Instrument Description

The MMS instrumentation consists of three major systems:

1. An air motion sensing system to measure the velocity of the air with respect to the aircraft, i.e., the true air speed.
2. An inertial navigation system to measure the velocity of the aircraft with respect to the earth, i.e., the ground speed.
3. A data acquisition system to sample, process and record the measured quantities.

The air motion sensing system consists of sensors, which measure temperature, pressures, and airflow angles (angle of attack and yaw angle). The Litton LN-100G and Systron Donner CMIGIT-III Embedded GPS Inertial Navigation Systems (INS) provide the aircraft attitude, position, velocity, and acceleration data. The Data Acquisition System samples the independent variables simultaneously and provides control over all system hardware.

The instrumentation of the ER-2 MMS is described by Scott et al. [1990]. Fundamentally, subtracting the measured aircraft ground velocity from the true air speed vector produces the 3-dimensional wind vector. Details of the wind equation are documented in Lenschow [1972, 1986]. The ground speed vector is measured by the Inertial Navigation System, and the MMS air motion sensing system determines the true air speed vector. The calculation is difficult because the vertical wind ($\approx \pm$ 0.1 ms^{-1}) is several orders of magnitude smaller than the aircraft velocity and air velocity ($\approx$ 220 ms^{-1}). Small error in the aircraft and/or air velocity results in large error in the wind data. A contributing error source is that the instrumentation measures quantities with respect to the aircraft frame of reference. These measurements are then transformed to the earth coordinate system. The transformation depends on the accuracy of the attitude (pitch, roll, and heading) data. The attitude data are given by the Inertial Navigation System (INS), but they are susceptible to imperfect INS installation. In the ideal limit, the INS is installed squarely with respect to the aircraft frame. In practice, there are always residual offsets, which are determined during system calibration. For the typical air speed of 200 ms^{-1} on the ER-2, the desired 1ms^{-1} wind accuracy requires $\pm$ 0.3° angular measurements.

The true airspeed vector depends on air data measurements, including static pressure, static temperature, pitot pressure, and air flow with respect to the fuselage. Accurate measurements of these quantities require judicious choices of sensor locations, repeated laboratory calibrations, and proper corrections for compressibility, adiabatic heating and flow distortion. The ground speed vector is derived from the integration of acceleration data using the appropriate numerical constraints and compensation. For example, the vertical acceleration data includes the compensation for distance above the surface ($1/R^2$), centrifugal effects, and non-spherical earth effects. The integration is constrained by an altitude derived from the hydrostatic equation.

The system calibration of the MMS consists of:

1. Individual sensor calibrations.
2. Sensor dynamical response tests.
3. Laboratory determination of the dynamic behavior of the inertial navigation system.
4. In-flight calibration.
5. Comparison with radiosonde and radar-tracked balloons.

Individual sensors are routinely re-certified to NIST standard by their respective calibration laboratories. Specific MMS sensor configuration are tested rather than the nominal set-up. For example, a temperature bath calibration is determined for a specific platinum sensor matched to a specific signal conditioner. Another example is that the recovery correction for a specific temperature probe is re-established by wind tunnel testing.

Particular attention has been given to the dynamic response of the MMS measurements. Both time shifts and the frequency response of various quantities have been determined by direct measurement and/or by calculations. The calibrations include effects due to filter response, gyros and accelerators response, pressure transducers (including plumbing) and temperature. For example, a chopped air stream that is directed at the plumbing line leading to a pressure transducer induces a step response output. Propagation delay as well as the transducer characteristic is determined from the analysis. A simple physical pendulum with measurable angular rate was constructed to determine the time delays of the INS data. Using the Lissajous plots to analyze the pendulum data, time delays as small as 0.01 second are detectable.

The MMS in-flight calibration is a self-consistency system test, requiring that the computed winds have minimum leakage from the aircraft motion. The maneuvers typically include 5 sinusoidal ± 2° of pitching, 5 sinusoidal ± 2° of yawing/heading, and 360° square box pattern. More fundamentally, the position error of the static pressure curve on the fuselage is determined by direct comparison between pressure altitude and the integrated altitude data. The winds computed during the maneuvers also determine the residual phase delays between the variables and the angular offset between the air speed and the ground speed vector.

Comparison of MMS measurements with Vaisala radiosonde and radar tracking of balloons and the ER-2 aircraft was conducted in 1986, reported by Gaines et al [1991]. Comparison of the wind data with radar tracked "Jimsphere" balloons were conducted in 1989. In both cases, the results support the MMS measurement accuracy.

Power spectra of the measured quantities are finally analyzed to determine the resolution and noise figure. Independent spectral and fractal analysis of the MMS data are documented in Bacmeister [1996] and Tuck [1999].