# ASTROMETRIC DETECTION OF EXTRA-SOLAR PLANETS WITH GAIA

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## ABSTRACT

The proposed baseline GAIA mission will be capable to detect the astrometric signature of Jupiter-size planets around half a million stars, using either global or narrow-angle astrometry. If the mission can realize the higher astrometric accuracy photon statistics allows for bright stars, lower-mass planets (from Earth size to ten times larger) can be found around ten to a few hundred stars.

## 1. ASTROMETRIC DETECTION OF A PLANET

The existence of planets around stars other than the Sun has been traditionally one of the 'great questions' of astronomy. The scientific relevance of this question centers on what can be learned about the formation of planetary systems from the statistical properties of a large number of such systems, especially if around stars of different mass, temperature, and age. In this sense, all planets, regardless of their mass and orbital period, are interesting, and the emphasis is in acquiring as large and statistically well-defined sample as possible.

Of course, the interest in the existence of other planetary systems goes beyond pure science. The underlying question—are we alone?—is one of great appeal to scientists and non-scientists alike. From this point of view, inhabitable planets are the most interesting, and Earth-like planets (rocky, massive enough to support an atmosphere, at the right temperature for liquid water) are the prime targets, because of the desire to look for places where humans could live.

Techniques that have been used so far to detect extrasolar planets include astrometric (see, e.g., Gatewood 1987) and radial velocity studies (see McMillan et al. 1994 and references therein). Both involve the detection of the reflex motion of the star with respect to the barycenter of the star-planet system; radial velocity is more sensitive to planets with short orbital times, while astrometry is more sensitive to long period—as long as the orbit is properly sampled in time. Other proposed techniques involve microlensing, the detection of changes in the light curve due to transits of the planet in front of the star, and direct detection of the light emitted by the planet. A detailed summary of direct and indirect detection techniques, their current status and their future possibilities, can be found in the TOPS report (Burke et al. 1993).

If a planet is detected astrometrically, then its mass and orbital parameters can be determined with techniques similar to those used for binary stars (for a full discussion see Bastian & Bernstein 1995). Therefore, all planets identified astrometrically—unlike, for example, microlensing techniques—will have complete information on their orbits, which will prove invaluable for studies of the origin of planetary systems.

To date, the only planet-mass objects confirmed outside the solar system are those revolving around pulsars (see for example Wolszczan & Frail 1992). Because of their peculiar environment, such planets may not be significant in terms of the formation of planetary systems around normal stars, and they certainly do not represent good candidates for (human-like) life.

While there are good reasons to expect that planetary systems may be relatively common, such as the prevalence of binary stars and of circumstellar disks around young stars, there is no confirmed detection to date, even though ground-based astrometric and radial velocity techniques have started to probe an interesting region of parameter space. The negative results are not yet entirely significant, however, since the accuracy reached is comparable to the signal expected, and the sources of error from the ground are numerous. With continuing improvements, it is likely that a few Jupiter-like planets will be found from ground-based astrometric studies in the next few years (see for example Pravdo & Shaklan 1995). Direct detection of giant planets is also possible from the ground in the next 5–10 years (see for example Burrows et al. 1995).

Even so, space-based astrometry with the precision of the GAIA mission concept (Lindegren & Perryman 1995) will push the search for planets into a new dimension. GAIA will improve the astrometric accuracy by a factor 50—possibly more for bright stars; this means a factor 50 in distance, or a factor over $10^5$ in volume surveyed. Instead of a few cases, a few hundred thousand can be studied, making both the statistical properties (if planets are found) or the negative result (if none are) much more significant. Even if the *first* planet around a normal star will be found by some technique other than space-based astrometry, a GAIA-like mission has the potential to find *many* such planets, and thus to provide very valuable information on the statistical properties of solar systems and their formation process.

For simplicity, we restrict the following discussion to the case of a single planet: multiple planets create additional difficulties and increase the parameter space signficantly, so the possibility of multiple planets must be considered in any estimates of detection probability. Nevertheless, it is reasonable to expect that, in the case of multiple planets, one will provide the dominant signature, and the others can be considered as perturbations.

Which signature is dominant depends not only on its maximum amplitude, but also on the time scale of the observations—orbital periods much shorter than the sampling rate will be difficult to detect because of aliasing, and periods much longer than the total mission length will produce near-straight line motion, which will be difficult to separate from the proper motion of the star. In addition, periods very close to one year will be difficult to separate entirely from the apparent motion due to the star's parallax.

In this presentation, we neglect all these complications and consider simply the detection of a well-sampled orbit, without parallax degeneracy, and for a single planet. We consider such an orbit 'detectable' if the amplitude $\alpha$ of the astrometric signature (equation 1) is larger than three times the standard error of the one-year normal point, namely the error accumulated in each coordinate of the star's position in one year of observations. All the additional complications mentioned above can be subsumed into an 'average detection probability', which will be a function of amplitude of the signature, orbital period, and mission parameters, and will reflect an average over properties such as ecliptic latitude (which determines the sampling law and the shape of the parallax ellipse), orbit inclination, eccentricity, and phase, and any other parameters that may be required to specify the orbit of the planet. We adopt the $3\text{–}\sigma$ requirement to ensure that the 'average detection probability' be reasonably large, at least for well-sampled periods. A detailed study of the actual detection probability, including a realistic scanning law, measurement errors, and random orbit orientation is under way.

## 2. NARROW ANGLE VS. GLOBAL ASTROMETRY

A global survey mission consists of measurements of stellar positions in a global reference system. With a design such as GAIA's, each measurement will be in essence unidimensional, since the coordinate along the scan direction is measured with much higher accuracy than the coordinate perpendicular to the scan. The full two-dimensional information results from combining a number of independent scans with different orientations. The astrometric signature of a planet can be recovered by modeling the position variation it would produce on individual scans, similar to what has been done for binary stars in Hipparcos data (see Bastian & Bernstein 1995).

The accuracy of individual position measurements depends on both the knowledge of the relative position of all optical elements, such as the baseline of each interferometer, and on how accurately the fringe center can be measured in the focal plane. The former depends on accurate position control and, presumably, on high precision metrology; the latter is a function of the star's brightness. For luminous stars, the metrology may set the ultimate limit to the global positional accuracy in each measurement. In this case, it is useful to explore the possibility of searching for planets with 'narrow angle astrometry' techniques, which rely on the determination of a star's position *relative* to other stars in the same field of view. This measurement is less sensitive than global ones to metrology errors, because each interferometer is seen as a single telescope and precise knowledge of its orientation with respect to the other interferometers is not required. A few necessary instrumental parameters, such as the instantaneous plate scale, can be determined by bootstrapping from the global solution using an ensemble of stars, and thus with higher accuracy than the position of a single star.

The narrow angle approach is possible with a mission such as GAIA because of the large number of stars present in a field of view—an average of about 1000. Even if only 10% of these stars can be used to determine an average reference frame—because of binaries, stars too far away within the field of view, and so on—we estimate that the instantaenous reference frame can be determined with an accuracy of about 12 $\mu$as, comparable with the global accuracy obtained with a baseline metrology error of 150 pm (metrology accuracy and its effect is discussed in Section 3.2 below).

The remainder of this document is concerned mostly with the global astrometry approach, which promises better results when very high accuracy is required. It is useful to keep in mind, hovever, that, even in the case of metrology significantly worse than our worst-case approach, very good results can be achieved in the field of planetary search, especially for Jupiter-like planets.

## 3. MEASUREMENT ACCURACY

### 3.1 Basic assumptions

The error of each positonal measurement is the combination of the error in the measurement of the fringe position and of the error in the knowledge of the effective baseline, which determines how the fringe position in the focal plane translates into an angle on the sky. Within the current GAIA concept, three interferometers are used, and their relative orientations (the 'basic angles') are expected to be known to very high accuracy. In practice, the necessary (sub-nm) accuracy will probably be reached by a combination of active control and laser metrology. Without entering into the details of how such a goal can be achieved, we consider the following simplified model: one of the three interferometers, called the 'reference' interferometer, is used to determine the instantaneous attitude of the on-board reference system, which is controlled with laser metrology, and the orientation of the effective baselines of the other two interferometers is therefore known with an accuracy given by the 'baseline error', due to combined metrology errors on both reference and science interferometers. This model is adopted for simplicity only; the satellite actually measures a large number of angles between stars, and the instantaneous position of the satellite can be reconstructed *a posteriori* from the global solution. Within this simplified model, it is appropriate to neglect the uncertainties in the baseline orientation arising from uncertainties in the stellar positions.

### 3.2 Metrology error

What is a likely figure for the metrology error? Both the OSI team at JPL (Gürsel 1993) and the POINTS team at CfA (Noecker et al. 1993, Noecker 1995, Reasenberg et al. 1995) have reported picometer level accuracy in relative measurements in a laboratory setting, where the limitation is fluctuations in air density in the path of the metrology laser beam. Such accuracy has ben reached over short (few wavelengths) variations in path length, which are appropriate to the GAIA design if a good active thermal control is included. (For comparison, Michelson designs such as POINTS and OSI need to measure accurately much longer path lengths, because of the delay lines involved.) An additional advantage of the GAIA design is that only variations over short time scales need to be monitored; thanks to $2\pi$ closure, the instrument self-calibrates over time scales of order of the spin period.

However, the few pm error quoted refers to the precision and stability of a one-dimensional laser gauge measurement of a single optical path. Maintaining the accuracy of the interferometer baseline is much more complex, first, because the three-dimensional position of many optical elements needs to be monitored simultaneously, and second, because of the possible differences between the optical path of starlight and of the laser gauge beams. Noecker (1995) lists a number of possible systematic errors for the POINTS mission concept. A similar study has yet to be carried out for the GAIA mission concept, but it is likely that controlling the interferometer baselines to a similar accuracy will prove similarly complex. Furthermore, pm level metrology has not been demonstrated in space, and therefore it would be overly optimistic to base our expectations on the best numbers obtained in a laboratory setting. Nonetheless, a total figure of 250 pm for the total baseline error, as defined above, can most likely be achieved without excessive difficulty; we will refer to this case as 'standard metrology'. A baseline error of 250 pm translates into a positional error of about 20 $\mu$as on a single measurement.

We consider also the possibility, not unlikely at this stage, of metrology which is 5 times more accurate, reaching an effective baseline error of 50 pm, corresponding to an angle error of 4 $\mu$as; this case will be called 'accurate metrology'. Finally, we will briefly consider a best-case scenario in which metrology accuracy is improved by an additional factor of 10, to an effective baseline error of 5 pm; this will require major developments in the field, but it is the only case in which a few Earth-like planets can be detected (see Section 5.3).

### 3.3 Photon noise and fringe measurement

Once the interference fringe is detected, either directly or through some form of grid modulation, its position with respect to the reference frame of each interferometer determines the 'position' of the star. Any uncertainty in the measurement of the 'fringe position' (in practice, this may mean its centroid, center of symmetry, or some other fiducial quantity) reflects directly into an error in the measured position of the star.

If the fringe is properly sampled, the accuracy with which its position can be measured is shown by Lindegren (1978) to be $\epsilon = \lambda/(4\pi x_{\rm rms}\sqrt{N})$, where $x_{\rm rms}$ is the rms size of the aperture in the measurement direction. For two circular apertures of diameter $D$ and with a central separation $B$, we have $x_{\rm rms} = \sqrt{(B/2)^2 + (D/4)^2}$; for the baseline GAIA parameters ($B = 2.45$ m, $D = 0.55$ m), $x_{\rm rms} = 1.23$ m (Lindegren & Perryman 1995). For $\lambda = 550$ nm, this translates into a theoretical measurement accuracy of 7.3 mas$/\sqrt{N}$.

Table 1: Single-observation positional error in the scan direction

| $V$ (mag) | Single-measurement error: Photon only ($\mu$as) | Single-measurement error: 250 pm metr ($\mu$as) | Single-measurement error: 50 pm metr ($\mu$as) | Single-pass error: 250 pm metr ($\mu$as) | Single-pass error: 50 pm metr ($\mu$as) |
|---|---|---|---|---|---|
| 0 | 0.100 | 20.0 | 4.00 | 6.32 | 1.26 |
| 1 | 0.159 | 20.0 | 4.00 | 6.32 | 1.27 |
| 2 | 0.251 | 20.0 | 4.01 | 6.32 | 1.27 |
| 3 | 0.398 | 20.0 | 4.02 | 6.33 | 1.27 |
| 4 | 0.631 | 20.0 | 4.05 | 6.33 | 1.28 |
| 5 | 1.00 | 20.0 | 4.12 | 6.33 | 1.30 |
| 6 | 1.59 | 20.1 | 4.30 | 6.34 | 1.36 |
| 7 | 2.51 | 20.2 | 4.72 | 6.37 | 1.49 |
| 8 | 3.98 | 20.4 | 5.64 | 6.45 | 1.78 |
| 9 | 6.31 | 21.0 | 7.47 | 6.63 | 2.36 |
| 10 | 10.0 | 22.4 | 10.8 | 7.07 | 3.41 |
| 11 | 15.9 | 25.5 | 16.4 | 8.07 | 5.17 |
| 12 | 25.1 | 32.1 | 25.4 | 10.2 | 8.04 |
| 13 | 39.8 | 44.6 | 40.0 | 14.1 | 12.6 |
| 14 | 63.1 | 66.2 | 63.2 | 20.9 | 20.0 |
| 15 | 100. | 102. | 100. | 32.2 | 31.6 |
| 16 | 158. | 160. | 159. | 50.5 | 50.1 |
| 17 | 251. | 252. | 251. | 79.7 | 79.4 |
| 18 | 398. | 399. | 398. | 126. | 126. |
| 19 | 631. | 631. | 631 | 200. | 200. |
| 20 | 1000 | 1000 | 1000 | 316. | 316. |

However, this optimal measurement accuracy can only be achieved in the monochromatic case. For a filter bandpass of 150 nm, the optimal measurement accuracy is about 12.0 mas/$\sqrt{N}$, or a factor 1.6 worse. In addition, some accuracy will be lost as a consequence of sub-optimal sampling in the focal plane (grid modulation, finite pixel size); it is likely that this process will cause an additional loss in accuracy of 20–40%. In the following, we assume a single-measurement accuracy of 16 mas/$\sqrt{N}$.

The number of photons detected depends on the magnitude of the object, the filter used, and the total system efficiency. In the following, we assume a filter somewhat wider than Johnson $V$ and a total system efficiency of 20%. These numbers should be indicative of realistic expectations for the system, and can be easily rescaled to different assumptions. The monochromatic flux equivalent of a zero magnitude object in Johnson $V$ is $3.80 \cdot 10^{-9}$ erg cm$^{-2}$ s$^{-1}$Å$^{-1}$, which, at 5500Å, corresponds to 1045 photons cm$^{-2}$ s$^{-1}$. At $V = 15$ mag, with a total collecting area of 4750 cm$^2$ (2 apertures of 0.55 m diameter each), an effective filter width of 160 nm (corresponding to a Gaussian of FWHM 150 nm), and an efficiency of 0.2, this corresponds to about 1585 photons s$^{-1}$. With a spin period of 2 hours and an effective field of view of 0.8 deg, each individual integration lasts about 16 s, for a total of 25,400 photons per pass at $V = 15$ mag. Thus, the single-pass accuracy of the measurement of the fringe position will be 100 $\mu$as at $V = 15$ mag. This number becomes 10.0 $\mu$as at $V = 10$ mag, and 1.00 $\mu$as at $V = 5$ mag. The single-measurement error due to photon noise becomes comparable to the metrology error at $V = 11.5$ mag for 'standard' metrology, and at $V = 8.0$ mag for 'accurate' metrology.

### 3.4 Total positional error; one-year standard point

With a scanning law similar to that used by Hipparcos, each star will be visible in an average of 5 consecutive scans, in each of which its position will be measured twice (by the two 'science' interferometers). The total positional error in each observation—which is taken to include a set of consecutive scans in which the star is present—will then be the combination of the metrology and the photon error, divided by $\sqrt{10}$. Table 1 summarizes the total single-observation error expected as a function of apparent magnitude for both standard (250 pm) and good (50 pm) metrology.

The error in the one-year standard points depends on the number of observations per year, which is a function of the ecliptic latitude: stars at high ecliptic latitude are observed more often. We assume a minimum of 6 observations per year. The error in each coordinate should then be approximately $\sqrt{2/6} = 0.58$ times the single-observation error (the $\sqrt{2}$ at the numerator takes into account that each observation is one-dimensional, but two coordinates must be measured). The actual error will be somewhat larger, because of the errors in the measured parallax and proper motion; the contribution of these terms varies, and will impact the accuracy on different time scales in a different way. We adopt a factor 0.8 as a reasonable compromise. Therefore we estimate the error in the one-year normal points to be 0.8 times the error listed in Table 1, probably a conservative estimate especially at high ecliptic latitude.

## 4. PLANET DETECTION

Let us try now to estimate the number of stars around which a planet of given characteristics can be found, if they had such a planet. Since there is no guarantee that stars possess planets of given characteristics, we refer to such stars as 'candidate' stars. One of the advantages of a survey mission is that all stars within a given range of properties can be searched for planets; if the number of candidates is large, the probability of finding a planet increases even if such planets are rare. For example, we will find that the number of candidate stars for Jupiter-like planets is in the hundreds of thousands; if Jupiters are rare, as some initial ground-based results seem to suggest, then the ability to search a very large number of stars is extremely important. Even if planets are relatively common, having a significant number of detections, each with full orbital information, will be very useful in testing theories of planetary formation.

We consider in the following three basic types of planets: 'Jupiter-like', which have mass and orbital period comparable with Jupiter; 'big Earth', which have orbital period like the Earth but a mass ten times larger, comparable to the rocky core of Jupiter; and 'Earth-like', which have both mass and orbital period comparable to the Earth's. Jupiter-like planets have the largest astrometric signature and are easiest to find; Earth-like have an astrometric signature smaller by a factor 1500, and are very difficult to find. Big Earths are hard to find, but not as hard as true Earth-like planets.

### 4.1 Astrometric signature and maximum detection distance

The astrometric signature $\alpha$ of a single planet of mass $m_p$, orbiting at a radius $r_p$ from a star of mass $m_s$ which is at a distance $D$ from the Sun will be

$$\alpha = \frac{m_p r_p}{m_s D} \,\mathrm{arcsec} = 2.94 \frac{m_p}{m_\oplus} \frac{m_\odot}{m_s} \frac{r_p}{D} \,\mu\mathrm{as}\,, \qquad (1)$$

where the orbit is assumed circular (the maximum correction for an eccentricity $e < 0.3$ is less than 5%), $r_p$ is measured in AU, and $D$ is in pc.

For a given system, the astrometric signature decreases with increasing distance, while the measurement error increases as the star becomes fainter with increasing distance; thus we can define the 'maximum detection distance' $D_{\mathrm{max}}$ as the maximum distance at which the 3-$\sigma$ condition for detection is fulfilled.

Explicitly, given masses of star and planet, orbital radius, and absolute magnitude $M_V$ of the star, the maximum detection distance $D_{\mathrm{max}}$ is the solution for $D$ of the equation

$$2.94 \frac{m_p}{m_\oplus} \frac{m_\odot}{m_s} \frac{r_p}{D} = 3\, \frac{0.8}{\sqrt{10}} \left\{ \left[ 100\,(D/10) \cdot 10^{0.2(M_V - 15)} \right]^2 + \sigma^2_{\mathrm{metr}} \right\}^{1/2}, \qquad (2)$$

where the left-hand side is the astrometric signature $\alpha$, and the right-hand side is thrice the error in the one-year normal point (both in $\mu$as), assuming a single-measurement error of 100 $\mu$as for a star with $V = 15$ and a single-measurement metrology error $\sigma_{\mathrm{metr}}$. The factor $0.8/\sqrt{10}$ effects the conversion from single-measurement error to one-year normal point, as discussed in Section 3.4. In the following, we have assumed a relation between mass and absolute magnitude typical of main-sequence stars; a different relation must be used for other evolutionary stages (giants, white dwarfs, etc).

### 4.2 Planet properties for non-solar-mass stars

While 'Earth-like' and 'Jupiter-like' planets can be defined unambiguously for stars like the Sun, the extension of these definitions to stars with mass (and luminosity) different from the Sun is ambiguous. For example, the planet's mass can be kept constant either in physical units or as a fraction of the mass of the central star; the latter implies constant amplitude of the astrometric signature, and, depending on how planets form, may well be more realistic. Similarly, as the mass of the central star changes, either the orbital radius or the period (but not both) can be kept constant; or it is possible to keep constant some combination of the two, in order, for example, to preserve the equilibrium temperature of the planet. The latter may well be the relevant combination in terms of physical properties of the planets, since it has been suggested that a specific temperature range is associated with the formation of gas giants.

In order to explore a variety of possibilities, we consider three cases: constant $m_p$ and $R$; constant $m_p/m_s$ and $R$; constant $m_p/m_s$ and $P$. The conclusions remain much the same for all three cases.

## 5. NUMBER OF CANDIDATE STARS

The total number of candidate stars for each set of planet properties can be determined by estimating the total number of stars which are closer to us than the maximum detection distance, as defined by their absolute magnitude. For distances larger than 20 pc, this can be done statistically, using the known luminosity function of nearby main sequence stars, which we take from the IAS Galaxy Model (Bahcall et al. 1987). This luminosity function is derived from those of McCuskey (1966) and of Wielen et al. (1983), with suitable separation into evolutionary sequences and density components. It has been used to represent successfully the observed properties of many different observations of nearby and distant star samples. It is certainly adequate for the present purpose. The mass-luminosity relation is taken from that tabulated in Mihalas & Binney (1981). For distances smaller than 20 pc, the average stellar density predicted from the luminosity function should be replaced with the actual stars found, for example, in the Gliese (1969) catalog, or from the revised sample of nearby stars derived from Hipparcos (Perryman et al. 1995). However, actual stars cannot properly be used unless the dependence of the detection probability on ecliptic latitude is assessed, and this information will only be available after the full simulation of the planet search. Therefore, in this exploratory study we consider only the average stellar density as determined from the luminosity function.

### 5.1 Case 1: Jupiter-like planets

Jupiter-like planets have a relatively large astrometric signature—500 $\mu$as at 10 pc for a solar mass star. With 'standard' metrology, Jupiter-like planets can be detected to over 200 pc for solar-type stars; this is the maximum detection distance for constant planet mass (see Fig. 1).

*Figure 1. Maximum detection distance (left) and number of candidate stars (right) for Jupiter-like planets. The three lines refer to the different cases identified in Section 4.2.*

For example, a solar mass star has $V \sim 11$ mag at 200 pc, thus an error on the one-year normal point of $\sim 7$ $\mu$as; at that distance, the astrometric signature is about 25 $\mu$as, over three times the one-year normal error. For constant $m_p/m_s$, the detection distance increases to 300 pc for very massive stars. With 'good' (50 pm) metrology, the maximum detection distance remains pretty much the same for all but the most massive stars.

The total number of candidate stars is $\sim 5 \cdot 10^5$ (Fig. 1), regardless of whether the planet mass or the mass ratio is held constant. This number may be slightly overestimated, by about 20%, because of the assumption of constant stellar density away from the galactic plane. The very large number of candidate stars promises a very clear answer to the question of how common Jupiter-like planets are, and what is the distribution of their properties with respect to those of the central star. The detection margin is large enough that numerous multiple-planet cases should be observable as well.

### 5.2 Case 2: Big-Earth planets

This case is somewhat artificial, and is included to bridge the gap of three orders of magnitude between between the astrometric signatures of Jupiter-like and Earth-like planets. We consider planets of 10 Earth masses at 1 AU from a solar-mass star, suitably rescaled for stars of different mass. The astrometric signature at 10 pc is about 3 $\mu$as, a factor of 150 less than for Jupiter-like planets. As a consequence, such planets can only be detected around only nearby stars. Since such stars are typically (apparently) bright, the metrology error is an important part of the total measurement error, and thus the quality of the metrology is crucial in determining the detectability of such planets.

The maximum detection distance is very small in the case of 'standard' metrology; very few candidates would be found in that case. With 'good' metrology, however, the maximum detection distance increases to about 10–12 pc, depending on the assumptions used, and of order of 100 candidate stars can be found (Fig. 2).

### 5.3 Case 3: True Earth-like planets

The considerations made for big-Earth planets apply *a fortiori* to true Earth-like planets. Even with good metrology, such planets, which have an astrometric signature 10 times smaller than big-Earths, cannot be detected beyond 1–2 pc, and therefore no suitable candidates exist. Is it possible to push the accuracy limits further, and detect a (small) number of Earth-like planets?

*Figure 2. Maximum detection distance (left) and number of candidate stars (right) for Big Earth planets. The three lines refer to the different cases identified in Section 4.2.*

As discussed in Section 3.2, laboratory experiments suggest that laser gauges can in fact achieve picometer-level accuracy. A comparable baseline accuracy, while certainly not easy, may not be out of the question with careful instrument design. Therefore the calculations for the Earth-like case have been repeated assuming super-accurate metrology, 10 times better than the 'good' metrology above, corresponding to an equivalent baseline error of 5 $\mu$m (Fig. 3). At this level, a large number of other systematic effects may appear and limit the accuracy of individual measurements (Noecker 1995). Reasenberg et al. (1995) show, from a detailed design analysis of the POINTS mission concept (with baseline similar to GAIA), that the systematic errors can probably be controlled to the $\mu$as level, which is what is required to allow the precision necessary to detect Earth-like planets. While we cannot be certain that the same study can be applied to GAIA, it is at least plausible that most of the metrology gain will be reflected in a more accurate baseline.

With super-accurate metrology, the maximum detection distance for Earth-like planets increases to about 6 pc for solar-type stars. On the basis of the average stellar density as determined from the luminosity function, about 10 candidate stars are expected (see Fig. 3), all apparently bright ($V$ = 3–7 mag). We do not use individual stars from the Gliese (1969) catalog because we do not know how to account for the dependence of sensitivity on ecliptic latitude.

On the basis of these considerations, detection of a small number of candidate Earth-like planets appears possible, with sufficient interest and expenditure of technical effort.

## 6. DISCUSSION

It is clear from the above discussion that the current GAIA mission concept (Lindegren & Perryman 1995) will be able to detect Jupiter-like planets around almost a million candidate stars. Detection also implies full knowledge of the orbital parameters. This exceeds the likely output of any existing or proposed program, regardless of the technique employed, and will generate invaluable data on the frequency, formation, and properties of planetary systems around normal stars.

Detection of less massive planets will require special attention to the baseline accuracy of the mission. Good metrology (at the 50 pm level) is required to detect planets of 10 Earth masses orbiting at 1 AU from a star some 10 pc away; a few tens of candidate stars can be found. Very accurate (5 pm) metrology appears to be required for detection of a few true Earth-like planets.

While these results are still preliminary and await a full study of the planet detection process, they clearly indicate the double strength of a high-accuracy survey mission like GAIA: the ability to find *many* objects of the Jupiter class, and a few objects requiring extremely high accuracy. They also indicate the need to place the appropriate emphasis on metrology development and baseline control in order to realize the full potential accuracy for bright targets.

*Figure 3. Maximum detection distance (left) and number of candidate stars (right) for Earth-like planets. The three lines refer to the different cases identified in Section 4.2.*

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