GODDARD SPACE FLIGHT CENTER SPACECRAFT MAGNETIC TEST FACILITY RESTORATION PROJECT

Robert Vernier, Todd Bonalksy and Dr. James Slavin
NASA Goddard Space Fight Center

ABSTRACT

The Goddard Space Flight Center Spacecraft Magnetic Test Facility (SMTF) was constructed in the 1960's for the purpose of simulating geomagnetic and interplanetary magnetic field environments. The facility includes a three axis Braunbek coil system consisting of 12 loops, 4 loops on each of the three orthogonal axes; a remote Earth field sensing magnetometer and servo controller; and a remote power control and instrumentation building. The inner coils of the Braunbek system are 42-foot in diameter with a 10-foot by 10-foot opening through the outer coils to accommodate spacecraft access into the test volume. The physical size and precision of the facility are matched by only two other such facilities in the world. The facility was used extensively from the late 1960's until the early 1990's when the requirement for spacecraft level testing diminished. New NASA missions planned under the Living with a Star, Solar Terrestrial Probes, Explorer, and New Millennium Programs include precision, high-resolution magnetometers to obtain magnetic field data that is critical to fulfilling their scientific mission. It is highly likely that future Lunar and Martian exploration missions will also use precision magnetometers to conduct geophysical magnetic surveys. To ensure the success of these missions, ground-testing using a magnetic test facility such as the GSFC SMTF will be required. This paper describes the history of the facility, the future mission requirements that have renewed the need for spacecraft level magnetic testing, and the plans for restoring the facility to be capable of performing to its original design specifications.

SPACECRAFT MAGNETIC TEST FACILITY DESCRIPTION AND HISTORY

The Spacecraft Magnetic Test Facility (SMTF) was conceived of in the early 1960's as part of a suite of test facilities designed to support the application of magnetic sensing to space flight missions. The test facility suite included two quiet laboratories equipped with a 12-ft diameter and 15 ft square Braunbek coil, as well as a Magnetic Instrument Test Laboratory (MITL) housing a 20 ft diameter Braunbek coil. Figure 1 shows the layout of the facilities. The original name of the SMTF was the Attitude Control Test Facility (ACTF) and as the name implies it was intended to provide the Goddard Space Flight Center (GSFC) with the capability to evaluate certain aspects of the problem of controlling the attitude of spacecraft in the magnetic environment experienced during space flight. The ACTF was intended to have the following capabilities:

- A controllable magnetic field large enough to accept complete flight-configuration spacecraft and components larger than can be tested in the MITL.

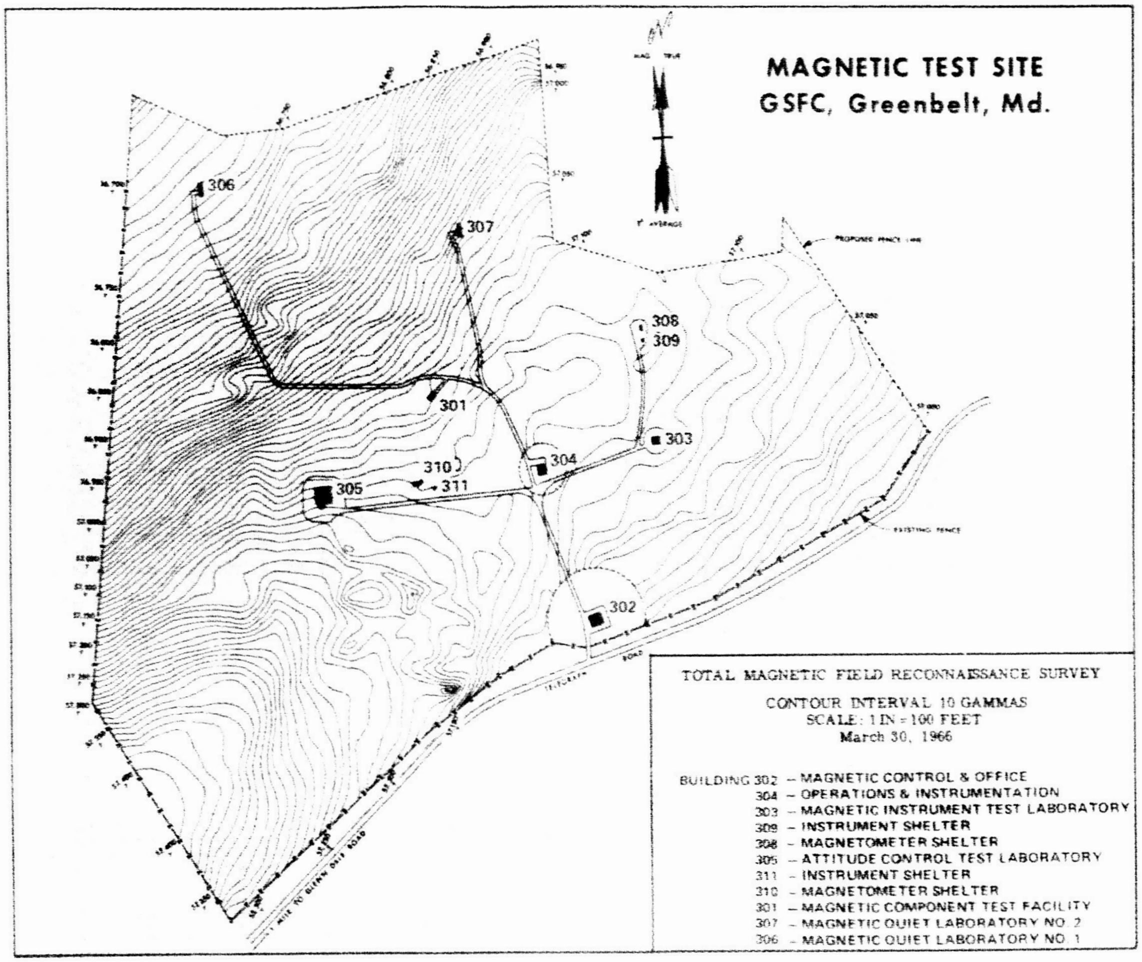

Figure 1: Layout of Magnetic Test Suites within the SMTF Complex.

- Controlled means for simulation relative motion between a spacecraft under test and surrounding magnetic fields in space in order to determine the resulting forces acting on the spacecraft.

- Capability of mapping contours of a spacecraft's own inherent magnetic field in a controlled magnetic environment.

- A means to verify the effect of magnetic forces deliberately produced to adjust and correct the inherent magnetic characteristics of spacecraft, subsystems, and components for attitude control or removal of interference with onboard magnetic instruments.

The central feature of the SMTF was envisioned to be the large arrangement of coil subsystems capable of producing at its center a homogeneous magnetic field 6 feet in diameter and controllable from Earth ambient to zero intensity with useful controllable work space extending to a considerably greater diameter. Electronics controls provide automatic compensation for fluctuations in Earth ambient magnetic field and a capability for manipulating the resultant controlled field in intensity and direction. Table 1 summarizes the SMTF technical capability.

Table 1: Summary of SMTF Technical Capabilities.

Physical Access	
• Building Access Opening	4.3 x 4.6 meters (14'9" wide x 15'3" high)
• Coil Access Opening	3.0 x 3.0 meters (10' wide x 10' high)
Static Magnetic Field Environment	
• Magnitude	0 to 60,000 nano-Tesla each axis
• Accuracy and Stability	0.5 nano-Tesla in 24 hours
• Homogeneity	0.001% for spherical diameter of 1.8 meters (6')
Dynamic Magnetic Field Environment	
• Magnitude	0 to 60,000 nano-Tesla each axis
• Rate	0-100 rad/sec
• Accuracy and Stability	2.0%

The Braunbek configuration chosen for the coil system affords a large volume of homogeneous field relative to its physical dimensions, provides a large access to the work space without the need for moving and repositioning any coil loops, and assures the simplest circuit for maintaining a precise relationship among loop currents since all loops on any axis are connected in series. Each of the three orthogonal coil sets has two large inner coil loops and two smaller outer coil loops. The orthogonal coil loops differ slightly in diameter to avoid physical interference. Each coil set has seven separate windings differing in function, number of turns, and wire size. The winding designations and functions are:

- Geomagnetic - *Mean Earth's Field Cancellation*
- Artificial - *Fixed and Dynamic Field Vectors*
- Variational - *Diurnal Variation Cancellation*
- Temperature - *Temperature Compensation*
- Gradient - *Field Gradient Compensation*
- Auxiliary - *Spare Windings (two sets)*

Coil dimensions and spacing are given in Table 2 and winding parameters are given in Table 3. Coils are wound from aluminum wire to match the expansion and contraction of the aluminum coil forms and support structure. Each turn of the winding is wound on the coil form in a uniform circle with connections made to the next turn at a junction box on each coil form. The transition to copper power control cables are made through a welded junction.

Table 2 Coil Dimensions and Spacing.

	Z (Vertical)	H (North-South)	D (East-West)
Diameter			
- Inner Coils	12.7 meters (41.7 ')	12.2 meters (40.1')	11.9 meters (39.0')
- Outer Coils	9.78 meters (32.1')	9.5 meters (31.2')	9.21 meters (30.2')
Separation			
- Inner Coil Pairs	3.5 meters (11.5')	3.4 meters (11.2')	3.0 meters (10.0')
- Outer Coil Pairs	10.7 meters (35.1')	10.5 meters (34.5')	10.1 meters (33.0')

Table 3 Winding Parameters.

Axis	Geomagnetic	Artificial	Variational	Temperature Compensation	Spares	Gradient
Z- Axis (Vertical)	11 Turns No. 2 AWG	11 Turns No. 2 AWG	11 Turns No. 8 AWG	2 Windings 1 Turn Each No. 14 AWG	2 Windings 10 Turns Each No. 8 AWG	1 Turn No. 14 AWG
D- Axis (East-West)	13 Turns No. 4 AWG	13 Turns No. 3 AWG	13 Turns No. 8 AWG	2 Windings 1 Turn Each No. 14 AWG	2 Windings 10 Turns Each No. 8 AWG	1 Turn No. 14 AWG
D- Axis (East-West)	12 Turns No. 4 AWG	12 Turns No. 2 AWG	12 Turns No. 8 AWG	2 Windings 1 Turn Each No. 14 AWG	2 Windings 10 Turns Each No. 8 AWG	1 Turn No. 14 AWG

Great care was taken in the design of the structure to minimize thermally induced stress that may distort the coils and result in non-linear magnetic fields effects. The aluminum structure was designed to be attached to the floor at a single support, allowing all other support columns to slide on hard coated aluminum plates. The structure holding the coils was designed to be stiff relative to the coil forms so that coil alignment and figure adjustments could be made to the coil forms without affecting other coils or other segments of the same coil. Each coil form is attached to the structure by 16 adjusting screw mechanisms that allow independent fine adjustments to be made in the radial, axial, and tangential direction. The mechanism provides 1.25 inches of adjustment in each axis with the purpose of allowing accurate circularity, location, and orientation of the coils so that the field homogeneity requirements could be achieved. Figure 2 is a photograph of the coil structure prior to installation of the working level floor. Figure 3 shows the coil adjusting mechanism.

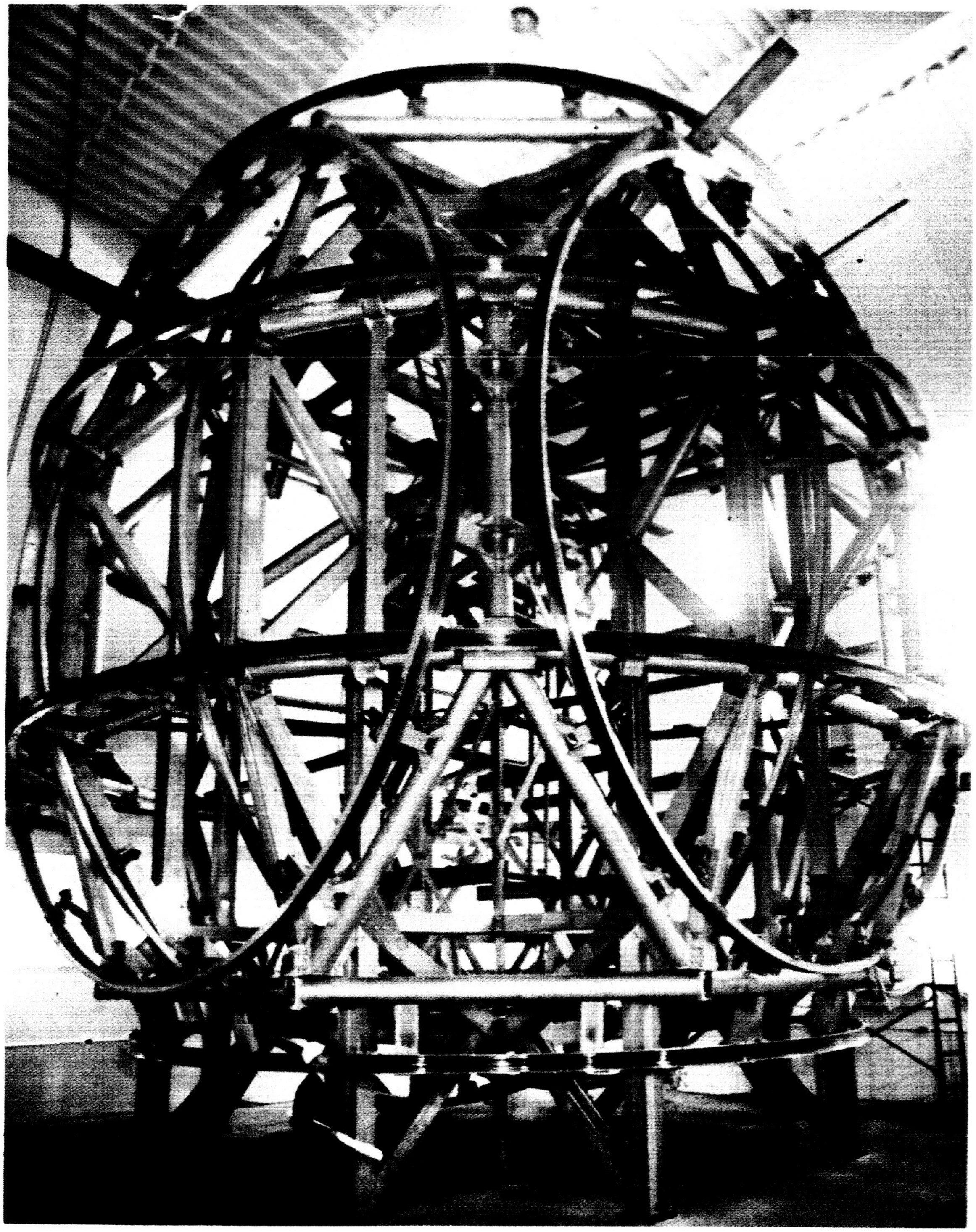

Figure 2: SMTF Braunbek Coil Structure Prior to Center Floor Installation (c1964).

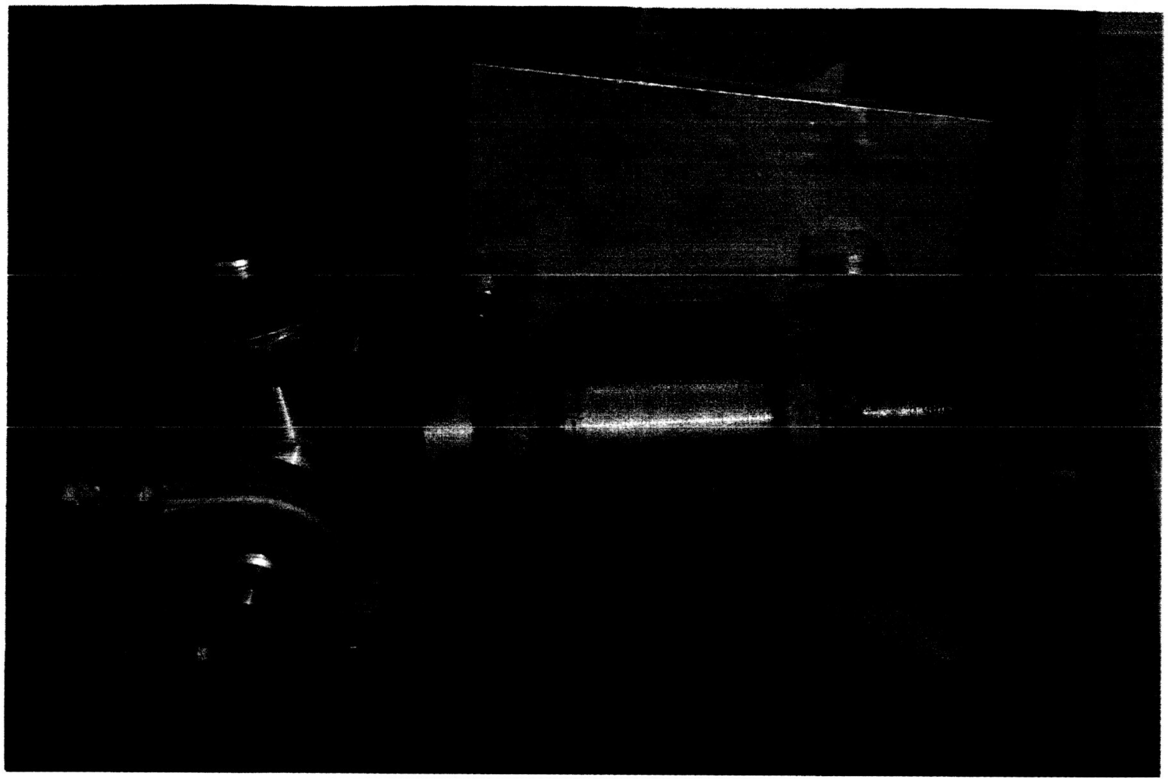

Figure 3: Coil Form Tri-Axial Screw Adjustment Mechanism.

The magnetic field control system utilizes three independent electronic control systems, one to control the geomagnetic field coils, a second to control the artificial field coils, and the third for controlling the gradient field coils. The geomagnetic field control system measures the Earth's field remote from the influence of the main SMTF field and compensates for any diurnal variations in the Earth's field. This was accomplished via an automatic geomagnetic servo control loop. The artificial field control system commands the artificial field windings so to control either statically or dynamically the magnitude and direction of an artificial field. The artificial field was then superimposed onto the geomagnetic field. The gradient field control system was designed to control the gradient field coils to compensate for any linear distortion in the geomagnetic fields induced by local variations.

MAGNETIC CLEANLINESS REQUIREMENTS FOR SCIENCE MISSIONS

Utilization of the SMTF has declined over the past decade and it is currently rarely used for its original purpose of investigating and verifying spacecraft attitude control systems. The advent of large spacecraft that physically cannot use the facility, sophisticated attitude control computer simulations, and precision instrumentation and techniques that do not require a special facility, resulted in a significant reduction in the SMTF workload. The small workload did not warrant the investment of significant maintenance resources. Therefore, only the most serious repairs were made keeping the facility at a minimal operational status with reduced reliability. This resulted in a further decline in the customer base.

Recently however, there has been a renewed interest in the requirement for a large spacecraft magnetic test facility. Scientific missions with primary requirements for precision magnetic field measurements will utilize constellations of small spacecraft and will need a precision ground test facility to verify that mission requirements will be met. Earth science missions that map the ever changing geomagnetic fields including Magsat, Oersted, and SWARM have end-to-end accuracy requirements on the measured magnetic field of ±1 nano-Tesla (nT) in 50,000 nT. This error includes not only the uncertainty in the knowledge of the magnetic fields arising from the spacecraft, but also errors internal to the magnetometers and the attitude transfer system that allows the magnetic vectors to be registered in inertial coordinates.

Space science missions that investigate the physics of the magnetic fields, dynamic plasmas, and energetic particles (that permeate the solar system from the solar corona to planetary magnetospheres, ionospheres, and outward to the local interstellar medium) often have even more restrictive magnetic cleanliness requirements. In these cases it is not that high absolute accuracy is needed, but rather that the magnetic fields to be measured are very weak (in the order of $0.1\,\text{nT} - 10\,\text{nT}$). Under these circumstances stray magnetic fields, especially if they vary significantly in time, can create a signal-to-noise and/or aliasing problems. The effects of these stray spacecraft magnetic fields are particularly deleterious to the measurement of low frequency plasma waves and the properties of naturally occurring electric current sheets both of which are essential features of space plasmas. Typical magnetic requirements for such space science missions (e.g., NASA's Magnetospheric MultiScale Mission) would include fixed stray fields at the magnetometer sensor of <0.1 nT while the maximum amplitude for variable fields $(0.1-100\,\text{Hz})$ is $<0.03\,\text{nT}$.

Stringent magnetic requirements can only be met through a careful multi-layer design approach. This includes avoiding current loops in the power system or in the spacecraft structure as a result of poor grounding, employing twisted pairs for power and return leads wherever possible, screening all components to minimize the amount of magnetic material present, careful mounting of magnetometers on long booms, and extensive system level testing to ensure compliance with the science-driven magnetic requirements. Spacecraft typically exhibit complex multi-polar magnetic fields at distance of less than 1 vehicle diameter and become predominantly dipolar by distances of 2 vehicle diameters where the boom mounted magnetometers usually reside. Hence, the accurate characterization of spacecraft fields at the location of magnetic field sensors requires accurate tracking and cancellation of the large ($\sim 50{,}000\,\text{nT}$) geomagnetic field and must be located remote from modern sources of magnetic noise such as power systems, elevators, and automobiles. Furthermore, the background magnetic field must be free from large gradients that would give rise to spurious magnetic signals in the presence of any mechanical motion or vibration of the spacecraft or the magnetometers used in the magnetic mapping process.

System level compliance testing for missions requiring the highest order of magnetic cleanliness is only possible if a large magnetic coil facility is available that can cancel the geomagnetic field and provide a quiet, uniformly stable, low intensity magnetic field environment. Only then is it possible to measure spacecraft magnetic fields of the order $0.1\,\mathrm{nT} - 10\,\mathrm{nT}$. Expressed as requirements, the test facility must be able to create a magnetic field over a volume of $\sim 8\ \mathrm{m}^2$ that is uniform to within ± 1 nT, whose magnitude can be pre-determined with an accuracy of ± 1 nT with a noise level of < 1 nT ($0 - 10\,\mathrm{Hz}$ rms). Additionally, the magnetic test facility must be able to impose vector changes in 3 directions and are orthogonal to ± 10 arcsec, whose drift will be $< \pm 1$ nT over a 12 hour period, and can impose low frequency (i.e. < 10 Hz) magnetic waveforms within the test volume for simulating spacecraft rotation and related dynamics. Finally, if flight programs are to embrace magnetic requirements and accept compliance testing, the testing facility must offer a suitable environment to handle flight hardware in a safe, low risk manner. As well, the magnetic test facility must function in an efficient manner so to maximize utility and minimize schedule and cost impacts.

SPACECRAFT MAGNETIC TEST FACILITY RESTORATION PROJECT

The renewed interest and requirements for a large precision spacecraft magnetic test facility resulted in the development of a restoration project for the GSFC SMTF. A previous attempt to improve the declining performance of the SMTF facility was made in 1984 with the integration of a series of new current amplifiers. The amplifiers were installed to provide better power regulation to each of the orthogonal Braunbek coils. Unlike the original 1960's linear current amplifiers, the new amplifiers implemented a PWM (Pulse Width Modulated) topology. This made the new amplifiers much smaller and far more efficient than the original linear amplifiers. However, due to the nature of the new amplifier's PWM topology, their limited dynamic range compromised the original specifications of the SMTF facility. Equally, inadequately filtered PWM switching noise and offset drift of these amplifiers imposed additional problems to the system. Therefore, improvements to the SMTF facility using the new PWM amplifiers were marginal at best.

Due to the uncertainty in the application of the new PWM current amplifiers and the requirement to maintain the system operational during modifications, it was decided to leave the original 1960's linear amplifiers in place as backup. To do this a series of high current switches were installed in order to have either the original linear current amplifiers, or the new PWM current amplifiers, engaged at any given time. This required an extensive rewiring of the SMTF power and control infrastructure – greatly complicating an already complicated control system. In the end what was left was a control system that was unreliable and unstable in one switch position, or more reliable but with more noise and limited dynamic range in the other.

RESTORATION STAGE 1 – FACILITY ASSESSMENT

An engineering assessment of the SMTF power and control system was made in the Spring of 2004. It was found that although the original linear current amplifiers were still in the system via the aforementioned power switches, they had degraded to a point where it was unrealistic and uneconomical to restore them to their original operating condition. Furthermore, the original geomagnetic cancellation control system (the controls that monitors and corrects for any observed diurnal changes) was still in use and simultaneously connected to both the original linear power amplifiers and the PWM current amplifiers installed in 1984. This "shared" wiring of the geomagnetic cancellation control system with both the original and PWM power amplifiers resulted in multiple ground-loops which in turn caused notable control system instability and self oscillation (i.e., "ringing"). This inevitably lead to a closer and more detailed examination of the geomagnetic cancellation control system.

Originally, the Earth's field (or geomagnetic) cancellation control system was composed of 3 optically pumped Rubidium magnetometers enclosed within 3 tri-axial Helmholtz coils. That is, since the original magnetometers were scalar, 3 separate Rubidium magnetometers and 3 separate tri-axial Helmholtz coils were required to properly detect and cancel the orthogonal components of the Earth's magnetic field (i.e., North/South, East/West, and vertical components). Furthermore, the output of the original optically pumped magnetometers were frequency modulated in that the frequency of their outputs were linearly proportional to the magnitude of flux density sensed in its particular component direction. This was ideal since the magnetometer output signals needed to travel approximately 600 ft. back to where the geomagnetic feedback controller and power amplifiers were located. Being frequency modulated, this effectively eliminated most common and differential mode interferences (i.e., noise) due to the long transmission.

However, in the mid 1970's after repeated electrical and mechanical problems with the 3 original optically pumped magnetometers, it was decided to replace all 3 of the scalar magnetometers with 1 tri-axial (i.e., vector) fluxgate magnetometer. This in turn required only 1 geomagnetic sensing Helmholtz coil since each Helmholtz coil assembly contained all 3 orthogonal cancellation coils. Thus, with a single Helmholtz coil assembly and a single fluxgate magnetometer, the Earth's magnetic field could be properly detected and negated.

The switchover from scalar to vector magnetometer systems in the mid 1970's left one important factor un-addressed – that was, how to transmit the vector magnetometer output signals, now 3 low-voltage analog outputs, back to the controller with optimum common and differential mode noise rejection. An obvious choice would have been to convert the analog voltage signals at the magnetometer source to proportion output frequencies (i.e., using serial voltage-to-frequency converters) so that the original scalar magnetometer feedback link could still be used effectively. This however was not done and the output of the vector magnetometer was left as 3 low-voltage analog signals. Additionally, given the output of the original scalar magnetometers were frequency modulated, their 600 ft transmission link back to the geomagnetic controller used common RG-58/U coaxial cable. Subsequently, the low-voltage analog outputs of the vector magnetometer were transmitted back to the geomagnetic controller utilizing these same coaxial cables, resulting in large common and differential mode interferences due to the length of this transmission. In the years to follow, it is clear that there have been numerous attempts to rectify the noise issue caused by this arrangement. At the time of the Spring, 2004 assessment, it was apparent that all such attempts had failed since this noise issue was still unacceptably high; thus, further degrading the performance of the SMTF facility relative to its original specifications.

RESTORATION STAGE 2 – CLEAN UP

In order to improve the power quality and thus the magnetic stability of the SMTF coil facility, all of the original power amplifiers, geomagnetic cancellation controls, and various system modifications had to be removed. This entailed removing all of the 1984 modifications including the power switches between the original linear and updated PWM current amplifiers. As well, it was found in the above assessment that the geomagnetic sensing magnetometer, a ring-core fluxgate, had substantial offset drift. Given this magnetometer's age and degraded condition, it was decided to remove the vector magnetometer equipment including all associated coaxial cabling.

RESTORATION STAGE 3 – REFIT TO DATE

Since it was discovered that the original 1960's linear current amplifiers were too degraded for repair, it was decided to temporarily reinstall the PWM current supplies. This entailed wiring the PWM supplies directly to the coil system via a grounding switch. When the facility is not in use, this switch effectively isolates all orthogonal coil sets from the current amplifiers while simultaneously grounding each coil and transmission cable so to eliminate electrostatic charge from building up within the coil system. As well, this switch has been installed with an automatic emergency release mechanism that disengages the coils from the current amplifiers if an over-current/over-voltage condition is detected and the current amplifiers fail to disable themselves. This redundancy offers a high degree of circuit protection for the SMTF coil assembly.

As mentioned, the geomagnetic sensing and cancellation control systems were also removed due to their degraded condition. In their place, a new geomagnetic sensing magnetometer and control electronics were installed. The newly installed vector magnetometer is an ultra-low noise fluxgate whose low voltage tri-axial outputs are digitized to eliminate any common and/or differential mode interference due to the 600 ft. transmission link back to the controller. Once at the controller the digitized magnetometer information is read serially into a microcontroller running a proportional/integral (PI) control algorithm. Within this algorithm both proportional and integral gains have been selected as to optimize the control and stability of the geomagnetic cancellation servo-loop as per the intended SMTF specifications. As well, the microcontroller is monitored and controlled by a graphical interface program running within the Microsoft Windows environment. This graphical interface enables the operator of the coil facility to both monitor and control all aspects of geomagnetic cancellation, servo-lock, and artificial field operations.

RESTORATION STAGE 4 – FUTURE WORK

Although the PWM current supplies provide the SMTF coil facility with sufficient power and efficiency, their limited dynamic range and offset instability cause the SMTF to operate just outside its intended specifications. Therefore, new current supplies are currently being developed to allow the SMTF to operate at its full capability. The new current supplies are comprised of both linear and switch mode power topologies. The linear portion of the supplies provides highly stable, ripple-free output current via high power FET drivers. The switch mode portion of the supplies provides a highly regulated, isolated, and noise-free power platform for the linear output stages. As well, in order to maintain the high degree of current regulation required by the SMTF coil facility, the supplies have been designed using a multiple control-loop architecture. By this hybrid arrangement it was found that this topology provides a high degree of performance while maintaining the smallest possible amplifier footprint.