

**TO:** ARISTO-LAMS archive

**FROM:** Al Cooper

**SUBJECT:** Studies of the measurements of wind using LAMS – C130 ARISTO2015/2016

## **1 Introduction**

During the 2015 and 2016 ARISTO projects on the C-130, the LAMS was flown in a 4-beam configuration. The beam assignments were non-standard, though, with beam 2 forward, beam 1 downward, beam 3 outboard and upward, and beam 4 inboard and upward. Beams 1, 3 and 4 were approximately  $35^\circ$  from the forward direction, and relative to an azimuthal angle starting from the downward direction they were, respectively,  $0$ ,  $-120$  and  $120^\circ$  in clockwise rotation about the forward longitudinal axis.

There were five research flights in ARISTO-2015 and six in ARISTO-2016. Data from both projects are included in this memo, which is somewhat disorganized in that the discussions have not been merged well except in the conclusions. All flights had some degree of measurement problems, so data for this study have been selected from the periods that appear to provide the best measurements. The following table provides a few of the characteristics of these flights:

<b>date</b>	<b>start</b>	<b>end</b>	<b>profile</b>	<b>problems</b>
150916	160225	200605	climb->20kft, level, stepped descent to BL, no maneuvers	LAMS IRU attitude angles bad
150923	135907	204016	mostly low level until near end; LAMS reasonable, although weak; some speed variations	actual takeoff about 170000; BEAM2speed weak, BEAM2_LAMS (Scott's value) better.
150925	162500	214500	both upper and lower-level legs; speed runs, some turbulence	CPITCH_LAMS bad before 192300, and CROLL also, so wind measurements from LAMS unavailable until after then.
150930	170100	205000	good pitch and yaw maneuvers; also a partial speed run.	Beams 1 and 4 problematic before 1915 in high-level leg; beam 2 probably useful for TAS.
151002	143000	184400	upper-level pitches and lower-level turbulence	LAMS beam peaks look very weak to me, questionable although SMS processing seems reasonable.
160802	162500	183500	profiles; no sign. cloud, no low-level & max ca. 7 km	LAMS mostly good; some brief gaps.
160808	150500	160000	brief flight at low level	some beam-1 problems at low level
160809	160000	183235	some cold cloud near max altitude ca. 7km; LAMS appears bad there.	some LAMS-beam gaps at upper level.
160810	134539	184016	only brief cold cloud; up to 5-6km.	LAMS good
160812	190000	203616	smoke-plume study; high CDP conc. in plumes.	LAMS good
160816	130138	264829	long flight with near-sea-level leg for PCOR study; refueling stop at about 1800–1900. Some low-level cloud near 1900–1930, with shorter cloud passes during return leg. Good short maneuvers also.	LAMS problems early after refueling and some also prior to descent for refueling, esp. beam 2. Looks OK for critical part near 2100–0100.

For ARISTO-2015, the line-of-sight beam speeds were determined in two ways. Scott Spuler used principal-component analysis to find the beam speeds, and usually this worked very well, although there are some suspicious times. For example, the peaks in Flight 5 look very weak, yet

the PCA method continued to find output values. Because there was tight coupling to the expected measured TAS (with adjustment for the beam angles), it appears suspicious that the method may be duplicating the TAS value at times without having an adequate signal. The match to TASX looks so good that it seems suspicious, as discussed later. A second method was to fit the background using Savitzky-Golay polynomials and then search for peaks above this background. When signals were strong, the method usually produced the same result as the PCA method, but it was more prone to failure during periods where the signal was weak. (A signal-to-noise test of  $\geq 4$  was required for a valid measurement.) Results from both these peak-detecting algorithms will be discussed in this memo.

For ARISTO-2016, only the second method of processing was available at the time of this study, so results will all be based on the second method for that portion of the project.

There are several objectives that can be met by using the LAMS-derived measurements:

1. The LAMS provides an independent measurement of angle-of-attack and sideslip angle, so these measurements can be used to check the empirical relationships used to calibrate the radome-based measurements of these angles.
2. LAMS provides an independent measurement of the airspeed, so from that measurement it is possible to determine the expected dynamic pressure. This was used previously (Cooper et al., 2014) to calibrate not only the dynamic pressure but also the static pressure as measured on the C-130. However, since then the offset between the avionic static pressure and the research static pressure calibrated in this way has changed, so it is important to learn if the static defect actually changed or perhaps the avionic value changed. This has an important effect on the longitudinal component of the measured wind as well. ARISTO-2016, esp. the last flight, provided an opportunity to extend the fit conditions to cover low-altitude flight of the C-130.
3. The paper by Cooper et al. (2014) developed a method for measuring temperature using the LAMS, which might have potential to provide a valid measurement of temperature in clouds. However, only a small sample of measurements were available for use in that paper, so it will be useful to explore if further measurements from ARISTO help characterize this measurement.
4. The method used to calibrate the radome is based primarily on slowly varying measurements, such as the variation in angle-of-attack during a speed run. It is of concern that the calibration used might not apply in the case of rapidly changing flight conditions, when for example there might be transient adjustment of the airflow pattern toward a new steady state. Because the LAMS measures wind well ahead of the aircraft, such effects should not appear in the LAMS-based measurements, so a comparison of the LAMS-based and radome-based measurements might either identify transient-response problems or place limits on how large such effects might be. Some rapid changes in pitch were included in the last flight of ARISTO-2016 that can be used for this study.

## 2 Data processing

The original netCDF files, with names like ARISTOrf01.nc, contain histograms of the LAMS frequency measurements, with names like BEAM{1-4}\_LAMS. For ARISTO-2015, Scott Spuler has processed these to produce files like ARISTOrf01\_LAMS.nc with new variables Beam{1-4}\_LAMS containing the line-of-sight speeds measured in each beam. In addition, the Python program LAMS\_ARISTO.py has been used to process these further to files ARISTOrfxx\_LAMSLAMS.nc, which contain additional variables BEAM{1-4}speed also representing the line-of-sight speeds. Only the latter processing has been performed for ARISTO-2016, for which the resulting files have names like ARISTO2016rffxLAMS.nc. Both sets of variables, Beam{1-4}\_LAMS and BEAM{1-4}speed, will be used below when available but they appear to have different strengths:

1. The variables Beam{1-4}\_LAMS are produced by Spuler's PCA routine. This is the most sensitive detection method, but there is some suspicion that it produces values when there is inadequate signal, perhaps by too much reliance on TASX to determine where the peak should be.
2. The variables BEAM{1-4}speed are produced by smoothing the histograms with Savitzky-Golay polynomials and then searching for peaks above the smoothed background. This algorithm also uses TASX to determine likely locations for the peaks, but with a fairly large tolerance, and it requires a signal-to-noise ratio  $\geq 4$  or else it produces a missing-value result. In ARISTO2015, this algorithm was significantly less sensitive than the PCA algorithm, and for example in Flight 5 it mostly did not produce useful results while the PCA algorithm produced almost continuous results for the line-of-sight beam speeds.

The Python routine also produced new variables named WD\_LAMS, WS\_LAMS, WI\_LAMS, ATTACK\_L and SSLIP\_L, using the processing algorithms for a 4-beam LAMS that were discussed in the documents LAMSprocessing4Bwind.pdf and LAMSprocessing3Dwind.pdf. However, these variables were not used in the study reported here. Instead, all variables derived from the line-of-sight LAMS measurements were recalculated in the present R routine (this file) to generate measurements of vertical and horizontal wind, airspeed, and angles of attack and sideslip. For airspeed, angle of attack, and sideslip, these steps were used:

1. The four-beam measurements were used to determine a three-dimensional relative wind vector  $\mathbf{RW} = \{RW_x, RW_y, RW_z\}$  with components inbound along the longitudinal forward, lateral starboard, and lateral downward axis in the coordinate frame of the LAMS IRU (with attitude angles CPITCH, CROLL, CTHDG). The algorithm is documented in LAMSprocessing4Bwind.pdf.
2. The airspeed is then the magnitude of the vector  $\mathbf{RW}$ .
3. The angle of attack is  $\alpha = \arctan(RW_z/RW_x)$  and the sideslip angle is  $\beta = \arctan(RW_y/RW_x)$ .

For measurements of wind, the Ranadu routine `Ranadu::WindProcessor()` was used to calculate the wind based on LAMS-based variables for airspeed, angle of attack, and sideslip and the INS-provided attitude angles, with complementary-filter adjustment of the INS-provided groundspeed components based on the corresponding GPS-provided measurements.

For completeness, here are suggested procedures for using the Python routine `LAMS_ARISTO.py`, with comments regarding future use with new data files:

1. On tikal, copy the routine `~cooperw/LAMS/LAMS_ARISTO.py` to another directory where you have write permission.
2. On lines 252 and 253, change the names of the data file and the directory containing the file to be processed. Do not include the trailing “.nc” in the file name, and if the file already contains Scott Spuler’s processing add “\_LAMS” to the file name as on line 251. Save the edited file. CAUTION: This routine will create a new file in that same directory with “LAMS” appended to the name supplied, and if that file is present it will overwrite the file. This won’t overwrite Scott’s files because it adds “LAMS” instead of “\_LAMS”, but if Scott’s files are used the new file will end in “\_LAMSLAMS”. In that case, the new file will contain the line-of-sight speeds obtained by both algorithms, in Scott’s case with the names `Beam1_LAMS – Beam4_LAMS` and in the case of the Python program with names `BEAM1speed – BEAM4speed`.
3. Run the program using the command “`python LAMS_ARISTO.py`”. There will be regular messages during processing, ending (if successful) with the message “Reached end of routine ...”. This will typically take a few minutes. If this fails immediately, there may be a problem with the available python packages that need updating or changing.
4. On successful completion, there should then be a new file with a name ending in “LAMS.nc” in the prescribed working directory. It should be slightly larger than the original file because a few variables are added containing the line-of-sight LAMS speeds and some derived quantities. These are then the netCDF files that are read by the next routine to produce the final document,.

The next step is then to run the present routine, “ARISTO-LAMS.Rnw”, in RStudio to generate the PDF document.

Some results for the various processing schemes are shown in Fig. 1.

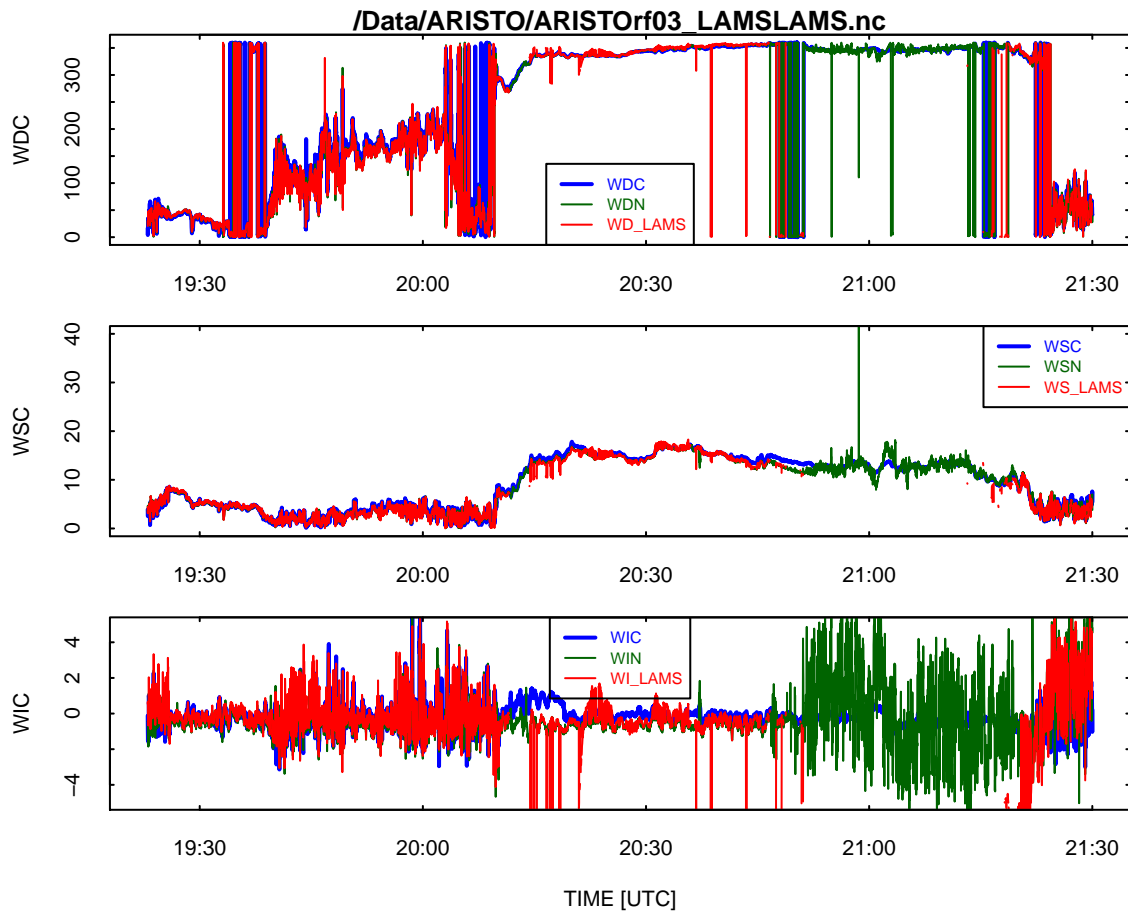


Figure 1: Wind measurements: conventional (blue), PCA-based (green), SG-based (red). The time period is restricted to 19:23–21:30 UTC because the LAMS IRU produced erroneous values for the attitude angles at other times.

### 3 Sensitivity coefficients

#### 3.1 Angle of attack

The following speed-run maneuvers are available from ARISTO2015:

#	flight	start	end	comments
1	2	183200	185500	PCA, not SG
2	2	192100	193800	PCA or (SG exc 193000)
3	3	171300	173800	CPITCH bad
4	3	183400	185700	CPITCH bad
5	3	205500	210000	slowdown only; PCA only
6	4	174300	180700	PCA only
7	4	191200	193000	PCA only; SG weak
8	4	202500	203900	PCA; SG B1 weak

The values of vertical wind as originally processed did not look very good, so the first step was to determine a conventional set of sensitivity coefficients to use as a radome calibration. For this purpose, a data.frame consisting of a concatenation of the eight speed runs in the preceding table was constructed and a reference value for calibration (AOAREF) was added to the data.frame. AOAREF, defined below, is the value that should be measured for angle of attack if the true vertical wind is zero during the maneuver:

$$\text{AOAREF} = \theta + \frac{w_p}{V} \frac{180}{\pi} \quad (1)$$

where  $\theta$  is the pitch angle (variable PITCH),  $w_p$  is the rate of climb of the aircraft (variable GGVSPD), and  $V$  is the true airspeed (variable TASX). The conventional fit is then

$$\text{AOAREF} = c_0 + \frac{\text{ADIFR}}{\text{QCF}} (c_1 + c_2 \text{MACH}) \quad (2)$$

where MACH is the Mach number determined from the uncorrected measurements PSFD and QCF (cf. the technical note on processing algorithms). In addition, a data.frame consisting of all measurements from flights 2–4 was constructed and coefficients were also determined for a fit to those data.

Figure 2 shows the resulting fit, with coefficients  $\{c_0, c_1, c_2\} = \{4.7314, 11.5015, 3.0546\}$ . However, the results differed for the three flights, and the differences were significant, as shown in the following table:

Flight	$c_0$	$c_1$	$c_2$
speed runs	4.7314	11.5015	3.0546
all rf02–04	4.6298	11.7147	1.5477
2	4.1623	6.0555	13.9073
3	4.5892	8.4874	8.5789
4	4.9885	12.4355	2.0626

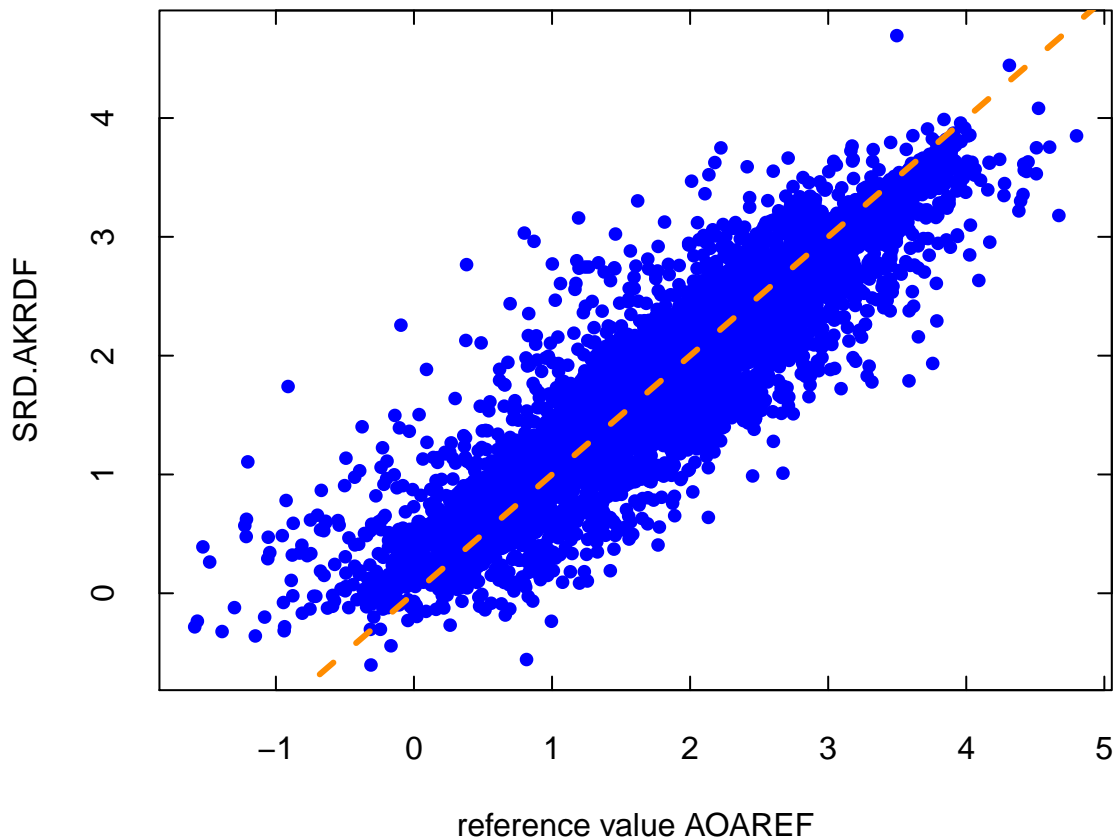


Figure 2: Angle of attack from the new calibration vs. the corresponding value of the reference variable AOAREF.

Therefore, the individual-flight coefficients will be used to determine AKRD and hence WIC in the following studies in this report.

An additional adjustment of the measurements is useful because the LAMS is not installed parallel to the centerline of the aircraft. For example, the average measurement of pitch from the LAMS IRU, CPITCH\_LAMS, is  $1.0^\circ$  larger than the corresponding measurement of pitch from the Honeywell IRU. To account for this offset, it is useful to correct both the pitch and angle-of-attack from LAMS by the subtraction of  $1.0^\circ$  so that the measurements will be comparable to those from the standard radome-based system. That correction has been made in the following when the LAMS-based angle-of-attack is discussed.

With these corrections, the standard angle-of-attack can be compared to that determined from the LAMS. The first speed run in the table above will be skipped here because there are too many bad measurements from LAMS. For the second speed run, Figure 3 shows the comparison of the two angles of attack. There is a clear difference between the two measurements. Speed runs #3 and #5



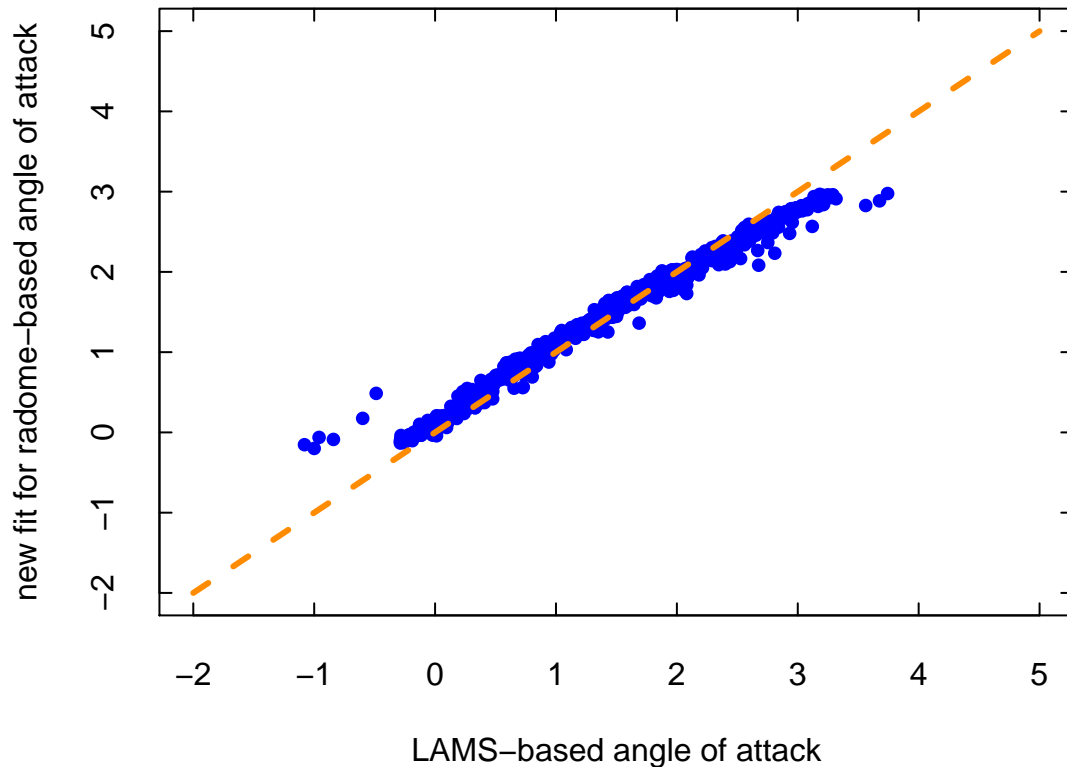


Figure 3: Angle of attack from the new fit to the radome values, plotted against the corresponding angle-of-attack as measured by the LAMS, for speed run #2.

have too much scatter in the LAMS measurements to be useful, but speed run #4 has apparently good measurements as shown in Fig. 4. Here the scatter is much higher than in Fig. 3 because this is a low-level flight segment in boundary-layer turbulence, but the measurements still show an offset like that in Fig. 3, although perhaps with a smaller offset. Speed runs #6 and #8 have high scatter and are inconsistent with other apparently good speed runs, but speed run #7 led to good agreement between the values of the radome-based and LAMS-based angles of attack, as shown in Fig. 5.

Figures 3 and 5 show reasonable consistency between the two measurements, while there is a significant offset evident in Fig. 4. Because speed run #4 is a low-level boundary-layer leg, there may be bias introduced by the proximity of the ground and strong reflection from it that could affect the downward-pointing beam. A fit to the radome-based angle of attack as a function of the LAMS-based value gave regression coefficients of 0.66 (offset) and 0.70 (slope), so these measurements are clearly inconsistent.

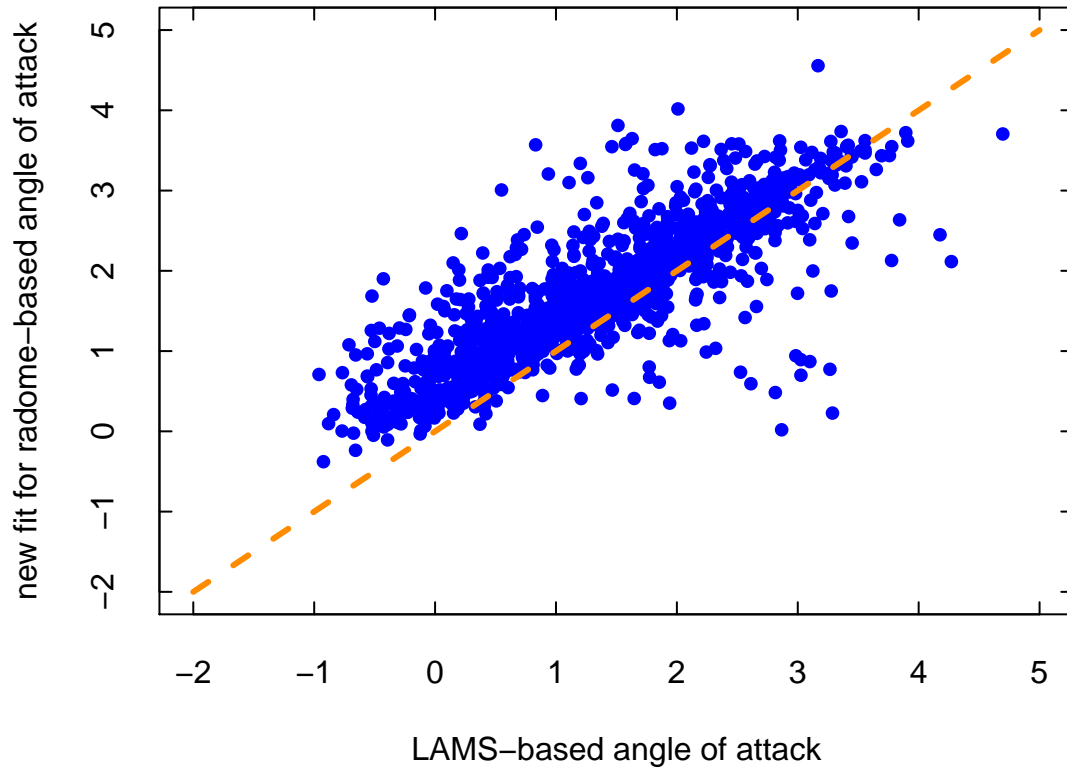


Figure 4: Angle of attack from the new fit to the radome values, plotted against the corresponding angle-of-attack as measured by the LAMS, for speed run #4.

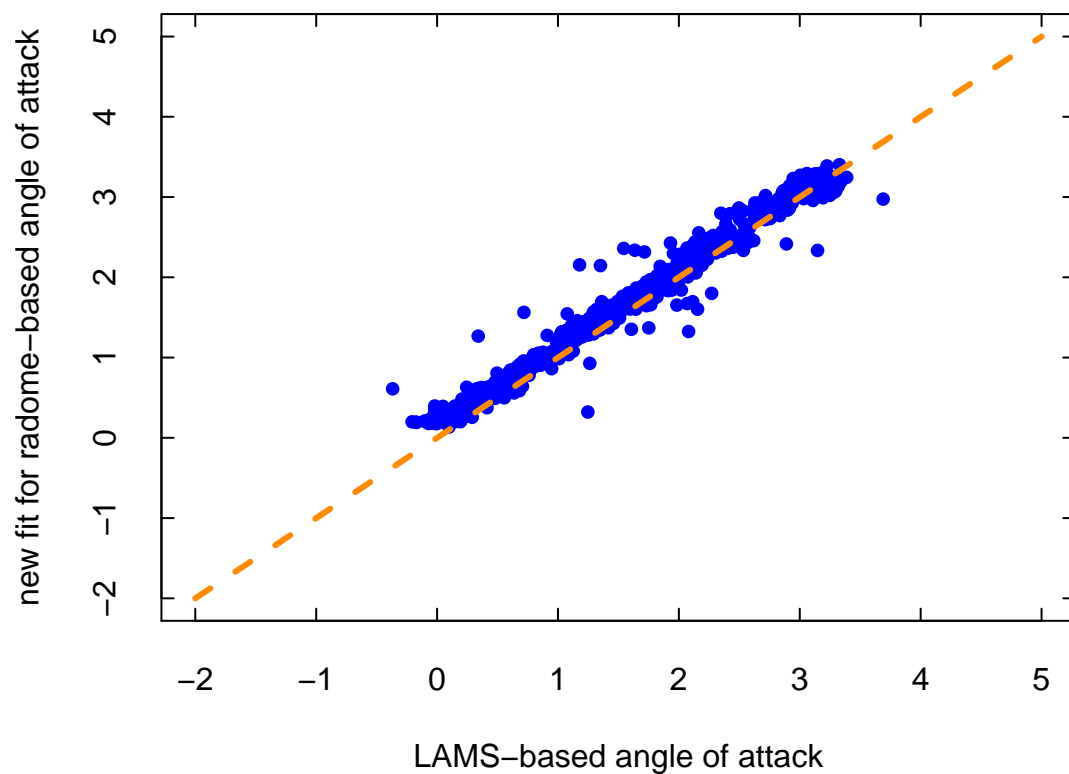


Figure 5: Angle of attack from the new fit to the radome values, plotted against the corresponding angle-of-attack as measured by the LAMS, for speed run #7. Some additional outlier points having difference between the measurements larger than 1 degree have been excluded from the plot.

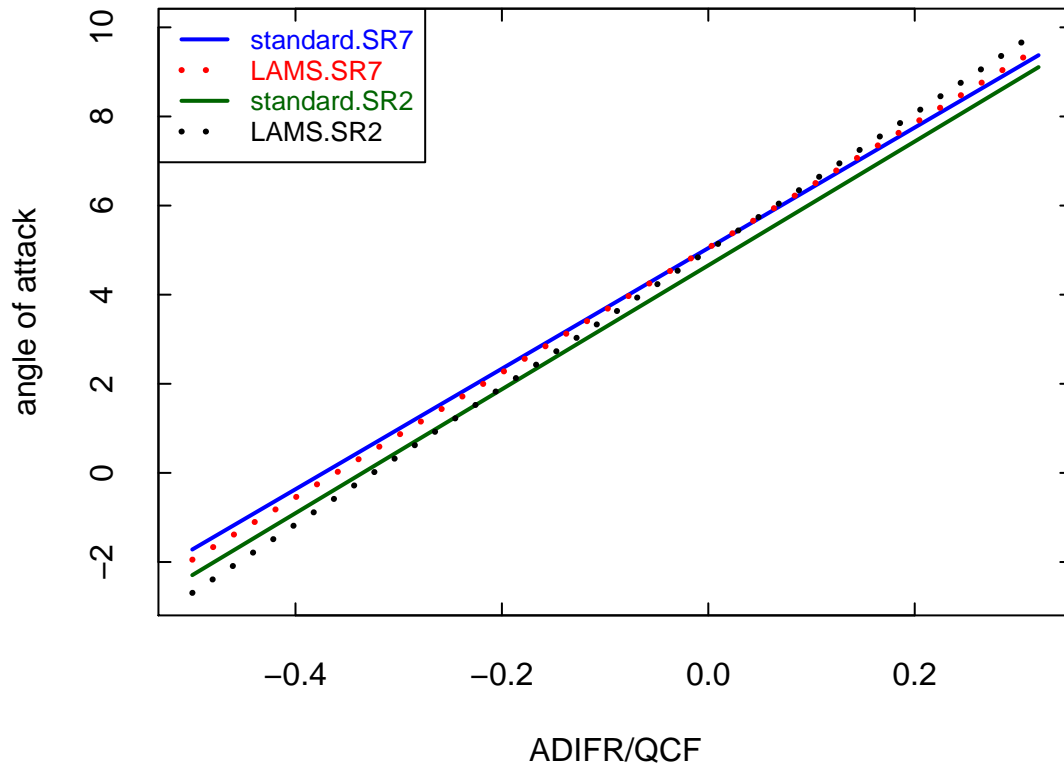


Figure 6: Comparison of the standard and LAMS-based calibrations for speed run #7.

A revised LAMS-based calibration for the radome sensitivity coefficients can then be determined by using the LAMS-based angle of attack as the reference for the fits. Separate fits for speed-run #2 and for #7 produced significantly different results, so both the conventional and LAMS-based calibrations differ for the two speed runs. The following table summarizes the results:

speed run	source of calibration	$c_0$	$c_1$	$c_2$
#2	AOAREF	4.6576	13.9045	0
#2	LAMS ATTACK	4.9945	15.3775	0
#7	AOAREF	5.0451	13.5299	0
#7	LAMS ATTACK	5.0512	13.9997	0
#2+#7	LAMS ATTACK	4.6694	9.7585	8.4181

The four calibrations in the preceding table are plotted in Fig. 6. For speed run #7, the calibrations based on LAMS and on AOAREF are close to the same, although there are small differences of typical magnitude of about  $0.1^\circ$  for angles-of-attack in the typical range of operations ( $0-4^\circ$ ).

However, the different calibrations for speed run #2 are not as consistent, and both calibrations differ significantly from those for speed run #7. A fit to the combined data from #2 and #7 is also shown for the LAMS calibration, but this fit was much worse than the individual-flight calibrations and showed two distinct lines with little overlap for the two plots, so this is not a good calibration to use for these flights. For the conventional calibration, the difference might be attributed to a non-zero vertical wind during the calibration maneuver, but the LAMS calibration is not affected by the vertical wind so it should be definitive unless there was some problem with detection of the LAMS beams. Other possibilities are drift of the CPITCH\_LAMS measurement or differences in altitude or Mach number. However, the difference between PITCH and CPITCH\_LAMS is the same for speed run #2 as for speed run #7 and both were flown at almost the same altitude and range in Mach number, so these explanations appear to be ruled out.

The result is that the two best speed runs, #2 and #7, are inconsistent. Calibrations for speed run #7 support the validity of each, but there is larger than expected difference between the two calibrations for #2 and between the corresponding calibrations for #7 vs #2. These are the best calibration data available, so more measurements with adequate LAMS signal-to-noise would be valuable. Pending such measurements, the LAMS-based calibration for #7 may be the most reliable.

Another conclusion from the study of the speed runs is that the PCA analysis does not always produce reliable line-of-sight speeds. A good example is speed run #6. There are values for all four beam line-of-sight speeds through this maneuver, and the speed in the forward beam (Beam 2) matches the true airspeed (TASX) well. However, Fig. 7 shows that the angle-of-attack determined from these measurements does not match that determined from the radome-based system and looks very noisy. This raises a warning that sometimes the line-of-sight speeds are not valid even when the PCA algorithm detects peak values.

See also Section 4.3, where sensitivity coefficients are determined from the last ARISTO-2016 flight. These are based on the widest range of flight conditions and are suggested as the best for general use for C-130 projects since 2011.

### 3.2 Sideslip angle

There were four yaw maneuvers that can be used to find the sensitivity coefficients for the sideslip measurement, as listed in the following table:

maneuver #	flight	start	end
1	2	194100	194330
2	4	182800	183100
3	4	190130	190400
4	4	201830	202130

First, for completeness, the conventional fit will be used:

$$\beta^* = -\Psi + \arctan \frac{u_p - u}{v_p - v} \quad (3)$$

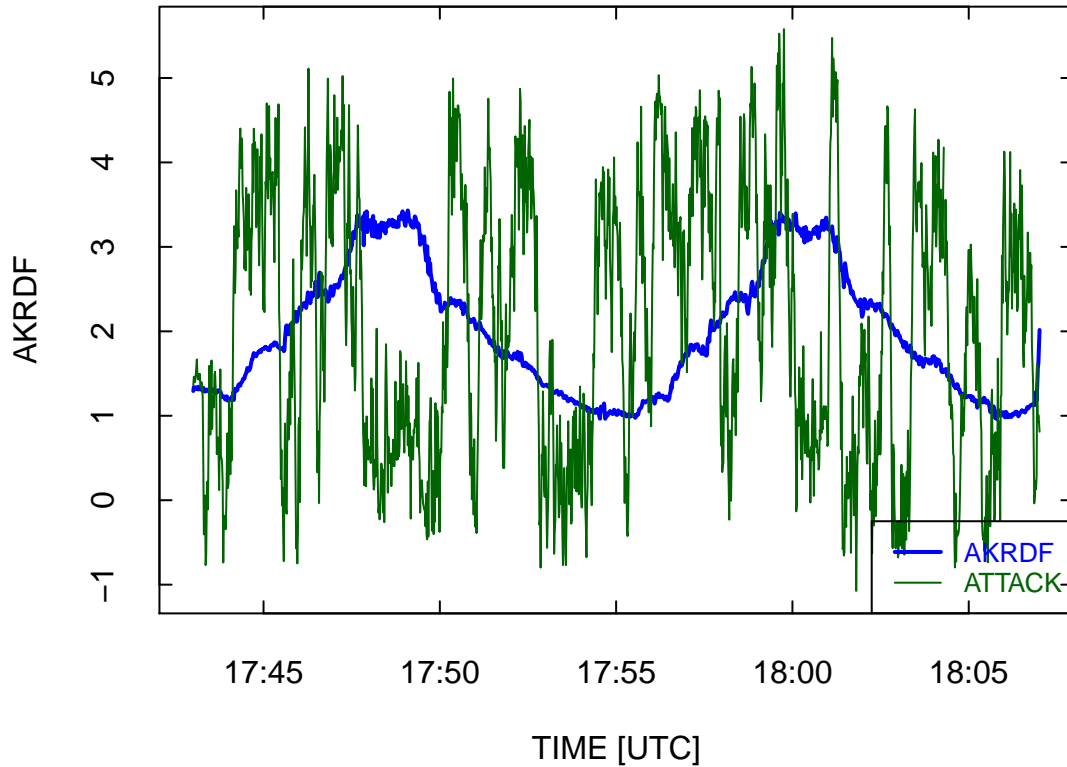


Figure 7: Angle of attack from the new fit to the radome values (blue line) and the angle-of-attack determined from the LAMS measurements (green line), for speed run #6.

where  $\beta^*$  is the reference value for the fit,  $\Psi$  is the heading,  $u_p$  and  $v_p$  the eastward and northward components of the aircraft ground-speed and  $u$  and  $v$  are the east and north components of the wind. The empirical relationship for sideslip then can be found by fitting for the coefficients  $\{s_0, s_1\}$  in:

$$\beta^* = b_0 + b_1 \frac{\text{BDIFR}}{\text{QCXC}}$$

and then finding the sideslip angle from

$$\text{SSRD} = b_0 + b_1 \frac{\text{BDIFR}}{\text{QCXC}} . \quad (4)$$

Figure 8 shows that the resulting values for SSRD are in close correspondence to the reference values for the four combined yaw maneuvers.

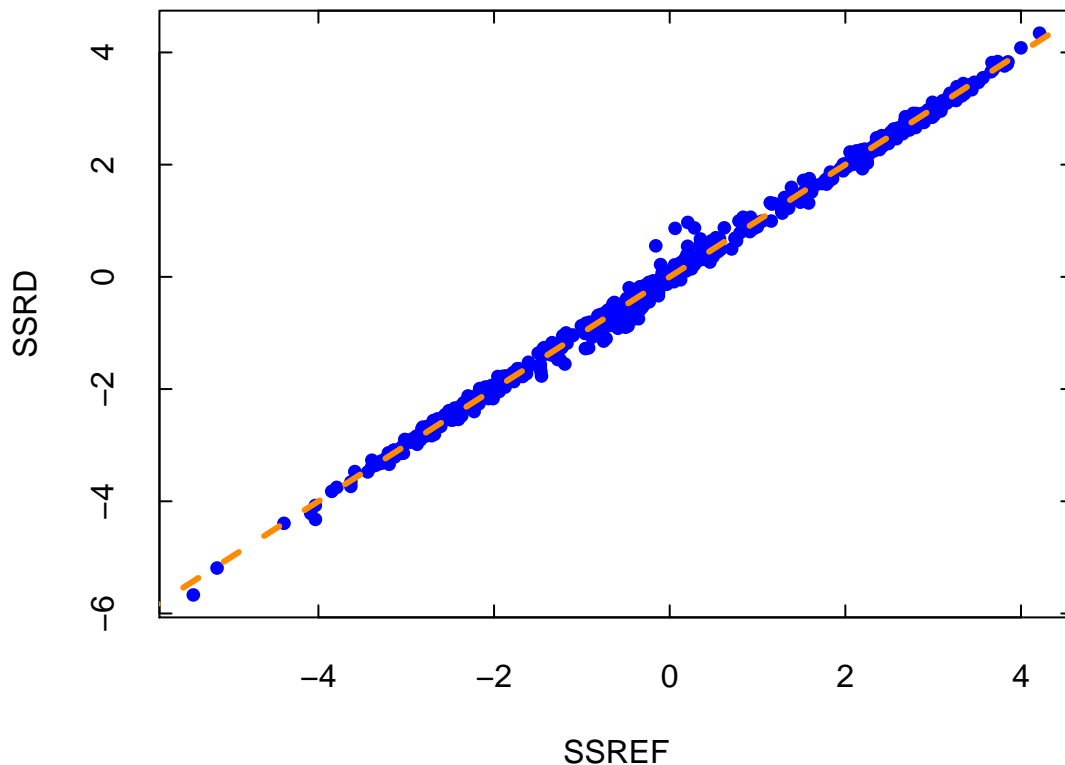


Figure 8: Sideslip angle calculated using new fit coefficients (SSRD) as a function of the reference value for sideslip (SSREF). The relationship determined by regression is shown as the dashed orange line.

The resulting sensitivity coefficients for sideslip are  $\{b_0, b_1\} = \{1.5478, 12.6582\}$ . The fit was very good, with a residual standard deviation of  $0.12^\circ$ . For comparison, the standard values in the Technical Note on Processing Algorithms are  $\{0, 12.2115\}$ . As discussed in the Technical Note on Wind Uncertainty, it is difficult to separate an offset in sideslip from an offset in heading, so the difference in the first coefficient may instead apply to heading.<sup>1</sup> The difference in offsets for these two calibrations is large, although the slope coefficients are in reasonable agreement.

The LAMS measurement of sideslip provides an alternate means of determining the slope parameter.<sup>2</sup> The reference value  $\beta^*$  for the fit can be determined from the LAMS-based measurements of the relative wind, as discussed in the introductory section:

<sup>1</sup>An offset of  $-0.1^\circ$  applied to heading in the original processing has not been removed here.

<sup>2</sup>The appropriate offsets in sideslip and heading will still need to be found from analysis of circle maneuvers.

$$\beta^* = \arctan\left(\frac{RW_y}{RW_x}\right) \quad (5)$$

The LAMS-based measurements of sideslip bear little similarity to those from the radome for sideslip maneuvers #2 and #3, so there are evidently measurement problems that make those unreliable. Maneuver #4 is good, and maneuver #1 appears valid for the period 194130–194305, so those measurements were used for the fit. The LAMS-based fit gave coefficients  $\{b_0, b_1\} = \{1.5995, 12.3612\}$ , with a residual standard deviation about the fit of  $0.13^\circ$ . These values are close to those determined in the standard way, so this calibration provides support for the conventional approach, although the difference in slope is significant (with estimated standard uncertainty in  $b_1$  of  $0.05^\circ$ ). The value for  $b_1$  determined from the LAMS-based measurements,  $12.361^\circ$ , appears to be the best available, but the value of  $b_0$  still needs to be determined from the circle maneuvers that can separate an offset in sideslip from an offset in heading.

## 4 Calibration of the pressure defect

### 4.1 Previous LAMS-based calibration

A previous calibration of the C-130 pressure defect was published in Cooper et al., 2014. The key to this calibration is that LAMS provides a measurement of airspeed, from which the dynamic pressure can be calculated if the temperature and pressure are known. The result is relatively insensitive to temperature and pressure, so this is an accurate result despite the need to know the airspeed to calculate the temperature and the need to know the static defect to calculate the pressure. Because a pitot tube is thought to provide a valid measurement of the total pressure, subtracting the dynamic pressure from the total pressure gives the true ambient pressure. The difference between this value and the measured pressure is then the static defect. Furthermore, because the measured dynamic pressure is based on a measurement of the difference between the total and static pressures, the same correction represented by the static defect applies with reversed sign to the measured dynamic pressure.

The equation published there, Eq. 11, was subsequently revised to avoid circularity in data processing by basing the empirical relationship on uncorrected quantities, as discussed in the Technical Note on Processing Algorithms [version as of June 2016]. For the C-130, the error in the measurement of ambient or static pressure ( $\Delta p$ ) was found to be given by the following empirical representation, to an uncertainty of less than 0.3 hPa:

$$\frac{\Delta p}{p} = a_0 + a_1 \frac{\alpha}{a_r} + a_2 M \quad (6)$$

where  $p$  is the uncorrected measurement of pressure (PSFD or PSFRD),  $\alpha$  is the angle of attack (AKRD), calculated from uncorrected measurements as described in the Algorithms document,  $a_r$  is a constant with value  $1^\circ$  (included only to keep the equation dimensionless), and  $M$  is the



### Histogram of PS\_A – PSFDC

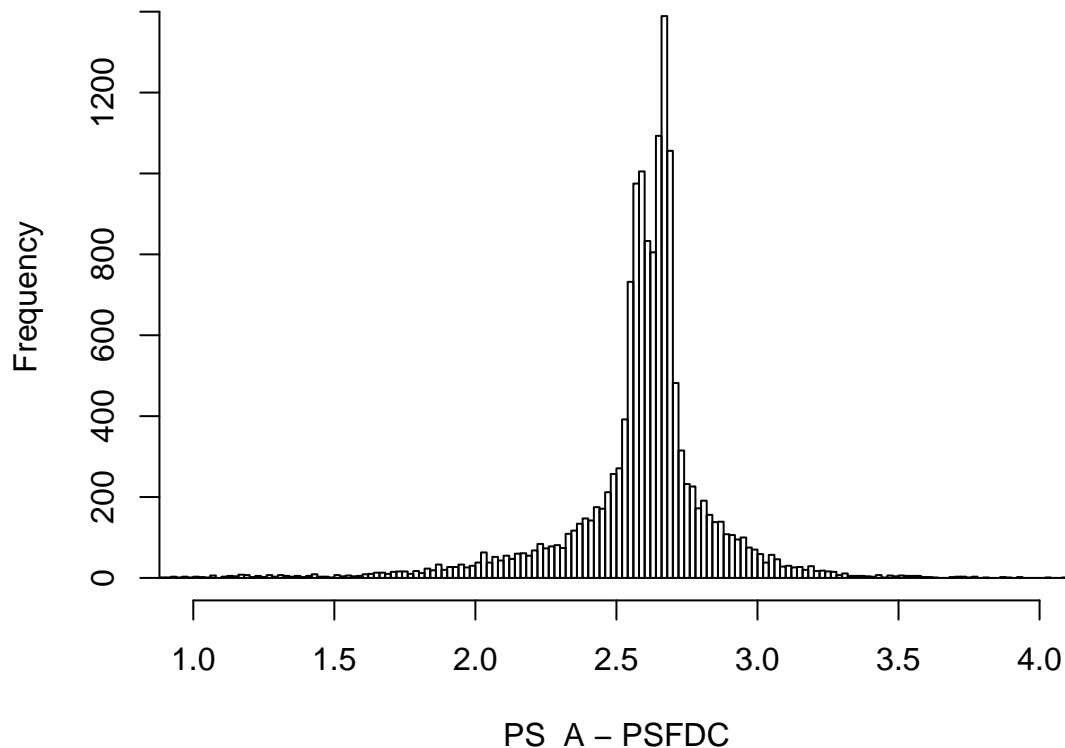


Figure 9: The difference between the avionic-provided pressure (PS\_A) and the standard pressure after the correction as expressed in (1) (PSFDC).

Mach number calculated from uncorrected measurements of static and dynamic pressure. The coefficients are  $\{a_0, a_1, a_2\} = \{-0.00637, 0.001366, 0.0149\}$  for PSFD and  $\{-0.00754, 0.000497, 0.0368\}$  for the alternate pressure measurement PSFRD.

These coefficients were based on measurements collected during the IDEAS project of November 2011. However, this original parameterization did not lead to consistent differences when compared to the avionics-system pressure PS\_A in subsequent projects. A representative example from the FRAPPE measurements is shown in Fig. 9. The mean offset between the avionics-supplied pressure and the research pressure is 2.6 hPa, a value that is similar to the differences measured in other projects including NOMADSS, WINTER, and ARISTO-2015. However, this difference is significantly different from the  $-1.08$  hPa offset found in the original IDEAS-4 study. Because it is expected that PS\_A has remained consistent, it appears that the pressure correction that is being applied is not consistent with the original calibration.

## 4.2 Reason for repeating the calibration

A weakness in the available calibration, present also in ARISTO-2015, is that measurements at altitudes between sea level and about 850 hPa have not been available. Problems may arise with use of the PCOR function as expressed in (6) to such low-level flight, so the following paragraphs will revisit the determination of the empirical relationship for the static defect using low-level measurements from ARISTO-2016 flight 6.

As discussed in Cooper et al., 2014, the key to the LAMS-based calibration of dynamic pressure is to find the airspeed  $v$ , from which the dynamic pressure  $q$  is found from

$$q = p \left\{ \left( \frac{v^2}{2c_p T} + 1 \right)^{c_p/R_a} - 1 \right\} \equiv p\chi(v, T) \quad (7)$$

where  $p$  is the ambient pressure,  $c_p$  the specific heat of air at constant pressure,  $T$  the absolute temperature, and  $R_a$  the gas constant for air, and  $\chi(v, T)$  is defined by (7) to simplify terminology. Although the corrections for humidity are small, humidity-dependent value for  $c_p$  and  $R_a$  will be used in this equation.

The error arising from the static defect  $\Delta p$  that applies to the measured pressure  $p_m$  should be included when (7) is used ( $p = p_M - \Delta p$ ), although this normally makes little difference because the fractional error in  $p$  is small. It was argued in Cooper et al. (2014) that the error in dynamic pressure  $\Delta q$  is the negative of the error in ambient pressure  $\Delta p$ . Then the errors in dynamic pressure and ambient pressure are given by

$$\Delta q = q_m - p\chi(v, T) \quad (8)$$

$$\Delta p = -\Delta q = \frac{-q_m + p_m\chi(v, T)}{1 + \chi(v, T)} \quad (9)$$

where  $q_m$  is the measured dynamic pressure. Because LAMS provides an independent and low-uncertainty measurement of the airspeed  $v$ , it is possible to determine the errors in both  $q_m$  and  $p_m$ .

The procedure used in Cooper et al.(2014) and in the RAF Technical Note on Processing Algorithms was to determine parametric fits to the errors in terms of quantities like Mach number, angle of attack and sideslip angle. Such a parameterized fit can then be used to correct the measurements when LAMS is not present or not functioning. The approach described in the Processing Algorithms Technical Note led to the parameterization represented by (6) above, However, here data spanning a larger range of flight conditions will be used.

## 4.3 Revised angle of attack

Because angle of attack ( $\alpha$ ) is an important contributor to the parameterized representation (6), and because there have been some problems representing angle of attack over the full operating range

of the C-130 including near sea level, it is useful to determine the angle-of-attack relationship again using flight 6 of ARISTO-2016, which included flight segments at low level. The evidence in the previous section on angle-of-attack coefficients indicated that there were flight-to-flight variations in sensitivity coefficients for ARISTO-2015 flights, so only this one flight will be used here, and the LAMS-provided angle of attack will be used as a calibration reference for determining the sensitivity coefficients. The same procedures were followed as in that earlier section, with the result that the sensitivity coefficients determined from the LAMS-based reference value were  $\{c_0, c_1, c_2\} = \{4.7532, 9.7908, 6.0781\}$ . These coefficients represented the LAMS-based measurements of angle of attack with standard deviation  $0.17^\circ$  and, because the LAMS mean angle of attack differs from that relative to the fuselage, these coefficients have been adjusted to match the mean angle of attack provided by the conventional radome-based measurement and calibration. This LAMS-based angle of attack was then used for the following processing. Because there was unexplained variation in the characteristics of the radome-based measurement from flight to flight in ARISTO-2015, it may be necessary to develop a new calibration for each project or even each flight, but once that calibration of the radome is determined then the pressure corrections developed below should apply to new projects.

Candidate variables for the parameterization include the measured dynamic pressure, measured ambient pressure, angle of attack, sideslip angle, Mach number (a function of dynamic and ambient pressure with minor dependence on humidity), so for the purpose of determining this parameterization a special R data.frame was constructed that contained these variables along with the LAMS-determined airspeed and the temperature and water vapor pressure for all cases where this could be determined reliably. With four-beam LAMS the measured airspeed is over-constrained so the chisquare for the airspeed measurement provides an indication of the quality of that measurement and can be used to identify suspect measurements. The formula used is listed later in this report, as (15), and as defined there (with arbitrary specification of the expected standard deviation as 1 m/s) a limiting value of  $\chi^2 < 0.1 \text{ m}^2\text{s}^{-2}$  appears to be a reasonable choice for excluding measurements. This test was therefore applied when compiling the data.frame, and it was also required that valid measurements (as determined by the Python processing program) be available for all four beams. The residual scatter for the fits was improved if the measured dynamic pressure  $q_m$  was shifted earlier in time by about 105 ms, which is reasonable because the LAMS observes ahead of the aircraft so a time shift of about this magnitude between LAMS line-of-sight airspeeds and  $q_m$  is expected.

#### 4.4 New empirical fits

An overly complex fit with 23 coefficients, as listed in the R code, gave a parameterized representation of  $\Delta q$  with standard deviation 0.19 hPa about the values given by LAMS via (8). This was based on about 15,600 1-Hz measurements that, in addition to the chisquare test, met the requirements that  $\text{TASX} > 90$ ,  $|\text{ROLL}| < 5$ , and  $\text{PITCH} < 20^\circ$  (to eliminate some obviously bad measurements from the INS). The tests eliminated turns and times near takeoff and landing. This fit provides an indication of the approximate target standard deviation for the fit, but a much simpler fit is desirable because, even though all 23 coefficients meet tests of significance  $p < 0.001$ , there

could well be complex interactions dependent on the particular flight profile or other peculiarities of the data that could lead to problems when extrapolated beyond the range of the measurements or to new data. For that reason, a much simpler fit was sought that could give almost as small a standard deviation about the reference measurements from LAMS. The approach was to consider analysis-of-variance tables as guides to selecting the factors accounting for significant parts of the total variance. A five-coefficient fit gave a residual standard deviation of 0.22 hPa with 15575 degrees of freedom and accounted for 85% of the total variance (vs 90% for the 23-coefficient fit), so this appeared to be an acceptable compromise.<sup>3</sup>

$$\frac{\Delta q}{p_m} = b_0 + b_1 \frac{q_m}{p_m} + b_2 \frac{\alpha}{a_r} + b_3 M + b_4 \frac{q_m}{p_m} \left( \frac{\alpha}{a_r} \right)^2 \quad (10)$$

with coefficients  $\{b_{0-4}\} = \{-0.004389, -0.02966, -6.831 \times 10^{-5}, 0.02672, 0.002447\}$  for the sensing pair producing PSFD and QCF. For that producing PSFRD and QCFR, the corresponding coefficients are  $\{0.007372, 0.12774, -6.8776 \times 10^{-4}, -0.02994, 0.00163\}$ .

The mean deduced error in measured dynamic pressure is  $2.23 \pm 0.39$  for QCF, but it is much larger for QCFR,  $5.86 \pm 0.69$ . The mean error in ambient pressure (respectively PSFD and PSFRD) is therefore the negative of these values. These are the errors in the measurements, so to obtain corrected values these errors should be subtracted from the measured values; i.e.,  $q_c = q_m - \Delta q$  and  $p_c = p_m + \Delta q$ .

A test for consistency is that airspeed calculated from the corrected dynamic pressure and ambient pressure should match the airspeed measured by LAMS. Figure 10 shows that there is good agreement between these two measurements for cases where the LAMS-based airspeed meets the quality check discussed above, with mean difference of  $10^{-4} \pm 0.23$  m/s.

These corrections are significantly different from those obtained earlier by Cooper et al. (2014) and as revised in the Technical Note on Processing Algorithms. For this flight, the average correction applied to pressure using the old parameterization in the Processing Algorithms document would be 1.34 hPa. This difference does not only occur at low level but also is present when measurements are restricted to those at pressure below 800 hPa. In comparison to the avionics-system pressure PS\_A, the new parameterization gives mean values about  $-1.16$  hPa lower than PS\_A, while the old parameterization gave mean values about  $-2.26$  hPa lower. The original values were based on flight 8 from the 2011 project IDEAS-4, and for that flight the difference between the corrected pressure and PS\_A was  $-1.08$  hPa, close to the value found for this flight using the new parameterization. The larger difference obtained using the old parameterization suggests that the characteristics of the aircraft have changed, either affecting the static defect of the research static ports, the radome, the sensor calibrations, or some unknown change. It may be useful to use the new parameterization for intervening C-130 projects like WINTER and FRAPPE, but that needs further study.

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<sup>3</sup>The residual variance was reduced by shifting the measured sequence of QCF forward in time by 105 ms, a reasonable value to compensate for the displacement of the LAMS measurements ahead of the aircraft.

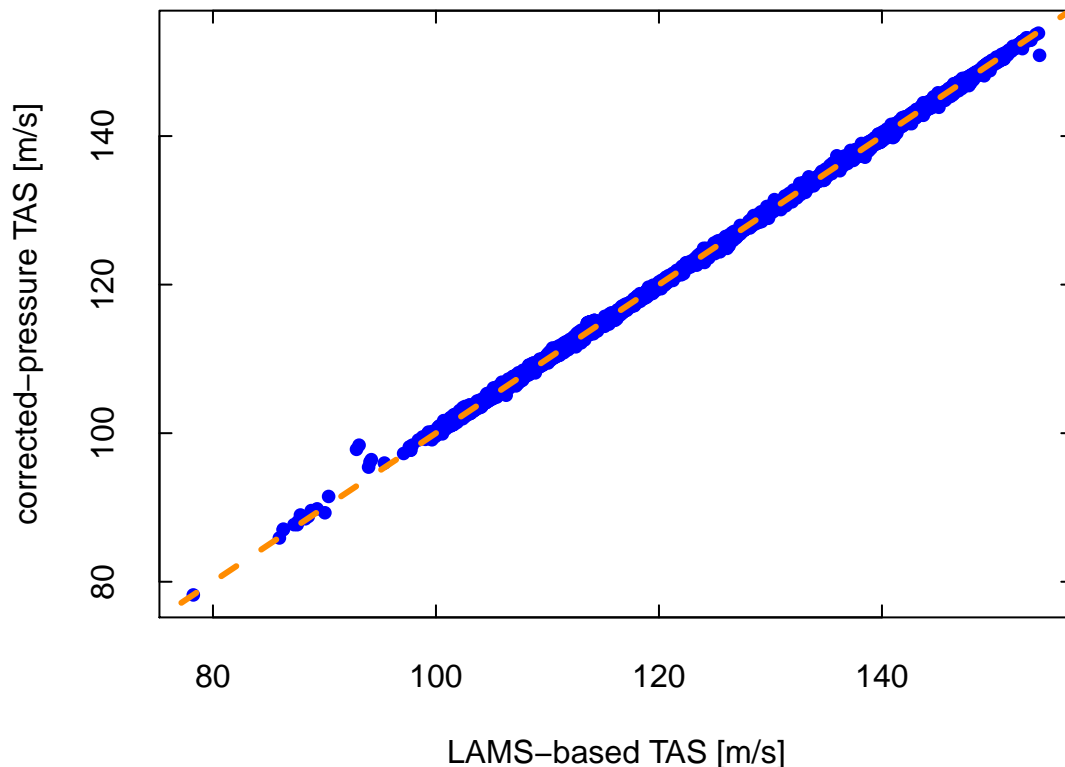


Figure 10: Comparison of airspeed calculated from the corrected dynamic and ambient pressure to the airspeed measured by LAMS. The dashed orange line is a 1:1 reference line.

## 5 LAMS-based measurement of temperature

### 5.1 Theory and data available

It was demonstrated in Cooper et al. (2014) that the LAMS-measured airspeed  $v_L$  can be used to measure the temperature in a way that is independent of any temperature sensor. One important aspect of this is that  $v_L$ , combined with the measurements of total pressure ( $p_t$ ) and of ambient pressure ( $p$ ), might provide a valid measurement of temperature in clouds. This independent measurement of temperature arises from the relationship between temperature and the speed of sound, because the Mach number ( $M$ ) can be determined from the measurements  $p_t$  and  $p$  so the speed of sound can be found from  $v_L/M$ . That measurement of temperature will be explored in this section.

The equation leading to temperature, Eq. (24) in Cooper et al. (2014), is

$$T = \frac{v_L^2}{2c_p \left[ \left( \frac{p_t}{p} \right)^{R_a/c_p} - 1 \right]} \quad (11)$$

where  $T$  is the temperature on an absolute-temperature scale,  $c_p$  is the specific heat of air at constant pressure, and  $R_a$  is the gas constant for air. For a selected region with strong LAMS signals in clear air, the resulting temperature (converted to °C) was on average 1.4°C lower than the standard temperature ATX. However, this result is very sensitive to  $v_L$  and increasing  $v_L$  by 0.35 m/s (the measured difference between  $v_L$  and TASX) completely removed the offset. That may be an indication that the airspeed from LAMS shows a small effect from airflow distortion even though the beams are displaced XXX m ahead of the instrument.

To investigate the performance of this measurement of temperature in cloud, the in-cloud measurements from ARISTO-2015 and ARISTO-2016 (flight 6 only) were examined. The in-cloud measurements included those in the following table, along with a few other brief passes through rain, ice, or cloud. There were a large number of cloud passes (>27) in ARISTO-2016 flight 6, but only three examples are included in the table and discussed in this report.

flight	start	end	nature of cloud	performance of LAMS
1	173000	173800	warm, no 2D	mostly NG
1	174145	174600	warm, no 2D	maybe OK
1	184740	184830	only 2D; cold	OK
2	173000	192000	warm; high 2D	sporadic, weak
3	181000	182000	repeated cloud, warm	questionable, maybe OK
3	200900	201000	short, warm cloud	LAMS good
4	171500	172500	cold, ice	LAMS mostly OK
4	173000	174500	cold, ice	Beam1 NG, others weak
5	170600	171100	near 0C, short	Beam2 OK; Beam1 gaps
5	182200	182400	2D only; cold	LAMS NG
2016-6	230510	230620		
2016-6	240250	240415		
2016-6	250040	250130		

## 5.2 Case studies

### Case 1: Flight 3, 20:09:00 to 20:10:00

Flight 3, 20:09:00 to 20:10:00, is a short pass through a warm cloud with no ice or rain. Close inspection of the forward-pointing beam (beam 2) indicates that there are a few bad points in the center of this cloud, at times 20:09:48, 20:09:51. and 20:09:54, so these were set missing and then

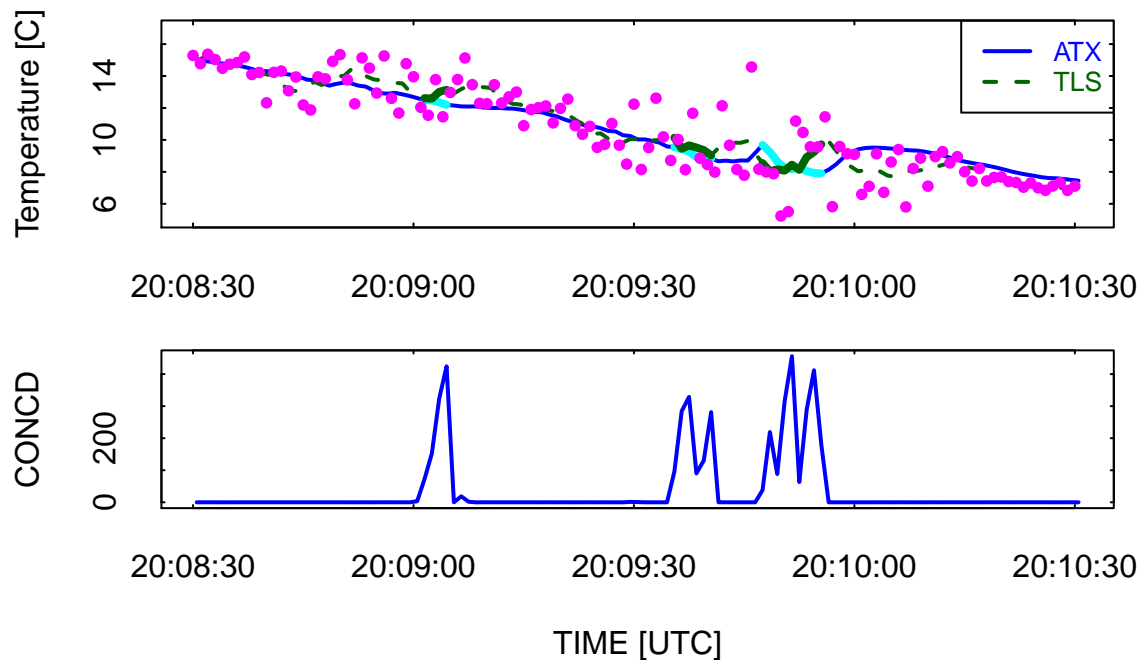


Figure 11: The temperature deduced from the measurement obtained using the LAMS-measured airspeed (magenta dots), adjusted as described in the text, and plotted with a smoothed version (TLS) and with the standard measurement of temperature (ATX). The measurements from periods where the CDP concentration exceeded  $5\text{ cm}^{-3}$  are shown as thicker lines plotted, in the case of ATX, in a different color.

interpolation was used to fill in missing points in this time period.<sup>4</sup> The mean difference between airspeed determined in the conventional way and airspeed from LAMS was 0.55 m/s, consistent with the value found in the clear-air flight segment used in the preceding paragraph. To make it easier to judge differences produced by the cloud, this mean value was added to the LAMS-measured airspeeds and then smoothing over approximately a 5-s period was applied to the temperature calculated from the LAMS airspeed. The resulting temperature measurement for the cloud pass is shown in Fig. 11, where the magenta-colored points are the unsmoothed measurements of temperature. The unsmoothed measurement is quite noisy, so smoothing is important in order to see trends.<sup>5</sup>

<sup>4</sup>Beam 2 appeared to be affected in cloud more than the other beams, perhaps because of water striking and remaining on the forward-pointing aperture more than on the other beams pointing  $35^\circ$  from the forward direction.

<sup>5</sup>ATX is not smoothed, but it is thought to have a response time between 2 and 3 s.

Despite the noisy signal, particularly in the vicinity of the clouds, the LAMS-based temperature shows good correlation with the standard temperature. There is also a suggestion of a trend in the cloud passes: As the cloud pass proceeds, ATX tends to become lower relative to TLS. Because of the variability present, this is only suggestive, but there is some match to what would be expected if the ATX sensor (in this case, a HARCO anti-iced sensor) becomes wet in cloud because in that case evaporative cooling from the element in the dynamically heated and therefore <100%-humidity air in the housing causes an error of negative sign.

### Case 2: Flight 2, 17:30:00–19:20:00

Next, the long cloud pass from flight 2 was examined. These measurements were from a low-level flight leg (near 7000 ft) at high temperature,  $>10^{\circ}\text{C}$ , and there were high concentrations of particles measured by the 2DC. The LAMS-measured line-of-sight speeds were not always reliable, but it was possible to select regions of strong and apparently consistent signals from this long cloud pass. CDP-measured concentrations were often several hundred  $\text{cm}^{-3}$ , and 2D-measured concentrations ranged from 1–100  $\text{L}^{-1}$ .

As was the case for the flight-3 case examined above, beam 2 appears to be more noisy than the other beams, and there are some cases where beam 1 (looking downward) appears to be affected by returns from the ground. Because the measurement of airspeed is over-constrained in the case of valid measurements from four beams, it is possible to use a chisquare test of consistency among the four beams as a test of validity of the solution. The chisquare for the solution was developed in the LAMSprocessing4Bwind.pdf memo:

$$\chi^2 = \sum_i \frac{(a'_i - a_i)^2}{\sigma^2} \quad (12)$$

where  $a'_i$  are the line-of-sight airspeeds measured in the four beams and  $a_i$  are the corresponding airspeeds determined using the direction-cosine matrix for the four beams and the best-fit result for the vector wind. For the four-beam case, the solution for the vector wind is

$$\mathbf{v} = \mathbf{M}\mathbf{a}' \quad (13)$$

and

$$\mathbf{a} = \mathbf{S}\mathbf{v} \quad (14)$$

where  $\mathbf{M}$  and  $\mathbf{S}$  are given by Eqs. 9 and 2 from that earlier memo. The solution to (12) is then given by

$$\chi^2 = \frac{1}{\sigma^2} \sum_i (a'_i - S_{ij}v_j)^2 \quad (15)$$

Code to calculate this value, using  $\sigma=1$ , is included in the “ProcessWind()” function in this code. For the region from flight 3 shown in Fig. 11, the mean value was  $0.16 \text{ m}^2\text{s}^{-2}$ , so these 4-beam measurements were reasonably consistent, but there were five outliers with values exceeding  $1 \text{ m}^2\text{s}^{-2}$



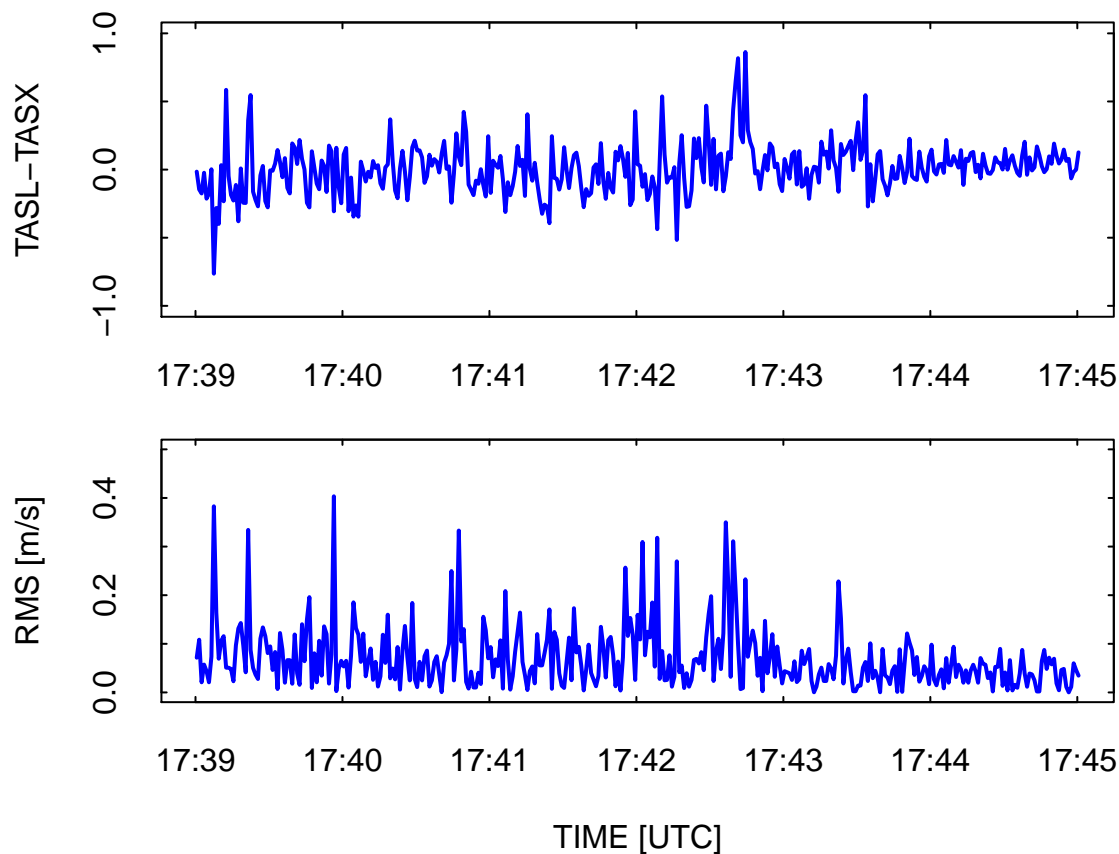


Figure 12: (top) The difference between the LAMS-derived airspeed (TASL) and the conventional airspeed (TASX), for the period from 17:39:00–17:46:00 from ARISTO-2015 flight 2. (bottom) The RMS error for the fit to the four measured line-of-sight beam speeds, for the same flight segment.

that should be excluded as being inconsistent among the four beams. The value of  $\chi^2$  can thus be used to identify regions where the 4-beam solution is questionable, and a requirement that it be smaller than about  $0.5 \text{ m}^2\text{s}^{-2}$  appears reasonable on the basis of values from good flight segments.

Figure 12 shows a segment from this flight for which the measurements appear consistent among the four beams, especially for the last 2-min period that is not in cloud. This flight segment was selected because the LAMS measurements are mostly consistent with the standard airspeed and have low RMS. Figure 13 shows the corresponding measurements of temperature from the two sources and also the droplet concentration. The in-cloud LAMS temperature is on average slightly lower than the standard temperature, by about  $-0.21^\circ\text{C}$ , while the out-of-cloud measurements are offset in the other direction, with a mean difference of  $0.17^\circ\text{C}$ . There is some correlation between the temperature difference and the liquid water content, as shown in Fig. 14. The observed

difference is in the opposite direction to that expected if ATX is cooled as a result of wetting of the sensor, so this result is not an indication of sensor wetting. An alternate explanation might be that the returned signal has greater contributions from locations closer to the LAMS in the high-backscatter of a cloud, so that the airspeed and hence temperature is biased low in such a region, with the bias increasing with the density of the cloud.

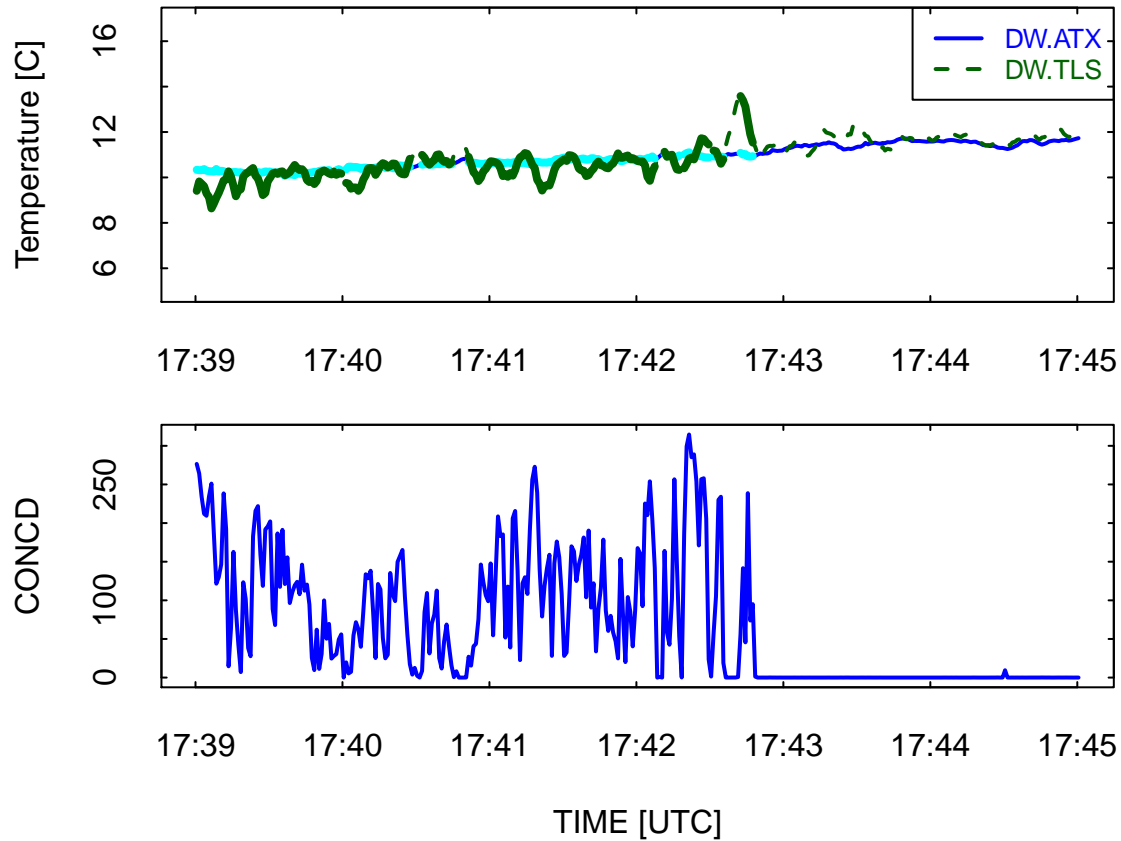


Figure 13: For the same flight period shown in the previous figure, the temperature deduced from the measurement obtained using the LAMS-measured airspeed (dark green line), adjusted as described in the text, plotted with the standard measurement of temperature (ATX). The measurements from periods where the CDP concentration exceeded 5 cm<sup>-3</sup> are shown as thicker lines plotted, in the case of ATX, in a different color.

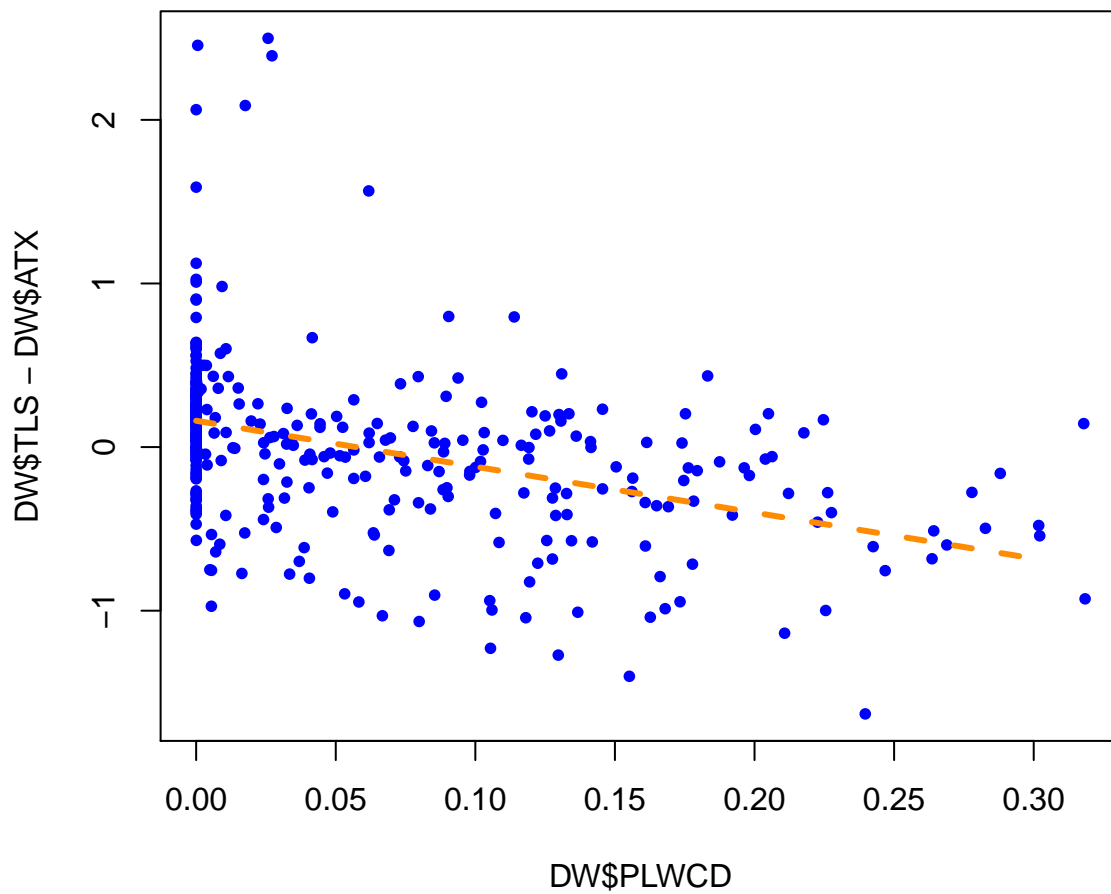


Figure 14: Dependence of the difference between the LAMS-derived temperature (TLS) and the standard temperature (ATX) as a function of the liquid water content measured by the CDP (PLWCD), for the same flight period shown in the preceding two plots.

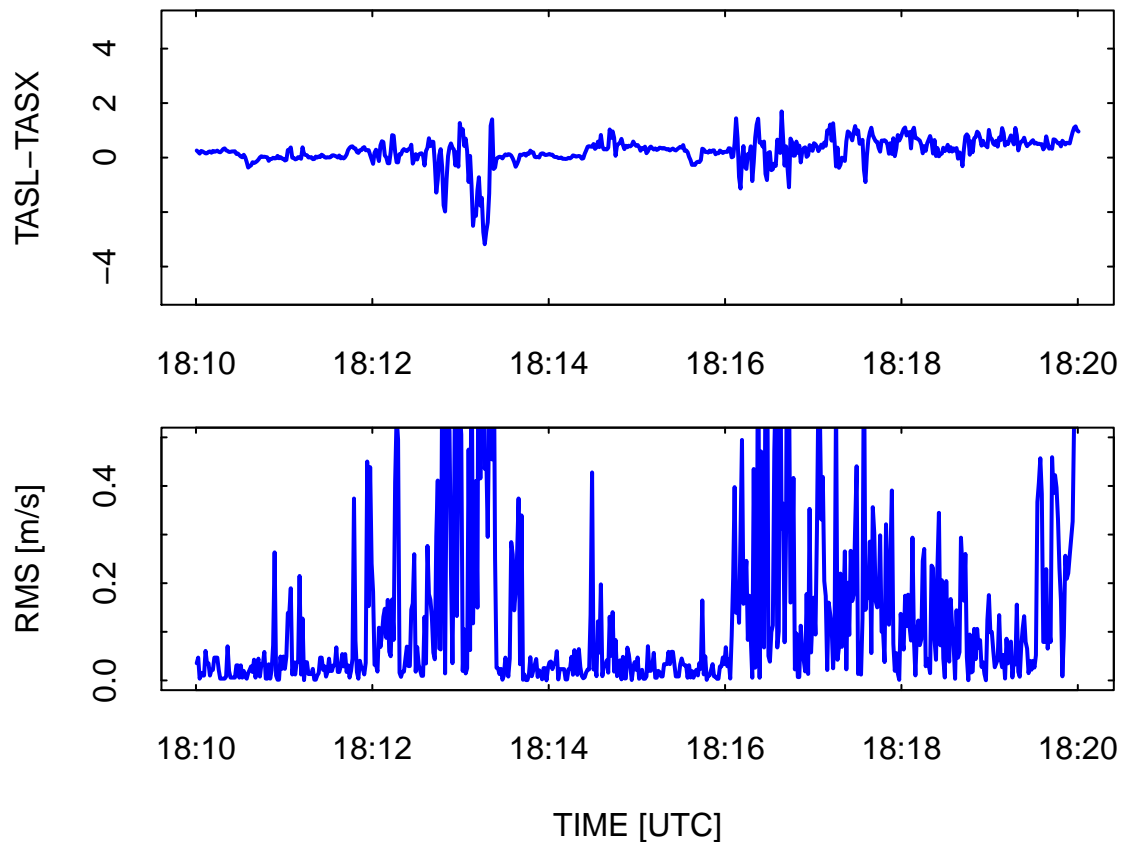


Figure 15: (top) The difference between the LAMS-derived airspeed (TASL) and the conventional airspeed (TASX), for the period from 18:10:00–18:20:00 from ARISTO-2015 flight 3. (bottom) The RMS error for the fit to the four measured line-of-sight beam speeds, for the same flight segment.

### Case 3: Flight 3, 18:10:00–18:20:00

The third case examined here is a series of passes through clouds at temperatures near freezing. Droplet concentrations were often several  $100/\text{cm}^3$ , and there were 2D particles often in concentrations of 1–10/L. The cloud pass near 18:13 was a more dense cloud than those presented above, with droplet concentrations around  $400 \text{ cm}^{-3}$  and liquid water content above  $0.6 \text{ g m}^{-3}$ . It serves as a good illustration of the problems with LAMS that occur in a dense cloud. The measurements of airspeed and the associated RMS for this flight period is shown in Fig. ??, and the associated measurement of temperature for the pass through particularly dense cloud is shown in Fig. 16. In this dense cloud, the RMS for the four-beam measurements became  $>0.5$  inside the cloud, the LAMS-measured airspeed was about 2 m/s below the conventional measurement, and as a result the LAMS-measured temperature was as much as  $10^\circ\text{C}$  below the standard temperature ATX.

However, this large error arose mostly from beam 2, which alone would give an error of more than  $30^{\circ}\text{C}$ . If instead airspeed is determined using the three beams slanted into the wind by about  $35^{\circ}$ , the result (plotted as TLS3, the orange line in Fig. 16) shows a smaller but still significant negative bias relative to ATX. This shows the value of using four beams and applying an RMS test to exclude bad measurements, because the measurements were quite seriously biased in this dense cloud and only this RMS test was able to identify the regions where measurements are unreliable.

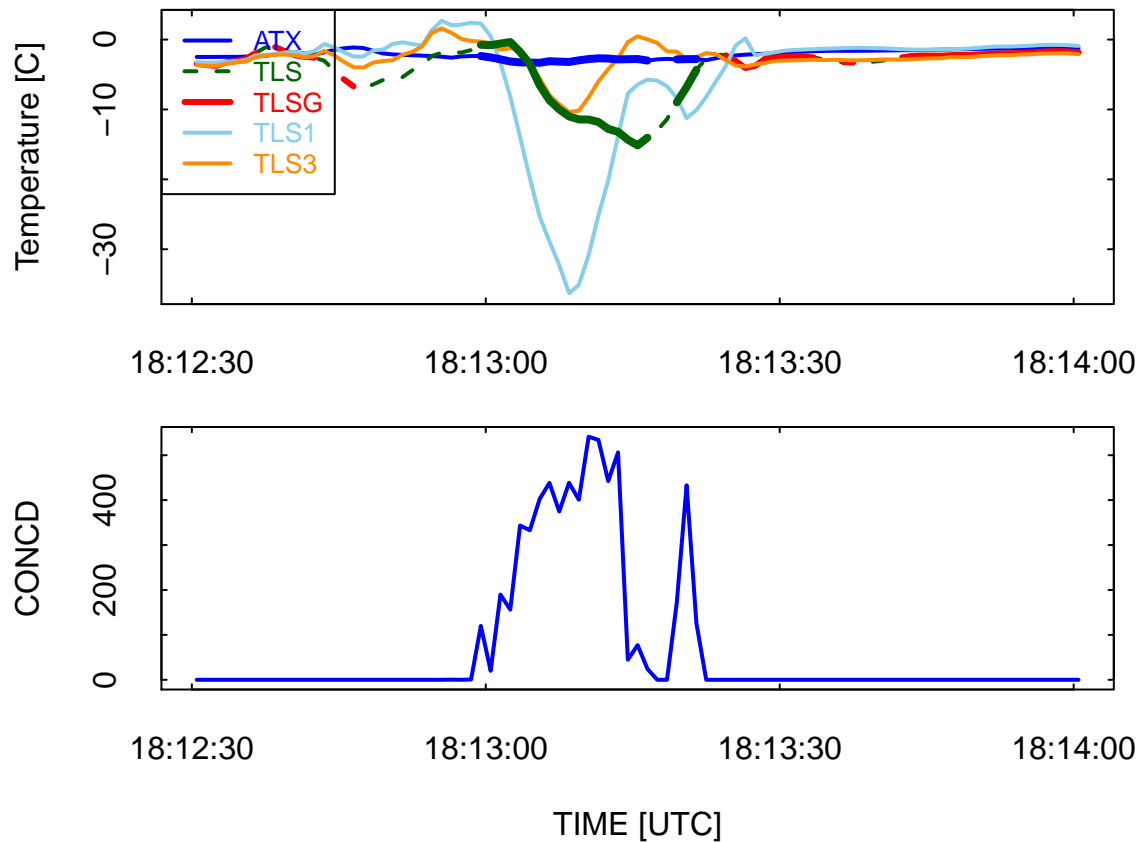


Figure 16: For the subset of the flight period shown in the previous figure from 18:12:30–18:14:00, the temperature deduced from the measurement obtained using the LAMS-measured airspeed (TLS, dark green line), adjusted as described in the text, plotted with the standard measurement of temperature (ATX). The measurements from periods where the CDP concentration exceeded  $5\text{ cm}^{-3}$  are shown as thicker lines. The red line on this plot (TLSG) shows the periods where TLS was based on measurements with RMS smaller than 0.2 m/s. The cyan line (TLS1) is the result based only on the forward-pointing beam 2, and the orange line (TLS3) is the result based on the 3-beam result using beams 1, 3, and 4.

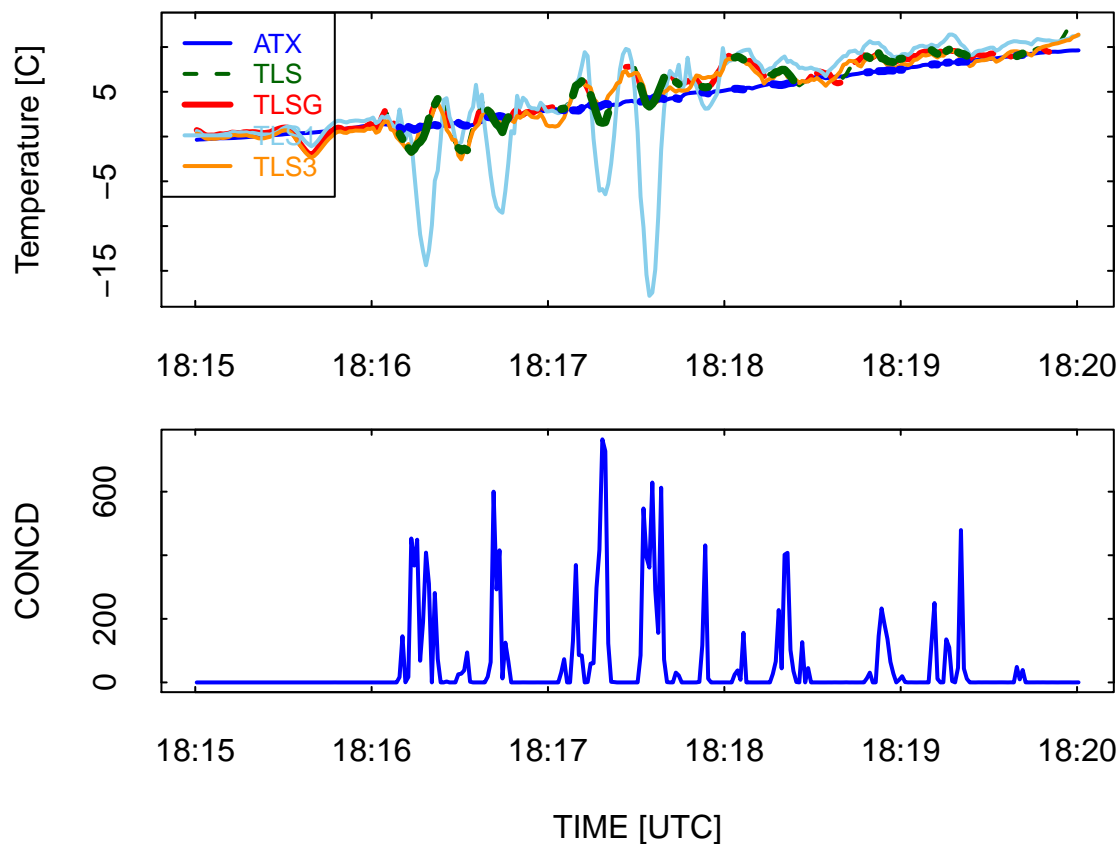


Figure 17: Same as in the previous plot, but for a later portion of the flight segment. See the caption for the previous plot.

Figure 17 shows a similar plot for a subsequent period of flight through this sequence of small clouds. The temperature based only on beam 2 is again strongly affected and evidently too low in this sequence of weaker clouds. However, it has less influence on the 4-beam solution, and both the 4-beam and the 3-beam solution appear reasonable. The difference between the 3-beam solution (TLS3) and ATX is  $0.3^{\circ}\text{C}$  for locations out-of-cloud but  $0.48^{\circ}\text{C}$  for in-cloud measurements. Because errors in the LAMS-derived temperature are negative when influenced by cloud, these differences suggest possible evaporative-cooling influence on the standard temperature probes.



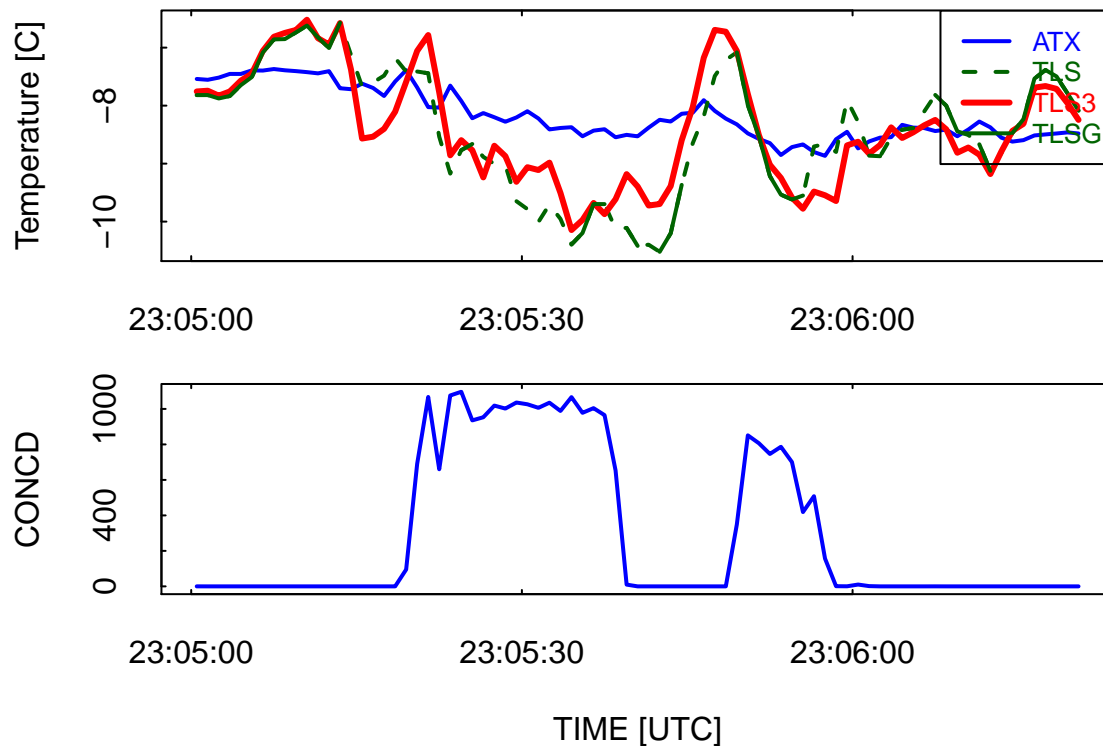


Figure 18: The temperature deduced from the measurement obtained using the LAMS-measured airspeed (TLS, dashed green line), adjusted as described in the text, plotted with the standard measurement of temperature (ATX). Where the chisquare of the fit (as defined in the text) was larger than 0.1, the line is plotted as a solid line (TLSG). Also shown is the temperature determined using only the three off-axis beams (TLS3, red line). Data from ARISTO-2016 flight 6, 23:05:00 – 24:06:20 UTC.

#### Case 4: Flight 2016-6, 23:05:00 – 23:06:20

Figure 18 shows the conventional temperature ATX and the LAMS-derived temperatures TLS and TLS3, the first found from the four-beam solution and the second from the three-beam solution excluding the forward beam. Portions of the TLS3 line where the chisquare as defined above is larger than 0.1 are shown as dashed lines. In this very dense cloud, with droplet concentrations as measured by the CDP exceeding  $1000 \text{ cm}^{-3}$ , the forward beam (not plotted) shows departures of many degrees and this appears to bias the four-beam solution toward low values. Even the three-beam solution (red line) appears to be affected. The measurement appears to recover in the gap between clouds, but this appears to be a case where the temperature from the LAMS is affected by the presence of the cloud droplets to such an extent that it is not reliable.

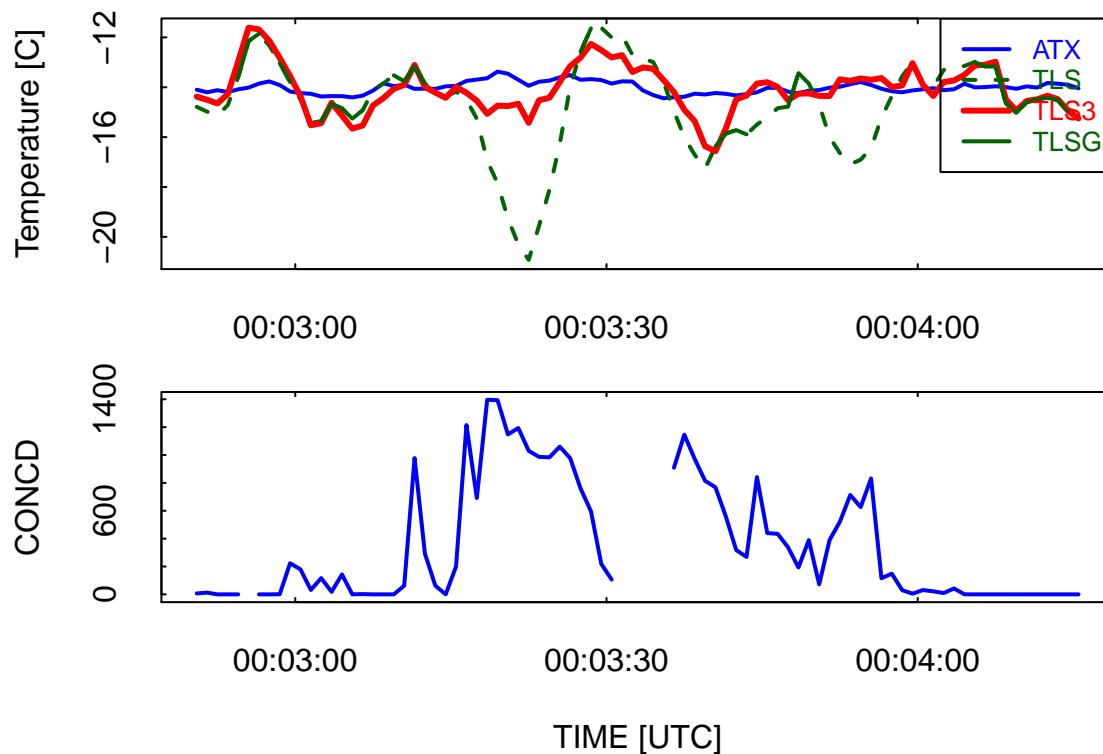


Figure 19: See the caption for the preceding figure. Data from ARISTO-2016 flight 6, 24:02:50 – 24:04:15 UTC.

#### Case 5: Flight 2016-6, 24:02:50 – 24:04:15

See Fig. 19. In this case the 3-beam solution (red line) appears reasonable except for two possible errors toward low temperature in regions of very high cloud droplet concentration. The 4-beam solution shows pronounced errors in those locations, and the high chisquare confirms inconsistency among the line-of-sight airspeeds.

#### Case 6: Flight 2016-6, 25:00:40 – 25:01:30

See Fig. 20. The LAMS-based temperature shows higher values on the edges of the cloud and lower values inside the cloud in comparison to the conventional measurement. The slow time response of the sensor measuring ATX, with around 3-s time constant, may smooth the measurements from that sensor. The agreement between 3-beam and 4-beam results lends some support to the LAMS-based measurements, as does the mostly low chisquare for the 4-beam measurements, even in cloud.

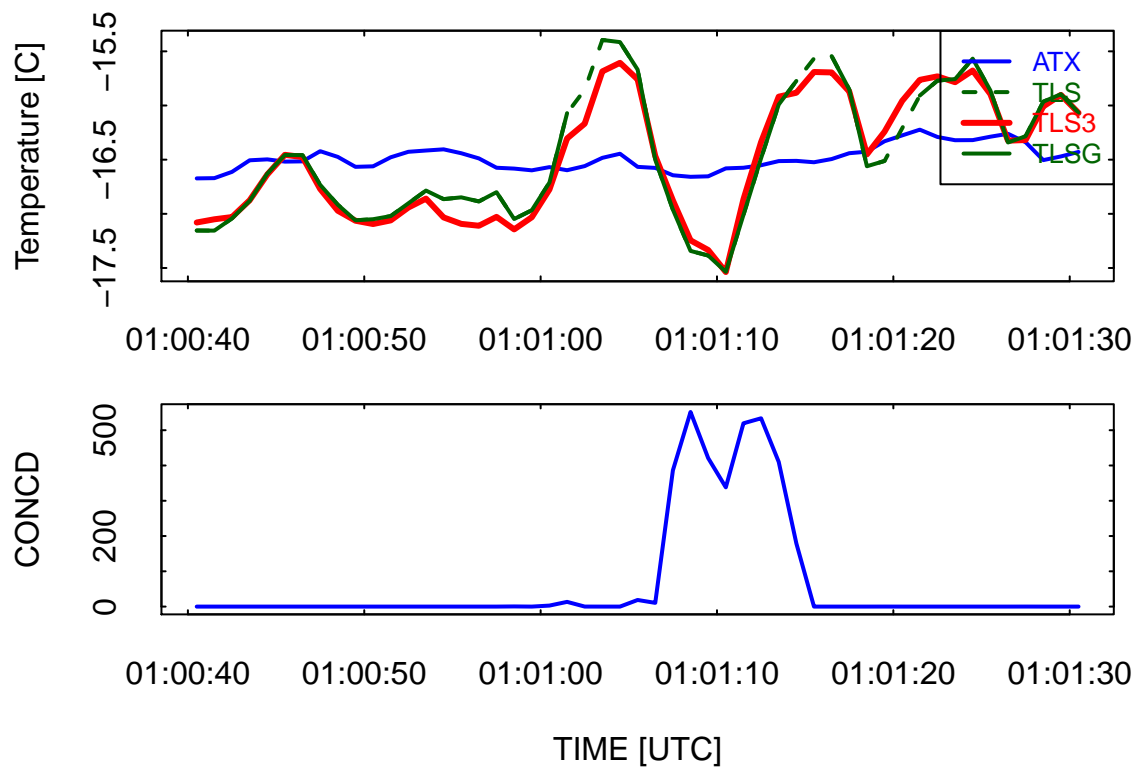


Figure 20: See the caption for the preceding two figures. Data from ARISTO-2016 flight 6, 25:00:40 – 25:01:30 UTC.

### 5.3 Conclusions, LAMS-measured temperature

The three cloud regions discussed in the first three case studies are the best measurements from ARISTO-2015 for this study, and the last three appear to be the best from ARISTO-2016. The following assessment is based on those studies:

1. The temperature deduced from LAMS is mostly valid out-of-cloud. Because it is only dependent on the LAMS-deduced airspeed and on the Mach number that is in turn based on ambient and dynamic pressure, themselves calibrated by the LAMS measurements, and it does not rely on any temperature sensor beyond that needed for the initial calibration. The LAMS-derived temperature therefore can be a useful check on the performance of standard temperature sensors and may be useful in flagging problems with those sensors. However, the LAMS-based measurement of temperature is noisy, especially in turbulence, so averaging over periods of at least 10 s or more appears necessary.
2. When in cloud, beam 2 is often strongly biased toward negative temperature because the measured airspeed appears to be too low. The problem does not appear as strongly in the other three beams, perhaps because they are at a  $35^\circ$  angle to the relative wind. Possible causes are water on the forward surface that causes defocusing of the beam or strong scattering or multiple scattering that displaces the effective sample volume closer to the aircraft into distorted airflow. The temperature measurement based on a single forward-pointing beam therefore is not useful in cloud.
3. The RMS for the four-beam solution for airspeed is a valuable indicator of quality, and it often flags regions with bad measurements when both available processing schemes for the LAMS line-of-sight velocities otherwise indicate good measurements. This benefit from the 4-beam configuration was not anticipated but appears to be a particularly important reason for using that configuration.
4. The airspeed based on the three off-axis beams is much less affected by cloud and appears to provide a valid measurement except in very dense cloud. The temperature deduced from that measurement of airspeed tends to be slightly higher than the standard measurement in warm cloud, as would be expected if there is evaporative cooling as a result of wetting of the temperature sensor. However, this conclusion is based on only a few case studies and is not applicable to all cases, so no strung conclusion can be drawn.
5. It would be especially useful to operate a 4-beam LAMS with the in-cloud radiometer and perhaps an unheated temperature sensor to obtain further tests of the LAMS-based temperature measurement.

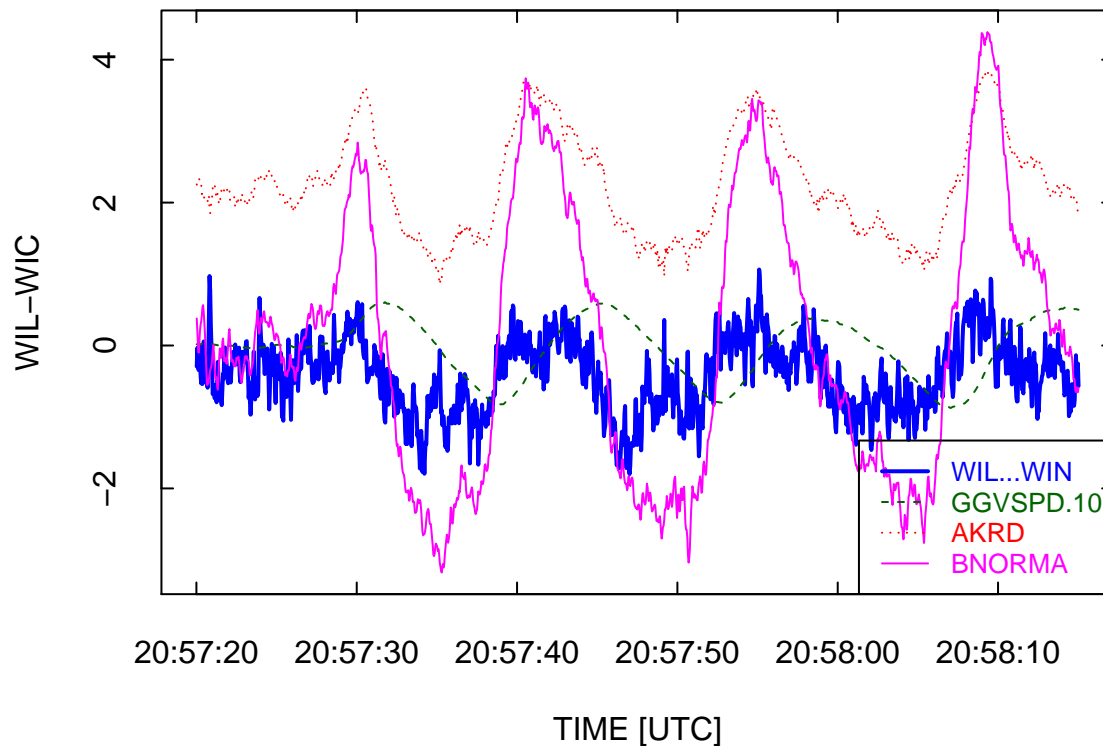


Figure 21: A flight segment with pitch variations from flight 6 or ARISTO-2016. The blue line shows the difference between the LAMS-based vertical wind (WIL) and the conventional measurement (WIC). Also shown are the rate-of-climb divided by 10 (GGVSPD/10, dashed green line), the angle of attack (AKRD, dotted red line), and the normal component of aircraft acceleration (BNORMA, magenta line).

## 6 Transient effects on wind measurements, C-130

Transient effects on measurements of vertical wind were discussed for the GV in this earlier memo. The conclusion of that memo was that effects, while detectable and correctable, were at the margin of uncertainty for wind measurements and so had little significant effect on wind measurements from the GV. A similar study is not possible with ARISTO-2015 flights because there wasn't a good pitch maneuver to use for this purpose. Two good maneuvers were flown in flight 4, 18:21:00–18:26:00 and 18:58:00–19:01:00, but in each case the LAMS signals were inadequate to provide a good measurement of vertical wind, as needed for this study. Other pitch maneuvers were flown, but some were compromised by times when the LAMS IRU was not working or, in the last 2015 flight, when LAMS signals were too weak.

There were two good maneuvers with rapid pitch changes on flight 6 of ARISTO-2016, at 20:57:00–20:59:00

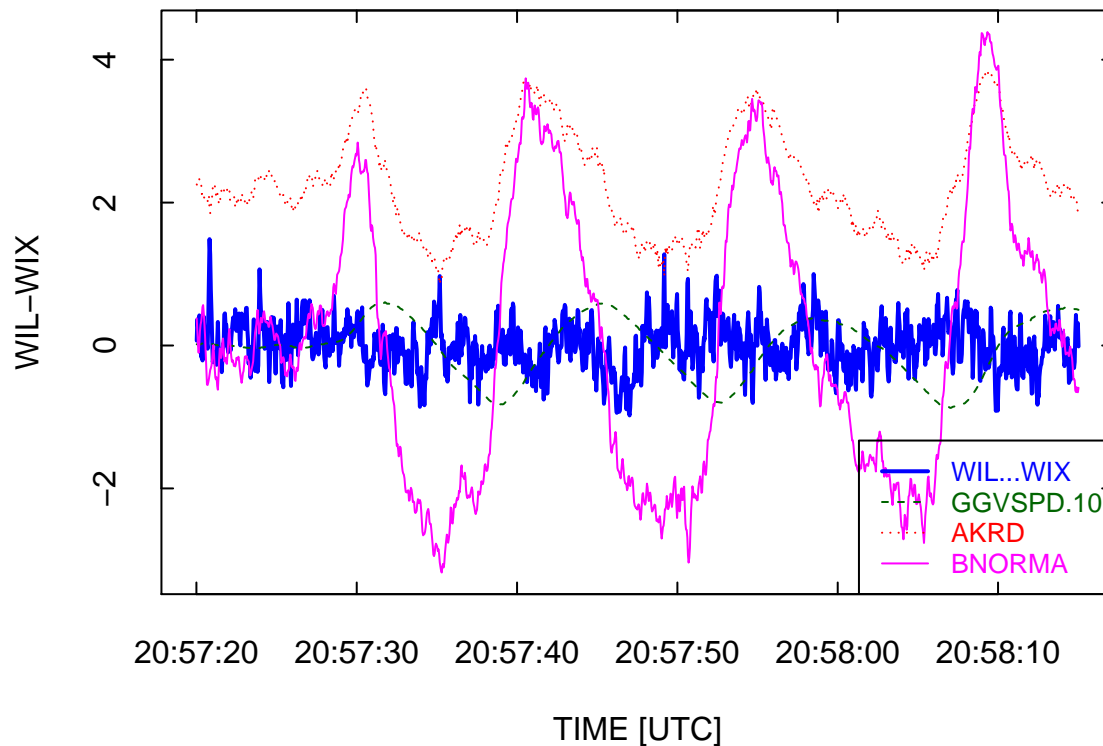


Figure 22: As in the preceding figure but for the vertical wind error after correction for the assumed dependence on normal acceleration, as described in the text.

and 21:15:00–21:17:00 UTC. The same approach was taken to these maneuvers as for the earlier study of the GV:

1. Produce a high-rate (25 Hz) netCDF file for the period of the two maneuvers. This was saved as `/scr/raf/cooperw/AR16rf06hr.nc` on the EOL file system. Note that there is an apparent bug in nimbus that prevents production of the beam-speed histograms (BEAM1\_LAMS, etc) at 25 Hz, giving all-zero values, so these variables were produced at 50 Hz instead and the next processing step was modified to average those to 25 Hz before proceeding. The
2. Process this file using the Python program `LAMS_ARISTO.py`. This was modified from the one used for other data files to include the averaging of the 50-Hz beam-speed histograms to 25 Hz before proceeding. That program produced a new netCDF file named `AR16rf06hrLAMS.nc` with added variables `BEAM[1-4]speed`, needed for the present R program.
3. This program (`ARISTO-LAMS.Rnw`) then read a subset of variables from that file and calculated WIL, the LAMS-based vertical wind. The conventional wind (WIC) was also re-

calculated using the sensitivity coefficients recommended in this report. To compensate for the displacement between the LAMS-based vertical wind and that based on the radome, the LAMS-based value was delayed by 100 ms after some study of how the difference between WIL and WIC varied with this choice.

The resulting difference between WIL and WIC then was used to investigate if there appeared to be a false signal in the vertical wind and, if so, to search for its source. Figure 21 shows that this difference shows clear dependence on angle-of-attack, rate-of-climb, and normal acceleration of the aircraft. The dependence on angle of attack is surprising because this flight was used to determine the sensitivity coefficients in use, so residual dependence on angle-of-attack indicates that this region has a different dependence in comparison to the entire flight. The variable showing the strongest correlation to the error, however, is BNORMA, as was also found in the study of the GV. In the interval plotted, the correlation between (WIL-WIC) and BNORMA is 0.82. As in the case of the GV, the correlation with rate-of-change of pitch was almost identical to that with BNORMA, and the correlation to angle-of-attack was 0.77, but other variables (GGVSPD, rate of change of angle of attack, PITCH) gave significantly lower correlation to the error.

As for the GV, a suggested correction for this effect is to add  $g_0 + g_1(\text{BNORM})$  to WIC, where  $\{g_0, g_1\} = \{-0.436, 0.198\}$ .<sup>6</sup> When this correction is made, the new variable (WIX), shown in Fig. fig:Transient-12, no longer appears to depend on any of the other plotted variables. With this correction, the standard deviation in the difference between the LAMS-based and corrected vertical wind was 0.34 m/s, similar to the standard deviation for a similar 30-s period just before the maneuver (0.49 m/s). The applied correction had a standard deviation of 0.37 m/s, so about half of the observed variance between WIL and WIC is removed by this correction.

The second pitch maneuver (21:15:00 – 21:17:00 UTC) was a little more turbulent, but the results were consistent with those from the first.

## Summary - Transient Effects

1. The pitch maneuver revealed that the difference between the LAMS-derived vertical wind and that from the radome-based system varied with the vertical acceleration. The estimated magnitude of the combined effects, however, is modest, leading to typical errors in WIC of about 0.4 m/s when the vertical acceleration was in the range  $\pm 2 \text{ m s}^{-2}$ , as is typical of all but the most extreme flight conditions.
2. A correction can be used to remove this error in vertical wind. After application of that regression correction based on the pitch maneuver, the measurements of vertical wind from the radome-based system agree with those from the LAMS with a standard deviation between the two measurements of about 0.4 m/s during that pronounced maneuver. This was significantly larger than that obtained for the GV, but this maneuver was flown in more turbulent conditions where the true fluctuations in wind were about of this magnitude.

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<sup>6</sup>Perhaps better would be to make the equivalent correction to AKRD before calculation of the vertical wind.

## 7 Summary and Conclusions

1. The four-beam LAMS produced useful measurements in all four beams for major parts of the ARISTO flights.
  - (a) The overconstrained solution for airspeed using all four beams provided a useful measure of consistency that can be used to avoid instances where the algorithm providing the line-of-sight airspeeds produced erroneous results. A proposed limit on the chisquare from the fit appeared to be useful, as described in Section 2.
  - (b) The airspeed from the forward beam usually measured an airspeed that was within about 0.3 m/s of the airspeed determined from the other three off-axis beams.
  - (c) Dense cloud appeared to affect the measurements, especially for the forward beam. The three off-axis beams were less affected, but very dense cloud produced erroneous measurements in all four beams.
  - (d) The downward-slanted beam occasionally was contaminated by return from the surface during low-level flight.
  - (e) One flight (flight 6 of ARISTO-2016) included a wide range of conditions spanning the altitude range of the C-130 and gave a good basis for determining the fitted coefficients for the radome sensitivity and the static defect based on the the range of conditions normally encountered by the C-130, including for flight near sea level.
2. New sensitivity coefficients were determined for the radome:
  - (a) For angle of attack, new suggested sensitivity coefficients based on calibration to match LAMS-based measurements are  $\{c_0, c_1, c_2\} = \{4.7532, 9.7908, 6.0781\}$ . Cf. Equation (2). These coefficients have been adjusted to account for the offset in vertical alignment between the LAMS IRU and the upward axis normal to the longitudinal axis of the aircraft.
  - (b) For sideslip, the suggested coefficients are  $\{b_0, b_1\} = \{1.5478, 12.3612\}$ . (Cf. Eq. (4). The second coefficient is based on the LAMS-based calibration, while the first was determined from a conventional calibration using yaw maneuvers; the justification is that the relative offset in installation orientation between the LAMS and the longitudinal axis of the aircraft is uncertain so this coefficient is chosen to match the conventional-calibration value. (The value determined from the LAMS calibration is only about  $0.05^\circ$  larger than the coefficient listed.) The first coefficient (i.e., the offset in sideslip) still needs to be determined from good circle maneuvers, which can separate an offset in heading from one in sideslip. It is significant, though, that these calibrations suggest a change in offset of about  $1.6^\circ$  from the standard coefficients. This will have a significant effect on calculated horizontal wind.
  - (c) Because the LAMS provides reference values for calibrations such as these that are superior to those obtained in the conventional way (dependent on zero vertical wind),



it will be useful to include LAMS-based calibration in future projects where the measurement of vertical wind is needed with low uncertainty.

3. A new parameterized correction to static and dynamic pressure was determined using a wide range of flight conditions spanning the altitude range of the C-130. The suggested formula is (10) with coefficients  $\{b_{0-4}\} = \{-0.004389, -0.02966, -6.831 \times 10^{-5}, 0.02672, 0.002447\}$  for the sensing pair producing PSFD and QCF and  $\{0.007372, 0.12774, -6.8776 \times 10^{-4}, -0.02994, 0.00163\}$  for the sensor pair producing PSFRD and QCFR. This correction provides a consistent offset from the avionics-provided pressure (PS\_A) for recent C-130 projects since IDEAS-4-C130 in 2011, where a different correction is needed.
4. The LAMS-based measurement of temperature provides measurements out-of-cloud in good agreement with the conventional temperature sensors. In cloud, the measurements are sometimes compromised, especially in very dense cloud, but sometimes suggest possibly real differences from the conventional sensors. This portion of the study was mostly inconclusive. See Sect. 5.3 for a more extensive summary.
5. As was found for the GV, there are indications of transient effects on the measured angle-of-attack of the C-130 when the pitch changes rapidly. The best correction appeared to be to apply an empirical correction based on the measured upward acceleration of the aircraft, as was also the case for the GV. The correction based on a linear fit to the measured normal acceleration BNORMA made corrections of typically about 0.4 m/s to the vertical wind, a value considerably larger than the typical correction of about 0.1 m/s that applied to the GV. However, except for this increased magnitude of the correction, the features of the transient effects appeared similar for the two aircraft.

– End of Memo –

Reproducibility:

**PROJECT:** ARISTO-LAMS  
**ARCHIVE PACKAGE:** ARISTO-LAMS.zip  
**CONTAINS:** attachment list below  
**PROGRAM:** ARISTO-LAMS.Rnw  
**PYTHON:** /h/eol/cooperw/RStudio/LAMS3D/LAMS\_ARISTO.py  
**ORIGINAL DATA:** /scr/raf\_data/ARISTO{2015,2016}/rfxx.nc  
/scr/raf/cooperw/AR16rf06hr.nc  
**WORKFLOW:** WorkflowARISTO-LAMS.pdf  
**GIT:** <https://github.com/WilliamCooper/ARISTO-LAMS.git>

**Attachments:** ARISTO-LAMS.Rnw  
LAMS\_ARISTO.py  
ARISTO-LAMS.pdf  
SessionInfo  
WorkflowARISTO-LAMS.pdf  
SaveRData.zip