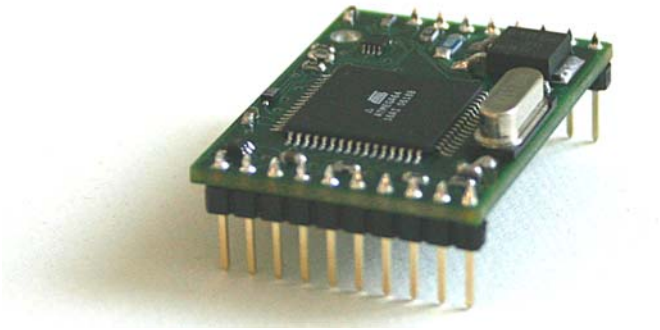
L-MOD-2

8/15/2008

Digital Wideband Lambda (Air/Fuel Ratio) Controller Module
PRELIMINARY DATA SHEET

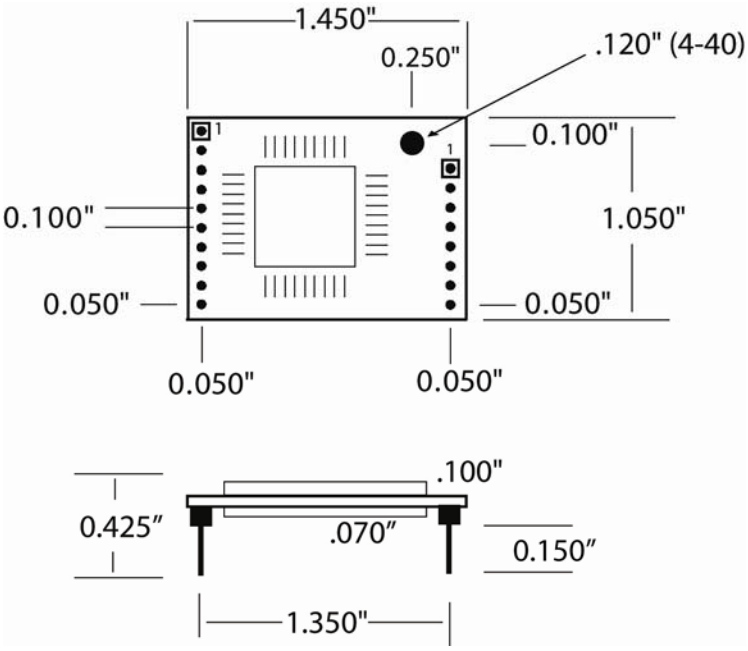


Overview

The Innovate L-Mod is a digital lambda measurement controller packaged as a small form-factor modular subsystem. The L-Mod utilizes Innovate's patented measurement principle to control a wideband oxygen sensor, and precisely measures the oxygen content of a gas, most commonly applied to measuring the air/fuel ratio of the exhaust gas of an internal-combustion engine. Key features include:

- <120ms response time (from free air to 0.8 λ)
- <20ms response time (from 20 AFR to 12 AFR)
- Accurate to +/- 0.007λ
- SPI Interface
- Self-calibrating circuit compensates for changes in temperature, altitude, and sensor condition
- Does not use "factory calibration" resistor therefore equally accurate with multiple sensors

Mechanical Specifications



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Electrical Specifications

1. Hardware Interface

The L-Mod module has two interface connectors: JP1 and JP2. JP1 contains the host device interface signals. JP2 contains mainly the sensor interface signals.

The standard LMOD2 is designed for Bosch LSU 4.2 five-wire wideband sensors. Other wideband sensors can be accommodated by special request.

1.1 Sensor Interface JP2

The JP2 interface connector is an 8-pin 0.1" single row header located on the right side of the module.

The sensor interface requires no external components.

Pinout of J1:

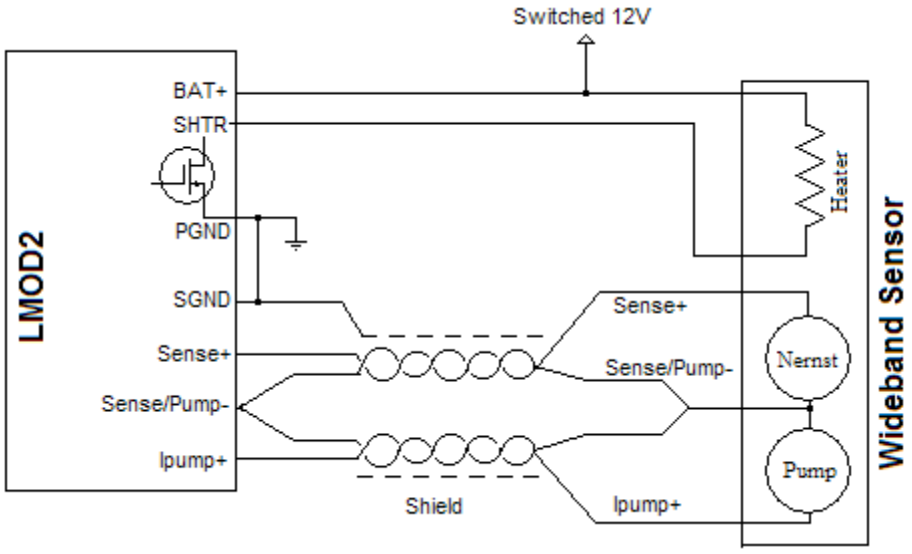
Pin	Name	Description
1	Sense+	Nernst Cell Output from Sensor
2	Ipump+	Pump cell drive to Sensor
3	Sense/Pump-	Common Nernst/Pump line
4	PGND	Power Ground for Sensor heater[1]
5	PGND	Power Ground for Sensor heater[1]
6	BAT+	Battery+ reference [2]
7	SHTR	Sensor Heater- [3]
8	SHTR	Sensor Heater- [3]

Note 1: Power Ground shall be tied to Signal Ground on JP1-10 on the host PCB. Heater Ground carries up to 2.5A continuously during sensor warmup.

Note 2: BAT+ is a battery voltage reference signal. It does not carry sensor heater power. Instead one leg of the sensors heater MUST be connected to switched battery power.

Note3: Sensor Heater is ground side PWM controlled. JP2-7 and JP2-8 carry Sensor heater current of up to 2.5 A continuously.

Note4: For sensor cables longer than 2 feet, with a maximum length of 10 feet, the sensor cable shall be shielded with Sense+, Sense/Pump- and Ipump+ inside the shielding and the Sensor heater wires outside the shielding. The shielding shall be connected to Signal Ground (JP1-9) on one side only. Sense/Pump- shall be carried by two wires of which each is one leg of two twisted pairs inside shield. The first twisted pair consist of Sense/Pump- and Sense+. The second twisted pair consists of Ipump+ and Sense/Pump-. The Sense/Pump signal wires shall not be smaller than 28 gauge. Recommended size for heater wires is 14 gauge.



1.2 Host Interface JP1

The JP1 host interface connector is a 10-pin 0.1" single row header located on the left side of the module. Inputs (IN) are Data signals driven by the Host. Outputs (OUT) are driven by the LMOD2.

Pin	Name	Direction	Description
1	/CS	IN	Chip Select/Sync, Input, active low
2	SCLK	IN	Serial Clock
3	DIN	IN	Serial Data Input
4	DOUT	OUT	Serial Data Output
5	/RESET	IN	Reset input of LMOD2, active low, pulled internally high with 10kOhm
6	/RDY	OUT	Data Ready Output
7	/REQ	IN	Request Data Transfer Input
8	Spare	undef	For future use
9	VCC	IN	5V +- 0.25V, 100mA max
10	SGND	IN	Signal Ground

All digital signals are TTL level signals.

2. I/O Operations

The LMOD2 interface uses the common SPI bus interface. All data transfers are in big endian mode where the most significant bit of a Byte is transferred first. On multi-Byte transfers the most significant Byte is transferred first.
All status reads from the LMOD2 are 2 Bytes in length. All commands to the LMOD are 1 Byte in length.

All operations are to be performed Byte-by-Byte. This means that no more than one Byte shall be transferred with de-asserting the /CS line and then re-asserting /CS when the LMOD2 is ready for the next byte.

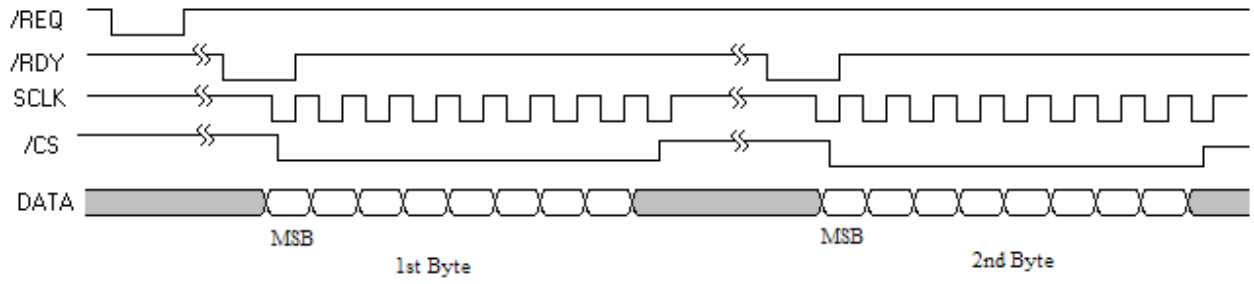
The host shall ALWAYS read 2 Bytes from LMOD2.

LMOD2 outputs the MSB of a data Byte a max. of 15 nsec after /CS is asserted. The host shall sample the data with the rising edge of SCLK. LMOD2 will hold the data until max 10nsec after the falling edge of SCLK.
Maximum SCLK speed is 2 MHz. Minimum SCLK low time is 250 nsec. Minimum SCLK high time is 250 nsec.

2.1 Normal status/data read mode

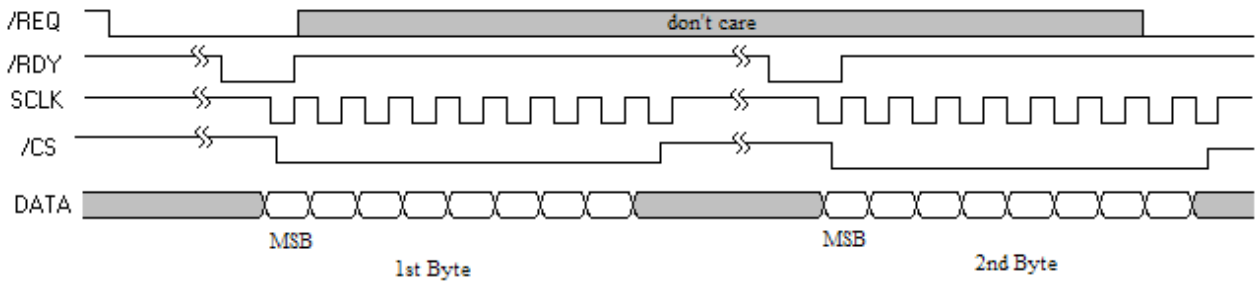
In normal operation the LMOD2 will continuously measure at the maximum speed the sensor can be sampled, based on Innovate Motorsports patented measurement principle. These measurements are accumulated internally in a summing buffer and the number of measurements since the last read is counted.
To read the lambda data the host asserts /REQ for a minimum of 1 microsecond. This causes an interrupt in the LMOD2, during which the LMOD2 calculates the average Lambda since the last data read operation.
LMOD2 then asserts the /RDY line to signal to the host that the first Byte of the result can be read.
The host then asserts the /CS line and de-aserts the /REQ line (if not already de-asserted) and procedes to clock out the serial data from the LMOD2 with SCLK. /CS shall be de-asserted after 8 clock cycles of SCLK. LMOD2 de-asserts the /RDY line with next high phase of SCLK after the assertion of /CS.
One LMOD2 interrupt latency later (1-500 usec) LMOD2 re-asserts the /RDY line again to allow the reading of the second status/data Byte. Again the host then asserts the /CS line and procedes to clock out the serial data from the LMOD2 with SCLK. /CS shall be again de-asserted after 8 clock cycles of SCLK. LMOD2 de-asserts the /RDY line with next high phase of SCLK after the assertion of /CS.
All /REQ assertions by the host are ignored until both status bytes are read.

Normal Read Mode:



2.2 Fast data read mode

The LMOD2 can sample the sensor data at speeds up to 300 Hz or higher, depending on Lambda and the particular sensor. To read the sensor data at the LMOD2 sampling speed, the host holds the /REQ line low. The first read of the two status/data Bytes will proceed as described in Normal read mode. If /REQ is asserted at the end of the second Byte transfer, LMOD will automatically re-assert /RDY again when a new measurement is available.



2.3 Write Operation

Commands to be sent to LMOD2 are 1 Byte in length. The host transfers a command byte during the read of the SECOND byte of a data transfer. Data sent during the first byte is ignored by the LMOD2.

The host shall apply the data bits on the DIN port at least 10nsec before the rising edge of SCLK
The host shall hold the data for at least 70 nsec after the rising edge of SCLK.

3. Interface protocol

3.1 Reset Operation

After power-up or a Reset, wait at least 200 msec before the first read/write operation. /RDY line will be held high during reset operation. After power-up the LMOD2 is in normal mode.
The host can also assert the /RESET line (internally pulled up with 10 kOhm) to restart the LMOD2, or hold off LMOD2 start and sensor warmup under certain conditions. These conditions can include for example to delay sensor warmup in extreme cold where there is a chance of condensation water or ice in the exhausts system that can be blown at the sensor if the sensor warmup is started to early, e.g. right after cranking.

3.2 Modes of operation

LMOD2 can (after sensor warmup) output Lambda/O2 content, Fuel/air equivalency ratio or sensor read frequency, depending on the mode set. The normal mode is Lambda/O2 content, where the LMOD2 outputs Lambda in the range 0.512 to 8.512 when Lambda is < 8.512 at ~0.001 Lamba resolution or outputs exhaust data O2 content in 0.1 % resolution when Lambda is >= 8.512. This is the default mode after the LMOD2 powers up or after LMOD2 reset. See command details below on how to change modes.

In Fuel/air equivalency ratio mode LMOD2 outputs the data in the range of Fuel/air equivalency ratio (1/Lambda) with a resolution of 0 to 1.999 with a resolution of 1/4096 fuel air equivalency ratio.

In frequency mode the LMOD2 outputs the sensor read frequency in the range of 0..1024 Hz with a resolution of 1/8 Hz.
This mode is useful for sensor diagnostics where the sensor read speed is compared to a reference read speed at a fixed operating point (for example in free air). A 5-wire wideband sensors response speed will slow down with age or heavy metal contamination (lead for example). By comparing sensor read frequency to the same sensors read frequency when new under the same operating condition, sensor aging and usefulness can be diagnosed.

Table of Modes

Mode	Note	Number of Bits for value	Calculation
0	Lambda < 8.512	13	Lambda = (value + 512)/1024
0	Lambda >8.511	8	O_2% = value / 10
1	FAER	13	FAER = value / 4096
2	Freq	13	Freq = value / 8

3.3 Read data formats in operation

On ALL data reads the high bit of the first Byte is always set (1), the high bit of the second Byte is always reset (0). This allows easy Byte synchronisation by the host.

3.3.1 Lambda reading (Mode 0, Lambda < 8.512)

1st Byte

MSB Bit7	Bit6	Bit5	Bit4	Bit3	Bit2	Bit1	Bit0
1	**0**	**L12**	**L11**	**L10**	**L9**	**L8**	**L7**

2nd Byte

MSB Bit7	Bit6	Bit5	Bit4	Bit3	Bit2	Bit1	Bit0
0	**L6**	**L5**	**L4**	**L5**	**L2**	**L1**	**L0**

Lambda is calculated by concatenating L12..L0 into a 13 bit WORD value. Lambda is then **(value + 512) / 1024,**

If Lambda is bigger than 8.512, the data output changes to O2 % reading with a resolution of 0.1%. In this case the output is:

(Mode 0, Lambda > 8.511)

1st Byte

MSB Bit7	Bit6	Bit5	Bit4	Bit3	Bit2	Bit1	Bit0
1	**1**	**0**	**0**	**0**	**0**	**0**	**O7**

2nd Byte

MSB Bit7	Bit6	Bit5	Bit4	Bit3	Bit2	Bit1	Bit0
0	**O6**	**O5**	**O4**	**O3**	**O2**	**O1**	**O0**

The O2 % of the exhaust gas can be calculated by concatenating O7..O0 into an 8 bit unsigned value. The O2 % content then is **value/10**. During free air calibration the LMOD2 uses air as reference gas with an assumed O2% content of 20.9%.

3.3.2 Fuel/air equivalency ratio reading (Mode 1)

1st Byte

MSB Bit7	Bit6	Bit5	Bit4	Bit3	Bit2	Bit1	Bit0
1	0	F12	F11	F10	F9	F8	F7

2nd Byte

MSB Bit7	Bit6	Bit5	Bit4	Bit3	Bit2	Bit1	Bit0
0	F6	F5	F4	F3	F2	F1	F0

The fuel/air equivalency ratio is calculated by concatenating F12..F0 into a 13 bit WORD value. The ratio is then calculated with **value / 4096**.

3.3.3 Sensor Frequency reading (Mode 2)

1st Byte

MSB Bit7	Bit6	Bit5	Bit4	Bit3	Bit2	Bit1	Bit0
1	0	F12	F11	F10	F9	F8	F7

2nd Byte

MSB Bit7	Bit6	Bit5	Bit4	Bit3	Bit2	Bit1	Bit0
0	F6	F5	F4	F3	F2	F1	F0

The read frequency is calculated by concatenating F12..F0 into a 13 bit WORD value. The actual read frequency is then calculated with **value / 8**.

4. Error indications

The LMOD2 can detect various kinds of sensor error conditions. An error status is indicated by all bits of the first byte being set. The error code itself is then carried in the lower 7 bits of the second Byte.

1st Byte

MSB Bit7	Bit6	Bit5	Bit4	Bit3	Bit2	Bit1	Bit0
1	1	1	1	1	1	1	1

2nd Byte

MSB Bit7	Bit6	Bit5	Bit4	Bit3	Bit2	Bit1	Bit0
0	E6	E5	E4	E3	E2	E1	E0

The following error codes are currently defined:

Error Table

Error Code	2nd Byte value	Description
0	00h	No error, last error cleared
1	01h	Heater circuit shorted
2	02h	Heater circuit open
3	03h	Pump cell circuit shorted or too low an impedance
4	04h	Pump cell circuit open or too high an impedance
5	05h	Nernst cell circuit shorted or too low an impedance
6	06h	Nernst cell circuit open or too high an impedance
7	07h	For future use
8	08h	Sensor timed out, possible damaged sensor
9	09h	Battery voltage too low
10	0Ah	Sensor undercooled, can't maintain sensor operating temp
11	0Bh	Sensor overheated, can't maintain sensor operating temp

5. Status indications

The LMOD2 will report the sensor and operational status or status as response to a command.

5.1 Heater Warmup Status

This status is reported when the sensor is not fully up to its operational temperature. The % heating value is calculated from the nominal resistance of the heater circuit, and is just for informational purposes.

1st Byte

MSB Bit7	Bit6	Bit5	Bit4	Bit3	Bit2	Bit1	Bit0
1	1	0	0	0	0	1	H7

2nd Byte

MSB Bit7	Bit6	Bit5	Bit4	Bit3	Bit2	Bit1	Bit0
0	H6	H5	H4	H3	H2	H1	H0

Heater warmup status in % is the value of H7..H0 divided by 2.

5.2 Heater Calibration Status

1st Byte

MSB Bit7	Bit6	Bit5	Bit4	Bit3	Bit2	Bit1	Bit0
1	1	0	0	0	1	0	0

2nd Byte

MSB Bit7	Bit6	Bit5	Bit4	Bit3	Bit2	Bit1	Bit0
0	0	0	0	H3	H2	H1	H0

Heater calibration is necessary for a new sensor with the LMOD2. The LMOD2 regulates the sensor heater not by the Nernst cell impedance as conventional widebands, but by the pump cell impedance. Because wideband manufacturers do not specify the pump cell impedance, only the Nernst impedance, this calibration step is necessary when changing sensors. During heater calibration the LMOD2 will regulate the sensor temperature to the nominal operating temperature of the sensor by measuring the Nernst cell impedance and regulating to the sensor specific impedance. It then measures the pump cell impedance at that temperature and stores it internally in non-volatile memory.

The value in H3..H0 will count down from 9 to 0 during this calibration step.

Heater calibration is initiated automatically by the controller.

5.4 Free air calibration needed

1st Byte

MSB Bit7	Bit6	Bit5	Bit4	Bit3	Bit2	Bit1	Bit0
1	1	0	0	0	1	1	X

2nd Byte

MSB Bit7	Bit6	Bit5	Bit4	Bit3	Bit2	Bit1	Bit0
0	X	X	X	X	X	X	X

5.5 Free air calibration in Progress

1st Byte

MSB Bit7	Bit6	Bit5	Bit4	Bit3	Bit2	Bit1	Bit0
1	1	0	0	1	0	0	X

2nd Byte

MSB Bit7	Bit6	Bit5	Bit4	Bit3	Bit2	Bit1	Bit0
0	X	X	X	X	X	X	X

During free air calibration (with sensor in clean free air), the sensor response to air is measured and stored by the LMOD2 in non-volatile memory. This is necessary for a new sensor and also should be performed for most accurate results, for every oil change or whenever the operating altitude changes by more than 3000 feet.
Free air calibration is initiated with an air-calibration command, see Commands.

5.6 Read Mode Command Response

This status is sent as the first double Byte read after a "Read Current Mode" command is sent. The current read mode is indicated in the second Byte, bits M3..M0.

1st Byte

MSB Bit7	Bit6	Bit5	Bit4	Bit3	Bit2	Bit1	Bit0
1	1	0	0	1	0	1	X

2nd Byte

MSB Bit7	Bit6	Bit5	Bit4	Bit3	Bit2	Bit1	Bit0
0	0	0	0	M3	M2	M1	M0

6. Commands

Commands are sent to the LMOD during the second Byte of a data transfer. The next read after the command is sent will indicate a status change as response to the command

COMMANDS SHALL NOT BE TRANSFERRED DURING FAST READ OPERATIONS.

Command	Hex Code sent	Description
Null command	00h	No command, allows Data IN line of LMOD2 to be held low during normal reads.
Initiate free air calibration [1]	01h	Initiates free air calibration
Cancel free air calibration [1]	02h	Cancels earlier issued free air calibration command if sent after initiation and at the latest 1 second after free air calibration completes
Initiate fast free air calibration [1]	04h	Initiates free air calibration without cancel time delay
Switch to Mode x	1xh	Switches read mode to mode x
Read Current Mode	07h	Returns the current Read Mode in effect, See 5.6
Null command	FFh	No command, allows Data IN line of LMOD2 to be held high during normal reads.

Note 1:
Free air calibration is necessary for a new sensor to characterize its response and O2 flow rate through the pump cell. (By default, the first time an L-Mod "sees" a new sensor, it performs both heater and free air calibration). Once a sensor is calibrated properly (in free air) this first time, it will not drift significantly over its entire usable life. Worst case is that the sensor will drift the same amount as analog sensors/controllers (with factory calibration resistors) from other suppliers.

However, the sensor response can change with age (especially with race gas, running very rich, etc.) and when outside air pressure changes. Therefore, for complete drift elimination, it can also be re-calibrated at intervals of about 10,000 miles (15,000 km) or, for most accurate results, for an altitude change of more than 3000 feet (1000 meters).

Free air calibration should be ideally performed with the sensor out of the exhaust in clean outside air. Alternatively, the calibration can be performed during coast-down when the injectors of the fuel injection system are shut off and the exhaust system has been purged by all remaining exhaust gas. The actual calibration does not take more than 2 seconds. If during that time the injectors need to be switched on again because of user action, a Cancel free air calibration command can be sent to disregard the calibration. LMOD2 will store the free air calibration results in non-volatile memory one second after the completion of a calibration IF no Cancel command is sent between the time free air calibration is initiated and one second after completion of the calibration.

7. Re-Flashing LMOD2 Firmware

LMOD2 uses an Atmel Atmega64 Microcontroller as main processor (16 MHz clock speed). The firmware and EEPROM of this microcontroller can be re-flashed via the SPI interface bus on JP1 using the standard Atmel serial programming protocol. See the Atmel AtMega64 data sheet for details.

Revision History

1.0 – 2/28/2007
Initial release

1.1 – 3/28/2007
Corrected various errata in overview and updated photo.

1.2 – 5/21/2007
Updated with actual product photo.

1.3 – 8/22/2007
Corrected pin designations in section 1, 1.1, 1.2, and 7. Specifically, corrected JP1, pin 9 and pin 10 description errata (swap).

1.4 – 8/24/2007
Updated mechanical specifications to reflect header height options. Added section 8.

1.5 – 1/30/2008
Updated mechanical specifications to remove header height options. Removed section 8.

1.6 – 3/13/2008
Added fast free-air calibration.

1.7 – 8/15/2008
Clarified free-air calibration and heater calibration.