

NOAA Technical Memorandum ARL-257

**NOAA ARL MOBILE FLUX PLATFORM INSTRUMENTATION INTEGRATION ON  
UNIVERSITY OF ALABAMA SKY ARROW ENVIRONMENTAL AIRCRAFT**

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## List of Abbreviations and Acronyms

A/D	Analog-to-Digital
ARL	Air Resources Laboratory
ASCII	American Standard Code for Information Interchange
ATDD	Atmospheric Turbulence and Diffusion Division
AUX BOX	Auxiliary Box
BAT	“Best” Aircraft Turbulence
C	C computer programming language
CPU	Central Processing Unit
DSP	Design Stagnation Point
FUST	Fast Ultra-Sensitive Temperature
GCC	GNU Compiler Collection
GPS	Global Positioning System
IDL	Interactive Data Language
IR	Infrared
MATLAB	Matrix Laboratory
MFP	Mobile Flux Platform
NetCDF	Network Common Data Format
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
PAR	Photo synthetically Active Radiation
PPF	Photosynthetic Photon Flux
PPS	Pulse Per Second
REM	Remote
VAC	Volts Alternating Current
VDC	Volts Direct Current



## List of Symbols and Variables

$P_x$	Dynamic Pressure (x-axis)
$P_y$	Differential Pressure (y-axis)
$P_z$	Impact Differential Pressure (z-axis)
$P_s$	Static Pressure
$P_r$	Reference Pressure
$A_x$	BAT Probe Acceleration (x-axis)
$A_y$	BAT Probe Acceleration (y-axis)
$A_z$	BAT Probe Acceleration (z-axis)
$A_{xb}$	Backseat Acceleration (x-axis)
$A_{yb}$	Backseat Acceleration (y-axis)
$A_{zb}$	Backseat Acceleration (z-axis)
$T_{bar}$	Slow Response Thermistor Temperature
$T_{slow}$	$T_{bar}$ Corrected for Compressibility Effects
$x', y', z'$	Aircraft Coordinate Reference Frame
$X, Y, Z$	Earth Coordinate Reference Frame (East, North, Up)
$\vec{U}$	Three Dimensional Wind Velocity Vector
$\vec{V}_a$	Air-relative Probe Velocity Vector
$\vec{V}_g$	Ground relative Probe Velocity
$\Phi$	Roll Angle
$\Theta$	Pitch Angle
$\Psi$	Heading Angle
$\alpha$	Angle of Attack
$\beta$	Angle of Sideslip
$K_\alpha$	Sensitivity Coefficient to Angle of Attack
$K_\beta$	Sensitivity Coefficient to Angle of Sideslip
$Q$	Dynamic Pressure
$Err_Q$	Sensitivity Coefficient to Dynamic Pressure
$\epsilon_P$	Pitch Misalignment Error
$\epsilon_R$	Roll Misalignment Error
$\epsilon_H$	Heading Misalignment Error
$\alpha_0$	Angle of Attack of Zero Lift
$U$	East Wind Component
$V$	North Wind Component
$W$	Vertical Wind Component
$C_l$	Coefficient of Lift

## **Abstract**

The University of Alabama and the NOAA Air Resources Laboratory (ARL) entered into a cooperative agreement to conduct atmospheric research using a Sky Arrow 650 Environmental Research Aircraft. In 2004 the Sky Arrow Aircraft was instrumented with the Mobile Flux Platform (MFP) instrument suite developed by NOAA/ARL. The University of Alabama manages the aircraft program, and the instrumentation was integrated by NOAA/ARL. Both groups are involved in data analysis, research, and instrumentation. The instrument suite includes a wind measurement system, environmental instrumentation and a data collection system. This technical memorandum gives the reader a description of each system installed in the aircraft and how they are integrated into the data collection system.



**Figure 1. University of Alabama Sky Arrow**

## **1.0 Introduction**

A cooperative agreement exists between the University of Alabama and the NOAA Air Resources Laboratory (ARL) to conduct atmospheric research using a Sky Arrow 650 Environmental Research Aircraft (ERA) (Figure 1). The Sky Arrow 650 ERA is manufactured in Italy by, Iniziativa Industriali Italiane S.p. and been type certified in the U.S.A. It is a two place, tandem configured composite aircraft with a maximum gross takeoff weight of 1430 lbs, length of 24.9 ft, wingspan of 31.8 ft, and a typical cruise speed of 90 knots.

The Sky Arrow Aircraft is instrumented with the Mobile Flux Platform (MFP) instrument suite developed by NOAA/ARL. These specially designed instruments measure exchange of carbon dioxide, water, and energy between the Earth's surface and the atmosphere. Two features make the Sky Arrow aircraft especially well-suited for collecting these types of measurements. Firstly, it is a *pusher* aircraft; the propeller is located behind the engine nacelle and the wing is farther aft. Propeller airflow and wing disturbance is reduced on a pusher aircraft, compared with a tractor (prop in front) type aircraft. Secondly, it has favorable low speed handling characteristics that make the Sky Arrow suitable for low altitude flights.

In 2004 NOAA/ARL integrated the Mobile Flux Platform instrumentation suite into the Sky Arrow Aircraft. In May 2004 commercial hardware and specialized electronic hardware were purchased. From June through August, NOAA/ARL fabricated the gust probe's aluminum hemispherical head, electronic sensor and amplifier boards, air temperature sensors, and auxiliary electronics box. Sensors were repackaged and mounted on instrument plates. The aircraft manufacturer provided the aerodynamic fairing to Sky Arrow's nose. Final calibration and bench testing were completed in August 2004. The physical installation of the sensor package on the Sky Arrow took about three weeks and was completed in September 2004.

Following the installation, initial test and calibration flights were conducted with the aircraft based in Knoxville, Tennessee. For the next several months, the data from these flights were examined and initial aircraft calibration constants determined. A preliminary field test program was conducted in December 2004 with the aircraft based in Gainesville, Florida. These data were studied by NOAA/ARL. Noteworthy were problems with the Licor 7500 instrument due to aircraft vibration. In April 2005, NOAA/ARL spent a month working on some of the issues discovered by the Florida flights. The Licor 7500 vibration problems were resolved by the fabrication of an external stiffener (see Figure 2). The vibration issues are discussed in greater detail in Section 3.1.2.



**Figure 2. Stiffened Licor Mount**

This document describes the Sky Arrow instrument suite, and lab and in-flight calibrations of the instruments. Section One gives an overview of the aircraft instruments and their integration into the Sky Arrow. The wind measurement system: the basic theory behind it and the technical details of the instruments are explained in section two. Section Three describes the suite of instruments that measure other environmental variables. Section Four details the analog instrument signal digitization, collection, and storage. The creation of calibration constants from data processing procedures and calibration maneuvers are explained in Section Five.

## **1.1 Wind Measurement System Overview**

The wind measurement system consists of sensors that measure pressure, acceleration, aircraft attitude, position and velocity. From these measurements the winds, and subsequently fluxes, can be calculated. These sensors are contained in an instrumentation package known as the "best" aircraft turbulence (BAT) probe. The BAT probe instrument is the result of collaboration between NOAA ARL and Airborne Research Australia (Crawford and Dobosy, 1992; Hacker and Crawford, 1999).

The BAT probe housing consists of a 15 cm diameter aluminum hemisphere mounted on a carbon-fiber cylinder. The probe fits over the Sky Arrow factory nose cap (Figure 2). The hemisphere houses pressure transducers, accelerometers, temperature sensors, and related circuit boards (see Section 2). A BAT REMote module (REM) located in the cylinder converts analog measurements from the BAT circuit boards to digital signals (see Section 4). Having the A/D conversion take place in close proximity to the sensors reduces the chance for electrical noise to degrade the analog signal. GPS serial data for position, velocity, and attitude is fed directly into the aircraft data system.

## 1.2 Environmental Sensors Overview

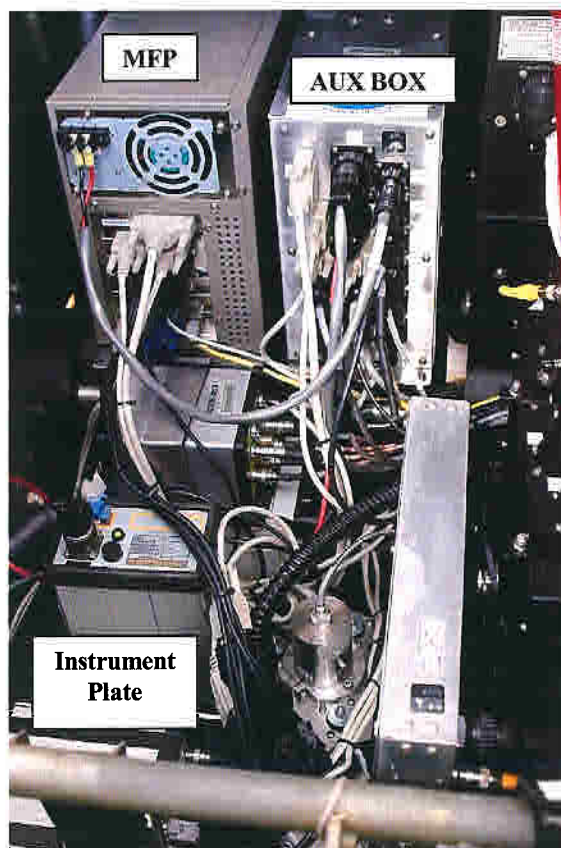
Various environmental sensors are installed on the Sky Arrow. Sensors on the BAT probe measure air temperature and concentrations of carbon dioxide (CO<sub>2</sub>) and water (H<sub>2</sub>O). Sensors installed on the horizontal stabilizer measure components of solar radiation. An instrument plate (Figure 3) installed in the belly of the aircraft, under the passenger seat provides mounting locations for down-looking sensors that measure distance to the ground, dew point, and infrared surface temperature.

## 1.3 Data Collection Overview

The data collection system consists of two distinct parts: the MFP computer and custom-made aluminum auxiliary box (AUX BOX). The AUX BOX serves as the physical junction for all signals from the instruments. The MFP computer and AUX BOX (Figure 3) are mounted in the baggage compartment located behind the rear seat.

In addition to the data from the BAT probe which is passed to the AUX BOX digitally, the AUX BOX contains a second BAT-REM module that provides the additional channels of A/D conversion for sensors located external to the BAT probe. The AUX BOX also serves as the electrical power distribution, receiving raw 12-volt aircraft power and providing clean/fused power to the computer system and all of the instruments.

The MFP computer is a custom-made x86 computer with a Pentium 3, 850 MHz processor running the Linux operating system kernel version 2.6.10. Digital signals from the AUX BOX, forward BAT REM module, and other instruments are transmitted via RS232 and RS422 serial connections into the MFP computer. Data collection software, written in C programming language, is used to receive, align, and store the data on hard disk. The raw data are post-processed after they have been copied from the MFP computer. Additional information about the MFP computer, AUX BOX, data system software, and processing can be found in Section Four.



**Figure 3. MFP Computer, Aux Box & Instrument Plate**

## 2.0 Wind Measurement System

Winds are computed using measured pressure, acceleration/velocity, and temperature. From these measurements, two velocity vectors are derived:  $\vec{V}_a$  is the velocity of the air with respect to the aircraft, and  $\vec{V}_g$  is the velocity of the aircraft with respect to the earth. The result of adding these two vectors together is  $\vec{U}$ , the velocity of the wind with respect to the earth (Crawford and Hacker, 2002). At typical flight speeds and in normal winds,  $\vec{V}_a$  and  $\vec{V}_g$  are opposite in direction and nearly equal in magnitude. They are related by the following equation:

$$\vec{U} = \vec{V}_g + \vec{V}_a.$$

The wind measurement is made nominally at 50 Hz. Figure 4 illustrates an example of the velocity vectors used in computing winds.

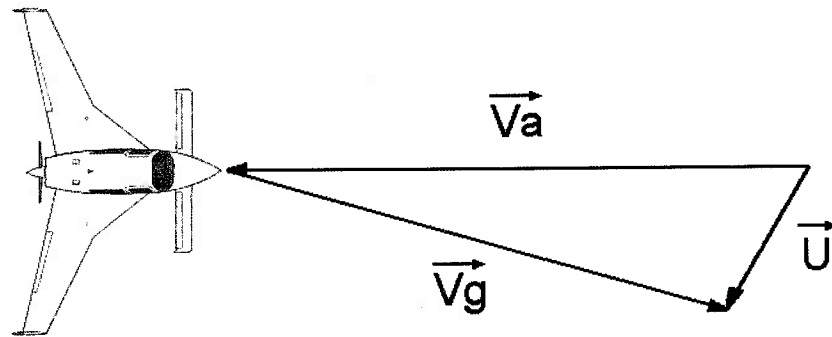
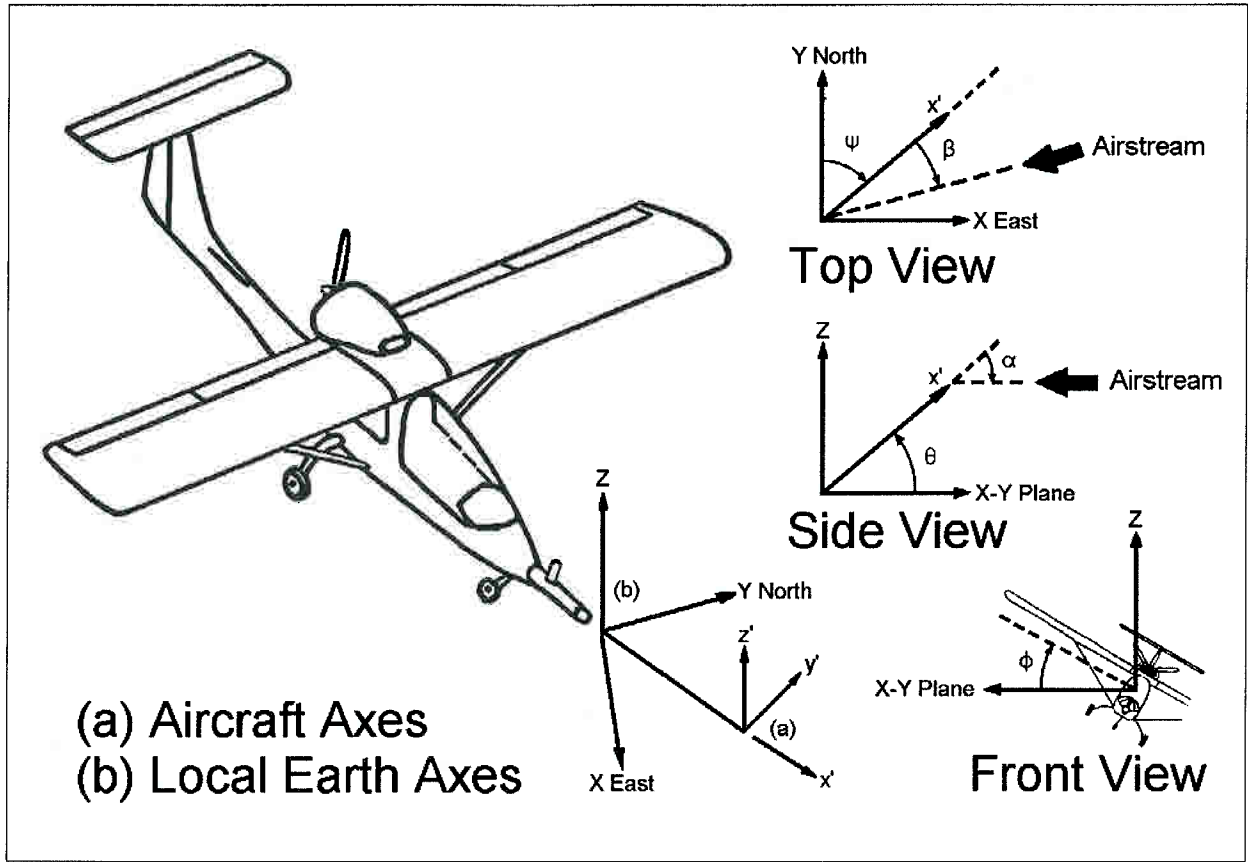


Figure 4. Wind Vector Example

## 2.1 Aircraft Axes Defined

Air-relative probe velocity, sensed in the airplane's reference frame, is measured as well in the airplane's coordinate system:  $x'$ , positive forward;  $y'$ , to port; and  $z'$ , toward the airplane's roof. Earth-relative probe velocity is measured in the earth's reference frame and coordinate system  $x$ , positive eastward;  $y$ , northward; and  $z$ , upward. A transformation matrix, which is defined by measurements of the three conventional attitude angles: roll ( $\phi$ ), pitch ( $\theta$ ), and heading ( $\psi$ ), accomplishes rotation from one coordinate system to the other. These must be sampled simultaneously with all other quantities involved in wind computation. Their definition, including sign convention, is shown in Figure 5, along with angles of attack ( $\alpha$ ) and sideslip ( $\beta$ ). These last two angles define the direction of the air-relative probe velocity.





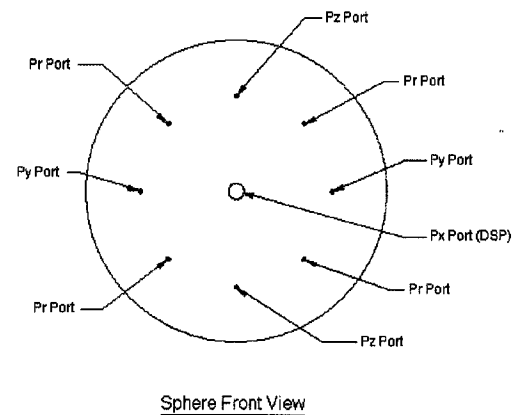
**Figure 5. Diagram of Aircraft Coordinate System and Local Earth Coordinate System**

## 2.2 BAT Pressure Sensors

The BAT probe hemisphere has nine precisely machined holes that are connected to solid-state pressure sensors. Reference pressure, ( $P_r$ ) is measured by taking the pneumatic average of four off-axis pressure ports, as shown in Figure 6. This measurement is used to calculate the static pressure.

The dynamic pressure is computed from the raw differential impact pressure, ( $P_x$ ).  $P_x$  is measured using a differential pressure sensor between the design stagnation point (DSP) and the reference pressure ports. The dynamic pressure and reference pressure measurements are used with temperature to calculate true airspeed.

Two additional differential pressure sensors



**Figure 6. BAT Sphere Pressure Ports**

measure the difference in pressure across the horizontal (Py) and vertical (Pz) axes. These pressure measurements are used to calculate sideslip and angle of attack. See Table 1 for pressure sensor specifications.

**Table 1. BAT Pressure Sensor Specifications**

Model	DCXL05DN	DCXL20DN	XCX15ANQ
Application	Side-slip and Angle of Attack	Dynamic Pressure	Reference Pressure
Type	DIFF: +/- 12.46 mb	DIFF: +/- 49.83 mb	Absolute: 0 TO 1034 mb
Error	+/- 0.03 mb	+/- 0.12 mb	+/- 0.21 mb
Output (Amplified)	± 5 VDC	± 5 VDC	± 5 VDC
Measurement Variable	Py, Px	Px	Pr

Honeywell Sursense Ultra Low Pressure Sensors

Features: millivolt output, high accuracy, temperature compensated, printed circuit board mount.

Sensor Mechanism: micromachined silicon sensor (piezoresistive strain gauge).

### 2.2.1 Calibration

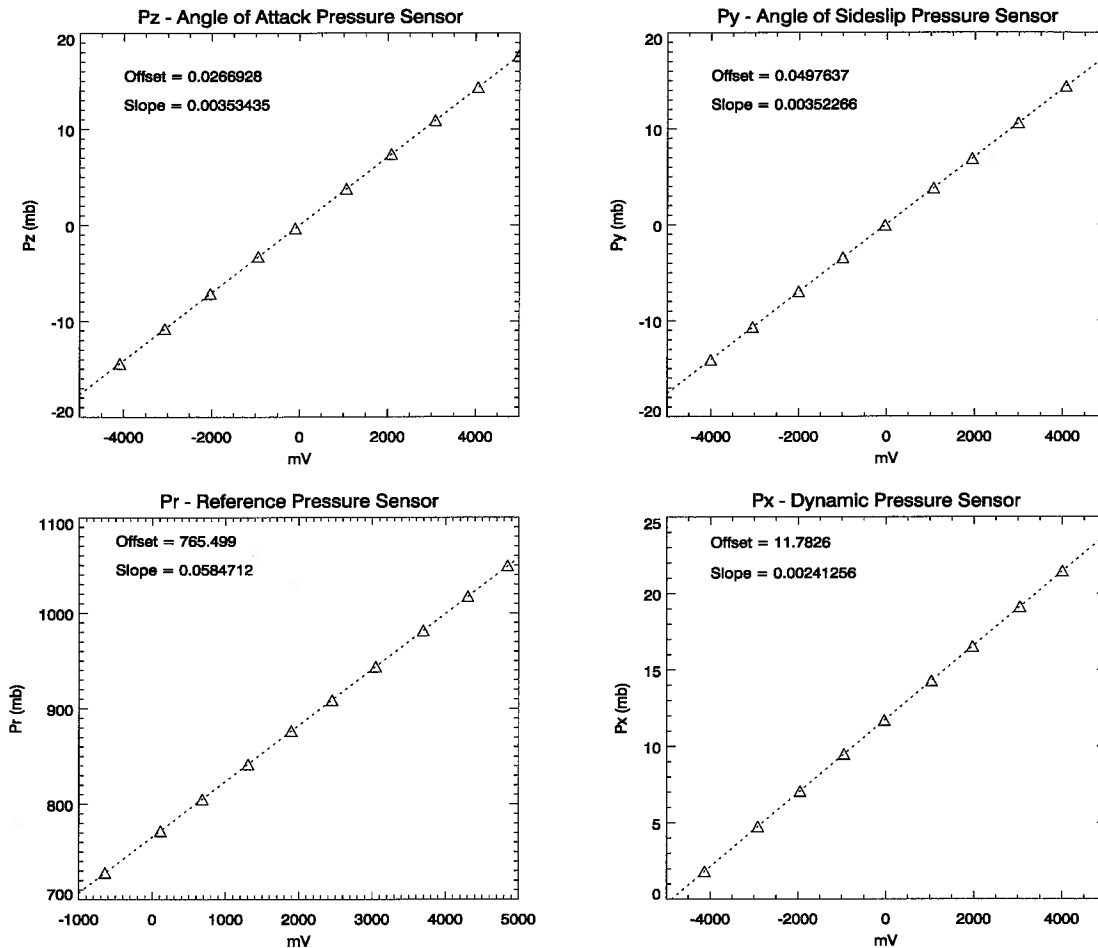
The reference pressure sensor is calibrated by connecting the pressure port in parallel with an AIR Model DB-1B certified pressure sensor. Both pressure sensors are attached to a syringe, suitable for creating pressure changes of 300 mb. The pressure is measured from the certified pressure sensor, and the voltage output of the reference pressure sensor is recorded. The pressure is adjusted from 1040 mb to 700 mb. The resultant least-squares-linefit for pressure and voltage is used to determine sensitivity and offset coefficients for converting the millivolt output of the pressure sensor to a pressure measurement in millibars.

The differential pressure sensors are calibrated using a similar process. The certified standard is a Mensor model 4040 pressure sensor, with output in pounds per square inch (psi). Figure 7 shows the results of the pressure calibrations.

### 2.3 BAT Accelerometers

Three accelerometers are attached to the circuit board mounted in the BAT hemisphere. One accelerometer is oriented to measure acceleration along each aircraft axis ( $x'$ ,  $y'$ ,  $z'$ ). The acceleration measurement is integrated post-flight to produce a velocity measurement of the BAT probe. The resultant velocity is high-pass filtered and blended with the low-pass filtered velocity measurements from a Novatel GPS system. This blending technique is described by Eckman *et al.*, 1999.





**Figure 7. Pressure Sensor Calibration Curves – Measured Pressure vs. Voltage Output**

Three additional accelerometers are mounted to a circuit board (Figure. 8) in the AUX BOX. These ‘backseat’ accelerometers in combination with measurements in the BAT probe provide a means for determining high-frequency variations in pitch and heading. The measurement from the accelerometers aligned with the z'-axis (from BAT and backseat) are differenced and divided by their separation distance. The results are then twice integrated and passed through a high-pass filter. The accelerometers aligned with the y'-axis are treated similarly. Finally, these measurements are blended with the low frequency heading and pitch calculations from the Javad attitude system in post-processing. Accelerometers used are IC Sensors Model 3022 Accelerometer which features:  $\pm 5$  VDC output, printed circuit board mount, low cost, piezoresistive silicon accelerometer.



**Figure 8. Backseat Accelerometers**

### 2.3.1 Accelerometer Calibration

The accelerometers, which are sensitive to gravity, are calibrated by tipping the sensors to specific angles. For example, when the accelerometer sensor axis is vertically oriented (parallel to gravity), it reads 1 G. When the sensor axis is rotated to horizontal (perpendicular to gravity), it reads 0 G. Using a custom made tilt-wheel, the angle of the accelerometer may be determined to within  $\sim \pm 0.2^\circ$ . Each sensor is rotated through  $180^\circ$ . The raw voltage output (after amplification) is plotted versus the gravity component. From this, sensitivity and offset coefficients are computed. Figure 9 shows the results of the calibration.

### 2.4 Novatel GPS System

A Novatel GPS antenna is mounted to the carbon fiber cylinder of the BAT probe. The antenna is connected to a Novatel GPS receiver (Figure 10) mounted on the instrument plate in the aircraft. GPS time, position, and velocity data are all recorded by the scientific-data collection system. Additionally, if desired, the system has the capability of measuring and recording raw pseudo-ranges. In this instance, a ground-based Novatel GPS System identical to the aircraft system is also set up to record pseudo-ranges. These data are then used to compute differentially corrected position and velocity post-flight.



Figure 10. Novatel GPS Receiver

Data from the BAT probe GPS antenna provides the low frequency component of velocity and position. This component is blended with the integrated accelerometer high frequency velocity and position data. All of the measurements provided by the Novatel GPS system are transmitted via RS232 serial interface to the data system. The GPS receiver is the Novatel OEM-G2-RT20 GPS receiver card with PROPAK-G2 receiver enclosure. GPS specifications are as follows: Single-Frequency, 12-Channel, L1 C/A code 20 cm real-time kinematic positioning, real-time DGPS positioning, raw data output.

The GPS system also provides timing synchronization for the data system. All serial data is collected by the computer and time synchronized by using a 1 pulse-per-second (PPS) timing signal generated by the Novatel GPS system. Additionally, the 1Hz Novatel GPS pulse provides the input to a timing circuit to trigger the BAT REM modules at 50 Hz.

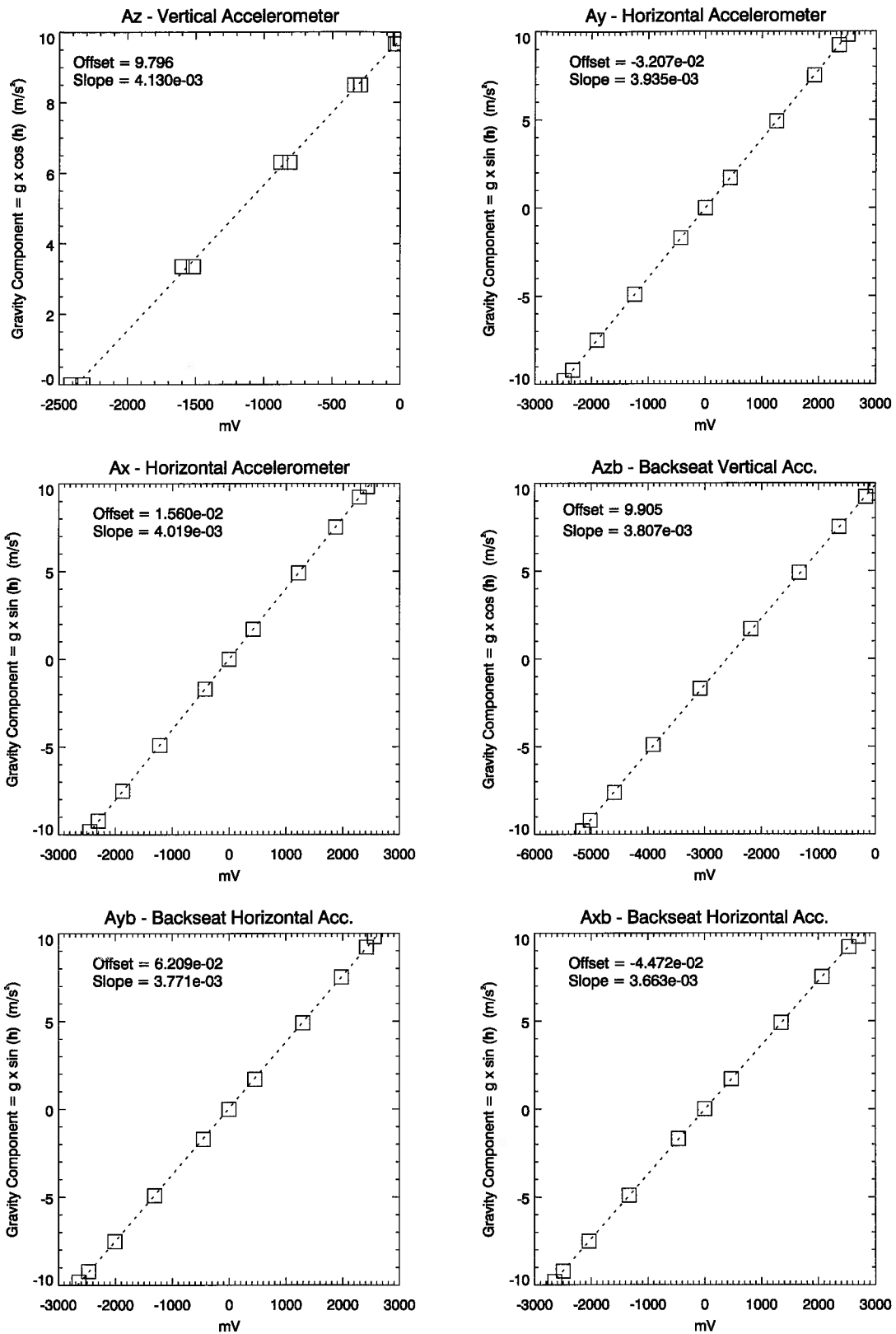


Figure 9. Acceleration Sensor Calibration Curves – Gravity Component vs. Voltage Output

## 2.5 Javad Attitude System

Aircraft attitude measurements are made using the Javad GPS attitude system (Figure 11). This system uses four GPS antennas to determine real time aircraft attitude. On the Sky Arrow, one GPS antenna is located on top of the horizontal stabilizer, one on top of the engine nacelle, and one on top of each wing.

The Javad JNSGyro-4 attitude system contains four dual frequency GPS receivers. It is mounted on the instrument plate, which is mounted behind the passenger seat. The dual frequency code and carrier data from four antennas are processed to determine the three attitude angles (pitch, roll, and heading) up to 20 times per second. The Javad specifications are shown in Table 2.



**Figure 11. Javad Receiver**

**Table 2. Javad Attitude System Specifications**

<b>Tracking Specifications</b>	
Tracking channels	20 L1+L2 channels GPS on four boards
Signals Tracked	L1/L2 C/A and P Code and Carrier
<b>Performance Specifications</b>	
Real time position accuracy	Autonomous ~3.0 [m] 3D RMS Carrier Phase Differential ~0.01 [m] 3D RMS
Real time attitude accuracy	Heading ~ 0.004/L [rad] RMS, (L = antenna separation in [m]) Roll/Pitch ~ 0.008/L [rad] RMS
Cold start / Warm start	< 60 sec / < 10 sec
Reacquisition	< 1 sec
Output	RS232 serial data

### 2.5.1 Calibration

The Javad system is capable of self-calibration. To calibrate the Javad system, the aircraft is positioned to known pitch, roll, and heading angles. The Javad system is allowed to run for several hours during which time it system calculates the relative positions of each antenna accurately while the aircraft position is static. From this baseline calibration, aircraft pitch, roll, and heading angles can be determined.

### 3.0 Environmental Sensors

#### 3.1 Licor 7500 Open Path CO<sub>2</sub> / H<sub>2</sub>O Gas Analyzer

This instrument allows fast, precise measurements of in-situ densities of CO<sub>2</sub> and H<sub>2</sub>O in turbulent air structures. In eddy covariance studies, these data are used in conjunction with BAT turbulence data to determine the fluxes of CO<sub>2</sub> and H<sub>2</sub>O. The LI-7500 Open Path CO<sub>2</sub>/H<sub>2</sub>O gas analyzer consists of two components: the analyzer sensor head and the control box housing the electronics.

##### 3.1.1 Licor 7500 Specifications

The sensor head (Figure 12) has a 12.5 cm open path, with single-pass optics, and a large 1 cm diameter optical beam. Reference filters centered at 3.95 μm and 2.40 μm provide for attenuation corrections at non-absorbing wavelengths. Absorption at wavelengths centered at 4.26 μm and 2.59 μm provide for measurement of CO<sub>2</sub> and water vapor, respectively. These features minimize sensitivity to drift and dust, which can accumulate during normal operation. The LI-7500 operates over a temperature range of -25 to +50 °C.

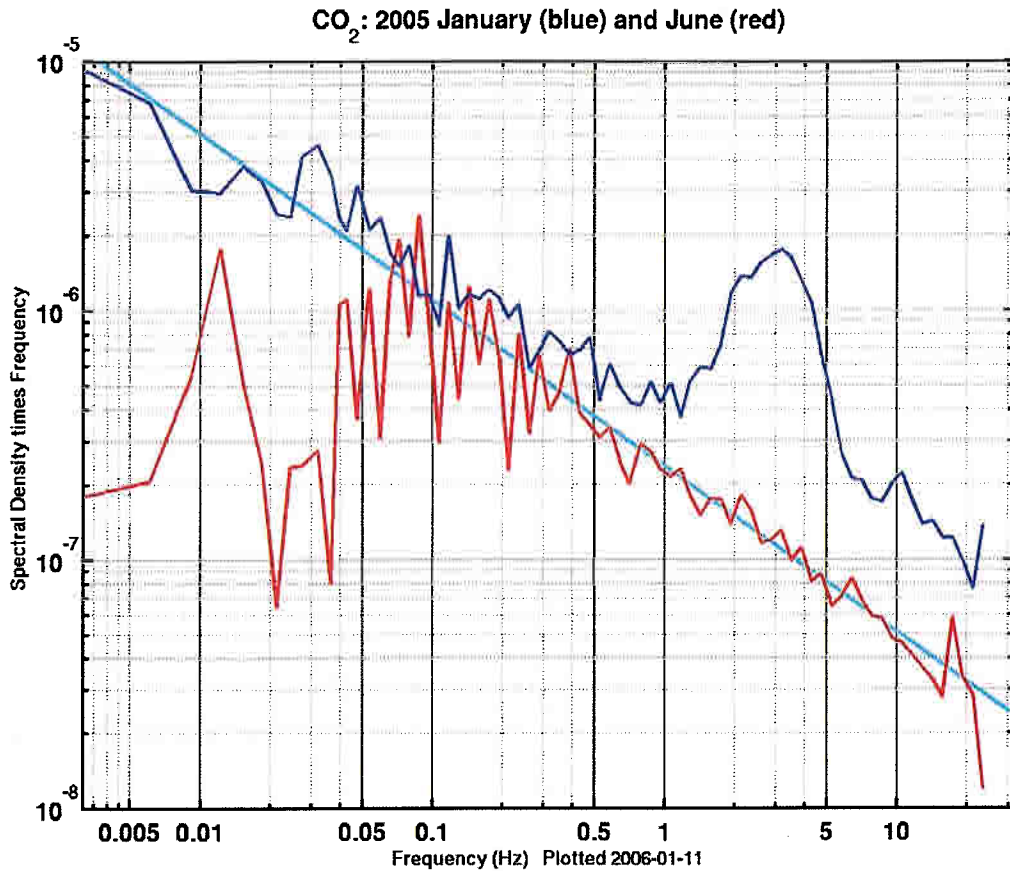


**Figure 12. Licor Sensor Head (before stiffening)**

##### 3.1.2 Licor 7500 Calibration

The Licor 7500 is calibrated by the manufacturer before delivery. Data output is available in both analog and digital format. NOAA uses a 0-5 volt DC analog signal generated by the Licor 7500 as an input to the A/D system. Optional capability exists to read data through the serial port. Field verification of operation is completed before mission flights.

Following the initial 'test' Sky Arrow field campaign, anomalies were detected in the Licor 7500 CO<sub>2</sub> signal. It was determined through spectral analysis that the anomalies were due to engine vibration. There was sufficient engine vibration to cause the Licor 7500 sensor head to vibrate. This introduced a vibration-dependent error in the measurement. This error has been reduced with the addition of a stiffener to the Licor 7500 sensor head. Figure 2 shows the Licor 7500 installed with the stiffener. Figure 13 shows the power spectrum of the CO<sub>2</sub> concentration before (blue) and after (red) the stiffener was installed. The vibration is apparent in a signal peak centered at 3 Hz in the non-stiffened sensor signal (blue). After stiffening (red), the 3 Hz peak is absent.



**Figure 13. Comparison of power spectrum of CO<sub>2</sub> concentration from Licor 7500 before (blue) and after (red) the stiffener was installed.**

### 3.2 Edgetech DewPoint Sensor System

Dewpoint measurements are made using the Edgetech 200M DewTrak System. The system measures dewpoint using a sensor that incorporates a chilled mirror hygrometer. A polished mirror, which is exposed to ambient air, is cooled to the dewpoint temperature and condensation forms on the mirror. Optical sensors detect condensation by measuring the quality of light being reflected by the mirror. A control circuit keeps the chilled mirror in a state where evaporation and condensation are occurring at the same rate. The measured temperature of the mirror in this state is equal to the dewpoint of the air.

The chilled mirror hygrometer is installed on the belly instrument plate. It is mounted so that the mirror is exposed to the free stream air. It connects to the 200M DewTrak control unit, which is also mounted to the instrument plate.



**Table 3. DewPoint Sensor Specifications**

Range	Dew Point	-50° C to +60° C
	Temperature	-75° C to +60° C
	% Relative Humidity	approx. 5% to 95% (Equivalent Range)
Accuracy	Dew Point and AT	± 0.25°C
	% Relative Humidity	± 1.0 to 1.5%
	Dew Point Depressions	45° C
	Temperature Sensors	PRT (Platinum Resistance Thermometer)
	Output	0 – 5 VDC

### 3.2.1 DewPoint Sensor Calibration

The Dew Point Hygrometer was calibrated at the Edgetech factory.

### 3.3 Everest Infrared Temperature Sensor

Surface temperature measurements are made using the Everest Interscience 4000.3ZL self-contained infrared (IR) temperature sensor (Figure 14). The sensor measures infrared radiation emissions from the ground and converts that measurement to an analog voltage.

**Table 4. IR Temperature Sensor Specifications**

Scale Range	-40°C to 100°C or -40°F to 212°F
Resolution	0.1°C
Accuracy	±0.5°C
Spectral Pass Band	8 < Wavelengths < 14 μm
Field of View	4°
Response Time	0.10 second
Operating Distance	2 cm to 300 meters
Output Signal	0 – 5 VDC



**Figure 14. Everest Temp Sensor**

#### 3.3.1 IR Temperature Sensor Calibration

The manufacturer, Everest Interscience, Inc., calibrated the Everest infrared temperature sensor with NIST traceable calibration equipment. Calibration coefficients for slope and offset can be derived from manufacturer's calibration data. Periodic checks are also made using an Everest blackbody calibration source in the field.

### 3.4 Apogee Photosynthetically Active Radiation (P.A.R.) Sensor

The PAR sensor (Figure 15) measures the radiation between 400 and 700 nanometers, which are the most important wavelengths for plant growth. Photosynthesis is largely driven by the number of photons between these wavelengths, so this radiation is called the Photosynthetic Photon Flux (PPF) and is measured in  $\mu\text{mol m}^{-2}\text{s}^{-1}$  (micromoles of photons per square meter per second). A quantum is the energy carried by a photon so this is a quantum sensor. The AUX BOX amplifies the low-level output signal of this instrument to appropriate level. The PAR sensor has a range of 0 to 4000  $\mu\text{mol m}^{-2}\text{s}^{-1}$  (full sunlight: 2000  $\mu\text{mol m}^{-2}\text{s}^{-1}$ ) and a Fixed output of 0.1 mV per  $\mu\text{mol m}^{-2}\text{s}^{-1}$ .



Figure 15. P.A.R. Sensor on Mount

#### 3.4.1 P.A.R. Sensor Calibration

The manufacturer, Apogee Instruments, Inc., calibrated the P.A.R. sensor to a known radiation standard. A field check is done by determining the output of the sensor when either the up or down direction is blocked from the sun and noting the sensor response in the appropriate direction.

### 3.5 Kipp & Zonen Net Radiometer Sensor

Net radiation is a measurement of the difference between the up-welling and down-welling radiation of all wavelengths. The Kipp and Zonen NR LITE (Figure 16) is designed for outdoor net radiation measurements. It is attached to the Sky Arrow horizontal stabilizer on



Figure 16. Net Radiometer on Mount

a custom-made aluminum boom. This is a passive instrument, which generates an electrical current based on the radiation measurement. The current is converted to a low-level voltage, which is amplified by the AUX BOX. This provides a  $\pm 5$  VDC signal for the A/D converter.



**Table 5. Net Radiometer Specifications**

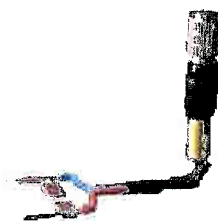
Spectral response	0-100 $\mu\text{m}$
Detector protection	Teflon coated
Sensitivity (upper detector)	10 $\mu\text{V}/(\text{Wm}^{-2})$
Recommended output range for atmospheric application	-25 to +25 mV
Sensor asymmetry	$\pm 20\%$
Range	-2000 to + 2000 $\text{Wm}^{-2}$
Response time (1/e)	20 sec (nominal)
Temperature Range	-30 $^{\circ}\text{C}$ to +70 $^{\circ}\text{C}$
Directional Error (0-60 $^{\circ}$ zenith angle with 1000 $\text{Wm}^{-2}$ beam)	< 30 $\text{Wm}^{-2}$

### 3.5.1 Net Radiometer Calibration

The Kipp & Zonen NR LITE is calibrated individually by the manufacturer against a pyrheliometer in controlled conditions. A field check is done by determining the output of the sensor when either the up or down direction is blocked from the sun and noting the sensor response in the appropriate direction.

### 3.6 Temperature Sensors

High-resolution temperature measurements are made on the BAT Probe using a Cu-Co (copper constantine) thermocouple and a thermilinear bead network. The Cu-Co thermocouple is called the fast ultra sensitive temperature circuit (FUST) because it has a fast response to temperature perturbations. The FUST thermocouple (Figure 17) senses the temperature difference between the thermocouple element (0.003 inches or 76 $\mu\text{m}$  diameter wire) in the free-stream and its reference junction in microvolts. The low voltage FUST signal is amplified through a two-stage low noise amplifier (LNA), filtered, and temperature calibrations are applied to produce a FUST temperature.



**Figure 17. FUST Probe**

A glass bead thermilinear network (network of thermistors) is installed at the reference junction. Ideally the reference junction and the glass bead thermistor are at the same temperature. Using a wheatstone bridge circuit, small changes in the resistance of the beads, due to temperature change can be accurately measured. The glass bead thermistor senses absolute temperature and generates a millivolt level voltage output and has a response time of 2-3 seconds. The millivolt signal is amplified to produce a  $\pm 5$  VDC signal that is fed into the A/D system. This absolute temperature is referred to as  $T_{\text{bar}}$ , and when corrected for a compressibility effect, is called  $T_{\text{slow}}$ . (French *et al.*, 2001)

The FUST temperature by itself only indicates temperature difference from the reference temperature,  $T_{\text{bar}}$ . The FUST temperature is corrected by post processing for compressibility effects. The actual (high frequency) temperature is determined by adding the temperature departure measured by the FUST to the temperature measured by the slow thermistor. This measurement is called  $T_{\text{fast}}$ . This instrument was developed by NOAA/ARL.

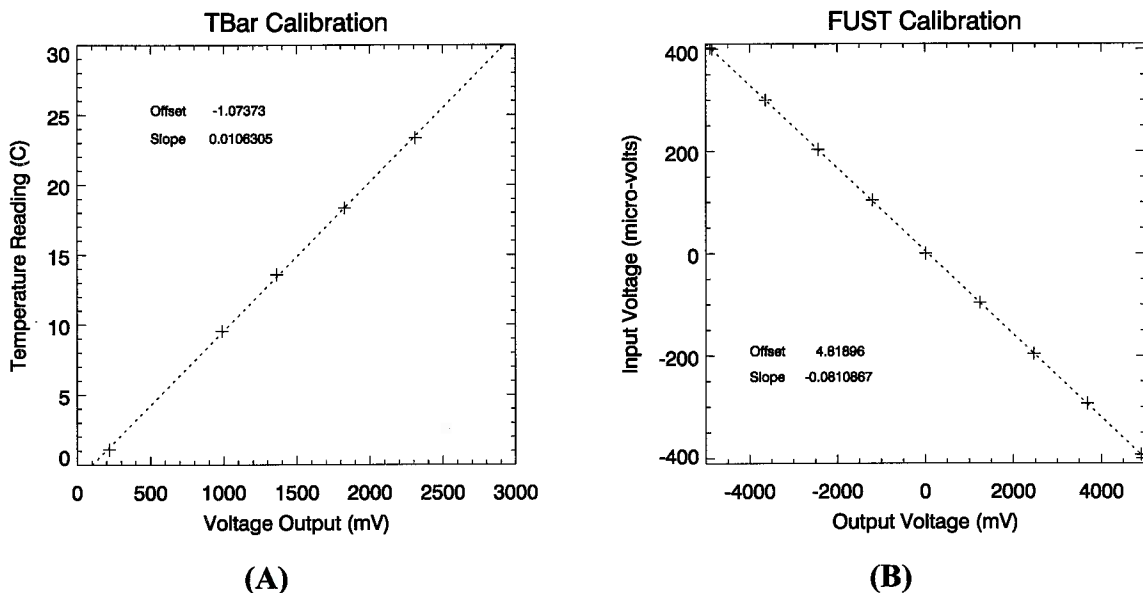
**Table 6. Temperature Sensor Specifications**

	<b>Cu-Co Thermocouple</b>	<b>Thermilinear Bead Network</b>
Response Time	50 ms	2.5 s
Sensitivity	40 $\mu$ V / °C typical	10 °C / Volt
Range	$\pm$ 400 $\mu$ V (eqv. to $\pm$ 10 °C)	$\pm$ 50 °C
Output	$\pm$ 5 VDC (after 2 step LNA)	$\pm$ 5 VDC (after amplification)

**3.6.1 Temperature Sensor Calibration**

**Tbar:** The thermilinear bead network has the advantage of a linear temperature response over a large range compared to other thermistors. For calibration, the voltage response of the temperature sensor is compared with the temperature reading of a calibrated precision mercury thermometer (accuracy =  $\pm$  0.15°C). Five different temperatures are compared over a range of 0 – 30°C by immersion in a water bath.

**FUST:** The thermocouple itself requires no calibration. The voltage response to temperature is a standard value. For both the thermilinear bead network and the thermocouple, amplification circuits are calibrated. Precision voltages to simulate the output of the sensors are placed on the input side of the amplification circuit. The output values are adjusted to produce the desired amplification factors. See Figure 18A & B for Tbar and Fust calibration plots, respectively.



**Figure 18. Temperature Calibration Curves**

### 3.7 Laser Altimeter

The range from the aircraft to the surface is measured using a Riegl model LD90-3300HR Laser Distance Meter (Figure 19). The Riegl company literature describes its operation:

“The sensors of series LD90-3 are based upon the well-proved principle of time-of-flight measurement of short laser pulses.

They can be operated with practically any target surface, i.e. "reflectorless" up to many hundred meters, and with reflecting foil or retroreflectors up to more than 1000 m.

An electrical pulse generator periodically drives a semiconductor laser diode sending out infrared light pulses, which are collimated and emitted by the transmitter lens. Via the receiver lens, part of the echo signal reflected by the target hits a photodiode, which generates an electrical receiver signal. The time interval between the transmitted and received pulses is counted by means of a quartz-stabilized clock frequency. The result is fed into the internal microcomputer which processes the measured data and prepares it for the various data outputs.” (Riegl Distancemeter LD90-3, 2006)

**Table 7. Laser Altimeter Specifications**

<b>Riegl model LD90-3300HR</b>	<b>Class 1 Laser</b>
Range (non-coop. targets)	5 to 500 m
Range (cooperative targets)	3 to 1000 m
Accuracy	$\pm 5$ cm
Sampling rate	adjustable up to 100 Hz
Output	RS232 Serial Data



**Figure 19. Riegl Laser Altimeter**

#### 3.7.1 Laser Altimeter Calibration

The instrument optics, and onboard processing are all self-contained. No calibration is required. The RS232 serial output is feed directly into the MFP data system. The only adjustment that can be made by the user is the sampling rate, which is set to 50 Hz.

## 4.0 Data Collection System

### 4.1 Analog-to Digital Conversion System

The majority of instruments provide analog signal outputs that are first filtered to prevent aliasing then digitized by one of two BAT REM modules. The digital outputs for the BAT REMs are transmitted to the MFP computer via RS422 serial interface. Measurements from additional instruments that provide serial output are transmitted to the MFP computer via RS232 serial interface. Table 1 displays a summary of signal type, sample rate, and description for each instrument.

**Table 8. Instrument Variable List**

Variable	Units	Freq (Hz)	Signal Type analog or digital	Description
Px	mb	50	A	Impact Differential Pressure (x-axis)
Py	mb	50	A	Differential Pressure (y-axis)
Pz	mb	50	A	Differential Pressure (z-axis)
Pr	mb	50	A	Reference Pressure
Ax	$m s^{-2}$	50	A	BAT Probe Acceleration (x-axis)
Ay	$m s^{-2}$	50	A	BAT Probe Acceleration (y-axis)
Az	$m s^{-2}$	50	A	BAT Probe Acceleration (z-axis)
Axb	$m s^{-2}$	50	A	Backseat Acceleration (x-axis)
Ayb	$m s^{-2}$	50	A	Backseat Acceleration (y-axis)
Azb	$m s^{-2}$	50	A	Backseat Acceleration (z-axis)
FUST	°C	50	A	Fast Response FUST Probe Thermocouple
Tbar	°C	50	A	Slow Response Thermilinear Network Temperature
Par_UP	$\mu mol m^{-2} s^{-1}$	50	A	Photosynthetic Photon Flux
Par_DN	$\mu mol m^{-2} s^{-1}$	50	A	Photosynthetic Photon Flux
Net	$W m^{-2}$	50	A	Net Radiation
F_H2O	$mmol m^{-3}$	50	A	Licor 7500 Water Vapor
F_CO2	$mmol m^{-3}$	50	A	Licor 7500 Carbon Dioxide
DewPt	°C	50	A	Chilled Mirror Dew Point Temperature
IRT_DN	°C	50	A	Infrared Surface Temperature
LRange	meters	50	D	Laser Range Altitude
NLat	deg	10	D	Novatel Latitude
Nlon	deg	10	D	Novatel Longitude
Nalt	meters	10	D	Novatel Altitude
Nu	$m s^{-1}$	10	D	Novatel Velocity (east)
Nv	$m s^{-1}$	10	D	Novatel Velocity (north)
Nw	$m s^{-1}$	10	D	Novatel Velocity (vertical)
GPSTime	sec	1	D	Novatel Time
JPitch	deg	20	D	Javad Pitch Angle
JRoll	deg	20	D	Javad Roll Angle
JHdg	deg	20	D	Javad Heading
Jflag	none	20	D	Javad Error Flag (reports quality of attitude solution)

### 4.1.1 Analog-to-Digital System Overview

The rear half of the BAT Probe consists of a constant-diameter carbon fiber tube that contains a BAT-REM for analog-to-digital conversion for instruments located in the front of the aircraft. A second BAT-REM is located inside the BAT AUX BOX, next to the MFP computer. The second BAT-REM digitizes signals from the remaining instruments on the aircraft. The REMs (designed and built by Graham Wilkins of Airborne Research Australia) filter and digitize all analog signals from the various atmospheric instruments. (French *et al.*, 2004)

Each REM module consists of two 8-channel A/D boards with 16-bit resolution. The analog input voltage ranges from  $-5$  to  $+5$  volts, translating to a digital resolution of about  $0.15$  mV. The incoming analog signals are filtered using a 5-pole Butterworth anti-aliasing filter with a low-pass cutoff of  $30$  Hz. The signals are 32 times over-sampled for further alias control before being averaged to  $50$  Hz. The A/D conversion process is driven by a  $20$  ms timing pulse provided to each REM from an external source. The digital signals are transmitted to the MFP computer for data storage via RS-422 serial lines operating at  $460.8$  Kbaud. The two REM modules allow a total 32 analog channels. (Crescenti *et al.*, 2001)

### 4.1.2 Calibration of BAT REM

NOAA ARL calibrates the BAT REM electronic circuits. A precise calibration voltage is applied to each input REM channel. The input voltage is varied over the acceptable range of input voltages ( $-5$  to  $+5$  VDC). The output is a 2-byte short integer that ranges from  $-32,768$  to  $+32,767$  (16-bit resolution.) Counts are displayed by the MFP computer and recorded for each calibrated voltage input. The resultant linear relationship is used to calculate a slope and offset for the conversion between counts to mv. Figure 20 shows the calibration curves for the BAT REM modules.

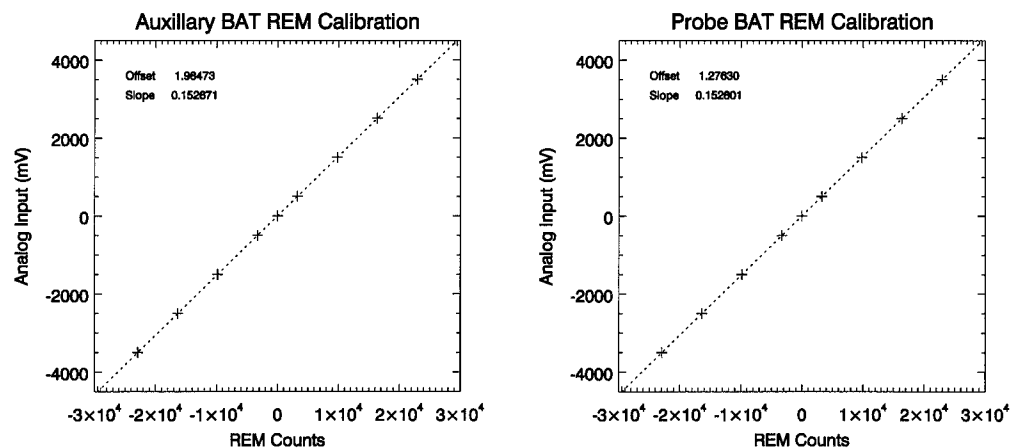
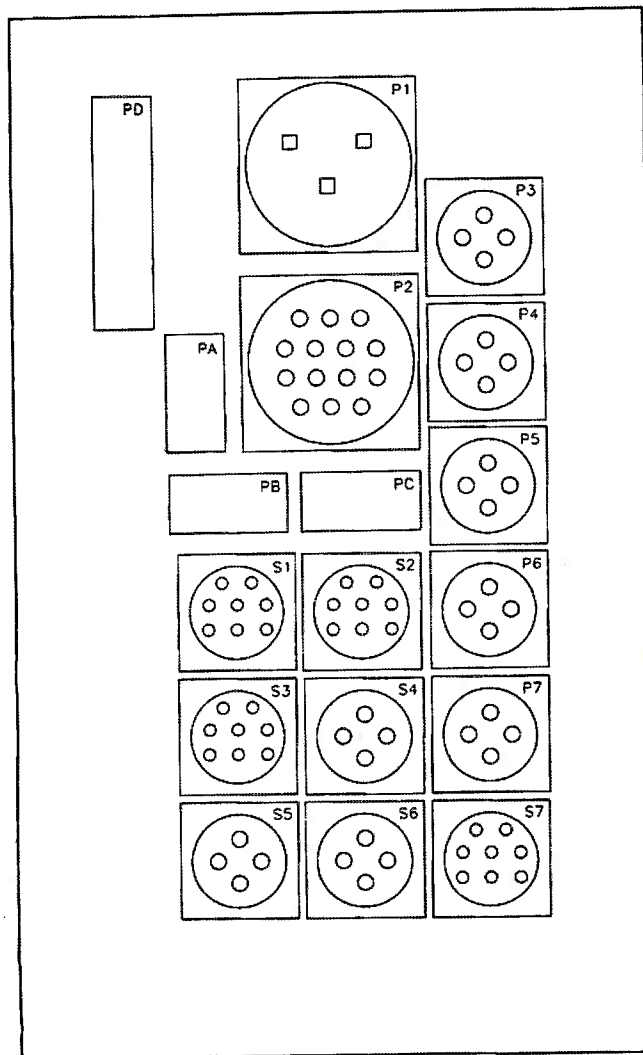


Figure 20. BAT REM Calibration Curves



Connectors:

- P1 12 VDC Input
- P2 BAT Probe
- P3 Computer Power
- P4 General Power
- P5 General Power
- P6 General Power
- P7 General Power
- S1 Switch Box Controller
- S2 Licor 7500
- S3 Spare
- S4 Surface Temp
- S5 Dew Point
- S6 Spare
- S7 Par / Net
- PA Novatel I/O
- PB BAT Probe Serial
- PC BAT Aux Serial
- PD Switch Box Data (To MFP Computer)

**Figure 21. AUX BOX Connections**

## 4.2 Auxiliary Box

The AUX BOX (Figure 21) provides instrument power, houses electronics and instrumentation, and collects signal data. The AUX BOX is also a collection point for signals from both BAT REMs. The AUX BOX input power source is taken from aircraft-generated 12 VDC.

**Power:** The AUX BOX provides a 12 VDC source and circuit breaker protection for the MFP computer power supply, both BAT REMs, and all scientific instruments.

**Signal Collection:** A BAT REM module is installed inside the AUX BOX. Circuitry in the AUX BOX is capable of providing some signal conditioning if necessary. The AUX BOX



collects digital signals from each BAT REM. The AUX BOX handles time synchronization for both BAT REM modules. A 1 PPS signal is generated by the Novatel GPS. This signal is routed through the AUX BOX to a pulse generator on each BAT REM. The pulse generator on the BAT REM generates a 50 Hz pulse, which is used to trigger each BAT REM module. The 1 PPS signal from the GPS keeps the two BAT REMs synchronized.

**Instrumentation:** The AUX BOX contains the back seat 3-axis accelerometer. This measures x, y, z accelerations, as discussed previously in section 2.3

### 4.3 Mobile Flux Platform Computer

The MFP computer is a ruggedized x86 computer with a 850 Mhz Pentium III CPU running the Linux operating system. BAT-REM serial data from the BAT probe and AUX BOX is received via a two-port Quatech DSC-200/300 PCI card. These RS-422 ports communicate at 460.8 kbaud to meet the bandwidth requirements of the BAT-REM data stream. Serial data for all other instrumentation arrives via an eight-port Quatech ESC-100 PCI card. A 72-pin connector on the rear of the PC connects to an octopus cable with 8 cables terminating in DB9 connectors. Each of these RS-232 ports can communicate at a maximum speed of 115.2 kbaud.

In flight control of the MFP Data System is made through a switch box. The switch box provides a means by which the pilot or on-board scientist may apply instrument power, computer power, turn on/off file write, and provide data markers and events.

#### 4.3.1 MFP Data Collection

The data collection software is written in C programming language and compiled using the gcc compiler on the Linux operating system with the 2.6.10 kernel. The code is open source.

##### Overview of Software Features:

- Extensible: Modules supporting sensor devices can be added or removed with minimal effort.
- Asynchronous: Devices can report at any frequency.
- Robust: Self-describing data packets.

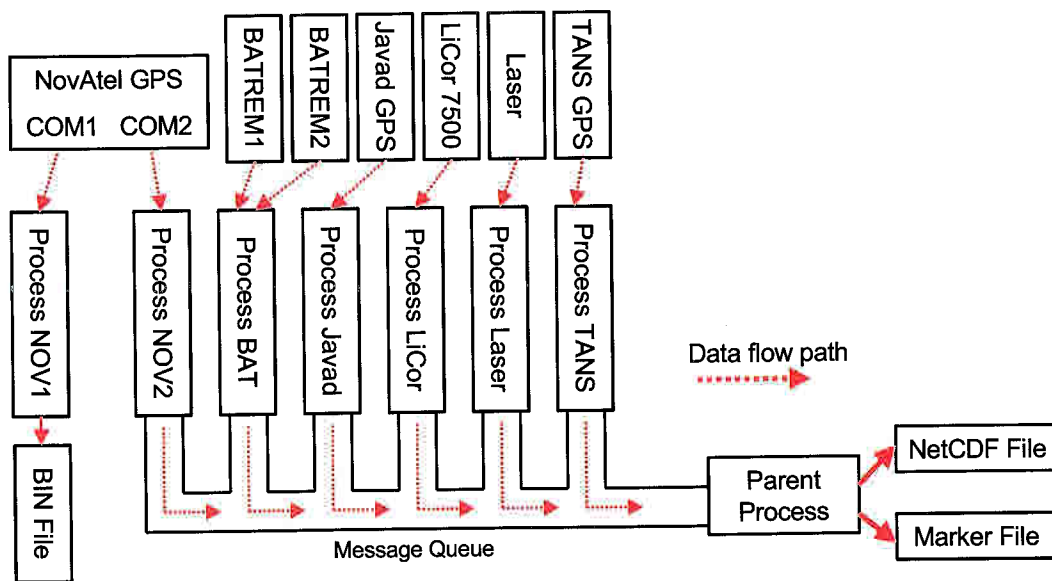


Figure 22. MFP Computer

- ASCII setup table: Easy editing of storage frequency, calibration factors, *etc.* for each device.
- Standard Linux: Real-time kernel unnecessary.
- NetCDF output: Facilitates exchange of raw data.
- Data all aligned in time.
- Open source code: Anyone with knowledge of C can design improvements.

The heart of the MFP code is the parent process. When the parent process is executed, it starts a child process for each data port or device. These child processes are treated as stand alone, independent programs by the computer. Each child process collects data from its device through the serial port and sends the data to a common message queue. This data message includes a description of the data packet and GPS time. The parent process takes the data from the message queue and writes it to the appropriate place in the netCDF data file. The CPU shares processor time with all parent and child processes. Functionally, each process is running simultaneously.

The variables *GPStime* and *scan number* are shared among all processes. GPS time is the number of seconds since 00:00:00 GPS Sunday and is generated by the Novatel GPS. Scan number is the number of seconds since the file write switch was turned on. Data from all child processes are tagged with these variables, ensuring that the data are aligned properly in the netCDF data file. This process is illustrated in Figure 23.



**Figure 23. MFP Code Diagram**



NetCDF stands for Network Common Data Format and is a binary data format for exchanging scientific data (more information available at [www.unidata.ucar.edu/software/netcdf](http://www.unidata.ucar.edu/software/netcdf)). Data files are self-describing and platform independent. Binary data are stored in an array oriented data structure. The file contains a header describing the variable dimensions, local attributes and global attributes for the file. Local variable attributes include data frequency, units, calibration coefficients, and description of the variable, while global attributes include flight information, date, and corrections that have been applied to the data.

Typically a single data file is written for each flight. For each data file there exists an associated marker file. When the marker switch or event switch is activated the time and position are recorded in the marker file. Typically the marker switch is used to record the beginning and end of a specific event, such as the beginning and end of a transect. The event switch is used to record a single event, such as flying over an exact location on the ground. The marker file also includes diagnostic and trouble shooting information, written by the data acquisition program. The following table describes each part of the marker file. See Appendix A for an example of a raw marker file and an annotated marker file.

**Table 9. Raw Marker File Labels Produced by Data System**

<b>Marker File Label</b>	<b>Description</b>
File OPENED (CLOSED) at XXX -1 (0)	GPS time when data write switch turned on (off) marker switch turned on (turned off)
EVT	event switch activated
Total scans	total number of seconds file write switch turned on
Missed Ints	missed hardware interrupts
BAT0 (1) Dropouts	percentage of lost data packets for BAT REM module $100 \times (\text{actual data packets} / \text{expected data packets})$
POS Dropouts	same for Novatel Position
VEL Dropouts	same for Novatel Velocity
JAV Dropouts	same for Javad
LAS Dropouts	same for Laser Range
GPSTime Resets	Reset system time to GPS time (reset occurs whenever system time and GPS time are not aligned)
CRCTime Errors	Cyclic Redundancy Check (Novatel GPS time checksum error indicating bad data package)
CRCTotal Errors	Cyclic Redundancy Check (Novatel checksum for POS, VEL, and time)

The Novatel GPS is programmed to output a binary data stream of raw pseudo-range information for each satellite tracked. This information is required for post-processing GPS differential corrections. The data passes through the MFP computer and is stored on the hard drive without alteration. In order to provide differential corrections, a Novatel GPS ground station collects identical data to those collected on-board the aircraft. Both Novatel binary files are post processed to provide differential corrections to the position and velocities.

## 5.0 Data Post Flight Processing

The purpose of data processing is to process the raw instrument measurements into useful atmospheric state variables. Table 10 lists the variables and their units description and dependencies (the measurements that each processed state variable is derived from). The following functions are accomplished in data processing:

- Application of corrections to raw data file, such as changing an incorrect calibration coefficient;
- Application of error removal tools to raw data file, such as removing spikes from data;
- Application of temperature and pressure corrections to instrument measurements;
- Merger of data from high and low frequency instrumentation to one variable (e.g. blending high frequency velocity derived from accelerometers with low frequency velocity from GPS);
- Transform to earth coordinate and reference frame; and
- Derivation of useful scientific variables (such as winds) from instrument measurements.

Software tools for processing instrument data have evolved over time. Processing software has been written in C, MATLAB, and IDL (Interactive Data Language) programming environments. All these tools use similar algorithms to process instrument data. The following discussion is specific to set programming tools written in IDL by NOAA/ARL. Table 11 is a listing of the various filenames given to data files. Figure 24 is an overview of the process.

Features of IDL processing procedures:

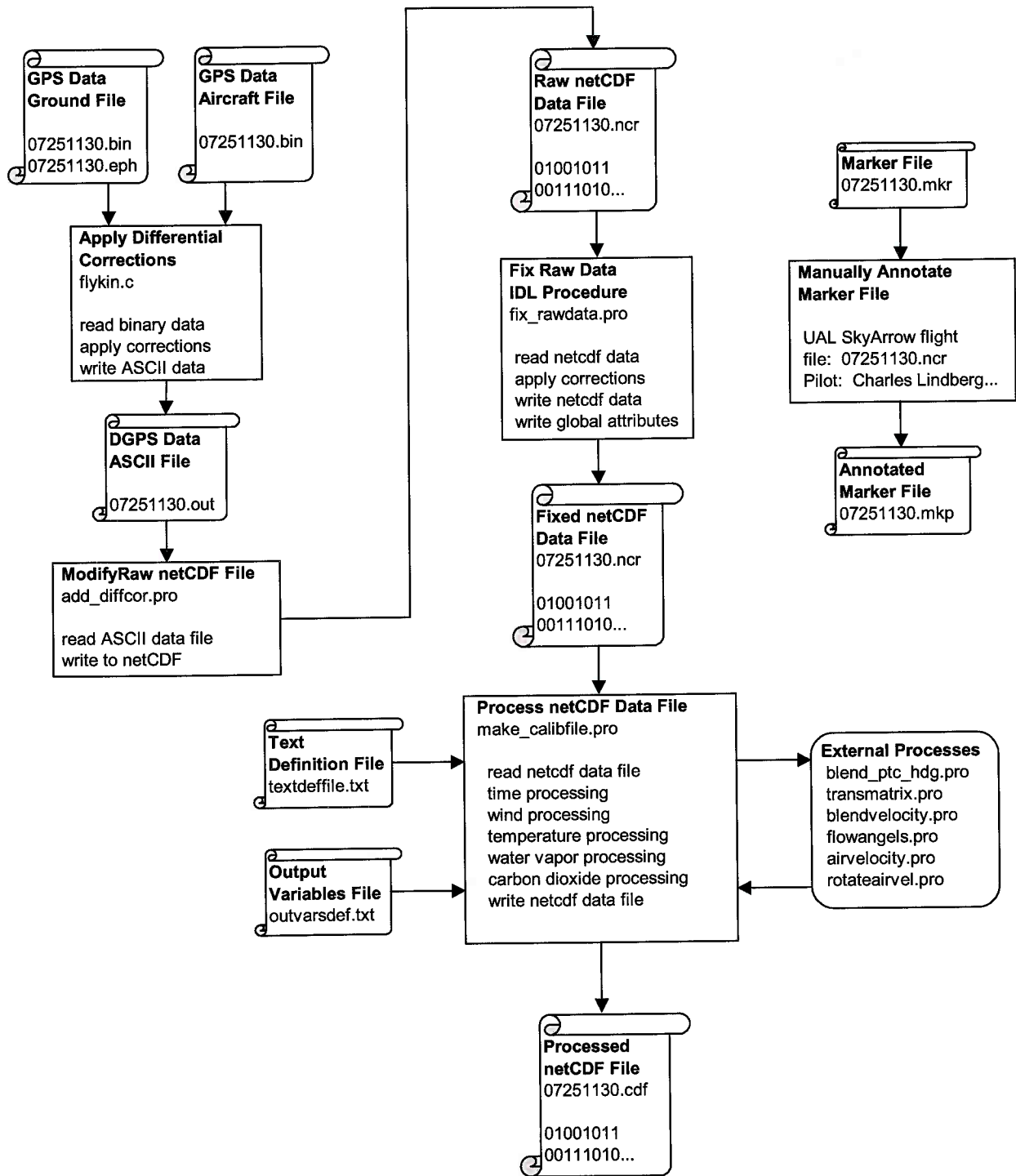
- Airborne platform independent – the same processing code can be used for any airborne platform that generates variables in netCDF format. The user-defined text definition file sets the attributes that are specific to the aircraft and data set.
- Modular – each processing module is an independent function or procedure. The user can determine which modules are appropriate, as well as add modules for new instruments.
- NetCDF standard – the processing code reads and writes standard netCDF files which are widely used for scientific data.

**Table 11. Data Processing Files**

<b>Filename</b>	<b>Description</b>
<i>mmddhhmm.ncr</i>	raw netCDF written by MFP computer during data collection
<i>mmddhhmm.mkr</i>	marker file written by MFP computer during data collection
<i>mmddhhmm.bin</i>	binary data collected by GPS (one for aircraft & one for ground station)
<i>mmddhhmm.out</i>	differentially corrected GPS data
<i>mmddhhmm.txt</i>	text definition file to provide user input to processing program
<i>mmddhhmm.skyarrow.cdf</i>	processed netCDF file written by processing program
<i>mmddhhmm.mkp</i>	marker file that has been annotated by user
<i>outvars.txt</i>	contains output variables and attributes used by processing program to write processed netCDF file
<i>(mmddhhmm)</i>	month-day-hour-minute filename generated by MFP software

**Table 10. Processed Variable List**

<b>Variable</b>	<b>Units</b>	<b>Description</b>	<b>Dependencies</b> (state variable measurement is derived from)
GPStime	sec	seconds from GPS midnight	GPS clock
Daysec	sec	seconds from beginning of day	GPS clock
U	m s <sup>-1</sup>	east wind component	Px Py Pz Pr Tbar DewPt Nu Nv Nw Ax Ay Az Axb Ayb Azb JPitch JRoll JHdg
V	m s <sup>-1</sup>	north wind component	Px Py Pz Pr Tbar DewPt Nu Nv Nw Ax Ay Az Axb Ayb Azb JPitch JRoll JHdg
W	m s <sup>-1</sup>	vertical wind component	Px Py Pz Pr Tbar DewPt Nu Nv Nw Ax Ay Az Axb Ayb Azb JPitch JRoll JHdg
TAS	m s <sup>-1</sup>	true air speed	Px Py Pz Pr Tbar DewPt
PS	mB	static pressure	Px Py Pz Pr
alpha	deg	angle of attack	Px Py Pz Pr
beta	deg	angle of sideslip	Px Py Pz Pr
Heading	deg	aircraft heading	Ay Az Axb Ayb Azb JPitch JRoll JHdg
Pitch	deg	aircraft pitch	Ay Az Axb Ayb Azb JPitch JRoll JHdg
Roll	deg	aircraft roll	Ay Az Axb Ayb Azb JPitch JRoll JHdg
Tslow	°C	slow response thermistor	Px Py Pz Pr Tbar
Tfast	°C	fast response temperature	Px Py Pz Pr Tbar FUST
Dewslow	°C	slow response dew point	Dewpt
Fh2o	gram m <sup>-3</sup>	fast water vapor	Licor, Dewpt
Fco2	gram m <sup>-3</sup>	fast carbon dioxide	Licor
Ug	m s <sup>-1</sup>	east ground speed component	Nu, Ax, Ay, Az
Vg	m s <sup>-1</sup>	north ground speed component	Nv, Ax, Ay, Az
Wg	m s <sup>-1</sup>	vertical ground speed component	Nw, Ax, Ay, Az
Lat	deg	latitude	Nlat (Novatel GPS)
Lon	deg	longitude	Nlon (Novatel GPS)
Alt	m	altitude	Nalt (Novatel GPS)
PAR_up	μmol m <sup>-2</sup> s <sup>-1</sup>	photosynthetic active radiation	PAR
PAR_dn	μmol m <sup>-2</sup> s <sup>-1</sup>	photosynthetic active radiation	PAR
Net	W m <sup>-2</sup>	net radiation	NET
Lrang	m	distance to ground	Riegl Laser



**Figure 24. Data Processing Flowchart**

**Scrolls Represent Binary or Text Files and Squares Represent Computer Processes**

## 5.1 Data Processing Procedure - Steps

### 1). Differential GPS Corrections

Wind calculation accuracy may be improved with higher GPS velocity accuracy. The GPS position and velocity accuracy are increased using differential GPS techniques. A GPS ground station receiver, located at a fixed point on the ground, is used to collect identical information as the aircraft GPS receiver. GPS data are written to a file with the name *mmdhmmss.bin*.

Differentially corrected GPS data are generated by University of Calgary's FLYKIN™ commercial software package using the aircraft and ground data files as input. The output is in the form of an ASCII text file, that contains latitude, longitude, altitude, and *u*, *v*, *w* velocity data. An IDL procedure replaces the GPS position and velocity data in the netCDF file with the differentially corrected data generated by FLYKIN™. The procedure also adds a global attribute to the netCDF file to indicate that differential corrections have been added.

### 2.) Corrections to Raw NetCDF File (*fix\_rawdata.pro*)

This IDL procedure is executed to modify the instrument raw data file created by the MFP computer. Currently, procedures have been created to remove data spikes, correct calibration coefficients, and time-shift data. A global netCDF file attribute will be written to the data file when data has been 'fixed'. The raw data are archived before the data are modified in case there are errors introduced by the 'fix raw data' process. Figure 25 gives an example of some global attributes written to a raw data file. The last three attributes were written during the 'fix raw data' process.

```
// global attributes:  
:title = "University of Alabama Sky Arrow Test Flight Header" ;  
:date = "12/20/2004" ;  
:fix_data_1 = "fix_gpstimescale" ;  
:fix_data_2 = "fix_fustcal" ;  
:Despike = "Despiked data..." ;
```

**Figure 25. Global Attributes of 'Fixed' Raw Data File**

### 3.) Text Definition File (*make\_calib\_textdeffile.txt*)

This text file contains input parameters to the processing procedure. These parameters include the variable names to process, names for the input and output data files, and Sky Arrow specific variables and constants. Dimensional constants and calibration constants specific to the University of Alabama Sky Arrow are put in this file and read during data processing. See Appendix B for an example of the text definition file used during the initial Florida test campaign with the University of Alabama Sky Arrow. Comments are preceded by a semicolon ( ; ) and the

input parameters are read sequentially. The first input parameter is the input filename path, the second is the output, and so on for sixteen parameters. The 5<sup>th</sup> parameter listed is the blending frequency for pitch and heading determined during the initial calibration of the aircraft system.

#### 4.) Output Variables File (*outvars.txt*)

This text file is used by the processing procedure to write the processed netCDF data file. The file includes a list of variables and their attributes, descriptions, dependencies, and other important parameters. This information can be viewed in the header of the processed netCDF file. See Appendix C for an example of an output variables text file.

#### 5.) Process NetCDF Datafile (*make\_calibfile.pro*)

This IDL procedure is at the heart of the data processing routine. It takes the 'fixed' raw netCDF file, runs various algorithms on the variables and writes the new variables to a 'processed' netCDF file. This procedure calls on a number of external procedures and functions to process the data. Control of the processing is through the input contained in the text definition file. The processing procedure also controls the frequency of the data in the output netCDF file. Currently, all data is written at 50 Hz. Data that is collected at lower frequencies are interpolated to 50Hz. The following is a list of processing algorithms.

##### Time Processing

This algorithm interpolates 1 Hz frequency GPS time into a 50 Hz time variable.

##### Wind Processing

1. Interpolate input variables for wind processing from various sources to 50 Hz.
2. Blend pitch and heading from low frequency Javad and high frequency accelerometer variables. This reads a blending frequency and the BAT probe's location on the aircraft from the text definition file. Procedure name: (blend\_ptc\_hdg); interpolate JAVAD roll to 50 Hz.
3. Computer transformation matrix using pitch, roll, and heading. (transmatrix)
4. Blend aircraft velocities from the high frequency accelerometer velocities and low frequency GPS variables. This reads a blending frequency from the text definition file. The velocities calculated are in earth coordinates. (blendvelocity)
5. Calculate the flow angles, dynamic and static pressure from the pressure measurements. This reads calibration constants specific to the aircraft:  $k\alpha$ ,  $k\beta$ , and  $errQ$ . (flowangles)
6. Calculate the air relative probe velocity in aircraft coordinates. This requires  $\alpha$ ,  $\beta$ , dynamic and static pressure, and temperature. (airvelocity)
7. Transform the air-relative probe velocity from aircraft coordinates to earth coordinates. (rotateairvel). Once this information has been determined, the wind data along the aircraft track can be calculated using the equation from section 2.0 *Wind Measurement System*.

### **Temperature Processing**

Tslow is calculated from application of adiabatic heating corrections to the Tbar variable (thermilinear bead network). Tslow is the slow response temperature.

Tfast is calculated from the FUST variable (Cu-Co thermocouple). The FUST temperature is the departure of the thermocouple from the Tbar temperature measurement. Combining the FUST departure (corrected for adiabatic heating) to the Tslow variable gives Tfast, fast response temperature.

### **Water Vapor and Carbon Dioxide Processing.**

These modules convert the Licor 7500 data from the units of  $\text{mmol/m}^3$  to  $\text{gram/m}^3$ .

### **Pass-Through Variables.**

Variables that do not require post processing are written directly to the output netCDF file. These variables include: GPS data, PAR data, net radiation data, and laser altimeter data.



## 5.2 Aircraft Calibration Constants

The BAT Probe's raw measurements are used to calculate air-relative probe velocity, earth-relative probe velocity, and, subsequently winds. The equations used to derive winds from pressure measurements include sensitivity coefficients,  $K_\alpha$  and  $K_\beta$ . Both  $K_\alpha$  and  $K_\beta$  are initially set to their theoretical value of  $2/9$  (.222). Calibration maneuvers are conducted to adjust these coefficients in consideration of the actual aircraft installation and aerodynamics. For the Sky Arrow both  $K_\alpha$  and  $K_\beta$  were determined to be 0.19

Airspeed is a function of dynamic pressure ( $Q$ ).  $Q$  is derived from  $P_x$ . The multiplier  $ErrQ$  is introduced as a sensitivity coefficient to remove errors in the  $P_x$  measurement. The greatest contributions to error are the small holes in the side of the center port used for removing water introduced by rain. These holes reduce  $P_x$  below the actual dynamic pressure. Theoretically  $ErrQ$  is 1.0. For the Sky Arrow,  $ErrQ$  was determined to be 1.10.

During the Javad static calibration, the reference frame for pitch, roll, and heading are determined. Calibration maneuvers were used to determine any misalignments between the Javad system and the BAT Probe reference frame. These errors are called error pitch ( $\epsilon_P$ ), error roll ( $\epsilon_R$ ), and error heading ( $\epsilon_H$ ).

The measurement of vertical wind must take upwash into consideration. Upwash is the vertical component of the air-relative velocity vector due to the aircraft generating lift. The angle of attack ( $\alpha$ ) when no lift is being generated is referred to as angle of zero lift ( $\alpha_0$ ). Upwash and  $\alpha_0$  are interrelated. The upwash sensitivity factor ( $K_u$ ) is determined to reduce the effect of upwash in the calculation of  $W$  (vertical wind; Crawford *et al.*, 1996).

The following calibration maneuvers are conducted in flight at survey speed and a safe altitude. The maneuvers are conducted in calm atmospheric conditions when turbulence is minimal, usually in the morning. They are derived with some modification from Bögel and Baumann, 1991.

### 5.2.1 Pitch Up / Down Maneuver

The goal of the pitch maneuver is for the pilot to pitch the aircraft through a small range of angles of attack - while maintaining constant airspeed and altitude. A pitch up/down cycle needs to be done at a high enough frequency that the airspeed and altitude are minimally affected.

The purpose of the maneuver is to vary the angle of attack systematically while there is no vertical wind present in the atmosphere. This is analogous to placing the aircraft in a large wind tunnel and adjusting the pitch angle up and down.

The sensitivity coefficient for attack angle is  $K_\alpha$ . The measurement of  $\alpha$  (angle of attack) is a function of pressure measurement terms and  $K_\alpha$ . In post-processing, vertical wind ( $W$ ) and  $\alpha$



are plotted for the pitch up/down calibration maneuver. The  $K_\alpha$  term is adjusted to minimize the variance in  $W$  with changing  $\alpha$  and to minimize any correlation between  $W$  and  $\alpha$ .

### 5.2.2 Yaw Side-to-Side Maneuver

The goal of the yaw maneuver is for the pilot to yaw the aircraft through a small range of angles, while maintaining constant airspeed and altitude. Similar in principal to the pitch maneuver, the purpose of this maneuver is to vary the angle of side-slip while the actual horizontal wind speed and direction are assumed to be constant.

The sensitivity coefficient for yaw is  $K_\beta$ . The measurement of  $\beta$  (yaw angle) is a function of pressure measurement terms and  $K_\beta$ . In post-processing,  $K_\beta$  is adjusted to minimize the variance in horizontal wind vector with changing.

### 5.2.3 Wind Box

The wind box maneuver assumes that horizontal wind speed and direction in the maneuvering area are constant. Prior to the maneuver, the horizontal wind is estimated. The aircraft then flies parallel and perpendicular to the prevailing wind in a box pattern. Altitude and airspeed are held constant. The heading error ( $\epsilon_H$ ) is most sensitive to wind for the crosswind runs. One can force the difference in magnitude of the computed winds for the crosswind runs to zero through an appropriate choice of  $\epsilon_H$ .

In a similar manner dynamic pressure error (ErrQ) is determined by minimizing the difference in wind magnitude for runs parallel to the wind.

### 5.2.4 Accelerate / Decelerate Maneuver

The goal for the accelerate / decelerate maneuver is to determine lift characteristics of the aircraft, and effect of upwash on the vertical wind measurement. The aircraft is flown in a straight line at constant altitude. Gradually the airspeed is reduced to a comfortable margin above stall speed. Then airspeed is increased to a maximum. The duration for the total deceleration and acceleration is about 7-10 minutes. During both maneuvers, altitude is kept constant. Using the lift equation and assumptions about aircraft weight and fuel burn, the coefficient of lift ( $C_l$ ) for the aircraft can be determined as a function of angle of attack  $\alpha$ . The angle of zero lift ( $\alpha_0$ ) can be determined from the relationship of angle of attack  $\alpha$  and  $C_l$ .

The sensitivity coefficient for upwash is  $K_u$ . The calculation of upwash is a function of airspeed,  $\alpha$ ,  $\alpha_0$ , and  $K_u$ . In post-processing  $K_u$  is adjusted to reduce the effect of upwash on the measured vertical wind ( $W$ ).

## **Acknowledgments**

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### Appendix A1: Raw marker file marker file example.

```
File OPENED at 158761
XXX -1 00530 20:14:51 29 44.0 -82 04.2
EVT 00746 20:18:27 29 45.4 -82 09.8
EVT 01256 20:26:57 29 48.8 -82 22.9
EVT 01306 20:27:47 29 48.7 -82 22.8
    0 01814 20:36:15 29 45.4 -82 09.8
XXX -1 02034 20:39:55 29 44.0 -82 04.2
EVT 02132 20:41:33 29 44.0 -82 04.2
EVT 02348 20:45:09 29 45.4 -82 09.8
EVT 02863 20:53:44 29 48.8 -82 23.0
EVT 02907 20:54:28 29 48.8 -82 23.0
EVT 03431 21:03:12 29 45.4 -82 09.8
    0 03652 21:06:53 29 44.0 -82 04.2
File CLOSED at 162946
Total scans      : 04186
Missed Ints     : 00000
BAT0 Dropouts   : -00.000% (209301 of 209300)
BAT1 Dropouts   : -00.000% (209301 of 209300)
POS Dropouts    : 000.005% (41858 of 41860)
VEL Dropouts    : 000.002% (41859 of 41860)
JAV Dropouts    : 000.786% (83062 of 83720)
LAS Dropouts    : 003.376% (202234 of 209300)
GPSTime Resets  : 0 (of 4186)
CRCTime Errors  : 0 (of 4186)
CRCTotal Errors: 1 (of 88526)
```

**Raw Marker File: 12201705.mkr**

## Appendix A2: Annotated marker file example.

```
UAL SkyArrow Florida04 flight
file: 12201705.ncr

takeoff: Keystone Heights
Pilot: Stan Allen
BackSeat: Empty
GrndCrew: Brooks, Kirby

notes:
  1) GPS time scale error
  2) fust cal coef error
  3) no differential corrections available
  4) Four transects
  5) weather observations: Temperature 48.0 F; Dew
Point: 7.0 F; Ps=1023.9 hPa; Winds E @ 3.5 Mph; clear
skies
  6) u, v, w spike at 2880 due to javad dropouts
  7) tfast & net(not sure if this is due to mic keying)
spikes noted during climb and descent due to mike keying
  8) par_up, par_dn, net spikes at 1280, 2080, 2880 due
to javad?

File OPENED at 158761
FLX -1 00530 20:14:51 29 44.0 -82 04.2 beginning of flux run
EVT 00746 20:18:27 29 45.4 -82 09.8
EVT 01256 20:26:57 29 48.8 -82 22.9
EVT 01306 20:27:47 29 48.7 -82 22.8
  0 01814 20:36:15 29 45.4 -82 09.8 end of flux run
FLX -1 02034 20:39:55 29 44.0 -82 04.2 beginning of flux run
EVT 02132 20:41:33 29 44.0 -82 04.2
EVT 02348 20:45:09 29 45.4 -82 09.8
EVT 02863 20:53:44 29 48.8 -82 23.0
EVT 02907 20:54:28 29 48.8 -82 23.0
EVT 03431 21:03:12 29 45.4 -82 09.8
  0 03652 21:06:53 29 44.0 -82 04.2 end of flux run
File CLOSED at 162946
Total scans : 04186
Missed Ints : 00000
BAT0 Dropouts : -00.000% (209301 of 209300)
BAT1 Dropouts : -00.000% (209301 of 209300)
POS Dropouts : 000.005% (41858 of 41860)
VEL Dropouts : 000.002% (41859 of 41860)
JAV Dropouts : 000.786% (83062 of 83720)
LAS Dropouts : 003.376% (202234 of 209300)
GPSTime Resets : 0 (of 4186)
CRCTime Errors : 0 (of 4186)
CRCTotal Errors: 1 (of 88526)
```

Annotated Marker File: 12201705.mkr

## Appendix B: Text definition file example: 12201705.txt

```
;12201705.txt
;*****
; Developed by Jeff French, NOAA/ARL
;   used in conjunction with 'make_calibfile.pro'
;   this text file contains names of variables,
;   filenames, cal constants etc...
;   needs to be changed for each file to be processed
;
;*****
;(1)  input file (raw netCDF filename, and path)
/home/phil/skyarrow_data/florida04/dec20/12201705.ncr

;(2)  output processed file (.ncp name, and path?)
; naming convention is MDDHMMSS.platform.format
/home/phil/skyarrow_data/florida04/dec20/12201705.ua_skyarrow.cdf

;(3)  description of the file
;   generally something like 'UA SkyArrow data from XXX Experiment'
U of A Sky Arrow data from Florida04, Experiment date: 20 Dec 2004

;(4)  outfile frequency
50

;(5)  blending frequency for pitch and heading
;   typically we have used lowblend ~0.75 and highblend ~1.333
;   this based on calibration checks by J French & P Hall from
;   early flights in September '04...should check these values periodically
0.75, 1.333

;(6)  distance from probe to backseat accelerometers (in meters)
;   J French: 3.4 m was a value provided by SDSU group when I worked with them
3.4

;(7)  blending frequency for velocities
;   typically we have used lowblend ~0.25 and highblend ~0.4444
;   this based on calibration checks by J French & P Hall from
;   early flights in September '04...should check these values periodically
0.25, 0.4444

;(8)  wind calibration constants
;   kalpha, kbeta, errq
0.19, 0.19, 1.10

;(9)  offsets in attitude angles
;   hdgoff, ptcoff, rolloff
2.0, 0.0, 0.0

;(10) alpha value for zero lift (alpha0) and upwash factor (kupwash)
-3.5, 0.1

;(11) FUST/Tslow temperature recovery factor
0.79

;(12) name of time variable in BAT file, frequency of variable
;   this is 1 hz variable, in seconds of the week (GPS)
GPSTime, 1
```

## Appendix B (con't)

```
;(13) variable names for winds processing
; first line after 'BEGIN' is either 'on' or 'off' to indicate if wind is to be processed
; these are the names of the variables as they appear in the raw data files
; in this order: px, py, pz, pr, T, Td, au, av, aw, ax, ay, az, axb, ayb, azb, ptc, roll,
hdg
; second column is the frequency
BEGIN
on
Px, 50
Py, 50
Pz, 50
Ps, 50
Tbar, 50
DewPt, 50
Nu, 10
Nv, 10
Nw, 10
Ax, 50
Ay, 50
Az, 50
Axb, 50
Ayb, 50
Azb, 50
JPitch, 20
JRoll, 20
JHdg, 20
END
```

```
;(14) variable names for temperature processing
; first line after 'BEGIN' is either 'on' or 'off' to indicate if temperature is to be
processed
; (for temperature processing, wind processing must be on...)
; in this order: slow (reference) temperature, fast (departure) temperature
; we assume both measurements are in degree C
; second column is the frequency
BEGIN
on
Tbar, 50
FUST, 50
END
```

```
;(15) variable names for water vapor processing
; first line after 'BEGIN' is either 'on' or 'off' to indicate if water vapor is to be
processed
; (for water vapor processing, wind and temperature processing must be on...)
; in this order: slow water vapor, fast water vapor
; we assume slow measurement is in degreeC (dewpt) and fast is in mmol/m3 (Licor7500 base
units)
; second column is the frequency
BEGIN
on
DewPt, 50
F_H2O, 50
END
```

```
;(16) variable names for carbon dioxide processing
; first line after 'BEGIN' is either 'on' or 'off' to indicate if carbon dioxide is to be
processed
; (for carbon dioxide processing, wind and temperature processing must be on...)
; in this order: carbon dioxide
; we assume measurement is in mmol/m3 (Licor7500 base units)
; second column is the frequency
BEGIN
on
F_CO2, 50
END
```



## Appendix C: Output variables file example: outvarsdef\_skyarrow\_florida04.txt

```

;outvars.txt
;*****
; Developed by Jeff French, NOAA/ARL
; used in conjunction with 'make_calibfile.pro'
; this text file contains names of output variables,
; associated attributes and their source
;
;
; RELEASE: 05 January 2005
;
; BUGS/GOTCHAS:
; no comments allowed between BEGIN/END combinations
;*****
; text file read by function 'READ_OUTVARSDEF' in procedure make_calibfile
; blank lines and lines beginning with semicolon ignored
;*****
;
; FILE STRUCTURE is as follows
;
; following lines contain output variable info, each bracketed by BEGIN/END
; lines are arranged in following order for each variable:
; name (as it will appear in output file, case sensitive)
; longname (attribute in outputfile)
; units (attribute--units that the output is in)
; ignored for all source other than pass
; depend (attribute--dependencies on other variables/instruments)
; ignored for all source other than pass
; comments (attribute--any additional comments user may want to add)
; source (attribute--either: time, wind, temper, h2o, co2, pass)
; time: output comes from time processing code
; wind: output comes from wind processing code
; temper: output comes from wind processing code
; h2o: output comes from water vapor processing code
; co2: output comes from carbon dioxide processing code
; pass: output that is passed through directly from the raw file
; and interpolated to higher frequency, if necessary
; rawname (takes on different meaning depending on value of source:
; 'pass' --> name of variable in raw file
; 'time' --> 'GTIME' for gpstime
; 'BTIME' for secs since beginning of day
; all others ignored
; 'wind' --> 'U', 'V', 'W' : u, v, w components of the wind
; 'TAS', 'PS' : true air speed, static pressure
; 'ALPHA', 'BETA' : angle of attack, angle of sideslip
; 'HEADING', 'PITCH', 'ROLL' : blended ptc, rol, hdg
; all others ignored
; 'temper' --> 'TSLOW' : slow temperature, ambient
; 'TFAST' : fast temperature, ambient
; all others ignored
; 'h2o' --> 'DEWSLOW', 'DEWFAST' : slow/fast dewpoints in degC
; 'FH2O' : fast water vapor
; all others ignored
; 'co2' --> 'FCO2' : fast carbon dioxide
; all others ignored
;
; NOTE: rawname is case sensitive!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
;
; Example:
; BEGIN
; U
; East wind component
; m/s --> this is ignored since U is a non 'pass' source
; pressure --> this is ignored since U is a non 'pass' source

```

## Appendix C (con't)

```

;      computed from BAT hemisphere
;      wind
;      U
;      END
;
;*****
;*****
; start with time vars first (2)
BEGIN
  GPStime
  gps time from novatel
  ignored
  ignored
  seconds from start of week
  time
  GTIME
END

BEGIN
  Daysec
  day seconds determined from novatel
  ignored
  ignored
  seconds from beginning of day
  time
  BTIME
END

;*****
; now move onto wind vars (10)
BEGIN
  U
  east wind component
  ignored
  ignored
  windspeed from west to east
  wind
  U
END

BEGIN
  V
  north wind component
  ignored
  ignored
  windspeed from south to north
  wind
  V
END

BEGIN
  W
  vertical wind component
  ignored
  ignored
  vertical wind speed, up is positive
  wind
  W
END

BEGIN
  TAS
  true air speed
  ignored
  ignored
  probe true air speed
  wind
  TAS
END

BEGIN
  Ps
  static pressure
  ignored
  ignored
  computed static pressure from probe
  wind
  PS
END

BEGIN
  alpha
  angle of attack
  ignored
  ignored
  probe angle of attack
  wind
  ALPHA
END

BEGIN
  beta
  angle of sideslip
  ignored
  ignored
  probe angle of sideslip
  wind
  BETA
END

BEGIN
  Heading
  aircraft heading
  ignored
  ignored
  blended with accelerometers
  wind
  HEADING
END

BEGIN
  Pitch
  aircraft pitch
  ignored
  ignored
  blended with accelerometers
  wind
  PITCH
END

BEGIN
  Roll
  aircraft roll
  ignored
  ignored
  nominal output 20 Hz, interpolated
  to 50 Hz
  wind
  ROLL
END

;*****
; now move onto temper vars (2)
BEGIN
  Tslow
  slow temperature
  ignored
  ignored
  slow response thermistor (FUST
  base)

```

## Appendix C (con't)

```

    temper
    TSLOW
END

BEGIN
    Tfast
    fast temperature
    ignored
    ignored
    fast response temperature (FUST)
    temper
    TFAST
END

;*****
; now move onto water vapor vars (3)
BEGIN
    Dewslow
    slow dew point
    ignored
    ignored
    slow response dew point, chilled
mirror
    h2o
    DEWSLOW
END

BEGIN
    Dewfast
    fast dew point
    ignored
    ignored
    fast response dew point, Licor 7500
    h2o
    DEWFAST
END

BEGIN
    Fh2o
    fast water vapor
    ignored
    ignored
    same device as fast dewpoint, Licor
7500
    h2o
    FH2O
END

;*****
; now move onto carbon dioxide vars
(1)
BEGIN
    fco2
    fast carbon dioxide
    ignored
    ignored
    fast carbon device, Licor 7500
    co2
    FCO2
END

;*****
; now move onto pass through vars
(10)
BEGIN
    Ug
    east ground speed component
    m/s
    novatel GPS
    nominal output 10 Hz, interpolated
to 50 Hz

    pass
    Nu
END

BEGIN
    Vg
    north ground speed component
    m/s
    novatel GPS
    nominal output 10 Hz, interpolated
to 50 Hz
    pass
    Nv
END

BEGIN
    Wg
    vertical ground speed component
    m/s
    novatel GPS
    nominal output 10 Hz, interpolated
to 50 Hz
    pass
    Nw
END

BEGIN
    Lat
    latitude
    deg
    novatel GPS
    nominal output 10 Hz, interpolated
to 50 Hz
    pass
    NLat
END

BEGIN
    Lon
    longitude
    deg
    novatel GPS
    nominal output 10 Hz, interpolated
to 50 Hz
    pass
    NLon
END

BEGIN
    Alt
    altitude
    m
    novatel GPS
    nominal output 10 Hz, interpolated
to 50 Hz
    pass
    NAlt
END

BEGIN
    PAR_up
    Licor photosynthetic active
radiation (uplooking--downwelling)
    uM/m2/s
    Licor PAR
    up looking wrt aircraft
    pass
    PAR_UP
END

BEGIN

```

## Appendix C (con't)

PAR\_dn  
Licor photosynthetic active  
radiation (downlooking--upwelling)  
uM/m2/s  
Licor PAR  
down looking wrt aircraft  
pass  
PAR\_DN  
END

BEGIN  
Net  
Kipp & Zonen NR Lite radiometer  
W/m2  
K&Z NET device

up/dn wrt aircraft  
pass  
Net  
END  
BEGIN  
Lrange  
laser distance to ground  
m  
Riegl laser device  
not corrected for aircraft attitude  
pass  
LRange  
END