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Micro-Arcsec mission: implications of the monitoring, diagnostic and calibration of the instrument response in the data reduction chain.

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Abstract. The goals of 21^{st} century high angular precision experiments rely on the limiting performance associated to the selected instrumental configuration and observational strategy. Both global and narrow angle micro-arcsec space astrometry require that the instrument contributions to the overall error budget has to be less than the desired micro-arcsec level precision. Appropriate modelling of the astrometric response is required for optimal definition of the data reduction and calibration algorithms, in order to ensure high sensitivity to the astrophysical source parameters and in general high accuracy.
We will refer to the framework of the SIM-Lite and the Gaia mission, the most challenging space missions of the next decade in the narrow angle and global astrometry field, respectively. We will focus our dissertation on the Gaia data reduction issues and instrument calibration implications. We describe selected topics in the framework of the Astrometric Instrument Modelling for the Gaia mission, evidencing their role in the data reduction chain and we give a brief overview of the Astrometric Instrument Model Data Analysis Software System, a Java-based pipeline under development by our team.

Key words. Astrometry - Methods: data analysis - Techniques: high angular resolution - Telescopes - Space vehicles: instruments

1. Introduction

SIM-Lite is a proposed space borne astrometric instrument, to be located in a solar Earth-trailing orbit (Goullioud et al. (2008) and Unwin et al. (2008)). In its narrow-angle astrometric mode, it will achieve 1 μas precision on bright targets (V= 6). The instrument consists of two Michelson stellar interferometers and a precision telescope. The first interferometer chops between the target star and a set of reference stars. The second interferometer monitors the attitude of the instrument in the direction of the target star. The telescope monitors the attitude of the instrument in the other two directions. As a pointing telescope and due to the attitude measurement process, the SIM observations don't show correlations among different measurements. On the other hand the instrument health check and monitoring is performed via hardware (Marr-IV et al. 2008), using dedicated metrology systems, which require better than *pm* level precision to obtain the predicted end-of-mission noise floor < 0.1 μas. This in-

Send offprint requests to: D. Busonero volves high technology efforts and high hardware cost.

Gaia is the only ESA space borne mission of the next decade devoted to very high-accuracy astrometric observations. Scheduled for launch in 2012, Gaia will perform global astrometric measurements with a parallax accuracy ranging from a few μas to few tens of μas for stars magnitude from V= 10 to V= 20.

Gaia operates in scanning mode through two telescopes separated by a base angle of 106.5°, feeding a common focal plane (FP) made of one hundreds CCDs (6 hour period, scan rate=60 arcsec/s), with continuous full-sky observation. Each CCD operates in Time Delay Integration (TDI) mode matching the scanning velocity with the CCD transfer velocity. The measurements cover repeatedly the whole sky, by composition of rotation, precession and orbital motion of the satellite (Perryman M.A.C. 2005).

Gaia is designed to be a self-calibrated instrument. The basic Gaia measurement is the "time of observation" for each star's crossing of a CCD. The general form of gaia observational equation is shown in eq. (1) where O is the observed location of the stellar image S on the FP, while f is a complex non linear function of the stellar position (function of time if parallaxes and proper motion are measured), A the attitude of the satellite, and C the instrument calibration parameters (e.g. the Effective Focal Length (EFL), detectors orientation....)

$$\Delta O = O_{S2} - O_{S1} = f(S_0, A_{S2}, C_{S2}) - f(S_0, A_{S1}, C_{S1})$$

$$= g(\Delta A, \Delta C). \quad (1)$$

For the sake of discussion, we assume that stars don't move on the sky between two subsequent transits 1 and 2. This results in a constraint on the observations, called a closure condition. The variations in the detected image location are related to the variation of attitude and instrument calibration parameters. This method introduces spatial correlations among the measurements which do not exist for a pointing satellite. Indeed for an attitude error at time t, all the Gaia observations over the current transit will be affected, introducing correlations between the Field Of View (FOV) and the matching positions separated by the base angle. On the other hand, it relaxes the requirements on instrument monitoring hardware, reducing complexity and cost.

Since we require as many observation equations as the stars to solve for their astrometric star parameters, the critical issue for the Gaia data reduction is the huge number of unknows that leads to a huge increment in data reduction software complexity and cpu load. There are about $\sim 5 \times 10^7$ attitude unknowns and about $\sim 2 \times 10^7$ for the instrument, the same order of magnitude of stellar unknowns, thus alternative procedures and tools dedicated to instrument diagnostic and calibration with the goal to reduce the parameters space and solve degenerations are needed. We are working on this topic, in the contest of the italian partecipation to the Gaia Data Processing and Analysis Consortium (DPAC), the scientific consortium in charge of the Gaia data reduction chain.

2. Modelling and diagnostics

The data analysis procedures are sensitive to several instrument parameters, which can be either disentangled from each other or estimated as collective contributions when degenerate, and to its variation over the field and with time The variation of the instrument response is quite unavoidable so its modeling is crucial to manage the effects that can affect the final μas level astrometric accuracy. It is necessary to model the transformation linking the linear coordinates of the image location on the focal plane to the field angle on the sky, taking into account the effects of the perturbations on the Gaia measured signal profile. The definition (forward analysis) is comparably straightforward from sufficiently detailed design data. The inverse problem (backward analysis) of disentangling both astrophysical and instrumental parameters from the set of science and auxiliary data is much more challenging.

Four different mission phases can be identified with respect to the data reduction process:

- Pre-launch phase: selection of those parameters (related to optics, attitude, detector response and operations) which have

an impact on the accuracy performance and analysis of the critical aspects for the formulation of the instrument calibration models and algorithms, i.e. the *forward analysis* (see also Gardiol et al. (2009));
- Commissioning phase: validation and update (if needed) of the parameters;
- Operations phase: data acquisition and processing for the instrument monitoring and for the improvement of the calibration models developed in the previous phases, i.e. the *backward analysis*: the inverse problem of disentangling both astrophysical and instrumental parameters from the set of science and auxiliary data.
- post-mission phase: delivery of final optimized parameters.

Below, we review selected items among the critical instrumental aspects. Others, as chromaticity (Busonero et al. 2006) and instrument deviations from uniformity (Gai et al. 2008), are discussed in the open literature. Due to lack of space the figures in the next sections are omitted and available on request by e-mail to busonero@oato.inaf.it.

2.1. Instrumental critical parameters

The astrometric performance is related to the quality and stability of the measured image profile: the Point Spread Function (PSF). Variation of the instrumental response (optics, attitude, detector response, focal plane geometry and operations) over the field, with wavelength and in time, e.g. the degradation of the Charge Transfer Inefficiency (CTI) depending on cumulative radiation damage, are potentially critical for keeping the quality of the PSF.

Due to residual aberrations from design, manu-facturing, on-ground alignment, in-orbit realignment and ageing, the individual telescope response changes over the FOV. Besides, they also induce a mismatch between the instrument arms. Several critical parameters are wavelength dependent, thus the spectral type of each source has a potential impact on the measurement. Some of the effects are largely common mode, mostly affecting the random noise, so that mainly the differential contribution is relevant to the systematic error.

2.1.1. Focal length and CCD displacements

A focal length variation from the nominal value introduces a variation in the optical scale on the Focal Plane. It induces a mismacth between the charge packet rate and the apparent star transit velocity, blurring the image profile and introducing a systematic error in the image location. The effect is common mode and it affects all the stars in a FOV in the same way, so it can be easily disentagled.

Through monitoring the science data with dedicated analysis algorithms we can identify the effect since all the measurements over all the focal plane CCDs show the same displacement in the image location. We can also distiguish this effect from a CCD displacement since in the latter case we will observe the variation of the image location only for the stars transisting over that CCD. A statistic analysis over the measurements allows us to discriminate against the two instrumental perturbations. The cause of the instrumental variations could be due e.g. to a temperature variation during a lunar eclipse.

2.1.2. Field distortion

Field distortion is an aberration affecting the image quality. It has impacts on the displacement of the image photocenter from the nominal image point and on the motion of the image through the whole focal plane. This means that the image doesn't move through the FOV at constant speed, on a straight line, also for the nominal optical configuration. The distortion provides a progressive variation in the object speed as seen through the optical system respect to the nominal scanning velocity; at the precision level of the single Gaia observation the deviation from the straight line trajectory becomes significant, from order of few μas to few hundred μas, depending on the position over the focal plane and the spectral type of the transit star.

2.1.3. PSF modelling for calibration

A complete PSF analytical modelling is essential for reaching the accuracy target level. For the PSF calibration we need accurate models having as few free parameters as possible.

From experiments with laboratory CCD data we found that the Bi-quartic spline are sufficiently flexible to give good fit everywhere in the image profile core and the residuals are fully consistent with expected noise. For the wings we can use an asymmetric Lorentzian function that, however fails in the presence of oscillations in the wings or inhomogeneous data (Busonero et al. 2009); in addition the transition from spline to Lorentzian is rather abrupt. On top of that the spline representation requires too many parameters to be estimated (almost 35 for each observation) (Lindgren 2009). We are working on a new model with much reduced dimensionality and free parameters (about ten) as much as possible directly linked to physical quantities. Preliminary study was carried on by Gai et al. (2007).

3. The AIM System

Science data can be used to trace directly the instrument response, taking advantage of the repeated measurements of stars over the field. This is one of the driver philosophies behind the Astrometric Instrument Model (AIM) concept. The AIM Data Analysis Software System is devoted to the processing of the Gaia astrometric raw data in order to monitoring and analysing the astrometric instrument response over the mission lifetime. It is one of the three components of the technical and scientific verification of the overall Gaia astrometric data processing. The goal is the identification of an efficient set of effective global parameters for the description of the instrument signature in the data, according to the probable degeneracy of the real physical parameters. This should optimize the estimation process within the sphere solution with respect to computation load, accuracy, or both.

The method consists of the analysis of the impact on the data of the perturbations due to instrument and operational factors (optics, attitude, detection system), including ground-to-orbit variations, ageing and noise. Its implementation uses instrument modeling tools (see Gardiol et al. (2009)), and appropriate analysis tools. Due to the mission characteristics, the AIM/DASS is critical for the short-term verification of the absolute quality of Gaia's astrometry. It also plays an important role in the medium and long term verification.

AIM is a collection of software modules, each dedicated to perform a particular analysis of the selected data set with the goal to extract information about instrument health and Astro instrument calibration parameters during in-flight operations.

There are five main software modules, each pertaining to the five activity AIM shall perform. The first module is in charge of the basic processing to convert the raw data into the observables and calculate the effective global parameters. This process include modules devoted to the generation of the reference image profile through the AIM models and the calibration/knowledge of the Astro instrument. The other three fundamental parts are the Monitoring package, the Diagnostic and Analysis package and the physical instrument simulation package, which correspond to the main AIM system activities.

More in-depth details on the calibration algorithms and their code implementation will be presented in a forthcoming paper (D. Busonero et al. 2010, in preparation).

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References

Busonero, D. et al. 2009, Gaia Linvelink pubblication, GAIA-C2-TN-INAF-DB-009-01
Busonero, D. et al. 2006, A&A, 390, 9
Goullioud, R. et al. 2008, SPIE, 7013
Gai, M. et al. 2008, MNRAS, 391, 1451
Gai, M. et al. 2007, MNRAS, 377, 1337
Gardiol, D. et al. 2009, This volume
Lindegren L. 2009, Gaia Linvelink pubblication, GAIA-C3-TN-INAF-LL-084-01
Marr-IV, J.C. et al. 2008, SPIE, 7013
Perryman M.A.C. 2005, ASP, 338, 3
Unwin, S.C., et al. 2008, PASP, 120,38