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# QSO observations with Gaia: principles and applications

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**Abstract.** The European space astrometry mission Gaia aims to produce a complete sky survey down to $V = 20$ with an astrometric accuracy of 25 $\mu$as at $V = 15$. During its 5-year mission the satellite will also repeatedly measure the position of $\sim$500,000 quasars in a consistent way, leading to a direct realisation of the primary inertial frame in the visible in the framework the ICRS concepts. At $V = 20$ the sky density of the QSOs is about 1000 times smaller than that of the stars at mid galactic latitude. Given their number and their stellar-like images, this implies the construction of an automatic recognition scheme of the non stellar sources with a sensitivity of the order of one part in a thousand. In this paper I discuss the estimation of the number of extragalactic point sources observable by Gaia and the expected performance for the realisation of the reference frame.

**Key words.** Quasars – Astrometry – Gaia

## 1. Introduction

Gaia will provide astrometric and photometric observations of a large set of quasars (QSOs) at $G < 20$ mag over the whole sky, typically four times larger than the number released from the Sloan Digital Sky Survey (but in this case with spectra). This will be the first all-sky, flux-limited survey to $V = 20$ of the extragalactic compact sources.

The internal photometric detection has been shown on simulated data very efficient to get rid of the traditional contaminants like the white dwarfs or very red stars. Final filtering with astrometry (parallaxes and proper-motions of these stars will be large and not compatible with extragalactic sources) will end up with a clean set containing nearly only extragalactic sources (Bailer-Jones 2008). Simultaneously photometric redshift measurements will be feasible without additional effort for most of the detected sources. Thus one may reasonably expect a census of several hundreds thousands quasars at galactic latitudes $|b| > 25° - 30°$, although these limits are not precisely known today. Closer to galactic plane, Gaia faces two difficulties: (i) the galactic extinction and reddening that will block off the light of these distant and rather faint sources, (ii) the difficulty to discriminate between the stars as their relative density to that of the quasars increases drastically at low galactic latitudes (this ratio is about 10,000 at $b = 10°$ and $G = 19$). Multi-images formed by lensing of intervening galaxies could be de-

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tected at separation as small as ∼ 0.2 arcsec, a significant improvement to the resolution of current ground based investigations with nice inferences in the distribution of distant galaxies.

Finally the extensive zero-proper motion survey will provide a direct realization of the quasi-inertial celestial reference frame in optics with a residual rotation less than 0.5 $\mu$as per year and an easy access for the user given the space density achievable. Many more secondary sources (stellar or extragalactic) will also facilitate the access to this frame over a wide range of magnitude.

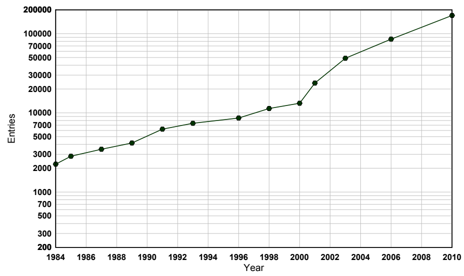


**Fig. 1.** Evolution of the number of known QSOs and AGNS over the recent years, shown as the number of entries in the successive versions of the Catalogue built by Véron-Cetty & Véron (2010). spray

## 2. Number of QSOs with Gaia

Back to the scientific proposal of Gaia, numbers of the order of 400 000 QS0s have been quoted as the probable size of the QSOs survey achievable with Gaia during its five-year mission. At this time, around year 2000, this was much larger than the largest data base available, coming primarily from the compilation made by Véron-Cetty & Véron (1998) giving about 13 000 extragalactic star-like sources. So the power of Gaia as a celestial measuring machine was amazing, but at the same time this big progress raised the issue of how to recognise these sources, given their very star-like appearance on the sky. Thanks to the successive releases of the 2DF survey (Croom et al. 2004) and of the SDSS (Abazajian et al. 2009), the total number of recognised QSOs and AGNs has steadily increased over the last ten years. The Large Quasar Astrometric Catalogue (Souchay et al. 2009) comprises nearly 114 000 quasars and integrates the 6th release of the SDSS[1], while the latest version of the Véron-Cetty & Véron (2010) includes 168 000 entries of Quasars and AGNs up to $V \approx 21.5$ taking into account the 7th SDSS release. This trend is shown in Fig. 1 with the number of entries of the 13 successive versions of the Quasar and AGN catalogue published over the years by Véron-Cetty & Véron.

The sky distribution of the known sources in these compilations is very irregular as illustrated in Fig. 2, just because no full-sky survey is yet available. Given their extragalactic nature, the overall distribution should be rather uniform, even though the optical observations in the galactic plane will leave a large empty gap for ever. The scatter plot is shown in galactic coordinates and one sees clearly the concentration in the vicinity of galactic poles, in addition to few very local, and deep, surveys at low declination. Assuming the local surveys are completed to $V = 20.5$, the maximum of the local concentration over a large enough area, can be used to estimate the luminosity function of the QSOs and then predict how many will be observed by Gaia outside the galactic plane, typically where $|b| > 25°$.

While simple in principle, the difficulty is to devise a robust way to estimate the surface density of QSOs from this data. The sky can be divided up into equal-area cells, or any other form of convenient pixelisation, provided the area of each cell can be easily established. Then one counts how many sources fall in each cell up to a certain magnitude. If the deep surveys have an extension larger than the cell size, it suffices to look at the cells with the largest numbers to assess the space density. But for too large areas, this will underestimate the actual density, since the local surveys will have an extension smaller than the cell area, while if the cells are too small, very local concen-

[1] A new version with 180 000 sources has been issued in 2012 (Souchay et al. 2012), after the analyses presented here have been completed

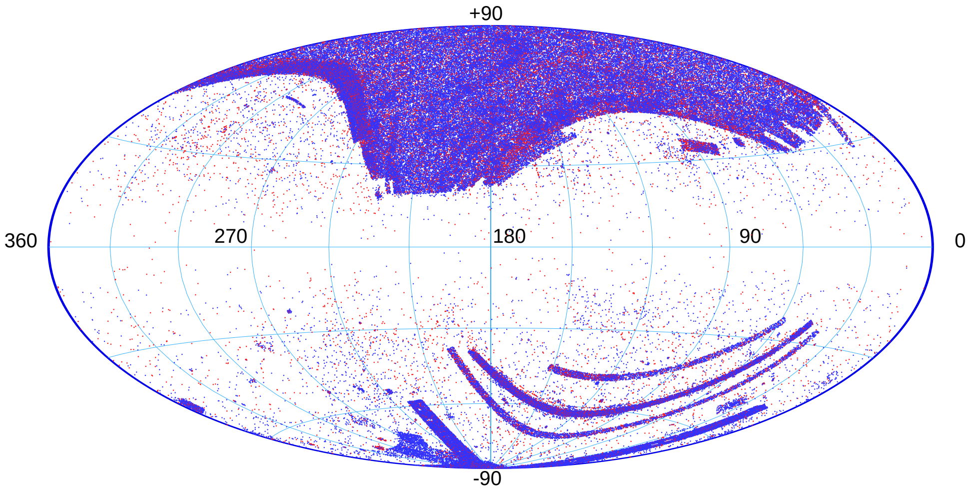


**Fig. 2.** Space distribution up to V = 21 of the ≈ 170 000 compact sources in the catalogue of Véron-Cetty & Véron (2010). The blue dots refer to QSOs and the red to AGNs, as they are defined by the authors. Local surveys around the galactic poles are prominent in this plot and used in this paper to estimate the luminosity function.

tration, not representative of the actual density will show up. In addition undesirable statistical effects from handling small numbers will make this method sensitive to outliers. I try to find a compromise between the two by plotting the observed surface density for all the sources brighter than $V_{max}$ and reading in the plot the largest, more or less regular, densities. This avoids the chance effects of spotting locally, on very small areas, very large densities. An example of this method is shown in Fig. 3, for $V_{max} = 20$, in which case I have retained a density of 22 sources/deg$^2$, although the largest density found in the data is about twice than number.

Producing similar plots for various maximum magnitudes yields the surface densities listed in Table 1 for sources up to the V magnitude given in the first column. Then the other columns give the number of sources expected on the whole sky, assuming isotropy, followed by the number observable by Gaia outside the galactic plane, the number of sources found in Véron-Cetty & Véron (2010) and the expected discoveries with Gaia. The last column is given for comparison with an earlier work by Slezak & Mignard (2007), used to generate the simulated catalogue of extragalactic point sources for the DPAC Universe Model. To read this column properly, the first column must be read as the G magnitude instead of V. Although not in full agreement, the figures in col. 3 and last column are rather similar and within the uncertainty due to the method used to determine the surface densities from local surveys. Given the steep rate of growth as a function of the limit magnitude, the difference between the two magnitude scales is also a sensitive factor. Finally it seems reasonable to expect at the end of the Gaia mission a catalogue of compact extragalactic sources around 30 to 40 000 for $V < 18$ and between $5 - 7 \times 10^5$ for the survey to $V = 20$, in which 80% will be new catalogued sources.

– The orientation is just a matter of convention to set the pole and the origin of the right ascensions in the equatorial plane. This has no deep physical meaning, if any at all. As always in metrology, we will endeavour to maintain the best continuity

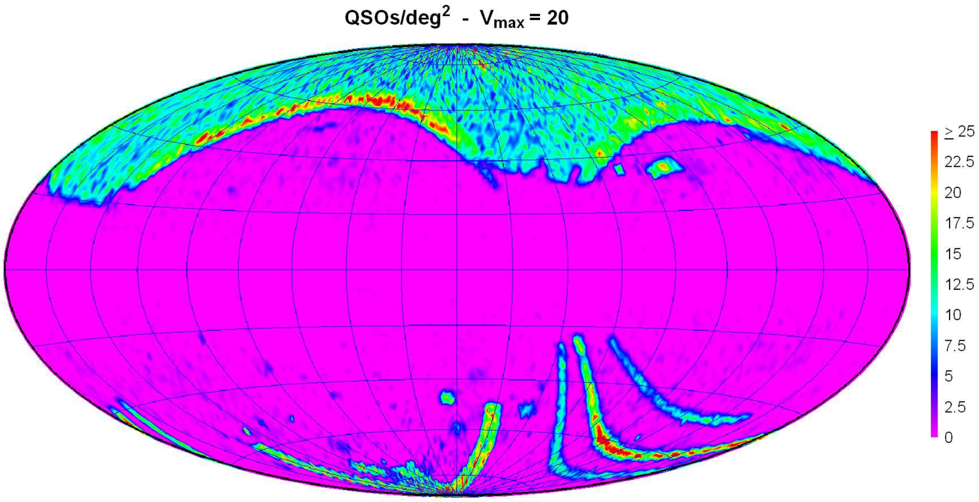


**Fig. 3.** Space density in galactic coordinates of QSOs in the current largest compilation, including the latest release of SDSS, for sources brighter than $V = 20$. Local deep surveys near the galactic poles indicates the typical space density one can expect for this magnitude and applicable to the full sky. Here this is about 22 QSOs per square degree.

with the ICRF by ensuring that the orientation of the Gaia-CRF triad is the same as the ICRF, within the uncertainties of either realisation or their combination. A set of extragalactic sources with good astrometry in the ICRF (not necessarily ICRF sources) and observed by Gaia will be selected to align the two frames. For details on how this selection is done in practice, see the paper by G. Bourda in this volume. It is important to notice that Gaia will observe the optical counterparts of the extragalactic sources detected and measured in radio bands in the ICRF frame, and that for a given source, they are not necessarily coincident. The possible systematic offset between the two positions will be closely investigated.

– The spin, or residual rotation, has much more physical significance since it is the way the Gaia-CRF will be turned into a kinematically non-rotating reference system. The ICRF paradigm is based on the fact there is a frame in which very distant extragalactic sources have no global rotation. By definition this frame is considered to be kinematically non-rotating. Its link to the inertial frame realised by applying the equations of motion to solar system objects has so far shown than the two have no relative rotation. Using the direct observation in the visible of $10^4$ – $10^5$ quasars or point-like galactic nuclei, and applying the constraint of non global rotation to their astrometric solution, will allow to determine the rotation $\omega$ and put the Gaia astrometric solution into this non-rotating frame. The expected accuracy of the residual rotation, or equivalently the default of inertiality of the final Gaia frame, is shown in Fig. 5, as a function of the $G$ magnitude of the faintest sources that might be selected. One sees that with the assumption that these extragalactic sources have no astrometric instability over short timescale, one could achieve a final accuracy in the frame rotation of the order of 0.2 $\mu$as yr$^{-1}$. Being more conservative by considering just a core of bright defining sources and allowing for a loss of 50%

**Table 1.** QSO surface density and luminosity function. The table gives as a function of the V magnitude, the surface density computed from a robust estimate based on the largest densities found in Véron-Cetty & Véron (2010). Then the total number expected on the sky, 60% from the coverage achievable with Gaia outside the galactic plane ($|b| > 25$deg), the number of known sources and the expected number of discoveries with Gaia. The last column gives for comparison the total number of sources in the sky in the simulated catalogue (full sky) Slezak & Mignard (2007) constructed with the SDSS 5th release. Here the first column must be interpreted at the G magnitude instead of V.

| V | density $\deg^{-2}$ | Full sky # | 60% sky # | known # | new # | Slezak et.al # |
|---|---|---|---|---|---|---|
| 18.0 | 1.5 | 63 000 | 38 000 | 12 500 | 25 500 | 40 000 |
| 18.5 | 3 | 126 000 | 75 000 | 23 000 | 52 000 | 113 000 |
| 19.0 | 8 | 340 000 | 200 000 | 45 000 | 155 000 | 314 000 |
| 19.5 | 15 | 630 000 | 380 000 | 85 000 | 295 000 | 680 000 |
| 20.0 | 22 | 920 000 | 550 000 | 115 000 | 435 000 | 1 200 000 |
| 20.5 | 30 | 1 260 000 | 750 000 | 140 000 | 610 000 | 1 700 000 |

of unsuitable sources (anomalous residuals due to internal motions affecting the photocentre direction over short timescales), we can safely say that the inertiality should be as good as 0.5 $\mu$as yr$^{-1}$.

## 3. Gaia Reference Frame

### 3.1. Principles and accuracy

The measurement principle in global space astrometry, and in particular for Gaia, leads to a system of positions and proper motions in a reference frame relatively free in orientation and spin. Without further constraint its orientation and spin are linked to the reference catalogue used to linearise the observation equations and determine the satellite attitude (Lindegren et al. 2011). Given the Gaia procedure, this will be very close to the existing ICRF (Fey et al. 2009), but the offset, both in orientation and spin, although small, must be determined by adding external constraints. The orientation and the spin are in this respect quite different from each other and must be examined separately.

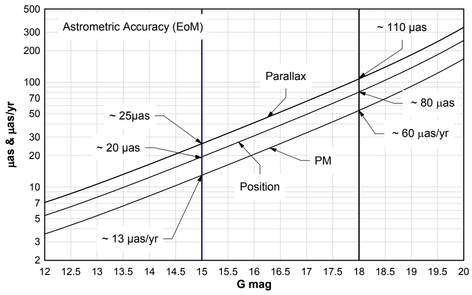


**Fig. 4.** Nominal astrometric accuracy achievable with Gaia at mission completion for well behaved sources. This applies to QSOs provided there is no significant astrometric jitter of their photocentre.

## 4. Astrometric accuracy

During the observations and the nominal Gaia processing, QSOs are no different from ordinary stars and are processed like single stars, to extract at the end of the mission the standard five astrometric parameters, namely the position at a reference epoch, a parallax and the two proper motion components. See Lindegren et al. (2011) for a comprehensive and technical presentation of the core astrometric solution. Assuming that QSOs are astrometrically

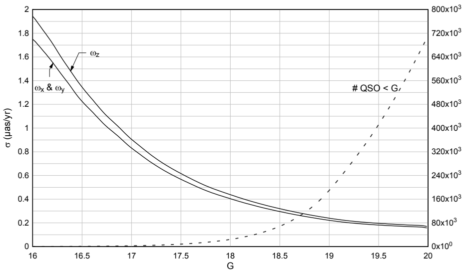

**Fig. 5.** Inertiality of the final Gaia Celestial Reference Frame based on the QSO observations, expressed by the accuracy of the residual rotation. The precision for a *G* magnitude is computed with only sources brighter than *G*. Here galactic coordinates have been used and the random instability has been taken equal to 20 $\mu$as yr$^{-1}$ and quadratically added to the single star noise. The asymmetry between the three axes comes from the Galactic plane screening. The right scale gives the number of sources found brighter than *G*.

quiet with no instability in their position over short timescale, larger than few tens of $\mu$as, the accuracy of the astrometric solution is shown in Fig. 4 as a function of the G magnitude. The positional accuracy should be about 80 $\mu$as at G = 18 and will degrade to 250 $\mu$as for the faintest sources measurable with Gaia. From Slezak & Mignard (2007) or from Table 1 one should have nearly 40 000 objects with G < 18, and many more fainter. The core of the defining sources for the reference frame will include many of the brightest sources and the space distribution should be uniform outside the galactic plane when $|b| > 25°$. This might be a conservative number and the actual limit will not be known before Gaia flies.

Proper motion will be part of the solution and will be initially free, since the general mathematical procedure does not constrain the reference frame. A constraint will be applied in the course of the astrometric solution by analysing the proper motion vector field and searching, and then removing, a global rotation. There will be no constraint set also on the parallaxes of the QSOs, even though the parallax of the extragalactic objects must be statistically zero for all the sources. But given the uncertainties seen in Fig. 4, it will be commonplace to see in the final solution, QSOs as bright as G = 18 given with a parallax somewhere between −300 to 300 $\mu$as, and this will be correct from a statistical standpoint. The overall analysis of the parallaxes per bin of magnitude, or weighted by the formal standard deviation, should show a normal distribution with zero mean. This will be a nice check to support the validation of the Gaia general astrometric solution. Taking the 40 000 sources brighter than G = 18 and an individual uncertainty of 110 $\mu$as for the parallax, this will allow us to check the parallax zero-point to 0.5 $\mu$as (one sigma).

### 4.1. Transverse motion

Nominally QSOs in a non-rotating frame are seen as sources exhibiting no displacement on the plane of the sky and are just comoving with the expansion of the Universe in the radial direction. This is the basic model used in the astrometric analysis of the VLBI, and largely confirmed at the current level of accuracy. This is true up to a certain point, and as the astrometric accuracy improves, one should one day or another see a departure from this simple model. Already the monitoring of ICRF sources in radio has allowed to see erratic displacements of the sources. The ICRF2 recently released (Fey et al. 2009) does not include proper motions of sources and has no epoch attached to it, because the more or less random motion of the sources associated to internal changes is larger than the astrometric accuracy achieved. During the preparation of the ICRF2 by Fey et al. (2009) source positional stability was investigated by generating time series of the source with repeated observations over several years. Only 39 were found requiring special handling, but the vast majority of the sources have not been observed with the frequency required to detect small systematic variation in position. In all cases the detected instability is in the sub-mas range, and very often larger than 100 $\mu$as, some showing consistency in the motion covering 2 to 5 years. Assuming that the photocentre exhibits similar displacement, this will be seen by Gaia as a measurable transverse motion. The astrometric model will have to be adapted to deal with these anomalous behaviour, intermediate between a systematic linear motion (like stellar proper motion) and a stochastic effect similar to a noise.

The relationship between astrometric displacement on the sky and the photometric variability will be of great value for Gaia, given the contemporary observations performed onboard in astrometry and photometry, both with excellent accuracy. Recently Taris et al. (2011) investigated this correlation with CFHT observations and they have found a link between the photometric variability and the structure of the PSF. While not yet a detection of motion in optical wavelength, this is at least a first hint towards the presence of a photocentric motion. Such a detection is probably not achievable in the visible with ground-based observations, but normally well within the reach of Gaia, provided a dedicated analysis of the observations is carried out allowing for a complex astrometric model.

However the most regular transverse motions of quasars expected for Gaia will be the so-called secular aberration, or cosmic acceleration. The acceleration of the Solar System barycentre translates into a systematic proper motion of the extragalactic source, with a well defined pattern: a regular dipolar-like field directed towards the galactic centre. The amplitude $a$ can be estimated to be of about 4 $\mu$as yr$^{-1}$. An actual measurement has been reported recently by Titov et al. (2011) from the VLBI observations of radio sources at $6.4 \pm 1.5$ $\mu$as yr$^{-1}$. Given the close mathematical relationship between the global rotation and the aberration drift (Mignard & KLioner 2008), the three components of the acceleration expressed in angular unit will be determined with exactly the same accuracy as the residual spin shown in Fig. 5. In the best case the amplitude $a$ will be known with a 10-$\sigma$ precision.

These systematic proper motions attached to extragalactic sources means that the Gaia Reference Frame will come with an epoch at which the source coordinates will be provided. But unlike the stars, for which each source comes with a particular proper motion, for the Gaia-CRF, it will be simply a set of three quantities to be plugged into a straightforward propagation model. Since these parameters will be measured, there will be a remaining error comparable to the formal uncertainty of $0.2 - 0.5$ $\mu$as yr$^{-1}$, and the frame materialised by the Gaia QSOs will degrade, albeit very slowly, with the time. Nothing dramatic in practice, since it will take at least 100 years to double the initial uncertainty of individual positions of the brightest defining sources. By that time the Gaia-CRF will have been superseded by a new version of the Celestial Frame.

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