FROM GAIA FRAME TO ICRF3 ?

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ABSTRACT. The Astrometric solution of Gaia will come with an internally built Celestial Reference Frame, based on the observation of extragalactic sources. This frame must be constructed in agreement with the ICRS overall principles to ensure that it is kinematically non-rotating and that its orientation is consistent with the ICRF. The general methods used within the Gaia community to build this solution are outlined together with the main properties of the Gaia Celestial Reference Frame. It is proposed to form an IAU-Division I-level working group to deal with the issues relating the Gaia CRF and the future realisation of the ICRF in the visible.

1. INTRODUCTION

The ESA space astrometry mission, due for launch in late 2013, will survey the sky down to the 20th magnitude with an unprecedented astrometric accuracy of 25 μas at 15 mag, carrying out simultaneously multi-epoch photometry and spectroscopy. The mission is optimised to observe stellar sources to produce a stereoscopic and kinematic census of about one billion stars in our Galaxy enabling to probe the formation and evolution of the Milky Way. The expected astrometric accuracy is shown in Figure 1 as a function of the G magnitude (very similar to R band).

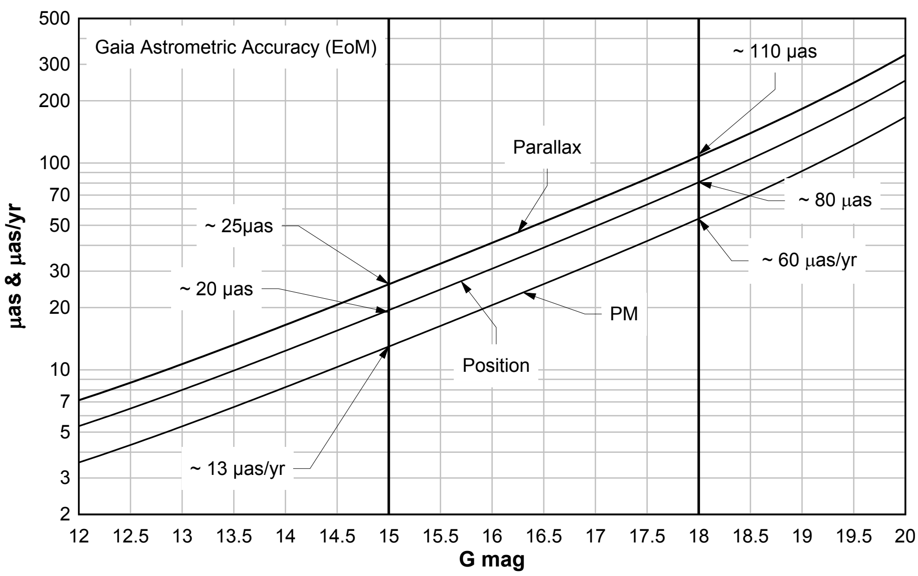

Figure 1: End-of-Mission astrometric accuracy expected with Gaia for the position, proper-motion and parallaxes, for point like sources (stars or QSOs).

While the core of the mission is dedicated to stellar and galactic physics, the sensitivity limited internal detection system will allow also to observe and astrometrically measure several 100,000s quasars, but also the fast moving objects from the solar system and other extended objects, like unresolved galaxies. These consistent and repeated observations will lead to the realisation of a kinematically defined inertial frame in the optical wavelengths. To achieve this goal one must first recognize the QSOs from the stars in an automatic and efficient way and select a clean sample of sources to serve as defining source for the frame. Then the astrometric solution for these point-like sources would not depart too much from the standard iterative process detailed in Lindegren et al. [3].

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 virtually only point-like extragalactic sources (unresolved galaxies will fall in another box). 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 $|b| > 25^\circ - 30^\circ$, 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 $b = 10^\circ$ and $G = 19$). Multi-images formed by lensing of intervening galaxies could be detected 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 of extragalactic sources will provide a direct realization of the quasi-inertial celestial reference frame in optics with a residual rotation less than 0.3 μas 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 magnitudes.

2. THE GAIA REFERENCE FRAMES

The astrometric solution resulting from the Gaia data processing carried out by the DPAC (Data Processing and Analysis Consortium) will be referred to a kinematically non-rotating frame thanks to the global zero-proper motion constraint set on the clean subset of quasars detected by Gaia. The positional accuracy of the individual sources will depend on their magnitude, but at least for the $\sim 30,000$ QSOs brighter than $G = 18$ this would be better than 80 μas and 60 μas/yr. This astrometric solution both for the stars and the quasars will be made available through the different releases of the Gaia products, culminating with the final solution to be published around 2020. From its very principle, Gaia is designed to carry out absolute astrometry from space observations and the Gaia releases will include simultaneously a set of extragalactic sources used to build its internal non-rotating frame, and a large stellar catalogue down to the 20th magnitude referred to the same frame. To fix the terminology I refer to the whole set at the Gaia-CRF (Gaia Celestial Reference Frame) which comprises:

- A set of defining sources from the clean subset of QSOs used to fix the frame spin
- A larger set of secondary QSOs not used to remove the residual rotation
- A very small set of QSOs common to Gaia and ICRF2 used to tie the orientation
- The Gaia-SRF (for Stellar Reference Frame)
  - **a-** About one billion stars with positions, proper motions and parallaxes
  - **b-** An average density of 25000 stars per square degree, highly variable with galactic latitude
  - **c-** This positional catalogue will degrade with time as shown in Figure 2.

The current realization of the International Celestial Reference Frame (ICRF2) is based on Very Long Baseline Interferometry (VLBI) positions of radio sources with accuracies or the order of 100 μas for the best sources. While the spin of the Gaia frame will come out naturally from the application of the ICRS paradigm to the quasars, it goes differently for the orientation (origin of right ascension and position of the pole) which is a free parameter. As always in metrology, Gaia scientists will endeavour to maintain the best continuity 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

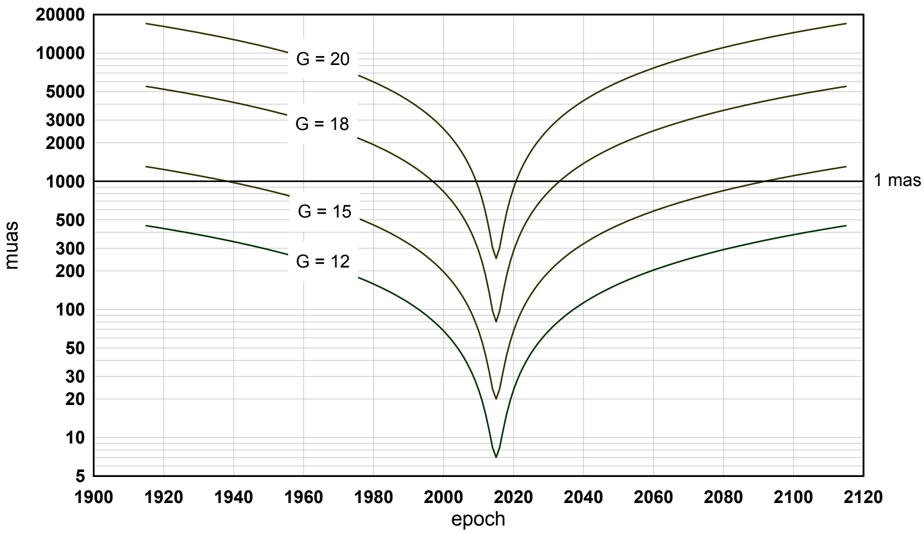

Figure 2: Evolution of the accuracy of the Gaia positional stellar catalogue with time due to the uncertainty in the annual proper motions of stars. The diagram refers only to the stars, not to the QSO-tied reference frame.

sources with good astrometry in the ICRF (not necessarily ICRF sources) and observed by Gaia will be selected to align the two frames (see [1], [2]).

However 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. Quasar optical emission may originate from three potential sources for which the detailed physics remains largely unknown: thermal emission from the accretion disk surrounding the black hole, non-thermal coronal disk emission, and for a sub-set of the extreme radio-loud quasars non-thermal emission from knots in the relativistic jet. For radio-loud quasars part of the emission very likely takes place in the jets aligned with the axis of the accretion disk. Therefore one cannot exclude an offset between the two centres of emission. The comparison of the pos-alignment residuals in the common sources will provide valuable insight into the physical processes responsible from the light or radio emission. By directly aligning the two frames through quasar astrometry one will be able to investigate the relationship between the radio core and optical photocentre at unprecedented accuracies.

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 ω 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 Figure 3, 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 μas yr^{-1}. Being more conservative by considering just a core of bright defining sources and allowing for a loss of 50% 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 μas yr^{-1} as illustrated in Figure 3. The plot is based on a realistic simulation of the distribution of QSOs on the sky, including a no-observation zone around the galactic plane. The luminosity function has been scaled with local surveys, providing a complete census of QSOs beyond the detection limit of Gaia. Then this density has been used to generate a full-sky catalogue.

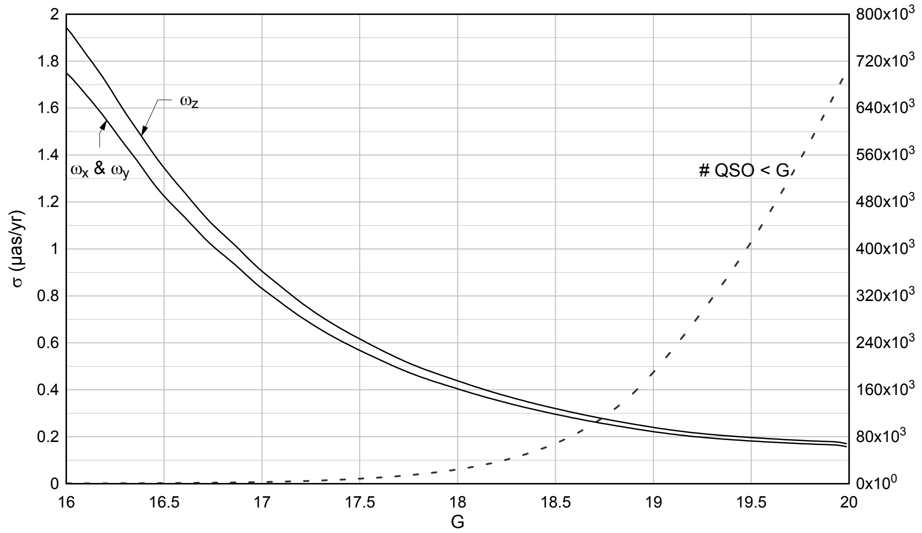

Figure 3: Inertiality of the final Gaia Celestial Reference Frame based on the QSO observations, expressed by the accuracy of the residual rotation. The precision for a G magnitude is computed with only sources brighter than G. Here galactic coordinates have been used and the random instability has been taken equal to 20 μas 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.

3. THE EPOCH OF THE GAIA CRF

Once the global rotation of the defining QSOs has been removed, each source will still show some residual proper motion. Although the magnitude of these proper motion components will be dominated by the random noise, a global pattern is expected resulting from the acceleration of the solar system with respect to the distant extragalactic sources. This is a well known effect widely documented for its theoretical principles. 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 μas yr^{-1} from the Galactic rotation parameters. An actual measurement has been reported recently by Titov et al, ([4]) from the VLBI observations of radio sources at 6.4 ± 1.5 μas yr^{-1}. Gaia will be able to determine this parameter to an accuracy of about $0.2 - 0.3$ μas yr^{-1}. The whole pattern of proper motion is fully determined by only three parameters (the direction of the drift axis and its magnitude) and enables us to update the position of the QSOs at any epoch before or after the mean Gaia epoch of observations. This means that the Gaia-CRF will come with an epoch attached to it, even though the annual corrections (typically of 4 μas yr^{-1}) will be much smaller than the individual random error in position (typically 80 μas for the core of the defining sources). The associated degradation of the frame will be very slow if the dipole is really determined with the expected accuracy of $0.2 - 0.3$ μas yr^{-1}.

4. THE GAIA CRF AND IAU

The final Gaia solution will be fully consistent with the ICRS overall principles and given the easy access to this frame through the Gaia stellar catalogue, one may anticipate that the Gaia-CRF will be widely used in numerous astronomical research works. The set of defining QSOs with their astrometric solution, including the dipolar drift, will materialise the realisation of the axes. The system will be aligned to the ICRF version available at the time of Gaia completion. We hope to provide also at this time some preliminary assessment of the difference between the centre of emission of the radio signal and the photocentre for the sources used to perform the alignment.

Clearly a further step is needed to have this frame recognised by the IAU as being an optical realisation

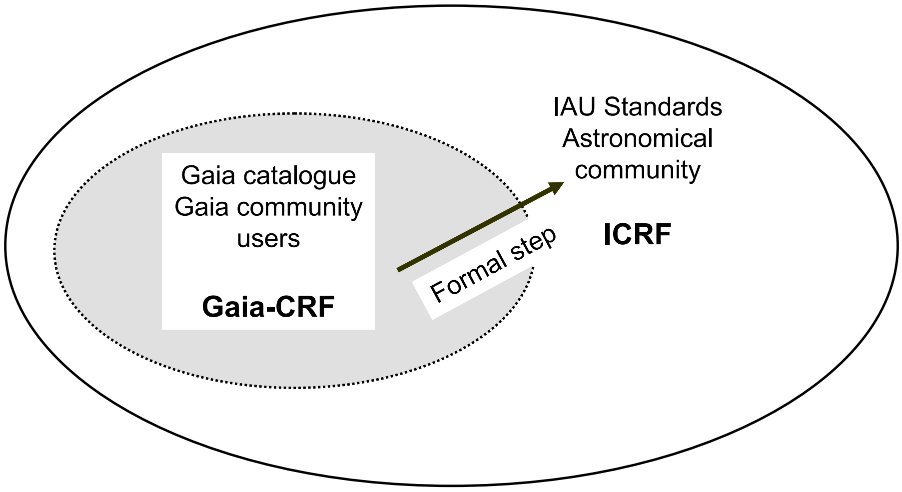

Figure 4: Schematic relationship between a Gaia-defined reference frame and an IAU-endorsed version of an ICRF.

of the ICRF, to be used by every astronomers in needs of accurate astrometry. This step is sketched in Figure 4. A formal contact must be established between the Gaia community in charge of producing the intermediate and final Gaia solutions and the astronomical community, as this was done during the Hipparcos mission to ensure a good communication between the Hipparcos scientists and the international group building the first realisation of the ICRF with VLBI. Something similar should be established at the IAU Division I level between the radio ICRF and the Gaia astrometrists. The main topics that should appear in the Terms of Reference will comprise at least,

- Construction of the Optical ICRF with Gaia
- Qualification of the Gaia frame at the international level
- Relationship between the Radio and optical frames
- Extension to fainter magnitudes

The qualification of the intermediate and final realisations of the Gaia frame should involve a wider group than the Gaia subgroup performing the astrometric solution, with expertise on ICRF (radio or optical), QSO physics, high accurate astrometric modelling to guarantee the adherence to ICRS principles and the use of standardized theoretical and numerical models identical in Radio and Optics. This is also essential to prepare the final adoption of the Gaia-CRF as a new realisation of the ICRF. The same group should also advise IAU on how to deal with two realisations, one in optical, one in radio serving different purposes. The long term consistency between these two solutions would require careful thinking. The WG should report at the 2015 IAU General Assembly and make proposals on how to realise an ICRF in the optical wavelength, in parallel to the Radio realisation.

5. REFERENCES

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