Supplement to "Calibration and Quality Assurance of Flux Observations from a small Research Aircraft"

Olaf S. Vellinga *

Earth-System Science Group, Wageningen University & Research Centre, Wageningen, the Netherlands

Ronald J. Dobosy

Air Resources Laboratory, National Oceanic & Atmospheric Administration, Oak Ridge, Tennessee, Usa

Edward J. Dumas

Air Resources Laboratory, National Oceanic & Atmospheric Administration, Oak Ridge, Tennessee, Usa

Beniamino Gioli

Institute of Biometeorology, National Research Council, Firenze, Tuscany, Italy

Jan A. Elbers

Alterra, Wageningen University & Research Centre, Wageningen, the Netherlands

Ronald W.A. Hutjes

Earth-System Science Group, Wageningen University & Research Centre, Wageningen, the Netherlands

1. Part A: Detailed In-Flight Calibration Maneuvers

This appendix contains a detailed description of the in-flight maneuvers that have been used in retrieving the set of calibration parameters specific to the MFP-system on board of the PH-WUR. The maneuvers are mainly modified versions of those reported by Bögel and Baumann (1991) and Lenschow (1986) and Leise and Masters (1993).

Some basic rules are followed during the implementation of the maneuvers. First, maneuvers are flown with respect to cardinal or true headings, because this will result in stable and meaningful signals as much as possible for both horizontal wind components, u and v (e.g. Fig. 6 in main article). For this, the directional gyro is reset soon after takeoff to match the INS/GPS heading. Second, wings are kept as level as possible, preferably, within $\pm 2^\circ$ during most maneuvers, provided there is little or no turbulence. Third, airspeed is always kept as close to the target as possible. Fourth, the fuel level is recorded before and after the flight to know the total amount of lift for each maneuver. Finally, for a given power setting, the airplane is trimmed to fly hands-off, so that constant pressure altitude can be easily maintained within ± 10 ft.

1) Acceleration/Deceleration Maneuver

The 'Acceleration/Deceleration Maneuver' is flown at constant pressure altitude, on a constant cardinal heading, and wings level, while maintaining a constant airspeed of 110 kias with the airplane in steady flight. The first 30 s of the flight, this condition is maintained. After this short period, power is reduced for creating constant decrease of airspeed at a rate of 10 kts min^{-1}. During the power reduction, constant pressure altitude is maintained and the airspeed is reduced until 60 kias. This part of the maneuver takes about 5 minutes to complete. The pitch angle of the aircraft will smoothly increase during this maneuver.

Once 60 kias is attained, the whole procedure is done in reverse. Power is increased, again, in a smooth manner, so that airspeed is allowed to increase gradually at a rate of 10 kts min^{-1}. Constant pressure altitude is maintained and airspeed is increase until 110 kias. The pitch angle is smoothly decreased during this portion of the maneuver. After airspeed has reached 110 kias, the maneuver is finished.

During the whole maneuver, altitude variance needs to be ± 10 ft., airspeed variance needs to be ± 1 kts, and heading variance needs to be $\pm 1^\circ$. It is, therefore, probably the most difficult maneuver with the Sky Arrow 650 ERA. Also, because the airplane does not have an autopilot, altitude must be maintained manually while performing smooth power and pitch changes. Pitch control should be done with the trim as much as possible. Perfecting this maneuver takes some practice.

2) Yaw Maneuver

The 'Yaw Maneuver' starts with the aircraft in straight and level flight on a cardinal heading at 70 kias for 30 s. While maintaining wings level with aileron input, the left rudder pedal is depressed until the ball on the turn coordinator displaces approximately $\frac{1}{4}$ ball width. The heading of the aircraft begins to change as rudder input is introduced. This is normal and is allowed to continue as necessary. The deflection of a $\frac{1}{4}$ ball is maintained for 10 s, then the left pedal is depressed further until the ball deflection is $\frac{1}{2}$ ball-width. This condition is kept for 10 s. The rudder pedal is depressed until the ball deflection is approximately $\frac{3}{4}$ ball-width which is maintained for 10 s. Finally, the pedal is depressed until the ball is displaced a full ball-width, and this condition is kept for 10 s. After that, the aircraft is gradually returned to properly coordinated flight, where constant pressure altitude, airspeed, and heading are maintained for 30 s. During this maneuver, altitude variance needs to be ± 10 ft., airspeed variance needs to be ± 1 kts, and bank angle variance needs be $\pm 2\,^\circ$.

Previous steps are repeated using right rudder pedal deflections. The right rudder deflections is performed in the same order and maintained with the same tolerances as mentioned before.

3) Box Maneuver

The maneuver starts with the aircraft, trimmed for hands-off flight at constant altitude, on a heading of $0\,^\circ$ true (due North), as measured by the INS/GPS, with at 70 kias. A leg in this condition is flown at constant airspeed and constant heading for 2 min. After that, a standard-rate turn to the left is performed, while maintaining altitude and airspeed. Aircraft is rolled out of the turn on the heading $270\,^\circ$ true (due West). After 2 min, the aircraft is smoothly rolled into a left standard-rate turn, again, maintaining constant airspeed and altitude, and it is rolled out of the turn on a heading of $180\,^\circ$ true (due South). Again, a leg is flown at constant airspeed and constant heading for 2 min. After that, a standard-rate turn to the left is performed, again, while rolling out on a heading of $90\,^\circ$ true (due East). After another leg is flown for 2 min, a standard-rate turn to the left is performed, again, while rolling out on heading of $0\,^\circ$ true (due North). Finally, a last leg is flown at constant airspeed and constant heading for 1 min.

During the entire maneuver, altitude variance needs to be ± 10 ft., airspeed variance needs to be ± 1 kts, and during the straight legs, heading variance needs to be $\pm 1\,^\circ$.

4) Pitch Maneuver

The maneuver starts with flying for $30\,s$ with wings level at constant pressure altitude, a constant cardinal heading and at 70 kias. Next, the airplane is pitched up allowing the nose to reach a maximum pitch angle ($\approx 5\,^\circ$) during approximately 5 s. immediately, after the nose reaches the maximum nose-up angle, the nose is pitched down. After 5 s, the plane should be nose-level, and the pitch maneuver is continued smoothly until the nose is approximately $5\,^\circ$ down after approximately 5 s. The nose is then smoothly brought back to level, again, taking approximately 5 s. The idea is to complete one pitch-up/down cycle in 20 s. The 20-second cycle is then repeated 6 times, taking two minutes for the full maneuver. After completion, the nose is level and the aircraft is held straight and level for another 30 s. Altitude variance during this so-called 'slow frequency' pitch maneuver is allowed to vary as necessary, but altitude is always returned to the original starting altitude as the plane passes through nose-level. The airspeed variance needs to be ± 1 kts and heading variance needs to be $\pm 1\,^\circ$ during the entire maneuver.

The same procedure is repeated, again, but now using a 2.5-second period instead of a 5-second period. This is the so-called 'medium frequency' pitch-up/down maneuver. The maneuver starts straight and level for 30 s. In this case, each pitch up/down cycle is repeated 6 times to make the duration of the complete maneuver one minute. After the pitch cycles, the maneuver ends straight and level again for 30 s. The same altitude, airspeed, and heading tolerances are maintained as mentioned before. The maximum pitch angle is adjusted to keep the altitude excursions within a reasonable tolerance.

The final pitch up/down maneuver is made at high frequency. The complete pitch cycle (nose up, nose down, nose up) takes ≈ 1 s to complete. The altitude variation need to be within ± 20–50 ft. during the pitching portion of this maneuver. The maneuver starts again straight and level for 30 s. Now, 30 pitch-up/down cycles at high frequency are carried out and ending with 30 seconds of straight and level flight. Again, the same airspeed and heading tolerances are maintained as mentioned before. Maximum pitch up and down angle are adjusted again as necessary to prevent excessive altitude excursions.

This maneuver has the potential to introduce large vertical accelerations on the aircraft unless the pitch angle is carefully monitored. A consequence of excessive vertical accelerations is that things will float in the cockpit. Also, the fuel could float and possibly introduce air into the fuel line. If this happens, the engine could run rough or stop completely. Use of the auxiliary fuel boost pump may be necessary. If engine problems do occur, abandon the maneuver and introduce positive g's with a pull-up or turn until the engine runs smoother or restarts.

2. Part B: Tools included in Wurmfp-toolbox

This appendix highlights the most important tools included with the WURMFP-toolbox (contact corresponding author for a copy) for analyzing and/or processing data obtained by the mobile flux platform that uses the BATSTORE software developed by the National Oceanic and Atmospheric Administration (NOAA). The toolbox contains, however, many more scripts and it is continuously under development.

a. Pre-Processing

Pre-processing scripts are meant for getting general insights about how the MFP-system performed and about how a flight was carried out.

`<mfpchk>` Quick look of important signals for visual quality check.

`<mfpflight>`, `<mfpflight3>` View whole or sections of the flight track in 2D or 3D based on marker log.

`<mfptrim>` Trim MFP-file to remove erroneous data at ends of data set.

`<mfptrk2ge>` Export flight track to Google-Earth.

b. Processing

The heart of the toolbox with scripts for de-spiking, retrieving wind components from the BAT-probe and calculate fluxes and footprints.

`<mfpraw>` Quality check all signals, including attitude signals.

`<mfpwind>` Filter out aircraft attitude and calculate wind components, air speed and ground speed.

`<mfpflux>` Calculate length averaged horizontal transect fluxes and/or fixed-height averaged vertical concentration profiles.

c. Plotting & Exporting

Scripts for exporting or plotting data.

`<mfp2ge>` Export most MFP-data to a Google Earth.

`<mfp2lum>` Plot fluxes and wind data on top of an imported land-use map (in ARC ACII-grid format).

`<mfpprof>` Plot vertical profiles (CO_2, theta, U_{dir}) from output file of script 'mfpflux'.

d. System Check

These scripts should give the user a helping hand about the correct hardware set-up of the mobile flux platform.

`<mfpchkw>` Visual check wind components as output of script 'mfpwind'.

`<mfpcorr*>` Simple visual check correlation between two or more signals. * = wild-card character for a set of scripts.

`<mfpspec>` Simple spectral analysis on a selected signal.

e. Utilities

Set of script to modify or extract data, retrieve basic information about the data or calibrate script 'mfpwind'.

`<cmg2mfp>` Merge C-Migits data (*.cmg) into MFP-files.

`<mfphist>` Displays history of changes performed on MFP-file.

`<mfpinfo>` Displays header information of MFP-file.

`<mfpattest>` Estimate attitude signals from MFP gps-system, like NovAtel.

`<mfpmod>` Store new parameter settings from MFP-header file, except for precision specifier.

`<mfpmodc>` Similar to 'mfpmod', but now stores new precision specifier for all parameters declared in input header file.

`<mfpwindc>` Determine calibration parameters for use with script 'mfpwind'.

REFERENCES

Bögel, W. and R. Baumann, 1991: Test and calibration of the dlr falcon wind measuring system by maneuvers. *Journal of Atmospheric and Oceanic Technology*, **8 (1)**, 5–18.

Leise, J. A. and J. M. Masters, 1993: Wind measurement from aircraft. Unpublished report, Aircraft Operations Center, National Oceanic and Atmospheric Administration, MacDill AFB (Florida), USA.

Lenschow, D. H., 1986: Aircraft measurements in the boundary layer. *Probing the Atmospheric Boundary Layer*, D. H. Lenschow, Ed., American Meteorological Society, 39–55.