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Modeling the Gaia instrument

D. Gardiol, D. Bonino, D. Busonero, L. Corcione, M. Gai, M.G. Lattanzi, D. Loreggia, A. Riva, F. Russo, and J. C. Terrazas Vargas

Istituto Nazionale di Astrofisica – Osservatorio Astronomico di Torino, via Osservatorio 20, I-10025 Pino Torinese, Italy, e-mail: gardiol@oato.inaf.it

Abstract. The ESA-Gaia astrometric mission, for which launch is foreseen spring 2012, is expected to provide measurements with unprecedented accuracies. This requires a realistic model of the many components of the payload and of the data processing for realistic simulations and to verify the performances of both the instrument and the software data reduction pipeline. We present a sample of the most relevant challenges related to the current Gaia Instrument modeling.

1. Introduction

Gaia is an ESA Cornerstone mission currently scheduled for launch in spring 2012 dedicated to precise measurements of the positions and motions of over a billion stars in our Galaxy. It will be the second astrometric space mission, the first being the successful Hipparcos satellite. Oss. Astr. di Torino (OATo) is heavily involved in the Gaia mission through the Data Processing and Analysis Consortium (DPAC), an international consortium of over 300 scientists charged with processing the data that will arrive from the Gaia satellite.

2. The Gaia instrument model

Among the DPAC activities, Osservatorio Astronomico di Torino is responsible for the Gaia instrument model. Gaia is expected to provide unprecedented results based on the mission requirements: complete down to V=20, accurate to $7\mu as$ at V=10, $10 - 25\mu as$ at V=15 and $300\mu as$ at V=20. This also poses very stringent requirements for modeling the instrument performance. The instrument model must be able to reproduce fine details of the instrument, enabling the generation of realistic simulated data to feed the data reduction algorithm and provide a reliable tool for instrument calibration.

2.1. Instrument modeling approach

The instrument modeling approach is twofold. From the point of view of the simulations, starting from the design characteristics and parameters the instrument model can be used to predict the instrument behaviour and check the predicted performances (forward analysis). But once in operation, when observations become available, the instrument model will use the real data to interpret the instrument behaviour and provide inputs to the calibrations (backward analysis). This second part is the purpose of the Astrometric Instrument Model and is described in Busonero et al. (2009). In the following the focus of our discussion will be on the forward analysis.

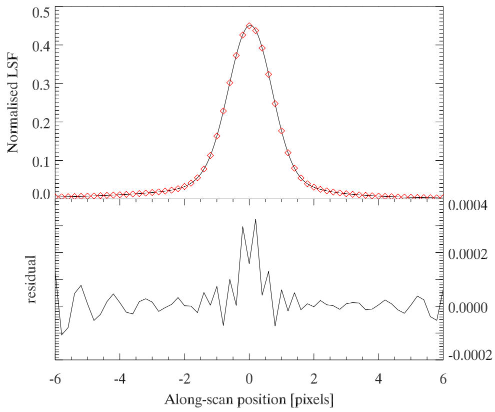

Fig. 1. Result of a LSF fitting: data and fit results are shown for comparison (top) together with the residuals of the fit (bottom)

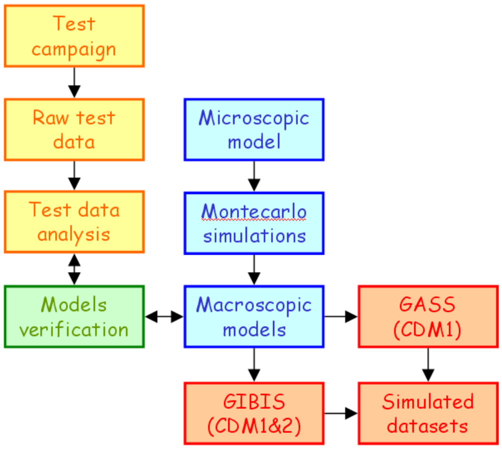

Fig. 2. Diagram of the radiation modeling test campaign

2.2. Instrument model structure

The structure of the Gaia instrument model depends upon the main instrument subsystems, namely: Optics, Dispersers, CCDs and Focal Plane Assembly, PSF/LSF, Basic Angle Monitoring device, Orbit and Attitude, On-Board processing. In the following sections we will give examples of modeling challenges for some of the model subsystems.

3. PSF/LSF model

A reliable point spread function (PSF) model is mandatory to precisely estimate the sources position (by PSF here we intend the source image as sampled onto the CCD rather than the optical PSF). The model must be able to describe the PSF shape variation with respect to all relevant parameters (such as the position of the object onto the field of view, the object spectrum, etc.). Given the particular data readout scheme, also the linear spread function (LSF) plays a fundamental role in the data reduction and must be modeled. The full PSF/LSF model used for simulation is described in Gardiol et al. (2008).

The model is based on a dual representation. The starting point is a *numerical library* (discrete sampling) where the elements are generated from the optical design of the instrument (WFEs generated by ray-tracing code), plus the CCD readout and some ad-hoc introduced effects. The elements of the *analytical library* are then generated from fittings of suitable functions to the elements of the numerical library. Interpolation may be used when appropriate. The advantages of such a model are:

– the analytical and numerical library are used to generate data with different purposes. The numerical library contains the maximum level of realism, but can be sometimes computationally heavy. The analytical library is simpler and can be used when a large amount of simulated data is needed;
– many effects are introduced at the level of the numerical library and therefore will automatically be present in the analytical representation, ensuring homogeneity in data simulations;
– the analytical representation requires a minimal number of computations, this is a good compromise between realism and efficiency;
– nonetheless, many effects are not properly described by means of precomputed libraries (e.g. charge transfer inefficiency, noise, magnitude, non-linearity, saturation) and have to be treated separately.

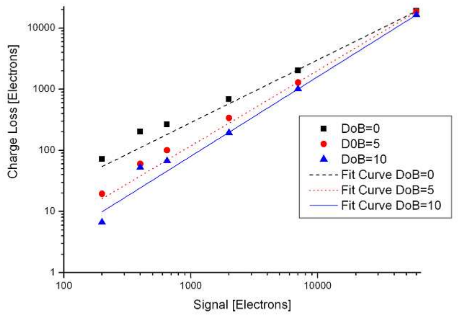

Fig. 3. Charge loss vs. source magnitude for different observing conditions

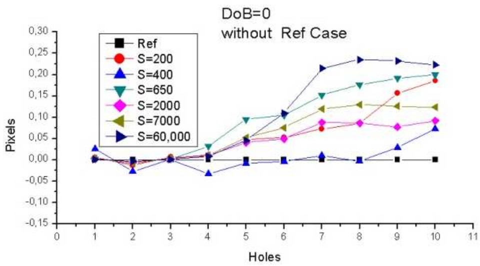

Fig. 4. Example of star packet displacement due to charge trapping in Gaia CCDs

Figure 1 shows an example of the fitting of a numerical LSF with an analytical function for a sample point in the Field of view and source spectrum.

The residuals of the fit are always small enough to ensure that the analytical library can be used without significant loss of realism. The behaviour of the PSF/LSF coefficients in the parameters space domain is smooth enough to permit interpolation.

4. CCD Charge Transfer Inefficiency

Gaia will be placed at L1 and will operate for five years. In this environment, high energy solar radiation creates traps into the semiconductor devices. This causes the CCD lattice to capture photoelectrons and to release them after some time, increasing the CTI of the CCD. As a result, the charge packet is displaced (retarded) with respect to the source. If not treated properly in the calibration phase, this effect could completely compromise the astrometric accuracy. For this reason test campaigns on real (damaged) CCD data have been carried out in order to be able to well understand and model the CTI of the Gaia CCDs. The logical flow diagram is shown in Figure 2. The test campaign results (yellow boxes) are used to validate the charge distortion models (blue boxes) in order to be able to produce reliable data (red boxes). Details of the test campaign results can be found for example in Corcione et al. (2009). The effect of the CTI has implications for both astrometry and photometry.

For the photometry, the displacement can be large enough to move a significant part of the charge outside the readout window, resulting in a variable charge loss. Figure 3 shows an example of this effect for different source magnitudes and observing conditions. The average amount of charge loss is higly correlated to the signal intensity, in good agreement with a power law. As expected, the charge loss affects the star signal mostly at the first transit. In other words, the first object to transit onto a given portion of the CCD will "fill" the traps that will be basically inactive for a given time period.

Figure 4 shows a typical result of the star packet displacement for increasing source magnitude. The displacement of the object position in the CCD damaged region (on the right in the figure) with respect to the position of the same object evaluated on the undamaged region (on the left in the figure) is clearly detectable. At high signal levels the displacement is correlated with the signal level, and the techniques proposed to reduce the trapping of charges (such as periodic charge injection) seem to provide a mitigation of the CTI effect. At lower signal levels the measurements are largely affected by uncertainties related to the test campaign experiment setup.

5. Basic Angle Variation and Monitoring

The Gaia optical configuration is based on two telescopes looking at two different fields of

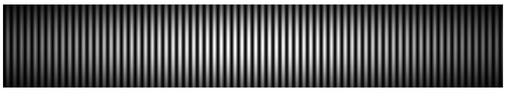

Fig. 5. Example of simulated BAM fringe pattern

view (FOV) mapped on the same Focal Plane (FP) and therefore superimposed on the same image. The angle between the two pointing directions is called Basic Angle (BA). Consider two stars in the sky separated by exactly the BA, and two telescopes in their nominal configuration pointing at them. The position of the stars on the FP defines the BA value as the distance between the two star images, nominally zero. A variation of the BA can then be measured as a change in the stars position onto the FP.

It can be shown (Gardiol et al. 2004) that the error associated with the measurements can be severely affected by a fluctuation of the BA of the same order of magnitude, and therefore adequate knowledge of the BA behaviour becomes a crucial issue. Low frequency BA variations, induced by mechanical distortions due to thermal fluctuations, will be recovered by the astrometric solution over a few spin periods. To monitor the BA variation on shorter timescales, a dedicated instrument, the Basic Angle Monitoring device (BAM), will be associated to the payload. The BAM principle is based on the generation of two artificial stars by mean of a coherent monochromatic laser diode source. Each star feeds one of the two telescopes, and is focused onto the same BAM dedicated CCD. To improve the resolution of estimated stellar position, an interference pattern is generated by splitting the original beam. Figure 5 shows a simulated example of such an image. A change in the BA due to small movements of the telescopes mirrors induces a differential fringe motion that can be detected and measured. The BA shall be monitored with accuracy better than 0.5 μas rms over 5 minutes; this variation corresponds to an optical path difference of 1.5 pm rms (equivalent to $\sim 1.8 \times 10^{-6} \lambda$ at 850nm), roughly 0.1 nm phase shift onto the focal plane.

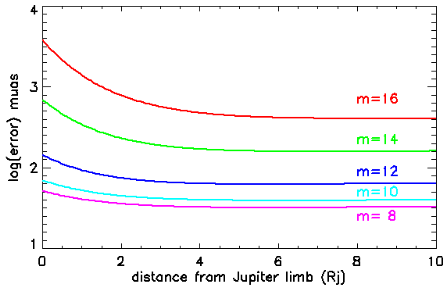

Fig. 6. Astrometric error as a function of distance from Jupiter limb for different star magnitudes

6. Astrometric error prediction for Gaia Relativity Experiment

One proposed experiment to be carried out with Gaia is the first measure of the Jupiter gravitational quadrupole (Crosta et al. 2008). To verify the feasibility of such a measurement with Gaia, we evaluated the astrometric accuracy in presence of significant background. The result can be expressed as an analytical law, derived from Montecarlo simulations, shown in Figure 6 for some selected source magnitude as a function of the distance from the Jupiter limb. Some relevant features of the simulations are: partial saturation of the CCD pixels is taken into account, background level due to Jupiter induced stray-light, error refers to a single CCD transit. Combining this result with the 8552 candidate stellar fields investigated, several good fields are available.The experiment can be performed very early in the missions lifetime, and repeated a few times during the mission operation timeframe.

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