ATTITUDE DETERMINATION AND CONTROL FOR MICROARCSEC ASTROMETRY

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ABSTRACT

Some critical issues are discussed which are related to the attitude determination and control for the GAIA mission. The necessity of an on-board data reduction, at the present level of the proposal to perform mainly by analogic computation, motivates the main stringent requirements concerning the payload attitude. The rotational motion must be very smooth, and the attitude must be determined on-board with a high accuracy relative to the along-scan speed. It is shown how the requirements related to the smoothness of the attitude motion should be considered as one of the critical points of the GAIA project. An on-board autonomous attitude determination system is proposed, which is independent of the payload, and devoted to the satellite manoeuvering and attitude control. An accuracy improvement is required for the on-board data reduction, which is obtained by processing the Hipparcos star transits in the incoherent imaging field. Requirements and strategies for the on-ground attitude reconstitution are outlined.

Key words: attitude measurement, attitude control, star sensor, Fizeau interferometer, GAIA

1. INTRODUCTION

The diffraction image of the nominal interferometer will consist of a set of Young's fringes having an angular period of l/B rad (about 40 mas at 500 nm) which have an outer envelope in the shape of the diffraction image corresponding to one of the pupils, i.e, with a radius to the first minimum of $1.22\lambda/D$ (about 220 mas at 500 nm).

If such an image should be sampled, in order not to lose significant information, the following periods should be used: 5 mas along the scanning direction; and 50 mas along the fringe direction.

Given a scanning speed of 120 arcsec/s, a sampling period not larger than 5/120 ms should be used. For a single star image restricted to the size of the Airy disk, this results in a data rate of about 20 Mwords per second. By considering a mean value of 1000 stars per field of view, and assuming words of 8 bits, just for the coherent imaging mode, the global data rate requirement is about 5×10^{11} bit/s. In order to make data transmission to ground possible, it is necessary to introduce a compression factor of about 10^6, which must be obtained by on-board data reduction.

Use of the modulating grid and of the light integration by the photons shifting back and forth at the modulation frequency, as proposed by Lindegren & Perryman (1994), it is possible to reduce the data rate of a single star to 8 words every 0.2 s, that is to 40 words/s, reaching approximately the desired data compression factor.

The above data reduction roughly corresponds to the binning procedure, which has been applied on-ground to the Hipparcos main detector data before the phase estimation. The peculiarity is that now the data reduction is made on-board by an analog computer with all the merits and the limits which are typical of analog computation. Here the main limit lies in the necessary assumption that the diffraction pattern moves with known and constant speed across the grid.

Two error sources arise: (a) the jitter, that is the fact that the speed is not constant during the time interval considered (0.2 s); (b) the error in the on-board attitude determination and prediction.

2. ATTITUDE REQUIREMENTS

The effects on the final accuracy of the above causes of error should be limited by imposing requirements on the telescope attitude on-board determination and control, so that the resulting errors are negligible (or in the worst case of the same order) with respect to the error induced by the Poisson photon noise.

After some very preliminary computations it appears that: (a) the jitter is particularly dangerous in the frequency band 1–10 Hz, and it should be limited in the amplitude range of a few mas; (b) the error in the mean value, predicted on-board in the time interval of 0.2 s, of the diffraction pattern speed across the grid, should be less than about 50 mas/s.

The jitter requirement should be applied to the spacecraft structure design and to the attitude control system. It will be briefly discussed in the following section.

The accuracy requirement in the prediction of the diffraction pattern speed can be translated into accuracy requirements of the telescope rotation speed, as follows: (a) the on-board prediction error in the rotation speed about the spin axis should be less than 50 mas/s; (b) the on-board prediction error in the rotation speed about the optical axis should be less than 5 arcsec/s.

3. TELESCOPE ATTITUDE CONTROL REQUIREMENT

There is no stringent requirement in tracking the nominal scanning law, which must be followed with errors of the order of arcmin in the spin axis pointing, while the displacement with respect to the nominal value along the scanning direction can be much larger, practically without any limit. The true problem in the attitude control is the fulfillment of the requirement in the telescope jitter amplitude, which should be less than a few mas during the scientific data collection.

Two main lines of work can be envisaged. The first is the one followed in the Hipparcos design, which had very similar constraints. It consists of making spacecraft and telescope as rigid as possible, avoiding any variation of the telescope parameters, which cannot be calibrated in the on-ground data reduction. In this case a three-axis control by cold gas jet can be considered, similar to that used in Hipparcos. Also now, as in Hipparcos, it will be necessary to disregard the scientific data collected just after the gas jet actuation, not only because of the presence of jitter, but also for the difficulty in the rotation speed prediction. This aspect of the problem will be considered in the next section.

Against this solution there is the difficulty of getting, during the interferometer manufacturing, ultra-precise on-ground alignment, which should be stable during the whole mission.

The second approach is, then, the introduction of an active pointing system which sufficiently attenuates all kinds of disturbances ranging from 0 Hz up to few hundred Hz. Such a system has still to be investigated.

4. ON-BOARD ATTITUDE DETERMINATION

As already stated, the accuracy requirements in the on-board estimation of the telescope rotation speed are of the order of 50 mas/s for the spin axis, and of the order of 5 arcsec/s for the pointing.

No requirement of particularly high accuracy has to be considered for the attitude angle estimation. Tentatively, an accuracy requirement of the order of 1 arcsec for the three axes may be considered satisfactory. It seems unlikely (or not economically convenient) that an attitude determination system independent of the payload can fully satisfy all the on-board attitude requirements.

In any case, for many reasons, it seems convenient to have an independent attitude determination system, so as to satisfy all requirements related to the attitude control problem, even if it cannot reach the accuracy required by the scientific data collection and on-board reduction.

The accuracy requirements of this independent attitude determination system should be within approximately 1 arcsec in attitude angles, and 1 arcsec/s in rotation speed for all three axes. The above system could be denoted as the spacecraft attitude determination system. It should be integrated within the telescope attitude determination system, which should improve the attitude knowledge at the accuracy level required by the scientific collection of an on-board reduction by processing on-board star images collected by the interferometers.

4.1. An Autonomous Independent Attitude Determination System

Early successes in developing autonomous stellar attitude determination systems, which originated mainly in the USA (van Bezooijen 1994, Bank 1995, Cassidy & Schlom 1995), but also in Europe (Donati 1995), suggest that such systems will be available for GAIA.

A totally autonomous attitude determination system can be conceived, based on two CCD cameras fitted at 90°, one with respect to the other, and lying in the plane orthogonal to the spin axis. Tentative specifications of such a system are as follows: focal length: 50–100 mm; F-number 1.4; pixel size 6×6 μm^2; field of view: 5×5 to 10×10 square degrees; limiting magnitude $m = 6.5 - 7.5$ mag; sampling rate in the range 2–10 Hz.

The above system, equipped with its own star catalogue and star pattern catalogue, can work in a totally autonomous way, within the above stated accuracy of 1 arcsec in attitude angle and of 1 arcsec/s in rotation speed, without requiring any other attitude sensor.

4.2. The On-board Along-scan Speed Determination

The above independent system, while it can satisfy any requirement for the satellite manoeuvering and control, is far from the accuracy of about 50 mas/s in the along-scan speed, which is required by the data collection in the coherent imaging mode. To reach such an accuracy it will be necessary to improve the above measurements by on-board processing incoherent star images collected in some dedicated part of the field of view.

The incoherent star images should be sampled at a frequency of about 300 Hz. Assuming the pixel size given by Lindegren & Perryman (1994), the coordinates in the focal plane of the photocentre of sufficiently bright stars can be evaluated on-board to an accuracy of 10–50 mas in the along-scan direction and a few arcsec in the orthogonal direction. Given that the Hipparcos catalogue accuracy at that time will be of the order of 50 mas, the best accuracy of the telescope attitude measurements that we can assume, in the along-scan direction, is about 50 mas for each Hipparcos star transit. Then, using all stars included in the Hipparcos Catalogue, for each interferometer, it is possible to get about one attitude measurement, at the accuracy of 50 mas, every 10 s (that is with a mean frequency of 0.1 Hz).

With the above measurement data, the accuracy which can be obtained in the estimation of the along-scan speed, depends on the smoothness of telescope rotation motion and on the accuracy of the attitude mathematical model used. With reference to the Hipparcos experience, if it were possible to get a similar satellite rotation motion, it would also be possible to get an accuracy which is, most of the time, much better than required, but not sufficient during a short time interval just following gas jet actuations.

If, similarly to Hipparcos, a gas jet attitude control is adopted for GAIA, the problem arises of determining the along-scan speed just after the gas jet actuations. This problem does not seem to have a solution using only star measurements immediately after a gas jet actuation: because of insufficient accuracy in the along-scan speed determination, some observation time (1–2 s) will be lost in the coherent mode data collection.

In the hypothesis of a gas-jet attitude control, the above conclusion could also be motivated by the necessity to wait some time for the jitter damping. A considerable advantage could be obtained with a spacecraft design which minimizes the solar perturbing torque. In particular the component of the perturbing torque acting along the spin axis should be reduced so that its periodic effect on the spinning speed can be tolerated without requiring any control action, but for an occasional way.

5. ON-GROUND ATTITUDE RECONSTITUTION

The knowledge of the telescope attitude is required in order to process the scientific data on-ground, and the error on the final attitude reconstitution gives an effect which should be considered in the astrometry error budget. At the beginning of the scientific data reduction an along-scan attitude accuracy of about 10 mas, and a similar accuracy in the star along-scan abscissae, is required in order to solve the grid ambiguity problem. Moreover a final attitude accuracy is required at the level of 1 mas in order to get the astrometric goals of the mission.

To reach the above final accuracy, an on-ground attitude reconstitution is necessary which should be carried out by iterations with the produced star catalogue, as in the Hipparcos data reduction. The on-board attitude determination will not be sufficiently accurate to solve the grid ambiguity. Thus, before starting the coherent image processing, it will be necessary to make an on-ground attitude reconstitution by processing at least a subset of the star incoherent imaging data.

Different approaches can be followed between the two extreme cases listed below:

(a) Global approach: at first, the incoherent imaging mode data are processed. Following an iterative procedure a complete star catalogue at the sub-milliarcsec level and the whole mission attitude reconstitution at the level of 1 mas, are obtained. Such a star catalogue and global attitude reconstitution are then used as inputs to the coherent imaging mode data processing.

(b) Local approach: by processing the incoherent mode data collected at the boundary of the focal plane, when each star comes in and out of the field of view, the star field coordinates and the diffraction pattern speed across the grid can be determined with the necessary accuracy to solve the ambiguity problem. In this approach to the data reduction, the grid ambiguity resolution of the interferometer star images and the telescopes attitude reconstitution become two distinct problems.

6. CONCLUSIONS

Probably the most critical point is the necessity of an on-board data reduction, which at the present level of the proposal should be mainly developed by analog computation. This on-board data reduction has to get a compression rate of about 10^6 between the amount of ideal raw data which describe the interferometer star images and the reduced data which can be transmitted to ground. To perform this on-board data reduction, two main requirements are stated about the payload attitude. The rotation motion must be suitably smooth, and the attitude must be determined on-board with a high accuracy relative to the along-scan speed.

The first requirement involves the satellite structural design and the attitude control system. The opportunity of introducing an active telescope pointing system should be investigated, particularly considering also other problems related to the stability in time of some critical parameters of the interferometers. The requirements related to the smoothness of the attitude motion should be considered as one of the critical points of the GAIA project.

The accuracy requirement related to the on-board attitude determination is not in principle a critical problem, since it is clear how the required accuracy can be obtained. Problems may arise in the implementation of the necessary estimation algorithm in the on-board computer, but it does not seem a particularly critical point. The future availability of powerful and cheap digital processors for space suggests a revision of the actually proposed on-board data reduction, which should be much more advantageously based in digital rather than in analog computations.

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