data and improved forecasts for the Alaska region. Improvements in forecasting and model accuracy for both the PenAir fleet and the Mesaba fleet have been documented in several papers [1-11]. Further advances have been the equipage of Horizon Dash-8 Q400s (West Coast), Piedmont Dash-8 Q100s and Q300s (East Coast US), Chautauqua ERJ-145s (Eastern US), AeroMexico ERJ-145s (Mexico), and five Beech 1900C turbo props in the Alaskan interior.

AirDat currently has 160 planes equipped with TAMDAR. A typical 24 hours of flight tracks is shown in Figure 2. Current coverage includes much of CONUS, as well as Alaska and Mexico.

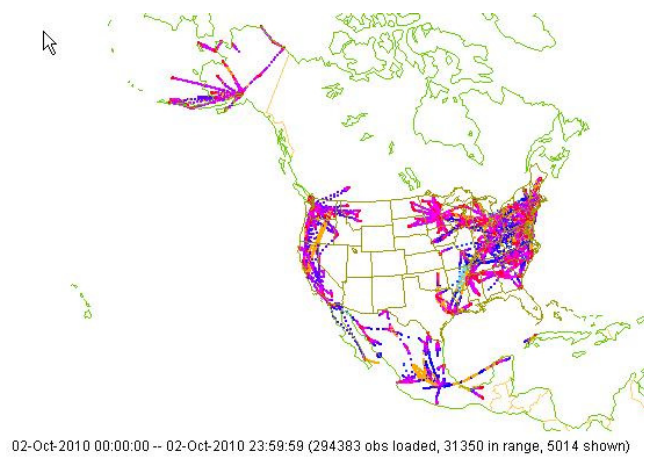

Figure 2. TAMDAR Data, all fleets, from the GSD web site map. 2 Oct 2010.

Observations are generally reported every 10 hPa up to 100 hPa above ground level. Above 100 hPa, observations are made every 50 hPa. If a pressure change threshold isn't exceeded for 3 minutes below 20,000 or 7 minutes above 20,000 feet, an observation is generated. These observations are then sent to the AirDat ground system via the Iridium satellite system where they are quality controlled and distributed.

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Accurate heading is important for an accurate wind calculation; the magnetic based heading systems (on SAAB-340s, Q100s, Q300s, Beech 1900s, and some ERJs) are less accurate than the laser gyro based systems (on Q400s and some ERJs). In keeping with AirDat's goal of constantly improving the quality of the atmospheric measurements, an effort was initiated to improve the accuracy of the horizontal wind calculation on planes using flux valve (magnetic) based heading systems.

3 Wind Calculation and Errors

Wind speed and direction can be calculated from true airspeed (TAS) and aircraft heading—air track ; and GPS ground speed and track angle—ground track (equation 1).

$$\mathbf{V_W} = \mathbf{V_G} - \mathbf{V_A}. \quad (1)$$

Bolded variables are velocity vectors. The 2-dimensional (horizontal) wind velocity ($\mathbf{V_W}$) is the velocity of the air with respect to (w.r.t.) the earth. It is calculated from the aircraft velocity w.r.t. the air ($\mathbf{V_A}$) and the aircraft velocity w.r.t. the earth ($\mathbf{V_G}$).

Since wind speeds are generally small compared to groundspeed and airspeed, the vectors $\mathbf{V_G}$ and $\mathbf{V_A}$ need to be measured accurately. The ground track speed and track angle for $\mathbf{V_G}$ is obtained from TAMDAR's built-in GPS and is assumed to be very accurate. The magnitude of $\mathbf{V_A}$ is obtained by calculating the true airspeed (TAS) from TAMDAR's pitot and static pressure transducers or, on some planes, TAS can be obtained directly from an ARINC data bus. The angle of $\mathbf{V_A}$ is the aircraft heading and is obtained from an aircraft heading system over some type of data bus. The biggest contributors to errors in the wind calculation are heading and TAS inaccuracies.

4 Flux Valve Heading Systems

The flux valve (also called a flux gate) is an electronic magnetometer that measures the direction of the horizontal component of the earth's magnetic (geomagnetic) field relative to the aircraft (magnetic heading). In order to provide a stable heading, especially during maneuvers, the final heading is obtained from a system where a gyroscope is slaved to the flux valve output. Before being used in the wind calculation, the true heading is calculated from the magnetic heading by applying the magnetic variation (declination) for the particular latitude, longitude and date.

Any long-term systematic errors in the flux valve will propagate through the system and cause errors in the heading provided to TAMDAR and degrade the wind calculation accuracy.

The heading error as a function of measured heading is called the "magnetic deviation." Two common sources of error are those caused by soft iron effects and hard iron effects (also known as subpermanent magnetism). Soft iron effects are due to magnetic material that temporarily is affected by an external magnetic field (in this case the earth's field) whereas hard iron effects are due to permanently magnetized material. The magnetic fields from these sources will add to the earth's field and produce a distortion in the magnitude and direction of the measured field. Since the hard iron is fixed relative to the plane, its effect is a function of heading and usually to a lesser extent, attitude of the platform. The general equation for magnetic deviation is

$$d = A + B\sin(z') + C\cos(z') + D\sin(2z') + E\cos(2z'), \quad (2)$$

where d is the magnetic deviation and z' is the heading as seen by the magnetic based system. The coefficients A, B, C, D and E are constants [12].

At low levels, hard iron errors alone produce an approximate sinusoidal error curve in the heading. In other words the coefficients D and E in the equation are zero. The sinusoidal nature of the heading errors observed on TAMDAR equipped flux valve planes suggest that hard iron effects are the dominant factor and so the deviation can be characterized using only the A, B and C coefficients. A is an offset and the phase and amplitude of the sinusoidal component is determined by B and C. The fixed offset component could be caused by inaccurate flux valve mounting or calibration issues whereas the sinusoidal component is likely caused by hard iron effects.

The strength of the horizontal component of the earth's field is strongest near the magnetic equator and weakest near the magnetic poles. Thus the magnetic deviation curve will vary over magnetic latitude for a constant hard iron effect. The attitude of the aircraft (pitch and roll) will also have some effect. Pitch of the aircraft is unknown but wind observations when the roll angle exceeds 10 degrees are not used. Although eq. 2 assumes magnetic heading, the same general trend occurs when one considers true heading since it is based on the magnetic heading. True heading is used in the AirDat method described unless otherwise specified.

About half the flux valve aircraft heading systems on the Mesaba SAAB-340s have been found to have heading errors that significantly degrade the accuracy of the wind calculation. This error could be reduced by carefully done compass swings and a calibration; however, accurate swings are difficult to accomplish and do not fit in well with the airline's standard maintenance practice. Furthermore, errors less than 3-4 degrees may be considered acceptable to an airline and no adjustments may be made during a routine compass check. Errors this large will seriously degrade wind calculation accuracy.

5 Data and Method Summary

The method described is designed to characterize the magnetic deviation as a function of measured heading on a particular aircraft. This is done by comparing wind data from thousands of TAMDAR observations to weather model analysis data. A lookup table based on this characterization is then uploaded to the TAMDAR and used to correct the heading before the wind calculation is done.

The basic method is:

- Calculate the ground track vector (speed and direction) for each weather observation based on the latitude and longitude of three adjacent observations.
- Calculate air track vectors (TAS and aircraft measured heading) for the observation in 2 ways:
  1. Subtract the TAMDAR wind vector from the ground track vector. This is essentially recreating the air track vector used by TAMDAR to calculate winds.
  2. Subtract the model analysis reference wind vector from the ground track vector.
- Subtract the heading of the air track vector based on 2 above, from the heading based on 1 to get a heading "error."
- For data over a sufficiently long time period, form a table of heading errors versus aircraft measured heading.
- Fit a sinusoid curve (phase, amplitude and offset) to the table of heading errors as a function of measured heading. Derive the magnetic correction lookup table from the sinusoid. A plot of a typical data set and curve fit is shown in Figure 3. The data spans the period from 3 Aug 2008 to 28 Jul 2009.

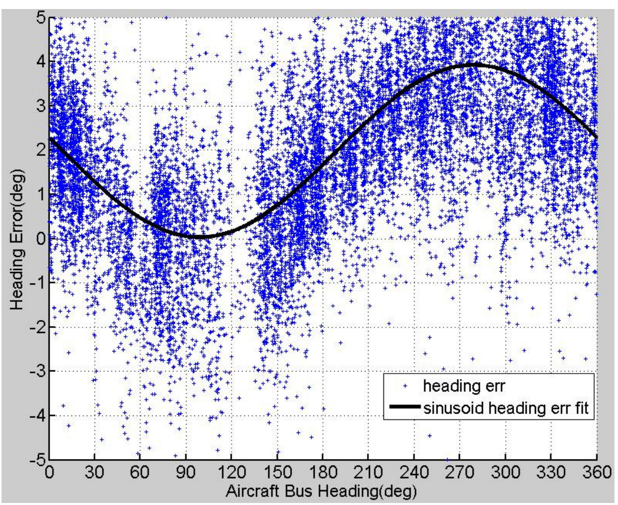

Figure 3. Heading Error: Difference between aircraft derived heading and model derived heading for a typical flux-valve aircraft, and a sinusoidal fit to the data as a function of aircraft heading.

Note, this is not a ground-based correction; the data mining and error analysis is only done once to determine the aircraft heading system deviation lookup table. This lookup table is then uploaded to TAMDAR which then corrects the heading in real-time as part of the wind calculation and before transmitting weather measurements over the satellite link.

The model comparisons were obtained from both the NOAA GSD Rapid Refresh RUC (RR) and the AirDat Real-Time Four-Dimensional Data Assimilation MM5 (RTFDDA) models whenever possible. Using both models gave more data over a given time period for a better curve fit and also provided a means to judge the reasonableness of the results: if both models predicted a similar curve then the results are believable. For the PenAir Alaskan analysis, AirDat RTFDDA data was not available and only the RR data was used for the actual curve fits. The NAM model and ACARS data were used in all cases to confirm that the results were reasonable. The data from these sources was not used in the final curve fit because they were considered too sparse and noisy.

5.1 Calculation of Heading Error

The method requires knowledge of:

1. The observed aircraft velocity vector—true airspeed (TAS) and true heading ($\mathbf{V_A}$).
2. The ground track velocity vector—ground speed and direction ($\mathbf{V_G}$).
3. A second aircraft TAS and heading calculated from the ground track vector and the model wind vector ($\mathbf{V_A'}$).

The ground track vector and air track vector are not part of the downlinked observations but can be estimated by looking at the latitude, longitude and time of adjacent observations (when three observations are collinear and the airspeed is constant).

The observed air track speed and direction is calculated by the formula

$$\mathbf{V_A} = \mathbf{V_G} - \mathbf{V_{W,TAM}}, \qquad (3)$$

where $\mathbf{V_A}$ is the observed air track vector, $\mathbf{V_G}$ the ground track vector, and $\mathbf{V_{W,TAM}}$ is the wind vector in the TAMDAR observation. $\mathbf{V_A}$ is good estimate of the vector used in TAMDAR to calculate the winds and any magnetic deviation errors will be present in its angle.

An estimate of the "actual" air track vector is then calculated based on the wind vector from one or more weather model reference sources using the formula,

$$\mathbf{V_A'} = \mathbf{V_G} - \mathbf{V_{W,REF}}, \qquad (4)$$

where $\mathbf{V_A'}$ is the air track vector and $\mathbf{V_{W,REF}}$ is the wind vector from a weather model. Both the $\mathbf{V_A}$ and $\mathbf{V_A'}$ calculations are noisy because of the quantization error in the lat and long fields but the noise is unbiased and uncorrelated.

Figure 4 shows the vectors involved. The magnitude of $\mathbf{V_A}$ is the TAS; the angle of $\mathbf{V_A}$ (ψ) is the heading. The magnitude of $\mathbf{V_G}$ is the ground track speed and the ground track angle is η. The difference in angles between $\mathbf{V_A}$ and $\mathbf{V_A'}$ as a function of the aircraft heading (ψ) is then used to define a function for correction of the direction of ψ.

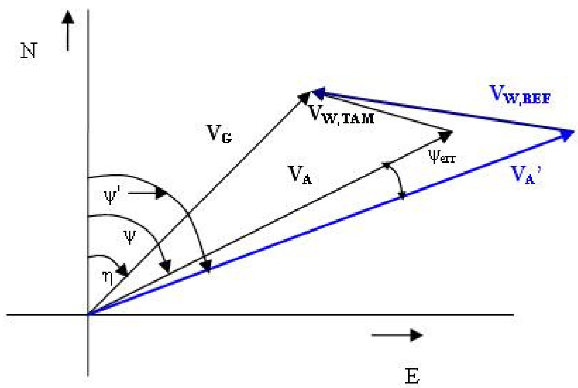

Figure 4. Vector calculations for characterizing magnetic deviation based on model winds, TAMDAR winds, and ground track.

This calculation is done for every observation in the data set that passes quality checks. For a stable analysis, the length of the data set should span at least several months.

In order to avoid a more complex data analysis process, the method described used true heading (obtained from magnetic heading with a magnetic variation applied). Since Equation 2 is based on magnetic heading, the effect of calculating deviation based on true heading rather than magnetic heading needs to be considered. The magnetic variation is not a constant offset and does vary over geographic region. This results in a slightly noisier data set for the curve fit and a final magnetic deviation curve that might be shifted along the x-axis by a few degrees depending on the geographic region. These effects were considered to be small and were ignored for this study.

5.2 Assumptions

There are several requirements for the method to produce reliable results. They are listed here with comments and justifications:

- *Induced errors are dominated by hard iron effects that do not change significantly over time or the operational geographic area.* The sinusoidal nature of the magnetic deviation suggests this is the case.
- *The strength of the horizontal component of the earth's magnetic field does not change significantly over time or geographic area.* The effect of a fixed hard iron error will be a function of the strength of the earth's field. This means the calibration may only apply over a limited geographic region and may be dependent on magnetic latitude.
- *Model wind speeds and directions are not significantly biased over the data gathering period.* Speed and direction biases will shift the phase and magnitude of the sinusoidal curve fit reducing its effectiveness. RR model comparisons to ACARS data show the unbiased assumption to be true.
- *The primary cause of errors in the TAMDAR winds is due to heading errors, not TAS errors.* Bill Moninger at GSD has shown this to be the likely case for the Mesaba SAAB-340 aircraft [13]. Reasonable care has been taken to provide an accurate TAS by proper calibration.
- *The heading errors of the aircraft at given magnetic latitude with the plane in level flight are a function of heading only.* This is likely the case as heading errors are typically caused by fixed local hard iron magnetic effects in the aircraft.
- *The magnetic variation correction applied by TAMDAR (from the Garmin GPS) is accurate.* Since we see significant variations in wind quality from different planes in the Mesaba fleet, and they all use the same GPS, the magnetic variation is assumed not to be the main contributor to the error. Studies by AirDat of the Garmin GPS magnetic variation calculation show good comparison to the DoD World Magnetic Model. It is still likely that magnetic variation errors will be corrected to some extent by this method.
- *Model errors are not correlated with the heading of the aircraft.* The model doesn't know which direction the airplane is flying.
- *The particular plane being used hasn't had the flux valve system recalibrated during the period of data analysis or after the method is applied.* This is beyond our control, but from discussions with Mesaba and PenAir we know that even though heading checks are periodically done, an actual calibration doesn't happen very often. Other maintenance that may affect flux valve accuracy such as changes that affect hard iron effects is also possible but not within our ability to determine. Since wind quality is constantly monitored, any changes due to maintenance that degrade winds significantly will be quickly noted [14].

6 Longitudinal and Transverse Wind Errors

Three metrics are used to evaluate wind measurements:

1. The total wind RMS vector magnitude error (RMS wind error).
2. The longitudinal component of the RMS wind error.
3. The transverse component of the RMS wind error.

The wind error is computed by taking the difference between the TAMDAR wind and the model wind vectors for each individual observation. The root-mean-square (RMS) value of the magnitudes for data error set then calculated to get the RMS vector magnitude error for the time span of the analysis. This method of using the wind vector magnitude error (wind RMS error) is convenient because errors in both direction and speed are reflected in the result.

The relative effects of TAS errors and heading errors on the wind accuracy can be seen by calculating the wind error as two component vectors: the longitudinal (along-track); and transverse (across-track) error vectors [13]. The longitudinal component is along the axis of the aircraft and the transverse component is perpendicular to the body of the aircraft. AirDat's "Delta Hound" software used to evaluate and maintain the quality of atmospheric data also has the capability of calculating these wind error components [14].

Heading errors will contribute primarily to the transverse wind error component. Errors in TAS will contribute primarily to the longitudinal component. An example of wind performance for aircraft with very good heading systems is shown in Figure 5. The set of aircraft used are Chautauqua ERJ-145s that have the Honeywell AH-900 attitude and heading reference system (AHRS) which provides heading from a laser gyro source. Note that longitudinal (pink) and transverse (brown) wind errors are similar suggesting that neither TAS errors nor heading errors dominate the total error (blue).

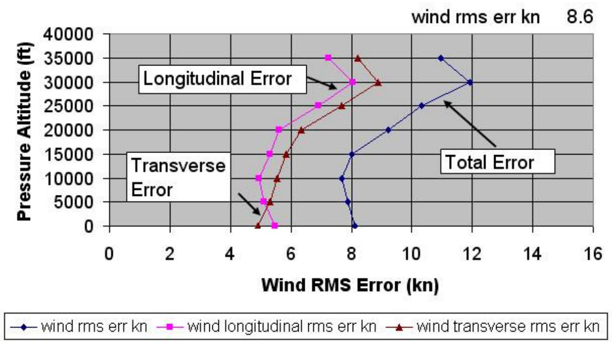

Figure 5. Longitudinal, transverse, and total RMS wind vector magnitude error for 9 selected Chautauqua ERJ-145 planes for 21 Oct 2009 to 21 Nov 2009. These planes have very good heading systems (AH-900).

Figure 6 shows another group of Chautauqua ERJ-145s for the same time period; however, these planes have the Honeywell AH-800 ARHS system which provides heading from a flux valve source inferior to the laser gyro system using in the AH-900. The transverse wind error component is clearly much worse than the longitudinal which is consistent with an inaccurate heading source. The trend of transverse error getting worse with altitude may be because the effects of heading errors are more significant as the plane moves faster. Both RR and AirDat RTFDDA model comparisons are used for the analysis.

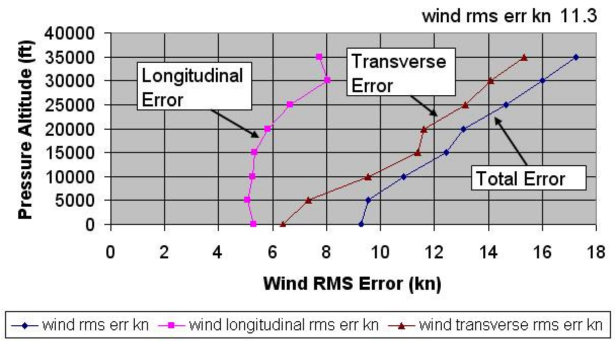

Figure 6. Longitudinal, transverse, and total RMS wind vector magnitude error for 9 selected Chautauqua ERJ-145 planes for 21 Oct 2009 to 21 Nov 2009. These planes have poor heading systems (AH-800).

7 Magnetic Field Horizontal Component Geographical Effects

The effects of the changes in the horizontal component of the earth's magnetic field over the regions of interest need to be considered. The changes in the strength of the horizontal field based on the DOD World Magnetic Model were found to vary by about 30 % over either the Mesaba fleet region or the PenAir fleet region. Based on a fixed hard iron error causing a typical deviation swing of about 4 degrees peak-to-peak (p-p) at the center of the region, the peak magnetic deviation at either extreme is estimated to be about 5 degrees at p-p one extreme (closer to the magnetic pole) and 3.4 degrees p-p at the other (Figure 7). Clearly a single sinusoid correction will not do equally well over the whole region, but for the most part can still provide significant improvement for poorly performing planes. The sinusoid being based on data from the entire region will be weighted more heavily to those areas where there are more flights (more data) and thus the method will tend to have better corrections in those areas too.

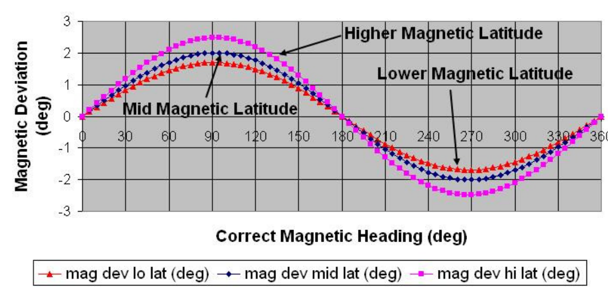

Figure 7. Theoretical example of the variability of the magnetic deviation for a fixed hard iron error at three magnetic latitudes chosen to approximate the region the Mesaba fleet covers.

8 Results

Some quality assurance (QA) decisions were made to ensure that a particular model comparison was reasonable to use. Only observations that passed basic quality checks were used (e.g. no banking and reasonable GPS data, TAS and altitude).

8.1 Magnetic Deviation Curves

As mentioned earlier, small hard iron effects relative to the horizontal strength of the earth's field were expected to produce an approximately sinusoidal shape to the magnetic deviation curve. There may also be an offset present. Planes having poor performance have distinctly sinusoidal error curves. The sinusoid is much less pronounced on planes that had good winds.

The sinusoidal nature of the results was also a good predictor as to whether the method would produce significant improvements. The method may still be valid for distortions other than a sinusoid with an offset or just an offset; however, those other cases suggest that the effect may be due to something besides a hard iron effect. These effects may not be stationary over time. Thus, non-sinusoidal or non-offset errors may not produce good results. In cases where there is small sinusoidal component but a large offset, correction will still provide significant improvements.

The typical example for a specific airplane is repeated for convenience in Figure 8. The actual data from several months of flights are shown along with the sinusoidal fit to the data. Rather than using an actual sinusoid for the final correction, an 8-point lookup table is used and a piece-wise linear fit closely approximating the sinusoid is used in the TAMDAR to obtain the heading correction. This correction is a function of the aircraft system's measured heading. It is then applied to the aircraft heading to get the corrected heading which is used in the wind calculation.

In the example shown there is both a heading offset of about 2 degrees and a sinusoidal swing of about 4 degrees p-p. Errors of this magnitude if not corrected are significant and seriously degrade the wind calculation quality.

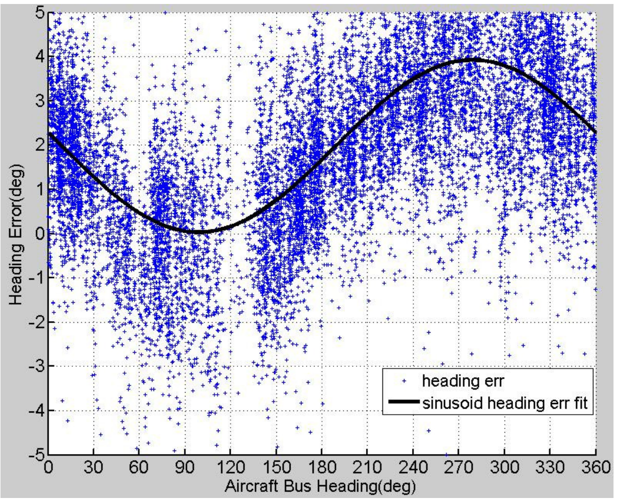

Figure 8. Difference between model derived heading (Ψ') and aircraft derived heading (Ψ) for a typical flux-valve aircraft, and a sinusoidal fit to the data (3 Aug 2008 to 28 Jul 2009).

8.2 Mesaba Improvement Statistics and Metadata

8.2.1 Wind RMS Error

Table I shows the improvement after the magnetic deviation lookup tables were uploaded to 19 of the Mesaba SAAB-340 planes chosen for their poorer wind quality. The remaining 17 Mesaba planes (no tables uploaded) were analyzed for the two time periods to adjust the results for model performance changes. The overall error increased for this control group and this increase was removed from the results to arrive at an overall improvement of 2.4 kn (23 %) after the magnetic deviation lookup table was uploaded. The actual improvement in terms of percentage is undoubtedly better because the model noise was not taken into account in the calculation. The time periods chosen are not adjacent because not all the TAMDAR Sensors were changed at the same time.

Table I. Model comparison statistics of Mesaba planes with poorly performing heading systems before (15 Aug to 15 Sep 2009) and after (21 Oct 2009 to 21 Nov 2009) magnetic deviation lookup tables were applied to poorly performing planes.

Airplane Group	Time Period	Wind RMS Error
Poorly Performing Heading Systems	Before	10.8 kn (knots)
	After (adjusted for model variation)	8.4 kn
	Improvement	2.4 kn (23%)

Table II shows more details and includes the changes in the longitudinal and transverse wind error components. The root-sum-square (RSS) of longitudinal and transverse RMS wind does not exactly equal the total wind RMS error. This is because the method used to calculate the components had inherent inaccuracies: the actual heading is not known so the heading is estimated from the track of the observations which have limited resolution for latitude and longitude. The total wind RMS error calculation is not affected by these track errors. Note that the vast majority of the improvement lies in the reduction of error in the transverse component. This is consistent with the premise that heading errors were the main problem.

Table II. Detailed Model comparison statistics of Mesaba planes with poorly performing heading systems before (15 Aug 2009 to 15 Sep 2009) and after (21 Oct 2009 to 21 Nov 2009) magnetic deviation lookup tables were applied to poorly performing planes.

Airplane Group	Time Period	Wind RMS Error	Longi-tudinal Wind RMS Error	Trans-verse Wind RMS Error
Poorly Performing Heading Systems	Before (165,846 obs)	10.8 kn	5.4 kn	9.8 kn
	After (142,971 obs)	9 kn	5.5 kn	6.8 kn
	After (adjusted for model variation)	8.4 kn	5.1 kn	6.3 kn
	Improve-ment kn	2.4 kn	0.3 kn	3.5 kn
	Improve-ment %	23%	4%	36%
Healthy Heading Systems (Control)	Before (143,248 obs)	8.8 kn	5.4 kn	7.1 kn
	After (132,887 obs)	9.4 kn	5.8 kn	7.6 kn
	After (adjusted for model variation)	8.8 kn	5.4 kn	7.1 kn

The wind RMS errors w.r.t. the models for the individual planes are shown in Figure 9. The maroon colored bars are the RMS wind errors for the time period preceding any changes. The white and green bars are for a time period after changes were applied. The white bars are for the 17 TAMDARs that were not changed while the green bars are for those that had the magnetic deviation lookup table applied. It can be seen from the control group that the model performance relative to the TAMDAR data is slightly worse for the latter period; nevertheless, there is still a clear improvement in almost all the changed TAMDARs. If the slight model degradation is taken into account, the improvement for the calibrated aircraft would be about 0.6 knots better than what is shown on the chart.

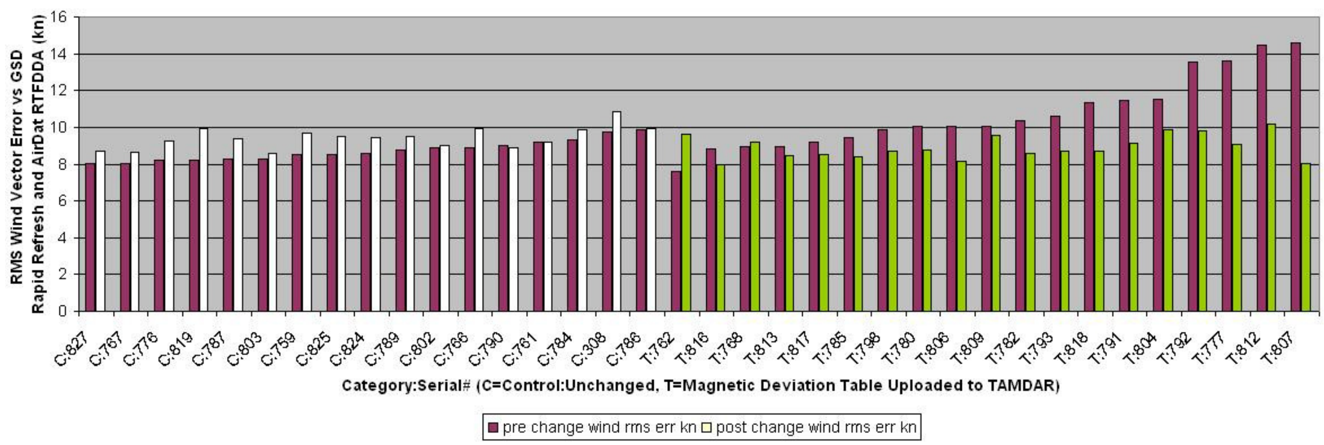

Figure 9. Wind RMS error w.r.t. combined GSD RR and AirDat RTFDDA model data, by TAMDAR serial # (individual planes) before (15 Aug 2009 to 15 Sep 2009) and after (21 Oct 2009 to 21 Nov 2009) the magnetic deviation lookup tables were uploaded. Maroon bars are before the magnetic deviation lookup table was uploaded. White bars are control units—no changes applied—for the after period . Green bars are units that had the lookup tables uploaded and are for the after period.

8.2.2 Mesaba Metadata Wind Categories

AirDat maintains a quality system to ensure that only good quality data is distributed [14]. As part of this process, metadata flags for the various atmospheric measurement fields are set to either trustworthy or untrustworthy for each plane. Wind data from planes with an untrustworthy metadata setting will not be distributed to meteorologists or modeling systems. It is of interest to note the change in the number of planes with trustworthy metadata flags on the Mesaba fleet for the before and after periods of this study. Figure 10 shows the number of planes in the untrustworthy (blue) and trustworthy (green) wind metadata category over time. The top of the plot is the total number of planes. The levels on the plot vary over time due to plane maintenance and flight schedules.

After the implementation of the magnetic deviation method in this paper, and after a short evaluation period, the number of planes in the trustworthy category noticeably increased. There were approximately 89% of the planes with trustworthy metadata flags before the method was applied; after the method was applied the percentage of planes with trustworthy metadata increased to about 97%. Several sensors that already had trustworthy wind metadata settings still benefited from uploading the magnetic deviation lookup tables.

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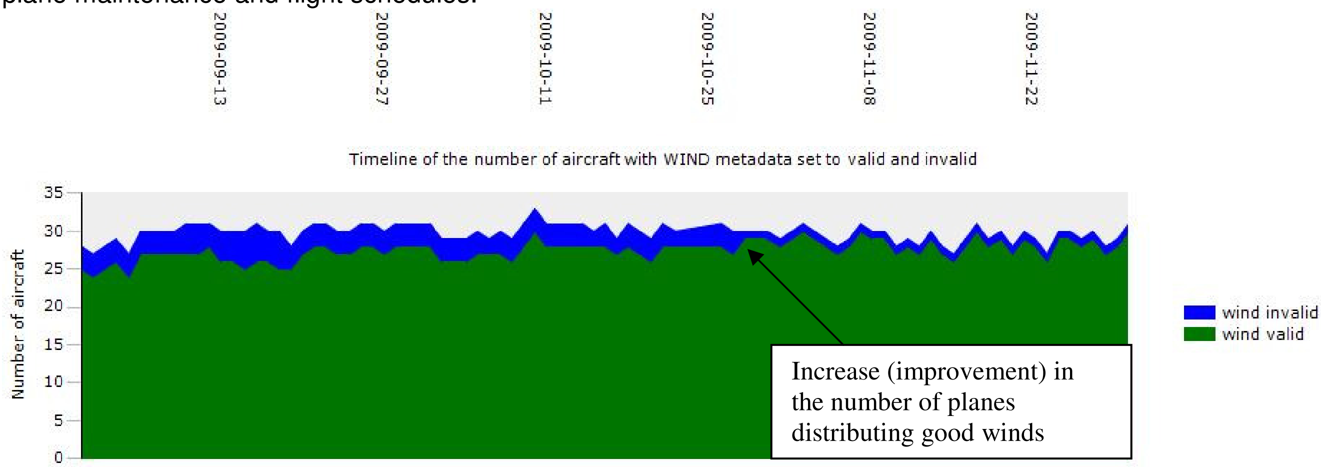

Figure 10 Wind metadata settings for 1 Sep 2009 to 30 Nov 2009

8.3 PenAir Improvement Statistics

The method was later applied to four PenAir SAAB-340s that had poorly performing heading systems. It should be noted that PenAir flies routes in Alaska which generally has higher magnetic variations and lower model accuracy than the Mesaba region. The magnetic variation inaccuracy in Alaska, also a potential contributor to wind errors, is generally also greater than that of the Mesaba region. Since it's impossible to separate actual system heading errors from errors in magnetic variation, it is possible that some of the improvement from the method is a result of compensating for magnetic variation errors as well as heading errors. The data gathering period for the PenAir magnetic deviation curve fits was 1 Feb 2009 to 9 Mar 2010. Only the RR model was used since the AirDat RTFDDA domain did not cover Alaska. ACARS and NAM data were used to verify the trend. The first two rows in Table III show the change in performance for the four PenAir SAABs. As expected, the primary change is a reduction in the transverse wind error component. The overall improvement is significant.

Table III Model comparison statistics of PenAir SAAB-340 planes with poorly performing heading systems and healthy control planes before (9 Jan 2010 to 9 Mar 2010) and after (27 Mar 2010 to 27 May 2010) magnetic deviation lookup tables were applied to poorly performing planes.

Airplane Group	Time Period	Wind RMS Error	Longi-tudinal Wind RMS Error	Trans-verse Wind RMS Error
Poorly Performing Heading systems (511, 542, 506, 524)	Before (16,833 obs)	16.4 kn	6.3 kn	15.6 kn
	After (25,306 obs)	9.1 kn	5.6 kn	7.0 kn
	After (adjusted for model variation)	8.2 kn	4.8 kn	6.2 kn
	Improve-ment kn	8.2 kn	1.5 kn	9.4 kn
	Improve-ment %	50.1%	23.7%	60.3%
Healthy Heading Systems (Control) (510, 566, 502)	Before (15,901)	11.0 kn	6.5 kn	8.8 kn
	After (21,201)	11.9 kn	7.2 kn	9.7 kn
	After (adjusted for model variation)	11.0 kn	6.5 kn	8.8 kn

8.4 Chautauqua Improvement Statistics

A limitation of TAMDAR at the time of these analyses that has since been rectified is that the TAMDAR firmware was only able to apply these heading corrections if the aircraft provided heading was magnetic heading, not true heading. Even though the ERJs with the poorly performing AH-800 AHRS base the heading on a magnetic flux valve system, the on board avionics does its own magnetic variation correction to supply TAMDAR with true heading. This restricted any changes to offset corrections only (no sinusoidal heading variations could be corrected). Three planes that had high offset errors (as high as 6 deg) and small sinusoidal errors were chosen for this method. The results in Table IV show a significant improvement. The data gathering period for the Chautauqua curve fits was 9 Mar 2009 to 9 Mar 2010.

Table IV Model comparison statistics of three Chautauqua ERJ-145 planes with poorly performing heading systems and healthy control planes before (10 Jan 2010 to 10 Mar 2010) and after (11 Mar 2010 to 11 May 2010) magnetic deviation lookup tables were applied to poorly performing planes.

Airplane Group	Time Period	Wind RMS error	Longi-tudinal Wind RMS Error	Trans-verse Wind RMD Error
Poorly Performing Heading systems	Before (29,723 obs)	30.0 kn	6.4 kn	32.1 kn
	After (40,319 obs)	10.7 kn	6.1 kn	9.0 kn
	After (adjusted for model variation)	9.5 kn	5.3 kn	8.2 kn
	Improve-ment kn	20.5 kn	1.1 kn	23.9 kn
	Improve-ment %	68.3%	17.2%	74.5%
Healthy Heading Systems (Control)	Before (99,064 obs)	8.8 kn	6.2 kn	6.2 kn
	After (118,980 obs)	10.1 kn	7.0 kn	7.1 kn
	After (adjusted for model variation)	8.8 kn	6.2 kn	6.2 kn

Figure 11 and Figure 12 show the total RMS wind error, and its longitudinal and transverse components for the before and after periods, versus altitude for these ERJs. There is a huge reduction in transverse wind error as a result of the method.

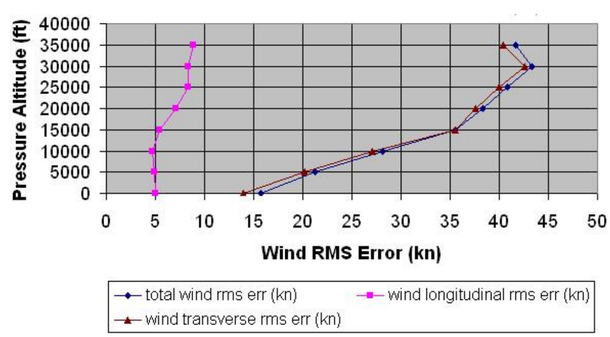

Figure 11 Model comparison statistics of Chautauqua ERJ-145 planes with poorly performing heading systems before (10 Jan 2010 to 10 Mar 2010) magnetic deviation lookup tables were applied.

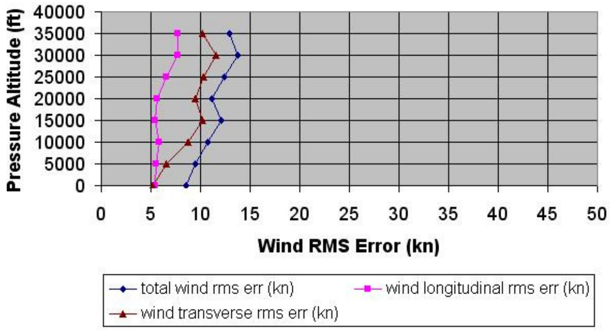

Figure 12 Model comparison statistics of Chautauqua ERJ-145 planes with poorly performing heading systems after (11 Mar 2010 to 11 May 2010) magnetic deviation lookup tables were uploaded. Overall model degradation of 1.2 kn is not reflected so the net change is better than shown.

8.5 Descent Wind Improvements

The SAAB-340 descent wind quality in the past was never as good as those on ascents. The descent winds were in most cases considered poor and were generally not used. Aircraft maneuvering on descent causing TAS and heading errors was suspected to be one cause.

An unexpected result of the magnetic deviation correction method was a significant improvement in the quality of the descent and level flight winds. Figure 13 and Figure 14 show the wind errors versus altitude for ascent, descent and level flight phases for the period before the magnetic deviation lookup table was uploaded, and after the table was uploaded. Since the change in the control group's overall error from the before period to the after period was 0.6 kn, this number was subtracted from the wind RMS errors for the after period in Figure 14. Note that RMS wind errors during level flight are also reduced.

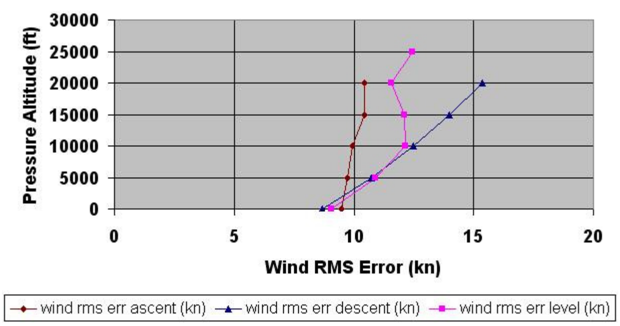

Figure 13 Model comparison statistics for three flight phases—ascent, descent, level—of Mesaba SAAB-340 planes with poorly performing heading systems before (15 Aug 2009 to 15 Sep 2009)) magnetic deviation lookup tables were applied.

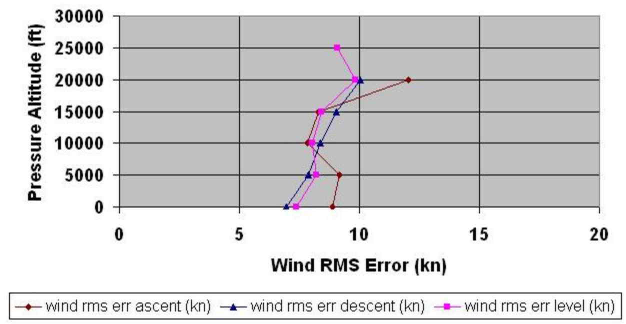

Figure 14 Model comparison statistics of Mesaba SAAB-340 planes for three flight phases—ascent, descent, level—with poorly performing heading systems after (21 Oct 2010 to 21 Nov 2009)) magnetic deviation lookup tables were applied. Wind errors are adjusted to take out effect of changes in model performance based on control group.

9 Discussion and Conclusions

The analysis described in this paper has shown that the relatively high RMS wind errors on many TAMDAR equipped aircraft using flux valve based heading is due to inaccurate heading systems. It was also shown that the heading inaccuracies (magnetic deviation) can be characterized by comparing the TAMDAR reported winds to weather model winds. This process needs to be done with care as wind direction and speed biases in the model may cause poor results. Comparisons to various sources—AirDat RTFDDA, GSD RR, NAM and ACARS—were done to ensure the same general trends were observed. The result of the analysis is generally a sinusoid with an offset describing the magnetic deviation as a function of aircraft heading. The sinusoidal nature of the curve suggests that the errors are primarily due to hard iron effects. A lookup table based on this aircraft specific correction curve is uploaded to the TAMDAR unit which compensates for heading errors as part of the wind calculation.

Wind RMS error components were separated into longitudinal and transverse components. Errors in the transverse component suggest inaccurate heading whereas errors in the longitudinal component suggest inaccurate true airspeed. In all cases of poorly performing systems the transverse component error dominated the total error. After the magnetic deviation correction method was applied, the transverse errors were reduced significantly resulting in a significant reduction in total RMS wind error. This error reduction occurs when comparing to ACARs and ground station measurements as well as model comparisons.

The method was applied to 19 of the worst performing Mesaba SAAB-340s with a resultant 2.4 kn reduction in the error w.r.t. the GSD RR and AirDat RTFDDA models. It was also applied to four PenAir SAAB-340s which fly in the Alaska region with and error reduction of 8.4 kn w.r.t. the GSD RR. Three Chautauqua ERJ-145s with very poor winds had an error reduction of 20.5 kn w.r.t. both models. The vast majority of planes that had the method applied were able to provide winds of satisfactory quality.

It was also demonstrated that the higher wind errors during descent were significantly reduced for the SAAB-340 planes. These descent winds were previously considered untrustworthy but have been moved to the trustworthy category after the method was applied.

In some geographic regions magnetic variation inaccuracies may also be a contributor to heading errors. This method may partially be correcting those errors too but that effect is difficult to separate from the effects caused by actual flux valve errors.

One of the assumptions of the method is that the horizontal component of the earth's magnetic field is constant over the region of interest. The method may not work well over regions that span large changes in magnetic latitude. Results show that the method works well at least over the areas covered by the Mesaba SAAB-340 fleet (midwest US), the PenAir SAAB-340 fleet (Alaska), and the Chautauqua fleet (eastern US). Future enhancements could adjust the heading correction based on the magnetic latitude of the observation.

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