Magnetic cleanliness verification of telecommunication satellite payload

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ABSTRACT : The magnetic moment of the satellite and the magnetic induction of the earth create a perturbation torque that needs to be compensated by means of the AOCS (Attitude and Orbit Control System).

To reduce the magnetic moment impact on the satellite attitude control, it is requested to achieve acceptable magnetic cleanliness level on each subsystem of the satellite.

The magnetic cleanliness activities done in the frame of the telecommunication satellite payload will be discussed in this paper.

Keywords: Magnetic cleanliness, magnetic moment, magnetic field, telecommunication satellite payload.

1. Introduction

There are several reasons why it is generally desirable to characterise the magnetic effects of a satellite or its components. For example, the magnetic moment of the satellite will create a torque by interaction with the earth magnetic field depending of the orbit.

Such a torque will disturb the attitude of the satellite, and consequently the AOCS of the satellite must be designed to cope with this disturbance.

Another example is when satellite carries a magnetometer on board for determination of the satellite location and attitude in the known earth's field. In these case, the magnetic field of the satellite at the location of the sensitive equipment (magnetometer) must be known in order to evaluate correctly the data collected by the equipment during the mission.

The satellite magnetic cleanliness depends on each functional magnetic material used inside the satellite and on the magnetic field developed by each equipment with its power supply harness. The magnetic cleanliness is defined by the value of the maximum magnetic moment of the magnetic dipole and its acceptable variations. It should be noted that for most space applications the dipole model is a sufficient approximation.

The magnetic cleanliness activities done in the frame of the telecommunication satellite payload will be discussed in this paper. The different steps of the magnetic cleanliness verification are the following :

1. Characterisation of the field induced by the microwave equipment. This is carried out in the special test environment allows to measure the unit in the fully DC magnetically compensated area.
2. Evaluation of the magnetic moment produced by the payload. This calculation takes into account the results of the induced fields measured on each microwave unit including ferromagnetic materials and the communication module layout of the satellite.
3. Calculation of the static magnetic field produced by the payload at the location of the sensitive equipment.
4. Evaluation of the static magnetic field compatibility between payload equipment.
5. If necessary, try to improve the payload magnetic cleanliness by specific magnetic design rules (avoid ferromagnetic material wherever feasible, optimum equipment orientation for mutual DC H-Field compensation, minimise current loops which generate magnetic fields, shielding of the magnetic sources,…).

2. Magnetic testing of satellite equipment

2.1 Magnetic test facility

The magnetic field tests are carried out in the special test environment allows to measure the equipment in the fully DC magnetic compensated area as shown in figure 1.

Figure 1 : INTESPACE magnetic test facility

The heart of the test facility is a tri-axial square Helmhotz coil system of side length approximately 6 meter that is able to generate very homogeneous magnetic fields inside. The facility is located in a magnetically mostly clean and quiet area. In the centre of the coil system the terrestrial field is cancelled with +/- 10^{-9} Tesla residual field. The facility is capable to generate an adjustable additional field until 60 µTesla in all directions. A magnetometer in the direct neighbourhood measures the variation of the local earth magnetic field to control those currents to compensate the field inside the coil system.

This test facility allows :

- to measure the permanent magnetic field emitted by the equipment or a small satellite in compensated terrestrial magnetic field.
- to simulate DC H-field of known direction and amplitude (calibration of sensor, study of the induced magnetic fields);
- to control the immunity of the equipment to DC H-field.

2.2 Magnetic measurement on equipment

2.2.1 Magnetic state of equipment under test

In many applications of magnetic testing is space application, the equipment under test can be measured repeatedly in various magnetic conditions ; most commonly the following three types of magnetic state are considered :

- **Initial :** magnetic state of equipment under test at start of magnetic test. This gives an indication of the magnetic history experienced by the equipment.
- **Depermed :** demagnetised state after exposure to a steadily decreasing magnetic AC H-field of stated maximum amplitude in order to place the equipment under test in a known and as low as possible magnetic state;
- **Permed :** magnetised state after exposure to a magnetic DC H-field of stated maximum field strength (generally ten times the strength of the earth magnetic field) in order to characterise the ability of the equipment under test to acquire a permanent magnetisation.

2.2.2 Types of magnetic field or moment to be measured

- **Permanent field (moment) :** It is the magnetic field (moment) originating from the equipment under test due to its residual magnetism after either demagnetisation or magnetisation. The direct and accurate measurement of the permanent field requires a zero magnetic field environment at the test location of the equipment under test.
- **Induced field (moment) :** This effect is only present in a non-zero magnetic field environment. For weak external fields (order of magnitude of the earth magnetic field) the measured induced field (moment) is proportional to the external magnetic field strength, the induced field. The true induced field (moment) is never measured directly. The measurable quantity is rather the sum of the permanent field (moment) plus the true induced field (moment).
- **Current produced magnetic field (stray fields) :** Electrical currents which enclose a loop area produce a magnetic field proportional to the current strength and to the loop area. These stray fields must be measured when there is a danger of their disturbing the attitude control system or on-board instrumentation.

2.2.3 Measurement of static magnetic moment (example of application)

The test method consist in a measurement of the three orthogonal components of the DC magnetic field at some distance from the equipment under test after compensating the terrestrial field.
The equipment under test is mounted on a turn table in the centre of the coil system where the terrestrial field is cancelled. A three axis "flux gate" magnetometer allows to record the magnetic flux density values Bx , By, and Bz. Two measurements by axis are carried out after a 180 ° rotation of the equipment under test. Half of the difference between both measurements provides the strength of the permanent magnetic field on this axis, assuming the equipment under test is a perfect dipole. Generally this assumption is validated by a serial of measurement at several distances and by checking a variation of the field strength proportionally to the inverse cube law. These measurements are done for different states ; after 40 Gauss peak, 50 Hz deperm in three axes during 1 minute in a decreasing field, after 5 Gauss perm also in three axes, and stray field during power switched on of the equipment under test. Table 1 shows typical magnetic flux density measurements results radiated by a satellite microwave equipment (14 / 12 GHz Down Converter).

Axis	Measurement results after deperm		Measurement results after perm	
	Equipment OFF (without harness)		Equipment OFF (without harness)	Equipment ON
	d = 0,5 m	d = 1 m	d = 1 m	d = 1 m
+X	23 nT	5 nT	2 nT	4 nT
-X	-5 nT	1 nT	-3 nT	-2 nT
+Y	60 nT	11 nT	6 nT	7 nT
-Y	-64 nT	-4 nT	-10 nT	-10 nT
+Z	-11 nT	0 nT	1 nT	1 nT
-Z	6 nT	3 nT	-1 nT	0 nT
Bx	14,0 nT	3,0 nT	2,5 nT	3,0 nT
By	62,0 nT	7,5 nT	8,0 nT	8,5 nT
Bz	8,5 nT	1,5 nT	1,0 nT	0,5 nT
B	64,1 nT	8,2 nT	8,4 nT	9,0 nT

Table 2 :Magnetic flux density measurement results radiated by a 14/12GHz Down Converter unit

with :

$$B_X = \frac{|+X| + |-X|}{2} \qquad [1]$$

$$B_Y = \frac{|+Y| + |-Y|}{2} \qquad [2]$$

$$B_Z = \frac{|+Z| + |-Z|}{2} \qquad [3]$$

and

$$B = \sqrt{B_X^2 + B_Y^2 + B_Z^2} \qquad [4]$$

- **<u>Verification of the dipole law</u> :**

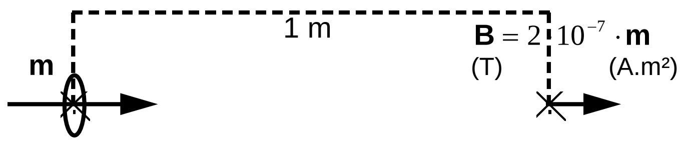
The magnetic field generated by a dipole decreases as the third power of the distance

$$B = B_0 \cdot \left(\frac{d_0}{d}\right)^3 \qquad [5]$$

	Bx	By	Bz
B (measured at d=1m)	3,0 nT	7,5 nT	1,5 nT
B (theoritical at d=1m)	1,8 nT	7,8 nT	1,1 nT

- Calculation of the total magnetic moment

The magnetic dipole moment **m** of the equipment is deduced from the magnetic induction B measured at 1 m as follow :



	Magnetic moment calculation after deperm	Magnetic moment calculation after perm	
	Equipment OFF (without harness)	**Equipment OFF (without harness)**	**Equipment ON**
	d = 1 m	**d = 1 m**	**d = 1 m**
B	8,2 nT	8,4 nT	9,0 nT
m	41 mA.m²	42 mA.m²	45 mA.m²

3. Methodology of magnetic field analysis for a telecommunication satellite payload

3.1 Calculation of the payload magnetic moment and resulting torque

3.1.1 Theory

The magnetic moment of the satellite and the magnetic induction of the Earth create a perturbation torque that needs to be compensated by means of the AOCS.

Ferromagnetic materials used in microwave devices (isolators, switches, TWTs (Travelling Wave Tube),etc) create magnetostatic fields which are a contribution to the global magnetic moment of the satellite.

All payload units are considered as magnetic dipoles whose magnetic moment can be calculated from static H field measurements at one meter.

A magnetised piece of matter has a dipole moment defined by the integral :

$$\vec{m} = \int_V \vec{M} \cdot dV \qquad [6]$$

m = magnetic moment ($A.m^2$)
M = magnetisation of the matter (A/m)
V = volume of the magnetised matter (m^3)

The magnetic field created by the dipole expresses as a function of the moment as follows :

$$\vec{H}\,(A/m) = \frac{1}{4\pi} \cdot \left[\frac{3 \cdot (\vec{m} \cdot \vec{R}) \cdot \vec{R}}{R^5} - \frac{\vec{m}}{R^3}\right] \qquad [7]$$

where **R** is the vector joining the dipole to the point of observation. The magnetic induction is

$$\vec{B}\,(Tesla) = \mu_0 \cdot \vec{H} \qquad [8]$$

$$\text{with } \mu_0 = 4\pi \cdot 10^{-7}\ Henry/m \qquad [9]$$

Let expand the Cartesian components of $\vec{B}$:

$$B_X = 10^{-7} \cdot \left[\frac{3 \cdot (m_X.\Delta X + m_Y.\Delta Y + m_Z.\Delta Z) \cdot \Delta X}{R^5} - \frac{m_X}{R^3}\right] \qquad [10]$$

$$B_Y = 10^{-7} \cdot \left[\frac{3 \cdot (m_X.\Delta X + m_Y.\Delta Y + m_Z.\Delta Z) \cdot \Delta Y}{R^5} - \frac{m_Y}{R^3}\right] \qquad [11]$$

$$B_Z = 10^{-7} \cdot \left[\frac{3 \cdot (m_X.\Delta X + m_Y.\Delta Y + m_Z.\Delta Z) \cdot \Delta Z}{R^5} - \frac{m_Z}{R^3}\right] \qquad [12]$$

Consider a dipole having a single component m_z

- at the poles (X = Y = 0),

$$B_x = B_y = 0 \text{ and } B_z = 2 \cdot 10^{-7} \cdot \frac{m_z}{R^3} \qquad [13]$$

- at the equator (Z = 0),

$$B_x = B_y = 0 \text{ and } B_z = -10^{-7} \cdot \frac{m_z}{R^3} \qquad [14]$$

So the magnetic moment m of an unit can be deduced from the magnetic induction **B** measured or specified at 1 m from the centre of symmetry of the unit, on a direction corresponding to the maximum value

$$B\,(Tesla) = 2.10^{-7}.m\,(A.m^2) \qquad [15]$$

3.1.2 Payload Magnetic Moment evaluation

This evaluation is performed in 3 steps.

- The 1st step is to obtain the magnetic moment components of each equipment in their geometrical reference (i) from tests according to the method described in the previous paragraph. For example, a typical magnetic moment of a TWT is :

$$m_{TWT} = \begin{bmatrix} m_{xi} \\ m_{yi} \\ m_{zi} \end{bmatrix} = \begin{bmatrix} 0{,}02\ A.m^2 \\ 0{,}02\ A.m^2 \\ 1{,}12\ A.m^2 \end{bmatrix}$$

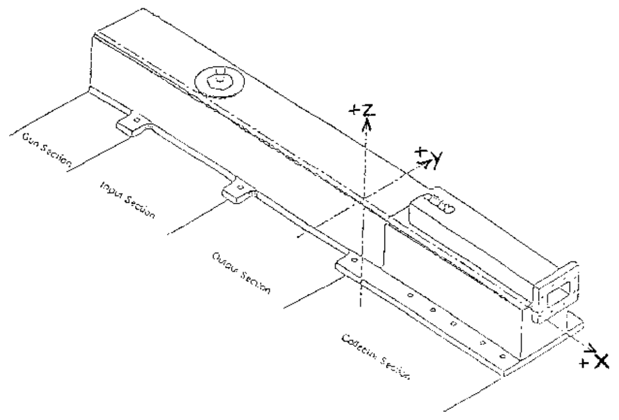
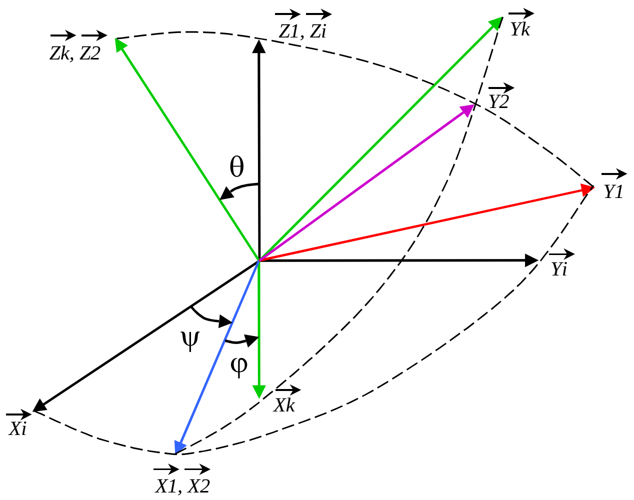


Figure 2 : TWT geometrical reference (i)

- The 2nd step consists to transform for each unit the geometrical reference (i) into the satellite geometrical reference (k) using the Euler Classical Angles (Type I) according the figure 3 and the matrix coefficients hereafter.



$$\begin{bmatrix} \cos(\psi).\cos(\varphi) - \sin(\psi).\cos(\theta).\sin(\varphi) & \sin(\psi).\cos(\varphi) + \cos(\psi).\cos(\theta).\sin(\varphi) & \sin(\theta).\sin(\varphi) \\ -\cos(\psi).\sin(\varphi) - \sin(\psi).\cos(\theta).\cos(\varphi) & -\sin(\varphi).\sin(\psi) + \cos(\varphi).\cos(\theta).\cos(\psi) & \sin(\theta).\cos(\varphi) \\ \sin(\psi).\sin(\theta) & -\cos(\psi).\sin(\theta) & \cos(\theta) \end{bmatrix}$$

Figure 3 : Transformation between two orthogonal reference by EULER Classical Angles (Type I)
(i) → (1) → (2) → (3) → (k)

For example, with the angles θ = + 90 ° , φ = 0 ° , ψ = - 90 ° , the TWT magnetic moment in the satellite geometrical reference (k) becomes :

$$m_{TWT} = \begin{bmatrix} m_{xk} \\ m_{yk} \\ m_{zk} \end{bmatrix} = \begin{bmatrix} -1{,}12 \text{ A.m}^2 \\ 0{,}02 \text{ A.m}^2 \\ -0{,}02 \text{ A.m}^2 \end{bmatrix}$$

This transformation is automatically carried out by the CATIA® software used to design the layout of the payload panels. Then, we obtain in this way the complete coordinates table of all units magnetic moment directly in the satellite geometrical reference (k).

- The last step consist to add the magnetic moment components of each equipment to obtain the global payload magnetic moment.

  The table here below shows an extract of this analysis.

		Magnetic Moment components of each unit in geometrical reference of the satellite		
		m_{Xk} (A.m²)	m_{Yk} (A.m²)	m_{Zk} (A.m²)
Receivers	2RE1-01	0,032	0,16	0,0
	2RE1-02	0,032	0,16	0,0
	2RE1-08	-0,032	-0,16	0,0
IMUXs	2ME2-01	0,2	0,2	0,2
	2ME1-01	0,2	0,2	0,2
	2ME4-01	0,2	0,2	0,2
R-Switches	1SR14-01	0,037	0,000	0,093
	1SR12-01	-0,093	0,037	0,000
	1SR12-02	-0,093	0,037	0,000
SSPAs	2SA1-01	0	0,2	0
	2SA1-02	0	-0,2	0
CAMPs	2CA1-01	0	0	0
	2CA1-02	0	0	0
	2CA1-21	0	0	0
TWTs	2TW1-01	0	0	1,12
	2TW1-02	0	0	1,12
	1TW2-06	0	1,12	0
HPIs	2HP1-01	0	-0,56	0
	2HP1-02	0	-0,56	0
	2HP1-19	0	0,56	0
T-Switches	7ST1-01	0,056	0,015	-0,004
	7ST1-02	0,056	0,015	-0,004
	7ST1-65	-0,004	0,056	0,015
		m_{Xk} (A.m²)	m_{Yk} (A.m²)	m_{Zk} (A.m²)
Magnetic Moment components of the payload (m_{Xk}, m_{Yk}, m_{Zk})		4,94	3,26	-2,30
Module of the Payload Magnetic moment		**| m | =**	**6,35**	**A.m²**

The result can be compared to the magnetic moment budget allocated at payload level.

3.1.3 Perturbation torque evaluation.

The magnetic moment of the payload allows to compute the perturbation torque between the satellite and the earth as the following example :

Earth input data :

Earth South geomagnetic pole (78,8 °N , 289,1 °E)

Earth North geomagnetic pole (78.8 °S , 109,1 °E)

R = radius of the Earth = 6 371 km

Cartesian coordinates of the South geomagnetic pole (expressed in the geometrical reference of the Earth) $\begin{bmatrix} 0{,}064 \\ -0{,}184 \\ 0{,}981 \end{bmatrix} \text{x R}$

Cartesian coordinates of the South geomagnetic pole (expressed in the geometrical reference of the Earth) $\begin{bmatrix} -0{,}064 \\ 0{,}184 \\ -0{,}981 \end{bmatrix} \text{x R}$

Unit vector in the direction of the Earth's magnetic pole (expressed in the geometrical reference of the Earth) $\begin{bmatrix} -0{,}064 \\ 0{,}184 \\ -0{,}981 \end{bmatrix}$

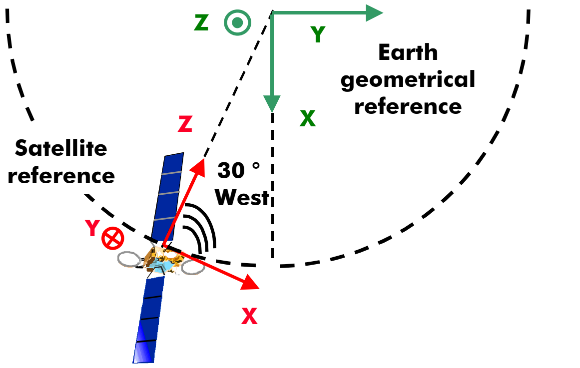
Module of the Earth dipole's magnetic moment

$$|\ m\ | = 79{,}1.10^{21}\ \text{A.m}^2 \qquad [16]$$

Earth dipole's magnetic moment calculation result (expressed in the geometrical reference of the Earth) $\mathbf{m} = \begin{bmatrix} \text{-5E+21} \\ \text{15E+21} \\ \text{-78E+21} \end{bmatrix} \text{A.m}^2$

Example of application :

Considering a position of a telecommunication satellite (0 °N , 30 °W) at 42 164 km distance from the Earth centre



Cartesian coordinates calculation result of the satellite (expressed in the geometrical reference of the Earth) $\begin{bmatrix} \text{37E+6} \\ \text{-21E+6} \\ \text{000E+0} \end{bmatrix} \text{m}$

Payload magnetic moment calculation result (expressed in the satellite geometrical reference) $\begin{bmatrix} 4{,}94 \\ 3{,}26 \\ -2{,}30 \end{bmatrix} \text{A.m}^2$

Earth's magnetic field calculation result at the satellite position (expressed in the geometrical reference of the Earth) $\mathbf{B} = \begin{bmatrix} \text{-34E-9} \\ \text{4E-9} \\ \text{104E-9} \end{bmatrix} \text{Tesla}$

Magnetic moment calculation result of the repeater (expressed in the geometrical reference of the Earth) $\mathbf{m} = \begin{bmatrix} 4{,}46 \\ 3{,}13 \\ -3{,}26 \end{bmatrix} \text{A.m}^2$

$$\text{Perturbation Torque : } \vec{T} = \vec{m} \wedge \vec{B} \qquad [17]$$

Perturbation torque calculation result given by the vectorial product $\mathbf{T} = \begin{bmatrix} \textbf{336E-9} \\ \textbf{-353E-9} \\ \textbf{122E-9} \end{bmatrix} \textbf{N.m}$

and the perturbation torque module

$$|\ T\ | = \sqrt{T_X^2 + T_Y^2 + T_Z^2} = .10^{-6}\ \text{N.m} \qquad [18]$$

This result must be take into account in the AOCS design

3.2 Calculation of the magnetic field at sensitive equipment level.

From the distance given by CATIA® software, and the table of magnetic moment calculation, it is possible to calculate the magnetic field produced by each unit at the location of one sensitive equipment (magnetometer, sensors, etc) with [10], [11] and [12].

Then, we add the magnetic flux density components produced by each equipment to obtain the global magnetic flux density at the sensitive unit location point as shown in the table here after.

Coordinates of a sensitive unit location in the satellite geometrical reference		
X (mm)	Y (mm)	Z (mm)
-2 492	0,0	0,0

		Magnetic flux density at sensitive unit location		
		Bx (nT)	By (nT)	Bz (nT)
Receivers	2RE1-01	3,9	-3,1	0,9
	2RE1-02	4,3	-3,5	1,1
	2RE1-08	-2,0	1,6	-0,4
IMUXs	2ME2-01	4,6	-3,7	-1,0
	2ME1-01	8,5	-1,9	-0,6
	2ME4-01	5,9	-6,2	-1,4
R-Switches	1SR14-01	0,4	0,0	-1,1
	1SR12-01	-1,1	0,0	0,7
	1SR12-02	-1,0	0,0	0,7
SSPAs	2SA1-01	-1,1	-14,0	-0,2
	2SA1-02	-1,1	14,0	-0,2
CAMPs	2CA1-01	0,0	0,0	0,0
	2CA1-02	0,0	0,0	0,0
	2CA1-21	0,0	0,0	0,0
TWTs	2TW1-01	-5,9	0,3	-6,5
	2TW1-02	-5,7	-0,6	-6,4
	1TW2-06	5,0	-8,4	-0,4
HPIs	2HP1-01	1,5	4,1	-0,1
	2HP1-02	0,7	4,3	-0,1
	2HP1-19	1,6	-4,1	0,2
T-Switches	7ST1-01	3,7	-0,1	1,4
	7ST1-02	4,2	0,1	1,6
	7ST1-65	-0,4	-0,2	0,1
		B_x µT	**B_y µT**	**B_z µT**
Resultant magnetic flux density components at sensitive unit location		**0,13**	**-0,02**	**0,06**
Resultant flux density B at sensitive unit location		**|B| =**	**0,14**	**µT**
		|B| =	**43,0**	**dBpT**
Resultant DC magnetic field at sensitive unit location		**|H| =**	**0,11**	**A/m**

The result can be compared to the radiated susceptibility DC magnetic field level specified for the sensitive unit or the threshold magnetic field level acceptable by this unit.

3.3 Magnetic field compatibility between equipment

In order to ensure self magnetic compatibility between units of the payload, it can be necessary to respect a sufficient distance between them.
The minimum distance d between units to avoid any DC magnetic field compatibility problem is derived by computing the distance at which the susceptibility level is reached as follow according the dipole law :

$$\left(\frac{H_1}{H_2}\right) = \left(\frac{d_2}{d_1}\right)^3 \Rightarrow d = \sqrt[3]{10^{\frac{H_1 - H_2}{20}}} \qquad [19]$$

For example, from a typical radiated susceptibility requirement of 170 dBpT and radiated emission limit of 100 dBpT at 1 m distance of the equipment, the minimum distance d between units is :

$$d = \sqrt[3]{10^{\frac{100-170}{20}}} \approx 7 \text{ cm} \qquad [20]$$

This distance can be used as a design rule for the implementation of units which radiate strong DC magnetic field (TWT, HPI (High Power Isolator), etc) with regards to the sensitive units (TWT, Switches, MLO (Main Local Oscillator), etc).

It should be noted that the calculation of the magnetic field at the sensitive unit described in the paragraph 3.2 allows to extend this calculation at any location inside the payload, in order to analyse the self magnetic compatibility between all payload units.

4. Conclusion

In this paper we have presented a magnetic cleanliness analysis methodology applied to a telecommunication satellite payload.
The magnetic analysis described, based on the magnetic dipole model, provides a simple way of predicting the total magnetic moment of the payload and the disturbing torque with the terrestrial magnetic field to be expected, and permits a reliable evaluation of the magnetic compatibility between the various equipment composing the satellite payload.

The most significant point of this methodology is the knowledge of the magnetic field levels radiated and acceptable by each type of payload equipment. The magnetic cleanliness analysis of the payload will be all the more right as these data equipment will be known accurately.

As in general the DC magnetic field radiated by the payload equipment is very low, all precise measurements of permanent and induced magnetic fields or moments must be performed in a controlled environment. For that special test set-up is required allows to measure the equipment in a fully DC magnetically compensated area. It’s the only way to guarantee reproducible and reliable measurements.

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