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Initial Evaluations of the MMS Maneuvers on the NASA Global Hawk

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Introduction

The Meteorological Measurement System (MMS) provides in situ static pressure, static temperature, and three dimensional wind data from the Global Hawk aircraft. While similar measurements can be derived from standard avionics data systems, suitable for basic aircraft navigation, the demands of scientific research require highly accurate values of these quantities and at higher frequencies (20 Hz or greater). The higher frequencies data also permit the evaluation of atmospheric turbulence and eddies.

A number of steps must be taken to reach this goal. Induced aircraft maneuvers including pitching, yawing, and box or reverse heading turns are required by the Meteorological Measurement System in order to understand the aerodynamics of the Global Hawk and its effects on the pressure, temperature and air flow (attack and yaw angle) measurements collected. The raw measurements, after being subjected to precise laboratory and aerodynamic corrections, are used as inputs to a series of calculations which determine the static pressure, temperature, and the three-dimensional wind vector, aiming to a mean accuracy (at all aircraft speeds as well as flight altitudes) of ± 0.3 mb, ± 0.3K, and ± 1 ms^{-1}, respectively.

Pitch and yaw maneuvers are used to determine the aerodynamic characteristic of the flow angle probes, inlets and the associated sensors and transducers. Box maneuvers are employed in determining the static pressure defect (bias of the static pressure distribution on the fuselage), as well as the offset geometry between the air-frame and flow angle measurement system. The maneuver data are interpreted with respect to sound meteorological and physical principles, in order to quantify the imperfect measurement errors for each event. Besides the aerodynamic calibration offered by the maneuvers; they also serve as a check of data quality and sensor performances. For example, a partially defective pressure sensor is undetectable just from the measured data; but it is readily isolated and recoverable from the induced maneuver data.

It is desirable to have a minimum of 5 – 10 of each kind of maneuver from a particular mission (such as GloPac), in order to relate the results from the entire ensemble of “pitches”, “yaws” and “boxes” statistically to the controlling aerodynamic parameters. These include, but are not limited to, angle of attack (AOA), aircraft speed (Mach number), and a measure that is proportional to air density (e.g., Reynolds number).

Since opportunities to obtain flight maneuvers are by nature limited, the aerodynamic parameters are used in conjunction with the maneuver results to help chart the correction profile to MMS measurements across the entire flight envelope.

For example, so far we have determined that our measured static pressures are too low. Without having referenced the aircraft avionics data or sonde data, we have determined that we need to raise our pressures by some 1.4 – 2.2 mb in order to compute good pressure, temperature and winds. Static pressure is a fundamental variable that impacts all of our data in some way.

While the majority of the maneuvers flown so far have been beneficial to us, some have been relatively better (or more useful) than others. Below are some descriptions of the different events we have examined so far, what has been good about them, and (also) what could use improvement in future flights. These accompany three figures that compare and contrast pairs of pitching, induced yawing, and box maneuvers.

Examples

Pitching via Altitude Perturbation

Figure 1 shows a strong, well-executed pitch maneuver from the GloPac flight on 20100413 (top panels), and a weaker event from the flight on 20100407 (bottom panels).

During the better pitching event, the Global Hawk descended from 13.72 to 13.34 km in a series of three distinct steps over 75 sec. During this time, the aircraft was allowed to descend rapidly, and then suddenly leveled out for ~5 seconds prior to initiating the next stair step. Despite the well-defined (and at times rapid) change in altitude, Mach number was held within a narrow (± 1%) range of values (0.513 – 0.525).

The weaker pitching event showed the aircraft descending from 16.88 to 16.40 km over a period of 200 sec. The descent rate was much more gradual, and while the Global Hawk gently pitched down twice, it didn't effectively pitch up to halt its descent. Both the more gradual altitude loss and the poorly defined stair steps contributed to a lack of variation in MMS angle of attack (AOA) data. Regardless of what the pitch and vertical velocity data show, a well-executed pitching maneuver will force MMS AOA to vary by ± 1 - 2º.

A third pitching maneuver on 20100402 (not shown) was of intermediate quality. During this event, pressure altitude was iteratively increased, and then decreased, by ~50 m. This produced vertical aircraft velocities of ± 6.5 ms^{-1} at a mean pressure altitude of ~13.1 km, within a narrow range of Mach (0.501 – 0.512). Maintaining the aircraft at a constant mean altitude had no impact on reducing Mach variability, so it appears that allowing the aircraft to descend is preferred for inducing a larger AOA response.

Induced Yawing via Heading Perturbation

Figure 2 shows a strong, well-executed rolling maneuver which induces yaw on 20100413 (top panels), and a relatively weak event from a later time (bottom panels). Since the Global Hawk has no rudder control, yawing is produced by rapid changes in roll angle from heading change execution.

The first event was performed at a pressure altitude of 16.7 km with Mach = 0.605. The second event was executed at 13.15 km altitude with Mach = 0.505. Unlike the pitch maneuvers, induced yawing produces very little altitude change (± 25 m). In both cases, the Mach number remained quite steady with little significant variation (< 1 %).

The largest yaw signals are produced when aircraft roll is quickly changed from a maximum (positive) to a minimum (negative) value. It is much less effective to change roll from zero value to a maximum or minimum, and then allow the roll to decay to zero. This effectively cuts the signal to noise of the yaw angle signature in half, and introduces "dead space" in the maneuver where nothing is happening.

The series of rapid changes between maximum and minimum values of roll angle, seen in the upper panels, is much preferred. Since the induced yaw signal has been recorded within a short time after maximum or minimum roll is obtained, this maneuver can be improved on by reducing the time full roll is held steady from 20 to ~5 seconds. This will reduce the overall time needed to execute each "yawing" by 90 seconds or more.

Boxes

Figure 3 shows two examples of MMS box maneuvers flown during GloPac. The top panels show a right-turn event from 20100413, high up in the stratosphere at 18.5 km altitude. The bottom panels are from a lower altitude (13.1 km) left-turn on 20100402.

The event on 20100413 shows four full roll/unroll sequences, taking the aircraft around a complete 360º turn from its initial to its final heading of 180º. It is highly desirable to complete the box maneuver to the same heading just prior to the box maneuver.

However, the altitude variations seen in the top panel can introduce undesired uncertainty in the MMS calibration process, if the winds at this location in the stratosphere are highly variable with respect to altitude. Maintain altitude during the box turns helps to minimize wind variation, resulting in improved calibration.

In contrast, the bottom panels show that altitude was almost perfectly constant during the turn on 20100402. This eliminates any possible feed-through from the vertical variability in the atmosphere. Unfortunately, the unroll following the fourth leg of the turn was incomplete, and the aircraft overshot its initial heading by some 40º. It is important for the aircraft to return to its initial heading, so that MMS winds computed at the beginning and end of the turn can be matched and unphysical differences eliminated by calibration.

Impact on MMS Temperature and Winds

Figures 4 – 6 compare MMS temperature and wind data during calibrated and uncalibrated maneuvers from 20100413. Figure 4 shows the pitching event, figure 5 displays the induced yawing, and figure 6 shows the box maneuver. In all three plots, calibrated data is shown in the top panels, while un-calibrated data is displayed in the bottom panels. Here, "uncalibrated" means that all aerodynamic corrections are set to nominal values, with zero offset corrections for attack and yaw angle, no static pressure correction, and no time response delays for the air flow angle system.

Figure 4 shows that in the pitching maneuver without calibration (bottom panels); vertical winds are in error by nearly 10 ms^{-1}, with variations of ± 3 ms^{-1} that are correlated with angle of attack (AOA). Temperature is also ~1K too cold, mainly due to the lack of static pressure correction. After calibration (top panels), vertical winds are $< \pm 1$ ms^{-1}, and have only a slight response to AOA.

Figure 5 shows that in the induced yaw maneuver without calibration (bottom panels); horizontal wind components have 2 – 4 ms^{-1} variation which correlates with yaw angle.

Also, the mean values of U and V are shifted by 6 and 4 ms^{-1}, respectively, mainly due to static pressure error. After calibration, variance in the wind components is reduced to ± 1 ms^{-1}. Further improvements and reduction in error will be made post-mission by relating the calibration constants statistically to aerodynamic parameters.

Figure 6 shows that during the box turn without calibration (bottom panels); large heading-dependent oscillations dominate the signal in the horizontal wind components. These are reduced, but not eliminated, in the calibrated winds (top panels). Some variation (± 2.5 ms^{-1}) remains in the wind during this turn, due to localized mesoscale variability in the atmosphere, particularly from vertical gradients of wind in the stratosphere (see top panels of figure 3). In general, these effects can be mitigated by maintaining a level altitude, and by executing these turns in a region of the atmosphere were horizontal wind gradients are also minimized.

Recommendations

For specific instructions on how the maneuvers may be programmed in the flight control system, see the Appendix.

Pitching

During this maneuver, the aircraft can either be allowed to descend up to ~1000 ft, and a maximum descent rate of -10 ms^{-1} is optimal. However, loss of altitude need be interrupted several times by brief periods (5 – 10 sec) of flight at level or rising altitude. In spite of the necessary altitude changes, the mean Mach number need be maintained at a near-constant value.

Yawing

Instructions to change heading angle in one direction (say, toward greater values) can be superseded approximately 5 seconds after maximum (+15º) roll has been attained, with instructions to change the heading in the opposite direction. This process can be repeated until there have been 5 positive and 5 negative rolls. Roll angles are changed from positive to negative and back to positive values quickly. There is no need or value in holding heading angle constant at any time during the yawing maneuver. However, Mach number need be maintained at a near-constant value as possible.

Boxes

It is important to execute the boxes at a nearly constant altitude in order to avoid wind shear, and to begin and end the box maneuvers at nearly the same heading angle. The straight and level sections only need to be 5 sec in duration.

Conclusion

There has been an MMS maneuver during each of the first three flights of GloPac. We understand and appreciate that the platform is not a normal piloted aircraft. The flight command is more of a request and there is not a direct control. The maneuver also requires flight planning effort and consumes flight time.

We are grateful to have these events, which have contributed to our understanding of the aircraft aerodynamics and made it possible for us to compute accurate meteorological data from this airplane. We anticipate these maneuvers will continue to improve and will help us understand the response of the aircraft across a greater range of flight conditions.

We expect there will be continued discussions on the quality of MMS maneuvers, and we will do our best to define what is needed in order for us to obtain the best scientific data quality possible. It is a learning experience for all; but we believe it is a very worthwhile challenge and value-added investment.

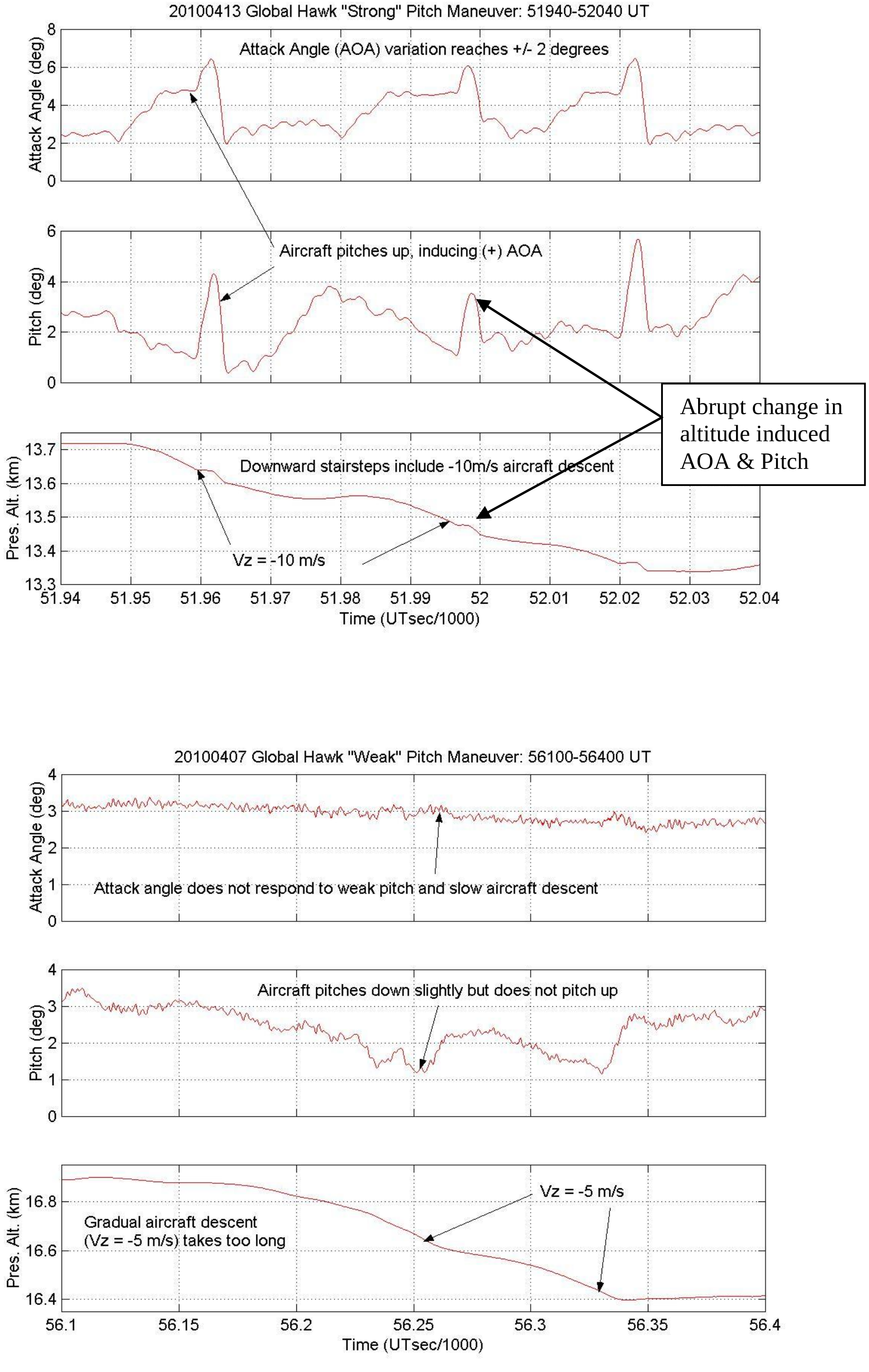


Figure 1: MMS pitching maneuvers from GloPac. The strong, well-defined event on 20100413 (above) is preferred over the weaker incident on 20100407 (below).

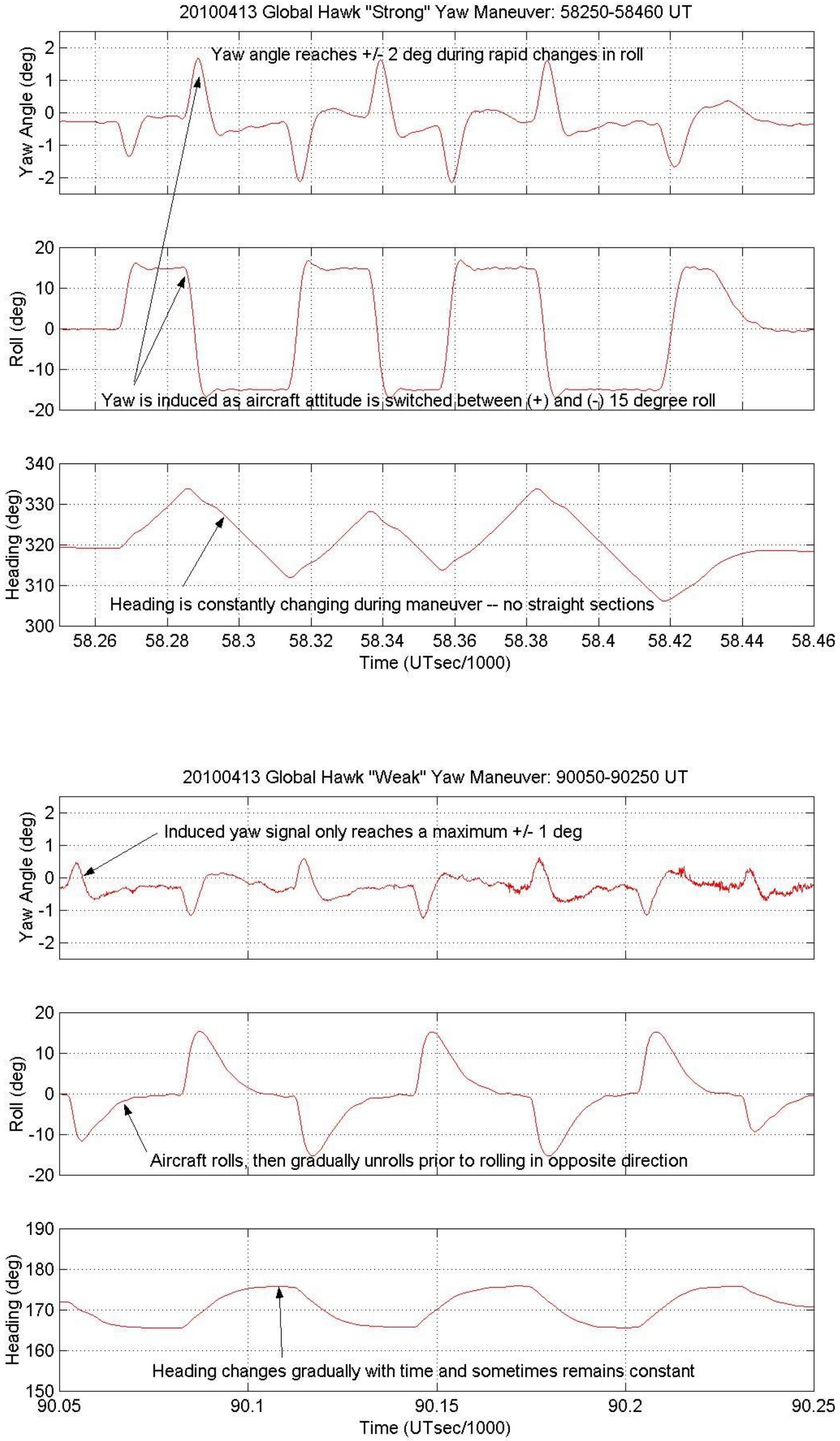
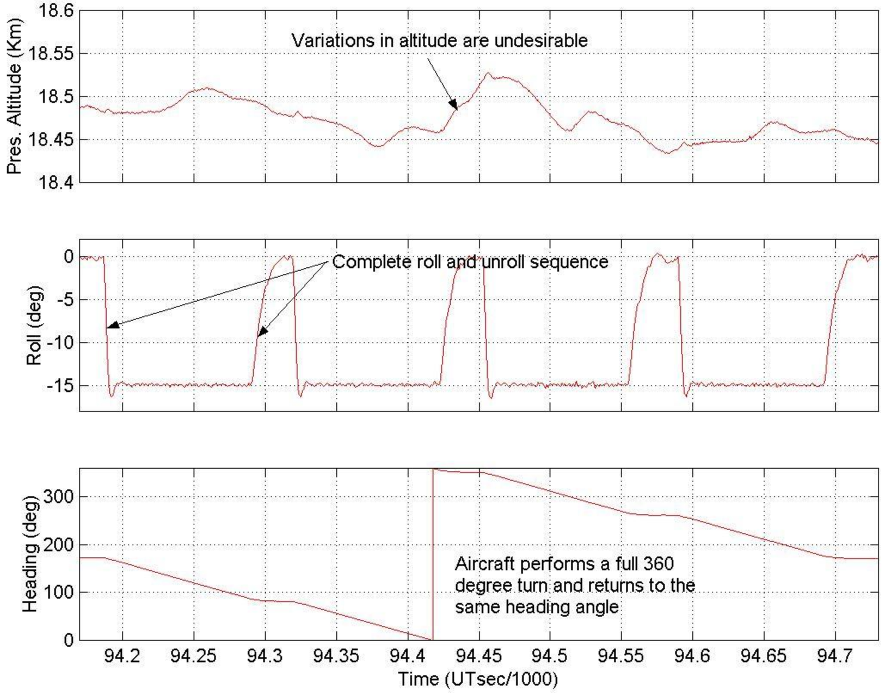
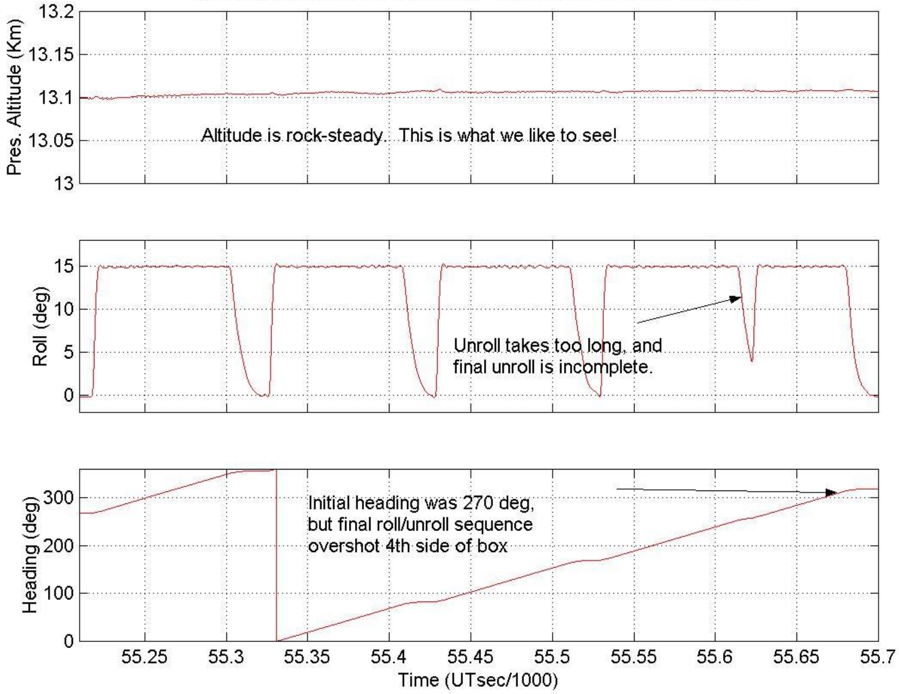


Figure 2: MMS induced yaw maneuvers from GloPac. The strong event earlier on 20100413 (above) is preferred over the weaker event performed later on (below).

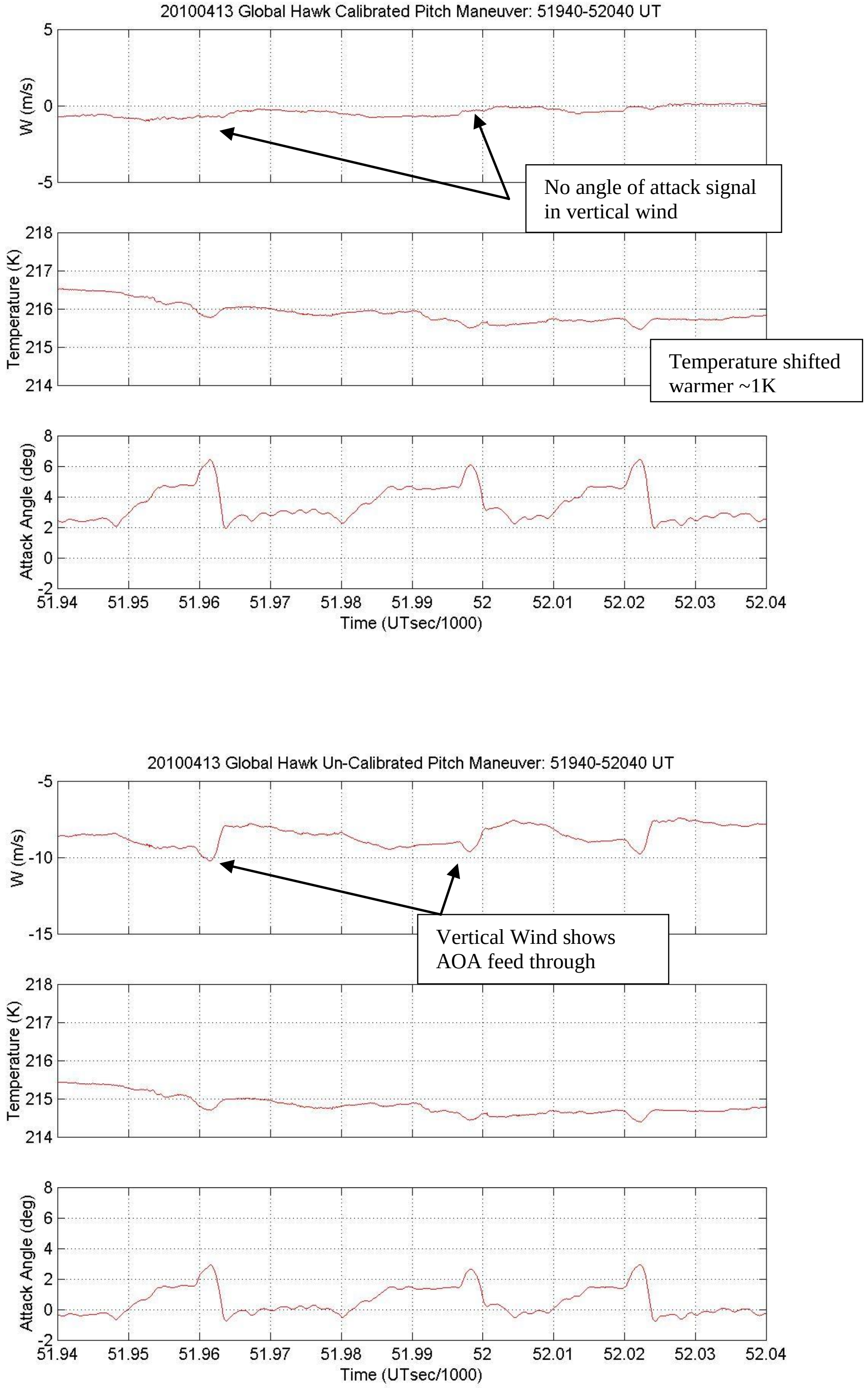


20100413 Global Hawk "Unsteady" Box Maneuver: 94170-94730 UT



20100402 Global Hawk "Overshoot" Box Maneuver: 55210-55700 UT

Figure 3: MMS box maneuvers from GloPac. The "unsteady"event from 20100413 (above) is compared with the "overshoot" event performed on 20100402 (below).

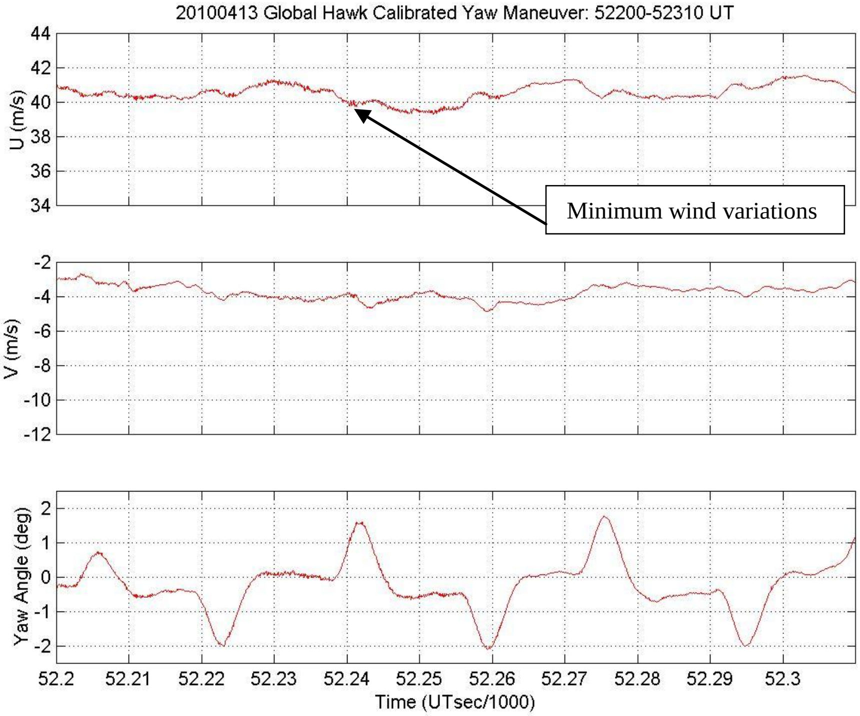


No angle of attack signal in vertical wind

Temperature shifted warmer ~1K

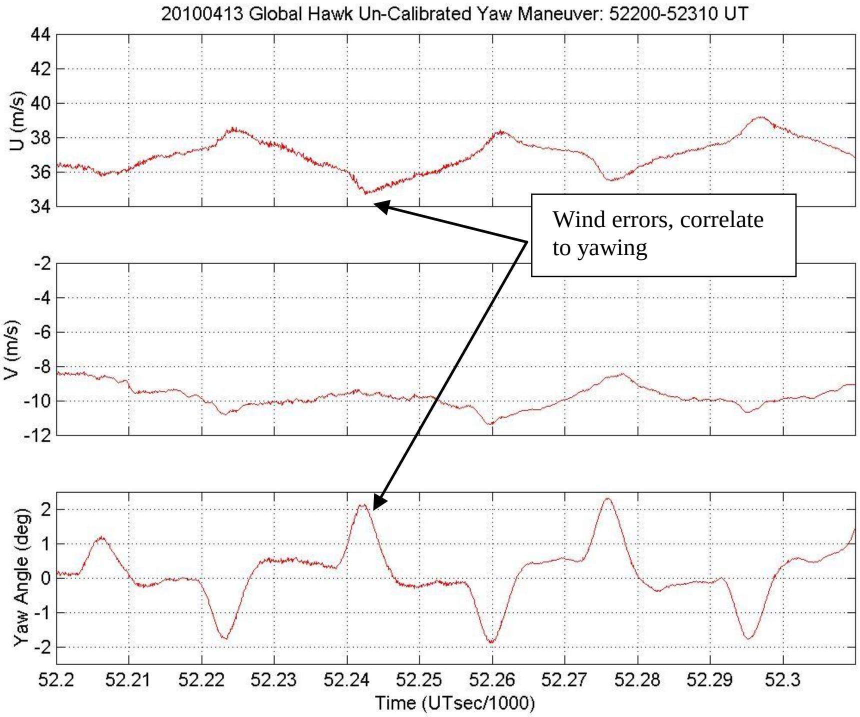
Vertical Wind shows AOA feed through

Figure 4: MMS vertical wind and temperature during a GloPac pitching maneuver. The calibrated values (above) are compared with the un-calibrated values (below).



20100413 Global Hawk Calibrated Yaw Maneuver: 52200-52310 UT

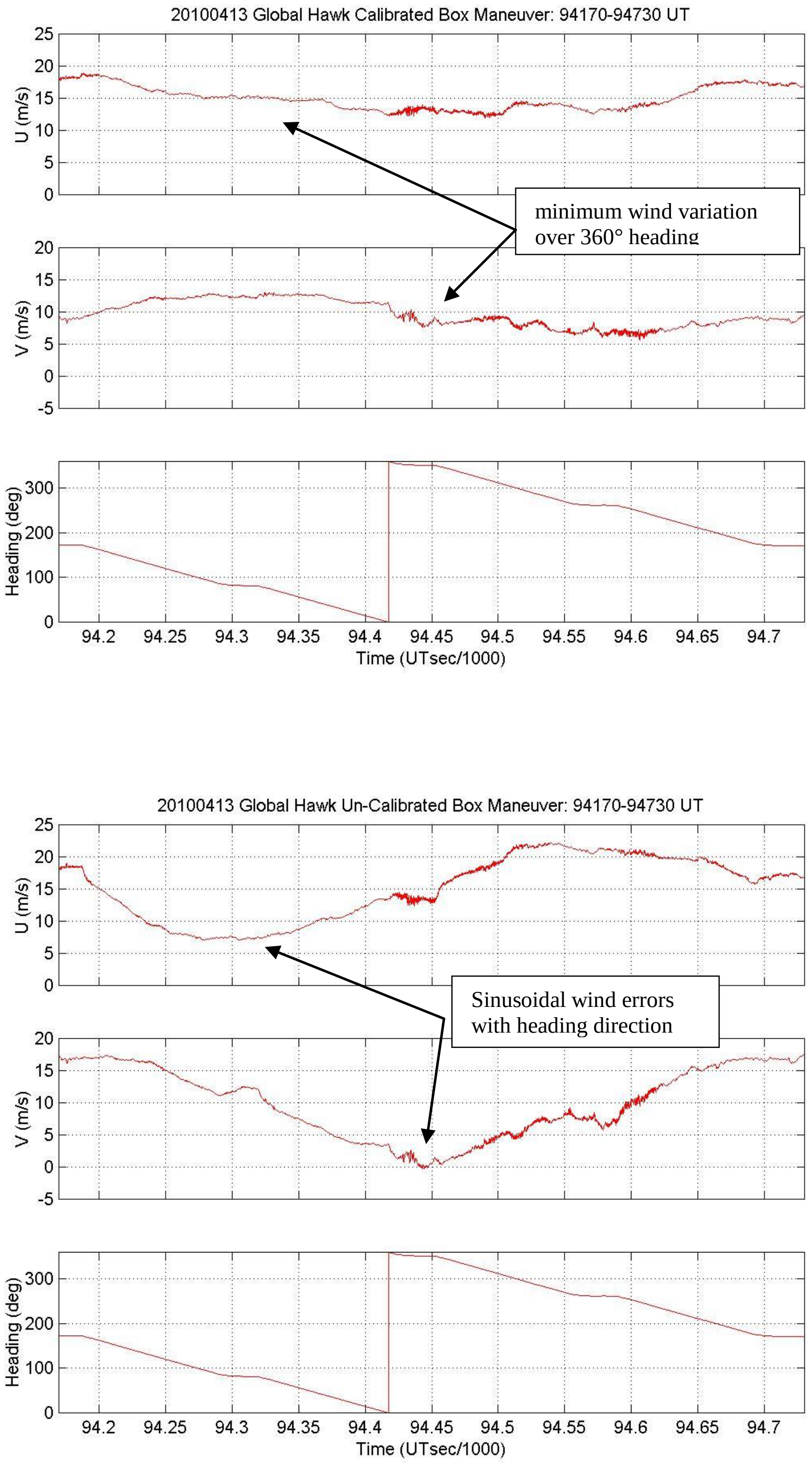
Minimum wind variations



20100413 Global Hawk Un-Calibrated Yaw Maneuver: 52200-52310 UT

Wind errors, correlate to yawing

Figure 5: MMS horizontal winds during a GloPac rolling maneuver. The calibrated winds (above) are compared with the un-calibrated winds (below).



minimum wind variation over 360° heading

Sinusoidal wind errors with heading direction

Figure 6: MMS horizontal winds during a GloPac box maneuver. Calibrated winds (above) are compared with the un-calibrated winds (below).

Appendix: Maneuver Procedures

1. Pitching by obtaining +-200 ft altitude deviation from present flight level in quick succession:
   (Abrupt altitude command seem to induce pitch & angle-of-attack)

   +300 ft , upon reaching +200 ft, enter -500 ft
   upon reaching -200 ft, enter +500 ft
   upon reaching +200 ft, enter -500 ft
   upon reaching -200 ft, enter +200 ft

   Example: cruising at 43000 ft; the altitude inputs are:

   43300 <execute>, preset 42500, at alt = 43200, <execute> 42500
   , preset 43300, at alt = 42800, <execute> 43300
   , preset 42500, at alt = 43200, <execute> 42500
   , preset 43000, at alt = 42800 , <execute> 43000

2. Rolling by sending +-10 deg heading deviation from present heading in quick succession:
   (abrupt heading command seem to induce roll & yaw)

   - 25 deg, upon reaching -10 deg, enter +25 deg
   upon reaching +10 deg, enter -25 deg
   upon reaching -10 deg, enter +25 deg
   upon reaching +10 deg, enter -10 deg

   Example: if cruising heading is at 100 deg; the heading inputs are:

   75 <execute>, preset 125 deg, at heading 90 deg, <execute> 125 deg
   preset 75 deg, at heading 110 deg, <execute> 75 deg
   preset 125 deg, at heading 90 deg, <execute> 125 deg
   preset 100 deg, at heading 110 deg, <execute> 100 deg

3. Box maneuver by send successive 90-deg heading change, pausing for 5 sec of fixed heading leg:
   (Specific aims: maintain altitude, start & end box at same heading setting)

   +90 deg, wait 5 sec after roll = 0
   +90 deg, wait 5 sec after roll = 0
   +90 deg, wait 5 sec after roll = 0
   +90 deg, wait 5 sec after roll = 0

   Example: if cruising heading is 10 deg; execute the following heading command:

   100 deg, wait for roll = 0; count 5-sec
   190 deg, wait for roll = 0; count 5-sec
   280 deg, wait for roll = 0; count 5-sec
   10 deg, wait for roll = 0; count 5-sec