

The EPSL and the solar system objects

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Abstract

This note deals with the observational features of the solar system objects (SSOs) during the use of the scanning law in the ecliptic poles mode (EPSL). The goals are firstly, to seen the peculiarities of the observations of moving object during this particular phase of the mission and then to show how one can use the displacement of theses sources on the Gaia focal plane to validate specific science requirements for moving objects during the commissioning period.

Document History

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Acronyms

The following table has been generated from the on-line Gaia acronym list:

Acronym	Description
AC	Across-scan
AL	Along-scan
CCD	Charge-Coupled Device
DPAC	Data Processing and Analysis Consortium
EPSL	Ecliptic Pole Scanning Law
FOV	Field of View (also denoted FOV)
FPA	Focal Plane Assembly (Focal Plane Array)
FPRS	Focal Plane Reference System
FoVRS	Field-of-View Reference System
IDT	Initial Data Treatment
MBA	Main-Belt Asteroid
NEA	Near-Earth Asteroid
NEO	Near-Earth Object
NSL	Nominal Scanning Law
SRS	Software Requirements Specification
SSO	Solar-System Object
TDI	Time-Delayed Integration (CCD)

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1 Introduction

The main features of the observations of solar system objects with Gaia have been investigated many times, starting at the time of the Mission study phase, using the general properties of the scanning law. It is known that observations of main belt asteroids are possible only at solar elongations between 45 to 135 degrees, the median being at the quadrature, and tend to cluster around the two extremes. This is rather easily accounted for using a simple orbit of a standard main belt asteroid (MBA), with low inclination onto the ecliptic and small eccentricity. For Near Earth Objects (NEOs) the situation is different, since they can be observed at small distance from the Earth and with more uniform directions on the sky. In this case the distributions of the geometric parameters are less regular and can only be obtained by running realistic simulations. The main difference with the observations of star-like sources is the significant sky motion of the solar system sources over a time scale comparable to the crossing of one of the field of view of Gaia. A main belt object moves with a typical velocity of 10 mas/s, amounting to nearly one pixel during one CCD crossing, when this velocity is along scan and has implication on the windowing as explained in (FM-024). The near Earth objects are much less numerous and fainter, but their geocentric apparent motion could be much larger and above 50 mas/s, a valuable feature to qualify the on-board detection of moving objects.

The goals of this note are twofold: (i) to see the impact of the Ecliptic Pole Scanning law on the observations of solar system objects, (ii) to determine how many of these objects could be available during the commissioning period to validate the on-board procedures implemented specifically for fast moving objects. This investigation has started after a discussion with J. de Bruijne on how to carry out the in-flight verification of some of the Mission Requirements specific to solar system objects. This discussion itself was triggered by the Initial in-orbit calibration workshop held in Leiden in February, whose Minutes prepared by A. Brown will appear very soon under the entry GAIA-CO-MN-LEI-AB-023.

2 Ecliptic Pole Scanning Law

2.1 General features

During this particular phase of the mission, covering a period of two or three months after launch, the spin axis precession is turned off, meaning that the spin axis keeps a fixed direction with respect to the Sun. More precisely it will be kept in the ecliptic, in a direction either leading or trailing the sun, according as it lies ahead of the Sun on the ecliptic or behind, as illustrated in Fig. 1. The choice can be optimised for better science return and will depend on the launch date (HL-006). With a spin axis in the ecliptic, the instantaneous scanning circle is perpendicular to the ecliptic and its ascending node advances on the ecliptic at the same rate as the sun motion, on the average 0.9856 deg/day (or 41.5 mas/s), with a small yearly modulation about the mean proportional to the eccentricity of the Earth orbit.

The corresponding leading and trailing scanning planes are also shown in Fig. 1, leading in blue and trailing in red. With respect to the Sun, the ascending node of the scan circle is at constant elongation of 135 or 45 deg, respectively for the leading and trailing mode, and conversely 315 and 225 deg (equivalently -45 and -135 deg) for the descending node. The actual sky coverage over few months is pictured in Fig. 2 in ecliptic coordinates and Fig. 3 in equatorial coordinates. This is plotted for three months, and about half of the sky is scanned during this interval. The instantaneous nodes of the scan circles on themselves are fixed in the sky at the north and south ecliptic poles. This is a very distinctive feature compared to the nominal scanning law where these nodes are constantly moving on the sky. Therefore areas around these poles enter repeatedly the Gaia Fields of View every six hours, but with slowly changing scan direction.

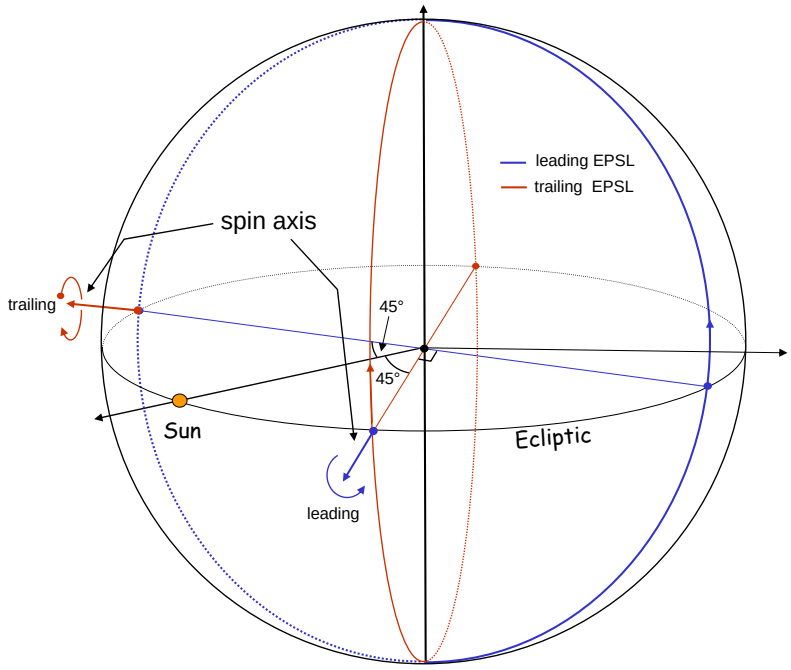


FIGURE 1: Illustration of the relative position of the two possible choices for the EPSL. In the leading (resp. trailing) EPSL, the direction of the spin axis is 45 deg ahead of (resp. behind) the sun. Due to the sun-aspect angle of 45 deg, there are some degeneracies in the plot, with spin axes being identical to ascending or descending nodes of the scanning circle. The diagram is drawn in a frame rotating with the Sun, leading to a fixed geometry and closed scan circles. Main belt asteroids are observed close to the ecliptic, that is to say near the nodes (ascending or descending), with a proper velocity primarily across-scan at solar elongations of 45 or 135 degrees. On the other hand, NEAs will be seen even at large ecliptic latitudes. To help visualise the depth in this plot, the reader must consider that the solid lines are in the front of the main section of the sphere and the dotted lines are behind.

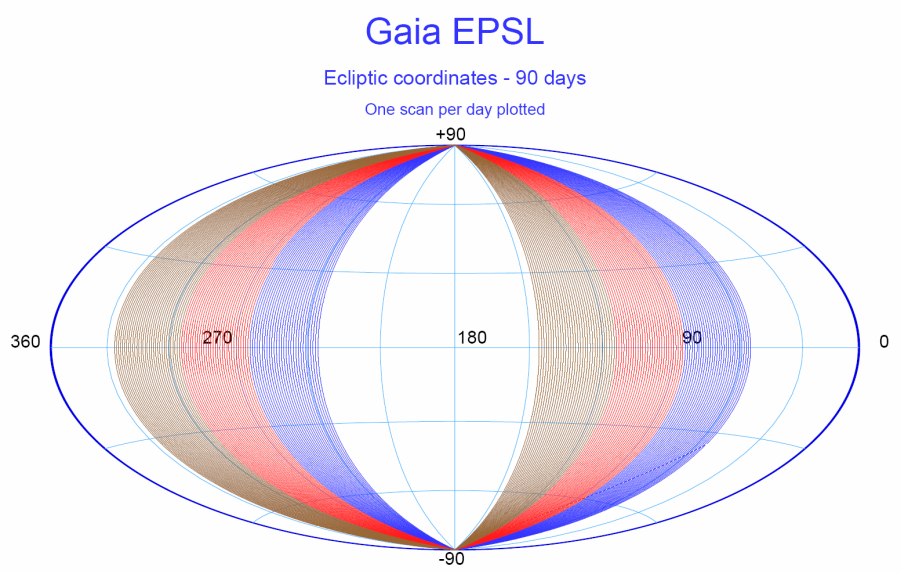


FIGURE 2: Scanning the sky in the Ecliptic Pole mode over three months, with one colour per month. Plot drawn in ecliptic coordinates. For better clarity, only one scan out of every four is plotted.

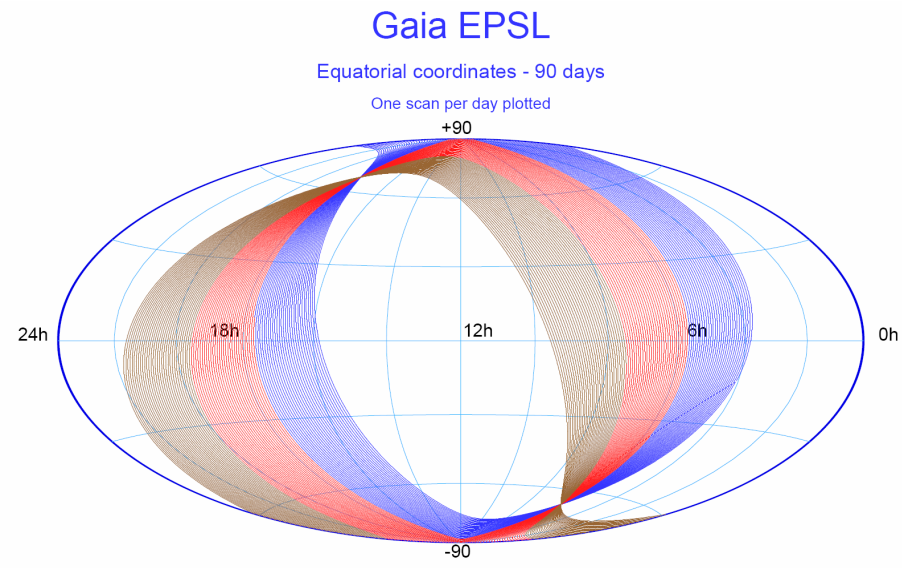


FIGURE 3: Scanning the sky in the Ecliptic Pole mode over three months, with one colour per month. Plot drawn in equatorial coordinates. The north and south ecliptic poles are located at the common nodes of all the scan circles. For better clarity, only one scan out of every four is plotted.

2.2 Implication for the solar system objects

Most of the minor planets to be observed by Gaia will be asteroids of the main belt with semi-major axes in the range of 2.5 to 3.5 au, and orbital plane close to the ecliptic. Therefore observations with Gaia will take place only in the immediate vicinity of the intersection of the scanning plane with the ecliptic, that is to say close to the nodes. There will be several $100,000$s objects of this population observable with Gaia and on the average one expects between$10,000$ to $15,000$ field transits per day (there is a slight modulation with the ecliptic latitude of the spin axis). For the nominal scanning law, observations are only feasible in a range of solar elongation from 45 to 135 deg, with an observation density showing a sharp accumulation toward the two extreme values. These features are presented in detail in SAG-FM-009.

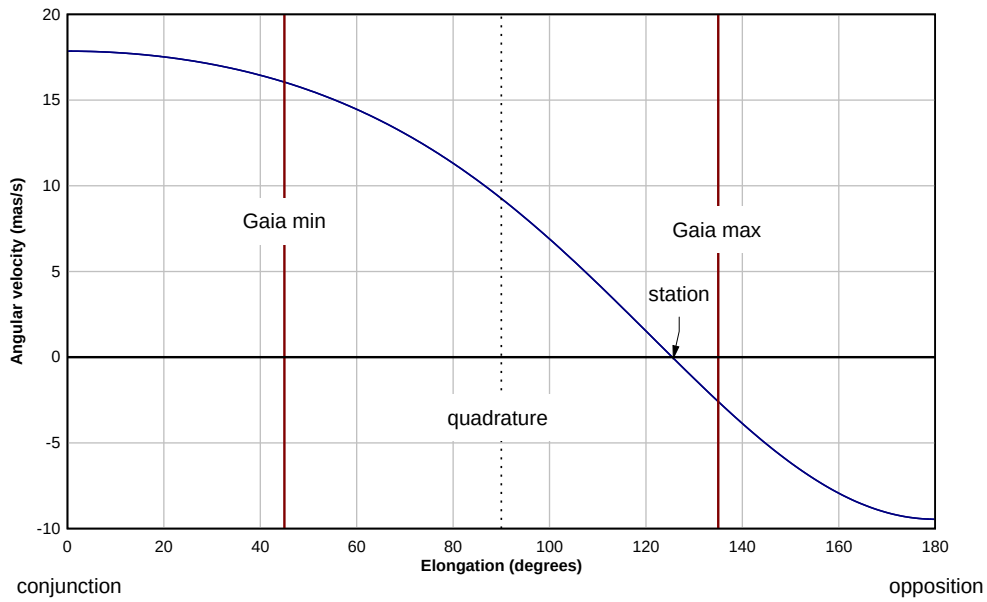


FIGURE 4: Angular velocity of a standard main belt asteroid during its geocentric motion from the conjunction to the opposition. This velocity lies almost in the ecliptic. During the EPSL, the scanning plane is perpendicular to the ecliptic, with the ascending node ahead of the sun by 45 or 135 degrees and observations are only achievable at the two extremes elongations, resp. 45 and 135 degrees. The space velocities are then well defined, around 15 mas/s and ~ -3 mas/s respectively. (This very small velocity is accounted for by a contingent effect: it happens that the elongation of 135 deg, is very close to the station during the synodic cycle, the point in the geocentric orbit when the planet stops its retrograde motion and returns to the prograde's.)

With the EPSL, the geometry is even simpler since the nodes are at constant elongation of 45 or 135 deg, and all observations will happen there. One can see in Fig. 4 that the geocentric

(or Gaiacentric at this qualitative level) angular rate of motion takes well defined values around these two elongations, either ~ 15 mas/s or ~ -3mas/s. Since this displacement is along the ecliptic for the MBAs, it will be essentially across-scan on the Gaia focal plane. The actual observed value on the CCD will be a linear combination of the orbital motion with the contribution following from the slow drift of the scanning plane at a rate of 41 mas/s, but with a different direction in the ascending and descending node. In any case, the total AC velocity will never be larger than 50-60 mas/s on the CCDs.

This simple picture does not apply for the small population (~ 2000) of near Earth asteroids (NEAs) with geocentric motion much less regular and observable significantly above or below the ecliptic. Not only are their hourly displacements larger than that of the MBAs, but the directions are also not necessarily nearly parallel to the ecliptic. Therefore, during a Gaia transit in the EPSL mode, one may have large along-scan displacements, above 30 mas/s, easier to detect than the transverse motion, and entirely due to the orbital motion. This is a very distinctive feature compared to the stars. But nothing comes for free, and most of these sources will be faint, close to the detection limit of Gaia, as illustrated in Fig. 10. See also SAG-FM-007 for a more comprehensive description.

A simulation has been run with the EPSL to determine more carefully the number of transits in each of the two populations that could be used to test the on-board software handling the fast moving objects and allocating the complementary windows. The simulator is the one developed internally in CU4 and later transported into Java for CU2, and producing the transits lists for the Universe Model of CU2. The only significant change is the replacement of the routine generating the Nominal Scanning Law by a new one for the EPSL. Few other and minor adjustments had to be done to produce the outputs needed for this work. It is important to notice that the Gaia orbit used in this work is the nominal one around L2, as used in every DPAC simulation, and the best available orbit will have to be used to provide the required information during the commissioning phase. However, this need not to be extremely accurate, and the analytical representation of the Lissajous orbit with the two independent amplitudes and the initial phase at injection epoch, will be sufficient to provide prediction good enough for the in-flight performance on moving objects.

3 Main belt asteroids velocity during EPSL

The simulation was run on the first 2000 asteroids, all in the main belt, over a duration of 200 days, resulting into about 15,000 field transits. When necessary, i.e in most cases, results are shown separately for the leading and trailing EPSL. This gives a sufficient number of transits to produce significant statistical results, that can be scaled either to a shorter interval or to a much larger number of planets. The results presented focus only on the velocity during the transits, along- or across-scan, always expressed in milliarcsecond per second of time (mas/s).

The along-scan velocity is the orbital displacement on the sky and amounts to the image displacement on the CCDs not taken into account by the TDI. It gives the drift (positive or negative) of a planetary image compared to that of a star. The reference frame is the FoVRS as defined in BAS-003, that is this velocity is positive when $d\eta/dt \geq 0$. This is opposite to the nominal direction of the image displacement on the CCD given in the FPRS. See Fig. 4.6 in BAS-003.

The across-scan velocities come into two guises. The first one is again the component of the orbital velocity of the planet on the SRS (or FoVRS, since they share the same ζ direction), which is just what an astronomer would compute by rotating its standard frame to the SRS. The corresponding transverse velocity would be nearly zero for a star (given the size of the annual proper motion). While this component reflects precisely the difference between a star and a moving object, this is not the quantity that would be detected on board as *across-scan motion*, since the latter includes a large contribution from the scanning. The motion of a stellar image, either with the NSL or the EPSL, is not strictly along-scan. Due to the precession motion in the NSL, there is a transverse component, with a sinusoidal variation over one spin period, with an amplitude of 172 mas/s. Solar system object proper velocity comes on top of this displacement, adding or subtracting few 10's mas/s, and up to 100 mas/s for the faster moving near Earth objects.

In the case of the EPSL, even without precession, there is still a motion of the spin axis at the same rate as the solar displacement on the ecliptic, close to 1 deg/day. This generates also a transverse motion of the FOVs for the stars, modulated with a six hour period and with an amplitude of 41.5 mas/s (equivalent to 1 deg/day). It is maximum on the ecliptic and goes to zero at the ecliptic pole. On the FPRS, this transverse image motion is in the negative direction at the ascending node, and positive in the descending node. In the following plots, the orbital velocity components (AL, AC) are given in the FoVRS axes (an astronomical frame), while the across-scan displacement on the CCDs, combining the proper and scan reflected motion, is given in the FPRS (an instrumental frame). The transverse directions are parallel but opposite in orientation.

3.1 Along-Scan velocity

For the MBAs, the AL velocity distribution is shown in Fig. 5, with no distinction between the leading/trailing mode, since there is no significant difference. As explained earlier, there is almost no orbital displacement of these planets in the AL direction, since their orbital velocity is practically along the ecliptic and then perpendicular to the scan. No detection of AL motion is achievable on-board for these sources, an unfortunate circumstance since there are plenty available, brighter than $G = 15$. However, with the EPSL parameters, it will be possible to predict rather accurately the passages of a small sample of MBAs of different magnitudes and check in the early DPAC processing whether they have been recorded. This won't be an easy task and will depend very much on the efficiency of the IDT cross-matching against the Initial Gaia Star List.

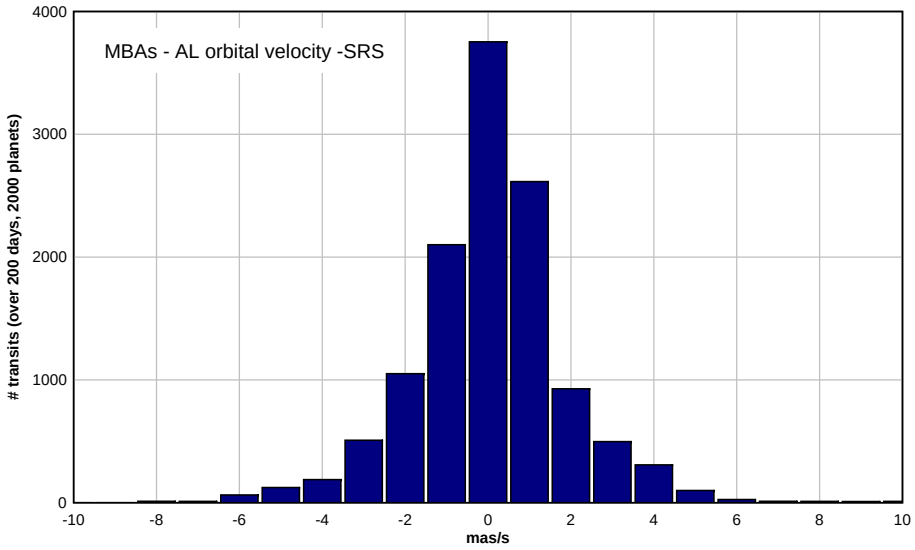


FIGURE 5: Main belt asteroids: distribution of the orbital along-scan velocity during Gaia observations performed with the EPSL. These velocities are all very small, since the motion of the MBAs is primarily along the ecliptic, and during EPSL has virtually no AC projection.

3.2 Across-scan velocity

The next two plots, Figs. 6–7, give the orbital across-scan velocity, for the leading and trailing EPSL, and for the same set of main-belt asteroids. The maximum velocity remains moderate, with a strong bi-modal distribution according as the transits are seen at the inner or outer elongations. There is also a nearly perfect symmetry between the leading/trailing EPSL, which is not too difficult to account for.

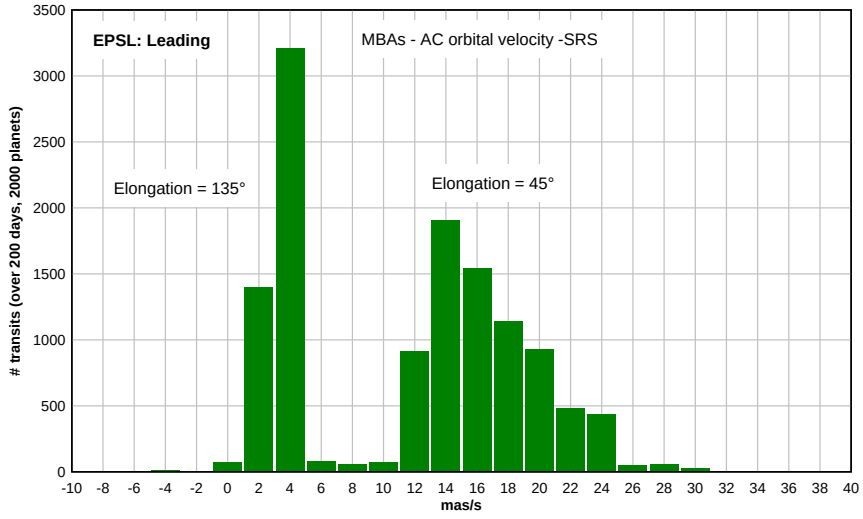


FIGURE 6: Main belt asteroids: distribution of the orbital across-scan velocity during Gaia observations performed with the EPSL, with the spin axis leading the sun.

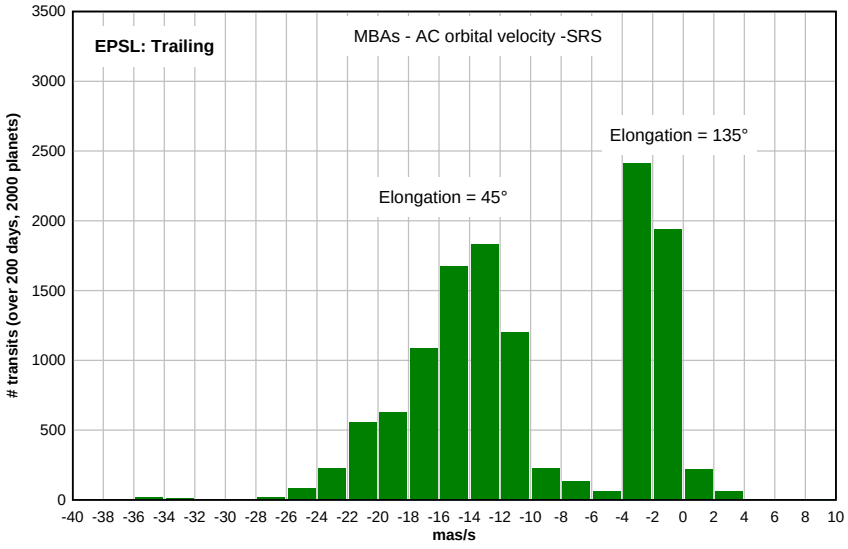


FIGURE 7: Main belt asteroids: distribution of the orbital across-scan velocity during Gaia observations performed with the EPSL, with the spin axis trailing the sun.

Finally, the combination of the orbital displacement and scan-reflex motion is shown in Figs. 8–9. The contribution from the scan essentially shifts the orbital distributions of Figs. 6–7 by ± 41 mas/s, with a change of sign with elongation and with the leading/trailing EPSL. For stars observed in the same conditions (close to the ecliptic) the AC motion would be rather uniform, at ± 41 mas/s.

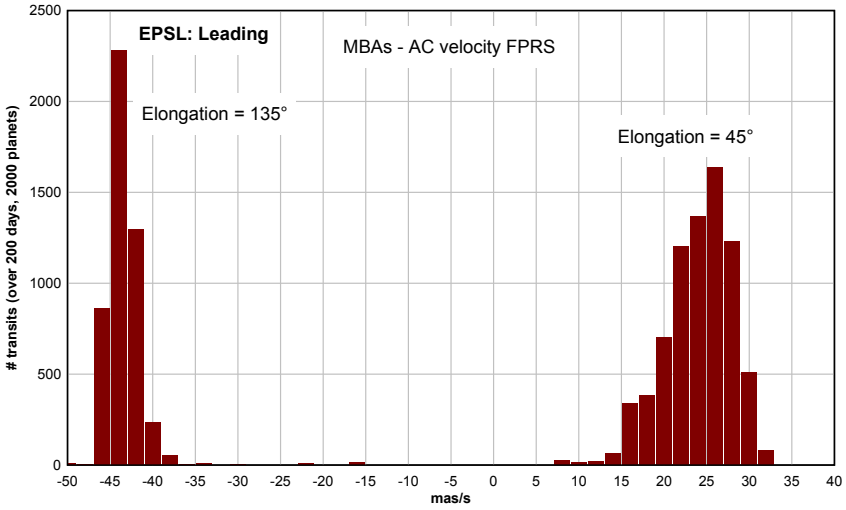


FIGURE 8: Main belt asteroids: distribution of the across-scan velocity (orbit + scan) during Gaia observations performed with the EPSL, with the spin axis leading the sun.

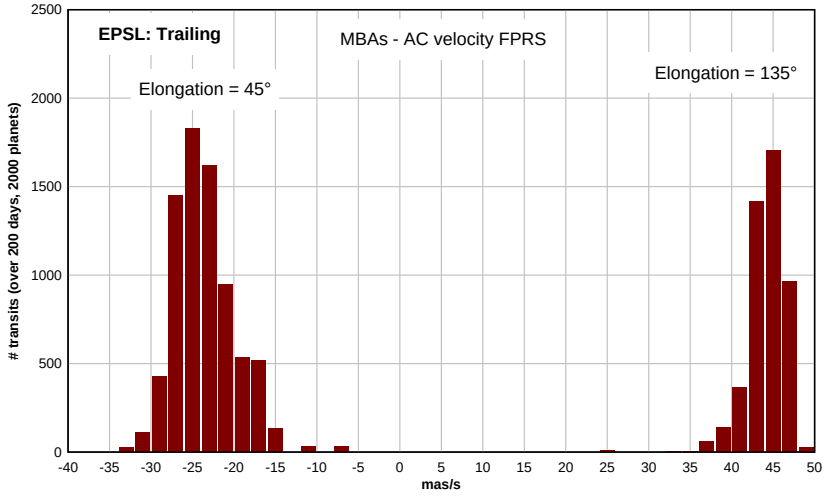


FIGURE 9: Main belt asteroids: distribution of the across-scan velocity (orbit + scan) during Gaia observations performed with the EPSL, with the spin axis trailing the sun.

The orbital contribution will be only noticeable in the small elongation geometry. To illustrate this point, if we take as in GAIA.ASF.BG.PLM.00015 an accuracy of the AC shift measurement

between SM and AF1 to 0.22 pixel (1 σ), or a velocity accuracy of 3.5 mas/s (SM1–AF1) or 8 mas/s (SM2–AF1), and applying at least a 3σ detection to keep the number of false detection at a low level (GAIA.ASF.MEM.PLM.00193), this gives a possible detection of the AC velocity above 10.5 mas/s in the best case (SM1–AF1). From Figs. 6–7, one sees that there is still a large population of MBAs falling in this configuration. We will come to this point again below.

4 Near Earth asteroids velocity during EPSL

The simulation for Near Earth asteroids is based on the known population of minor planets with semi-major axis less than 1.5 au. This is not the perfect definition of a NEA, but at least it includes all of them, and more significantly for this work, all the planets which can exhibit large orbital motion and observable well outside the ecliptic plane are there. We have found 2045 such objects among the $450,000$ already known minor planets. The simulation is run over 1500 days, again to increase the statistical significance. The number of transits for each bin of velocity must then be scaled to the relevant duration, typically dividing by 50 for the on-board commissioning of one month. Altogether we have found ~ 9000 transits with $G < 20$ during the 1500 days. Therefore, something like $150 - 200$ could be available over one month for the commissioning, and about 30 brighter than $G = 18$ (see the magnitude distribution below for the proportion), and then belonging to the AOCS subset (GAIA.ASF.BG.PLM.00015). This is a very small sample, but should be enough to find good candidates for an on-ground search.

Remark: In this simulation we have the same number of NEAs as MBAs (~ 2000), but even over 1500 days instead of 200, we end up with a smaller number of transits, typically 9000 instead of $15,000$. This is due to the magnitude cut-off at $G = 20$. The NEAs are intrinsically of small size, then faint, and during most of their passages in the Gaia FOVs, they are too faint to be detected.

4.1 Magnitude distribution

The magnitude distribution during FOV crossings is shown in Fig. 10, and indicates that 60% of the transits are fainter than $G = 19$ and $\sim 15\%$ are brighter than $G = 18$. These numbers are based on real sources and should be very close to what Gaia will really see. This leaves an average of 1 transit per day of a NEO with $G < 18$.

4.2 Proper and instrumental Velocity

The next set of plots follows the same arrangement as for the MBAs, with the along-scan velocity first and then the transverse component, both on the sky and on the FPA.

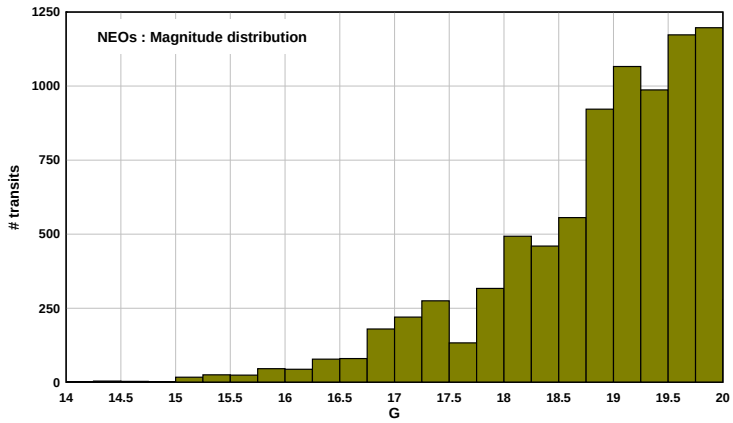


FIGURE 10: Statistical distribution of the G magnitude of the near Earth Objects during Gaia observations with the EPSL.

4.2.1 Along-Scan velocity

Figs. 11–12 give the statistical distribution of the orbital component of the motion in the along-scan direction. This time we have a sizeable fraction of transits with a velocity larger than 30mas/s (resp. 15 mas/s) (in absolute value), while it would be zero for the stars. Assuming this is the level at which a motion can be detected on board, we find about 1200 (resp. 3100) transits above this limit over 1500 days. Therefore we may find 25 (resp. 65) transits up to $G = 20$, and only ~ 4 (resp. 10) brighter than $G = 18$ over one month. This could be sufficient for validation purposes if predictions are made on-ground to help find the relevant transits. But we are no longer in a statistical regime, but on case by case basis instead.

4.2.2 Across-scan velocity

The next four plots show the across-scan velocity, first the orbital component in the SRS in Fig. 13–14 and then the combination with the scan reflex motion in Figs. 15–16. There are about 700 (resp. 4000) with an orbital AC motion larger than 60 mas/s (resp. 30 mas/) over 1500 days, and 50 times less for one month. The lower level of 30 mas/s is normally achievable on-board to discriminate stars from moving objets. There are so many more stars than NEAs, that a powerful test must be designed to avoid too many false detections, and this is closely connected to the precision of the on-board velocity. This issue is addressed in GAIA.ASF.MEM.PLM.00193 for the general asteroid population and the Across-scan motion, since there is no particular implication on the VPU from the AL velocity (BP/RP windows wings are large enough to absorb most of the cases (but probably not the fastest moving NEAs as shown in FM-024).

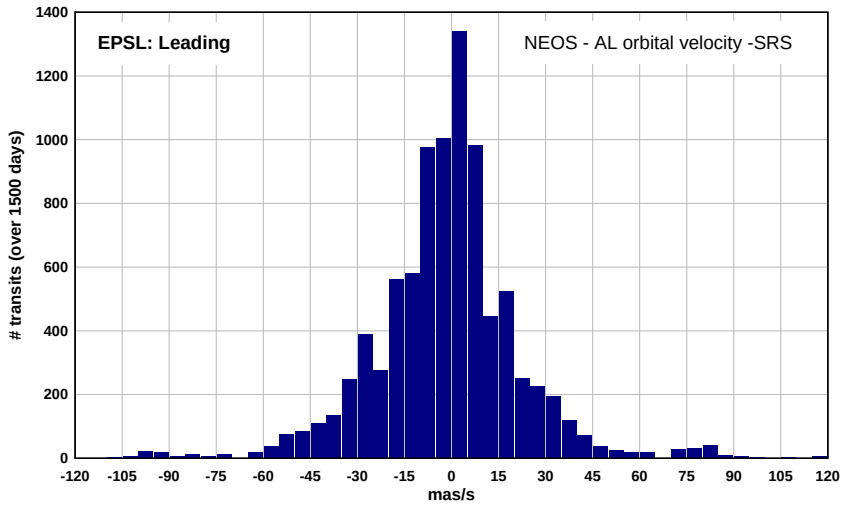


FIGURE 11: Near Earth asteroids: distribution of the orbital along-scan velocity during Gaia observations performed with the EPSL, with the spin-axis leading the sun.

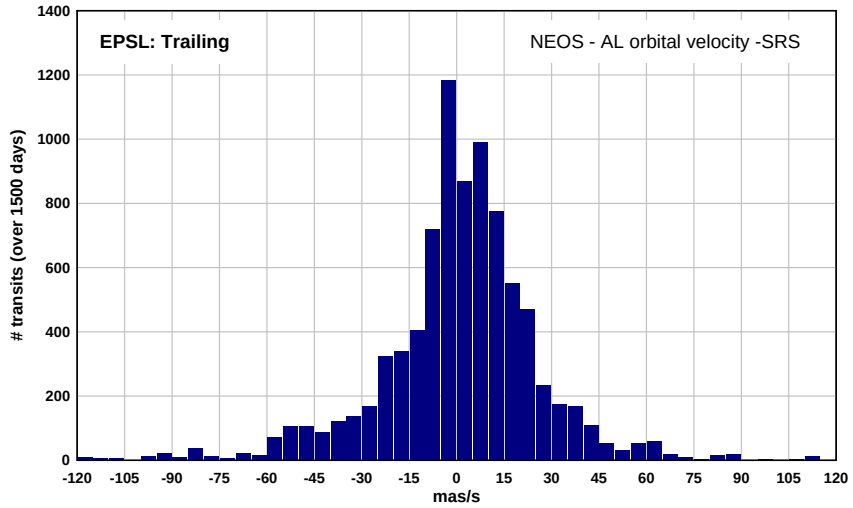


FIGURE 12: Near Earth asteroids: distribution of the orbital along-scan velocity during Gaia observations performed with the EPSL, with the spin-axis trailing the sun.

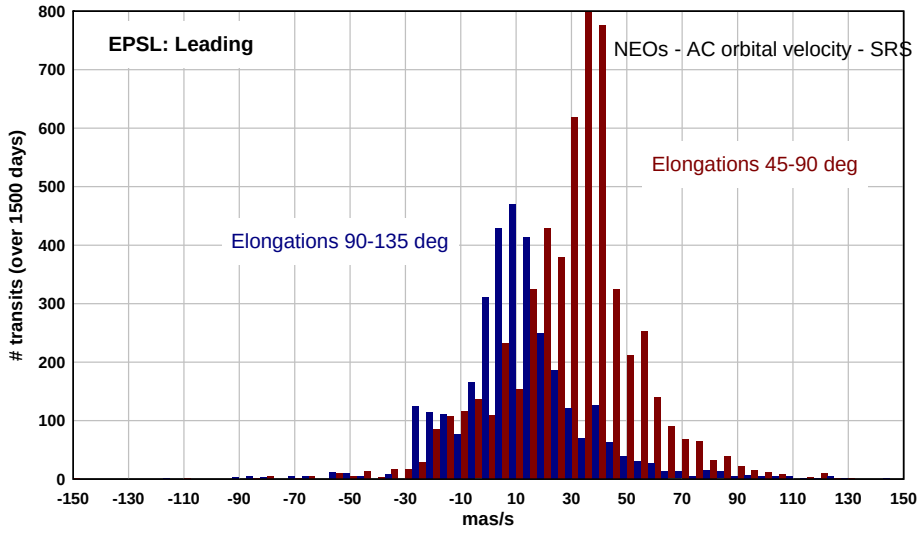


FIGURE 13: Near Earth asteroids: distribution of the orbital across-scan velocity during Gaia observations performed with the EPSL, with the spin axis leading the sun.

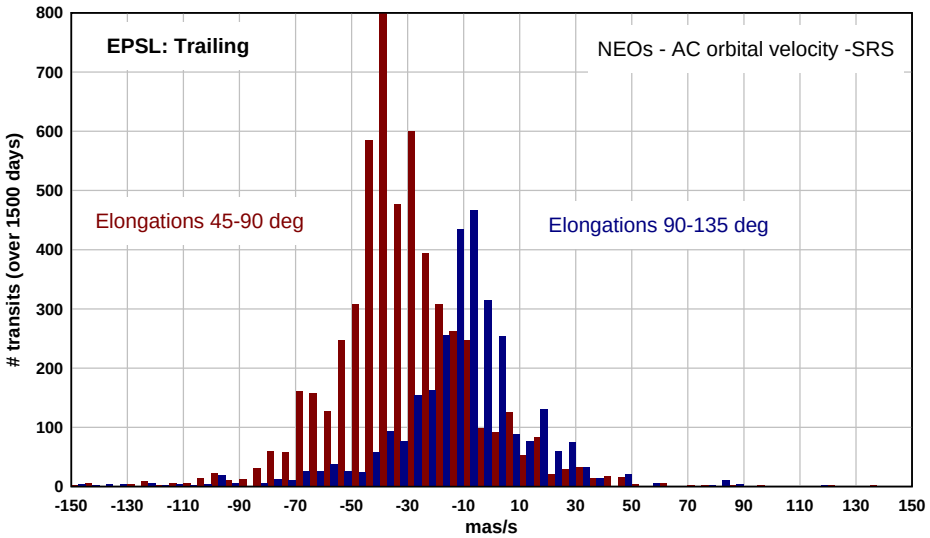


FIGURE 14: Near Earth asteroids: distribution of the orbital across-scan velocity during Gaia observations performed with the EPSL, with the spin axis trailing the sun.

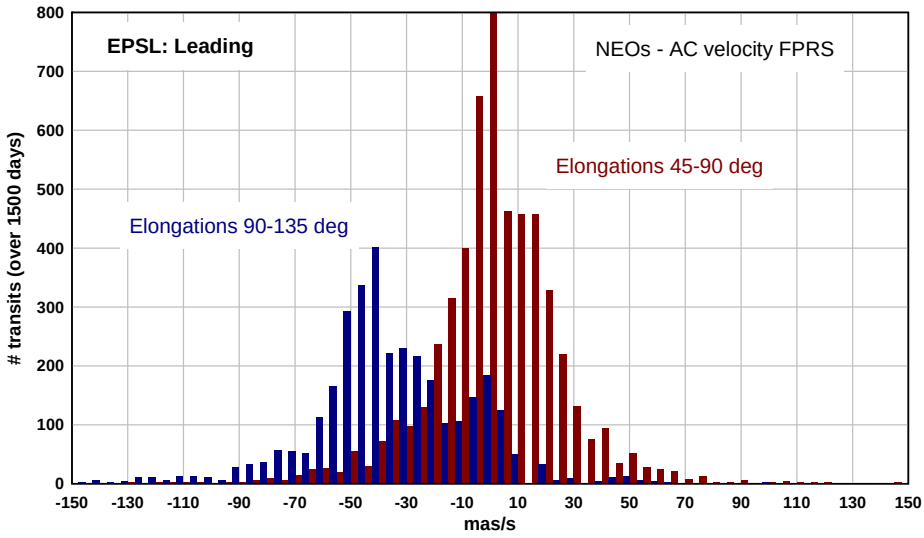


FIGURE 15: Near Earth asteroids: distribution of the across-scan velocity (orbit + scan) during Gaia observations performed with the EPSL, with the spin axis leading the sun.

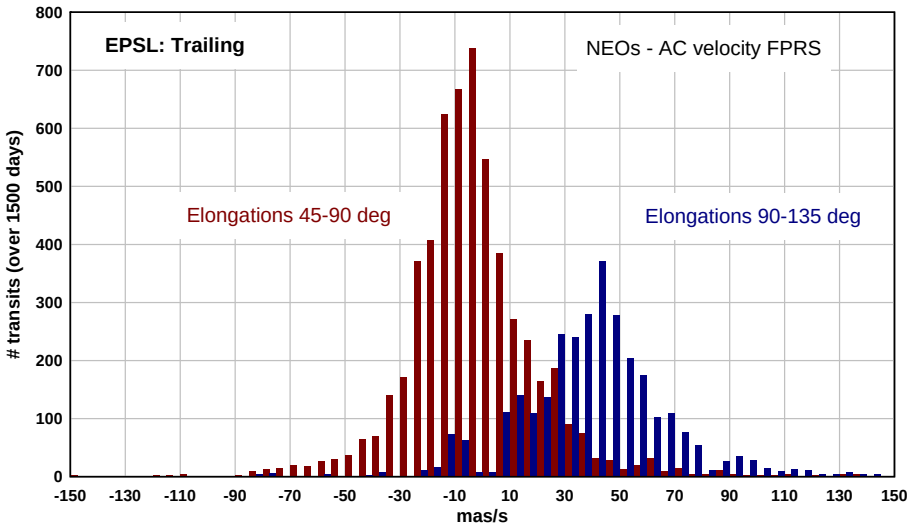


FIGURE 16: Near Earth asteroids: distribution of the across-scan velocity (orbit + scan) during Gaia observations performed with the EPSL, with the spin axis trailing the sun.

5 Conclusions and Recommendations

With the assumptions of this simulation, we can already draw several conclusions regarding the possibility to validate during the commissioning phase specific mission requirements pertaining to the observations of solar system objects.

We have considered that displacement between SM and AF1 can be detected on-board for moving object above 0.22 pixel (1σ) as indicated in GAIA.ASF.BG.PLM.00015 sect. 2.5.4. This is equivalent for ASM2 to AF1 (ASM2 is less favourable than ASM1) to a velocity AL of 2.6 mas/s and AC of 8.0 mas/s (1 σ). The proportion of solar system objects brighter than $V = 18$ to the stars is about 0.0004 (10^5 planets compared to 250×10^6 stars). A detection at 3.5σ will produce as many false detections of stars as planets rightly detected. This gives a threshold velocity of 9 mas/s AL and 27 mas/s AC. If such a motion is detected, it will be in 50% of the cases due to the motion of a planet. The above thresholds are typically twice smaller with the shift between ASM1 to AF1.

Remark: The number are not the detection thresholds adopted on-board (which are much slower), but the thresholds we propose to use on-ground to select useful instances of transits to validate the SMO detection during commissioning.

Therefore one arrives, from the preceding sections, at the conclusions:

- During the EPSL mode main belt objects will be seen only in the vicinity of the nodes of the scan circle with the ecliptic, and with no along-scan motion (Fig. 5). Their transverse motion, coming on top of the contribution from the scanning, will be less than 25 mas/s (Figs. 6–7), too small (albeit marginally) to discriminate with high-probability from stars. Despite their very large number and favourable brightness, we don't propose to use these sources for the validation of SMO detection and extra-window allocation.
- Restricting to the small population of Near Earth Objects, less than 2000, one should have about 200 transits during a commissioning of 30 days, with only ~ 30 of them brighter than $G = 18$. Among these 30 transits, about one third (~ 10) will have an AL speed above 15 mas/s. Although not detected on-board, these transits can be predicted on ground and then checked to see how they have been handled.
- For the same population, the transverse motion is somewhat larger, and over one month and for $G < 18$, one must have about 15 transits with AC velocity > 26 mas/s in absolute value. (In fact the sign is nearly fully determined by the choice of a leading or trailing EPSL). These transits will be predominantly found at small elongation, just above 45 degrees.
- Once the orbit around L2 and the initial conditions of the EPSL are known, CU4

should be in position to pinpoint the favourable transits and provide a good timing. The number of useful cases will depend on the actual velocity threshold and a reliable prediction will be provided once these numbers are final.

- To verify the detection performances for solar system objects to $G = 20$, it will be also easy to provide a list of expected transits for a sample of main-belts objects with predicted magnitude. One can also investigate the possibility to use the SSO short term module at DPPC, shortly after launch provided IDT can be run on this initial telemetry data.
- Finally it would also be possible to check the transits of the largest asteroids for the effect of the angular size on the on-board detection. There are very few larger that ~ 100 mas, but all with well known orbit.

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