WHAT TO EXPECT FROM OBSERVATIONS OF SOLAR SYSTEM OBJECTS WITH A GAIA-TYPE ASTROMETRIC MISSION

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ABSTRACT

We discuss in this paper of the opportunities and value of observations of solar system objects in a space astrometric mission. First we present the results already obtained from observations minor planets during the Hipparcos mission. We present the objects that could be observed in a GAIA type mission and the expected accuracies. From the interferometric mode it should be possible to determine positions with a sub-milliarcsec precision. In the incoherent mode a large number of objects can be observed and positions could be determined with a precision better or similar to that of Hipparcos. The value of these observations for photometry, improvement of ephemerides and frame linking is developed in the last sections.

Key words: Hipparcos; GAIA; astrometry; photometry; solar system; asteroids; ephemerides.

1. INTRODUCTION

Astrometry from space has many advantages: global astrometry, atmosphere-free observations, number of objects, great accuracy measurements in a relatively short period; and it can yield high value results in so many fields of astronomy, astrophysics and cosmology. Observations of star positions at optical bandwidth enable one to produce a very accurate and homogeneous sphere and kinematical reference frame. This reference frame however is not linked to the dynamical frame represented by the dynamics and motion of solar system bodies. There are different way to fix the ecliptic and the equinox in this cinematical frame, but the only way to obtain a direct link of the star catalogue to the dynamical reference frame is to have relative positions of the two kind of objects. So the very accurate positioning of solar system objects to the optical frame defined by the stars dramatically improves the frames linking. Among this frame linking, such observations can yield photometric and dynamical information for individual objects.

2. HIPPARCOS EXPERIENCE

The Hipparcos mission is the first experience of astrometry from space, its success is assured for the determination of astrometric parameters of about 120 000 stars. Due to the limiting magnitude of 12.5 and the limiting apparent diameter of about 1 arcsec, the only solar system objects observed by Hipparcos are 48 asteroids and 3 natural satellites (Europa, Titan and Iapetus). Beside these bodies, Uranus and Neptune have been observed within the Tycho experiment which results are not developed here. Hereafter we will discuss mostly about the data obtained for the asteroids, however the astrometric and photometric accuracies for the natural satellites are analogous.

The minor planets – observed around the quadratures – are all from the main belt, with apparent magnitudes between 7 and 12.5. These include the biggest and brighter ones: Ceres, Pallas, Vesta and Juno; nevertheless a great majority are small objects with apparent diameter ranging from 0.05 arcsec to 0.2 arcsec. Hipparcos measurements yield astrometric information but also photometric data in a wide bandwidth. Even though the photometric measurements were not the primary objectives of the Hipparcos mission, magnitudes can be determined with a precision of a few 0.01 mag, procuring for some of the minor planets absolute magnitudes over a whole rotation period (Morando & Mignard 1993). The minor planets astrometric directions are determined with a precision ranging from 5–40 mas and with a mean of ≈ 15 mas, this precision depends essentially on the magnitude of the minor planets and little on their apparent size (Hestroffer 1994).

From the positions gathered after 3 years of observations it is possible to determine the rotation of the Hipparcos sphere around the dynamical reference frame. This rotation is expressed by two vectors yielding the orientation at a given epoch and the rotation rate of the sphere. The other unknowns are the Earth and minor planets osculating elements, and a two parameter function expressing a common scatering law on the surface of the asteroids. Nevertheless the sphere orientation can not be disentangled from the orientations of the osculating trajectory of the planets (Hestroffer et al. 1995). However the Earth orbit is well known from other kind of observations (radar, LLR); we express then the time dependent rotation of the Hipparcos sphere as:

$$\mathbf{W}^{\mathrm{Hipp}}_{\mathrm{DE\,200}} = \mathbf{W}_o + (t - t_o).\mathbf{W}_1 \tag{1}$$

where $\mathbf{W}^{\mathrm{Hipp}}_{\mathrm{DE\,200}}$ is the rotation around the frame of the DE 200 system, $\mathbf{W}_o$ is the sphere orientation at epoch t_o and $\mathbf{W}_1$ is the rotation rate. The precisions are:

$$\left| \begin{array}{l} \sigma(\mathbf{W}_o) = 1 - 2\,\mathrm{mas} \\ \sigma(\mathbf{W}_1) = 2 - 3\,\mathrm{mas/year} \end{array} \right.$$

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Table 1: Characteristic values of the proposed instrument.

pupil diameter	D	0.55m
separation	B	2.45m
focal length	f	11.5m
revolving angle	ξ	55°
scanning velocity	$\dot{r}$	120 arcsec/s

where the orientation of the DE 200 ecliptic plane is better fixed to the Hipparcos sphere than its equinox position. The gain in precision thus obtained, when compared to similar methods used for the construction of the FK5 (Fricke 1982), is of magnitude 100 and with only three years of observations. The time dependant part of the rotation will be better determined when the Hipparcos observations will be completed with even more accurate positions made at an other epoch.

After 3 years of observations, the improvement of the asteroids ephemerides can not be complete. The orientation of the osculating orbit can be given with a very high precision of a few milli-arcsecond. On the other side, depending on the arc of the trajectory that has been observed, parameters that are time dependant are not or poorly determined. So the development of the dynamical frame tie to the optical reference frame (and indirectly to the ICRS frame defined by the positions of extra-galactic objects), as well as the osculating elements determination would be strengthened by the GAIA mission.

3. GAIA MISSION

The following sections and associated results are based on the work of Lindegren & Perryman (1994), where the baseline of a future astrometric interferometer is developed. The satellite's rotation axis will make a constant angle ξ with the direction of the Sun, and the telescope will consist in a Fizeau interferometer; some characteristic values of the proposed instrument are given on Table 1. As for the Hipparcos mission, GAIA observations of outer planets and bodies occur near quadratures; this is due to the particular systematic scanning law of the sky. Fig. 1 shows a schematic view of the observations geometry; if the the satellite rotation axis makes a constant angle of $\xi=55°$ with the direction of the Sun, observations will however occur on a wide range around the maximal phase angle (for a near Earth observer). This is of interest for both photometric and astrometric data. The apparent magnitude as well as the photocentre offset (due to the phase) depends on light scattering properties on the body surface. With the great accuracies available by a GAIA-type mission a stride should be made on the knowledge of the light scattering of the biggest asteroids and natural satellites.

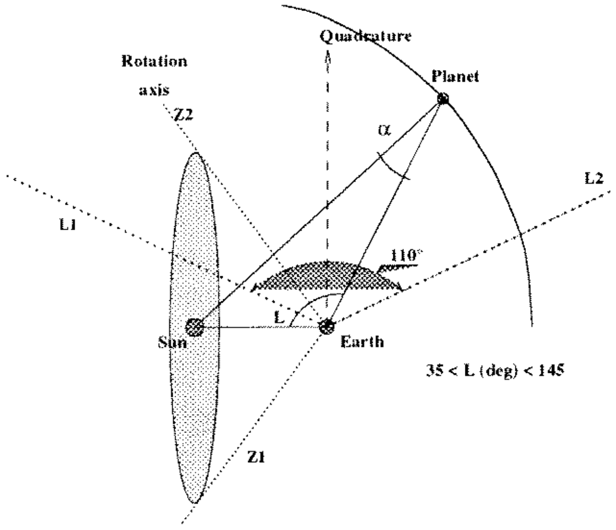

Figure 1: Geometry of observations. For solar system objects, observations will occur around the quadratures. Objects are of lower magnitude and present a phase.

Two different modes of observation are proposed with the GAIA baseline mission. The coherent mode, consisting on an interferometer coupled with a modulation grid; and the incoherent mode, where the Airy envelope is measured on a CCD chip. In the coherent mode, only small objects can be observed (as for the HST astrometric mode), candidates are then the minor planets and natural satellites; while in the incoherent mode, observations can be extended to larger objects.

4. Coherent mode

4.1. Asteroids

The systematic scanning of the sky may limit the number of observations for solar system objects, however with a 5 years mission, and asteroids gravitating between Mars and Jupiter, the number of observable asteroids should not be dramatically reduced. Asteroids visibility depends essentially on magnitude and apparent size. The visual magnitude is given by (transactions of the IAU):

$$\left\{ \begin{array}{lcl} V & = & H + 5\log(r\Delta) \\ & & -2.5\log\left\{(1-G)\phi_1 + G\phi_2\right\} \\ \phi_i & = & \exp\left\{-A_i(\tan(\frac{\beta}{2}))^{B_i}\right\} \end{array} \right. \qquad (2)$$

where the slope parameter G depends on the surface properties and i is the phase angle. Assuming a circular orbit of semimajor axis a, the magnitude can be given to the first order in G and i (around G=0.25 and i=0.35) by:

$$\begin{array}{lcl} V & = & H + 5\log(a\cdot\sqrt{a^2-1}) \\ & & -0.44 + 0.52\,G - 2.07\,i \end{array} \qquad (3)$$

In the coherent mode the measured quantity is the phase of the fringes. For an extended source and a given separation between the apertures, the bigger is the source, the lower is the contrast between these fringes. This contrast is proportional to the visibility of the fringes defined as:

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \qquad (4)$$

where $I_{\max}$ and $I_{\min}$ are respectively the maximal and minimal intensity of the fringes.

Table 2: Size limit in coherent mode. For a disk of uniform brightness, a minimal contrast between fringes of 0.58 (to yield efficient modulation of light) and a baseline of 2.45 m, the maximal apparent diameter is given as a function of the effective wavelength of the observation.

$\lambda\,[\mu m]$	0.35	0.5	0.65	0.8
$\rho\,[arcsec] \leq$	0.019	0.027	0.035	0.043

Modulation of light by an amplitude grid or a phase grid is efficient only if this contrast is strong enough. Let C be the contrast and ρ the apparent diameter of the extended source; with B the separation of the interferometer and λ the effective wavelength of observations, we have (for a spherical object of uniform brightness):

$$C \approx \left| \frac{2\,J_1(u)}{u} \right|, \quad \text{with } u = \frac{\pi \rho B}{\lambda} \tag{5}$$

where J_1 is the Bessel function of first order. With a limiting contrast C=0.58, we have u=2; this yields the limit in apparent diameter:

$$\rho \leq \frac{2\lambda}{\pi B} \tag{6}$$

Table 2 gives this value at different wavelengths.

Object with diameter greater than roughly 0.04 arcsec could not be observed in the coherent mode. One should note that this is also true for stars, a nearby giant may have apparent diameter similar to that of some asteroids.

In the coherent mode about 350 minor planets can be observed. Fig. 2 shows the distribution relative to their distance to the Sun, the great majority lies between 2.2 an 3.2 AU. There are however some Hildas and Trojans for whose dynamical studies are of great interest. Due to the scannig law, observation of the near Earth or Earth crossing asteroids is more troublesome and necessitate a simulation of the observations, nevertheless there is little hope to have observations well distributed over the trajectory of such an object.

4.2. Moons

As for minor planets, visibility of the moons depends on magnitude and apparent size, but also on the separation from the attracting planet. To get enough observation opportunities the moon must spend more than half of its trajectory in a region that can not be disturbed by the major planet light. When considering a circular orbit and measurement made by a detector within a disk of diameter D_d, half of the trajectory occurs if the moon's orbital radius is greater than about R_{min}=1.5 (D_d+R_p), where R_p is the apparent radius of the planet. In a first approximation the apparent magnitude depends on the planet distance. Let then V_{lim} be the limit magnitude, a the semimajor axis of the planet, the moon absolute magnitude *V(1,0)* must follow:

$$V(1,0) < V_{lim} - 5\log\left(a \cdot \sqrt{a^2-1}\right)$$

Table 3 gives, for each major planet, the limiting values of orbital radius and absolute magnitude of the satellites.

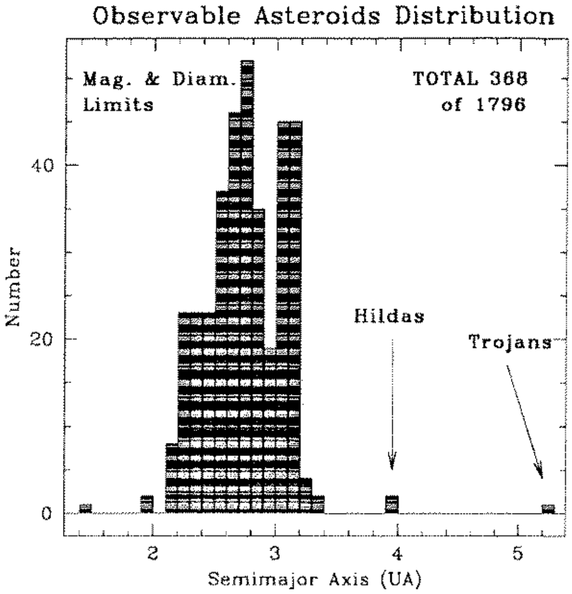

Figure 2: Distribution of observable asteroids

Table 3: Visibility criteria for moons. Minimal orbital radius (R_{min}), maximal absolute magnitude (H_{max}) and diameter (D_{max}) for the satellites. The magnitude refers to the coherent mode and the geocentric distance at quadrature; the maximal diameter is given for a wavelength of 0.5 µm.

Planet	Dist. [AU]	R_{min}. [10^3 km]	H_{max}	D_{max} [km]
Mars	1.7	61	15	33
Jupiter	5	273	9	97
Saturn	10	545	6	195
Uranus	20	698	3	390
Neptune	30	1017	1	585
Pluto	≥ 30	≥ 1017	≤ 1	≥ 585

Table 4 gives the corresponding list of observable moons. With a limiting magnitude of 16, 10 moons could be observed. But if we now consider the size of the natural satellites and take the limiting contrast of 0.58 in equation (4), the only observable moon will be S VII-Hyperion.

5. INCOHERENT MODE

5.1. Minor Planets and Moons

When the non-interferometric mode is used, not only smaller and fainter objects can be observed, but also the biggest asteroids and satellites whose photocenter offset is significant. With a limiting magnitude of 20 and no limitation in diameter, almost all minor planets and moons of Section 4.1. can be observed. Over the 1796 first numbered asteroids, 1794 can be observed. These are essentially asteroids of the main belt; observations of the Kuiper belt objects would require to push the limit in magnitude to 22-24.

If we do not consider observations of natural satellites

Table 4: Visible moons. Observable moons in the coherent mode, after rejection criteria of separation with the attracting planet (column R), limiting magnitude (M) and apparent diameter (D). Limit in size depends on the wavelength and on the affordable contrast of the fringes. For an acceptable contrast greater than 0.58, and observations at 0.5μm, only one natural satellite could be observed: S VII-Hyperion. Legend: (-): not possible, (x) : possible.

Planet	Satellite	R	M	D	Y/N
Mars	Phobos	-	x	x	-
	Deimos	-	x	x	-
Jupiter	Metis	-	-	x	-
	Adrastea	-	-	x	-
	Amalthea	-	x	-	-
	Thebe	-	-	-	-
	Io	x	x	-	-
	Europa	x	x	-	-
	Ganymede	x	x	-	-
	Callisto	x	x	-	-
	Leda	x	-	-	-
	Himalia	x	x	-	-
	Lysithea	x	-	x	-
	Elara	x	-	x	-
	Ananke	x	-	x	-
	Carme	x	-	x	-
	Pasiphaë	x	-	x	-
	Sinope	x	-	x	-
Saturn	Atlas	-	-	x	-
	Promotheus	-	x	x	-
	Pandora	-	-	x	-
	Epimetheus	-	x	x	-
	Janus	-	x	x	-
	Mimas	-	x	-	-
	Enceladus	-	x	-	-
	Tethys	-	x	-	-
	Telesto	-	-	x	-
	Calypso	-	-	x	-
	Dione	-	x	-	-
	Helene	-	-	x	-
	Rhea	x	x	-	-
	Titan	x	x	-	-
→	Hyperion	x	x	x	Yes
	Iapetus	x	x	-	-
	Phoebe	x	-	x	-
Uranus	Miranda	-	-	-	-
	Ariel	-	x	-	-
	Umbriel	-	x	-	-
	Titania	-	x	-	-
	Oberon	-	x	-	-
Neptune	Triton	-	x	-	-
	Nereid	x	-	x	-
Pluto	Charon	-	-	-	-
Total		17	24	20	1

Table 5: Observable moons in incoherent mode

Planet	Satellite	Planet	Satellite
Jupiter	Io	Saturn	Rhea
	Europa		Titan
	Ganymede		Hyperion
	Callisto		Iapetus
	Himalia		Phoebe
	Lysithea	Neptune	Nereid
	Elara		
	Ananke		
	Carme		
	Pasiphaë		
	Sinope	Total	17

close to their attracting planet, the unobservable moon from Table 4 is J XIII-Leda. Table 5 list the observable moons in incoherent mode: these are far from the major planets and do not necessitate any specific reduction or technique. However, observations can be extended to the cases of natural satellites being close to the major planets, by a specific reduction scheme (Vieira Martins & Veiga 1995) or by use of anti-blooming CCD chips (Colas 1995).

5.2. Major Planets

Because of the blooming effect on the CCD chip we should maybe reject observations of the brighter solar system objects (Moon, Mars, Jupiter and Saturn). On the other hand Mercury, being close to the Sun, will not be observable; but with a nominal 55° angle between the satellite's rotation axis and the direction of the Sun, Venus can transit the field of view. We are left then with possible observations of Venus, Uranus, Neptune and Pluto. From the astrometric point of view, these will yield only few positions compared to the orbital periods of the outer planets. However ephemerides of the outer planets are of lower quality than that of the moon or the inner planets; so that such fundamental observations of these planets (and/or of their natural satellites) are of great interest for ephemerides improvement.

6. PHOTOMETRY

The measurements consist essentially in a photons count at different wavelengths, so that valuable photometric information can be obtained from GAIA observations. Photometric data can be extracted from both coherent and incoherent modes. Because one forsees an optimal phase measurement in the coherent mode, the optical bandwidth is determined by the pupil geometry; Lindegren & Perryman (1994) give: $\Delta\lambda/\lambda_{\rm eff} \simeq 1.1\,D/B \simeq 0.25$. In contrast, in the incoherent mode, some of the CCDs chip are equipped with intermediate and narrow-band colour filters; these yield important photometric information in a modified $uvby\beta$+I system.

With a determination of apparent magnitude better than the order of 0.01 mag, very accurate lightcurves can be constructed; moreover the observations being made on a wide range of phase, resulting integral phase curves will improve the knowledge of the photometric parameters of

Table 6: Accuracies of the astrometric positions. Accuracies are given for solar system objects (planet) and for the parallax determination of stars (star). We give values obtained with the Hipparcos mission and those expected for GAIA: in the coherent mode, and in the complementary incoherent mode. All values are in mas.

Hipparcos		GAIA			
Main grid ($V < 12.5$)		Incoherent ($16 < V < 20$)		Coherent ($10 < V < 16$)	
Star	Planet	Star	Planet	Star	Planet
1	5	0.05	(1.5)	0.002	0.01
2	40	0.5	(15)	0.02	0.12

asteroids and moons. Such observations would complement the IRAS mission, yield accurate UBV colours, absolute magnitude and slope parameter.

7. ASTROMETRY

7.1. Accuracy Estimates

As for Hipparcos, we should construct a catalogue of positions where one normal point could be given for each transit in the field of view. With a rotation speed of $\dot{r}$=120 arcsec/s, a star will cross the field of the coherent mode in approximately 30 s and the CCD chips of the incoherent mode in approximately 10 s. For the accuracy of the determined direction we may write (Lindegren & Perryman 1994):

$$\sigma_{\rm coh} \approx F \, \frac{\lambda_{\rm eff}}{2\pi B\sqrt{N}}$$

where N is the number of detected photons and F is a scaling factor which can be taken ≈ 2. At magnitude V=15, taking a throughput of 10m^{2}nm, we will have $\sigma_{\rm coh} \simeq 0.075$ mas; at other magnitudes, the number of photons is given by: $N_1/N_2 = 10^{-0.4\cdot(V_1-V_2)}$.

Accuracy will depend on the contrast between the Young's fringes in the interferometric mode, but mostly on the magnitude of the objects. It should vary between $\approx$0.01 mas and $\approx$0.1 mas for objects brighter than V = 16 mag, so that directions of all solar system objects observed in the coherent mode will be given at a sub-milliarcsec precision level. In the non-interferometric mode, time of transit and precision of a single observation are smaller. When taking a scaling factor $\simeq$15 between the precisions in the two modes, the observed directions are given with precisions ranging from $\approx$1.5 mas to $\approx$15 mas for objects fainter than V = 16 mag; these accuracies are of the same order than that of Hipparcos observations. Table 6 resumes the limiting accuracies obtained for Hipparcos and expected for GAIA.

7.2. Dynamical Reference Frame

Fig. 3 shows the cumulative distribution of the asteroids versus their semimajor axis, after 5 years about 70% of the asteroids have done a complete revolution around the Sun; depending on the actual distribution of the observations on the orbit, this will yield very accurate ephemerides for bodies which predicted positions are still low, and it will by the way enhanced predictions of occultations of stars. Greater precision should also enable one to determine masses of some disturbing asteroids.

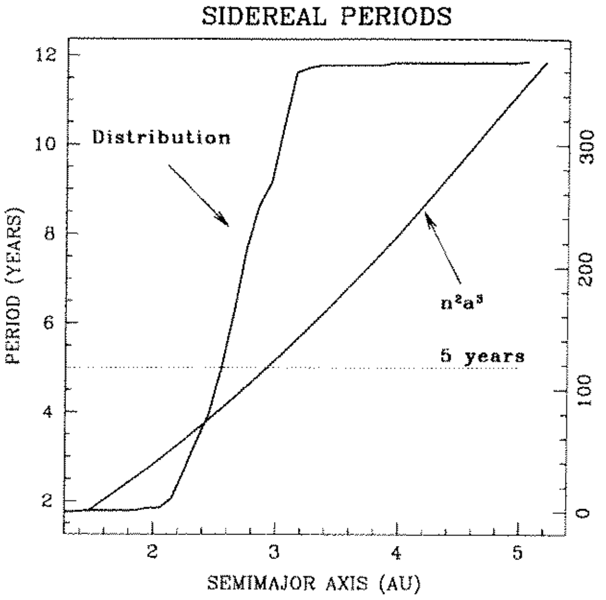

Figure 3: Sidereal periods of asteroids observed in coherent mode

The link of the dynamical reference frame defined by the motion of solar system bodies to the sphere of the stars will be enhanced by the greater precision of the measures, the greater number of reference points and the longer duration of the mission. With a time span of 5 years, secular terms such as the rotation rate will be better determined (particularly when combined with Hipparcos observations). For positions precision a hundred times better than that of Hipparcos, and a number of equations of condition ten times greater, the position of the ecliptic and equinox at a given epoch should be determined with an accuracy of $\approx$10μas.

The distribution in inclination of the asteroids will also strengthen the link of the sphere of the stars and the ecliptic-centered band defined by the asteroids trajectories; Fig. 4 gives an histogram of this distribution. The orbit inclination is greater than 20° for about 80 asteroids observed in the coherent mode, but small bodies observed in incoherent mode should also be used.

8. CONCLUSION

A new step in optical astrometry of solar system objects has been reached by ground-based CCD observations and the Hipparcos mission. While observations by the HST or with a CCD chip are still limited by the small number of reference stars in the field of view, Hipparcos-like measurements yield accurate positions directly related to the reference stars, and this not only in a narrow zone of the sphere. GAIA will provide very accurate positions of a great number of solar system objects. These are small bodies in the coherent mode: asteroids smaller than 0.04 arcsec and S VII-Hyperion.

In the incoherent mode systematic positions (refered to

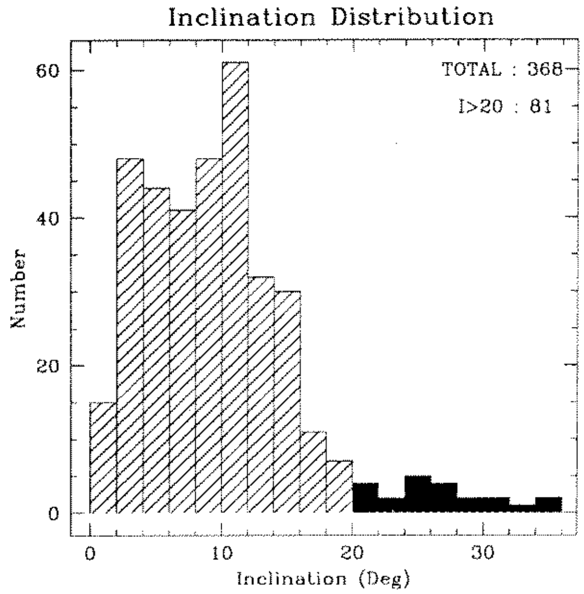

Figure 4: Inclination distribution of asteroids observed in coherent mode

the reference frame of the GAIA stars) can be obtained for about two thousand objects including main-belt asteroids, Trojans and Hildas, many natural satellites and outer major planets. Pushing the limiting magnitude in the incoherent mode would enable us to observe objects from the Kuiper belt. By providing accurate positions of fainter stars, GAIA will also enhance solar system objects observations made during the last decades. These observations wild yield accurate phase curves and some light curves, accurate positions of outer planets, improvement of the ephemerides (especially for small asteroids whose predicted positions are still poor) and improvement of the dynamical reference frame determination.

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