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The Solar System as seen by Gaia: The asteroids and their accuracy budget

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ABSTRACT

The Gaia cornerstone mission of the European Space Agency, scheduled for launch in mid-2013, is expected to produce a breakthrough in our understanding of the Galaxy, providing a full characterisation of all sources by extremely accurate astrometry and complementary spectral data. The continuous scanning of the sky and the fully automated selection of the sources also ensure that nearly all Solar System objects brighter than $V=20$ will be observed by Gaia. We describe the expectations of the mission in Solar System science and the peculiar properties of asteroid data, requiring appropriate data reduction procedures currently being implemented. Recent estimates of the number of observed sources and other statistical properties of the sample are presented.

1. Introduction: properties of Gaia observations

The Gaia satellite of the European Space Agency is expected to be launched in mid-2013. The scientific aim of Gaia is to obtain a new global picture of the Galaxy, by exploiting unprecedented astrometric accuracy and multi-wavelength data (Perryman et al., 2001). During its continuous scanning of the sky, it will observe all sources brighter than $V\sim 20$, thus also collecting valuable observations of Solar System objects. A wide and significant impact on Solar System science is foreseen (Mignard et al., 2007).

Gaia will orbit in regular loops about the Lagrangian point L2 of the Earth. It will operate a continuous scan of the celestial sphere, thanks to the combination of three simultaneous and non-commensurate rotational motions (spin; precession; revolution around the Sun). Two telescopes perpendicular to the spin axis direction (rotating with a period of 6 hours) will eventually perform $\sim 60-70$ observations of each Main Belt Asteroid (MBA) over the mission nominal duration of 5 years.

The scanning law ensures a rather uniform coverage of the celestial sphere, and is defined in such a way that the telescopes will never point into an avoidance cone (of 45° aperture) centred on the Sun. As well, a symmetric avoidance region exists in the opposite direction. When projected on the ecliptic plane, it is easy to see that the solar elongations reachable by Gaia are in the 45°-135° range, i.e. centred on quadrature. The opposition region usually exploited for the best observability of Solar System objects from Earth is thus out of reach from Gaia.

Peculiar properties of the Gaia data are related to the focal plane and to the specific strategy for data acquisition. The detector is composed of a large matrix of 106 CCDs used in TDI mode (Time Delay Integration) by shifting the collected photoelectrons from one pixel to its neighbour in perfect synchronisation with the spin-induced displacement. Therefore, this displacement of the signal follows the continuous motion of the image due the probe rotation (at first order). This way, the accumulating photoelectrons "follow" the image of a source all along the crossing of each CCD. Different CCD groups are affected to separate instruments. Here we just recall that, as far as Solar System objects are concerned, we will consider data coming from the Sky Mapper (SM, that provide a first detection of a source), the Astrometric Field (AF, 9 columns of unfiltered CCDs) and the Red and Blue Photometers (RP, BP) acting as low-resolution spectrographs (further detailed on the focal plane instrument for asteroid science are, e.g. in Tanga et al., 2007).

Among the main expectations concerning the Solar System, asteroid astrometry will result in orbit uncertainties not less than ~ 2 orders of magnitude smaller than the current ones. To reach this accuracy, the dynamical model has to take into account accurate masses of the ~ 100 most massive perturbers (Mouret et al., 2008) and relativistic parameters (Hestroffer et al., 2010) that will be determined altogether during the data processing. Physical data will include low-resolution spectra for most of the sample and a new taxonomic classification. Bulk shapes, modelled as 3-axial ellipsoids, will be derived by the inversion of sparse photometry, as well as the direction of the spin axis and period (Cellino et al., 2007). For a smaller number of asteroids, the disk-resolved signal will provide direct measurements of size. Planetary satellites and a small number of comets and Trans-Neptunian Objects will also fall into the magnitude range accessible to Gaia.

2. Windowing and source motion

In order to avoid an unacceptably high data rate, only small windows around each detected source will be read-out from the

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CCDs and sent to the ground during daily downlink sessions. A further binning, reducing the signal to a single, mono-dimensional vector of samples, will take place for the majority of sources ($V>16$). While reducing the information to an essentially mono-dimensional astrometry, this approach represents the best compromise to preserve the accuracy requirements of the mission (indicatively, $20-25\,\mu$ as for a star at $V=15$ mag) at the same time granting both completeness and manageable data rates.

As a consequence, Gaia will not directly produce images of each source. Also, sources larger than ~ 600 mas will not be selected by the on-board detection system, thus excluding from observation the largest Solar System bodies. If we consider the object size in a broad sense, we can include the effect of smearing due to the apparent motion of a source as a possible factor inducing a loss of observations.

The asteroid apparent motion also results in a loss of data due to the on-board windowing scheme. In fact, a window 12 pixel is assigned by the on-board Video Processing Unit as soon as an object is detected on an SM CCD and confirmed by a CCD in AF1 (the first column of AF). Its instantaneous position – as determined by a simplified on-board centroiding – is used to centre the window, which is then propagated to the other CCDs of the focal plane at the nominal scanning speed. If the asteroid moves relative to stars, a progressive displacement with respect to the window centre will occur. The result is a progressive truncation of the signal. As a consequence, the nominal single-transit accuracy (Fig. 1) will suffer a degradation.

The result depends, in fact, on the details of the windowing strategy and the statistics of asteroid proper motions.

The window that will be read out of the CCDs on board is 12-pixels wide (AL). The window transmitted to Earth will have the same width when considering the CCD columns 2, 5, 8, 9 of the AF instrument. For the other CCDs (AF1, 2, 4, 6, 7) only a 6-pixel window will be transmitted, centered on the signal peak.

Fig. 2 presents the statistics of asteroid proper motions including Near-Earth Objects (NEOs) and MBAs both along the scan direction and normally to it, by simulating the detection of 5000 objects. Since the mean value of the angle between the ecliptic and the scanning motion is 90°, it is not surprising that the distribution width is larger in the across-scan (AC) direction. However, the motion along-scan (AL) is very relevant, as its median absolute value is ~ 7 mas/s. An object at that speed will move over $\sim$ half a pixel AL during a single CCD crossing (one pixel is 60 mas in the AL direction). The offset will reach about 210 mas at the end of the whole focal plane crossing (nearly 4 pixels AL).

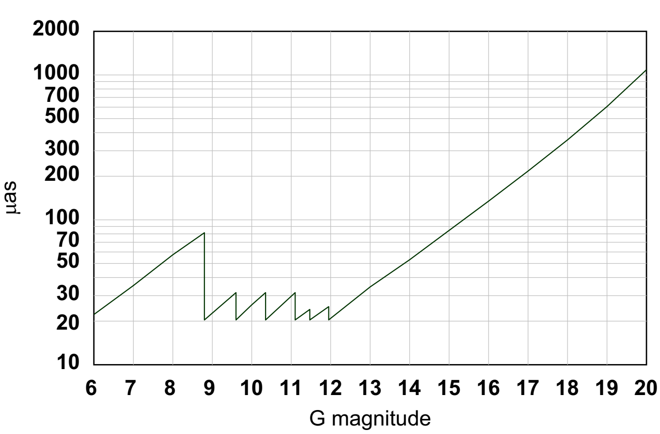

Fig. 1. The nominal astrometric accuracy in the direction of the scan, after a single transit of a non-moving source in the focal plane, as a function of magnitude. For $V<12$ saturation occurs. The saw-tooth appearance is due to the activation of on-chip gates for reducing the exposure time, in correspondence to pre-defined flux thresholds.

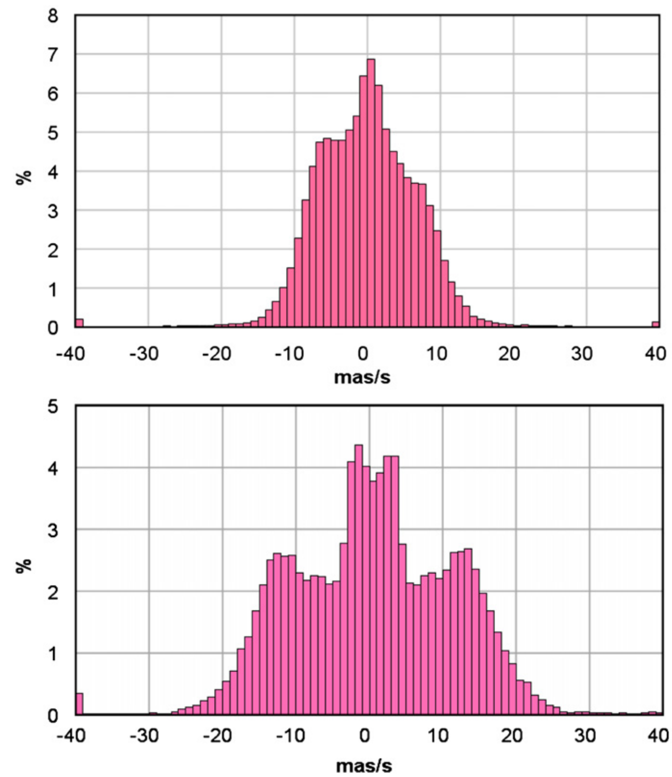

Fig. 2. The distribution of the apparent proper velocity (relative to stars) of a population of Main Belt and Near Earth objects. Five thousands asteroids are considered. The top histogram refers to motion in the scan direction ("along-scan", AL), while the bottom histogram is for a direction perpendicular to scan ("across-scan", AS). The median of the absolute value of speed in the AL direction is ~ 7 mas.

The motion above is thus rather limited and sufficient to keep the source centroid well within the edge of the transmitted window. Asteroids moving faster (NEOs in particular) can suffer a more severe signal truncation during the single focal plane crossing. In practice, the number of CCD columns with an exploitable signal will be smaller for larger motion than the nominal $N=9$.

Of course, these properties of the Gaia acquisition process are highly relevant for the data reduction pipeline that is being implemented in the context of the Data Processing and Analysis Consortium (DPAC). Motion, smearing and signal truncation, in particular, have required the implementation of a specific processing procedure that performs a more sophisticated centroiding than for stars.

Here we try to provide a simple, approximate estimate of the deterioration of the astrometric accuracy due to the signal loss/truncation, for each observed object. We consider that the astrometric accuracy depends upon the number n of CCDs transits usable from the source signal, as $\sqrt{n}$. The nominal single-transit performance is reached for sources that are observed over all the $N=9$ CCD columns of the AF instrument (Fig. 1). In the following we assume that an object is "observed" on a CCD if its shifting position (due to apparent motion) is not beyond 5 pixels in that CCD. We then use the information on the apparent motion provided by the simulation cited above for computing fraction of CCDs containing a usable signal, for each asteroid, averaged over all the transits:

$$f=\frac{1}{N_t}\sum_i (n_i/N). \tag{1}$$

where the sum is over the N_t observations (focal plane transits) of a given object.