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The daily processing of asteroid observations by Gaia

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ABSTRACT

The Gaia mission started its regular observing program in the summer of 2014, and since then it is regularly obtaining observations of asteroids. This paper draws the outline of the data processing for Solar System objects, and in particular on the daily "short-term" processing, from the on-board data acquisition to the ground-based processing. We illustrate the tools developed to compute predictions of asteroid observations, we discuss the procedures implemented by the daily processing, and we illustrate some tests and validations of the processing of the asteroid observations. Our findings are overall consistent with the expectations concerning the performances of Gaia and the effectiveness of the developed software for data reduction.

1. Introduction: Gaia and Solar System objects

The European mission Gaia observes the whole sky from the Lagrangian point L2, where the required thermal stability is guaranteed (details and capabilities are described in detail by Prusti (2012), De Brujine, 2012, and references therein). The satellite operates in continuous scanning mode, its spin being of 6 h. Two lines of sight separated on the scanning plane by 106.5° (the basic angle), are simultaneously imaging the sky on the same focal plane. This feature, reducing the measurements of large angular separations to small distances on the focal plane, is the essential principle allowing Gaia to have a homogeneous all-sky astrometric accuracy, without zonal errors. The slow change in the orientation of the scanning plane, steered by a 62.97-days precession and by the 1-year revolution around the Sun, determines a rather homogenous coverage of the sky resulting, over 5 years of nominal mission duration, in 80–100 observations for an average direction, slightly less on the ecliptic (60–70).

The images formed on the focal plane, consisting of a large giga-pixel array of 106 CCDs, are electronically tracked on the CCD itself by a displacement of the charge (Time Delay Integration mode, TDI) at the same pace as the image drifts due to the spacecraft rotation.

The CCDs are organized in the order of crossing by the drifting images. First, there are two CCD strips devoted to source detection (one for each of the two lines of sight); they constitute the instrument called Sky Mapper (SM). Then, 9 strips of astrometric CCDs follow (Astrometric Field, AF). Next, other CCD strips are devoted to low resolution spectro-photometry (red and blue photometer, RP/BP) and high resolution spectroscopy (Radial Velocity Spectrometer, RVS). RVS is not considered for asteroid studies, due to its narrow range of wavelength.

Each source that enters the field of view of Gaia will produce a signal on one SM CCD. If bright enough ($V < 20.7$ is the current threshold) and nearly point-like (about < 600 mas diameter) its position is then recorded by the on-board Video Processing Unit (VPU). The VPU automatically assigns a "window" around each object detected by the SM, and propagates these windows to the other CCDs in the direction of the image drift. Only these very small windows (the smallest, but more common ones spanning

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6 pixels only) are transmitted to Earth, in such a way that the telemetry does not exceed the possible downlink rate. Due to this windowing strategy, two point-like sources separated by more than ~300 mas (6 pixels) are detected as two different images and processed separately.

Due to its orbital motion, a Solar System object (SSO) may leave the transmitted window before arriving at the last CCD. As a consequence, each "observation" consists of a maximum of 10 positions (AF and SM instruments), distributed over 50 s (the duration of a transit).

One should note that the cut–off at magnitude $V = 20.7$ is not dictated by a threshold on the minimum, acceptable signal-to-noise ratio, as at this brightness level very accurate astrometry can still be obtained. Rather, the limit is imposed by constraints on the data downlink rate, especially in the densest areas of the Milky Way.

All source identifications and further processing are done on the ground and are part of the activities of the Data Processing and Analysis Consortium (DPAC). Also, DPAC is in charge of running the Astrometric Global Iterative Solution (AGIS), a highly optimized software system that looks for the best-fitting self-consistent attitude and astrometric solution on the sphere, taking into account all measurements and instrument calibration parameters. The astrometry based on the best AGIS result is used for the preparation of each intermediate release.

Starting from 2006, DPAC of Gaia was charged by ESA for implementing the data processing pipelines that will deliver the first-level analysis of Gaia observations. The Gaia outcome – in fact – will consist not only of the individual measurements, but also of calibrated data (fluxes, positions, spectra), global statistics, and the results of the exploration of the bulk properties of the sources (classification, distributions etc).

In this context, the Coordination Unit 4 (CU4) has the task of performing the analysis of objects deserving a specific treatment, namely multiple stellar systems, exoplanets (PI: D. Pourbaix, Brussels Univ.), Solar System objects (PI: P. Tanga) and extended sources (Ch. Ducourant, Obs. Bordeaux, France).

All the software produced within DPAC runs at Data Processing Centers; the Data Processing Center CNES (DPCC) in Toulouse, France, is in charge of Solar System data, among others. Essentially, the processing will proceed blindly for the whole DPAC community. This approach, along with the absence of any proprietary period, ensures that the data products of Gaia will be available to the whole scientific community (including the DPAC scientists) at the same time, as established by the ESA-DPAC agreement.

Gaia will obtain during its 5-year operation ~70 observations per object, on average, for about 350,000 asteroids.

We recall here that the scientific community was made aware of unexpected technical difficulties (in particular, the presence of stray-light) discovered during commissioning. Recent studies of these issues reveal that they will not affect the revolutionary potential of Gaia, with a very modest degradation in the expected performance (De Bruijne et al., 2006).

The DPAC CU4 has implemented two pipelines for Solar System processing (Tanga et al., 2007; Mignard et al., 2007):

- SSO-ST: the "Solar System short-term processing" is devoted to alert a ground-based network (Gaia-FUN-SSO, steered by IMCCE, Observatoire de Paris) in case a new asteroid is discovered. This pipeline will be running daily at DPCC (CNES in Toulouse) and is also used to verify and monitor the quality of the data received by Gaia.
- SSO-LT: the "Solar System long-term processing" will run for the data releases and perform a more sophisticated data reduction with the best possible astrometric solution and the advanced instrument calibrations. Also, it will eventually perform the global data reduction by executing tasks that require the largest possible set of observations.

The fist intermediate data release is planned for mid-2016, and is expected to provide data for not less than 90% of the sources observed by Gaia.

The SSO-ST chain is currently running at CNES for the validation of the data processing. This implies that the observations being processed are concerning – for the time being – known asteroids. This situation offers several opportunities for validating the performances of Gaia on asteroid detection, and for tuning the SSO-ST pipeline.

The goal of this paper is to illustrate the main processing steps of SSO-ST. First of all, we explain the approach and the performance of the software that we developed for predicting the observations by Gaia (Section 2), an essential validation tool. Then we review the SSO-ST pipeline step by step, starting from asteroid identification (Section 3). The processing continues with the measurement of asteroid positions on the focal plane (Section 4) and the subsequent coordinate transformations (Section 5) toward the sky reference. The observations of a target are grouped together and an orbital solution is determined. As the goal of SSO-ST is to provide a first, approximate orbit for the recovery of new objects from the ground, a statistical approach is adopted (Section 6). We conclude by describing the ground-based follow-up activities (Section 7).

2. Prediction of Solar System observations

To define more precisely the quality of the observations with respect to expectations, we can exploit the simulations produced by a software developed by F. Mignard and P. Tanga at Laboratoire Lagrange (OCA, Nice). This unique tool exploits the very stable scanning law and the full orbital data set from the Minor Planet Center to predict when and how often a source will be seen by Gaia. The accuracy of the predictions and crossing times, compared to real Gaia data, are excellent, so that reliable statistics can be built.

The transit predictor has been developed within the CU4/SSO in order to be able to compute in advance the observations of Solar System objects to be seen by Gaia during its operations.

The software is an outgrowth of a detection simulator used and maintained over the years, since the very preliminary studies on Gaia, based on similar overall principles, but aiming at accurate individual transit data instead of an overall statistical relevance. In the earlier phase some approximations were acceptable (such as the 2-body Keplerian motion). The same liberty was used for the Gaia orbit about L2, in absence of other constraints before launch.

Moving to a predictor of what actually happens during the real mission implied a more rigourous modelling of the mission environment and of the dynamical modelling of the planetary motion. With the predictor the use of an exact Gaia scanning law is mandatory to reproduce the actual pointing of each FOV. Similarly, the Gaia orbit should be as close as possible to the true path of Gaia on its Lissajous orbit. Finally, the orbital elements of the asteroids must be taken to full accuracy at a reference epoch and then the position and velocity must be propagated with planetary perturbations and numerical integration instead of the simplified 2-body problem.

The program essentially solves for any ith asteroid and for each Field Of View F over an interval of time $[T_b, T_e]$, the following equation in t

$$\mathbf{G}_F(t) = \mathbf{U}_i(t) \tag{1}$$

where $\mathbf{U}_i(t)$ is the unit vector of the asteroid proper direction at time t and $\mathbf{G}_F(t)$ stands for the pointing direction of Gaia FOV F. The