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BAM: A METROLOGY DEVICE FOR A HIGH PRECISION ASTROMETRIC MISSION

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RESUMEN

Gaia es la misión espacial astrométrica de próxima generación de la ESA, que será lanzada en diciembre del 2013. El principal objetivo de Gaia es el censo astrométrico de mil millones de objetos hasta magnitud 20. El nivel de precisión astrométrica será de entorno a los 10 microarcosegundos. Para lograr tales desempeños tan exigentes, la complejidad del satélite es enorme, y una operación completamente automatizada debe ser adoptada. Una de las partes esenciales del satélite es el instrumento BAM, un dispositivo interferométrico con la tarea de vigilar la variación del ángulo básico entre los dos telescopios que componen la carga útil. En esta contribución describimos las características principales de este sub-instrumento y sus desempeños.

ABSTRACT

Gaia is ESA next-generation astrometric space mission, that will be launched in December 2013. The main objective of Gaia is to produce an astrometric census of one billion objects down to the 20th magnitude. The level of astrometric precision will be around the 10 microarcseconds. In order to achieve such demanding performances, the complexity of the satellite is huge, and a proper fully automated operation must be adopted. One of the essential parts of the satellite is the BAM instrument, an interferometric device with the task of monitoring the variation of the Basic Angle between the two telescope that compose the payload. In this paper we describe the main features of this sub-instrument and its performances.

Key Words: space vehicles: instruments

1. INTRODUCTION

Gaia is the most important mission of the 21st century for the global high precision astrometry. High precision astrometric instruments are based on the demanding requirements of the payload and in particular on the opto-mechanical aspects of the instrument (Gai et al. 2012). Space missions involve several constraints that determine most of the physical instrument specifications. The instrument alignment can be affected during launch e.g. by the vibrations, by which point the remote instrument is inaccessible. The minimization of vibration is reflected on the constraints on the stiffness of the payload structure to prevent misalignments, which would exceed the maximum deviation from the nominal configuration and unacceptable degradation of the instrumental response. A reliable evaluator of the instrument performances can be based on the PSF (Point Spread Function) properties. The PSF may be affected by large aberrations resulting in a reduced precision of the astrometric measurement. The opto-mechanical active controls on the payload are reduced as far as possible to reduce risks of failures and to cope with limits such as the mass budget or the complexity. The end result of an in-orbit realignment is a working instrument with acceptable optical quality, but a response significantly different from the ideal diffraction limited performance. This generates stringent requirements on the instrument calibration in order to reach the goals for the precision. The astrometric measurement will be more and more precise with increasing calibration refinement. In the range of small perturbations, applied to the case of modern instruments aimed at high precision measurements, the short term disturbances to the instrument response can simply be monitored, without actually moving opto-mecahnical parts. The most precise calibration implies the need of onboard systems that can help in understanding the instrumental response throughout the operations.

Gaia is equipped with a relatively simple monitoring / metrology concept based on laser interferometry. In this paper, we focus on the analysis and implementation of the data reduction software for the Gaia metrology subsystem: the BAM (Basic Angle Monitoring).

The DPAC (Data Processing and Analysis Consortium) is organized in Coordination Units (CU). CU2 is devoted to the simulation of the instrument

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response and of the raw Gaia data, while CU3 takes care of the core processing. The activity described in this paper was deployed in the framework of CU3, in particular in the context of the Astrometric Verification Unit (AVU). AVU is composed of three systems: the Base Angle Monitoring (BAM) (Gardiol et al. 2010), the Global Sphere Reconstruction (GSR) (Vecchiato et al. 2012) and the Astrometric Instrument Model (AIM) (Busonero 2012).

2. BASIC ANGLE MONITORING INSTRUMENT

Astrometry in space is mostly based upon measurements performed by multiple telescopes, operating concurrently over different Lines of Sight. Different implementations can be found in ESA missions like Hipparcos (Arnoux et al. 1986) and Gaia (de Bruijne et al. 2010; Snijders et al. 2000; van Veggel et al. 2004), or in the NASA mission SIM (Moshir et al. 2010), in spite of dramatic differences in the design and operation principle. In such a scenario, in which the basic information comes from combination of multiple telescopes, the knowledge of the angle between the Lines of Sight and its monitoring becomes essential. Monitoring of the baseline or of the Base Angle (depending on the specific instrument concept) is thus a crucial issue for the calibration subsystems.

BAM is basically an interferometer devoted to the monitoring of the Line Of Sight (LOS) of each telescope. The instrument measures and monitors the variation of the Base Angle value between the two telescopes looking at the phase changes of the fringes. Any fringe envelope movement is conjugated to the relative movements of the apertures, associated to a LOS variation. The Base Angle has a design value of 106.5°. The BAM instrument is subdivided in two stages: in the former a collimated source is split into four arms (two per telescope), and the latter is the focusing stage corresponding to each Gaia telescope (Figure 1). Each pair of laser beams generates an interference pattern on the GAIA focal plane onto a dedicated CCD (Figure 2). Both beam pairs have a well defined baseline, equal for the two telescopes.

The main goal of the AVU/BAM subsystem is to develop, test and operate a data reduction pipeline able to measure and monitor the Basic Angle Variation (BAV) from the data of the Gaia satellite. The downloaded data correspond to a central region of the fringe envelope for each line of sight. In this paper we will describe the pipeline and its performance in some of the Operation Rehearsal (OR) that occurred in the months before the launch of Gaia (2013

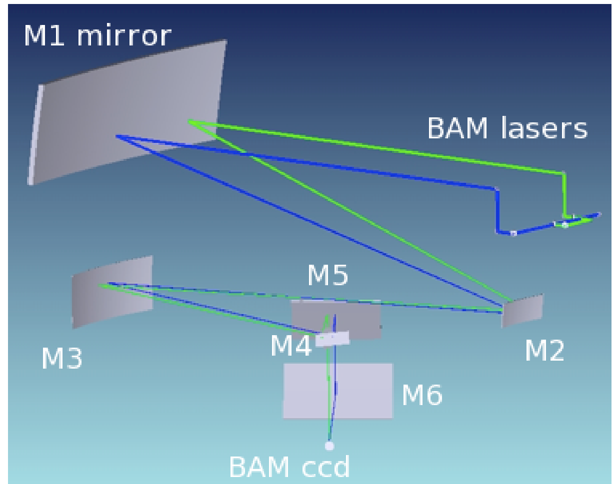

Fig. 1. Optical Layout of Gaia with BAM laser raytrace.

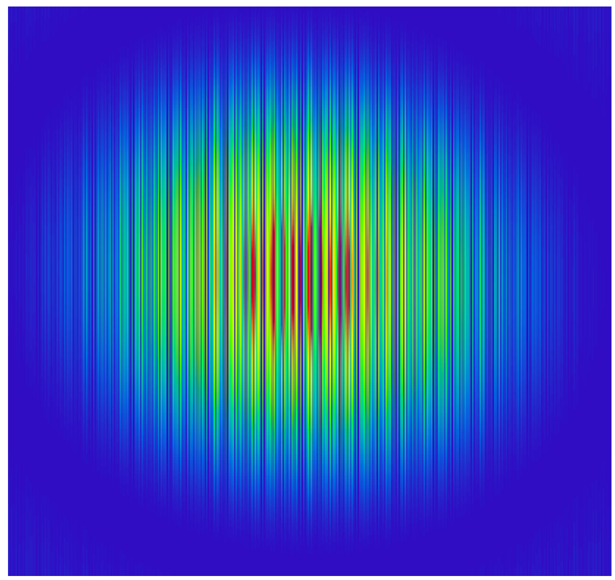

Fig. 2. Fringes simulated with Zemax.

December 19th). The simulated data used in the OR were produced by CU2.

3. PIPELINE

The AVU Basic Angle Monitoring (BAM) software system is in charge of processing the BAM telemetry in order to monitor and analyze the instrument behavior over time. It is a fundamental component of the technical and scientific verification of the overall Gaia astrometric data processing, developed within the context of AVU in CU3. Deployement and execution of the software occurs at the Data Processing Center of Turin (DPCT), which constitutes one of six DPCs within the Gaia DPAC (Martino et al. 2011).

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The AVU/BAM, besides producing the fundamental BAM measurements (e.g. time series of the phase variation), processes the elementary signal and provides an interpretation in terms of a physical model, to allow early detection of unexpected behavior of the system (e.g. trends and other systematic effects). The software also compares the measured data with the BAM model currently implemented into the system. Due to the mission characteristics, the AVU/BAM is critical for the short-term verification of the absolute quality of Gaia astrometry and also plays an important role in the medium- and long-time verification. In this respect, an important function performed by the BAM is to provide ways to identify and quantify the underlying causes in case the specific passive stability of the Basic Angle should be violated in orbit.

The AVU/BAM pipeline performs two different kinds of analyses: the first is based on daily runs, the second is focused on overall statistics on weekly basis.

3.1. *Daily Analysis*

AVU/BAM pipeline produces automatic daily reports, based on the analyses of the fringes transmitted to DPCT every 24 hours. There are three main categories of data and evaluations. The first part concerns the analysis of the Line of Sight variation; the two lines of sight are monitored independently. The second part is more focused on the Basic Angle (BA) variation over time. The third part is dedicated to the analysis of parameters that can support the evaluation of the BAV, like the Flux, the Fringe Period and the Contrast.

3.1.1. *Line of Sight*

There are two lines of sight in Gaia. Each line of sight produces a fringe set that monitors, at first order, the movement of the primary mirror of the respective telescope. The main part of AVU/BAM code is focused on monitoring of the individual lines of sight. The LOS deviation, or in other words the fringe movement in the AL (Along Scan) direction, is measured as the displacement of each fringe frame with respect to the current zero position, defined by the mean of one hundred images. After binning in the AC (Across Scan) direction, in order to maximize the Signal to Noise ratio, the code has two stages: in the first stage it acquires 100 images and produces a mean image, in the second stage it computes a cross correlation between each image and the mean image. Figure 3 shows a representative plot of the output produced for the Line of Sight 0 during the Operation Rehearsal 4 (OR#4). The plot shows the sinusoidal output that the CU2 simulated as a consequence of the spin period and the heat contribution of the sun (at 45°) inducing oscillations on the payload. It is possible to see that the software is able to detect jumps at revolution 3486 and 3488, that simulate microscopic settling of the mechanical structure.

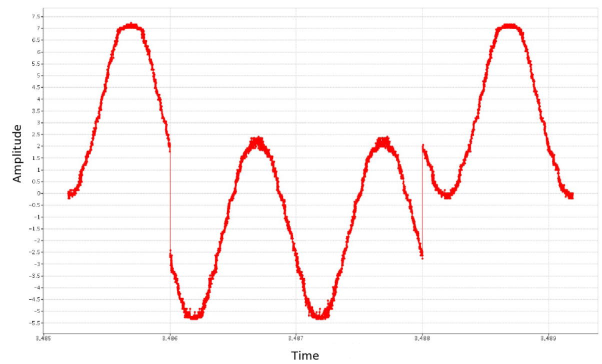

Fig. 3. OR#4 plot of Line of sight deviation.

3.1.2. *Basic Angle Variation*

The second step of the pipeline is the Basic Angle Variation (BAV) estimate. It is calculated through two different algorithms (Gai et al. 2013). The first algorithm (RDP) computes the difference between the two Lines of Sight deviations (LOS 0 minus LOS 1). The second algorithm (Gaiometro) makes a direct cross correlation between the images of the two different lines of sight. The Gaiometro is able to do a further computation of the images un-binned (Gaiometro2D). Figure 4 shows the three BAV estimates. The plot demonstrates how the three algorithms are able to see the same feature at 3976 revolution.

3.1.3. *Additional daily outputs*

Last step of the daily pipeline is devoted to other three properties. The first one is the Fringe Flux, calculated as the raw pixel sum of each frame. The second one is the Fringe Period x, that is given by

$$x = \frac{f\lambda}{b} \tag{1}$$

with, f is the focal length, λ is the wavelength and b is the baseline. This quantity gives a fast overlook to these three properties of the BAM instrument. The last quantity is the Fringe Contrast, that is basically related to the visibility of the fringes.

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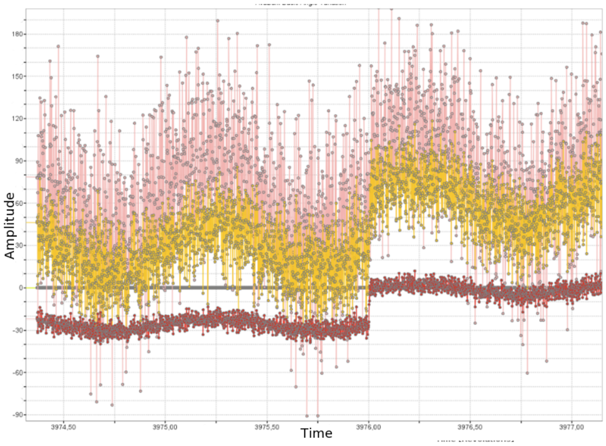

Fig. 4. Comparison between the BAV estimates made by RDP (red) , Gaiometro (yellow), and Gaiometro2D (pink).

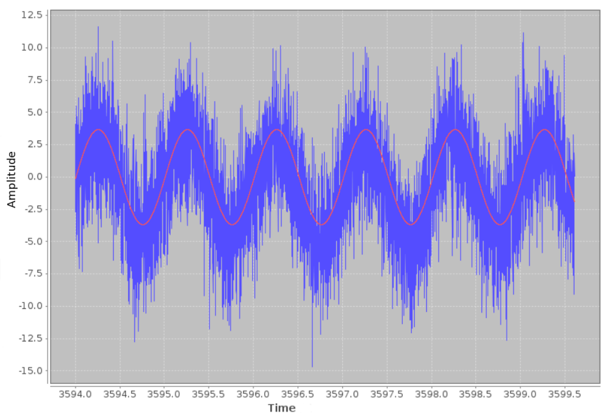

Fig. 5. Sinusoid (red) fitted to the BAV (blue) before removal.

3.2. *Weekly Analysis*

In OR#3 and OR#4 we produced also weekly analyses based on the output of an entire week of data. The main feature of this tool is to produce data binned in time. Each daily quantity is produced binned over 5 minutes. This reduces high frequency noise and provides evidence of the long term evolution of the system. Another feature of the weekly analysis is the removal of sinusoidal components of the BAV measurements. Through the DFT algorithm (Gai et al. 2007), we find the main frequency of the sinusoid and remove the sinusoid to the BAV measurement (Figure 5). This procedure is applied twice in order to remove the first two frequencies, and show the possible secular trend of the BAM instrument.

We also developed an automatic weekly tool, that will be used during mission operations. The goal is to extract some of the most interesting quantities averaged on the spin period time (i.e. 6 hours).

4. CONCLUSIONS

One of the most important metrology system of the ESA astrometric mission Gaia, launched the 2013 December 19th, is the Basic Angle Monitoring. The data collected by this interferometer are processed by AVU/BAM pipeline. In this paper we briefly described the AVU/BAM software that is operated at the Turin Data Processing Center during the Gaia mission. We described also the daily measures, like LOS deviation, BAV, Fringe Period, Fringe Flux and Fringe Contrast during the Operation Rehearsal. A brief overlook on the long term strategies (weekly analysis) is given.

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REFERENCES

Arnoux, J. J., Dubet, D., & Fruit, M. 1986, Proc. SPIE, 655, 380
Busonero, D., 2012, Proc. SPIE, 8449, 844917
de Bruijne, J., Kohley, R., & Prusti, T. 2010, Proc. SPIE, 7731, 77311C
Gai, M., & Cancelliere, R. 2007, MNRAS, 377(3), 1337
Gai, M., Busonero, D., & Riva, A. 2012, Proc. SPIE, 8442
Gai, M., Riva, A., Busonero, D., Buzzi, R., & Russo, F. 2013, PASP, 125, 1383
Gardiol, D., Bonino, D., Lattanzi, M. G., Riva, A., & Russo, F., 2010, ASP Conf. 434, 131
Martino, M., Ciampolini, A., Messineo, R., et al. 2011, Proc. IAU, 276, 539
Moshir, M., Murphy, D. W., Meier, D. L., & Milman, M. H. 2010, Proc. SPIE, 7734, 77341H–77341H–9
Snijders, B., Kappelhof, P., Braam, B. C.,et al. 2000, Proc. SPIE, 4006, 915
van Veggel, M., Vink, R., Rosielle, N., Nijmeijer, H., & Wielders, A. A. 2004, Proc. SPIE, 5495, 11
Vecchiato, A., Abbas, U., Bandieramonte, M., et al. 2012, Proc. SPIE, 8451–132