PROSPECTS FOR AN OPTICAL REFERENCE FRAME USING GAIA

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ABSTRACT. It is expected that at least half a million of objects, mostly QSOs, will be observed by GAIA. However, in order to build a celestial reference frame, it is necessary to identify among observations those that are without doubt extragalactic remote objects. An important effort is under way by the ESA Relativity and Reference Frames Working Group to produce tests, which will allow such an identification. About 50 000 objects will contribute to determine the reference frame and one expects to limit the remaining time dependent rotation to 0.3 μas/yr. There is a secular deformation of the frame due to the non-linear motion of the Sun. This raises the question whether the GAIA stellar positions will be in a barycentric or in a galacto-centric reference system and, in both cases, what corrections should be applied and published. Another difficulty will be to link it to the present ICRF.

1. WHAT CAN ONE EXPECT FROM GAIA?

The reduction of the cost of the GAIA project, requested by ESA in 2002, led to a major re-design of the spacecraft and the payload. The consequences are some adjustments of the expected performances as initially publicized (ESA, 2000). Although they affect only marginally the overall program, there is a significant increase of the expected uncertainties in the final astrometric parameters that will influence the final results. Let me state them.

- *Parallaxes and yearly proper motions.* For magnitude V=15, the expected accuracy is no more 10μas, but 12μas for M6V stars, increasing to 24μas for G to B stars on the main sequence. However a 20% margin is accounted for.
- *Bright stars.* The best attainable results are now 7μas rather than 4μas in positions, but, if the mission duration is 5 years, an accuracy of 10μas per year in proper motions remains possible up to magnitude 10.
- *Faint objects.* The limiting magnitude 20 may not be reached because of radiation damage.
- *Spectroscopy.* It is still expected an accuracy of 10 km/s for radial velocities at the limiting magnitude 17.
- *Photometry.* One or two channels for the medium band photometry are descoped or re-designed.

2. WHAT DID WE LEARN FROM HIPPARCOS?

The Hipparcos reference frame was constructed from the observations of 40 000 well observed single stars. The reduction procedure referred consistently the positions and proper motions to a well defined, but arbitrary, reference frame. This frame was defined in position and rotation yearly rate with a precision of 0.003 mas (ESA, 1997). This number is consistent with the 0.6 mas median error in position and 0.7 mas median error in the proper motions.

The next step was to link this reference frame to extragalactic objects so that it represents the extragalactic reference system ICRS. The problem was that no extragalactic object was observed by Hipparcos, with the exception of some 50 stars in the Magellanic clouds, which we knew have significant proper motions. It was necessary to realize independent connections between Hipparcos stars and extragalactic objects. This was essentially done using VLBI and other radio-interferometers to connect Hipparcos radiostars to ICRS, and by two epoch photographic plates to ensure the stability with respect to Galaxies (Kovalevsky and Lindegren, 1997). The final accuracy of the link was 0.25 mas/yr for each component of the rotation vector an 0.6 mas for the position of the axes at epoch.

3. CONSTRUCTION OF THE GAIA REFERENCE FRAME

As in the case of Hipparcos, the reduction procedure will provide an internally consistent, but arbitrary, reference frame. One might think that the presence of some 500 000 quasars (QSO) and active galactic nuclei (AGN) would permit to construct directly this frame in such a way that it is fixed with respect to the extragalactic objects. This should not be the case for two reasons.

1. There are almost no QSOs in a band of about $\pm 15°$ width around the galactic plane, while there are stars all over the celestial sphere, thus avoiding possible systematic errors in connecting the two galactic hemispheres.

2. Because of the crucial importance of the reference frame, it is desirable to use the best observed objects, which, in this case, would be single bright stars, for instance, magnitude 13 or brighter.

This implies that, like for Hipparcos, there must be a second step, which will provide the link of the established reference frame to the assumed fixed extragalactic objects, essentially QSOs and AGNs. In what follows, I shall consider only this second step.

Since the stellar reference frame will not be fixed, the extragalactic objects will have an apparent proper motion. Assuming that these objects have either no, or randomly distributed proper motions, the apparent proper motion will have a systematic behavior produced by two different effects.

The first effect is an aberration in proper motion due to the motion of the Sun in the Galaxy (GAIA Science Advisory Group, 2000). Let $l(t)$ and $b(t)$ be respectively the galactic longitude and latitude of an object, and l and b their values at a reference time t_0. Then, one has

$$\begin{aligned} l &= l(t) - s(t - t_0) \mid \sin l(t) \mid, \\ b &= b(t) - s(t - t_0) \cos l(t) \sin b(t), \end{aligned} \tag{1}$$

where s is the coefficient of the aberration effect due to the curvature of the motion of the Sun around the center of the Galaxy. If its velocity is V, the distance of the Sun to the center of the

Galaxy is R, and c is the speed of light, then s is given by

$$s = \frac{V^2}{cR}. \tag{2}$$

The second correction represents the rotation of the reference axes. Let ω_x, ω_y, and ω_z be the rectangular components of the rotation vector Ω of the stellar system with respect to the galaxies. The total equations, including (1) written in terms of proper motions μ_l and μ_b are

$$\begin{aligned} \mu_l &= s \mid \sin l \mid \cos b - \omega_x \sin b \cos l - \omega_y \sin b \sin l + \omega_z \cos b, \\ \mu_b &= s \cos l \sin b + \omega_x \sin l - \omega_y \cos l. \end{aligned} \tag{3}$$

4. EXPECTED ACCURACY

Simulations were performed, in particular by M. Froeschlé (Kovalevsky *et al.*, 1999), to assess accuracy of the determination of the rotation of the stellar reference frame with respect to an extragalactic one. A random distribution in positions was simulated taking into account the zone of absence of ±20° on both sides of the galactic plane. A total of 170 000 QSOs and AGNs were simulated with a magnitude distribution that conformed to the actual counts, while the uncertainties of observations were those announced in 2000. The results are presented in figure 1. The

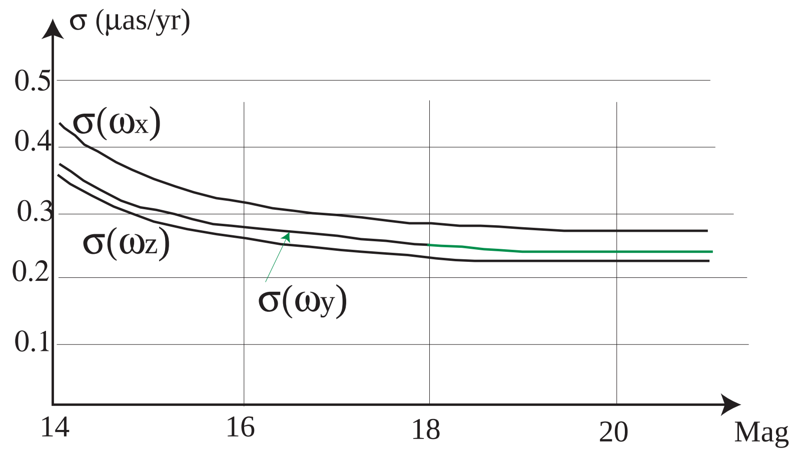

Figure 1: Uncertainties of the three components ω_x, ω_y, and ω_z of the rotation vector Ω as functions of the upper limit in magnitude.

uncertainties remain almost constant for magnitudes larger than V=18.5 despite the dramatic increase of the number of QSOs observed. Although there are about 3 times more objects than in the simulation, the conclusions remain unchanged. Table 1 gives an evaluation of the number of extragalactic objects suitable for the determination of the frame and the expected astrometric accuracy for proper motions for magnitudes larger than V= 14 with the re-designed payload. The number of stars is also given. The conclusion of the simulation is that adding objects of magnitudes larger than 19 does not change the accuracy of the results. The contribution between 18.5 and 19 is marginal. This means that taking only the 40 000 to 60 000 objects with V< 18.5 is sufficient to obtain the best possible results. Taking into account that in reality there will be three times more objects than in the simulation, but that the quality of the observations is degraded, one may expect an uncertainty of 0.3 μas/yr. It is to be noted, however, that one

Table 1: Number of suitable extragalactic objects and stars and the expected accuracy in yearly proper motions

Magnitude range	Number of QSOs and AGNs	Number of stars	Expected accuracies in proper motions in μas/yr
14-15	100	15 000 000	15
15-16	700	40 000 000	25
16-17	3000	80 000 000	40
17-18	35 000	140 000 000	70
18-19	150 000	250 000 000	140
19-20	300 000	450 000 000	300

assumes that there are no systematic motions of the extragalactic large structures.

5. SORTING OUT SOURCES

A major challenge will be to ensure that the objects used in the determination of the extragalactic frame are indeed QSOs and not stars (Mignard, 2002). In the magnitude range identified in the preceding section, the ratio between the number of stars and QSOs is of the order of 5000, so that the rejection tests must be particularly effective. Evidently, a preliminary elimination will be performed by rejecting objects whose observed proper motions or parallaxes are larger than 2.5 to 3 times the expected uncertainty given in table 1, depending upon the accepted risk of rejecting quasars. But this will be by far not sufficient. The ESA Relativity and Reference Frame Working Group made considerable efforts to design efficient rejection criteria. They are based on photometric properties of QSOs (Claeskens *et al.* 2005). Actually, they are just as important for the reference frame determination as for astrophysical studies of quasars.

The tests are based on the two photometric filter systems on-board of GAIA:

1. The 5 broad band (100-150 nm) interferometry filters situated in front of the five last CCD columns of the astrometric focal plane.
2. The 11 medium band (10-80 nm) filters are situated in front of 16 CCDs in two detection areas of the focal plane of the dedicated telescope for photometry and spectroscopy (Jordi and Høg, 2005).

The main signatures of quasars are:

1. Strong emission lines, whose position in the spectrum depends on the radial velocity of the QSO;
2. An important ultra-violet excess;
3. The Lyman α break absorption.

In order to prepare the tests, a catalog of 100 000 synthetic spectra of quasars was prepared, together with samples of spectra of all types of stars, including white dwarfs and double or multiple stars. These tests were applied to simulated quasar and star observations. The main results are as follows:

- White dwarfs are efficiently rejected.

- 92% of quasars are identified at magnitude 18 and only 55% at magnitude 20.
- At magnitude 18, the star rejection rate is 99.99%. This seems very good, but as table 1 shows, more than 1000 stars may still pollute the list. The other tests will then be essential.

6. WHAT REFERENCE SYSTEM?

The first question one can ask is whether the ICRF as realized at present by VLBI is suitable to remain the defining extragalactic reference system. Originally, ICRF was stable to 0.1 mas/yr. It is still being improved and extended (Fey *et al.*, 2004) but the asymmetric and often irregular shapes limit the precise definition of a photocenter. In some cases, the shape is even changing with time (Shaffer and Marscher, 1987). So, it is very unlikely that more than an order of magnitude can ever be gained in its stability. This is far from almost three that would be necessary to match the expected accuracy of the GAIA reference frame. To link the latter to ICRF cannot be done to better than the actual accuracy of the ICRF, and this would not be acceptable.

So one is led to define a new ICRS as realized by GAIA. The intrinsic expected stability of the GAIA reference frame (0.3μas) argues in favor of such a solution. But this will imply that it will be the realization of a completely new reference system, which will coincide with the present ICRS to the accuracy of the link to the ITRF (that is to the uncertainty of the ITRF). This is not really critical since the same problem existed with the Hipparcos system versus the FK5.

As shown in section 3, in determining the reference frame, the observed positions were reduced to some fixed time t_0 by applying the time-dependent aberration due to the non-linear motion of the barycenter of the Solar system. If the result is published as such, in order to obtain the coordinates of a source at a time t one will have to apply the correction (1) for $(t_0 - t)$. This is because the system is barycentric so that it undergoes the deformation due to this effect. If the coordinates of the sources are obtained for $t = t_0$, then the GAIA reference system will be galacto-centric. The positions of the QSOs will be those that would be seen from the center of the Galaxy. So, in the publication of the positions of the extragalactic objects one must either let the user to apply the correction (1), or to include in the catalog the annual variation of their positions. In my view, the second solution is the most sensible because this applies also to stars.

Indeed, the proper motions of stars as determined with respect to the GAIA reference system must also be corrected by the same quantity. But this not all because star positions undergo a similar effect, due to the non-linear motion of the stars, so that a similar correction must be added, depending on their velocity (Kovalevsky, 2005). In the vicinity of the Sun, galactic orbits are close to that of the Sun so that the two effects cancel. But at distances from the galactic center smaller than 4-5 kiloparsecs, the stellar aberration in proper motion becomes predominant, reaching 40 μas/yr. It must be corrected. But this will be a difficult task because the velocity of the star is a function of its three dimensional position, and will have a large uncertainty at such distances from the Sun for which the parallaxes are poorly determined. Furthermore, the correction depends also upon the kinematic model of the Galaxy. Hence, in addition to the classical astrometric parameters, one will have to give an evaluation of the correction, because the user will generally not be in a position to compute it.

In conclusion, the GAIA reference system will be galacto-centric, and all corrections necessary to transform the positions and proper motions to the usual barycentric system will have to be provided for all objects of the final catalogs.

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