STAR Cryoelectronics

MS-FLL User's Manual

Mr. SQUID Flux-Locked Loop

STAR Cryoelectronics

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U. S. A.

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Revision Record		
Date	**Revision**	**Description**
December 15, 2010	1.0.0	Initial Release
July 25, 2012	1.1.0	Revised for operation using MS-DAQ

TECHNICAL SUPPORT

If you have any questions or comments about this product or other products from STAR Cryoelectronics, please contact:

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WARRANTY

STAR Cryoelectronics Limited Warranty

STAR Cryoelectronics warrants this product for a period of twelve (12) months from date of original shipment to the customer. Any part found to be defective in material or workmanship during the warranty period will be repaired or replaced without charge to the owner. Prior to returning the instrument for repair, authorization must be obtained from STAR Cryoelectronics or an authorized STAR Cryoelectronics service agent. All repairs will be warranted for only the remaining portion of the original warranty, plus the time between receipt of the instrument at STAR Cryoelectronics and its return to the owner.

This warranty is limited to STAR Cryoelectronics products that are purchased directly from STAR Cryoelectronics, its OEM suppliers, or its authorized sales representatives. It does not apply to damage caused by accident, misuse, fire, flood or acts of God, or from failure to properly install, operate, or maintain the product in accordance with the printed instructions provided.

This warranty is in lieu of any other warranties, expressed or implied, including merchantability or fitness for purpose, which are expressly excluded. The owner agrees that STAR Cryoelectronics' liability with respect to this product shall be as set forth in this warranty, and incidental or consequential damages are expressly excluded.

SAFETY PRECAUTIONS

Do not remove product covers or panels other than as instructed in this User's Manual.

Do not operate without all covers and panels in place other than as instructed in this User's Manual.

Do not attempt to repair, adjust, or modify the instrument other than as instructed in this User's Manual. This could cause nullification of any warranty. For service, return the instrument to STAR Cryoelectronics or any authorized representative.

Do not operate this instrument in a volatile environment, such as in the presence of any flammable gases or fumes.

1 Overview

The Model MS-FLL Mr. SQUID Flux-Locked Loop accessory for STAR Cryoelectronics' Mr. SQUID Educational Demonstration System is used to operate Mr. SQUID in a locked-loop feedback mode. The Mr. SQUID FLL accessory is compatible with all STAR Cryoelectronics' Mr. SQUID probes and MS-EB03 control electronics (Rev. B or later).

The Mr. SQUID FLL is powered using the DC power source provided with the Mr. SQUID control electronics box. A 5-pin DIN cable included with the FLL accessory is used to power the Mr. SQUID electronics box through the FLL box.

2 Installation and Setup

2.1 Unpacking and Inspection

Prior to unpacking the Mr. SQUID FLL, inspect the shipping carton(s) for any signs of damage that may have occurred during shipment. If damage is observed, notify the carrier immediately to allow for a possible insurance claim.

The following sections list the items included with the Mr. SQUID FLL. If any items are missing, notify your STAR Cryoelectronics representative immediately.

MS-FLL	Mr. SQUID Flux-Locked Loop.
CBL-5DIN-24	Power cable, five-pin DIN plugs both ends, 24".
MS-BNC-12	BNC cables, 12", quantity two.
MS-FLL-BNC	BNC to DB-15 receptacle adapter.

2.2 Additional Equipment Required

The MS-FLL Mr. SQUID flux-locked loop module is intended for operation together with STAR Cryoelectronics' MS-EB03 Mr. SQUID electronics box and Mr. SQUID Educational Demonstration System.

An oscilloscope with X-Y mode or MS-DAQ Mr. SQUID Data Acquisition accessory is required to view the Mr. SQUID V-I and V-Φ characteristics and locked-loop output signal.

3 Operation

Before installing the MS-FLL Mr. SQUID flux-locked loop the MS-EB03 electronics control box must be configured for locked loop feedback operation. This is described in the section below.

3.1 Configuring the MS-EB03 Control Electronics

1. Remove the top cover of the Mr. SQUID control electronics box. Note that the board must be Rev. B or later for proper operation with the Mr. SQUID flux-locked loop.
2. Configure the external feedback input mode switch for direct (DIR) coupling to the Mr. SQUID external feedback coil (see Figure 3-1). This bypasses the buffer amplifier in the external feedback input circuit. The default position is BUF,

3. Move the two-pin jumper for the preamplifier balance (BAL) to the feedback (FB) position (see Figure 3-1). The default position is NO FB.
4. Confirm that the preamplifier gain is set to ×10,000 (default position).
5. Reinstall the top cover on the SQUID control electronics box.

Be sure to reconfigure the SQUID control electronics box with the default settings by reversing the steps above when you are finished using the Mr. SQUID flux-locked loop.

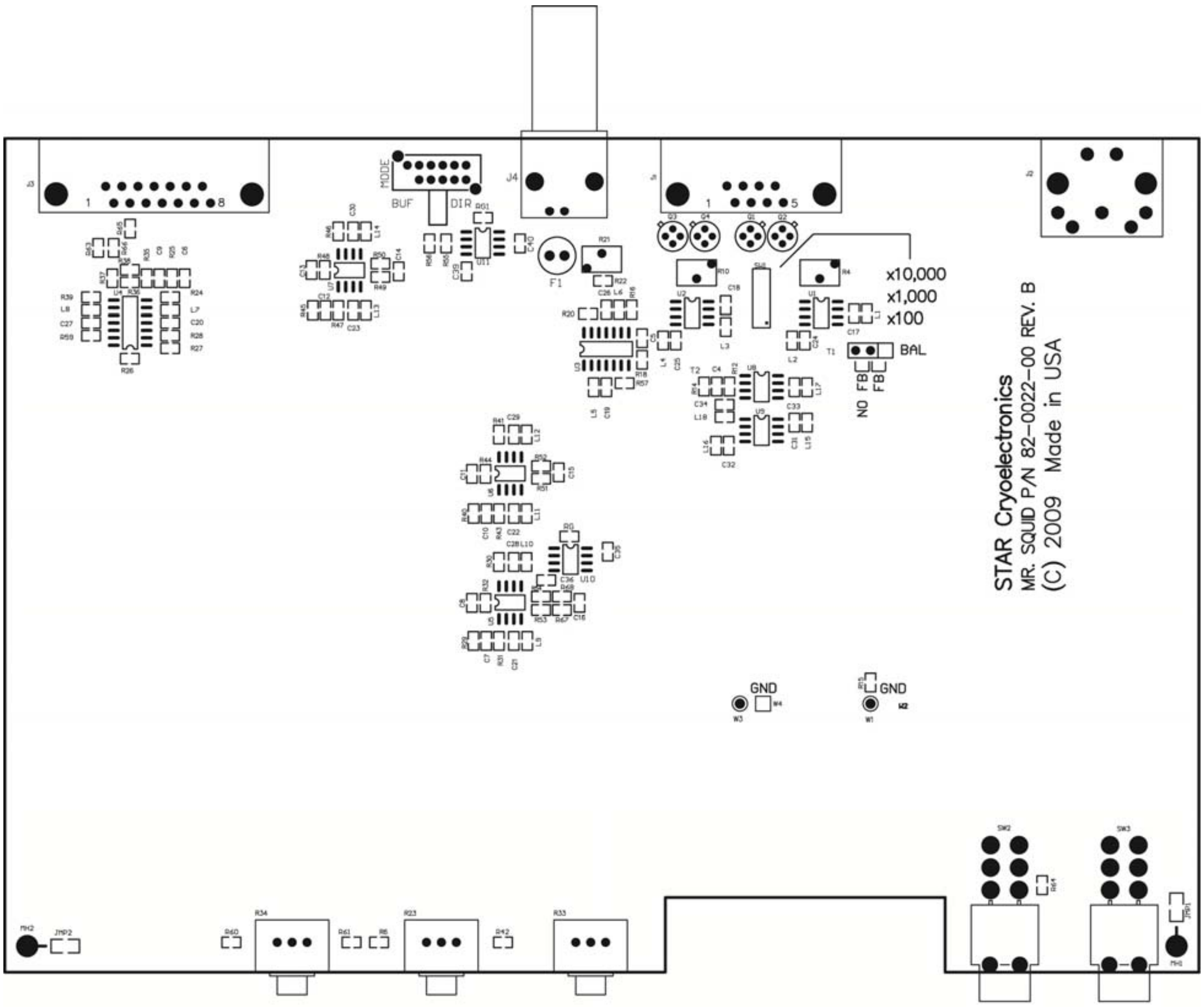

Figure 3-1. Assembly drawing of the MS-EB03 control electronics board.

3.2 Flux-Locked Loop Operation

1. Check that the power switch on the MS-EB03 control electronics is in the OFF position, the mode switch on the front panel of the MS-FLL flux-locked loop is in the TUNE position (down), and that the balance adjustment potentiometer (BAL ADJ) on the front panel of the MS-FLL flux-locked loop is in the 12 o’clock position.

2. Set up the Mr. SQUID system as described in Sec. 3 or Sec. 4 of the Mr. SQUID User's Guide, except use the five-pin DIN cable to connect the Power Out jack on the rear panel of the MS-FLL box to the power in jack on the rear panel of the MS-EB03 control electronics box.
3. Use a 36" BNC cable to connect the monitor current output signal on the front panel of the MS-EB03 electronics box to the horizontal input on the oscilloscope. Instead of connecting a BNC cable from the monitor voltage output on the front panel of the MS-EB03 electronics box to the vertical input on the oscilloscope, use a 12" BNC cable to connect the monitor voltage output to the voltage input (V IN) on the front panel of the MS-FLL flux-locked loop. Use a 36" BNC cable to connect the flux-locked loop output (FLL OUT) on the front panel of the MS-FLL flux-locked loop to the vertical input on the oscilloscope. Configure the vertical input for DC coupling, and adjust the vertical offset such that zero Volts is at the horizontal centerline.
4. Connect a 12" BNC cable from the Feedback Output on the rear panel of the MS-FLL flux-locked loop to the external feedback input (EXT INPUT) on the rear panel of the MS-EB03 electronics box.
5. Turn on the MS-EB03 control electronics and, as described in Sec. 3 or Sec. 4 of the Mr. SQUID User's Guide, adjust so that the Mr. SQUID V-Φ characteristic is visible on the oscilloscope or data acquisition device. Use the BAL ADJ control to center the V-Φ characteristic about zero Volts (horizontal centerline if the vertical offset has been adjusted properly).
6. Adjust the sweep output so that one period is displayed and centered about zero Volts. Now lock the feedback loop by moving the mode switch on the front panel of the MS-FLL flux-locked loop into the LOCK position (middle). The feedback loop should now be locked, and the linearized output should be a straight line. If you do not see a trace, try resetting the feedback loop by momentarily pressing the mode switch on the front panel of the MS-FLL flux-locked loop into the RESET position (upper). This momentary switch resets the feedback loop by shunting the integrator in the feedback loop circuit.
7. A rough estimate of the feedback loop calibration factor (V/Φ_0) can be determined from the displayed trace in locked-loop mode. The length of the trace along the horizontal axis is the current per flux quantum for external feedback coupling to Mr. SQUID, while the length of the trace along the vertical axis corresponds to the Volts per flux quantum at the output in locked-loop mode. The default value of the feedback resistor in the MS-FLL flux-locked loop is 10 kΩ, so the measured voltage divided by this resistance should equal the current per flux quantum.
8. A more accurate value for the V/Φ_0 calibration factor can be determined as follows. Reduce the sweep output to zero (the output should now be just a dot on the oscilloscope display), and use the FLUX OFFSET control on the MS-EB03 electronics box to shift the dot away from zero by around 1 V. Measure the locked-loop voltage output accurately (this is easiest to do by inserting a BNC tee at the FLL OUT on the MS-FLL front panel or vertical input on the oscilloscope and connecting this signal to a digital multimeter). Now reset the feedback loop by momentarily pressing the mode switch on the front panel of the MS-FLL flux-locked loop into the RESET position (upper) and measure the new output voltage. The voltage

change corresponds exactly to the V/Φ_0 calibration factor (or N times this factor if the output jumped through N flux quanta).

9. The calibration factor can be converted into magnetic field units using the magnetic field sensitivity B_Φ of Mr. SQUID, which is roughly 0.5 $\mu T/\Phi_0$. This number depends on the design of the Mr. SQUID chip. To convert the feedback loop calibration factor into units of magnetic field, the magnetic field sensitivity B_Φ is divided by the calibration factor in V/Φ_0 to give the calibration in, *e.g.*, μT/V.
10. With Mr. SQUID operating in locked-loop mode and calibrated, now you can see how the output changes as a magnetic object (e.g., small magnet, metal chair, *etc*.) is moved near Mr. SQUID. The magnetic field change as the object is moved can be determined by measuring the output voltage change and multiplying by the calibration factor in magnetic field units per Volt.

4 Theory of Operation

A schematic diagram of the MS-FLL flux-locked loop is shown in Figure 4-1. The schematic includes:

- Preamplifier balance circuit (U3). A DC voltage balance signal is supplied to the power connector (PWROUT pin 2) along with ±12 V and ground, which provides power for the Mr. SQUID MS-EB03 electronics box. The balance or offset of the preamplifier in the MS-EB03 electronics box is adjusted by the potentiometer BAL ADJ on MS-FLL flux-locked loop front panel.
- Feedback circuit. This circuit consists of an integrator (U1), a true differential output feedback buffer amplifier (U4), and a flux-locked loop output inverter (U2).

The DPDT switch MODE (SW1) provides three different operating modes of the system:

- TUNE mode. In this mode, the feedback circuit is disabled (SW1A, position 3) and the integrator is converted into an inverter (SW1B, position 6). This allows proper SQUID tuning by adjusting the SQUID bias current using the MS-EB03 control electronics and the preamplifier balance adjustment set by the MS-FLL flux-locked loop. After the desired working point is set (usually corresponds to the maximum slope of V-Φ characteristic crossing zero DC Volts), the system is ready to be flux-locked.
- Flux-locked loop mode mode. After tuning and setting the desired working point, the user can “flux-lock” the loop. To do this, the mode switch of the MS-FLL flux-locked loop is moved into the LOCK FLL position (middle). This engages the feedback circit and converts the inverter (U1) in the MS-FLL flux-locked loop unit into an integrator. The transfer function of the flux-locked loop is determined by the feedback resistors (R2 and R10) in the MS-FLL flux-locked loop box.

For small signals, the -3 dB cut-off frequency f_{-3dB} is given by the following expression:

$$f_{-3\mathrm{dB}} = \left(\frac{\partial V}{\partial \Phi}\right)\frac{GM_{\mathrm{ext}}}{2\pi\tau R_{\mathrm{FB}}}$$

where $\left(\frac{\partial V}{\partial \Phi}\right)$ is the Mr. SQUID flux-to-voltage transfer function, G is the gain of the preamplifier circuit (default value is 10,000), $\tau = RC$ (configured by R1 and C5) is the integrator time constant (default value is 10 μs), R_{FB} is the feedback resistor (configured by R2 and R10, 10 kΩ), and M_{ext} is the mutual inductance of the Mr. SQUID external feedback coil (for the external feedback coil, $M_{ext} = \Phi_0/\Delta I_{ext}$ or roughly 35 pH). By changing the values of R1, C5, R2 and R10 the user can modify the system -3 dB bandwidth and calibration factor in V/Φ_0. These key components are installed in sockets so that they may easily be changed without any soldering.

Note that if the bandwidth is set too high by decreasing the integrator time constant, the system may become unstable because in this particular circuit a small bandwidth operational amplifier is used as the integrator. In addition, the preamplifier circuit in the MS-EB03 electronics box has a bandwidth limitation of a few tens of kHz due to high gain of the first amplifier stage.

4.1 Modifying the Flux-Locked Loop Parameters

To modify the time constant of the feedback loop circuit or the feedback resistors, the top cover of the MS-FLL feedback loop must be removed as follows.

1. First adjust the FLUX and BIAS OFFSET controls on the front panel of the MS-EB03 electronics box so they are in the 12 o'clock position and turn the SWEEP OUTOUT fully counter-clockwise, then power off the MS-EB-03 electronics box.
2. Disconnect all cables from the rear panel of the MS-FLL flux-locked loop. Remove the hex nut and lockwasher from the BNC connector on the rear panel, and remove the for screws that secure the rear panel to the box.
3. Remove the rear panel and bezel, then slide the top cover off the box. Note that it may be necessary to loosen the top screws securing the front panel to the box if the top cover does not easily slide off the box.
4. Reinstall the bezel and rear panel on the back of the MS-FLL flux-locked loop. Do not over-tighten the rear or front panel screws, as this may damage the bezel. Reinstall the lockwasher and hex nut on the rear panel BNC connector.
5. Reconnect the rear panel cables.
6. The integrator time constant can be modified by changing the values for R1 and/or C5, the feedback loop calibration in V/Φ_0 can be modified by changing the values of R2 and R10, keeping R2 = R10. These components are installed in sockets so that they may easily be changed without any soldering.

   For example, to better resolve small magnetic field changes the feedback range can be expanded by increasing R2 and R10 to 100 kΩ from 10 kΩ, which will result in a feedback loop calibration factor of roughly 6 V/Φ_0. In order to maintain the same system bandwidth, the increased value of the feedback resistor needs to be compensated by a corresponding increase of the integrator time constant, in this case by a factor of 10×. Usually this would be done by increasing the value of the integrator capacitor C5, in this example from 3.3 nF to 33 nF. With these changes, the flux-locked loop output in resonse to a given magnetic field change will now be 10× higher. In this way smaller magnetic field changes can more easily be resolved.

7. After completing experiments with the MS-FLL flux-locked loop the default components should be reinstalled, and the top cover reinstalled following steps 1 – 4 above. Also return the external feedback switch and balance jumper inside the MS-EB03 electronics box to their default configuration (BUF feedback mode and NO FB for the BAL jumper).

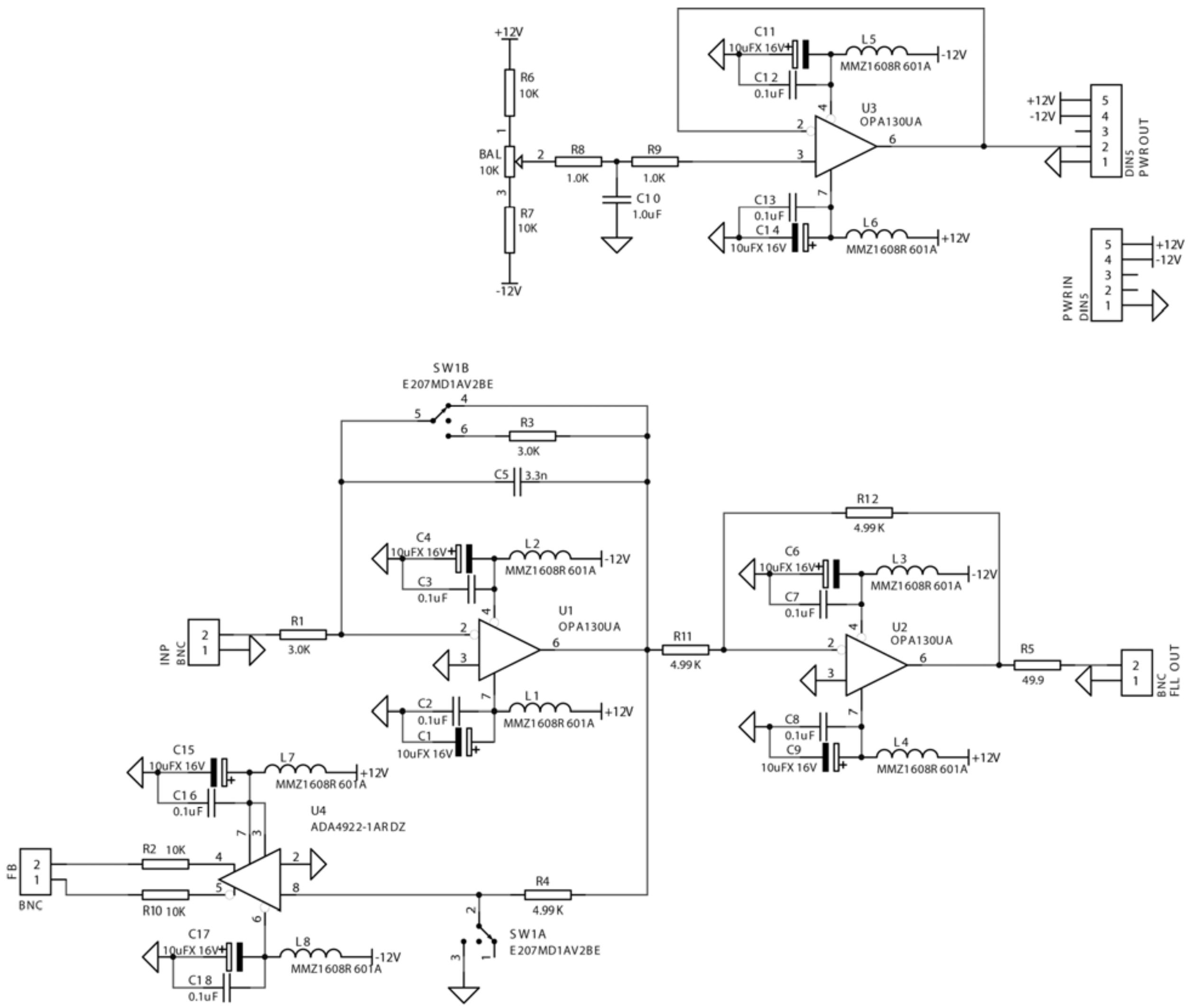

Figure 4-1. Schematic diagram of the MS-FLL flux-locked loop. An assembly drawing of the MS-FLL flux-locked loop board with component designators is shown in Figure 4-2.

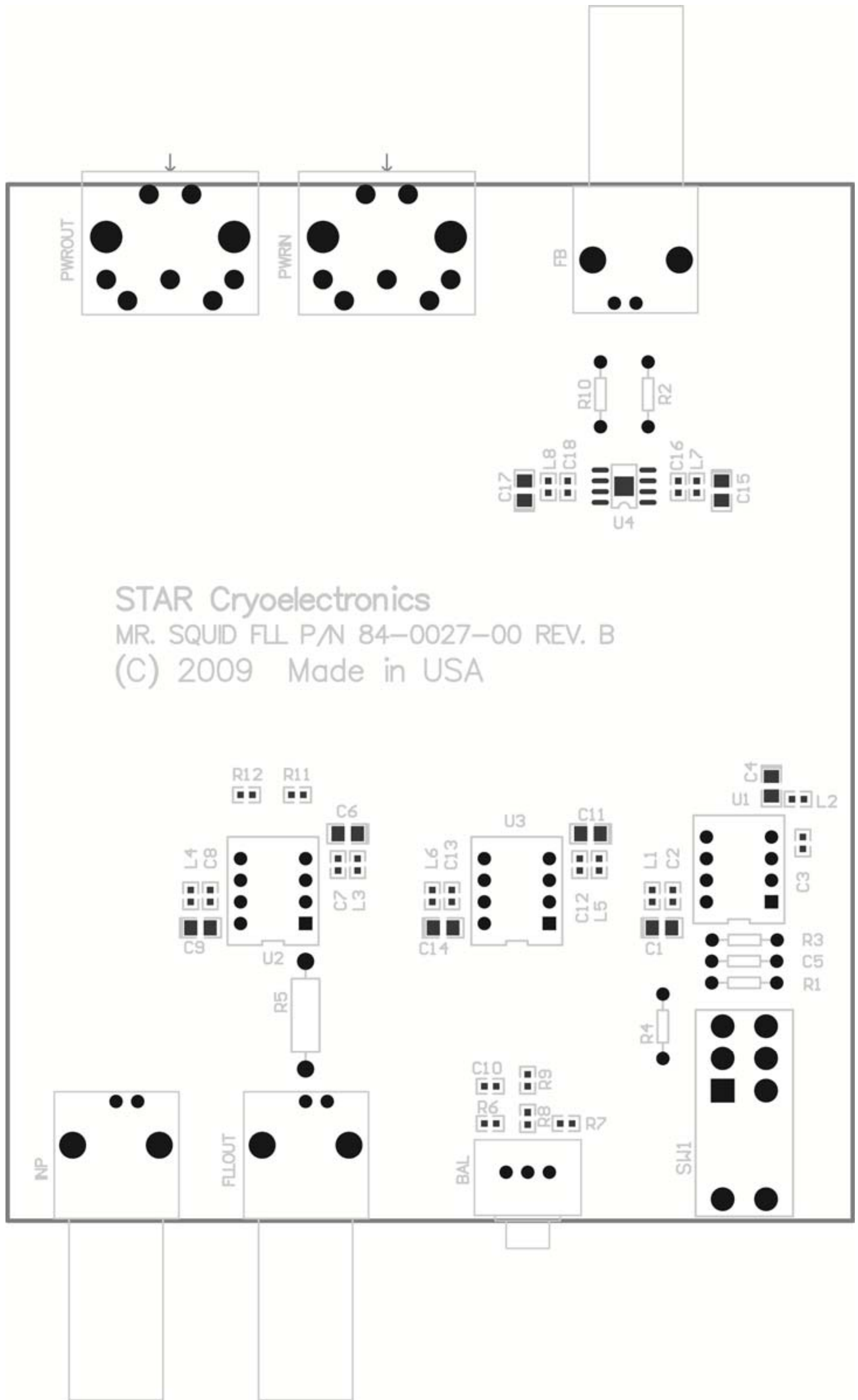

Figure 4-2. Assembly drawing of the MS-FLL flux-locked loop board with component designators.

5 Using the Flux-Locked Loop with MS-DAQ Accessory

The MS-DAQ data acquisition accessory can be used to display and acquire the locked SQUID output signal *versus* time. A special BNC to DB-15 adapter is required, which is included with the MS-FLL accessory.

1. Set up Mr. SQUID as described in Section 3.2 using the MS-DAQ data acquisition module and Mr. SQUID software. Instead of the two BNC cables connecting the output signals to an oscilloscope, use the DB-15 cable provided with the MS-DAQ accessory to connect the output signals available at the rear panel of the Mr. SQUID EB-03 electronics box to the data acquisition module.
2. Once you have tuned, locked and calibrated Mr. SQUID, disconnect the 15-pin cable from the data acquisition module and install the BNC to DB-15 adapter, then use a BNC cable to connect the voltage output signal FLL OUT on the MS-FLL module to the BNC adapter.
3. In the Mr. SQUID software panel, select for the operating mode Voltage-Time. Depending on the SWEEP OUTPUT level you should now see the locked Mr. SQUID output signal tracking the triangle-wave internal test signal. The horizontal time scale can be changed by adjusting the SCAN TIME setting in the Mr. SQUID software.
4. Displaying the locked Mr. SQUID output signal *versus* time is a convenient way to record time-varying signals such as the ambient power mains waveform shown in Figure 5-1 (recorded with the mu-metal shield on the end of the Mr. SQUID probe removed). Using the cursors, the period of the waveform is about 17 ms, which corresponds to a frequency around 59 Hz. The peak to peak amplitude of the waveform is about 0.28 V_{pp}. For this Mr. SQUID the locked-loop calibration factor is 0.62 V/Φ_0, which can be converted to magnetic field using the nominal field sensitivity of Mr. SQUID, 0.5 $\mu T/\Phi_0$, to express the calibration factor as 0.806 µT/V. Multiplying this by the peak to peak amplitude of the ambient power mains waveform gives 225 nT_{pp}. Typical ambient magnetic fields in laboratory environments due to power mains are of the order of 100 nT_{pp}. Note that the waveform is not sinusoidal due to the presence of harmonics of the fundamental power mains frequency.

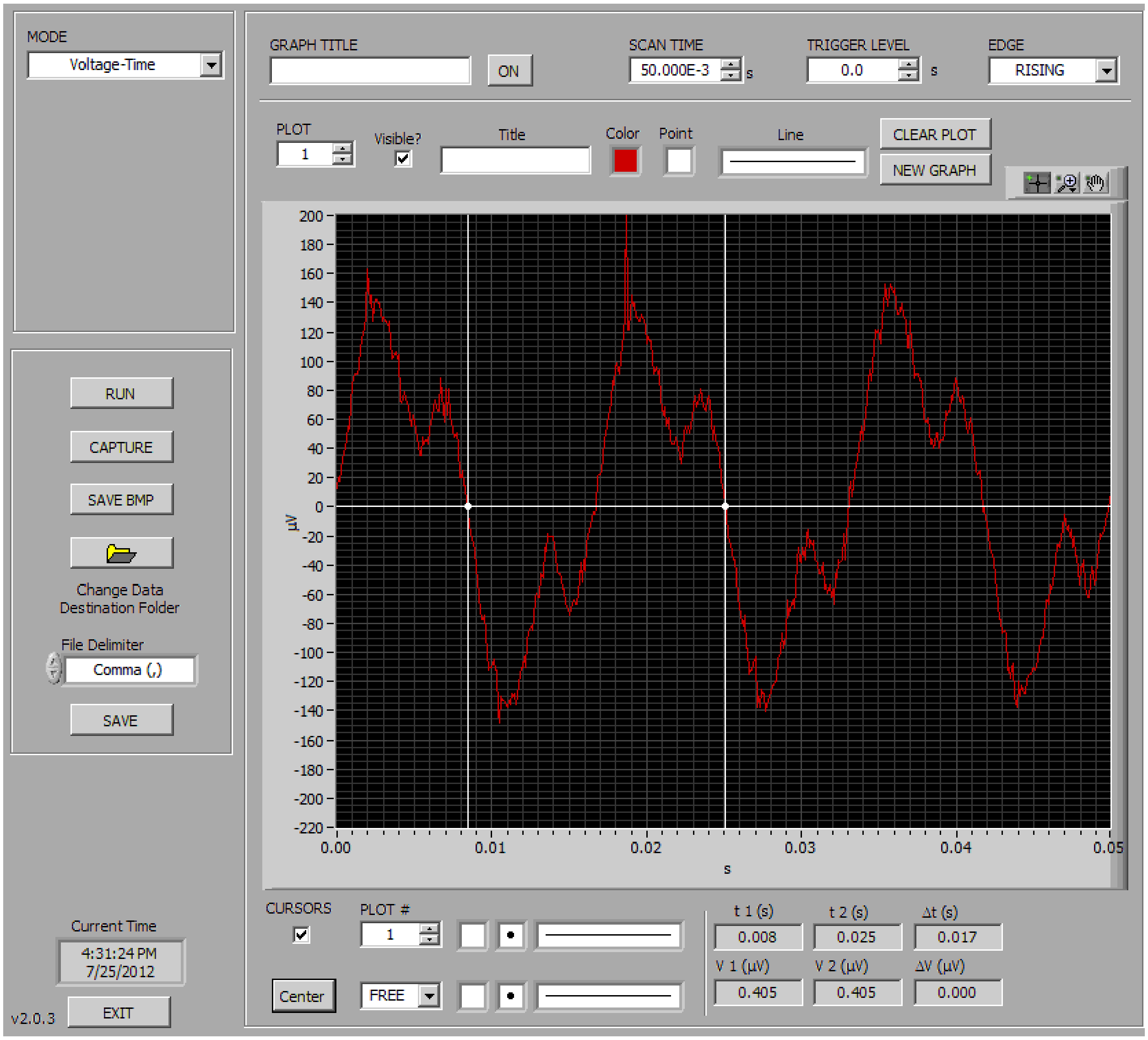

Figure 5-1. Ambient power mains waveform captured using a locked Mr. SQUID. For this measurement the magnetic shield at the end of the Mr. SQUID probe was removed.

6 Specifications

Parameter	**Value**
Voltage Input	BNC, Front Panel, ±10 V
Flux-Locked Loop Output	BNC, Front Panel, ±10 V, 50 Ω
Feedback Output	BNC, Rear Panel, ±10 V
Balance Adjustment	±10 V
Feedback Resistor	10 kΩ (default)
Integrator Capacitor	3.3 nF (default)
Integrator Time Constant	10 µs (default)
Bandwidth	~10 kHz (for ~10 μV_{pp} SQUID V-Φ)
Power Requirements	±12 V DC
Size	6.38” × 4.18” × 1.33” (162 × 106 × 34 mm)
Size and Weight	11 oz (300 g)

Specifications subject to change without prior notice.

Rear Panel Power In, 5-pin DIN Socket

Pin	**Function**
1	Analog Ground
2	N/C
3	N/C
4	-12 V
5	+12 V

Rear Panel Power Out, 5-pin DIN Socket

Pin	**Function**
1	Analog Ground
2	Balance Output
3	N/C
4	-12 V
5	+12 V