# TAM-2 SERIES THREE AXIS SATELLITE MAGNETOMETERS

## *SPECIFICATIONS*

*(Document No. 000257 )*

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# INTRODUCTION

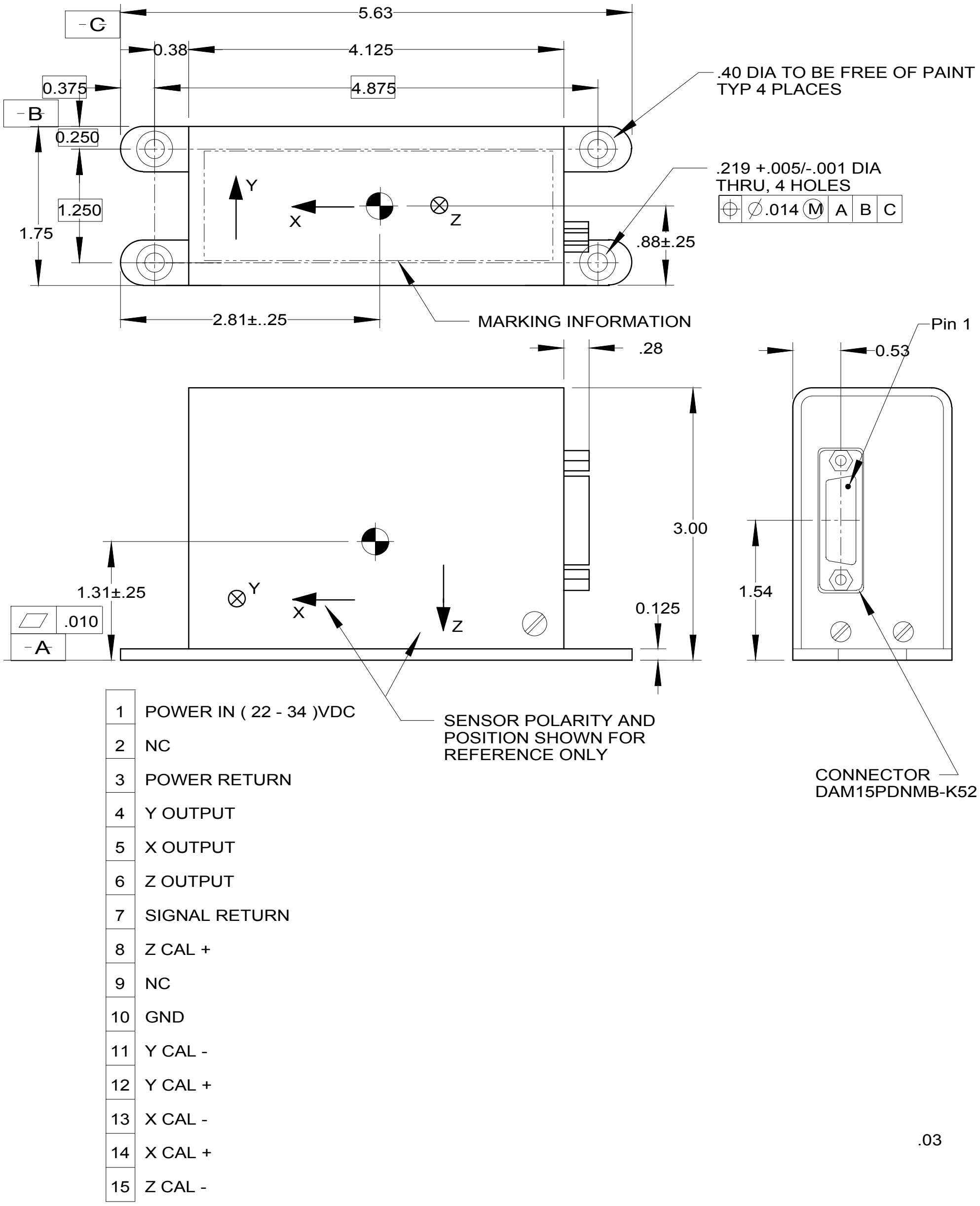
The TAM-2 series of three-axis satellite magnetometers is a derivative of our TAM-1 series. The TAM-1 series has had a long and successful history in space. The TAM-1 design had its beginnings in the late 1960's when the space industry was in its infancy. It was originally designed by Schonstedt Instrument Company and known as the SAM-63C series. In 1994 MEDA took over the design and manufacturing of this magnetometer and renamed it the TAM-1 series. It has flown on many military and civilian satellites without any documented failures. The initial design has evolved over the years into a very reliable, accurate and stable instrument through the judicious introduction of state-of-the-art technologies at appropriate points along the way.

The TAM-2 satellite magnetometer integrates the sensor and electronics into one package (the TAM-1 has separate sensor and electronics units). Also the TAM-2 was simplified to reduce its power consumptions and weight and to improve its reliability for space applications.

The large variety of TAM-2 output signal configurations provides the satellite attitude control engineer with a great deal of flexibility in satisfying a broad range of spacecraft attitude determination and control requirements. The following sections describe more fully the TAM-2 and its optional configurations.

# DESCRIPTION

The TAM-2 uses three fluxgate sensors to measure the three orthogonal components of the magnetic field. (See the Fluxgate Magnetometer Theory section for a description of how fluxgate magnetometers work). The three sensors and the electronics that are used to drive the sensors and condition the sensor output signals are housed in a single package with the dimensions and configuration shown in Fig. 1.



| | |
|---|---|
| 1 | POWER IN ( 22 - 34 )VDC |
| 2 | NC |
| 3 | POWER RETURN |
| 4 | Y OUTPUT |
| 5 | X OUTPUT |
| 6 | Z OUTPUT |
| 7 | SIGNAL RETURN |
| 8 | Z CAL + |
| 9 | NC |
| 10 | GND |
| 11 | Y CAL - |
| 12 | Y CAL + |
| 13 | X CAL - |
| 14 | X CAL + |
| 15 | Z CAL - |

*Figure 1 TAM-2 Physical Configurations*

## SPECIFICATIONS

The standard TAM-2 series of magnetometers have a common set of performance specifications which are listed in Table 1.

*Table 1 TAM-2 Series Performance Specifications*

| | |
|---|---|
| Number of Axes: | Three (3) |
| Coordinate System: | Right handed Cartesian |
| Axis Alignment: | ≤0.25° (0.1° typical) |
| Calibration Coil Constant: | 53 to 59 mG/mA |
| Scale Factor Accuracy: | ±1.0 % ($T_{min}$ to $T_{max}$) |
| Zero Field Output:* | |
| *±10 VDC range:* | 0 ± 0.030 VDC |
| *±5 VDC range:* | 0 ± 0.015 VDC |
| *0 to 5 VDC range:* | 2.500 ± 0.015 VDC |
| *0 to 3 VDC range:* | 1.500 ± 0.015 VDC |
| Linearity: | ≤0.05% |
| Frequency Response: | 3 dB point > 60 Hz |
| Output Impedance: | < 250 ohms |
| Power: | |
| *Input Voltage:* | +21 to +38.6 VDC |
| *Current:* | 20 mA nominal, 25 mA maximum |
| Weight: | 1.1 pounds (0.5 Kg) nominal |
| Size: | 1.75” x 5.63” x 3.00” (4.45 cm x 14.3 cm x 7.62 cm) |
| Temperature Range: | -39° to + 76°C |
| Mounting Surface: | Aluminum (6061-T6), Alodine 600, unpainted |
| Exterior paint: | Aeroglaze Z306-black |

* Optional biasing schemes.

## OPTIONS

The TAM-2 can be configured for a variety of different field ranges, voltage ranges and parts quality. These options are described in the following subsections.

### Field Range

The TAM-2 series magnetometers can have field ranges from ±100 mG to ±2000 mG. Table 2 lists the two standard field range options.

*Table 2 Field Range Options*

| Option | Range |
|---|---|
| A | ±1000 mG |
| B | ±600 mG |

## Output Voltage Range

The output voltage range options are listed in Table 3.

*Table 3 Output Voltage Range Options*

| Option | Range |
|---|---|
| A | ±5 VDC |
| B | ±10 VDC |
| C | 0 to 5 VDC |
| D | 0 to 3 VDC |

## Parts Quality

The electronic parts used to build the TAM-2 determine its reliability. The TAM-2 series of magnetometers can be manufactured using one of the two options defined in Table 4.

*Table 4 Parts Quality Options*

| Option | Microcircuits | Semiconductors | Resistors and Capacitors |
|---|---|---|---|
| R | Class B | JANTXV | S level failure rate (0.001% failures per 1000 hours) |
| S | JAN, MIL-M-38510, Class S | JANS | S level failure rate |

A TAM-2 built with option R parts has an MTBF of 23.30 x $10^6$ hours. The MTBF was calculated at a temperature of 23°C using MIL-HDBK-217F, Notice 1. The option S parts produce better reliability but are significantly higher priced and take longer to procure than the option R parts.

The TAM-2 series magnetometers can also be constructed using radiation hardened parts.

# QUALITY ASSURANCE PROGRAM

MEDA's Quality Assurance Program maintains total quality control of the design, manufacture, testing and shipment of products per the customer's requirements. Our QA Program is fully compliant with the requirements of MIL-I-45208A, "Inspection System Requirements" and the companion document NASA Handbook NHB 5300.4(1C). Our calibration system is fully compliant with MIL-STD-45662A, "Calibration System Requirements". We maintain a separate facility for the manufacture of satellite magnetometers. All parts and materials are inspected in this facility.

We have a Clean Room that exceeds the requirements of and is certified to the 100,000 level. All work stations are equipped to protect against electrostatic damage to parts. All soldering is performed by personnel who have been certified to NASA standard NHB5300.4(3A-2). Process specifications control all manufacturing activities.

Our QA Program has been approved by Lockheed Martin Astro Space, Lockheed Martin Astronautics, Lockheed Martin Missiles and Space, Space Systems/Loral, TRW and Raytheon Corporation.

## *QA PLAN FOR SPACE MAGNETOMETERS*

MEDA has a standard Quality Assurance Plan for the manufacture of space magnetometers. This plan is available upon request. The plan covers the following topics:

- Applicable Government and MEDA Quality Assurance documents
- The MEDA Quality Assurance Program
- Facilities and standards
- Procurement control
- Manufacturing control
- Handling, storage and delivery
- Coordinated Government actions
- Control of customer furnished material and equipment

## *MANUFACTURING PROCESS*

The TAM-2 series magnetometers are manufactured according to the following flow diagrams.

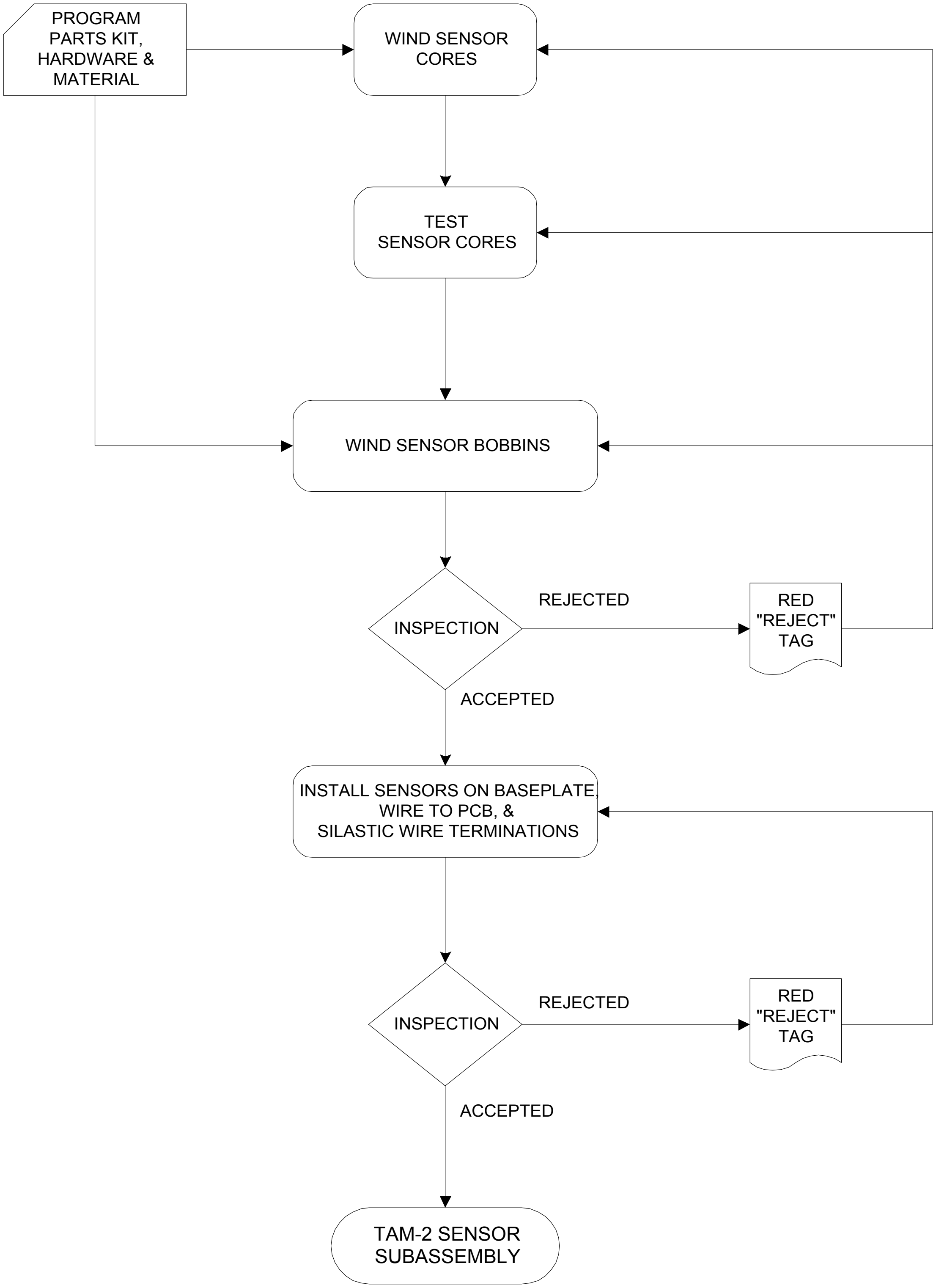


*Figure 2 TAM-2 Sensor Subassembly*

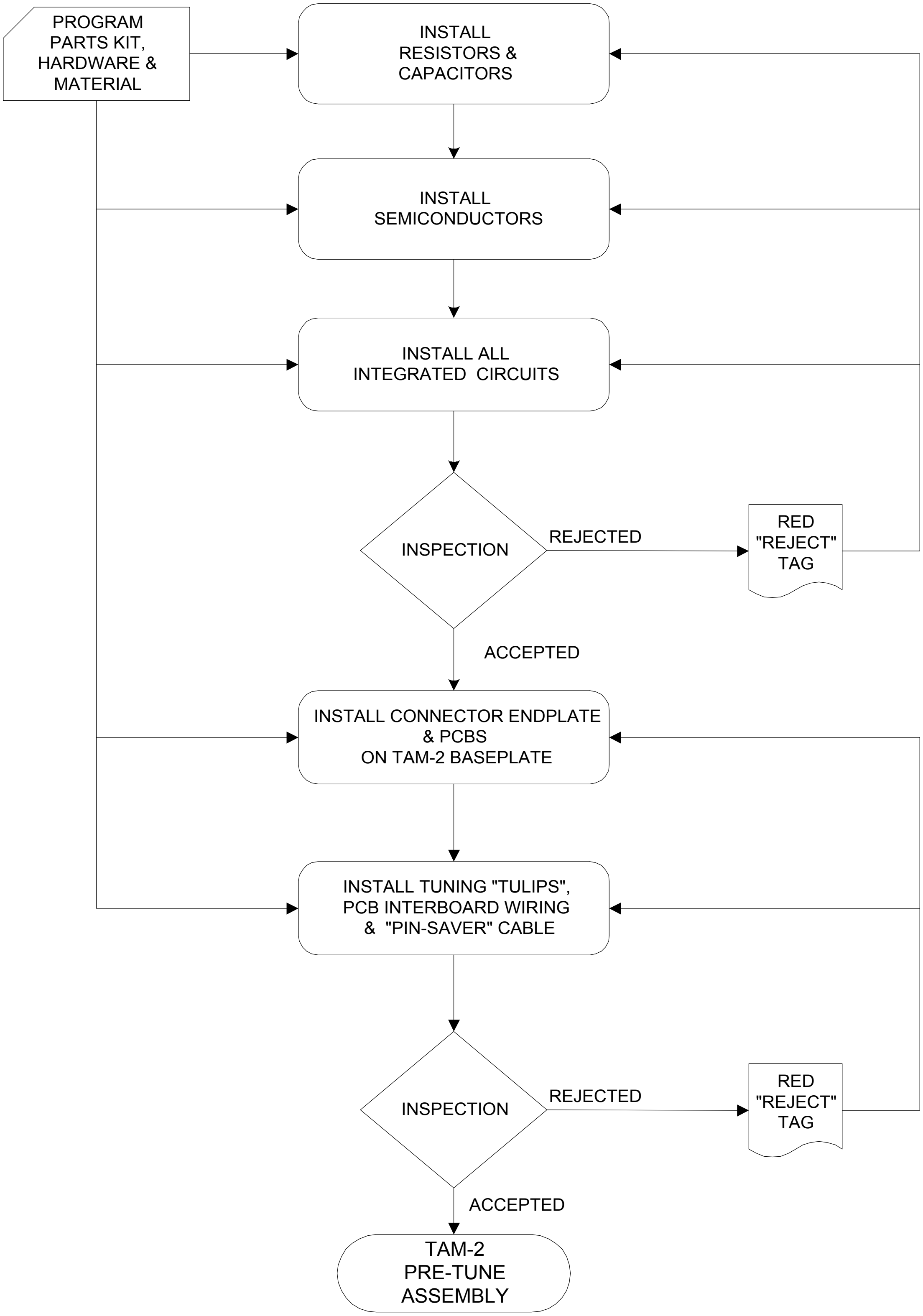


*Figure 3 TAM-2 PCB Subassembly*

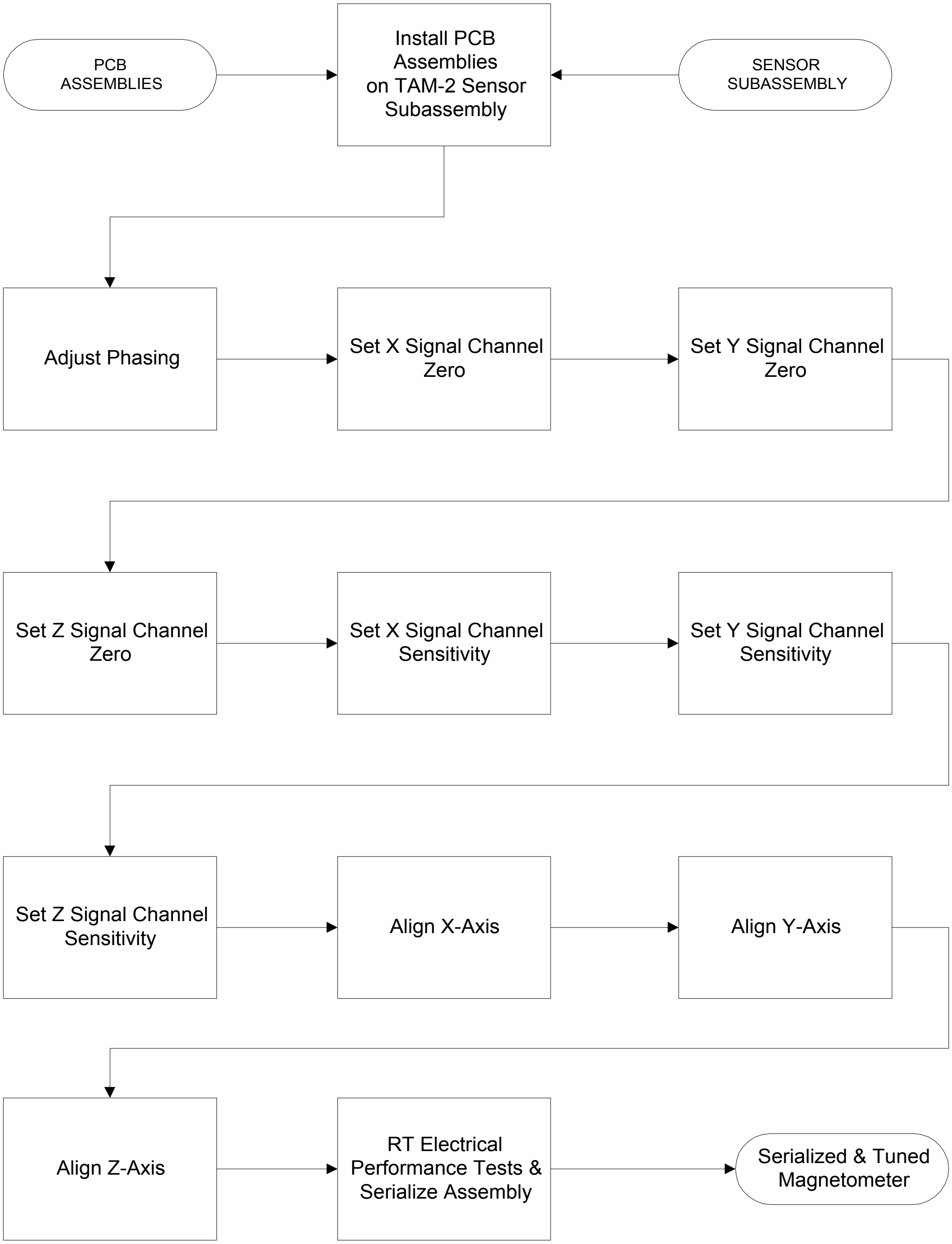


*Figure 4 TAM-2 Tuning and Alignment*

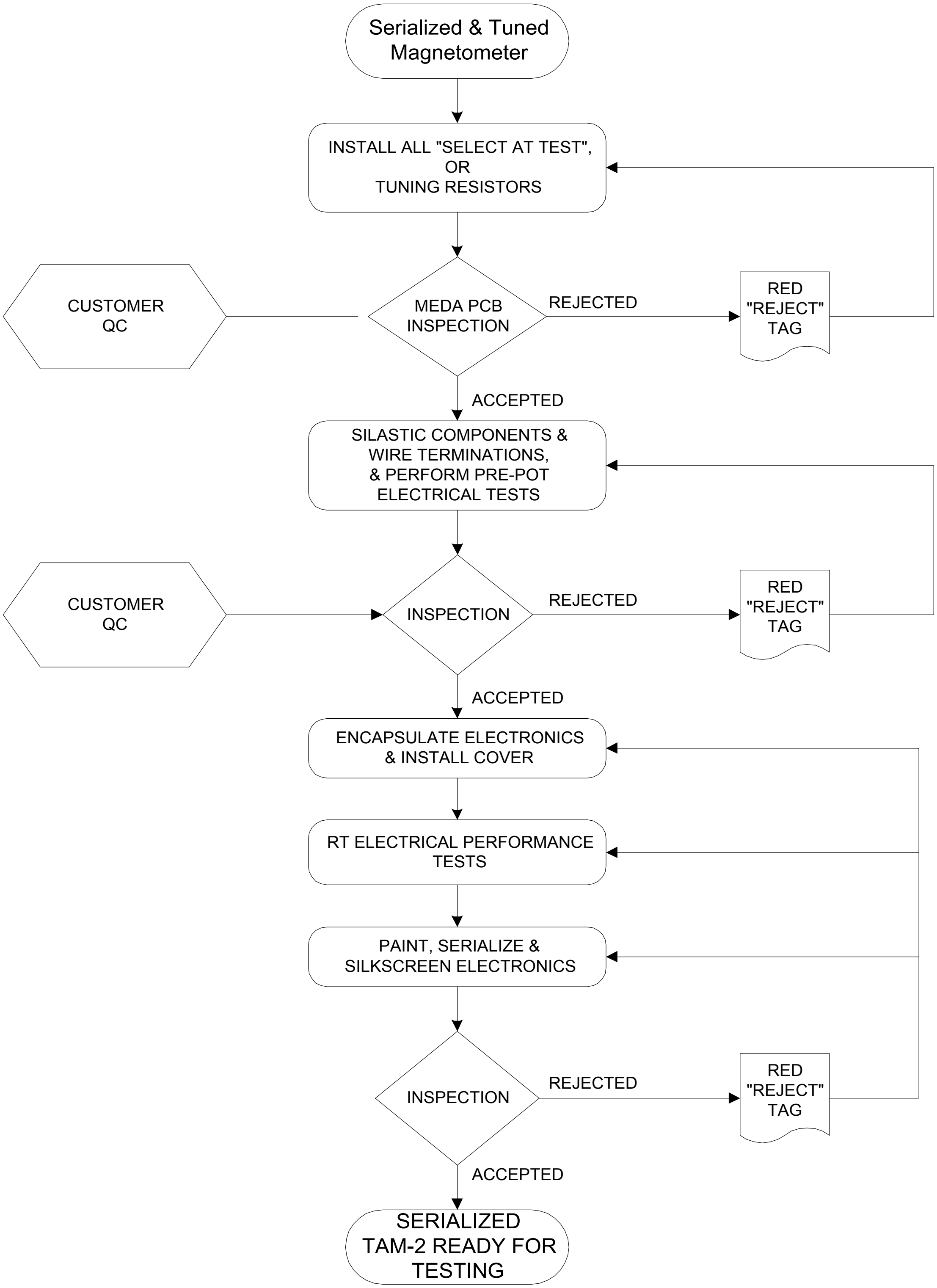
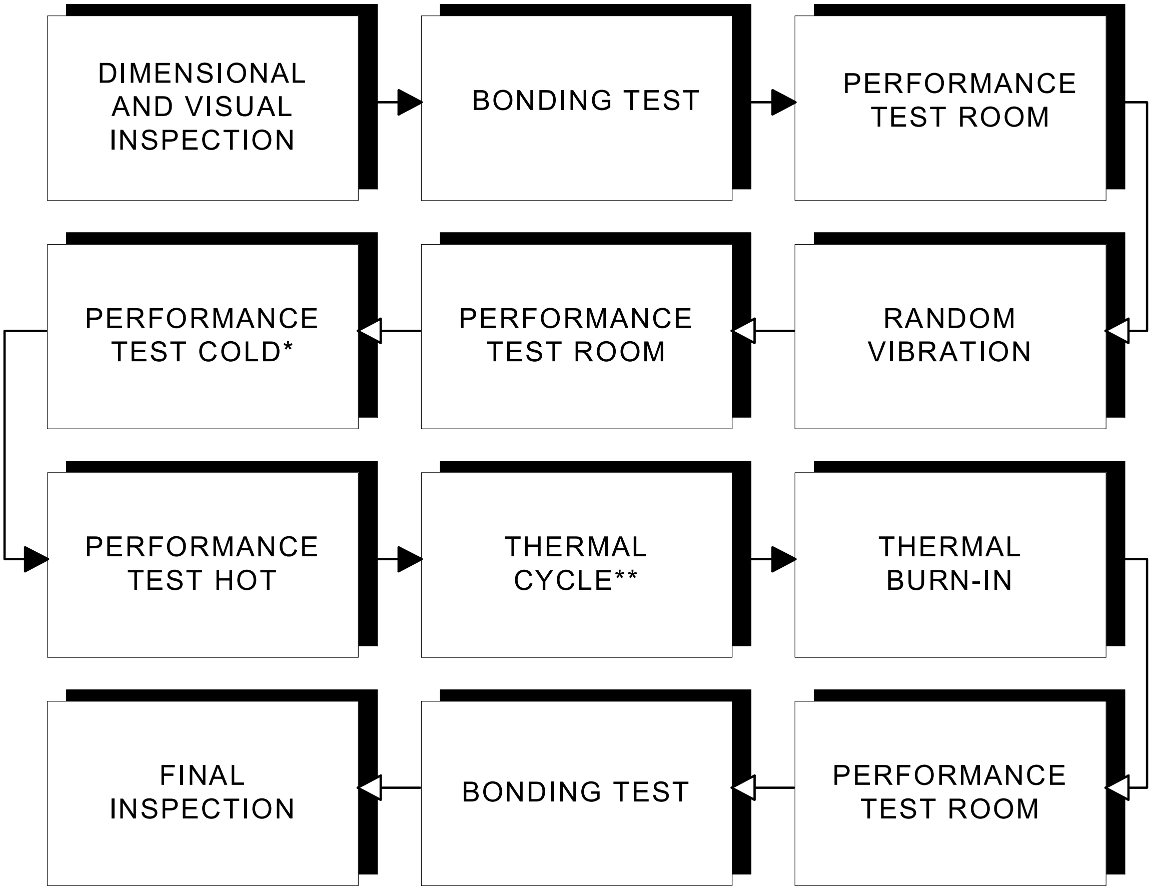


*Figure 5 TAM-2 Electronics Assembly*

# *TESTING PROGRAM*

The TAM-2 series magnetometers undergo a standard set of acceptance tests. The flow diagram given in Fig. 6 shows the type and sequence of these tests. The test methods are summarized in the following sections.



* Cold Start Test

** Eight cycles with Hot Start at the end of the last cycle. Abbreviated performance testing at each plateau. Combined Thermal Cycle and Burn-in time is 200 hours minimum.

*Figure 6 TAM-2 Series Standard Test Program Flow Diagram*

## Magnetometer Automated Test System (MATS)

Performance tests of the TAM-2 series magnetometers are controlled by MEDA's Magnetometer Automated Test System (MATS). The MATS system

- Powers the magnetometer under test
- Controls the temperature environment

- Sets magnetic field values in three orthogonal axes
- Measures the magnetometer outputs and stores the data in a disk file
- Continuously measures and records the temperature and current drain of a magnetometer during thermal cycling and burn-in
- Generates test reports

The MATS is a combined hardware and software system. A PC controls all of its functions.

A block diagram of the MATS is given in Fig. 7. The magnetometer under test is located in an environmental chamber inside a three axes Helmholtz coil system. The environmental and Helmholtz coil systems are self-contained and controlled remotely by the PC. An IEEE-488 bus is used by the PC to communicate with a dual power supply that provides magnetometer power and a 5½ digit multimeter that measures the magnetometer signals.

The Helmholtz coil control system and the Helmholtz coils form a negative feedback control system that maintains the field at the center of the coils near zero without intervention by the MATS PC controller. The PC controller applies voltages to the coil controller to trim the field inside the coils to zero and to apply precise magnetic fields in all three axes. Three of the 12-bit digital-to-analog converters (DAC) provide zero trimming. The three 18-bit DACs control the application of precision fields.

The thermocouple and temperature controller also form a negative feedback system that maintains the temperature inside the environmental chamber at a specified value. It can be programmed by the PC controller to ramp to the temperature at a specified rate and maintain the temperature within specified limits.

The analog signals from the magnetometer are connected to two (2) eight (8) channel differential input scanners which switch the magnetometer analog signals to the input of the multimeter. The multimeter digitizes the data and sends it to the PC over the IEEE-488 bus.

The power supplies, beside supplying power, measure the actual voltage applied to the magnetometer and its current drain.

Some TAM-2s require the temperature of the sensor unit to be different from the electronics unit. In these cases, the electronics unit is placed in a second thermal chamber that is also under the control of MATS.

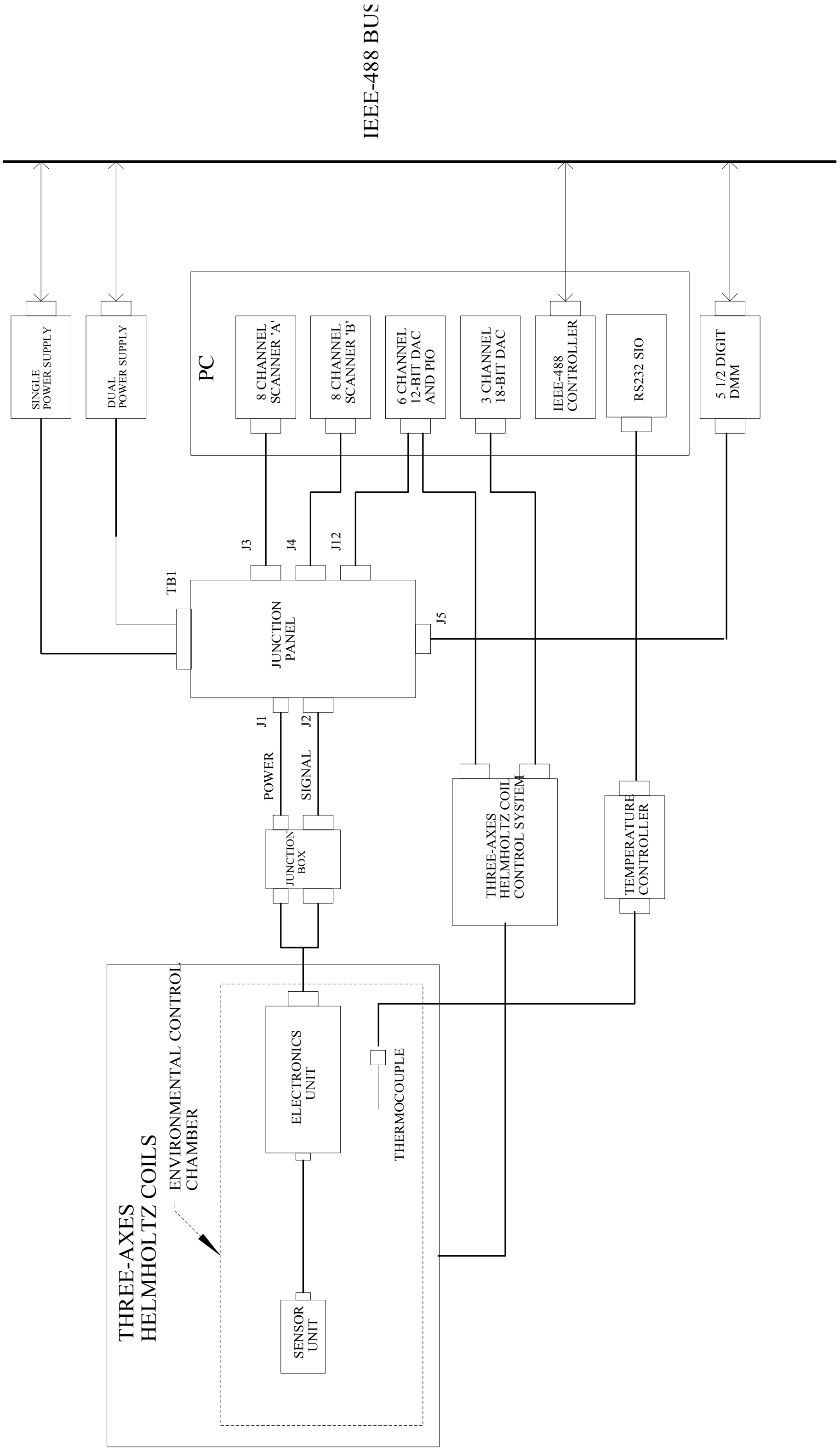


*Figure 7 MATS Block Diagram*

## Test Methods

The test methods described in the following sections are the standard ones used by MEDA to verify that a TAM-2 series magnetometer meets the customer's specifications. Additional tests or modifications to these methods can be specified by the customer. Any changes from the standard tests will impact cost.

### *Dimensional and Visual Inspection*

Each TAM-2 series magnetometer assembly is examined to verify that it meets the weight, dimensional, workmanship, finish, identification, and cleanliness requirements of the specification. A summary of the results from these inspections is recorded on a data sheet. The data sheet and ICD are included in the End-Item-Data package.

### *Bonding*

The bonding test setup is shown in Fig. 8. The resistance between the baseplate and backshell of the bulkhead connector is measured and recorded. The maximum allowable resistance is 2.5 milliohms per interface.

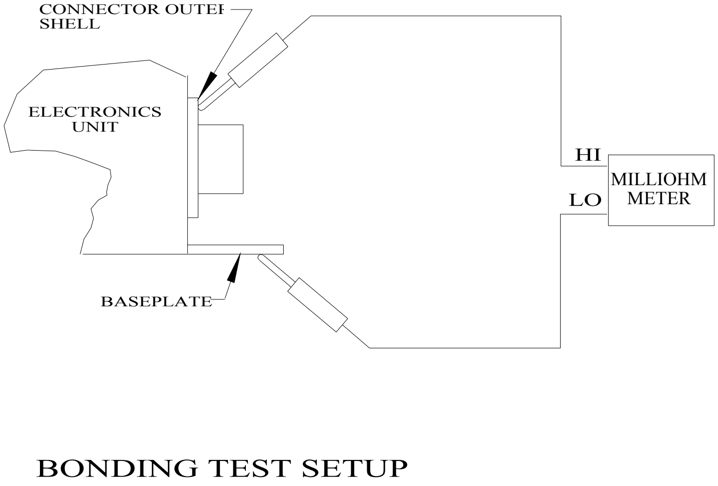


*Figure 8 Bonding Test Setup*

The Bonding test is performed at the beginning and end of the test program.

### *Performance Test*

These tests demonstrate compliance of the TAM-2 with the performance requirements of the customer's procurement specifications. The Performance Test consists of four separate procedures: Electrical Performance, Alignment, Frequency Response and Calibration Coil Constant. Table 5 shows the relationship between each measured test parameter and the procedure used to determine its value.

*Table 5 Performance Test Parameters and Associated Test Procedure*

| Test Parameter | Test Procedure |
|---|---|
| Field Measurement Range | Electrical Performance |
| Scale Factor Accuracy | Electrical Performance |
| Zero Field Output Voltage | Electrical Performance |
| Full Scale Output Voltage | Electrical Performance |
| Linearity | Electrical Performance |
| Axis Alignment | Alignment |
| Frequency Response | Frequency Response |
| Calibration Coil Constant | Calibration Coil Constant |

## Electrical Performance

The electrical performance of the TAM-2 is measured using the MEDA Magnetometer Automated Test System. MATS uses a special test script file that specifies the test parameters for all of the tests which will be performed on the magnetometer. All test data for a specific test are stored in a data file. The data file name is tied to the serial number of the magnetometer. A log file for each magnetometer keeps a list of all the tests that have been performed on the magnetometer. Figure 11 is an example of a typical Electrical Performance data sheet.

## Alignment

Figure 9 is the test setup for the sensor axis alignment test. This test consists of a series of rotations of the axis under test while in the presence of a magnetic field that is normal to the axis. Figure 10 is a typical Alignment Test data sheet.

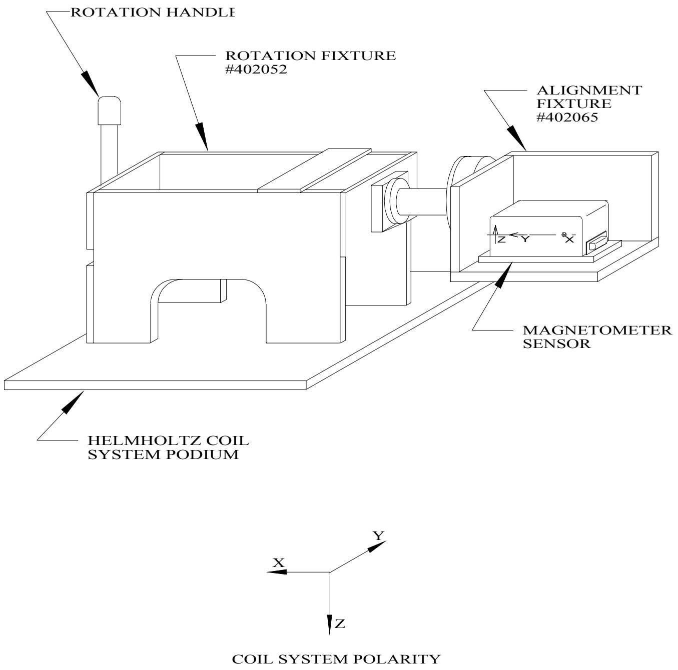


*Figure 9 Alignment Test Setup*

ELECTRICAL PERFORMANCE

Test No: 4

MODEL: TAM-2A S/N: 2852

Electronics Temperature: 23.0 C Date: 08/24/96

Sensor Temperature: 23.0 C Time: 13:27:30

Input Power

| Supply Voltage | | Current | Current | |
|---|---|---|---|---|
| | (VDC) | | (mA) | Limit (mA) |
| 1 | 30.0 | | 20.7 | 25.0 |

---

Signal: X

| Applied Field (mG) | Signal Output (VDC) | Least Sqr Best Fit (VDC) | Deviation From Best Fit (mVDC) |
|---|---|---|---|
| 600.0 | 5.009 | 5.009 | 0 |
| 500.0 | 4.009 | 4.008 | 1 |
| 400.0 | 3.008 | 3.007 | 1 |
| 300.0 | 2.006 | 2.007 | -1 |
| 200.0 | 1.005 | 1.006 | -1 |
| 100.0 | 0.025 | 0.025 | 0 |
| 0.0 | 0.004 | 0.005 | -1 |
| -100.0 | -0.015 | -0.015 | 0 |
| -200.0 | -0.996 | -0.996 | 0 |
| -300.0 | -1.997 | -1.997 | 0 |
| -400.0 | -2.998 | -2.998 | 0 |
| -500.0 | -3.998 | -3.998 | 0 |
| -600.0 | -4.998 | -4.999 | 1 |

Scale Factor: 8.340 V/G (Limits: 8.250 to 8.417) Chk: __®__ PASS_√_ FAIL____

Zero: 0.004 VDC (Limits: -0.015 to 0.015) Chk __®__PASS__√__FAIL____

Deviation from Best Fit Limits: -5 to +5 mVDC Chk: __®___PASS_√_FAIL____

Operator: WEITZ Checked By: Robert Kibler Date: 8/24/96

*Figure 10 Typical Electrical Performance Data Sheet*

ALIGNMENT
Test No: 10

MEDA Model: TAM-2A S/N: EM
Electronics Temperature: 23.0 C Date: 08/25/96
Sensor Temperature: 23.0 C Time: 12:45:36

Input Power

| Supply | Voltage (VDC) | Current (mA) | Current Limit (mA) |
|---|---|---|---|
| 1 | 30.0 | 20.7 | 25.0 |

---

Applied Field: 600 mG

X Axis

| Angle | X | Y | Z |
|---|---|---|---|
| 0 | 0.000 | 0.000 | 5.000 |
| 90 | 0.000 | -5.000 | 0.000 |
| 180 | 0.000 | 0.000 | -5.000 |
| 270 | 0.000 | 5.000 | 0.000 |

Polar misalignment angle: 0.00 Degrees ( Tol. <= 0.25 Deg.)
Checked:_®_PASS_√_FAIL___

Y Axis

| Angle | X | Y | Z |
|---|---|---|---|
| 0 | 0.000 | 0.000 | 5.000 |
| 90 | 5.000 | 0.000 | 0.000 |
| 180 | 0.000 | 0.000 | -5.000 |
| 270 | -5.000 | 0.000 | 0.000 |

Polar misalignment angle: 0.00 Degrees (Tol. <= 0.25 Deg.)
Checked:_®_PASS_√_FAIL___

Z Axis

| Angle | X | Y | Z |
|---|---|---|---|
| 0 | 5.000 | 0.000 | 0.000 |
| 90 | 0.000 | -5.000 | 0.000 |
| 180 | -5.000 | 0.000 | 0.000 |
| 270 | 0.000 | 5.000 | 0.000 |

Polar misalignment angle: 0.00 Degrees (Tol. <= 0.25 Deg.)
Checked:_®_PASS_√_FAIL___

Operator: Bill Reviewed By: Robert Kibler Date: 08/25/96

*Figure 11 Typical Alignment Test Data Sheet*

### Frequency Response

The frequency response of the TAM-2 series magnetometers is measured by applying a white noise (constant power spectral density) field to the sensor axis under test and measuring the transfer function between the white noise input signal and the magnetometer output signal of the axis under test. The corner frequency is defined as the frequency where the magnitude of the transfer function is 3 dB below its value at dc.

### Calibration Coil Constant

The calibration coil constants of the TAM-2 series magnetometers are determined by applying a field to the sensor along the axis under test and then passing a current through the associated calibration coil to produce a field that opposes the applied field. The magnitude of the current is adjusted until the output voltage of the axis under test is zero within a prescribed error band. The current required to cancel the applied field is measured, recorded on a data sheet and used to compute the coil constant (mG/ma).

## *Random Vibration*

A vendor selected by MEDA performs the random vibration test. Table 6 is the standard vibration power spectral density function used to test each axis of the TAM-2 series magnetometers. The customer may specify another power spectral density function.

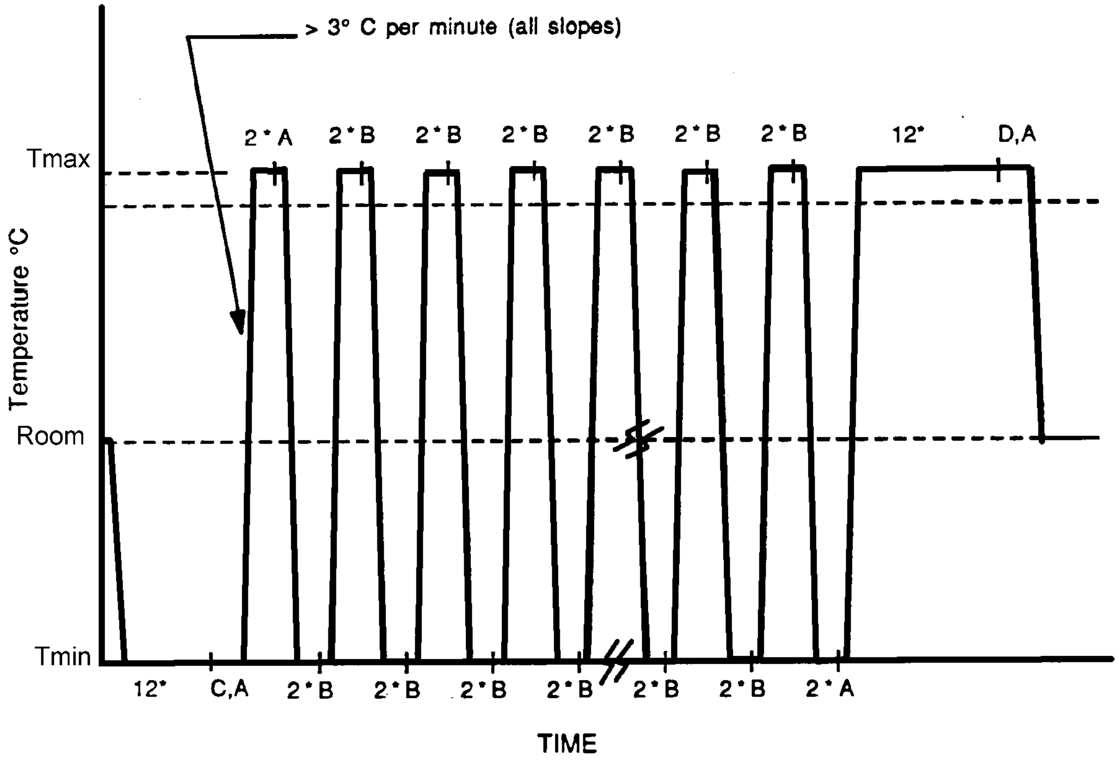
*Table 6 Acceptance Vibration Levels*

| **X and Y Axes** | | **Z Axis** | |
|---|---|---|---|
| **Frequency (Hz)** | **Level ($g^2$/Hz)** | **Frequency (Hz)** | **Level ($g^2$/Hz)** |
| 20 | 0.00071 | 20 | 0.015 |
| 150 | 0.04 | 70 | 0.18 |
| 600 | 0.04 | 355 | 0.18 |
| 200 | 0.0036 | 2000 | 0.0057 |
| Overall Level | 6.15 grms | | 10.39 grms |
| Test Time | 1 minute/axis minimum | | 1 minute/axis minimum |

The TAM-2 series magnetometers have been qualified at levels 6 dB above the ones shown in Table 6 with a test time of 3 minutes per axis.

## *Thermal Cycle*

Each TAM-2 series magnetometer is subjected to eight (8) thermal cycles as shown in Figure 12.



A. Electrical Performance tests are performed where indicated. Alignment test performed at temperature extremes of first cycle.

B. Electrical Performance tests are performed where indicated.

C. Cold Start.

D. Hot Start.

* Minimum number of hours at temperature before testing may begin.

*Figure 12 TAM-2 Standard Thermal Cycle Test*

## Thermal Burn-in

Upon completion of the thermal cycle tests, the TAM-2 is kept powered and at the maximum Acceptance Test temperature (Tmax) until the accumulated burn-in time (including thermal cycle) exceeds 200 hours.

## Final Inspection

The TAM-2 is visually inspected for any damage that might have occurred during testing. Discrepancies are recorded on the Final Inspection data page. All the test data are reviewed for discrepancies and the data is provided to Quality Assurance for End-Item-Data package preparation.

# END ITEM DATA PACKAGE

Each TAM-2 series magnetometer that is delivered is accompanied by an End-Item-Data package that contains all the required certifications, engineering drawings, instrument history and test data. Table 7 lists the major topics covered in a typical End-Item-Data package.

*Table 7 Typical End-Item-Data Package Contents*

| SECTION | TITLE |
|---|---|
| 1 | CERTIFICATIONS |
| 2 | DRAWINGS |
| 3 | INSTRUMENT QUALITY HISTORY |
| 4 | INSTRUMENT ASSEMBLY HISTORY |
| 5 | ACCEPTANCE TEST DATA PAGES |

# ENGINEERING ANALYSIS REPORTS

Listed below is the standard set of analyses that have been performed on the TAM-2 series magnetometers. Copies of these reports will be provided to the customer upon request. Revised or new analyses can be performed for an additional fee.

- Reliability Analysis
- FMEA
- Worst Case Analysis
- EMC Analysis
- Stress & Dynamic Analysis
- Mass Properties Report
- Thermal Analysis
- Radiation Vulnerability Assessment Report

# QUALIFICATION HISTORY

The TAM-2 series magnetometers are a derivative of the Schonstedt Instrument Company SAM-63C series space qualified magnetometers. Table 8 lists the history of the SAM-63C and TAM-2 series magnetometers from 1975 to the present.

*Table 8 TAM-2 Series Qualification History*

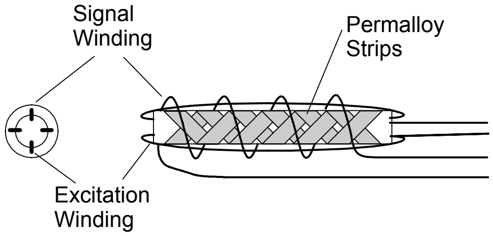
| MODEL | YEAR | SATELLITE | CUSTOMER | CONTRACT NO. |
|---|---|---|---|---|
| SAM-63C-5 | 1975 | Multimission Satellite, Solar Max, SM Repair, Landsat | GE/NASA | NAS5-23845 |
| SAM-63C-7 | 1980 | IRAS | Fokker | S753062 |
| SAM-63C-8 | 1981 | P80 Program | Rockwell/USAF | MC476-0210 |
| SAM-63C-9 | 1980 | Space Telescope | Bendix/LMSC | P/N 4172817 |
| SAM-61B-10 | 1981 | Dynamic Explorer B | GSFC | NAS5-25430 |
| SAM-63B-12 | 1980 | San Marco | Univ. of Rome | UA/7188 |
| SAM-63C-12 | 1981 | | GE/MMC | MMC-50021 |
| SAM-63C-13 | 1981 | Agena | LMSC/DOD | RC07E6600A |
| SAM-63B-14 | 1982 | | Ithaco/DOD | 46314 |
| SAM-63B-15 | 1982 | CRRES | Hanscom AFB AFSC | F19650-82-C 0024 |
| SAM-63C-15 | 1984 | GRO | TRW/GSFC | NAS5-27573 |
| SAM-63C-16 | 1982 | GEOSAT | APL/USN | N00024-81-C 5301 |
| SAM-63C-20 | 1983 | CRRES | BASD/MSFC | NAS8-34025 |
| SAM-63C-21 | 1984 | Space Telescope Spare | Bendix/LMSC | |
| SAM-63C-22 | 1981 | EXPLORER MACS | GE/GFSC | NAS5-30167 |
| SAM-63C-23 | 1985 | | LMSC/DOD | F33657-82C |
| SAM-63C-24 | 1985 | POLAR BEAR | JHU-APL | AC-17845 |
| SAM-63C-28 | 1988 | TOPEX/JPL | FSC/JPL | JPL-957849 |
| SAM-63C-29 | 1986 | GOES | FACC/GSFC | NAS5-29500 |
| SAM-63C-30 | 1988 | 1/MECB | Brazil | INPE-2703 |
| SAM-63C-31 | 1987 | Relay Mirror Experiment | BASD/AF | 01461 |
| SAM-63C-33 | 1990 | MSX | JHU-APL/USN | 605366-S |
| SAM-63C-34 | 1990 | SAX | AERITALIA | ECOP/DG/90/146 |
| SAM-63C-35 | 1991 | RADARSAT | BASG/CANADA | 01021 |
| SAM-63C-36 | 1991 | MMC-MACS | GE | HHMS01003 |
| SAM-63C-37 | 1991 | | LMSC/DOD | RYU1S041-O-A |
| SAM-63C-38 | 1993 | HST Repair | LMSC/GSFC | NAS5- |
| TAM-1 | 1995 | MACS-5 | LMAS | HVMS44022 |
| TAM-1A | 1996 | P81 | LMA | PP5-535055 |
| TAM-1B | 1996 | Gravity Probe "B" | LMMS | HG30A1250A |
| TAM-2 | 1996 | SBIRS-Low | TRW | 04723BRF6S |
| TAM-2A | 1997 | IMAGE | LMMS | HCBAL5001A |
| TAM-2B | 2000 | INDEX | Kawasho | ZB3789 |
| TAM-2C | 2001 | Swift | Spectrum Astro | 01-008 |

# FLUXGATE MAGNETOMETER THEORY

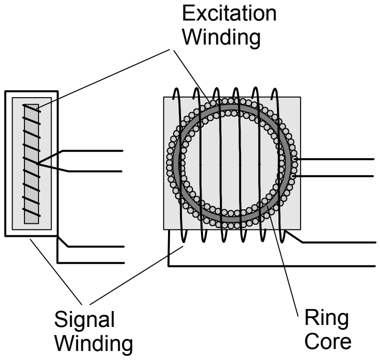
The fluxgate magnetometer has been and is the workhorse of magnetic field strength instruments both on earth and in space. It is rugged, reliable, physically small and requires very little power to operate. These characteristics, along with its ability to measure the vector components of magnetic fields over a 0.1 nT to 1 mT range from dc to several kHz, make it a very versatile instrument. Geologists use fluxgate magnetometers for exploration, geophysicists use them to study the geomagnetic field, satellite engineers use them to determine and control the attitude of their spacecraft, scientists use them in their research, and the military use them in many applications including mine detection, vehicle detection, and target recognition. Some airport security systems use them to detect weapons.

## The Fluxgate

The heart of the magnetometer is the fluxgate. It is the transducer that converts a magnetic field into an electrical voltage. There are many different fluxgate configurations. Two of the more popular ones are shown in Fig. 13. A very comprehensive explanation of the fluxgate principle and the different fluxgate configurations is given in Primdahl[1].



a) Schonstedt type



b) Ring core type

*Figure 13 Two popular fluxgate configurations*

The ring core fluxgate is constructed from a thin ribbon of easily saturable ferromagnetic material, such as 4-79 Permalloy wrapped around a bobbin to form a ring or toroid. As shown in Fig. 14, an alternating current is applied through a coil which is wound about the toroid. This creates a magnetic field that

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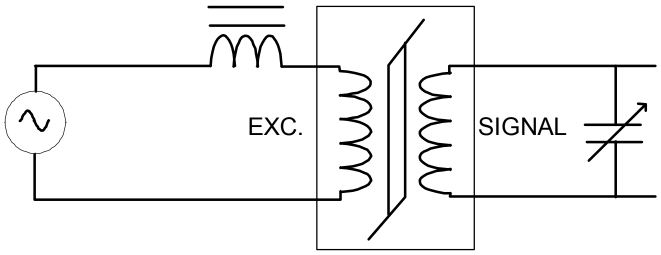
[1] F. Primdahl, The fluxgate magnetometer, *J. Phys. E: Sci. Instrum.*, **1**: 242-253, 1979.

circulates around the magnetic core. This magnetic field causes the flux in the ferrous material to periodically saturate first clockwise and then counterclockwise. A pickup (signal) winding is wrapped around the outside of the toroid. While the ferrous material is between saturation extremes, it maintains an average permeability which is much greater than that of air. When the core is in saturation, the core permeability becomes equal to that of air. If there is no component of magnetic field along the axis of the signal winding, the flux change seen by the winding is zero. If, on the other hand, a field component is present along the signal winding axis, then each time the ferrous material goes from one saturation extreme to the other, the flux within the core will change from a low level to a high level. According to Faraday's law, a changing flux will produce a voltage at the terminals of the signal winding which is proportional to the rate of change of flux.



Fluxgate

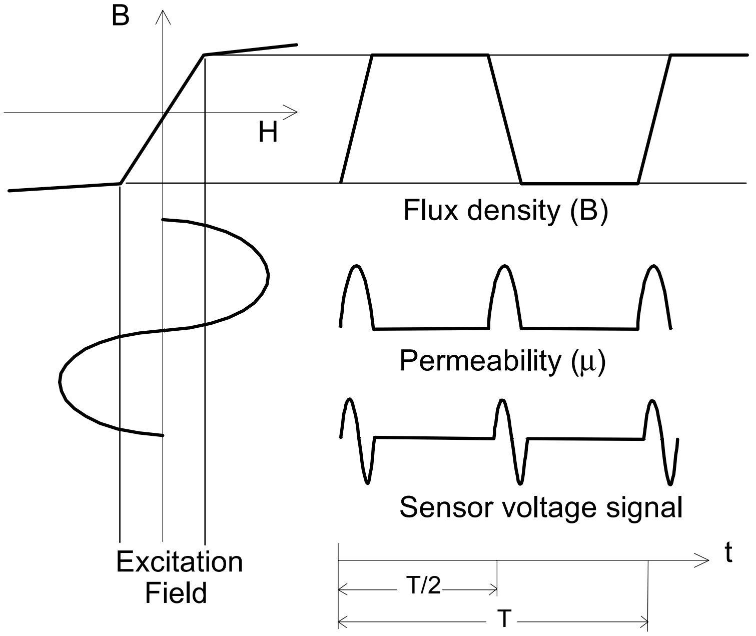


*Figure 14 Fluxgate waveforms*

For dc and low frequency magnetic fields, the signal winding voltage is

$$e(t) = nA\frac{d(\mu_0 \mu_e H)}{dt} = nA\mu_0 H\frac{d\mu_e(t)}{dt}$$

where $H$ is the magnetic field, $n$ is the number of turns on the signal winding, $A$ is the cross-sectional area of the signal winding and $\mu_e(t)$ is the effective relative permeability of the core.

As the core permeability alternates from a low value to a high value, it produces a voltage pulse at the signal winding output which has an amplitude that is proportional to the magnitude of the external magnetic field and a phase that indicates the direction of the field. The frequency of the signal is twice the excitation frequency since the saturation-to-saturation transition occurs twice each excitation period.

Consult Primdahl and Geyger[2] for comprehensive discussions about fluxgate effective permeability and signal characteristics as they relate to excitation field level, excitation waveform and winding geometry.

## *Signal Conditioning*

The signal from the fluxgate is an amplitude modulated suppressed carrier signal that is synchronous with the second harmonic of the excitation signal. In a simple low power magnetometer, this signal is converted to the base band using a synchronous demodulator, filtered and presented as the final output. Example circuits are given in Pellerin and Acuna[3] and in Marshall[4]. The accuracy of magnetometers that use this open loop architecture is limited by the linearity of the core's magnetization curve and is about 5% for earth's field (600 mG) applications.

More precise and stable magnetometers use magnetic field feedback rather than the open loop structure described above. A simplified schematic of a typical second harmonic field feedback fluxgate magnetometer is shown in Fig. 15. The circuitry to the left of the fluxgate is called the excitation circuit. It consists of an oscillator tuned to twice the excitation frequency, a flip-flop which divides the oscillator frequency by two and a power amplifier which is driven by the flip-flop and, in turn, provides the excitation current to the excitation winding.

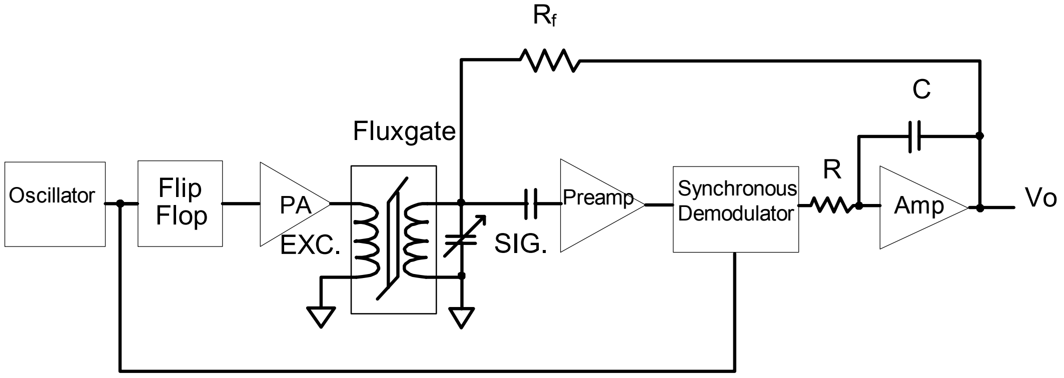


*Figure 15 Typical circuit configuration for a field feedback fluxgate magnetometer*

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[2] W. A. Geyger, *Nonlinear-Magnetic Control Devices*, New York: McGraw Hill, 1964.

[3] C. J. Pellerin and M. H. Acuna, A miniature two-axis fluxgate magnetometer, *NASA Technical Note,* TN D-5325: NASA, 1970.

[4] S. V. Marshall, A gamma-level portable ring-core magnetometer, *IEEE Trans. on Magnetics*, **MAG-7** (1): 183-185, 1971.

The circuitry to the right of the fluxgate is called the signal channel circuit. It amplifies the output from the fluxgate signal winding, synchronously demodulates the ac signal using the oscillator signal as a reference, integrates and amplifies the base band output and then feeds back the output through a resistor to the signal winding. The fed back signal produces a magnetic field inside the sensor which opposes the external field. This keeps the field inside the sensor near zero and in a linear portion of the magnetization curve of the ferromagnetic core.

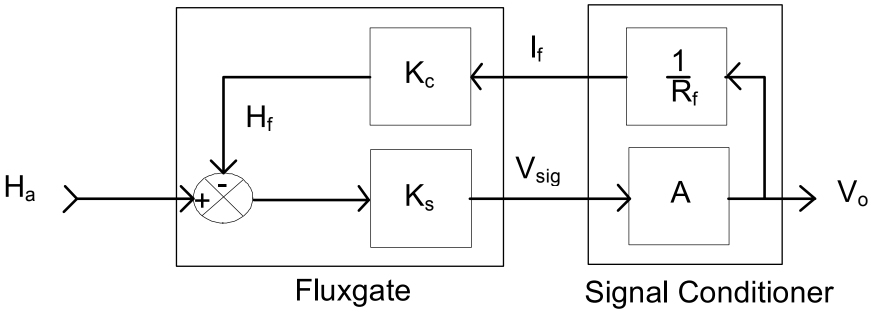

*Figure 16 Block diagram of a field feedback fluxgate magnetometer*

The flow diagram for the magnetometer is given in Fig. 16. The external field $H_a$ is opposed by the feedback field $H_f$, and the difference is converted into a voltage signal ($K_s$ represents the transfer function from field to voltage). This signal is amplified ($A$) and the amplified signal is converted into a current $I_f$ and then into the feedback field ($K_c$ represents the transfer function from current to field). The overall transfer function for the magnetometer is

$$\frac{V_0}{H_a} = \frac{AK_s}{1+\frac{K_c AK_s}{R_f}}. \quad (1)$$

The amplifier gain is normally very high such that the second term in the denominator is much larger than one and Eq. 1 reduces to

$$\frac{V_0}{H_a} = \frac{R_f}{K_c}.$$

Under these circumstances, the transfer function becomes almost completely determined by the ratio of $R_f$ (the feedback resistor) to $K_c$ (the current-to-field coil constant of the sensor winding). Both of these constants can be very well controlled. The consequence of this circuit topology is a highly stable and accurate magnetometer that is insensitive to circuit component variations with temperature or time. An accuracy of 1% over a temperature range of -80°C to 70°C is easily achievable. Accuracy and stability can be improved by using a current feedback circuit, like the one described by Acuna[5], that compensates for the resistance of the signal winding or by using a separate feedback winding and a high quality voltage-to-current converter instead of a simple feedback resistor.

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[5] M. Acuna, C. Scearce, J. Seek and J. Schelfiele, The MAGSAT vector magnetometer-a precise fluxgate magnetometer for the measurement of the geomagnetic field, *NASA Technical Report*.