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The THEMIS Magnetic Cleanliness Program

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Abstract The five identical THEMIS Spacecraft, launched in February 2007, carry two magnetometers on each probe, one DC fluxgate (FGM) and one AC search coil (SCM). Due to the small size of the THEMIS probes, and the short length of the magnetometer booms, magnetic cleanliness was a particularly complex task for this medium sized mission. The requirements leveled on the spacecraft and instrument design required a detailed approach, but one that did not hamper the development of the probes during their short design, production and testing phase. In this paper we describe the magnetic cleanliness program's requirements, design guidelines, program implementation, mission integration and test philosophy and present test results, and mission on-orbit performance.

Keywords THEMIS · Magnetic cleanliness · Spacecraft cleanliness

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1 Introduction

As with other space missions where a good measurement of the magnetic field is a primary mission requirement (Anderson et al. 2008; Kugler 2001; Narvaez 2004), the need to limit

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and calculate the spacecraft induced magnetic field is critical. Due to the small size of the THEMIS bus and the short length of the magnetometer booms, approximately 2 m for the Fluxgate Magnetometer (FGM), 1 m for the Search Coil Magnetometer (SCM) (Angelopoulos 2008), it was necessary to review subsystems and components early on in the program. To do this a Magnetics Review Board (MRB) was established that set out a Magnetics Control Plan (MCP).

The objectives of the plan were to; establish overall responsibility for magnetic cleanliness; state the system-level magnetic requirements; establish a magnetic moment budget; list special considerations and requirements for worst offender subsystems and assemblies; provide generic subsystem and assembly design requirements and guidelines; describe magnetic test methods and procedures for performing tests on subsystems and assemblies; and provide methods for preventing subsystems/assemblies from becoming magnetically contaminated.

Although the requirements did allow a small level of remnant spacecraft induced field, this was small enough to require that even unlikely items needed to be checked and recorded. It was realized early on, that even if each subsystem's magnetic moment was a small fraction of the magnetics budget, all together could easily add up and be greater than the requirement. Therefore care was taken to measure components, alleviate problems and compare all subsystems performance in order to achieve a low cost, scientifically optimal solution that impacted the project development the least.

2 Requirements

The requirements for the spacecraft to meet were levied on the instruments and the spacecraft contractor early in the program. These requirements were based on a trade-off between science objectives and engineering possibilities. The requirement for the DC magnetics was that the magnetic field generated by the Probe should not exceed 5 nT at the location of FGM sensor. The 5 nT requirement is derived from the stability requirement that the magnetic field measurement to be stable and known at the sensor to within 0.2 nT over 12 hours with a reasonable thermal fluctuation of the tentative error sources on the spacecraft. The stability of the probe induced field was set to be 0.1 nT over 12 hours.

The requirement for the AC magnetic noise generated by the Probe was driven by the location of the SCM sensor, the expected instrument sensitivity, and the amplitude of relevant geophysical phenomena in the regions of interest. Accounting for the locations of the sensor, the AC noise requirement referenced on a common 1 m distance from the spacecraft is shown in Fig. 1. Further information about the sensitivity and performance of the magnetometers is contained in the respective instrument papers (Auster et al. 2008; Roux et al. 2008).

3 Parts Selection, Design, Modeling and Early Testing

Key to the success of the magnetic cleanliness effort was early identification of potential sources of magnetic contamination. Starting this work early with the spacecraft contractor, Swales Aerospace (now ATK Space), enabled the magnetics requirements to be inserted in the procurement process. Working with vendors who understood the magnetics issue or by educating them in the importance of correct material choice was key. Having knowledgeable personnel who had experience from past programs helped enormously by providing advice

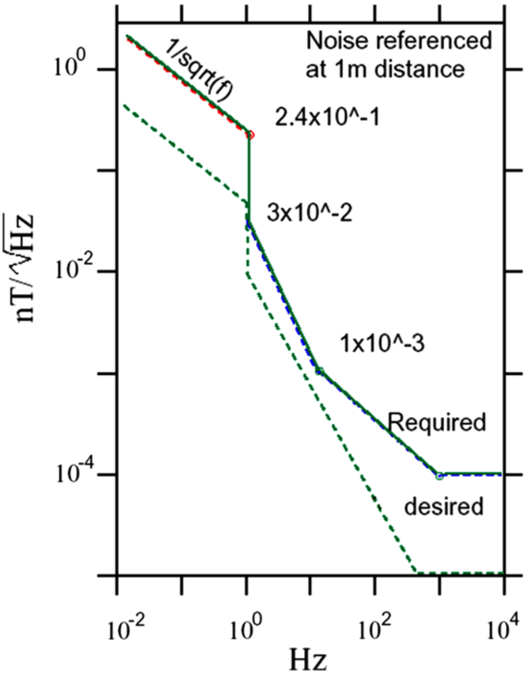


Fig. 1 AC magnetic noise level requirement (*solid curves*) and goal (*dashed curves*) at 1 m from the spacecraft. *Abscissa* is frequency in Hz. *Ordinate* is amplitude spectral density in nT/$\sqrt{}$Hz

and reassurance that the goals set out were obtainable. The MCP was distributed amongst the team and the magnetic items were identified and tracked. A survey of THEMIS components identified the main offenders. These were grouped into three categories; Hard Perm Fields including SST magnets, EFI Motors, Latch valves, Thruster valves, Tanks; Soft Perm Fields including Mu metal shielding, Welding, kovar cell interconnects; and AC Fields including Solar panels, Current loops, Battery, RF components and Power converters. Special considerations and plans were then outlined for each item. Examples of magnetic subsystem items are detailed below.

3.1 Solid State Telescope Magnets

As part of the Solid State Telescope instrument, Sm-Co permanent magnets were used to deflect electrons from the ion sensor. By matching the magnets closely, it was possible to attain the necessary field inside the sensor and have the field outside mostly cancel in the dipole regime. The non-canceling field was made up of the small unbalanced dipole field and quadrupole field which falls off as $1/r^4$. This resulted in a field of approximately 1 nT at 2 m. Pairs of SST sensors were also matched to ensure that the remnant field at the sensor for each spacecraft fell below the requirement. The Sm–Co magnets are extremely stable over time and temperature and so this field will not drift significantly over the course of the two-year mission lifetime. The testing also showed that orientation of the sensors would also help to reduce the DC field at the location of the FGM sensor.

3.2 Electric Field Instrument Motors

The second potentially large magnetic source in the instrument suite was from the Electric Field Instrument (EFI) Spin Plane Booms (SPB) that house brushed motors used to deploy wire booms from the probe. The magnets inside the booms were sufficiently strong to require shielding. Several shielding schemes were tried and tested before selecting a combination of Co-Netic AA and Netic S3-6 materials. This resulted in a field of less than 1 nT at 2 m from the sum of all SPB contributions.

3.3 Spacecraft Reaction Control System

The probe thrusters were selected to operate with a soft internal core. Redundant solenoids within them were wired anti-parallel, such that their operations would produce a remnant field in the soft cores that had a net quadrupole field, and thus a sharp drop off at distances comparable to the thruster dimension. Latch valves also were selected and wired anti-parallel to the internal solenoid wiring. However, due to their design the remnant field depended on the latch valve state, and thus changing the latch valve position changes the spacecraft magnetic field. Additionally a permanent small magnet (for position sensing) was a contributor to the total field from the propulsion system. Anti-parallel mounting of the latch valve sensing magnet, in its open (nominal) position was designed into the propulsion system tubing, in order to eliminate the total field at a distance, again by imparting a quadrupole field to the combined, two-latch valve system of the THEMIS propulsion system design. Inconel 718 propulsion tanks were approved for use on the THEMIS mission before the preliminary design review, based on analytical calculations of Inconel properties, and testing of scrap tanks at UCLA. Finally, structural welding on components such as the propulsion system pipes and tanks were done in accordance with mil standards, and fill material selection was based on fracture toughness and other mechanical properties, not driven by magnetic requirements but welds came out magnetically clean when tested. The propulsion system pipes were built from non-magnetic 304L stainless steel.

3.4 Spacecraft Power System

Current loops were minimized, by using the standard method of twisting power and return lines together. This was also extended to the design of the heaters and thermostat wiring. In the case of the solar arrays this required considerable effort during the design of the panels. By backwiring two return wires (return trace laid under the solar array cells on the forward lines) the field was reduced to first order quite significantly. Nearby strings (four per panel) were designed to conduct current in a way that when a panel was illuminated the four adjacent strings had such polarity so as to reduce the total field at the SCM and FGM sensors. Modeling of the stray field caused by the panels was performed by the vendor (COI-ATK). Analysis and modeling was repeated at UCLA. This analysis showed the field to be approximately 12 pT at the SCM sensor, which is commensurate with requirements. The panels were then tested by running current opposite to the cell at 2 kHz, at matching phases in all four cells, and measuring the response of the panel circuit at a mockup of the sensor location. When this was tested against measurements taken using a qualification panel, the results showed that the actual noise level was higher than expected by a factor of three. The discrepancy between model and test measurement was never understood to the team's satisfaction. Nonetheless the tests verified that the back-wiring and adjacent-string nulling was performing well because individual strings were tested separately and the noise was shown to decrease per model, when the strings were conducting in tandem.

Modeling of the magnetometer booms shadows and the EFI open door shadow on the solar arrays was also conducted. This was to determine the effect on string current and associated magnetic noise from one or multiple arrays turning off in the course of a single

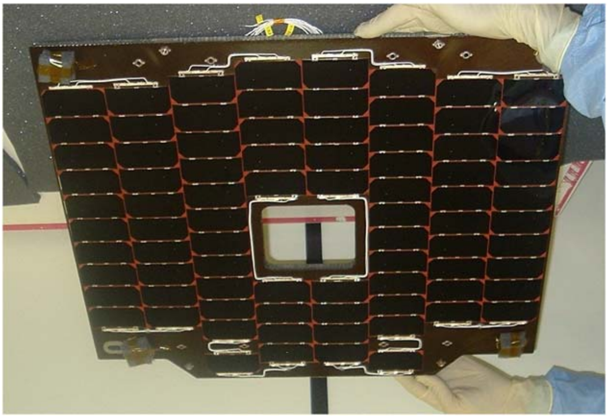


Fig. 2 Proper cell layout (above) and backwiring of solar panels reduced the total field generated by the spinning probe

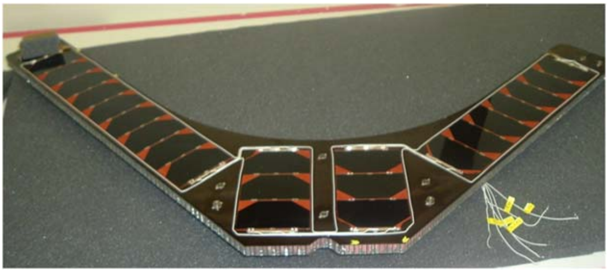


Fig. 3 The top (above) and bottom panels are single string and thus front-wiring was used there to run the return current and null the total field

spin. From this analysis it was found that the side panel design required two additional cells in the center strings, in order to withstand partial boom shadowing by the EFI snout and the magnetometer. It was found that at an angle of spin axis $<10^\circ$ to the sun these effects were minimized, and in that case both magnetic noise was reduced and power input to the probes became optimal. This placed a desire to operate the probes at an angle to the sun that was around 8°. The reduction of the spin ripple as function of the spin-angle due to the minimization of boom shadowing was later validated in orbit.

Similar to the solar panels, the layout of the battery cells was designed to cancel each other when operating. The battery strings were connected in a "horseshoe" arrangement, in order to ensure cancellation of magnetic contributions from nearby neighbors (Fig. 4) and wiring paths were designed to minimize induced field. The battery supplier, ABSL Space Products, identified the soft materials in the battery and was especially careful in the battery design. After successful degaussing of a test battery, all flight models were duly depermed before integration to the probe, and were handled very carefully thereafter.

3.5 Vigilance and Testing

The level of vigilance for magnetic items was kept high throughout all phases of the project. Personnel knew to pass on material data to the magnetics lead engineer every time a new component or part was identified. This caught several items, including proposed balance masses that were made from magnetic materials. Parts used in the magnetometer boom construction including the blankets were checked with a magnetometer in a shielding can to verify a non-magnetic boom. During transport to the launch site from JPL, 'witness plates'

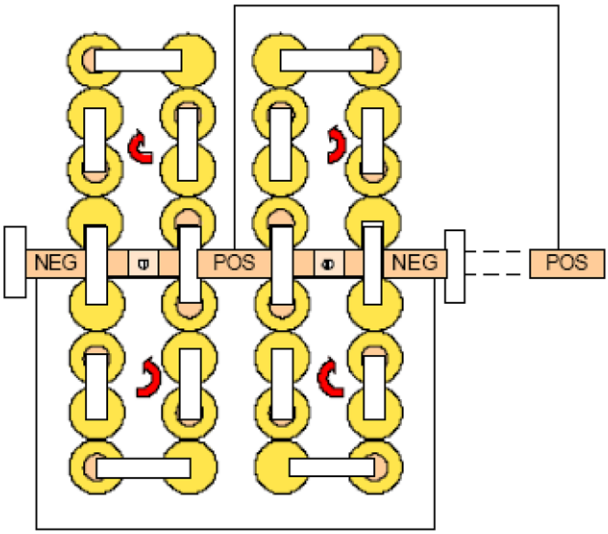


Fig. 4 Battery cells arranged in low magnetic, horseshoe configuration

made from soft perm able material traveled alongside the probes to detect if they were subjected to high magnetic fields. As the project progressed towards launch it became more and more important to protect the hardware from high magnetic fields. Personnel were regularly reminded of the requirements to survey the depermed (magnetically clean) tools and equipment that would come in close proximity of the probes and probe carrier. This continued right through to the white room and the fairing closure.

4 Unit Testing

All instrument units, except for the axial booms, for all five probes were tested using the Magnetic Coil Facility (MCF) loaned to UC Berkeley by Imperial College London (see Fig. 5). The coil arrangement allowed the Earth's field to be nulled and then a magnetic mapping of each unit was conducted by rotating it on a turntable. Most units were verified to be non-magnetic, other than as described above. One surprise was that the Instrument Data Processing Unit (IDPU) had a strong field associated with it when first tested. Troubleshooting of this lead to identification of transistors used extensively on one board. The cans of these transistors had sufficient amounts of Nickel in them that had been permed up in the manufacturing process. Deperming the boards individually lead to a significant decrease in the magnetic moment of the whole unit, this was then repeated on all units. The results of the measurements taken are tabulated in Table 1.

During development and flight model construction the SST sensors also were measured using an in-house test jig. Magnets were matched and yokes were trimmed to ensure lowest weight while there was sufficient material to avoid flux leakage from the assembly. The modeling was done in two dimensions (Fig. 6(a)), with a commercial fluxgate magnetometer. The magnetic moment was computed and numerical superposition of the results, taking into account the locations/orientations of the SSTs resulted in sensor matching to reduce the total SST-related field at the FGM sensor location.

As the spacecraft bus was assembled at Swales Aerospace the individual units did not under go unit mapping. In some instances when subsystem units were removed at UC Berkeley

Fig. 5 Magnetic Coil Facility used to map units individually

Table 1 Results from magnetic mapping of the instrument units

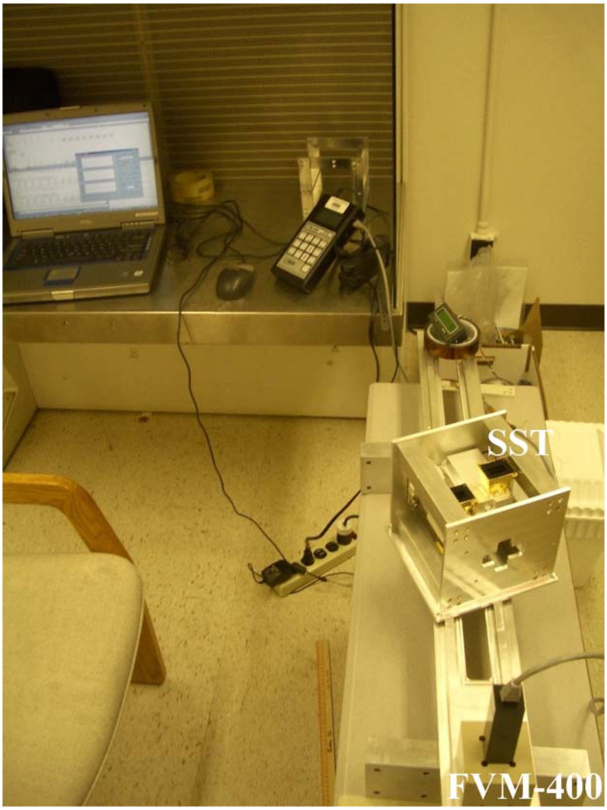
Instrument unit	FM1	FM2	FM3	FM4	FM5
Dipole magnetic moment (mA m^2)					
IDPU/ESA/SCM-PA	6.8	27.8*	3.9	9.4	4.3
SPB1	3.7	4.5	7.7	4.6	19.6
SPB2	8.9	4.6	2.8	4.1	7.2
SPB3	2.9	11.5	9.3	3.1	5.7
SPB4	5.0	9.7	8.2	8.8	1.5
SST1	31.2	10.1	32.5	28.7	23.8
SST2	36.2	34.6	35.0	32.6	30.8
Quadrupole magnetic moment (mA m^3)					
SST1	5561	4634	5424	5547	5455
SST2	5476	4681	4302	5343	5582

*Note the FM2 IDPU shows a higher moment than the others, this is the pre-deperm of the magnetic transistors

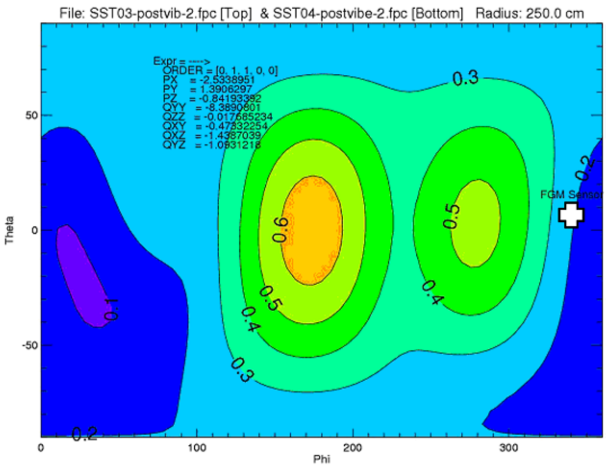
Table 2 FM2 measurements taken for some of the spacecraft bus subsystems

Probe Bus Units	FM2
Battery	8.4 mA m^2
Spacecraft computer	23.3 mA m^2
Transponder	28.2 mA m^2
Auxiliary Electronics Box	43.6 mA m^2

during integration, the opportunity was used to verify that the units were within the magnetic allocation. In the one instance when a flight battery was shipped independently it was checked at UC Berkeley prior to integration and found to be permed-up. It was successfully depermed and then installed in the spacecraft.



(a)



(b)

Fig. 6 (**a**) SST test configuration, with SST inside the manipulator, rotating on the horizontal plane. (**b**) Modeling the superposition of two SST sensors in nT on a phi-theta sphere, 2.5 meters away from the probe center, and recording the result at the location of the FGM instrument (*white cross*)

5 Spacecraft Testing

The spacecraft tests were carried out at JPL (Huang and Narvaez, May 2006a; Huang and Narvaez, Sept 2006b; Narvaez 2006; Ruff et al. 2006). Due to the small size of the THEMIS probes it was possible to fit them inside the JPL Helmholtz coil facility. The coil facility, built for the Mariner family of spacecraft in the 1960s, but recently refurbished, uses 3 pairs of coils to cancel out the Earth's magnetic in the center of the enclosed volume and has a single axis of deperming coils. See Fig. 7. The spacecraft magnetics tests were an important verification that the probe met the requirements. The 5 nT requirement was the most important and easiest requirement to test for, the 0.1 nT stability requirement was more difficult but tests were conducted that attempted to verify this requirement.

To verify the 5 nT requirement the spacecraft was rotated in the X–Y plane and then in the X–Z plane using a fixture that kept the center of the spacecraft in the center of the coil system. At each 5 degree interval a sample was acquired from the facility magnetometers located at 1.5 m and 2.5 m from the center of the probe. This data was then fed into in-house software that calculated the dipole and quadrupole magnetic moment of the spacecraft. The spacecraft was then depermed with a 1.5 mT (15 gauss) field with a linearly increasing then decreasing field while the probe was rotated around the X–Y plane followed by the X–Z plane. This was done with the SST sensor removed so the field from the sensor was not frozen into the soft materials in the solar arrays. Another survey with the SST installed gave the final spacecraft magnetic map which magnetic fields at the FGM location could be calculated. The details of this are presented in Table 3. The coil system was not actively compensated during the surveys and so it was important to verify no large shifts had taken

Fig. 7 Showing the coil facility with a THEMIS probe under test. The stand to the right supports the two test magnetometers

Table 3 Results of DC magnetics tests in dipole magnetic moment and calculated field at FGM sensor. The FGM sensor was located at [188 cm, 132 cm, 26 cm] from the moment location (top center of the spacecraft)

Probe	Dipole & quadrupole moments in S/C coordinates							Calculated field at FGM			
	M_x/Q'_{xx}	M_y/Q'_{yy}	M_z/Q'_{zz}	Q'_{xy}	Q'_{xz}	Q'_{yz}	M_{total}	B_x	B_y	B_z	B_{tot}
F1 Dipole	−27.64 mA m^2	111.97 mA m^2	15.98 mA m^2				116.43 mA m^2	1.18 nT	0.21 nT	0.40 nT	1.26 nT
F1 Quad	13.88 mA m^3	−11.41 mA m^3	−2.47 mA m^3	4.89 mA m^3	−5.62 mA m^3	−9.19 mA m^3	21.65 mA m^3				
F2 Dipole	−38.46 mA m^2	52.62 mA m^2	10.37 mA m^2				66.00 mA m^2	0.50 nT	0.32 nT	0.14 nT	0.61 nT
F2 Quad	17.91 mA m^3	−16.98 mA m^3	−0.94 mA m^3	6.32 mA m^3	−1.88 mA m^3	−3.42 mA m^3	25.79 mA m^3				
F3 Dipole	−74.79 mA m^2	71.15 mA m^2	41.63 mA m^2				111.31 mA m^2	0.34 nT	0.02 nT	0.10 nT	0.36 nT
F3 Quad	24.68 mA m^3	−13.71 mA m^3	−10.97 mA m^3	0.9 mA m^3	−5.3 mA m^3	−9.96 mA m^3	32.33 mA m^3				
F4 Dipole	51.27 mA m^2	91.71 mA m^2	−44.54 mA m^2				114.12 mA m^2	1.39 nT	1.31 nT	0.78 nT	2.07 nT
F4 Quad	19.62 mA m^3	−22.3 mA m^3	2.68 mA m^3	4.98 mA m^3	0.57 mA m^3	−7.17 mA m^3	31.08 mA m^3				
F5 Dipole	−66.87 mA m^2	52.65 mA m^2	12.08 mA m^2				85.96 mA m^2	0.05 nT	0.31 nT	0.19 nT	0.37 nT
F5 Quad	28.84 mA m^3	−26.24 mA m^3	−2.6 mA m^3	2.6 mA m^3	−3.76 mA m^3	−6.54 mA m^3	39.88 mA m^3				

place in the DC field during the test. If jumps were seen in the data, the coils had to be re-zeroed and the survey re-run.

To verify the probe 0.1 nT stability requirement a magnetic survey was conducted in Earth's field (with the nulling coils off) on the F2 probe only. By comparing the results from this test with the low field survey it was possible to estimate the change in the spacecraft generated field from low field at Apogee to higher field at Perigee. The results showed that in this extreme case of zero field to Earth's field the change would be a maximum of 0.2 nT. As the field at perigee is approximately half that at the Earth's surface it was agreed that this requirement was met.

A further opportunity to look at the permeability of the probes came when the deperm of the F1 spacecraft had to be halted when the field was 1.2 mT (12 gauss). A survey of the probe at this time found the field to be around 80 nT at 1 m, this translated to a field of approximately 10 nT at the FGM sensor. Even with this extreme case with a field many times more than normal Earth's field the probe did not perm up excessively, giving encouragement that the probes had been designed without too much soft material. The probe was depermed and the field was reduced to approximately 6 nT at 1 m.

At the first set of magnetics testing, on F2, a powered test of the probe inside the coils was included. The change in field at the location of the magnetometer was less than 1 nT from the tests involving the nonpowered probe. This showed that there would be no large DC offset when the probe was powered and therefore no large current loops, however it was not an AC magnetics test and so did not show up time varying fields from the power system of the probe nor was able to show how different spacecraft modes would change the field. Although the powered test was not repeated on the other four probes, a quick check using a gradiometer was conducted during a probe functional test at JPL. Using the gradiometer positioned at the same angle of the deployed FGM sensor but closer to the probe, the change in magnetic field was measured between the probe powered off and all the instruments on. For all probes the field change was negligible at the distance of the FGM sensor. The limitation of this test was that it did not test the full power system from the solar arrays to the battery and then through the distribution of power to the subsystems. However it is extremely difficult to reproduce the conditions of the spinning spacecraft and a fully illuminated and accurately measured induced field.

6 On Orbit Results

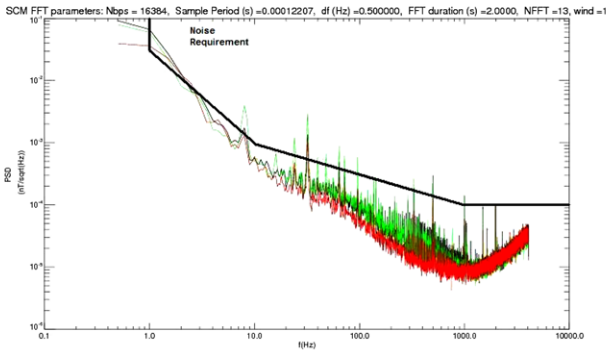
Post launch spacecraft induced fields at the FGM sensor are difficult to determine with certainty as they are tied together with the FGM sensor offsets, which drift over time. However the absolute offset (sensor offset plus spacecraft generated field) in all axes is less than the requirement of 5 nT in all but one axis of one probe. Also more importantly, this offset is seen to be stable and meets the 0.2 nT over 12 hours stability requirement. More details can be found in the FGM Instrument Paper (Auster et al. 2008). The offsets determined in-orbit at the FGM sensors are shown in Table 4.

The on orbit raw data from the SCM instrument shows noise levels above the requirement at a number of frequencies. However, these tones are fairly constant and so it is possible to remove them with standard data analysis techniques (see Fig. 8). There are two types of noise picked up, electronic noise (not discussed here, see THEMIS SCM instrument paper (Roux et al. 2008)) and magnetic noise. The magnetic noise is assumed to be from the power system and solar arrays as it is spin synchronous or at the switching rate of the charging circuitry. Despite a careful design of the solar arrays and power system there is still sufficient

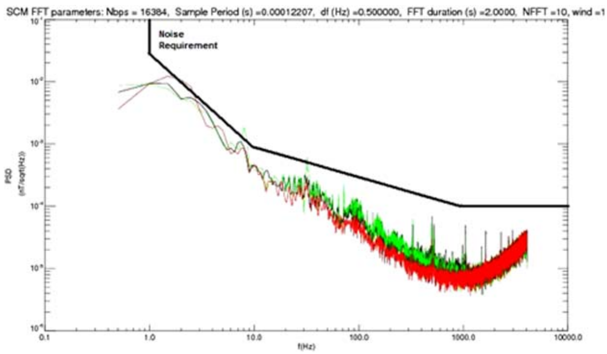
Table 4 Sample FGM offsets for all probes on March 2007

Probe	*X*	*Y*	*Z*
F1	−0.77 nT	−2.05 nT	1.14 nT
F2	−4.2 nT	0.04 nT	0.38 nT
F3	1.09 nT	−1.73 nT	−2.23 nT
F4	−6.15 nT	1.59 nT	2.04 nT
F5	−5.05 nT	0.85 nT	1.47 nT

Note that the sensor pre-flight offsets are in the range ±0–3 nT. The stability of these offsets is ∼0.2 nT / 6months (Auster et al. 2008)



(a)



(b)

Fig. 8 (**a**) Sample SCM FFT showing noise levels relative to the requirement and (**b**) after data clean up

noise to affect the SCM measurement. A longer boom, perhaps of another half meter, would have lowered the noise levels below the requirements. However, as engineering is often a trade in competing needs, a longer boom would have resulted in much more complex spacecraft balancing and dynamics which could not be met by a mission of THEMIS's size. However, considering the short length of the boom, the complexity of the spacecraft bus and the stability of the noise levels, the result represents a considerable success.

It was determined after launch that spin tones with peak amplitudes around the fourth harmonic were present in the FGM and SCM data. By comparison the 1st harmonic was quite low. Since the power system is such that one string from each panel is in series with its counterpart on all panels (in order to minimize power losses from rectification) this immediately suggested that the spurious signal is a result of some uncompensated loop from the internal power distribution arising from all panels, rather than radiation from the panel adjacent to the FGM or SCM sensors. The power was found to be sun-pulse synchronous and was removed to the extent possible from the SCM instrument (Le Contel et al. 2008). The same technique can be applied on the FGM instrument by special processing, but because the spin tone can be both related to the ripple in the power system and the orthogonality of the sensor, the spin removal is coupled to the calibration procedure. A routine process for removal of the spin tone from the FGM data signal is currently under construction.

7 Conclusions

The magnetic cleanliness program benefited from good early work to identify risks. With an experienced knowledgeable team that was able to balance the needs of the magnetics budget with the rest of the mission, the main magnetics requirements were met. Getting all personnel on the project aware of the requirements from subcontractors through to launch site personnel helped managing the magnetic budget. Continued vigilance through the project picked up small items that could have had a big effect on the FGM and SCM measurement. Whilst proper bookkeeping of the budget was kept, a detailed multiple dipole magnetic model of the spacecraft was not made. This worked for THEMIS due to its size and relative simplicity—there were few units that produced significant magnetic fields, by and large due to early work on the subsystems to remove magnetic components. For a larger mission a more robust approach with model and full verification might be considered as was done, for example, for Cluster. However, the THEMIS approach proves that this may not be necessary. Full spacecraft DC magnetics testing helped confirm a well built and clean spacecraft, however did not verify any AC requirements. This was done at a subsystem level, although the power system only really functions when fully assembled, and to a certain extent only after launch. The difficulties in testing the AC magnetics requirements presents a difficulty to any mission that needs low AC induced fields and therefore a thorough approach. On reflection more attention could have been paid to the AC budget to attempt to reduce the noise levels below the requirements. Finally it is noted that is possible to build identical spacecraft all with a high level of magnetic cleanliness without the use of compensation magnets on a medium sized mission budget.

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