30 June 2016

TO:	LAMS File
FROM:	Al Cooper
SUBJECT:	Studies of transient response to winds using LAMS

Overview

The procedure used to measure wind via the radome uses "sensitivity coefficients" that relate the pressure differences between vertically separated ports on the radome to angle of attack. These coefficients are usually determined using speed runs, where the angle of attack gradually changes as the speed increases and decreases in level flight. If it is assumed that the vertical wind is zero during the maneuver, or at least averages to zero, it is straightforward to determine the sensitivity coefficients from the corresponding measurements of ADIFR, QCF, PITCH, and GGVSPD, the latter near zero but possibly varying a litte during the maneuver.

The weakness in this approach is that the angle of attack changes slowly so the results might not represent the case where changes occur rapidly, as might be the case when encountering sudden gusts of wind. Lenschow, working with Marie Lothon, has presented evidence that the airflow can have transient differences vs. the steady-state conditions in the presence of such gusts. If those transients affect the airflow at the radome or the pitot tube used for QCF, they might caused the angle of attack inferred from the standard sensitivity coefficients to be in error.

Because the LAMS provides an independent measurement of the relative wind and measures well ahead of the aircraft, it may be possible to check for transient effects by comparing LAMS-based measurements to radome-based measurements. The purpose of this memo is to document a search for such effects and to place some preliminary limits on how large the associated errors might be..

Data Used

A test of the LAMS was conducted in Nov. 2014 during the project called HCRTEST. Here the focus is on flight 3, Nov. 24 2014, because LAMS worked well and the flight included standard maneuvers at altitudes where the backscatter from aerosols was sufficient to provide good signals for LAMS. The configuration for this flight was non-standard: Beam 1 was upward as usual, but beam 2 was forward along the longitudinal axis and beam 3 was outboard and downward. This is not an ideal configuration for determining three-dimensional wind, but problems with flow distortion when one beam was directed downward and inboard led to use of this configuration. It provides the advantage of having a longitudinal beam and so providing a good measurement of airspeed.

The flight included these maneuvers, flown at an altitude of about 6000 m and an airspeed of about 200 m/s except for the speed run:

Maneuver	start	end
circle	20:06:45	20:15:40
speed run	20:32:00	20:42:00
yaw	20:43:00	20:46:00
pitch	20:46:00	20:48:10

There was a change in system configuration around 21:00 UTC to test a different configuration, so that part of the flight will not be used here. There was also a descent to about 2000~m starting at 20:55, a climb from 2000 to 6000~m starting about 21:10, then a straight segment to about 21:40 before the descent back to RMMA. For most of these times, there was a solid LAMS signal, so the flight provides a good test of the 3-beam LAMS.

LAMS data processing

The calculations used to obtain wind measurements from the LAMS were documented previously and won't be repeated here. Two processing routes were used, that of Scott Spuler who obtained line-of-sight beam speeds using a principle-component analysis and another that used the Python processing program LAMS4beam-SG.py, which used Savitsky-Golay polynomials to smooth the measured histograms of beam speeds from the measured Doppler shift in the backscattered light and then detected peaks above these smoothed histograms. Both will be shown and used here. Once the line-of-sight speeds were measured, these were used to find the three components of the relative wind as described in the memo LAMS4beam-SG.pdf via combination of the relative wind and the ground-referenced motion of the aircraft as measured by the C-MIGITSIII inertial reference unit in the LAMS pod. The calculated variables are WD_LAMS, WS_LAMS, WI_LAMS, ATTACK_L, and SSLIP_L as well as U_LAMS, V_LAMS, and W_LAMS which represent the components of the three-dimensional wind.

An effect that is important in the following analysis is the correction made for motion of the sensing unit relative to the location of the GPS antenna, because GPS-derived velocity components are used to update the LAMS IRU via its internal Kalman filter. In addition, because the LAMS sensitive volume is displaced from the unit itself, the possible effect of this displacement during rotation of the aircraft needs evaluation.

The first effect is incorporated into the measurements within the IRU because the offset coordinates of the GPS antenna are transferred to the unit during initialization. However, because the GPS-dependent adjustment is a result of the internal Kalman filter, it is not clear how this affects the response of the results to rapid rotations of the aircraft. This will be discussed later in this note.

The second effect, the displacement of the LAMS sensitive volume from the LAMS unit itself, does not require a correction. If the sensor were a gust sensor located at that displaced location, it would detect a false contribution to the lateral components of the wind at that location. However, each LAMS beam measures only the longitudinal component of the wind along its line-of-sight, so as the position of the sensitive volume changes relative to the aircraft it remains at any time a valid

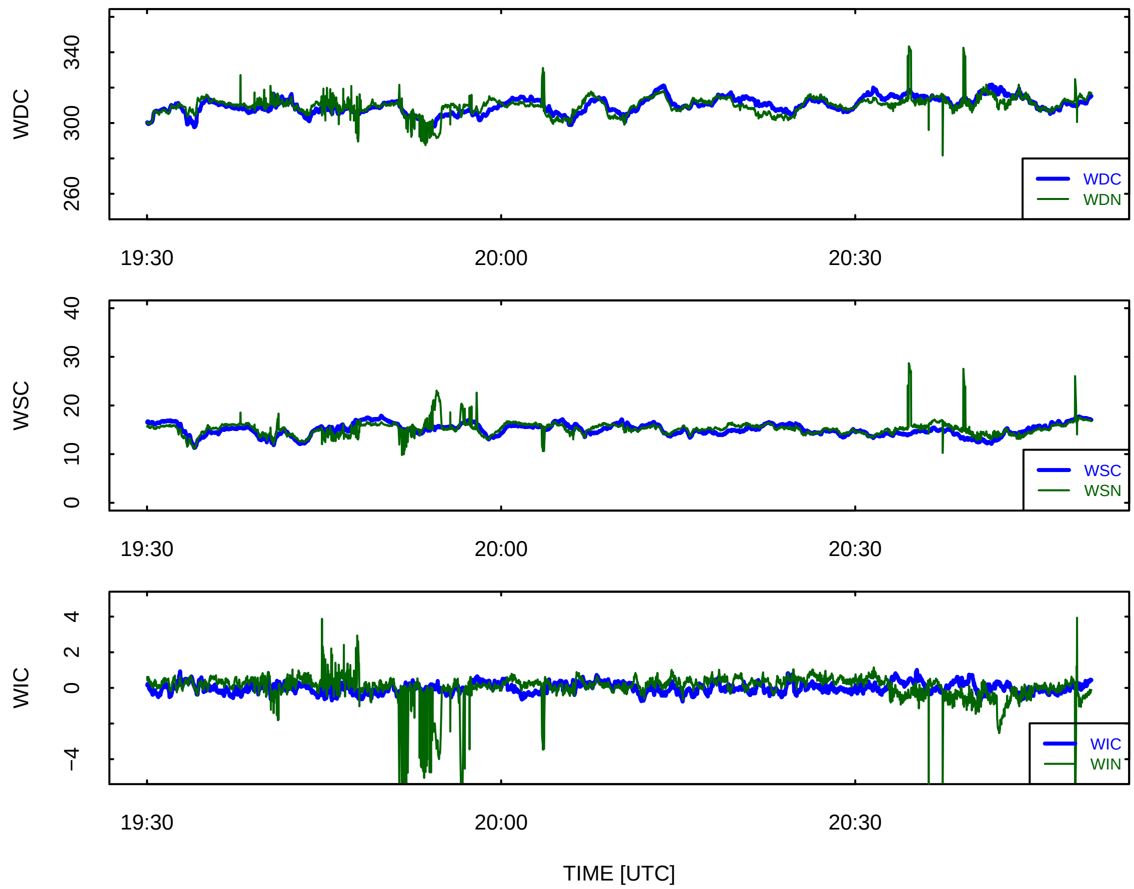

Figure 1: Wind measurements from LAMS (WDL, WSL, WIL) compared to those from the standard wind-sensing system (WDC, WSC, WIC) for a flight segment from the HCRTEST program, flight 3, 24 Nov 2014.

measurement of the line-of-sight airspeed even as the aircraft rotates. The correction for rotation rate of the aircraft is $\Omega \times R$ where Ω is the rotation vector of the aircraft and R the displacement between the reference location and the sensing point. The result is necessarily perpendicular to R so there is no contribution to the line-of-sight airspeed measured along the direction R, for any rotation Ω.

In addition, it was necessary to adjust the measurements of heading for a peculiarity in the data that introduced large jumps as the measurements moved through a heading of 180° and, if not removed, produced similar jumps in the measured horizontal wind. Interpolation through these bad points removed these spurious measurements. The error that led to this problem has since been corrected.

Example Results

Figure 1 shows the wind measurements obtained from LAMS and the standard measurements. . The measurements from LAMS are independent of those from the standard system, so the general agreement between these two sets of results is a good indication that the three-beam version of LAMS is working well. The mean speed detected in the forward-pointing beam was about 0.5 m/s larger than TASX and the standard deviation in the difference over the period of this plot is about 0.4 m/s. This is a little larger than the expected difference from the previous studies with the single-beam LAMS, but the difference remains relatively small so there is no evident problem.

Maneuvers

Speed run

The speed run flown from 20:30–20:45 UTC provides a check on the sensitivity coefficient determined for the standard system. The inertial system mounted with the LAMS pod is installed so that its pitch axis differs from the standard GV IRU by about 3.5°,with the CMIGITS-III pointing downward relative to the Honeywell IRU. Measurements from LAMS provide a measurement of angle of attack that is independent of the standard measurement, so this measurement from LAMS can provide an alternate reference angle for the determination of sensitivity coefficients, but the resulting coefficients will differ substantially in the constant-offset term because of the difference in installation angles. Nevertheless, other terms in the sensitivity coefficients determined in this way should match those determined in standard ways, because the measurements from LAMS provide an absolute reference for relative wind.

```
## [1] "Fit results using the standard sensitivity coefficients for the GV"
## lm(formula = DW$AKRD[rb] ~ DW$ATTACK[rb])
## [1] "Coefficients:"
##                 Estimate  Std. Error  t value Pr(>|t|)
## (Intercept)    3.683639 0.006958539 529.3696        0
## DW$ATTACK[rb]  1.040738 0.005052814 205.9719        0
## [1] "Residual standard deviation: 0.130, dof=594"
## [1] "R-squared 0.986"
```

Figure 2 shows that there is good correlation between these two measurements. The slope determined from a fit to these measurements is about 1.04, with a standard error of 0.005, and the correlation coefficient is above 0.99, so this fit provides a low-uncertainty check on the sensitivity coefficients for the radome. The residual standard deviation of AKRD measurements about the best-fit line is about 0.13°. The large offset between the two systems is as expected for the difference in installation angles. The 4% difference in slope would lead to measurements of vertical

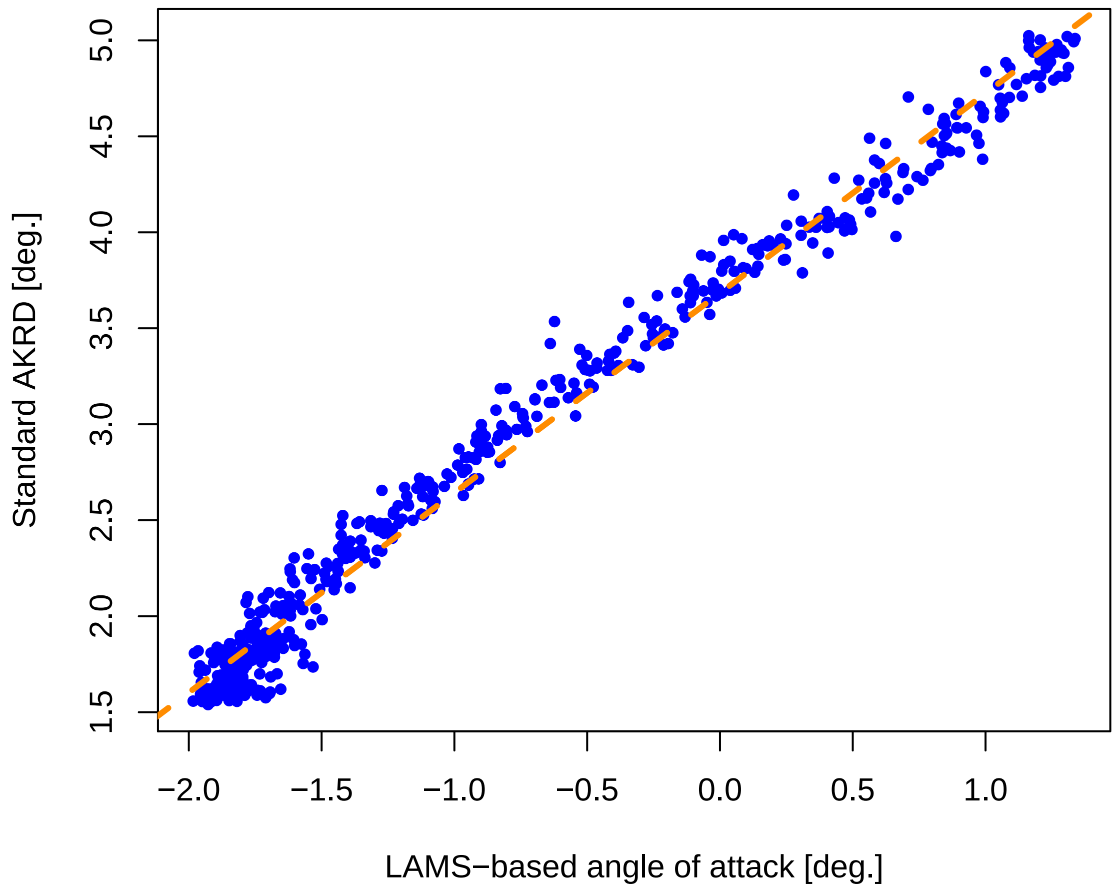

Figure 2: Angle of attack determined by the standard system (AKRD) plotted vs. the angle of attack determined from the LAMS. The orange dashed line is the regression line for AKRD as a function of the LAMS angle-of-attack.

wind that typically differ by a similar percentage, so the resulting change is small but not negligible. It is therefore useful to determine if there is other evidence for this departure from unity slope.

```
## [1] "Fit results using the DEEPWAVE sensitivity coefficients for AKRD"
## lm(formula = Data$AKDW[rc] ~ DW$ATTACK[rb])
## [1] "Coefficients:"
##                 Estimate  Std. Error  t value Pr(>|t|)
## (Intercept)   3.5775962 0.005870134 609.4574        0
## DW$ATTACK[rb] 0.9800301 0.004262489 229.9197        0
## [1] "Residual standard deviation: 0.109, dof=594"
## [1] "R-squared 0.989"
```

The calibration recommended for DEEPWAVE was slightly different and based on measurements that emphasized upper-altitude flight conditions. If those sensitivity coefficients, 4.468° and 21.481°, are used instead of the standard calibration then the regression slope changes from 1.04 to 0.98 and the standard deviation and standard error for the determination of slope both decrease, as shown in the fit summary above.. Use of the DEEPWAVE coefficients, according to the LAMS results, would lead to a 2% underestimate of vertical wind instead of a 4% overestimate.

From these results, it appears that the LAMS-provided measurements support the standard calibration of the radome to within the typical uncertainty of those determinations and there does not appear to be a systematic error in those coefficients.

Yaw maneuver

```
## [1] "Fit results using the standard sideslip calibration for the GV"
## lm(formula = DW$SSRD[rd] ~ DW$SSLIP[rd])
## [1] "Coefficients:"
##                Estimate Std. Error  t value      Pr(>|t|)
## (Intercept)  0.9927269 0.01891490 52.48387 1.221709e-110
## DW$SSLIP[rd] 0.9425721 0.01460267 64.54794 6.460954e-126
## [1] "Residual standard deviation: 0.067, dof=179"
## [1] "R-squared 0.959"
```

```
## [1] "Fit results using the DEEPWAVE calibration for sideslip"
## lm(formula = Data$SSDW[rc] ~ DW$SSLIP[rd])
## [1] "Coefficients:"
##                Estimate Std. Error  t value      Pr(>|t|)
## (Intercept)  1.1102984 0.01994044 55.68074 5.680121e-115
## DW$SSLIP[rd] 0.9936773 0.01539441 64.54794 6.460964e-126
## [1] "Residual standard deviation: 0.071, dof=179"
## [1] "R-squared 0.959"
```

The yaw maneuver flown from 20:43 to 20:46 UTC provides a similar opportunity to check the sensitivity coefficient in use for sideslip. Figure 3 shows the standard measurement of sideslip angle (SSRD) plotted against the sideslip angle determined from the LAMS measurements. The regression line has slope 0.94, indicating that the standard formula underestimates the sideslip angle by about 6%. However, repeating this with the calibration determined for DEEPWAVE, with coefficients {0.008, 22.302}, gave a regression slope of 0.994. During DEEPWAVE, the yaw maneuver was flown in a different manner to minimize roll changes, which may have affected previous calibrations, so the DEEPWAVE sensitivity coefficients are a better representation of the LAMS-measured sideslip and should be made the standard calibration for the radome. They also include an offset, as discussed in the Technical Note on wind uncertainty for the GV.

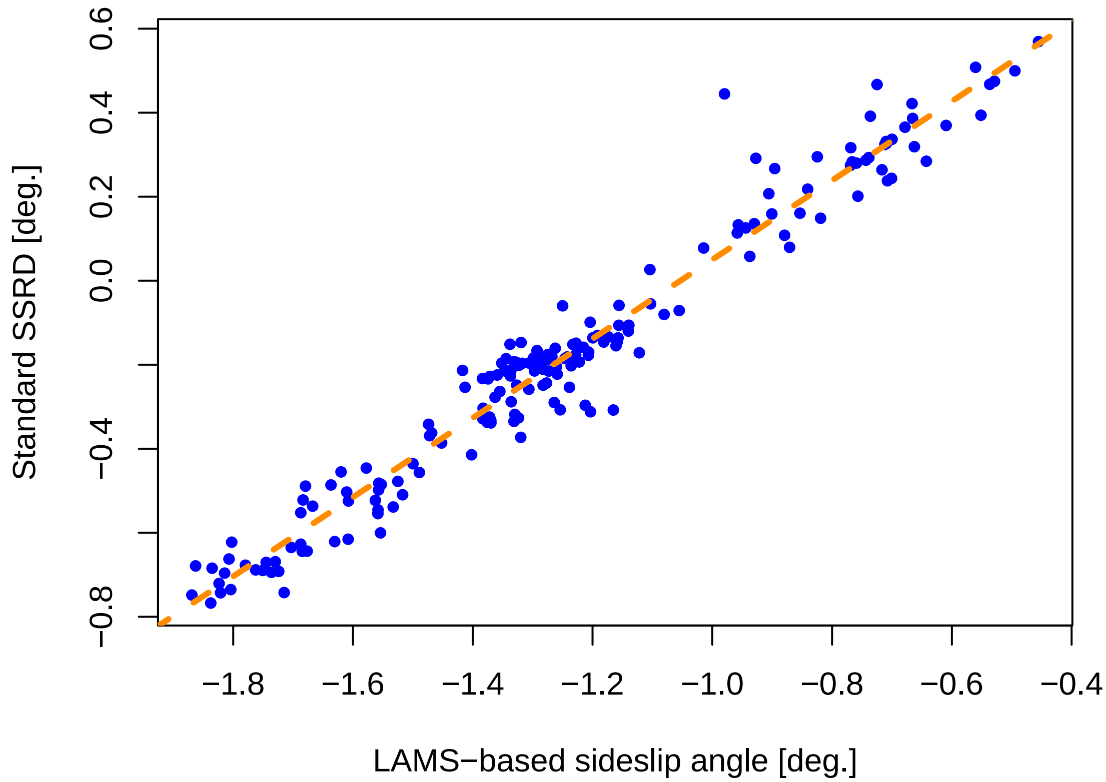

Figure 3: Sideslip angle determined by the standard system (SSRD) plotted vs. the sideslip angle determined from the LAMS, for HCRTEST flight 3, 20:43:00–20:46:00 UTC. The orange dashed line is the regression line for SSRD as a function of the LAMS-provided sideslip angle.

Pitch maneuver

The pitch maneuver (20:46:00–20:48:10 UTC) should show no residual pattern in the vertical wind that matches the imposed vertical motion of the aircraft if both systems are operating properly. Figure **??** shows that both systems pass this test well. While there is a residual standard deviation in vertical wind of about 0.15~m/s, this seems to be mostly natural variability in the vertical wind because there is little correspondence between the fluctuations and the imposed sine-wave pattern of the pitch maneuver. The small offset between wind as measured by the two systems appears to arise from differences in the pitch measurements from the two systems. Otherwise, the pitch maneuver provides a good indication that both systems are performing well.

The LAMS also provides an opportunity to check another assumption used when determining the sensitivity coefficients. The coefficients relating the radome measurements to angle of attack

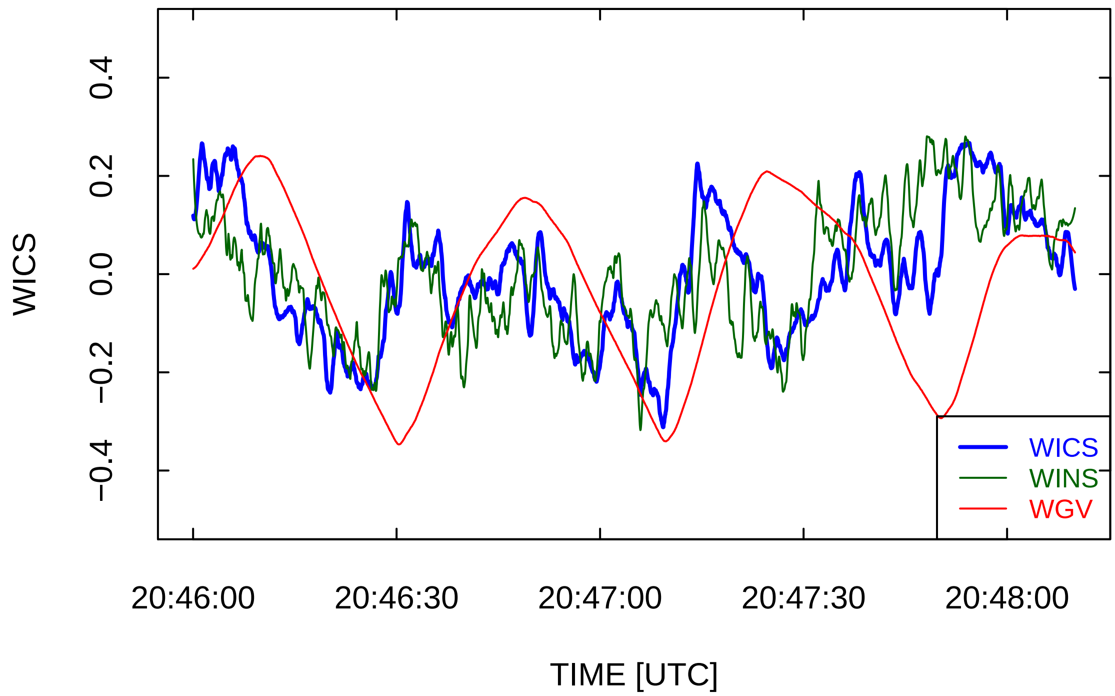

Figure 4: Comparison of WIC (from the radome-based system) and WIN (from LAMS). Both are smoothed to about 5-Hz response, and the mean value is removed from each to exclude differences arising from drifts in the measurements of pitch. For reference, the red line (WGV) is the vertical speed of the GV divided by 40, to show that the fluctuations in WIC and WIN are of about this magnitude despite the pronounced maneuvers.

are determined by fits to speed-run maneuvers, during which the pitch angle and angle of attack vary slowly. There has been evidence that some transient effects on the airflow might affect such measurements during more rapidly changing conditions, such as might be encountered during sharp changes in the vertical wind. To check for such effects, the pitch maneuver provides faster changes and might reveal a dependence on, for example, the rate of change of angle of attack or airspeed or pitch.

For this study, it is useful to use measurements at higher rate, so a different data file was constructed with measurements at 25 Hz for the conventional variables needed for calculating wind and with 100-Hz measurements from LAMS. The 100-Hz measurements were then averaged to 25 Hz. (This was necessary because of difficulty getting 25 Hz measurements directly from nimbus, possibly because the required averaging hasn't been implemented?)

The independent measurements of vertical wind, WIC from the radome-based system and WIN from the LAMS, are shown in Fig. 4. Also shown for reference is the vertical speed of the GV during the maneuver, divided by 40 to avoid enlargement of the scale. Both measurements of vertical wind are smoothed to about 5-Hz response to minimize fluctuations between the systems that are

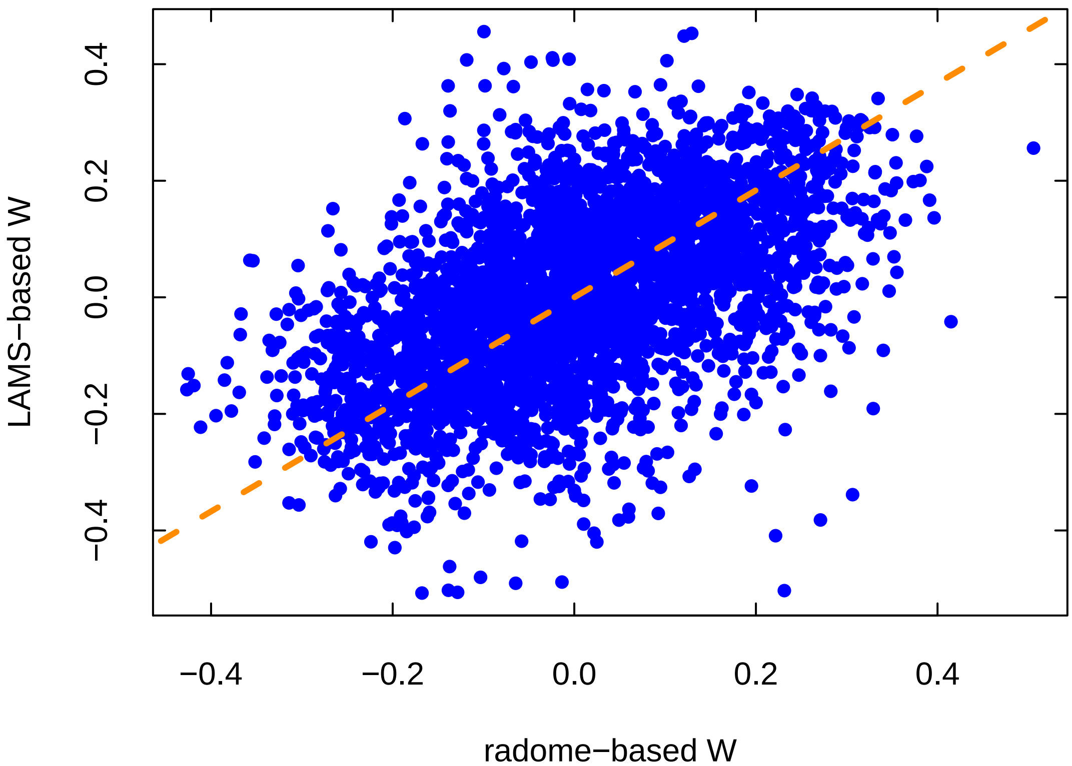

Figure 5: Corresponding measurements of WIC and WIN for the period of the pitch maneuver. The dashed orange line shows the result of a Deming fit to the measurements, as documented in the text.

likely of shorter scale than the separation among the sampled beams in LAMS or the separation of those beams from the radome. The resulting LAMS-based measurement WINS (green line) still shows more high-frequency noise than the radome-based measurement (WICS). The suspicious feature of this plot is the increase in WIC (blue line) near and following the troughs in the rate-of-climb (red line) and an associated decrease in WIC following the peaks in rate-of-climb, features that are not apparent in the LAMS-based measurement WIN. The pattern, correlated with vertical acceleration rather than vertical speed, is suggestive of some airflow effect on WIC that is associated with vertical acceleration,

Despite the consistency of the angle-of-attack comparison for the two systems, there is more scatter between the two signals than would be expected if both are measuring the same signal. For WIC, the standard deviation is 0.15 m/s for 25-Hz measurements and the corresponding standard deviation for WIN is 0.15, both similar to the standard deviation in vertical wind before and after

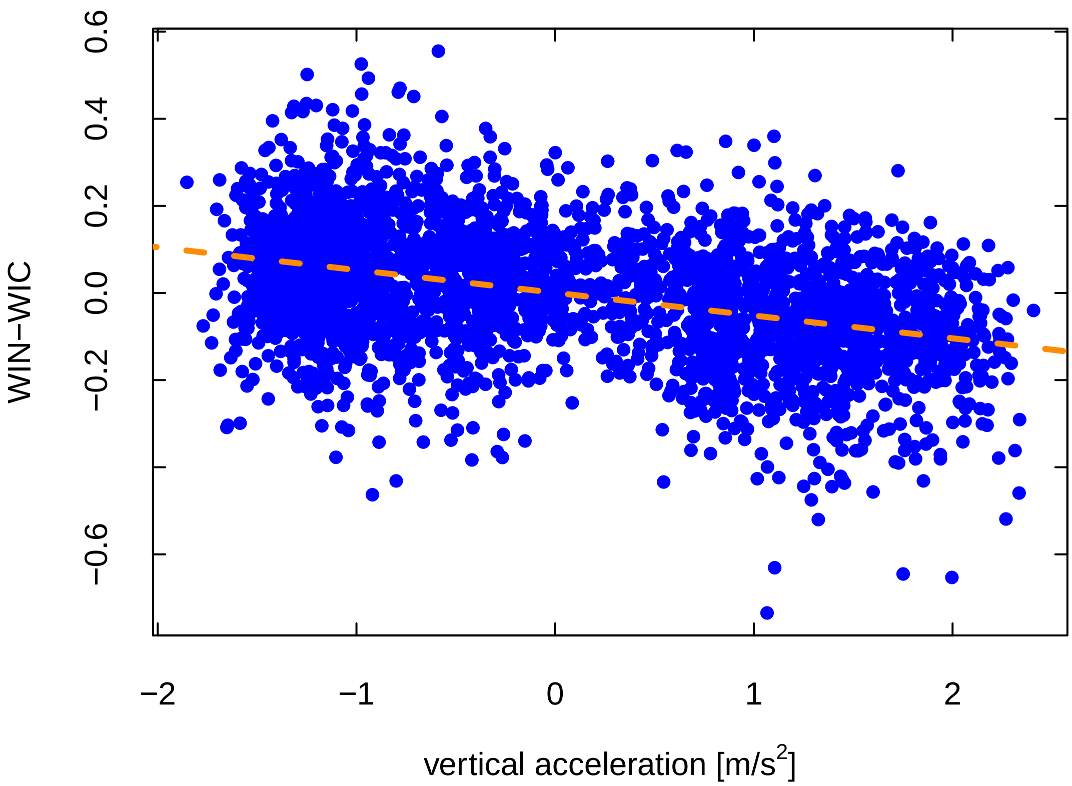

Figure 6: Difference in measurements of vertical wind (WIN-WIC) as a function of the vertical acceleration of the aircraft.

the pitch maneuvers, so the maneuver does not introduce a substantial false signal. However, a comparison of the two measurements shows considerable scatter, as shown in Fig. 5. A Deming fit to these measurements gives a slope of 0.92 (WIN:WIC), so they are about of the same magnitude, but the RMS of the Deming fit (characterizing the perpendicular distance from the points to the fitted line) is 0.14 m/s while the expected scatter for randomly distributed points with standard deviation in each variable of 0.15 m/s would be 0.21 m/s, so the scatter about the fitted line is about 68% of that expected without correlation. Although these differences represent fairly small errors and the two measurements characterize different spatial regions, this degree of scatter is still troubling because it is comparable to our best claimed uncertainty for vertical wind. It is therefore worthwhile to search for possible factors that might distort one of the measurements, perhaps WIC as a result of flow distortion.

To investigate possible sources of this distortion, the difference WIN-WIC was examined as a function of various factors with which it might be correlated. Candidate factors include the rate of

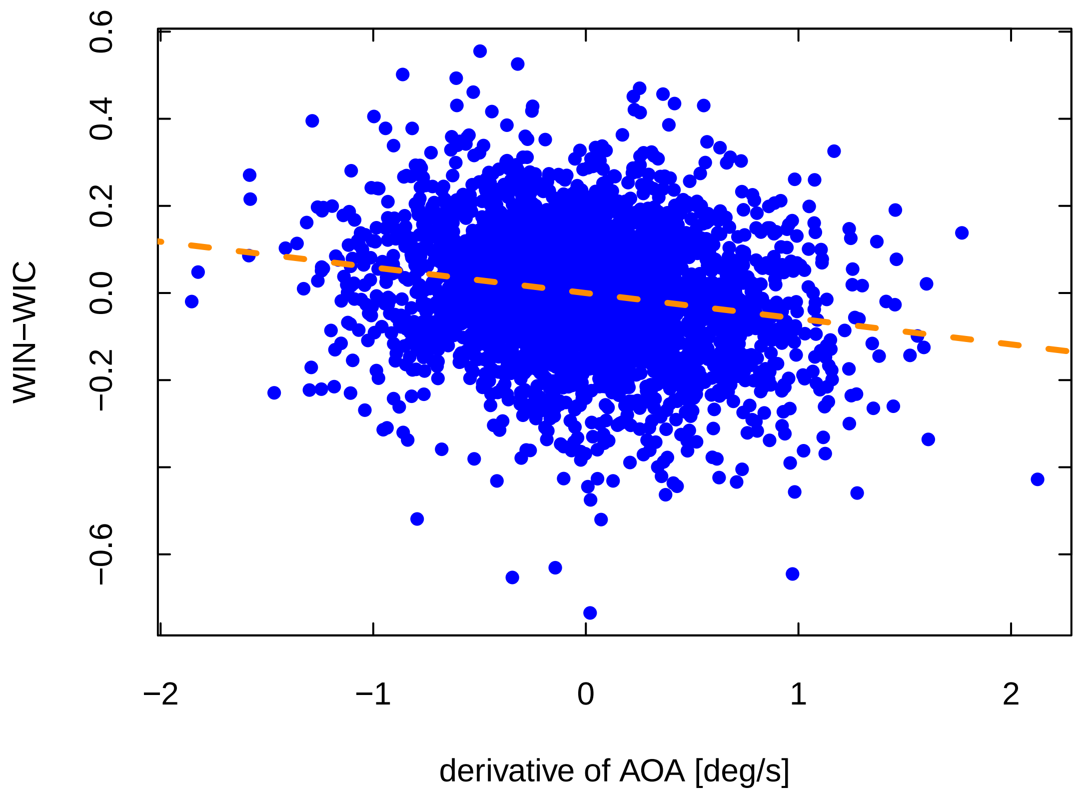

Figure 7: Difference in measurements of vertical wind (WIN-WIC) as a function of the rate of change of the angle-of-attack.

climb of the aircraft (GGVSPD), the attack, pitch and sideslip angles, derivatives of those angles, and the accelerations experienced by the aircraft. Of these, vertical acceleration of the aircraft is a prime candidate, as discussed in connection with Fig. 4, and is highly correlated with some of the other factors, so that is examined first. The correlation between δW=(WIN-WIC) and vertical acceleration, shown in Fig. 6, is 0.41, so this is strong evidence that the measurement of measured vertical wind WIC may depend on the vertical acceleration. The LAMS-based measurement WIN is sufficiently removed from the location of the aircraft that transient flow effects are unlikely to affect it, so the effect is more likely one on WIC. The regression leads to reduction of the residual standard deviation of δW from 0.145 to 0.133 m/s, which suggests that the false component of vertical wind introduced by vertical acceleration might be about 0.06 m/s.

Another prime candidate is the rate of change of angle of attack, possibly offset in time. Without an offset, the dependence of the apparent error in vertical wind on the derivative of the angle-of-attack is shown in Fig. 7. There is a definite correlation, 0.2, but it is much smaller than that for

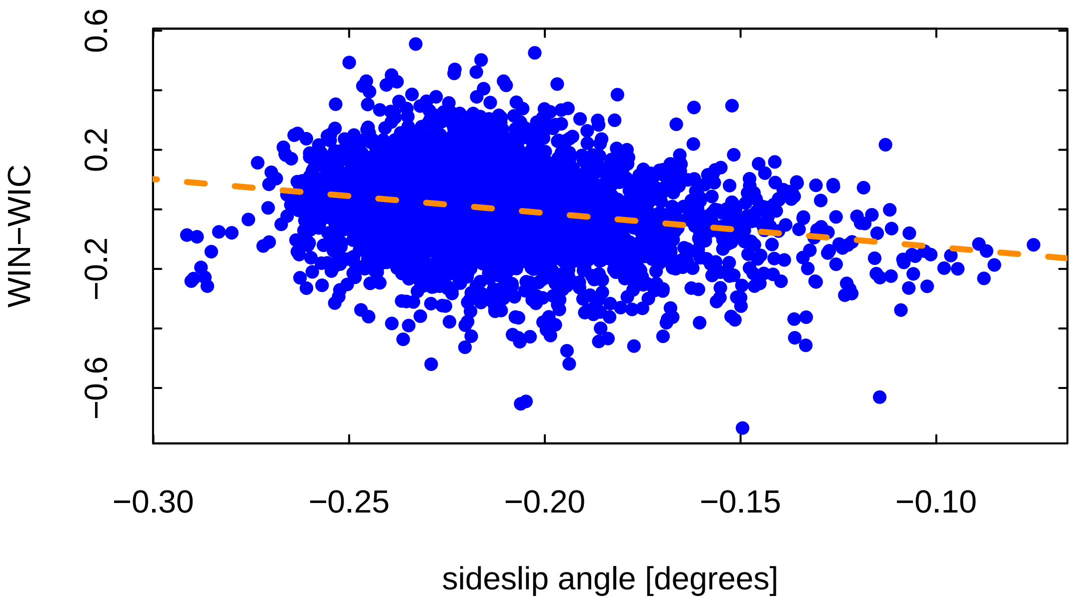

Figure 8: Vertical wind difference WIN-WIC as a function of sideslip.

vertical acceleration and the reduction in residual standard deviation in δW is also much less, to only 0.143~m/s. If the derivative of the angle-of-attack is shifted by -50 ms, the residual standard deviation reaches a minimum relative to other shifts of 0.156 m/s, still much less reduction than that based on vertical acceleration. However, there is almost no correlation between the derivative of angle-of-attack and the vertical acceleration, so the dependence represented in Fig. 7 might be used in combination with vertical acceleration to improve the fit.

Another flight characteristic with some correlation to WIN-WIC is sideslip, as shown in Fig. 8. In this case, the correlation is much smaller, about 0.14, but the dependence on sideslip appears to be real so including this dependence can reduce the residual standard deviation in δW slightly. The coefficients for the best fit including dependence on vertical acceleration, rate of change in angle-of-attack, and sideslip angle are $\{c_0, c_1, c_2, c_3\} = \{-0.1123\,\mathrm{m\,s^{-1}}, -0.0473\,\mathrm{s}, -0.0583\,\mathrm{m}/^\circ, -0.5349\,\mathrm{m\,s^{-1}}/^\circ\}$ as used in the following equation (where $\dot{w}_p$ is the vertical acceleration of the aircraft, β the sideslip angle, and $\dot{\alpha}$ the rate of change in angle of attack) and characterized by the table that follows:

$$\delta W = c_0 + c_1 \dot{w}_p + c_2 \dot{\alpha} + c_3 \beta \tag{1}$$

```
## lm(formula = D$DWIC ~ D$AZ + D$DAKRD + D$SSRD)
## [1] "Coefficients:"
##                Estimate  Std. Error    t value      Pr(>|t|)
## (Intercept) -0.11233940 0.017508111  -6.416421  1.597844e-10
## D$AZ        -0.04731957 0.002123861 -22.279978 1.897849e-102
## D$DAKRD     -0.05830238 0.004620459 -12.618310  1.135090e-35
## D$SSRD      -0.53486125 0.082332323  -6.496370  9.486823e-11
## [1] "Residual standard deviation: 0.129, dof=3247"
## [1] "R-squared 0.214"
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The value of the square of the correlation coefficient, 0.21 indicates that correlations with these variables account for a minor part (about 21%) of the total variance in the difference between the measurements of vertical wind.

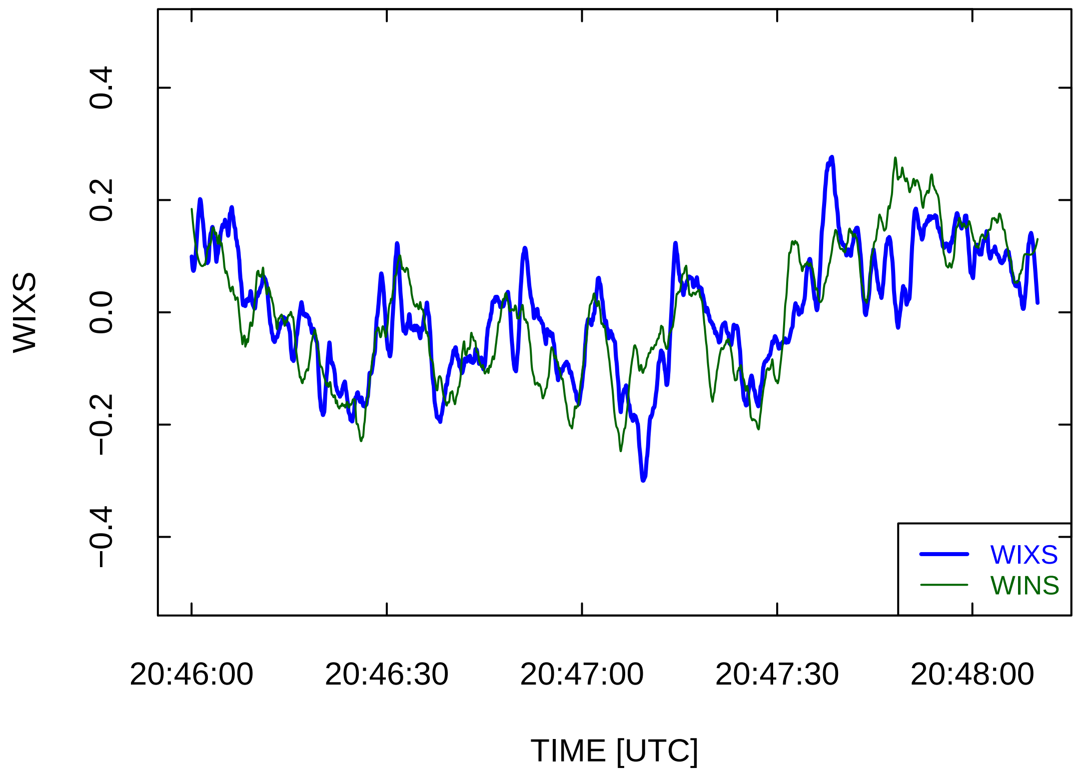

Figure 9: Wind measurements like those shown in Fig. 4 but after correction of WIC for effects of vertical acceleration and sideslip.

Angle of attack is highly correlated with vertical acceleration during the pitch maneuvers, so a plot like Fig. 6 but for AKRD shows a similar strong correlation. Because the direct dependence on AKRD is calibrated for the radome-based system, it is more likely that the dependence is on vertical acceleration, which is not significant during the speed runs used for calibration. A similar plot of δW (WIN-WIC) vs rate-of-climb shows only a weak correlation (about 0.15) and negligible reduction in the residual standard deviation, so rate-of-climb does not appear to introduce any substantial error. Longitudinal acceleration of the aircraft also does not show any substantial effect. Another factor showing negligible correlation to δW is the horizontal acceleration.

The other candidate factor that does show substantial correlation to δW is the rate of change of pitch, which is almost as strongly correlated to WIN-WIC as vertical acceleration. However, the rate of change of pitch ($\dot{\theta}$) is also highly correlated with vertical acceleration during the pitch maneuver (correlation coefficient 0.96) so it is not clear which is the cause of the difference between WIN and WIC. The rate of change of pitch enters the calculation of vertical wind directly because it determines the relative motion of the radome gust probe vs the IRU and GPS antenna, and a similar offset applies to the difference between the motion of the LAMS sensor, the LAMS IRU, and the GPS antenna. However, in the calculations of vertical wind used for this study, these rotation-rate effects were incorporated in the processing, using distances of 4.42 m (radome to Honeywell IRU), -4.30 m (Honeywell IRU to GPS antenna), and +6.0 m (LAMS to GPS antenna). A false correlation between δW and $\dot{\theta}$ of the magnitude observed would require an additional displacement of about 9 m (radome forward of the IRU by an additional 9 m or GPS antenna behind the IRU by an additional 9 m), or alternately the LAMS to be *forward* of the GPS antenna by an additional 9 m. The focal points for the LAMS beams are ahead of the housing by more than this distance, but they each detect only line-of-sight airspeed so no lever arm like that for the radome-IRU displacement is needed, and in any case the observed sensitivity to rotation would require a sensing location *behind* the LAMS housing. A correction has already been made for the 6 m longitudinal displacement between the GPS antenna and the LAMS IRU, so the rotation-rate correction to measured velocity does not appear able to account for the observed dependence.[1]

If the fit coefficients in the list of fit parameters as a function of vertical acceleration, derivative of angle of attack, and sideslip angle are used to correct the radome-based vertical wind, the result is the variable WIXS shown in Fig. 9 as the blue line. The match to the LAMS-measured vertical wind (green line) is good, and the problems evident in Fig. 4 have been corrected. The RMS difference between the two signals (after averaging to about 5-Hz signals) is 0.07 m/s, which is reasonable considering the claimed uncertainty in both and the difference in locations being measured by the two sensors. The vertical acceleration and the rotation rate experienced during the pitch maneuver are larger than those experienced during typical encounters with turbulence or waves, and the correction for vertical acceleration and sideslip in the pitch maneuver has a typical magnitude of 0.13 m/s, so the error arising from transient flow distortion (if that is indeed the cause) is smaller than the estimated uncertainty in the measurement of vertical wind (standard uncertainty of 0.12 m/s) in most representative measuring conditions. However, the RMS of the Deming fit to the LAMS-derived and the radome-derived vertical wind (WIN, WIC) is reduced from 0.14 to 0.10 by this correction, so the correction, although small, can be worth including in analyses requiring the lowest-uncertainty results.

[1] Evidence that the lever-arm correction is being applied correctly is that, after the 6-m correction was applied to CVSPD_LAMS, the difference between GGVSPD and CVSPD_LAMS showed no remaining dependence on $\dot{\Theta}$ and the two measurements were nearly identical (RMS difference of 0.05 m/s.and correlation coefficient of 0.99997).

Conclusions

1. The independent measurements from LAMS provide good support for the usual method used to determine sensitivity coefficients from maneuvers. The LAMS measurements confirm the values of the sensitivity coefficients in use to within a few percent. The revised SSRD sensitivity coefficients documented in the Wind Uncertainty Tech Note match the LAMS result very well and should be adopted as the standard GV coefficients.

2. 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, and that difference was larger than expected from uncertainty analyses of the two systems. Weaker dependences on sideslip and on the derivative of the angle-of-attack were also present. The estimated magnitude of the combined effects, however, is small, leading to typical errors in WIC of about 0.1 m/s when the vertical acceleration was in the range $\pm 1\ \mathrm{m\,s^{-2}}$, as is typical of all but the most extreme flight conditions.

3. A correction formula (Eq. 1) 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 only 0.07 m/s during that pronounced maneuver. This confirms the ability of the measuring system to remove the effects of even rapid pilot-induced changes in pitch, where rates-of-climb exceeded ± 10 m/s, so that less than 1% of the induced motion appears in the measurements.

– End of Memo –

Reproducibility:

PROJECT:	TransientEffects
ARCHIVE PACKAGE:	TransientEffects.zip
CONTAINS:	attachment list below
PROGRAM:	TransientEffects.Rnw
ORIGINAL DATA:	/scr/raf/cooperw/HT03HR.nc – special
WORKFLOW:	WorkflowTransientEffects.pdf – not yet available
GIT:	https://github.com/WilliamCooper/TransientEffects.git – not yet

Attachments: TransientEffects.Rnw
TransientEffects.pdf
TransientEffects.Rdata
SessionInfo