THE DESIGN, CONSTRUCTION AND TEST OF MAGNETICALLY CLEAN SPACECRAFT - A PRACTICAL GUIDE

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Preface

The purpose of this technical note is to briefly summarize proven, cost effective techniques used in the development and construction of magnetically clean spacecraft. These have been developed over many years by engineering and research groups in the US, Japan, Western and Eastern Europe. This note basically reflects the collective experience gained over many tens of space missions.

There exists a widespread and unfortunate misconception among Project Managers and Mission Designers that electromagnetically clean spacecraft are costly and difficult to build. Although this may have been true in the past, it is certainly not the case today. Modern, computer based instruments and the experience gained by research groups over many space missions make possible the achievement of excellent results with little cost or schedule impact to the programs. Detailed sp

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knowledge required for a successful scientific spacecraft design. The success of an electromagnetic "cleanliness" program depends critically on excellence in systems engineering, early involvement of experienced representatives of the sensitive subsystems in the design and review process and above all, on the open and fluid communication among all elements involved.

1.0 Introduction

This document deals with the task of designing and building "magnetically clean spacecraft". Magnetically clean means that the spacecraft residual magnetism, both static and dynamic, has been reduced below a given value determined by the application and the nature of the mission being considered. The most common application of magnetic cleanliness is in Earth orbiting spacecraft which use the geomagnetic field for attitude determination and control. Any magnetic fields generated by the spacecraft result in disturbance torques on the same that must be compensated either by propulsion or magnetic torquing. This represents a lifetime limitation and an additional drain on the power system that limits the resources available for other subsystems. The most challenging magnetic problems are associated with interplanetary missions to the outer Solar System. While the surface Earth's field at the equator is of the order of 30,000 nT ($1nT=10^{-5}$ Gauss), the average interplanetary magnetic field at the distance of Jupiter's orbit is only 0.5 nT and at Neptune 0.05 nT. These extremely weak fields require the use of special techniques for their measurement and the extremely careful design and construction of the spacecraft.

The two applications given above are very representative of the range of problems that must be addressed to achieve the desired goals. Because of the sensitive nature of their measurements scientific spacecraft carrying field and particle instruments usually impose the most stringent system requirements. In past projects where cost criticality was considered secondary, it was traditional to formally "flow down" these requirements to the spacecraft builders and assign responsibility for compliance and verification to the project organization. This was based on the approach used during the early phases of the space program where requirements for specialized components (i.e., military specifications, high reliability, radiation-hard, non-magnetic, etc.), and non-standard design and manufacturing techniques, were passed on to suppliers and subcontractors without concern for availability or cost. The verification program also required access to very specialized facilities and instruments which in general are not in widespread use in industry. When the above "uncommon" technical requirements are coupled to today's legalistic, lengthy and complex procurement process it is easy to see why electromagnetic cleanliness could be perceived as a major cost and schedule driver by many project managers.

The increasing cost and complexity of missions and the threat of "descopes" driven by complex technical requirements and their attending cost has forced a re-evaluation of many "text book" approaches used in the past. The recognition that industrial suppliers and manufacturers had equivalent reliability and quality assurance programs led to the acceptance of the same in lieu of the formal and more costly military standard requirements. In the area of radiation hardness tolerance it is no longer customary to impose "requirements" on parts but to test the standard products of manufacturers to verify suitability of performance to the intended application.

The current approach to magnetic cleanliness follows a similar path. Rather than impose stringent requirements on the system and components, a <u>magnetic characterization</u> effort is first conducted to identify those subsystems that will require special attention; many are accepted "as is". For scientific spacecraft the involvement of the science team in the magnetic cleanliness program is now customary rather than the total delegation to project management to verify compliance with the requirements. This approach recognizes that the experimenters involved already possess the specialized skills, instrumentation and facilities required to do the job, the vested interest in the results and the extensive experience and data base required to make difficult tradeoffs at the system level. The role of project organizations is thus that of promoting the communication between experimenters and spacecraft and subsystem builders, and to facilitate subsystem and system level tests and verification where necessary.

2.0 General approach

The objective of this document is to provide technical guidelines on how to achieve acceptable magnetic cleanliness within resource and time constraints. It considers the effects of hard and soft magnetic materials as well as those of "stray" fields resulting from currents circulating in the spacecraft electrical and thermal systems. Permanent fields, like those from relays and motors, can be controlled to some extent by careful positioning of the magnetic components (i.e., relays). However it is not always possible to position optimally some of the major contributing sources which have known or predictable magnetic signatures. Soft magnetic materials may introduce undesirable variability associated with their "ease" of magnetization which permanent magnets do not exhibit. Therefore parts and materials to be used on the spacecraft must be selected in principle as to minimize their contribution to the background magnetic field in the vicinity of the magnetic field sensors.

When considering fields from magnetized parts it is important to recognize the difference between hard and soft magnetic materials. The contribution from hard magnetic materials can be expected to be quite stable but that from soft materials may vary appreciably, particularly during launch and in response to varying electrical activity in the spacecraft (currents) such as that associated with the operation of magnetic torquers. In general the field due to hard permanent magnets and its temperature dependence can be measured accurately on the ground (within certain limits) and is not of great concern except perhaps for some local effects on other instruments or spacecraft subsystems. On the other hand the soft magnetic materials contribute a strong and variable component which is largely unpredictable and very difficult to estimate. Hence the use of these materials must be carefully controlled on most magnetically clean spacecraft.

The stray field due to circulating currents must also be controlled fairly strictly during the design phase to minimize their effect on spacecraft resources. As with permanent magnets, their position is important and must be considered along with the harness layout and construction. In this document we deal with the frequency range from DC to about 50 HZ but the standard techniques used for EMI control at higher frequencies are very effective in reducing the dynamic magnetic signature of the spacecraft and reducing overall noise levels.

In contemporary designs the major magnetic cleanliness effort has been concentrated on reducing the dynamic or time variable signature of the spacecraft. The cost of redesigning "heritage" and standard production subsystems precludes a strict adherence to the material and component selection criteria described above. Very high permeability foil magnetic materials like METGLAS (a Honeywell product) have become available that allow the easy shielding of "hot" subsystems to reduce their magnetic signature. The very large dynamic range of modern flight magnetometers permits operation with larger fixed bias fields without major difficulty as long as this bias is stable and can be measured prior to launch. In addition, personal computer based measuring instruments have been developed which greatly reduce the requirements for characterization measurements of subsystems at specialized magnetic test facilities. These tools and techniques simplify in a very significant manner the problems to be solved and will be described later on in this paper.

In many respects magnetic cleanliness is identical to reliability, quality assurance and particulate contamination control: to be cost effective they must be "built-in" at the beginning of the project and cannot be added later on as an afterthought. For contemporary missions the added cost of R&QA activities has been estimated at approximately 5% of the cost of the spacecraft. A corresponding estimate for magnetic cleanliness can be made and results in less than 2% of the same cost.

3.0 Design Approach

To meet the mission requirements and to reduce costs, magnetic cleanliness considerations must be taken into account immediately at the beginning of the design phase, when the design, selection and positioning of flight components and hardware must be evaluated for possible magnetic contamination. The experience of the experimenters is invaluable during this early phase since it can contribute key concepts that assure magnetic cleanliness at negligible cost. The selected design of hardware in the integrated spacecraft cannot conflict with other performance criteria defined in the specifications. These may relate to allocated mass, power, radiation effects, vibration, shock, etc. In addition programmatic considerations (cost, schedule) are major drivers in these early technical tradeoffs and critical decisions.

A fundamental decision usually associated with the incorporation of scientific magnetometers aboard spacecraft is whether to use a “boom” or not to separate the magnetic field sensor from the spacecraft bus where supposedly the sources of magnetic contamination reside. Clearly there is a system level tradeoff between the length of the boom and the level of spacecraft magnetic contamination allowable in order to meet requirements.

3.1 Approach to Minimizing Fields from Magnetized Materials

For the reduction and control of magnetized material field contamination levels, the major areas of consideration are as follows:

a) Subsystem and component evaluation - An initial survey of all subsystem designs on the spacecraft for the presence of magnetic materials, permanent magnets and total power consumption is of great value in isolating those that may require detailed attention later on.

b) Magnetic characterization of suspect component parts and subsystems, both mechanical and electrical. This activity can be conducted on site by representatives of the project or the experimenter's team depending on the most cost effective solution. Coupled to (a) above, it constitutes a very cost effective way of identification of magnetically significant components in the spacecraft design.

c) For those systems identified to contain magnetic components, determine (with the help of the experimenter if necessary) the optimum mechanical layout. A significant reduction can be obtained in many cases by mutual compensation (i.e., relays).

d) Determine if DC field compensation is required or warranted. This technique consists of adding small compensation magnets which create an opposing field to the one generated by the spacecraft at the location of the magnetic sensors. It is effective as a low cost solution when large permanent magnets are present in the spacecraft and instrument designs. However, modern magnetic field measuring instruments have very high resolution and dynamic range and if the permanent field is known with sufficient accuracy the use of compensation magnets may not be necessary or warranted.

e) Determine if magnetic shielding should be used to reduce the static field level to an acceptable value. The judicious use of foil materials like METGLAS can be of great help in reducing magnetic field contamination but it should never be considered as a "cure-all". Magnetic shields introduce soft magnetization components which may introduce more problems than the shielding solves.

3.2 Approach to Minimizing Time Variable and Stray Fields from Electrical Currents

This is the most important area for magnetics control in contemporary spacecraft designs. Static fields can be successfully controlled by the techniques described in (3.1) above at minimum cost. However the minimization of dynamic magnetic signatures is strongly coupled with system engineering concepts and the basic design of the spacecraft. The following areas should be considered for stray magnetic fields below 50 HZ:

a) Design of the spacecraft wiring and power distribution system, with special attention to potential current loops created by bonding, shielding and grounding.

b) The use of twisted pairs wherever possible. No primary supply currents should be allowed to flow through or into the spacecraft structure.

c) Subsystem location within the spacecraft to minimize effect on magnetic sensors.

d) Elimination of current loops in the primary side of the power system throughout the spacecraft ("star" or single point grounding concept for primary power).

As a rule, the major sources of time variable magnetic fields will be associated with the power, propulsion and attitude control systems. Solar panels, power conditioners and battery chargers all have associated with them large and variable currents. In the attitude control system reaction wheels, magnetic torquers and other actuators can generate large and time variable fields; in the propulsion system latch valves, thrusters and solenoids also can add large an variable components to the overall spacecraft generated field. Devices which involve mechanical motion must be carefully evaluated for shielding or mutual compensation (e.g., relays). Twisted pairs (not necessarily shielded) are extremely effective in eliminating the stray fields associated with electrical loads in the spacecraft.

3.3 Approach to Minimizing Fields from Thermoelectric and Eddy currents.

a) The spacecraft skin, thick electrostatic and thermal shields, metallic mounting plates, etc. can generate magnetic fields due to thermoelectric currents circulating in them driven by thermal gradients. It is not necessary to have dissimilar metals to generate significant magnetic fields. A temperature gradient as small as 1 deg.C across a 0.5 cm thick aluminum plate can generate a field of several nanoteslas at 3 cm above the surface. Magnetic field sensors should not be mounted on high conductivity metallic plates even if they are made of non-magnetic materials (e.g., aluminum).

b) Rapidly moving or spinning spacecraft interacting with the Earth's magnetic field can generate large eddy currents in conducting structures which in turn generate large stray magnetic fields. The physical principles are similar to those governing the "armature reaction" present in electric motors. If a magnetometer is to be mounted on a rapidly spinning spacecraft to be flown in a strong background field, extreme care must be exercised to "break-up" all conducting structural loops with insulating gaps.

3.4 Spacecraft Magnetic Moment Management - Hardware Analysis

The total magnetic moment of a spacecraft is important in determining the nature and magnitude of the stray field and, for low-Earth orbit applications, the residual torque disturbances that the satellite will experience in orbit. The techniques described above are usually very effective in minimizing this total moment. In addition to this it is also necessary to minimize the local, stray magnetic field that a sensor will see in flight since this constitutes a source of measurement error. For sensors mounted externally to the main body of the spacecraft (i.e., on booms), the total magnetic moment will in general be sufficient to determine the magnitude of the stray field present at the sensor. In the case of spacecraft without booms, the magnetic field sensors are usually mounted within the spacecraft main body and subject to the local fields which may not contribute vary significantly to the total magnetic moment but cause large errors in the measurements. The classic example is that of a slightly magnetic bolt located near a magnetometer sensor. The effect on the spacecraft magnetic moment is nil but the magnetometer measurements are lost! It is possible to reduce the total magnetic moment of a given spacecraft by adding compensation magnets in appropriate places. However, this may create local concentrations of field that will seriously disrupt magnetic field and possibly other sensitive measurements.

Attitude stability and control requirements usually dictate a maximum magnetic moment that is permissible for a given Earth orbiting mission. The basic approach to magnetic cleanliness in this case is to begin with the maximum allowable spacecraft magnetic moment and work backwards, developing maximum allowable magnetic moments for each spacecraft subsystem and then adding vectorially the individual contributions at the location of the magnetic field sensors. This approach has been demonstrated to be an excellent starting point when little is known about the magnetic characteristics of spacecraft subsystems. Experience shows that the static magnetic moment associated with a piece of hardware is usually (not always!) proportional to its mass, while its dynamic (variable) component is proportional to the power drawn by the system under analysis. After an initial allocation is made based on these two inputs, it is extremely important to characterize magnetically each subsystem as early as possible in its development cycle to identify sources of magnetic field and develop flexible, low cost solutions to reduce their effect. The solutions to magnetic field problems in hardware already developed or qualified for flight are extremely costly and seldom achieve the desired objective. The same reasoning applies to the selection of materials and passive hardware for the spacecraft structure and ancillary devices (antennas, mechanisms, diplexers, circulators, etc.).

3.5 Magnetic Shielding - Pros and Cons

In many magnetic control problems solutions are not practical, cost effective or even possible and the designer must resort to magnetic shielding as the only viable alternative left. It is not desirable to intentionally add magnetic material to a spacecraft but in some cases this is the only course of action left. Magnetic shielding is not a baseline solution and should be used very sparingly. The most effective use of magnetic shielding is to contain the large, permanent fields associated with relays, electromagnets, stepper motors and other time variable fields. The shielding material provides a "shunt" for the magnetic field lines so they return to the poles through a low reluctance path rather than free space. The shielding material should be used close to the source and possibly integrated into the structure of the device itself. For example, it requires far less material to directly shield a motor than to shield the entire system which may contain it. However, when large fields are involved saturation effects may dictate alternative solutions. The design of magnetic circuits should make use of yokes and pole pieces to minimize the fringing fields and leakage flux.

When the magnetic fields involved are <u>constant in time</u> (permanent magnets, hard magnetic materials) it may be better to ignore shielding or compensation altogether and simply <u>measure</u> the magnitude and direction of the error field.

3.6 <u>The Project-Science Team Interaction: Magnetics Control Program</u>

Mission with magnetic cleanliness requirements usually implement a "magnetics control program" (see below). A person with the appropriate training and good systems background is appointed as the "magnetics control engineer" and serves the dual function of <u>technical advisor</u> and <u>evaluator</u> of spacecraft subsystems from the magnetics point of view. Designers of subsystems need to be advised about magnetics requirements, constraints, options and solutions as early as possible to minimize cost and schedule impacts. In contemporary missions these responsibilities have been assumed more and more by the investigator teams due to the inherent efficiencies and cost savings of that approach. In general the steps outlined below are followed:

(a) Permanent Fields from Soft Magnetic Materials

A general survey of materials used in all spacecraft subsystems is conducted to establish the presence (or absence) of soft magnetic materials and parts size and geometry. A classification by subsystem has proven highly effective in managing the survey results. Aluminum, fiberglass, high pressure laminates, magnesium and titanium are all non-magnetic. These are among the most desirable materials for use in structures. Particular attention must be paid to non-magnetic stainless steel. Although not attracted to a magnet there is no such thing as a non-magnetic stainless steel (NMSS) bolt. The remnant field from this small NMSS bolt installed with a magnetically attached driver bit is sufficient to ruin the performance of the most carefully constructed magnetic field sensor if it happens to be in its immediate vicinity. However, under controlled conditions, use of NMSS bolts in the spacecraft structure represents no problem at all.

All materials considered for use in the spacecraft, if not known to be satisfactory, should be pre-tested as early as possible.

(b) Plastics and Epoxies

Plastics and epoxies are non-magnetic in themselves but some fillers are magnetic. Experience shows that "color" has magnetic fields associated with it, especially reds and blacks that tend to contain iron or iron oxides in various forms as coloring agents. White, clear and green exhibit the lowest magnetism.

(c) Electronic parts and packaging techniques

The difficulty of procuring reliable electronic parts that meet a variety of difficult criteria (including radiation hardness) as well as stringent magnetic requirements has reached astronomical proportions. Although in the past it may have been possible to specify these parts, the realism of today dictates that use be made of existing designs and that innovative techniques be used to meet the magnetic design requirements. Most of the magnetism found in electronic components is associated with the leads or cases of the devices. The extensive use of Kovar (a magnetic material) in glass-to-metal seals makes most hermetically sealed parts magnetic. On the other hand the increasing use of surface mounted devices tends to simplify the magnetics problem due to the absence of magnetic leads and the small geometry of the devices. Where available components should be selected with non-magnetic leads and/or case. Demagnetization of components with magnetic parts prior to installation is a very cost effective technique since good demagnetizers are available at very low cost. Latching relays are inherently magnetic and cannot be demagnetized but can be arranged in opposing pairs to cancel out their magnetic moment.

Wires and Cables present few problems if selected early for their magnetic properties. Many coaxial wires are constructed with "copperweld" or similar copper-clad steel alloys for their center conductor which are HIGHLY magnetic. Their use on a magnetically controlled spacecraft is not recommended and should be restricted to very short runs and only in critical areas remote from the magnetic field sensors.

Connectors and Connector Hardware should be specified as non-magnetic in all cases unless located remote from the magnetic sensors in which case demagnetization of "standard" connectors may be a cost effective alternative. Many miniature and subminiature non-magnetic connector types and hardware are available off-the-shelf without problems or cost penalties.

Integrated circuits are available in a large variety of configurations. As stated above, "leadless" packages will exhibit the least magnetic signature. In most cases minimizing the lead length to the smallest practical value reduces the magnetic field to acceptable values.

Printed Circuit Boards and Other Interconnecting Techniques

Most printed circuit board manufacturing techniques yield magnetically clean boards that require no further attention except for large current circuits which should be laid out such as to minimize the enclosed area of forward and return paths for the currents involved. There exist however "hybrid" electronic packaging techniques which involve partial or total "wire stitching" or "wire welding". These involve the welding of nickel or nickel alloy wires to posts connected to integrated circuit leads. This results in a highly magnetic "planar" geometry of interconnect wiring which can introduce very large stray magnetic fields which are very difficult to eliminate.

(d) Stray Fields Produced by Electrical Currents

Many techniques have been identified for minimizing the fields produced by currents circulating within the spacecraft. In addition to resulting in dramatic reductions of time variable magnetic field signatures the techniques described below fall under the category of "good engineering practice" when system performance, noise, accuracy and EMC/EMI requirements are taken into account.

1. Leads carrying appreciable current should be twisted with a balanced return lead such that the net current imbalance in the bundle is as close

to zero as possible. All primary power circuits on the spacecraft should follow this guideline. Each subsystem power supply line should be twisted with its return and returned to a central point (batteries, single point ground and power supply electronics).

2. The wiring through connectors should keep all leads as close as possible to their returns to obtain the best possible self cancellation.

3. In conjunction with (1) above a single point power grounding scheme should be implemented to avoid unknown current return paths and loops. Particular attention must be paid to the power ground returns of RF components, charge regulators, batteries, shunts and solar arrays.

4. Where current loops are unavoidable due to inherited hardware constraints or other considerations, compensating artificial current loops laid out in the opposite sense should be considered in the harness or interconnect. This technique is very low cost and has been used many times with excellent results.

5. Heater elements and their wiring must follow the same guidelines delineated above. The heater elements themselves should be of the "non-inductive" design and made of non-magnetic materials (e.g., Tophet A, Cupro-Nickel, etc.).

6. Magnetic components (transformers, chokes, etc.) in contemporary designs present much less of a problem than in older spacecraft due to the use of much higher frequencies and the smaller physical size of the components involved. Toroidal and closed geometries are highly recommended to minimize leakage fields which result in losses and inefficiencies. In

general all construction techniques used to minimize leakage inductance, core losses, etc. have direct benefit for EMC and magnetic cleanliness considerations.

7. The Solar Array can be the most significant source of stray magnetic fields in the spacecraft due to the large currents circulating there when illuminated. On the other hand its linear geometry makes it the most straightforward one to compensate or cancel out by correct placement of forward and return interconnections. The stray fields can be minimized by the technique of "backwiring". In backwiring the return wire from each string of solar cell modules is returned directly underneath the modules in that particular string and carefully routed along a line just behind the centerline of the modules. The advantages of backwiring are straightforward. Each string and module of the string is self-canceling and does not depend on the magnetic field of an adjacent module or string for cancellation. Thus if a module fails in flight the current in both the string and the return drop to zero simultaneously leaving no uncompensated currents in the array. Some contemporary arrays use string switching techniques which effectively change the current path dynamically in response to load and solar input changes. Unless backwiring is used it is extremely difficult to totally compensate the solar array.

A significant advantage of array geometries is that they can be easily modelled with piecewise linear current segments. Several computer programs exist which can produce an extremely accurate prediction of the resultant magnetic fields when the array is illuminated based on the geometry of the interconnect. Alternatively, the completed solar array can be tested for magnetic field generation by simply flowing current *backwards* through the solar cell strings and measuring the resulting field. This is a common and very cost effective technique which has gained widespread acceptance.

8. Special Problems

Some assemblies in spacecraft can be classified as "special problem areas". These typically involve moving mechanical assemblies, reaction wheels, stepper motors, linear displacement transducers, propulsion system valves and regulators, thrusters and other magnetically actuated devices. In addition batteries can be a major source of error fields. Careful design, compensation and testing can usually reduce the problem to manageable dimensions. Antennas and RF components sometimes use magnetically hard components (springs, magnets, gyrators, etc.). These elements have to be carefully tested and evaluated and shielding/compensation techniques applied, piece by piece. Travelling wave tubes are a known source of large magnetic fields and must be addressed early in the development cycle to reduce their effect.

4.0 Magnetic Field Testing and Instrumentation

Traditionally magnetic control programs have been the responsibility of Project organizations and system developers. However, the formality and rigidity of current federal procurement regulations and accounting practices has introduced many complications in the implementation of "hard to define beforehand" tasks like magnetics control. Costs have increased significantly, not because the technical problem has become more complex but because the cost of managing and accounting for the technical solution has increased dramatically. As a result, magnetic field researchers, both in NASA and ESA missions, have assumed more and more of the responsibilities associated with magnetics control programs. In addition they have developed specialized instrumentation that can be used on location to perform measurements which formerly required accessibility to an expensive magnetic test facility and transportation of the equipment to be tested to the same. This approach is presently baselined in all major missions which include sensitive magnetic field measurements. The advantages are that the measuring instrumentation can be carried to the locations where the hardware is being developed and the measurements performed without affecting the nominal flow of activities and thus their cost. Even at the spacecraft system level sensitive magnetic field measurements can be conducted using PC-controlled portable instruments that can dynamically cancel the Earth's magnetic field and obtain measurements achieving better than 0.25 nT resolution in many cases.

The cost savings and effectiveness of such programs are immediate. Magnetics becomes a routine matter, within the scope of normal design and verification activities. Proper training of personnel is essential in achieving these results and the investigators are encouraged to develop the necessary material which can be delivered through a series of lectures early in the development program.

4.1 Spacecraft System Level Tests

As mentioned at the beginning of this document, the primary objective of current magnetics control programs is to minimize the time variable part of the field generated by the spacecraft. The reason for this is the ready availability of large dynamic range instruments, high resolution A/D converters, etc., which allow the accommodation of large, steady, background fields without loss of resolution. This was not true in the past and much larger emphasis was placed on controlling the static as well as the dynamic stray fields. Fortunately, dynamic fields are much easier to reduce than static fields. Standard techniques developed for the reduction of EMI/EMC in electronic systems work very well for magnetics.

The most important system level task is therefore one of verification at the spacecraft level that the individual subsystems meet the goals of minimum variable magnetic fields. This testing can be performed without difficulty or impact taking advantage of the normal Integration and Test activities. A magnetically "quiet" period is selected (usually centered around midnight) and the immediate vicinity of the spacecraft is instrumented with several PC-based magnetometers (usually provided by the experimenters) which monitor the ambient field. The spacecraft subsystems are then commanded through those modes that result in significant power changes (already identified from subsystem level testing) and their magnetic signatures recorded. If harnessing and power distribution have been built following the guidelines laid out in this document, these signatures should match those already established individually and there should be no surprises. On the other hand if secondary current loops and unknown current return paths exist, they will be detected immediately by the test instrumentation allowing corrective action where required. The typical duration of such a test is a few hours depending on the commanding flexibility designed into the system and constraints associated with subsystems. These can be taken into account during I&T planning to minimize test duration and costs.

4.2 Static spacecraft field tests

As mentioned before, the prime focus of the effort is minimization of time variable fields. It is useful however to verify that unusually large static fields are not present in the spacecraft and which could cause saturation of the magnetometer sensors. This test requires rotation and/or displacement of the spacecraft with respect to a set of auxiliary magnetometers like the ones used for (4.1) above. Again, testing can be accommodated within normal I&T activities, particularly since static testing does not require powering the spacecraft.

Experience has shown that the most practical way to rotate and translate the spacecraft for these purposes is to use a non-magnetic "strap" or equivalent device to hang the spacecraft from bridge cranes which are normally available in high bay areas. The spacecraft can the be rotated by hand in incremental steps and its magnetic signature recorded. The same applies to small displacements (< 1 meter) which can be carried out without moving the overhead crane. Obviously, if a non-magnetic spacecraft handling fixture exists this is the preferred way of implementing the required rotations/translations. Like in 4.1 above, static testing can be completed in just a few hours depending on the handling fixtures and facilities available.