OBSERVING THE NATURAL SATELLITES OF SOLAR SYSTEM BODIES WITH GAIA

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ABSTRACT

The simulation of the detection sequence and geometry of planetary satellites allows the statistics of the expected Gaia measurements to be explored. Given the remarkably low level of instrumental light scattering, Gaia will be able to detect faint objects at extremely small angular distances from the apparent disc of the main Solar System bodies. The position and brightness of the satellites of Mars, and of the inner satellites of Jupiter and Saturn, for example, will be measured. Outer satellites, whose visibility is not affected by the brightness of the main body, will be detected down to the cut-off magnitude of the Gaia instruments. The unprecedented accuracy of the astrometry will allow several dynamical issues concerning satellites to be addressed that are difficult – or impossible – to access through ground-based instruments.

Key words: Gaia; Solar System: satellites; Instruments.

1. INTRODUCTION

During its survey, Gaia will detect several known satellites around Solar System planets. Today, satellite searches around the main planets are aimed at discovering faint bodies, the so-called 'irregular satellites', in the external part of the primary Hill sphere. Their luminosity, in general, is well below the expected detection limit of the Gaia instruments. However, brighter and well known satellites wait for physical and dynamical characterization, requiring precise astrometry over several years. Some relevant open problems are cited in Tanga (2005). Here we just want to stress particular aspects of Gaia observations of satellites, namely: the problem of detection of the inner bodies, always very close – in term of apparent angular separation – to the planet; the statistics and geometry of detections, starting point for a more accurate assessment of Gaia capabilities in this field.

As an example we illustrate in the following the case of the family of Jupiter regular satellites, a set of extreme brightness range and varying difficulties from object to object.

2. SIMULATED DETECTIONS IN THE ASTROMETRIC FIELD

In the frame of the activity of the Solar System Working Group of Gaia, software has been developed in order to simulate the detection sequence and statistics for asteroids and main planets. Later it was modified to include natural satellites. A simulation was run over the nominal mission duration of 5 years, starting at January 1.0, 2010, and recording all relevant data relative to satellite observations in the astrometric field of view (AF). In Table 1 we summarize some relevant figures concerning the detections of Jupiter and its regular satellites. Flux values are computed by using standard parameters that fit the phase-magnitude relationship providing V magnitudes (Veverka et al. 1982; Morrison et al. 1974).

One should note the size of the four Galilean satellites, very large relatively to one pixel (33 mas along scan). Further, their luminosity is very high, well beyond the saturation limit in the AF. On the other hand, even the faintest satellites are theoretically well within the detection range. However, the main characteristic of these particular objects is that their apparent distance to Jupiter remains always rather small. In practice, if Io reaches maximum elongations of about 120 arcsec in the simulated data set, that value reduces to 60 for Amalthea and to 40 for Adrastea. This must be compared with the apparent equatorial radius of Jupiter (about 20 arcsec).

Table 1. Average magnitude, sizes and surface magnitude for Jupiter and its regular satellites as detected in the Astrometric Field CCDs.

Name	m_V	diameter mas	$m_{\rm surf}$ mag/pixel
Jupiter	-2.34	39667.50	10.95
Io	5.35	1004.11	10.66
Europa	5.60	870.21	10.60
Ganymede	4.94	1452.33	11.05
Callisto	5.96	1334.78	11.89
Amalthea	14.43	55.19	13.44
Thebe	16.33	27.60	13.84
Adrastea	19.03	5.52	13.04
Metis	17.83	11.04	13.35

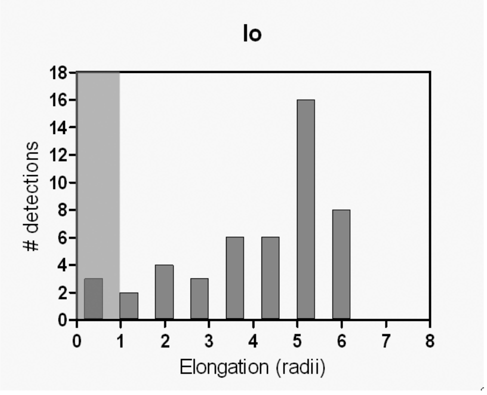

Figure 1. Distribution of the detection of Jupiter's satellite Io during 5 years, as a function of its apparent distance from the planet centre, expressed in Jupiter radii.

Two factors can thus be expected to play a role in limiting detection capabilities of the faint, inner satellites. The first one, is the geometry of the observation, since the obliquity of Jupiter is small and the satellite orbits under consideration lie very close to its equatorial plane. As a consequence, a significant fraction of their orbit is always hidden behind the planet or superimposed on it. Second, when not occulted or in transit on the planet disc, light scattering in the immediate vicinity of Jupiter limb could be the most relevant factor limiting detection.

The first factor is well illustrated in Figures 1 and 2. The plots show the distribution of the number of observations in the AF for the inner satellites of Jupiter, as a function of elongation (in Jupiter radii, R_J). The shaded area on the left (corresponding to an elongation smaller than 1 R_J) is not accessible since the satellite is either on the disc of Jupiter or occulted by it. However, it can be seen (most clearly in the case of Io) that the highest detection probability falls close to maximal elongation, as expected from the random sampling of the sky-projected position of an object moving on a nearly-circular orbit, with the observer lying close to the orbital plane.

3. STRAYLIGHT AND SIGNAL-TO-NOISE

The other component limiting detectability for elongations >1 R_J is the scattering of light coming from Jupiter. The internal straylight of the Gaia optical system was evaluated by Safa (2004), who provides a table allowing deduction of the signal falling on pixels in the immediate vicinity of the edge of a bright, extended source. We fitted the values of the table with a polynomial function, in order to reproduce the behavior without discontinuity (Figure 3). Then we used the simulated detections and the flux coming from the satellite to estimate the S/N ratio. We considered the faintest objects only and assumed the signal to be equal to the peak brightness of the PSF for a star-like body.

The first results are summarized in Figure 4. They are very encouraging: detections in the brightest part of the scattered light halo are extremely rare. This is mainly due to the extreme compression of the bright halo around the planet, with a steep fall in the first ∼10–20 pixels from

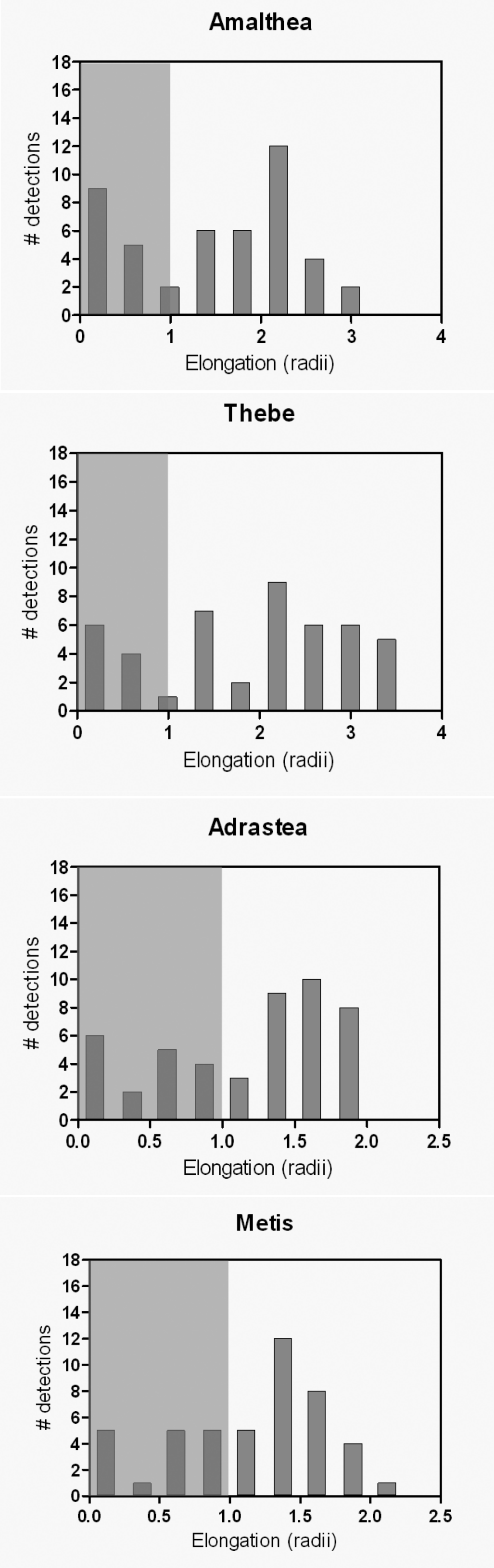

Figure 2. The same as Figure 1 for Amalthea, Thebe, Adrastea and Metis.

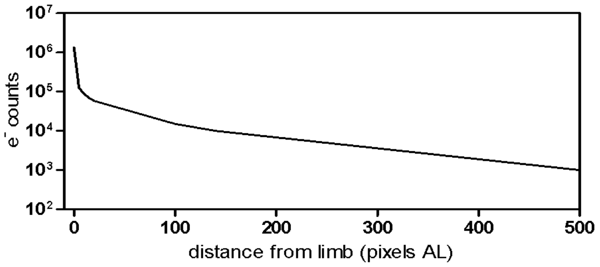

Figure 3. Signal due to straylight from Jupiter. The limb of the planet disc is at 0.

the limb (Figure 3) . For Thebe, Metis and Amalthea (not shown here) the S/N ratio always remain rather high ($>$20). It is lower for the fainter Adrastea, nevertheless allowing valuable astrometry to be performed. Thus, except for extremely rare detections $\sim$ 2 arcsec or less from the planet, light scattering will not be an issue, despite the extreme brightness of Jupiter.

4. THE GEOMETRY OF DETECTIONS

The study of subtle dynamical effects acting on satellite motion (gravitational perturbations of different origins, dissipative effects, etc) rely upon the capability of the astrometry to provide accurate measurements of its position on the orbit. The most important and sensitive measure in this case, is that of the orbital longitude of the body. Since the accuracy of Gaia astrometry is very different between the Along- and the Across-Scan directions, we can expect that the impact of each single detection in constraining the orbital position of a satellite will be strongly influenced by the geometry at the moment of AF crossing. For this reason, we consider here the angle α_{scan} between the perpendicular to the satellite plane (pole direction of Jupiter) and the Along Scan direction at the moment of detection. The scan direction follows a well-defined pattern, as a consequence it can (rarely) be perpendicular to the ecliptic but most of times it is around 40–70 degrees from it.

As mentioned before, the satellite moves on an orbit very close to the equatorial plane of the planet. Due to the obliquity of Jupiter and to the inclination of its orbit on the ecliptic, both very low, we can assume that the distribution of the angles $\alpha_{\rm scan}$ (referred to Jupiter spin pole) is very similar to those referred to the ecliptic pole. The simulated detection confirms that. The plot in Figure 5 shows an example of the distribution of $\alpha_{\rm scan}$. It can be immediately verified that the most precise measurement direction for astrometry (Along Scan) is never parallel to the orbital plane. However, in a relevant number of cases, the inclination is not greater than 45 degrees, allowing a useful improvement of the astrometric accuracy.

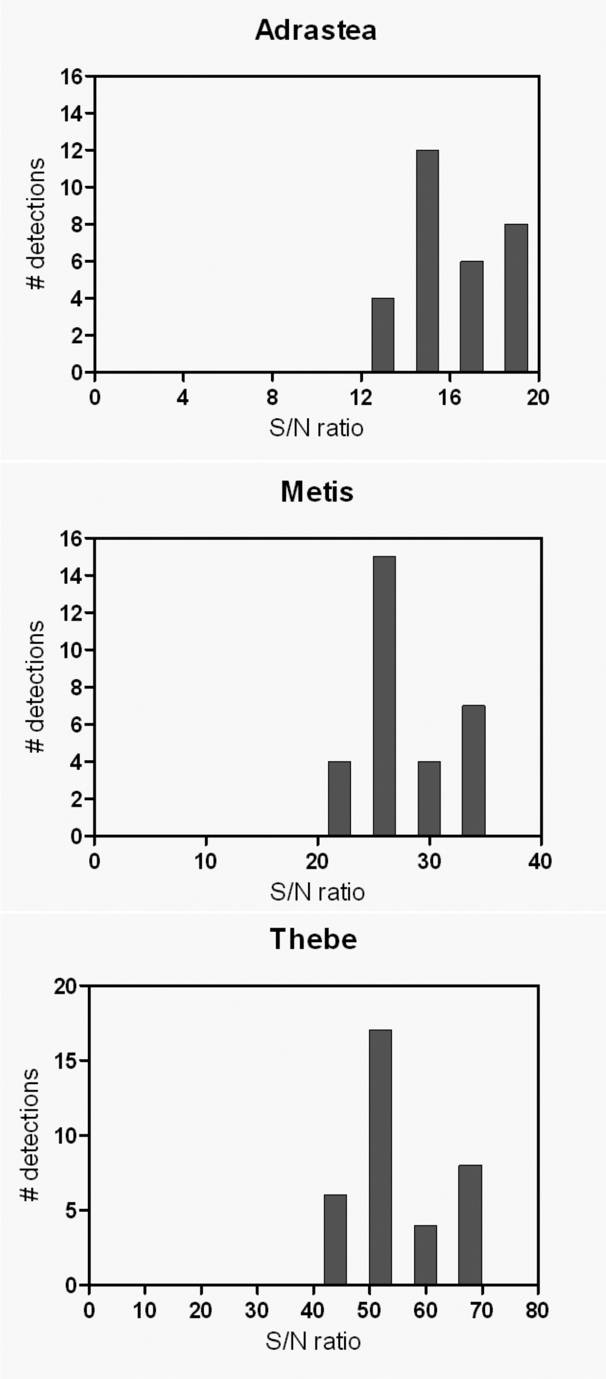

Figure 4. S/N ratio distribution computed for the faintest satellites of the inner Jupiter system.

5. CONCLUSIONS

In order to investigate the capabilities of Gaia in the study of planetary satellites and the statistics of detection, we considered here the regular satellites of Jupiter.

Excluding the observations lost due to superior and inferior conjunctions with the planet, a satellite of this family will be observed by Gaia about $\sim$40 times over 5 years of mission. Each astrometric measurement will be ex-

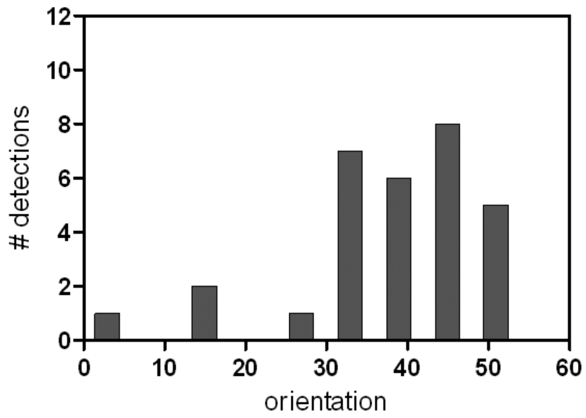

Figure 5. Histogram of the angle between the perpendicular to the orbital plane of the satellite, projected on the sky, and the along scan direction at the epoch of detection of Metis.

tremely more precise than allowed by Earth-based observers today, thus yielding a non-negligible contribution to the detection of subtle dynamical features.

The computed S/N ratios show that astrometry to better than 10 mas level (100 mas for Adrastea) should be possible. At the same time, straylight coming from Jupiter will have a very small influence on measurements. This situation is completely new to observers, since the brightness of the planet has always been the main problem for obtaining astrometry of faint satellites.

On the other hand, since it would be extremely important to include in the observable set very large objects such as the four Galilean bodies (Tanga 2005), a specific onboard detection strategy for bright, saturating sources is a requirement in this context. The large size of Galilean satellites should also be taken into account when defining the windowing on the AF CCDs.

Proposed solutions for saturating sources contemplates astrometry on diffraction spikes or intermediate CCD gate activation. Both of them result in a lower number of photons taken into account for astrometry, and in a consequent degradation of accuracy relative to the theoretically available flux. However, even with these limitations, Gaia measurements of the Galilean satellites remain of exceptional value. Together with the astrometry of the inner, fainter bodies, they provide access to astronomers to new possibilities of exploration of one of the most complex satellite systems. The same can be said for the families of the other main Solar System planets and for irregular satellites, that will be the object of future studies.

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