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ARISTOTELES: Preliminary Error Analysis of the Ambient Magnetic Field Recovery in the Presence of Satellite Magnetic Field Effects

Hüseyin Bâki Iz

Hughes STX Corporation

and

R.A. Langel

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Summary

One of the contributions that affect the total magnetic field as measured by satellite-borne magnetometers is due to the magnetic field generated by the spacecraft itself. The accuracy of the Earth's magnetic field determination therefore depends critically on how well these effects are known in practice. These satellite magnetic effects are reduced if the magnetic field sensors are located at the end of a long boom as far from these sources as possible. In this analysis, the optimum boom length for the Aristoteles spacecraft is investigated in the presence of imperfectly known satellite originated magnetic field effects and a distorted boom structure. Error propagation results indicate that the uncertainties due to the satellite sources will remain within the mission requirements if the boom length is longer than 4 meters. The uncertainties introduced by the boom distortion are not very influential if the boom bending remains less than 0.1°. The uncertainties inherent in the accuracy of the vector magnetometer measurements are the major source of error affecting the accuracy of the ambient field recovery.

1. Introduction

The determination of the ambient magnetic field by instruments on board the Aristoteles spacecraft will be complicated by magnetic fields produced by the spacecraft itself such as; magnetic fields produced by the satellite batteries, power systems, gyros, motors, relays and other magnetic material. The variable effects of switching satellite subsystems on and off, and of other operations that introduce magnetic disturbances are usually modeled on the ground, so these effects can be subtracted from measurements of the ambient magnetic fields in space. In any case, precise information about the location, magnitude and direction of all these effects is a necessity. In practice however, not only the imperfect knowledge about the satellite generated magnetic effects but also unknown stray fields and unaccounted moments induced by soft magnetic materials introduce additional uncertainties in the recovery of the ambient magnetic field.

All these effects are reduced if the magnetic field sensors are located at the end of a boom, as far from the spacecraft as possible. Yet, the length of the boom is limited and the boom itself may introduces additional uncertainties— especially for a vector magnetometer— since the boom is subject to bending and twisting in response to solar heating and torques applied to the spacecraft. Because the vector magnetometer component measurements refer to a coordinate system realized at the moment of the observations, precise information is needed about the orientation of the boom. The accuracy of this information depends on how well the boom distortion is monitored and modeled.

It is therefore the purpose of this study to determine the trade-offs involved among the boom length; uncertainties introduced by its distortion; and the imprecise knowledge about the spacecraft magnetic field sources.

The break down for the total error of the magnetometer instrument budget given in table 1 quantifies the upper limits for the effect of these uncertainties on the ambient field determination. For the total vector error budget, satellite attitiude error must also be included, but these are not considered in this study.

Type	Scalar	Vector
Instrument	1.0	2.0
Spacecraft Field	1.0	1.0
rss	1.41	2.24
Position and Time	1.3	1.3
Total (rss)	1.92	2.58

Table 1. Magnetometer Error Budget (units are in nT).

In this analysis, spacecraft magnetic sources are assumed to be known to within a given accuracy. They are represented as dipoles with specified accuracy. The magnetic fields at the magnetometers due to these sources are formulated and their uncertainties are propagated to the uncertainties of the ambient field recovery at a given epoch. The boom bending and twisting are assumed to be small and the boom bending is modeled as a parabola.

In the following sections, first the adopted satellite and instrument configuration are discussed. Physical and statistical modelings of the total magnetic field measurements are discussed in the subsequent sections. The error analysis results are then reported under the 'Numerical Results' section.

2. Instrument Configuration and Coordinate Systems

It is assumed that the magnetic field instrument package for Aristoteles consists of one fluxgate vector magnetometer and one scalar magnetometer, both located at the end of a boom. A set of star sensors at the foot of the boom together with an optical attitude transfer control system from the end of the boom relates the attitude of the instrument package to the star sensor. Errors in the field measurement due to the distortion of the boom are minimal in this configuration due to the directly observed attitude information.

The magnetometer coordinate system is centered on the vector magnetometer with axes defined by the magnetometer look angles, which are assumed to be orthogonal. For the scalar magnetometer, the coordinate system is centered on the magnetometer whose coordinate system is assumed to coincide with the spacecraft coordinate system. These coordinate systems will be displaced and rotated as a result of distortions of the boom and all the observed quantities will refer to these distorted coordinate systems.

The boom coordinate system has its origin at the base of the magnetometer boom, and its positive x axis is directed along the boom pointing away from the spacecraft. The y and z axes are orthogonal to the x axis.

Translation of the undistorted boom coordinate system in the x direction results in the **spacecraft coordinate system**. The spacecraft magnetic field is expressed in this coordinate system. All the above systems follow the right handed coordinate system convention.

3. Spacecraft Magnetic Field Model

The scalar magnetic potential at a point $\mathbf{r}' = (x\ y\ z)'$ due to a magnetic dipole at $\mathbf{r}_d$ can be expressed as

$$V_d = \frac{\mathbf{m} \cdot \mathbf{u}_d}{4\pi u_d^3} = \frac{1}{4\pi u_d^3}\left[m_x(x - x_d) + m_y(y - y_d) + m_z(z - z_d)\right] \qquad (1)$$

where $\mathbf{u}_d = \mathbf{r} - \mathbf{r}_d$ is the vector from the dipole to the point. $\mathbf{m}' = (m_x\ m_y\ m_z)'$ is the dipole moment vector (prime denotes transpose of a vector or a matrix, bold letters refer to vectors and matrices). Making use of (1), the magnetic field generated at $\mathbf{r}_d$ by this dipole moment is given, after some algebraic manipulations, by

$$B_d = -\frac{\mu_0}{4\pi}\nabla V = -\frac{\mu_0}{4\pi u_d^3}\left[\mathbf{m} - 3\frac{\mathbf{m}\cdot\mathbf{u}_d}{u_d^2}\mathbf{u}_d\right] \tag{2}$$

where μ_0 is the permeability of free space.

4. Model for the Boom Distortion

The magnetometer boom can be distorted by forces on the spacecraft, most notably by torques from the magnetorquers or uneven solar heating of the boom. These effects will cause the boom to bend and twist about its nominal position and orientation. For the purpose of modeling this distortion, it is assumed that the displacement of a point on the boom in the y or z direction is a quadratic function of its distance from the boom footpoint (the origin of the boom coordinate system defined above), i.e.,

$$y = bx^2, \quad z = cx^2 \tag{3}$$

where b and c are constants to be determined. Differentiating (3) with respect to x gives

$$\frac{dy}{dx} = 2bx = \tan\gamma, \quad \frac{dz}{dx} = 2cx = \tan\beta \tag{4}$$

where β (γ) is the angle between the x axis and the projection of the tangent to the boom at x into the (x - z) or (x - y) plane, i.e., β (γ) is a rotation about the y (z) axis (see Figure 1). If , at the origin of the coordinate system $(x_0, 0, 0)'$, this angle is given by β_0 (γ_0), then the small angle approximation i.e. ($\tan\theta \to \theta$) in (4) gives,

$$b = \frac{\gamma_0}{2x_0}, \quad c = \frac{\beta_0}{2x_0} \tag{5}$$

Therefore, at any point x along the boom,

$$\gamma(x) = \frac{x}{x_0}\gamma_0, \quad \beta(x) = \frac{x}{x_0}\beta_0 \tag{6}$$

and the y (z) displacement is given by,

$$y = \gamma(x)\frac{x}{2}, \quad z = \beta(x)\frac{x}{2} \tag{7}$$

By analogy with the above, the angle through which the boom is twisted about the x axis can be written as,

$$\alpha(x) = \frac{x}{x_0}\alpha_0 \tag{8}$$

where α_0 is the angular twisting about the x axis at the fiducial point x_0. In the small angle approximation, and to the first order, this twisting will not change the x coordinate. Therefore, the displaced position of a point initially at $(x,0,0)'$ on the boom will be

$$\mathbf{r}(x)' = (x, bx^2, cx^2) = (x, \frac{x^2}{2x_0}\gamma_0, \frac{x^2}{2x_0}\beta_0)' = (x, \frac{1}{2}\gamma(x)x, \frac{1}{2}\beta(x)x)' \tag{9}$$

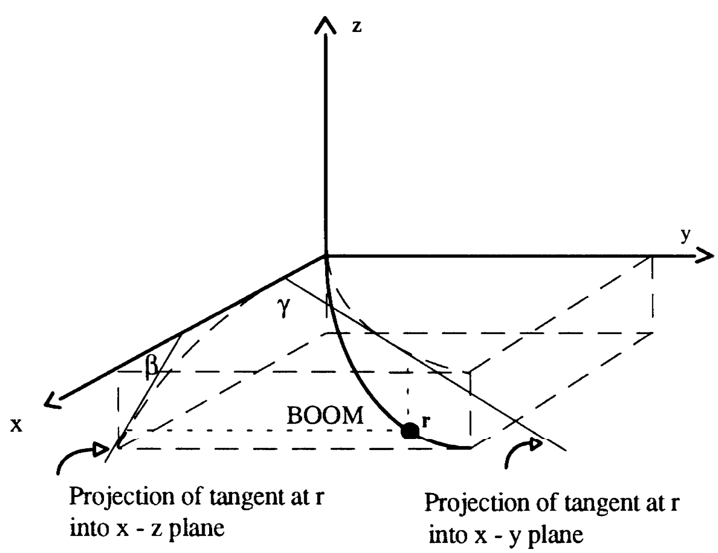


Figure 1. Definition of rotation angles

Besides this displacement, a set of axes with origin at $(x,0,0)'$, initially parallel to the axes of the boom coordinate system, and attached to the boom, will be rotated. From the above definitions of α, β, and γ this can be treated, again in the small-angle approximation, as consecutive rotations about the x, y, and z axes. The rotation matrix for this transformation is therefore

$$\mathbf{R}(\alpha,\beta,\gamma) = \mathbf{R}_x(\gamma)\mathbf{R}_y(\beta)\mathbf{R}_z(\alpha) = \begin{bmatrix} 1 & \gamma(x) & -\beta(x) \\ -\gamma(x) & 1 & \alpha(x) \\ \beta(x) & -\alpha(x) & 1 \end{bmatrix} \tag{10}$$

While the field is evaluated at the displaced position, it is assumed that the origin of the magnetometer coordinate system is still at $(x,0,0)$ for purposes of specifying the point about which the rotation takes place, since again in the small-angle approximation, the error generated by this is of second order.

The total magnetic field, as measured by a magnetometer at an arbitrary position on the boom, in a coordinate system that is rotated and translated with respect to the boom coordinate system, is obtained by applying (9) and (10) to the total field in boom coordinates. Applying the necessary rotations, the total magnetic field as measured by a vector magnetometer in the presence of various spacecraft magnetic sources is now given by

$$\mathbf{B}_T^v = \mathbf{R}'(\alpha,\beta,\gamma)\left\{\mathbf{B}_A + \sum_i \mathbf{B}_{d_i}\right\} \tag{11}$$

where the ambient field $\mathbf{B}_A$ and the dipole fields $\mathbf{B}_d$ are evaluated at their corresponding locations, i.e., at $\mathbf{r}(x)$ that is given by (9). The above expression is not only valid for relating the ambient field and the satellite magnetic field to the vector magnetometer components but also relates the scalar magnetometer measurements through the corresponding magnitude expression, i.e.,

$$B_T^s = \left|\mathbf{R}'(\alpha,\beta,\gamma)\left\{\mathbf{B}_A + \sum_i \mathbf{B}_{d_i}\right\}\right| \tag{12}$$

5. Statistical Model

Consider the following statistical relationship between the observation and the model parameters

$$\mathbf{B}_T^{v^{obs}} = \mathbf{R}'(\alpha,\beta,\gamma)\left\{\mathbf{B}_A + \sum_i \mathbf{B}_{d_i}\right\} + \mathbf{v} \tag{13}$$

where $\mathbf{B}_T^{v^{obs}}$ is the 3x1 vector of observed vector magnetometer component at a given epoch , $\mathbf{B}_A^v$ is the 3x1 vector of ambient field components at the same epoch, $\mathbf{B}_{d_i}$ is the 3x1 vector of spacecraft field effects modeled as dipole moments (2), and $\mathbf{v}$ is the 3x1 array of vector magnetometer component measurement disturbances with the following assumed statistical properties

$$E(\mathbf{v}) = \mathbf{0}, \qquad E(\mathbf{v}\mathbf{v}') = \sigma_v^2.\mathbf{I} \tag{14}$$

where $\mathbf{0}$ is a 3x1 zero vector. σ_v^2 is the a priori variance of unit weight of the vector magnetometer component measurements.

In the case of scalar magnetometer, measurements which are denoted by exponent indices "s," are scalar quantities and the observation equation for a scalar magnetometer measurement is expressed as

$$B_T^{s^{obs}} = \left|\mathbf{R}'(\alpha,\beta,\gamma)\left\{\mathbf{B}_A + \sum_i \mathbf{B}_{d_i}\right\}\right| + s \tag{15}$$

with the following assumed statistical properties for the observation errors,

$$E(s) = 0, \qquad E(s^2) = \sigma_s^2 \tag{16}$$

Stochastic vector $\mathbf{v}$ and s are further assumed to be uncorrelated, i.e.,

$$E(\mathbf{v}s) = \mathbf{0} \tag{17}$$

The above information about the magnetometer measurements is consolidated by the known information— from the laboratory or field calibration procedures — about the magnitudes of the satellite magnetic field sources and their error properties. This information is expressed as

$$\mathbf{m}_i^{prior} = \mathbf{m}_i + \mathbf{d}_i \tag{18}$$

where $\mathbf{m}_i^{prior}$ is th 3x1 vector of dipole known apriori with the following assumed distributional properties

$$E(\mathbf{d}_i) = \mathbf{0}, \qquad E(\mathbf{d}_i\mathbf{d}_i{}') = \sigma^2_{d_i}.\mathbf{I} \tag{19}$$

This random error is also assumed to be independent of the vector and scalar magnetometer measurements **e** and **s** as well as from the other satellite magnetic field sources. The orientations of these magnetic source components are assumed to be known and only their magnitudes are considered in this analysis. In the presence of n satellite magnetic field sources, (18) introduces 3nx1 vector of constraints on the magnitude of n satellite fields.

Ambuiguity introduced on the ambient field measurement component orientation as a result of the boom distortion can be resolved by the use of prior information about the ambient field at the time of the vector magnetometer measurement using models constructed from prior magnetic data. The introduction of this information provides necessary constraints for the reference system for the ambient field components. This additional information can be expressed as

$$\mathbf{B}_A^{prior} = \mathbf{B}_A + \mathbf{a} \tag{20}$$

where **a** is the 3x1 array of measurement disturbances with the following assumed statistical properties

$$E(\mathbf{a}) = \mathbf{0}, \ E(\mathbf{aa}') = \sigma^2_a.\mathbf{I} \tag{21}$$

where σ^2_a is the a priori variance of unit weight of the ambient field prior information. This random vector is also assumed to be independent from the above described random vectors.

Considering the above statistical relationship at a given epoch, the following set of non linear equations defines the observation equations of the parameters to be estimated and adjusted.

$$\mathbf{B}_T^{v^{obs}} = \mathbf{R}'(\alpha,\beta,\gamma)\left\{\mathbf{B}_A + \sum_i \mathbf{B}_{d_i}\right\} + \mathbf{v} \tag{22}$$

$$B_T^{s^{obs}} = \left|\mathbf{R}'(\alpha,\beta,\gamma)\left\{\mathbf{B}_A + \sum_i \mathbf{B}_{d_i}\right\}\right| + s \tag{23}$$

$$\mathbf{m}_i^{prior} = \mathbf{m}_i + \mathbf{d}_i \tag{24}$$

$$\mathbf{B}_A^{prior} = \mathbf{B}_A + \mathbf{a} \tag{25}$$

where

$$\mathbf{B}_{d_i} = -\frac{\mu_0}{4\pi u_{d_i}^3}\left[\mathbf{m}_i - 3\frac{\mathbf{m}_i \cdot \mathbf{u}_{d_i}}{u_{d_i}^2}\mathbf{u}_{d_i}\right] \tag{26}$$

Now observe that all the observed information on the left hand side of the above linear and non-linear equations are functions of the three ambient magnetic field components, three unknown boom distortion angles and 3n dipole moment components where n is the number of dipoles. In total, there are 3n + 7 equations for 3n + 6 unknowns, leaving one degree of freedom. The equations which are non-linear in parameters (22), (23) can be expanded into Taylor series about some nominal values of parameters, $\mathbf{x}_0$. Retaining only the first term of the expansion, they are,

$$\mathbf{B}_T^{v^{obs}} - \mathbf{B}_T^{v^o} = \left.\frac{\partial \mathbf{B}_T^v}{\partial \mathbf{x}}\right|_{\mathbf{x}_0} \Delta\mathbf{x} + \mathbf{v} \tag{27}$$

$$B_T^{s^{obs}} - B_T^{s^o} = \left.\frac{\partial B_T^v}{\partial \mathbf{x}}\right|_{\mathbf{x}_0} \Delta\mathbf{x} + s \tag{28}$$

$$\mathbf{m}_i^{prior} - \mathbf{m}_i^0 = [\mathbf{I} \quad \mathbf{0}]\Delta\mathbf{x} + \mathbf{d}_i \tag{29}$$

$$\mathbf{B}_A^{prior} - \mathbf{B}_A^0 = [\mathbf{0} \quad \mathbf{I}]\Delta\mathbf{x} + \mathbf{a} \tag{30}$$

where $\Delta\mathbf{x} := \mathbf{x} - \mathbf{x}_0$, the parameter vector $\mathbf{x}$ and the corresponding nominal vector are given respectively by

$$\mathbf{x}^T := [\mathbf{m}_1{}^T \quad \cdots \quad \mathbf{m}_n{}^T \quad \alpha\,\beta\,\gamma \quad \mathbf{B}_A{}^T] \tag{31}$$

$$\mathbf{x}_0^T := [\mathbf{m}_1{}^T \quad \cdots \quad \mathbf{m}_n{}^T \quad \alpha\,\beta\,\gamma \quad \mathbf{B}_A{}^T]_0 \tag{32}$$

Note that the identity matrix and the zero matrix in (29) are 3nx3n and 6 x 6 respectively, whereas in (30) the zero matrix is of dimension (3n+3) x (3n+3) and the identity matrix is of size 3x3 respectively.

The above model parameters include 3n dipole moment components (where n is the number of known dipole moments), three orientation angles at the time of the magnetometer measurements, and the three components of the ambient magnetic field as sensed by the vector and scalar magnetometers. Explicit partial derivatives for (27) and (28) can be found in Saba (1992). The above set of linear observation equations can now be represented in the following short form

$$\Delta\mathbf{y} = \mathbf{A}\,\Delta\mathbf{x} + \mathbf{u} \tag{33}$$

In the above expressions, $\Delta\mathbf{x}$ is the (3n+6) x 1 vector of corrections to be estimated to the nominal values of the model parameters under consideration. $\mathbf{A}$ is the (3n + 7)×(3n+6) design matrix whose elements are the partial derivatives of the magnetometer observations given by (26) through (29) with respect to the model parameters. $\Delta\mathbf{y}$ is the 3n+7×1 vector of the differences of the scalar and vector measurements together with dipole magnitudes and prior information about the ambient magnetic field from their corresponding nominal values computed at the moment of observation (collection of the left hand sides of (27) through (30)). **u,** the corresponding noise vector whose statistical properties are given by (14), (16), (19), is denoted by

$$E(\mathbf{u}) = \mathbf{0} \quad E(\mathbf{u}\mathbf{u}') = \Sigma_u \tag{34}$$

or, equivalently

$$\Sigma_u := \begin{bmatrix} \sigma_v^2.I & & \cdots & 0 \\ & \sigma_s^2.I & & \\ \vdots & & \sigma_{d_1}^2.I & \vdots \\ & & \ddots & \\ 0 & & & \sigma_a^2.I \end{bmatrix} \tag{35}$$

The well-known weighted least squares solution to the observation equations defined by (31) through (33) is given by

$$\Delta\hat{\mathbf{x}} = (\mathbf{A}'\,\Sigma_u^{-1}\,\mathbf{A})^{-1}\,\mathbf{A}'\,\Sigma_u^{-1}\Delta\,\mathbf{y} \tag{36}$$

The corresponding variance/covariance matrix for the adjusted parameters is

$$\Sigma_{\mathbf{x}} = (\mathbf{A}'\,\Sigma_u^{-1}\mathbf{A})^{-1} \tag{37}$$

Once (37) is given, the computed uncertainties of the parameters can be propagated to other parameters of interest using the similar steps as above. The uncertainty of the ambient magnetic field caused by the satellite field at the magnetometer location for instance can be computed using the following expression using the similar derivation steps in deriving the covariance matrix of the parameters,

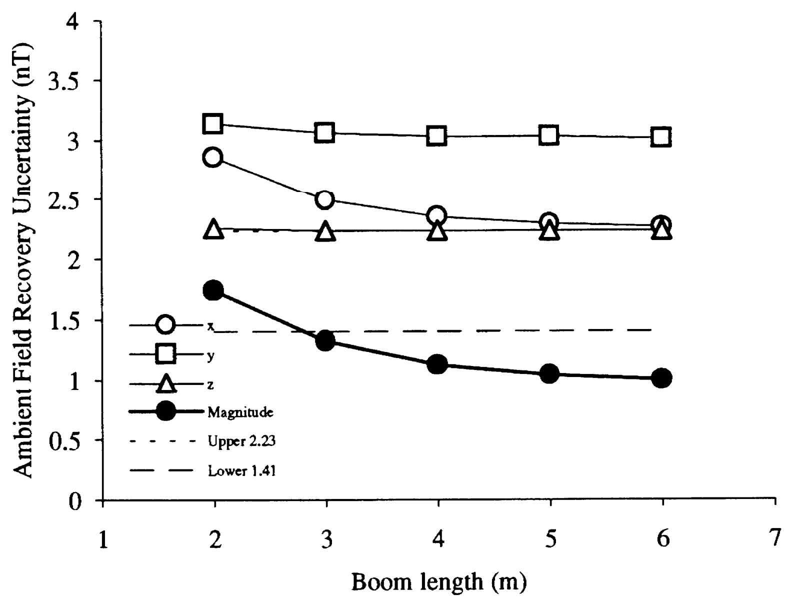
$$\Sigma^{A}_{B_d} := \mathbf{P}\Sigma_{\mathbf{x}}\mathbf{P}' \tag{38}$$

where **P** is the 3n x (3n+6) matrix of partial derivatives of (26) with respect to model parameters in (31) evaluated at the magnetometer location. In this study we are not interested in estimation of the parameters but their uncertainties which can be emulated using various parameter scenarios. Therefore, evaluation of (37) and (38) for various design parameters is the subject of the following section.

6. Numerical Results

Table 2 lists magnetic data characteristics of 25 sources, their dipole locations and vector components in the satellite coordinate system, that are used in the numerical computations. Only those spacecraft magnetic source magnitudes larger than 50 mAm^2 were considered as significant. It was assumed that the vector components of these sources are known within 10 percent of their magnitudes. Note that torquers are the major source of magnetic fields and how well they are known may need to be examined in more detail.

In figure 2, the variations of the ambient field uncertainty at different boom lengths are displayed against the "desired" and "acceptable" levels. The vector magnetometer measurement accuracy, which is assumed to be 3 nT, is the limiting factor since the spacecraft field uncertainties predicted and displayed in figure 2b are small and remain well below the lower (desired) level. All three ambient field components uncertainties (Figure 2a) are above the acceptable accuracy level although the uncertainty of the magnitude of the ambient field is about 1 nT . This is mainly because of the constraint imposed by the scalar magnetometer measurement whose accuracy is assumed to be also 1 nT.



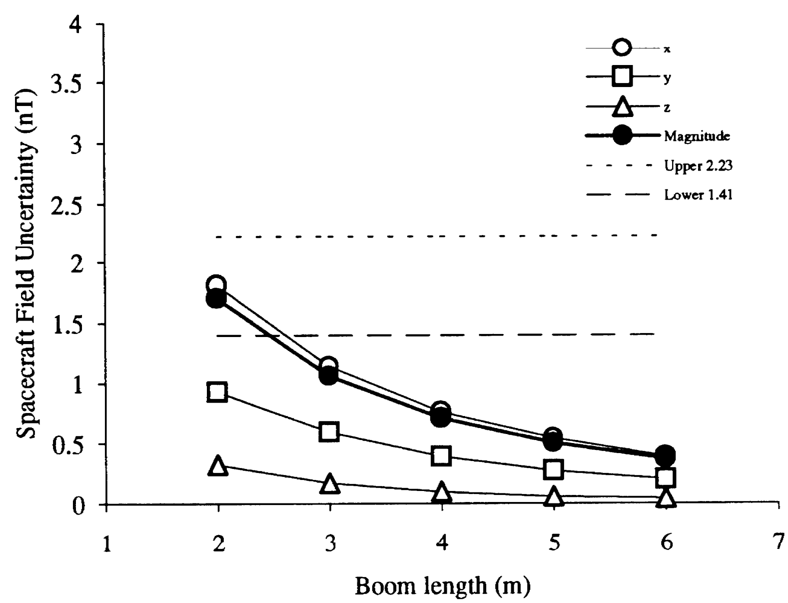


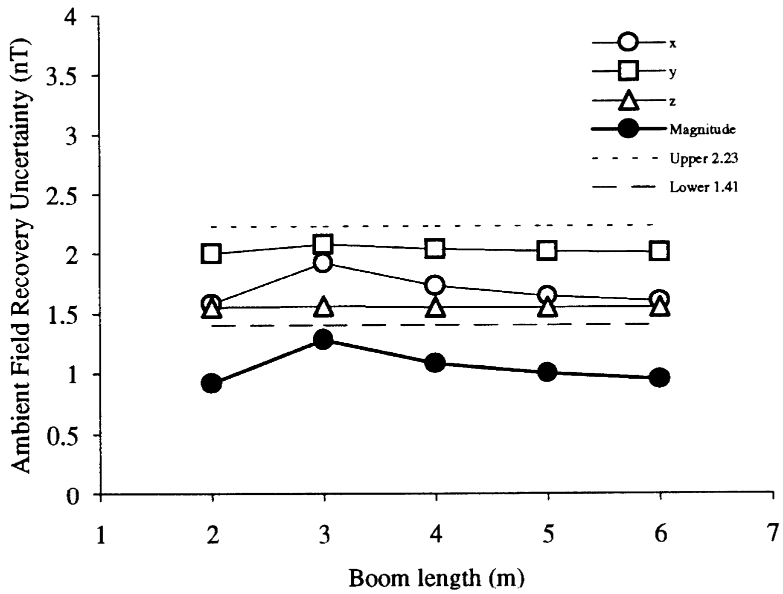
Figure 2. The influence of the various boom lengths on the recovery of the ambient field and the contribution of spacecraft magnetic field at different boom lengths. Input parameters include; Angular boom deflection at 5m is 0.1^{o}, σ of scalar measurements is 1.0 nT, σ vector measurements is 3.0 nT. Nominal ambient field and their corresponding uncertainties were assumed to be $(23000 \pm 10^6, 0 \pm 10^6, -23000 \pm 10^6)$.

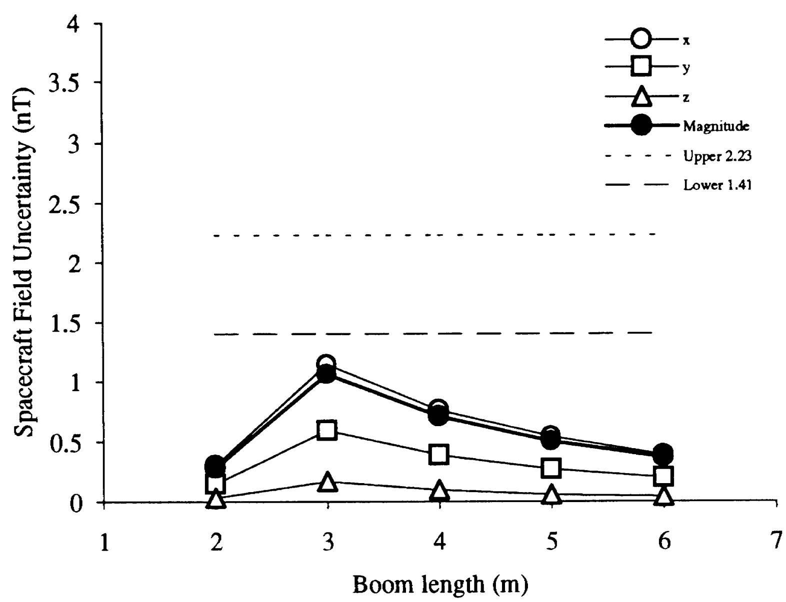
When the input parameter, angular boom deflection of 0.1^{o} at 5m was decreased to 0.01^{0} results displayed in figure 2 barely changed. The overall uncertainty of the ambient field components and the spacecraft field uncertainties at various boom lengths remained practically the same.

Table 2. Magnetic data characteristics (x,y,z) coordinates are in meters. Magnetic data components (m_x, m_y, m_z) are in Am^2. Data is in satellite coordinate system as defined in Vittone and Maggi (1992).

x	y	z	m_x	m_y	m_z	% σ	Description
4.362	0.683	0.068	0.0	0.0	0.095	0.1	STE1
3.689	0.683	-0.207	0.095	0.0	0.0	0.1	STE2
3.421	0.683	-0.160	0.0	0.0	0.095	0.1	STE3
4.120	0.113	-0.610	0.323	0.0	0.0	0.1	GYE1.
4.120	-0.149	-0.610	0.323	0.0	0.0	0.1	GYE2.
4.120	0.113	-0.610	0.323	0.0	0.0	0.1	GYE3.
4.161	-0.218	-0.555	0.0	0.263	0.0	0.1	AOCS ACE1.
3.841	-0.218	-0.555	0.0	0.263	0.0	0.1	AOCS ACE2.
1.194	0.181	0.595	0.0	0.071	0.0	0.1	ADE1
1.194	-0.173	0.595	0.0	0.071	0.0	0.1	ADE2
4.360	0.281	-0.595	0.0	0.0	0.05	0.1	FLAP
0.992	-0.395	0.648	20.0	0.0	0.0	0.1	Torquer 1
0.991	-0.019	0.648	0.0	20.0	0.0	0.1	Torquer 2
0.794	-0.174	0.588	0.0	-0.05	0.0	0.1	RPU
2.332	0.453	-0.445	0.185	0.100	0.185	0.1	ACC1
2.332	-0.453	-0.445	0.185	0.100	0.185	0.1	ACC2
2.332	-0.453	0.445	0.185	0.100	0.185	0.1	ACC3
2.332	0.453	0.445	0.185	0.100	0.185	0.1	ACC4
2.337	0.0	-0.215	0.120	0.0	0.0	0.1	Cal Dev 1
2.337	-0.180	0.0	0.0	0.120	0.0	0.1	Cal Dev 2
2.337	0.0	0.0	0.0	0.0	0.120	0.1	Cal Dev 3
1.712	0.286	-0.610	0.0	0.074	0.0	0.1	APO
3.776	0.220	-0.575	0.0	-0.120	0.0	0.1	PCU
0.887	-0.151	-0.571	0.233	0.0	0.0	0.1	Battery 1
0.887	0.160	-0.570	0.233	0.0	0.0	0.1	Battery 2

These results dictate that better vector magnetometer measurement accuracy is needed in order to meet the instrument error budget requirement. Results of the ambient field recovery uncertainties based on 2.0 nT vector magnetometer measurement accuracy level (Figure 3) indicates that this is indeed the case. Again the contributions of the spacecraft uncertainties remain comparatively at the same level as in the previous cases indicating weak correlation between the scalar field and ambient field.





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Conclusion and Recommendations for Further Studies

The numerical results indicate that for the spacecraft satellite magnetic field description given in table 2, known within 10 % accuracy, a 4m boom length for ARISTOTELES will enable the separation of the ambient magnetic field within the mission requirements. Total field measurements of accuracy of 1 nT and 2nT are needed for the scalar and vector magnetometers respectively.

These results, however, do not take into consideration the influence of unanticipated magnetic field sources which will also contaminate the recovery of the ambient field. Their effects need to be quantified for different source magnitudes.

It was assumed that the orientation of the magnetic sources are known with certainty which can not be achieved in practice. Although their effect on the results may be small for sources of small magnitudes, misalignments of dominant satellite sources, such as torquer coils, could be influential and need to be assessed.

Accounting for uncertainties for the satellite field larger than 10 % of their magnitudes also need to be investigated. Inclusion of the magnetic effects from solar panels and other sources is required, as information about their properties becomes available.

It is conceivable that laboratory-calibrated magnetic source effects will change after the satellite launch and in flight calibration of influential magnetic sources and other parameters will be needed. The degrees of freedom for a set of magnetometer observation equations discussed in this study is one, which is hardly meaningful for making statistical inferences about the calibration parameters. Therefore, real-time calibration procedures which make use of a multitude of observations under time invariance of the calibration parameters are to be investigated and developed.

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