Title: Calibration of the ER-2 Meteorological Measurement System

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The Meteorological Measurement System (MMS) on the high-altitude ER-2 aircraft was developed specifically for atmospheric research. The MMS provides accurate measurements of pressure (p), temperature (T), the wind vector (u, v, w), position (longitude, latitude, altitude), pitch (θ), roll (ϕ), heading (ψ), angle of attack (α), angle of sideslip (β), true airspeed, aircraft eastward velocity ($\dot{x}$), northward velocity ($\dot{y}$), vertical acceleration ($\ddot{z}$), and time (t) at a sample rate of $5\,s^{-1}$. MMS data products are presented in the form of either 5-Hz time series or 1-Hz time series. The 1-Hz data stream, generally used by ER-2 investigators, is obtained from the 5-Hz data stream by filtering and desampling.

The instrumentation of the MMS was described by *Scott et al.* [1990]. MMS data have been used extensively by other ER-2 investigators in studying the polar ozone chemistry, and applications of the MMS data on atmospheric dynamics are discussed in a companion poster paper by *Chan et al.* [1991]. The accuracies of the MMS primary products are:

	Typical value at ER-2 altitude	Accuracy		
Pressure	60 mb	± 0.3 mb	or	0.5%
Temperature	180 K	± 0.3 K	or	0.2%
Wind vector	30 m s^{-1}	± 1 m s^{-1}	or	3.3%

(resolution: 0.1 m s^{-1})

Accurate measurements of pressure and temperature require judicious choice of sensor location, repeated laboratory calibrations, and proper corrections for compressibility, adiabatic heating and flow distortion of these measurements. Accurate determination of the wind vector, computed from the true airspeed and ground speed vectors, is a difficult problem because the vertical wind ($\approx \pm 0.1$ m s^{-1}) is several orders of magnitude smaller than the aircraft velocity and true airspeed (≈ 200 m s^{-1}), and simultaneous measurements of about 20 independent variables are needed in order to compute the winds. If the variables are not simultaneously measured and properly calibrated, computed winds will exhibit undesirable "feedthrough" or "leakages" from the motion of the aircraft.

The calibration of the MMS consists of (1) individual sensor calibration, (2) system and transducer response tests, (3) laboratory determination of the dynamic behavior of the inertial navigation system (INS), (4) inflight calibration, and (5) comparison with radiosondes and radar-tracked balloons.

Particular attention has been given to the dynamic response of the MMS measurements. Both time shifts and the frequency response of various measurements have been determined by

direct measurement and/or by calculations. The calibrations include effects due to active anti-aliasing filters used on analog data and the inherent response of the INS outputs, pressure transducers (including plumbing) and temperature sensors. Power spectra of MMS products yielding useful system resolution and noise figure will be illustrated and discussed.

Individual pressure transducers were calibrated inhouse using a coiled quartz system accurate to $\pm$ 0.07 mb. The airflow angles (α, β) are determined by the differential pressure system at the nose cone. The Mach number dependence and angular offsets were calibrated by requiring that the observed winds show no dependence on induced pitch and yaw maneuvers or on aircraft heading in a uniform airmass. The position error for static pressure taps as a function of β was determined to be zero. However, a small α-dependent correction was found to be necessary.

Two temperature sensors (with different time constants) and matching amplifiers were calibrated by the manufacturer (Rosemount) over the range from -100°C to 0°C. Corrections for recovery factor, Mach number and time shift are then applied. Results of intercomparing the two sensors and intercomparing them with Vaisala radiosondes give $\pm$ 0.3 K accuracy.

The information of pitch, roll, heading, $\dot{x}$, $\dot{y}$, and $\ddot{z}$ from the INS are used for the wind computation, and the signal time delays of these variables are of primary importance. A simple physical pendulum was constructed. With the INS on the pendulum platform, the INS outputs and the swing angle (measured by a 16-bit x 8-synchro converter) were recorded. Variations in $\ddot{z}$ are generated as a function of the swing angle. By orienting the swing axis $\approx$ 45° from the north-south direction, $\dot{x}$ and $\dot{y}$ are generated during the swinging. By tilting the swing axis $\approx$ 20° from the horizontal, heading variation is generated during the swinging. By twisting the INS $\approx$ 45° on the platform, pitch and roll variations are generated during the swinging. From the Lissijous plots, the time delay of each variable can be determined to an accuracy of <0.01 s. For pitch, roll, heading, $\dot{x}$ and $\dot{y}$, only the swing angle (A) data were needed in the Lissijous plots. For the variable $\ddot{z}$, appropriate function such as $\{\dot{A}\sin A + (\dot{A})^2\cos A\}$ was computed for comparison in the Lissijous plots. For the INS (Litton LTN-72RH unit) we use, we found that pitch and roll have zero time delay, heading has 0.045 s delay, $\dot{x}$ and $\dot{y}$ have 0.08 s delay, and $\ddot{z}$ has 0.39 s delay (including the active filter delay of 0.27 s).

MMS inflight calibration is a self consistency test, requiring that the computed winds have minimum leakage from the aircraft motion (θ, ϕ, ψ). Comparison of MMS measurements with Vaisala radiosondes and radar tracking of balloons and the ER-2 aircraft was conducted in 1986 [*Gaines et al.*, 1991], and comparison of the MMS real-time wind profiling capability via telemetry with radar-tracked "Jimsphere" balloons was conducted in 1989. In both cases, the results of the intercomparisons support the accuracy of MMS measurements stated above.

References

Chan, K. R., L. Pfister, T. P. Bui, S. W. Bowen, and J. Dean-Day, Applications of the ER-2 Meteorological Measurement System, poster paper submitted to the *Fourth Airborne Geoscience Workshop*, La Jolla, CA, January 29 to February 1, 1991.

Gaines, S. E., R. S. Hipskind, S. W. Bowen, T. P. Bui, and K. R. Chan, Comparisons of the NASA ER-2 Meteorological Measurement System with radar tracking and radiosonde data, *in preparation*, 1991.

Scott, S. G., T. P. Bui, K. R. Chan, and S. W. Bowen, The Meteorological Measurement System on the NASA ER-2 aircraft, *J. Atmos. and Oceanic Technol.*, 7, 525-540, 1990.