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DETECTION OF THE SPACECRAFT STRAY MAGNETIC FIELD: AN APPROACH BASED ON DUAL SENSOR MEASUREMENTS

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Abstract. A method for identification and correction of the variable spacecraft (s/c) stray magnetic field contribution in measurements of the ambient space magnetic field is described, based on dual measurements with two sensors located at different distances from the spacecraft body. The time series of the differences of the measured field components of field at the two sensors is examined. Each step in the difference data corresponds to a switch-on/off event of one or more instruments on the s/c, producing a characteristic vector of differences assigned to each different state of the s/c; the ambient space magnetic field is superimposed to these step-like disturbances. The temporal variations of the time series of the two sensor differences are used for identification of jumps indicating the time of transition of the spacecraft system to another state. Two subsequent jumps define the interval of one state of the system. The average of the vector of two sensor differences during that interval is compared with those corresponding to the states defined in the training phase. A simplified approach assumes that all stray field variation effects can be characterized as step-like changes in the differences, to enable automation of the method of data analyzing and subsequent correction. The method requires a so-called "training phase", which is performed on data from the s/c commissioning phase, defining the s/c states and their combinations by averages of the differences in 3D space during the respective time intervals. For all s/c states the corrections to be applied to yield the ambient space magnetic field on outboard sensor are determined. The application of the method is illustrated on existing dual sensor measurements. The limits of the approach are discussed for the expected practical application on the magnetometer measurements from the Venus Express s/c mission.

1. Introduction

Magnetic field measurements are important for the exploration of interplanetary space and of planetary environments. The instrument measuring magnetic fields on the Venus Express mission and the scientific goals are described in (Zhang et al., 2005a,b); here, two identical magnetometers mounted at different distance from the s/c body are used.

Measurement of magnetic field in space puts special requirements on the spacecraft, due to the magnetic influence of other instruments onboard. Such measurement consists of three parts: the real ambient field in space, the non-zero sensor offsets, and the field generated by the different s/c components which varies according to the position of each sensor (Delva et al., 2002). The main task of the "magnetic field data correction" is to distinguish between the s/c originated field contribution and the ambient space field. Special techniques can be used for this task. One method is based on minimizing the influence of the s/c field through positioning the sensor(s) on a long boom. Another one requires special design of the s/c and its subsystems and instruments to make the s/c magnetic field stable. A third method is based on detailed measurements of all stray field variations generated by the s/c already on ground. While the first two methods largely restrict the construction possibilities, the third one is of limited use due to the different conditions during the flight compared to the on-ground measurements. Ness et al. (1971) first developed and discussed in detail a method for obtaining improved magnetic field results even in the presence of a large and variable s/c field, using simultaneous data from two magnetometers at different positions along a moderately long boom. At any time the magnetic field observed at a given position is a sum of (i) the ambient field, (ii) the absolute error of the field due to sensor zero offset at that position, and (iii) the s/c stray field; if the difference between the magnetic field vectors observed at two positions is constant, there is no s/c field variation.

We here illustrate the possibility to identify the changes of the s/c magnetic field, more specifically the step-like ones, using the differences constructed from the three components of the field measured by the two sensors at different distance from the s/c, and to suggest corrections for the outboard sensor measurement yielding the ambient magnetic field. The innovation of the current work is to develop an automatic procedure for the magnetic field data correction from dual sensor-measurements.

2. Method

The method is based on the calculation of differences of the 3 components of the magnetic field vector **B** measured simultaneously by the inboard and outboard sensor; inboard closer respectively outboard further from the s/c body The observations of the k-th component (k=1,2,3) at the two sensors are

$$B^{inb}_k = Bamb_k + Bsc^{inb}_k \qquad (1)$$

$$B^{outb}_k = Bamb_k + Bsc^{outb}_k \qquad (2)$$

where $Bamb_k$ is the k-th component of the ambient field, Bsc^{inb}_k and Bsc^{outb}_k are k-th components of the s/c originated field at the inboard and outboard sensor, respectively.
At any time t for each of three components k the differences are constructed

$$B_k(t) = B^{inb}_k(t) - B^{outb}_k(t) \qquad (3)$$

The difference (3) in each of the measured components is not affected by the ambient field. However, the magnetic field generated from a specific source within the s/c affects the measurements (1) and (2) in a different way due to the different distance of the source to the outboard and inboard sensor position. Let us suppose that the non-zero offset values for the measurements of each component at both sensors are known during the time of the mission. For simplicity we assume the switching on/off takes place during a short time interval. Thus a step-like behavior in time of the difference (3)-(4) is intuitively expected at each time when any of the instrument producing the effect is switched-on/off.
In a first test case, we describe these effects as switching on/off of magnetic dipoles within the s/c at the positions of the instruments, and real measurements of such operations are used. For a Multi-Magnetometer Sensing study (Delva et al., 2002) an experimental set-up with various dipole sources on a s/c mock-up was made and simultaneous measurements of switching operations of these dipoles at two magnetic sensors at different positions on a boom (inboard, outboard) were available.
In Figure 1 the differences of the experimental measurements (in nT) between outboard and inboard sensor in three components are shown (three top panels); the lower panel shows the jumps calculated using (6); significant jumps are identified either by the condition

$$|dBx(t)-dBx(t-1)| + |dBy(t)-dBy(t-1)| + + |dBz(t)-dBz(t-1)| > \Delta \qquad (6)$$

or by fulfilling the condition

$$|dBk(t)-dBk(t-1)| > \delta \qquad (7)$$

for at least one of the indices k; Δ and δ are the thresholds defining the jump condition.

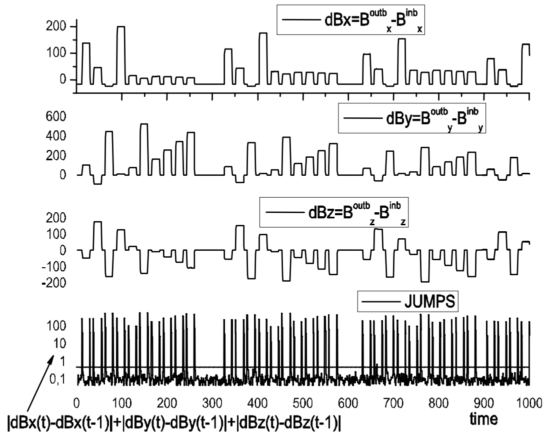

Fig. 1. Differences of inboard and outboard magnetic field components dBx, dBy, dBz (in nT) from data (Delva et al., 2002) for the first 1000 points. The lowest panel displays the value of the sum of absolute values of differences in two subsequent time intervals of elementary measurement.

For a real application on s/c data, the method consists of two parts: a training phase and a processing (cleaning) one. The training phase process identifies the simple distortions due to switch on/off of various instruments (and/or their measurement modes) and of their combinations, which we assume to lead to linear superposition effects. The result of this phase is a list of typical states of the s/c and suggested shifts of three components of outboard sensor measurements to extract the ambient field correctly. Each state is characterized by a point in 3D space of differences dBx, dBy, dBz obtained as the averages of these values during the whole interval when a given state is identified. The list summarizes all states (for each state the point in (dBx, dBy, dBz) space and shifts for each of the components at outboard sensors – 6 parameters – are listed).
For the Venus Express mission with an inboard and outboard magnetometer, the training phase will be using the data from the s/c commissioning phase (testing phase of the instruments on the s/c after launch), followed by the cleaning phase which starts with the measurements in interplanetary space. Applying the knowledge from the training phase we assign appropriate correction by shifts of the respective components at the outboard sensor to yield the ambient space field. Since the states of the s/c may have a long term evolution, a repetition of the commissioning procedure of the s/c instruments after some period of measurement is required.
To demonstrate the problem Figure2 shows in detail temporal changes at the inboard sensor corresponding to switch-on and off of a s/c subsystem simulated by a dipole source; measured data from Multi-Magnetometer Sensing study experimental verification phase (Delva et al., 2002).

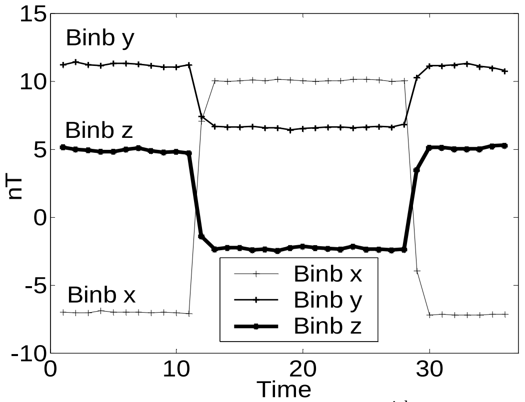

Fig.2. Example of magnetic signature in B^{inb}_k of switching operation on model of s/c. A step between the points 11 and 30 is indicated (one of the states of s/c systems).

Figure 3 shows on-ground measurements of the Mars Express s/c. Data were measured during magnetic cleanliness tests of the fully assembled s/c before launch (Delva et al., 2004). The steps defined by two subsequent jumps are better seen in differences (3), shown in Figure 3. Functional schemes of the training and the processing phases of the method are shown in Fig 4a, b.

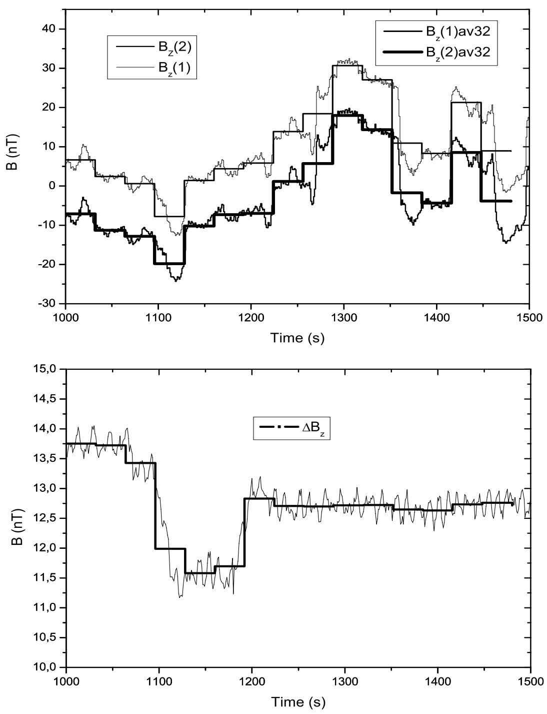

Fig.3. Data from Mars Express stray field measurements (Delva et al., 2004). The upper panel displays measurements of the inboard and outboard z-component of the field. The lower panel shows two jumps (>1nT) and a temporal transition to another state of the s/c system between them seen at in the difference (3).

3. Application of the method

To demonstrate the functionality of the method we generated a simulation of data as they are typical for the commissioning phase of a s/c.

In this test case the simulated data are used for the training phase of the procedure and the ambient field is supposed to be known (Figure 5).

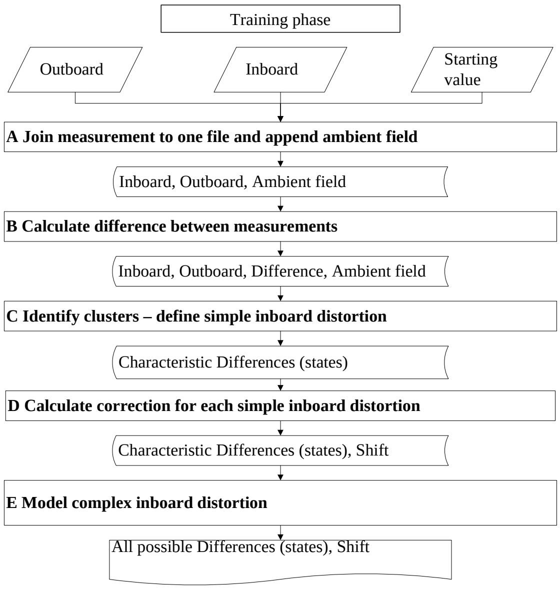

Fig.4a. Functional scheme of the training phase.

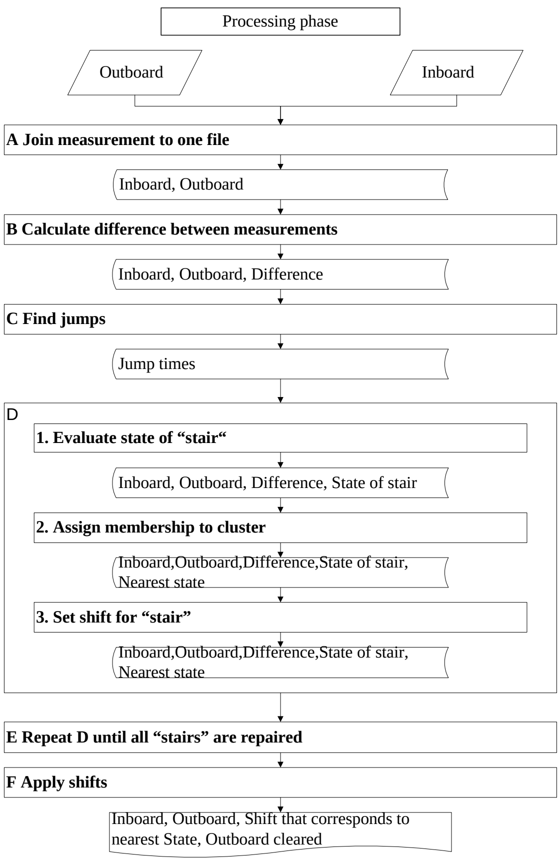

Fig.4b. Functional scheme of the processing phase.

As a result of the training phase, values for the characteristic differences between the sensor measurements for each separate state of the s/c are obtained, as well as corrections to be applied to yield the ambient space field value (Table 1). The processing phase is illustrated for a simulated case with additional slowly changing ambient field. The result after application of the procedure is compared to measured data (Figure 6).

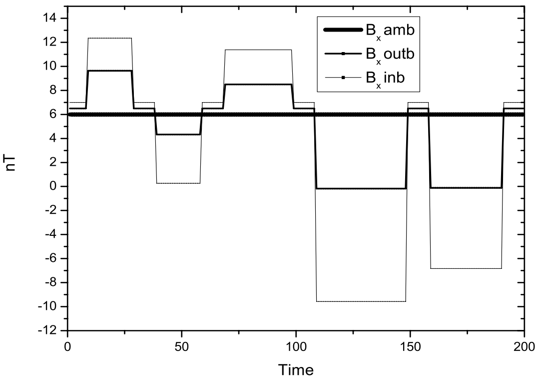

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Fig. 5. Simulated data, typical for the s/c commissioning phase. Here, six states of the s/c are identified, according to differences in the measured field components**.**

Table 1.

State\Value	$B_x$outb - $B_x$inb	Correction for $B_x$outb	Correction for $B_x$inb
1	-9.39	-6.18	-15.57
2	-6.71	-6.12	-12.83
3	-4.05	-1.68	-5.73
4	0.5	0.5	1
5	2.89	2.49	5.38
6	2.72	3.63	6.35

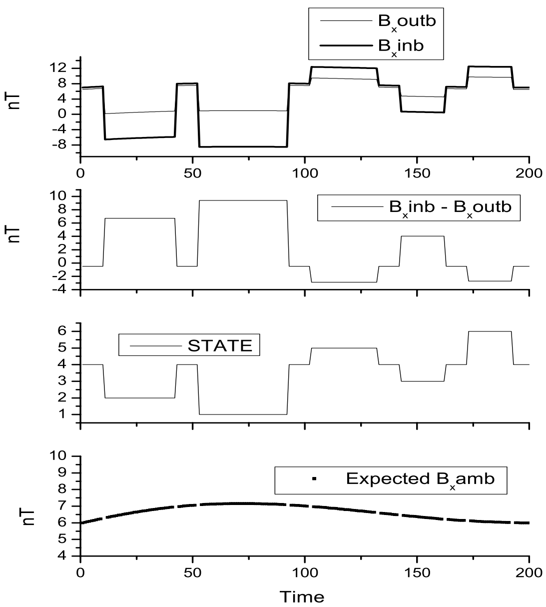

Fig. 6. Processing phase on simulated data for s/c states according to Table 1 and additional slowly varying ambient field; only x-components are shown. The lower panel shows the reconstructed value of the ambient field, after application of the correction terms to the (simulated) measurement data (transient time intervals between the different states are omitted).

4. Summary

A method is designed for identification of changes in the magnetic state of a s/c, which are generated by varying stray magnetic field sources on the s/c and which affect two sensors at different distances from the s/c body differently; eventual non-zero sensor offset effects are assumed to be known. The method is based on the differences in the respective magnetic field components measured at the sensors, varying stray field effects are assumed to be step-like distortions in the measurements. The temporal variation of the differences is analyzed and jumps are identified; the s/c states are defined as intervals between two subsequent jumps. In a training phase a list of modeled states of the s/c is determined and the corresponding optimal corrections to be applied to the outboard sensor measurements to yield the ambient space field are calculated. In a processing phase each elementary measurement in time is assigned to one of the states of the s/c system according to the distance of the measured difference to the points characterizing different states in 3D space of two sensor differences.

Limiting factors for the method are (a) amount of distortions that the s/c produces, (b) transitional time periods are omitted, (c) the method is sensitive to the selection of minimum thresholds in equations (4) and (5) and a minimum length of the constant levels for the s/c states, (d) only on/off effects are assumed as distortions, no long term variation of the differences is taken into account. The method is prepared for the magnetometer experiment on the Venus Express s/c. Its applicability will be tested in detail during the commissioning phase of the mission.

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