DETECTION OF POLARIZATION EFFECTS IN GAIA DATA

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Abstract. The Gaia satellite will observe about one billion stars and other point-like sources. The astrometric core solution will determine the astrometric parameters (position, parallax, and proper motion) for a subset of these sources, using a global solution approach which must also include a large number of parameters for the satellite attitude and optical instrument. The quality of the astrometric solution will depend on the validity of the instrument model. Optical simulations have showed that Gaia mirrors will be sensitive to light polarization because of their coating properties. This sensitivity results in a shift of the source image on the Gaia detectors, depending on its polarization. These microarsecond shifts can be in the order of magnitude of the expected accuracy of the instrument. Our simulations have showed that the global solution can be improved by including into the global solution approach additional parameters related to the apparent polarization of the sources. We discuss the possibility of deriving the apparent source polarization degree and angle from the global solution approach. Finally, some possible applications will be presented.

1 Introduction

Gaia is a European Space Agency (ESA) space mission in astrometry to be launched in August 2013 for a 5-year mission at the second Lagrange point (L2). It will perform micro-arsecond (μas) global astrometry for 1 billion sources in the magnitude range G=[6, 20]. It will deliver one of the most comprehensive stellar catalogs to date when completed providing unprecedented positional and radial velocity measurements for about one billion stars in our Galaxy and throughout the Local Group. Sources range from minor Solar System bodies (∼ 250,000), supernovae and burst sources (∼ 20,000) up to nearby galaxies and distant quasars (∼ 500,000). Similarly to its predecessor Hipparcos, Gaia consists of two telescopes providing two observing directions with a fixed, wide angle between them.
Fig. 1. Schematic of the adopted design for the Gaia payload. Two telescope system sharing the same focal plane. Each telescope is based on a three-mirror anastigmatic design with three flat-folding mirrors, the two viewing directions separated by a 106.5° basic angle. Beam combination is achieved in image space with a small beam combiner rather than in object space (saving mass, simplifying accommodation, and eliminating the directional ambiguity of the star transits). The primary mirrors are of dimension 1.450.5 m², the telescope focal length is 35 m, and the astrometric field of view is 0.7° (along scan) by 0.7° (across scan). Image courtesy of EADS Astrium.

(Fig. 1). The spacecraft rotates continuously around an axis perpendicular to the two telescopes’ lines of sight (LOS). The spin axis in turn has a slight precession across the sky, while maintaining the same angle to the Sun.

The reflective coating attached to each of the six mirrors of each telescope introduce some sensitivity to source polarization especially the flat mirrors M4 to M6 which have a significant incidence.

The astrometric core solution will determine the astrometric parameters (position, parallax, and proper motion) for a subset of these observed sources, using a global solution approach which must also include a large number of parameters for the satellite attitude and optical instrument. The impact of polarization on the astrometric core solution has been assessed to see if it affects the quality of the mission. Also, we have assessed the conditions under which the additional polarization parameters could potentially be derived as part as the astrometric core solution. In short, this means using Gaia as a polarimeter. Of course, the accuracy of the determination of the polarization parameters can not be compared to the one obtained with a standard polarimeter because of the restrictive conditions under which the parameters can be determined. However, we show that the number of sources for which polarization could be obtained would be substantial as compared to existing catalogs. Consequently, this would be a unprecedent sample
Fig. 2. Gaia astrometric model describes the apparent path of a star on the sky is described by the five astrometric parameters: $\alpha_0$, $\delta_0$, $\varpi_0$, $\mu_{\alpha_0}$, $\mu_{\delta_0}$. Image credit: L. Lindegren, Lund observatory.

of low precision but unbiased global polarimetry.

Although this sensitivity to polarization is usual for mirrors and subtracted in the case of polarization measurements, it was initially not planned to take advantage of it in order to derive more informations from the observations.

A first study of feasibility has been done and a team from Lund University joined the project.

2 Astrometry

The Gaia astrometric model (Lindegren 2011) assumes that a single star moves with uniform velocity through space relative to the Solar System Barycentre (SSB) and can be described by the six parameters being the components of the two vectors ($\vec{r}_0$) and ($\vec{v}$) expressed in the Barycentric Celestial Reference System (BCRS) whose spatial axes are aligned with the International Celestial Reference System (Feissel 1998). In practice, the kinematic parameters are transformed into a set of astrometric parameters more adapted to describe the apparent motion of sources on the sky as observed by Gaia (Fig. 2):

$\alpha_0$ the barycentric right ascension at the adopted reference epoch $t_{ep}$

$\delta_0$ the barycentric declination at epoch $t_{ep}$

$\varpi_0$ the annual parallax at epoch $t_{ep}$

$\mu_{\alpha_0}$ the proper motion in right ascension at epoch $t_{ep}$

$\mu_{\delta_0}$ the proper motion in declination at epoch $t_{ep}$
Fig. 3. The Gaia satellite will continuously spin around its axis $z$, causing the field of views of both telescopes (yellow squares) to scan across all objects located along the great circle which is perpendicular to the spin axis. Image credit: L. Lindegren, Lund observatory.

3 Gaia measurements: time of centroids

The Gaia satellite will continuously spin around its axis, causing the field of views of both telescopes to scan across all objects located along the great circle which is perpendicular to the spin axis (Fig. 3). Data is continuously read as the telescopes sweep out these great circles on the sky. For this reason, the CCDs will operate in time-delayed integration (TDI) mode. This means that the CCD electrodes are clocked at the same speed as the image scans along (AL) the focal plane (Fig. 4).

Given real-time processing constraints, limits on the acceptable CCD read-out noise, and the limited telemetry bandwidth, not all CCD pixel data can be read and subsequently transmitted to the ground. A limited number of windows, regions of interest around target objects, are therefore observed in the focal plane (Fig. 5). For most of the observations in the astrometric field, on-chip binning in the serial register is used to sum the charges over the window in the across-scan (AC) direction. This effectively results in a one-dimensional image of 6 to 18 AL samples, where the signal in each sample is the sum of 12 AC pixels. Each window sample is time tagged with the on-board clock when transferred to each CCD serial register. From the model of the sample values in the window, the along-scan (AL) pixel coordinate of the image centroid can be estimated and transformed to the observation time. The location of the centroid is expected to be determined with a precision of the order of 200 $\mu$as at magnitude 15. But an average of 700 of such measurements will be performed per source over the 5 years of the mission providing the requested $\mu$as accuracy on the astrometric position.
4 Impact of polarization on centroiding

The reflective coating attached to each of the six mirrors of each telescope introduces some sensitivity to source polarization especially the flat mirrors M4 to M6 which have a significant incidence. The phase difference between the two components of the reflected signal is at the origin of a wavefront error (WFE) variation with the source polarization which induces a small shift of the point spread function (PSF) in the field of view (FOV), but significant for Gaia astrometric precision. This shift is depending mainly on the source linear polarization parameters namely the polarization position angle of the polarization direction of the source with regards to the optical system axes. The effect has been analyzed (Boyadjian 2006) the instrument provider (Astrium) with a ray-tracing simulation.
Table 1. The second column displays the typical polarization shift for 3 different spectral types. For comparison, the maximum shift value is given in the third column. The last column gives the AL estimate of location error for 700 measurements at magnitude 15 which corresponds to the centroiding error without any polarization.

<table>
<thead>
<tr>
<th>Spectral type</th>
<th>shift [µas] (1% pol.)</th>
<th>max shift [µas] (1% pol.)</th>
<th>$\sigma_{loc}$ [µas]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1V</td>
<td>0.43</td>
<td>1.61</td>
<td>8.47</td>
</tr>
<tr>
<td>G2V</td>
<td>0.70</td>
<td>2.36</td>
<td>4.8</td>
</tr>
<tr>
<td>M6V</td>
<td>5.30</td>
<td>17.1</td>
<td>2.45</td>
</tr>
</tbody>
</table>

based on the properties of the reflective coatings of the mirrors such as reflection factors and phase values for various incidence angles and wavelengths. These ray tracing simulations use Jones matrix to account, in the S/P coordinate system, for each ray S/P transmittance mean phase error, and WFE variation with polarization. In this formalism, the wavefront error is generated by a retardance term which is the difference of S and P phase change.

The instrument response to source polarization can be described by a function $S_l(\lambda, \Delta \eta, \Delta \zeta, P_l, \theta)$ with:

- $P_l$ the level of polarization of the incoming light
- $\theta$ the orientation of the polarization vector of the incoming light
- $\lambda$ the wavelength of the incoming light
- $\Delta \eta$, the along-scan field angle
- $\Delta \zeta$ the across-scan field angle

It is actually mainly a cosine function whose parameters (amplitude and phase) have tabulated values. Because Gaia sources will not be observed in the same conditions during the 5 years of the mission, each polarization shift must be evaluated for each observation taking into account the scanning law. However, we can get a first order of magnitude by calculating the shifts for a randomly generated sample of transits in the FOV for a uniformly distributed sample of polarization angles. We can calculate the standard deviation of the shifts in the FOV to estimate the typical value for a source (see second column of Table 1) considering 700 observations during the mission. This value is around 3 times smaller than the maximum value of the polarization shift that can be reached.

In some conditions, the typical polarization shift is comparable to the centroiding error. The image shift is within the resolving capabilities of Gaia. Consequently, it can impact the accuracy of the astrometric solution. On the other hand, it is conceivable to determine the shift model parameters from the measurements.
5 Astrometric solution

The observation time $t_l$ of observations $t$ along AL can be modeled as a function $f_l$ and a noise (see 5.1).

$$t_l = f_l(\vec{s}, \vec{n}) + \text{noise}$$ (5.1)

where $\vec{s}$ is the vector of unknowns (parameters) describing the barycentric motions of the ensemble of sources used in the astrometric solution. Vector $\vec{n}$ is a vector of nuisance parameters mainly related to attitude and instrument calibration. The astrometric solution is a minimization problem of the weighted difference between measured observation time and calculated time solved by least squares (see 5.2) in an iterative process.

$$\min_{\vec{s}, \vec{n}} J = \sum_l (t_l - f_l(\vec{s}, \vec{n}))^2 w_l / (\sigma_l^2 + \epsilon_l^2) = \sum_l R_l(\vec{s}, \vec{n})^2 W_l$$ (5.2)

where $w_l$ is the weight factor (outliers are assigned smaller weight factors), $\sigma_l$ is the observation uncertainty and $\epsilon_l$ represent the error source extraneous to the observation uncertainty (Lindegren 2011) and $R_l$ is the residual.

6 Astrometric solution is non unique

The astrometric solution does not assume that any of the positions or proper motions are known a priori in the astrometric model. Consequently, there is no unique astrometric solution to the previous minimization problem as any (small) change in the orientation of the celestial reference system ($\vec{\epsilon} = [\epsilon_x, \epsilon_y, \epsilon_z]$) or any introduction of a (small) inertial spin of the system ($\vec{\omega} = [\omega_x, \omega_y, \omega_z]$), would leave all observations invariant. Consequently, the resulting system of positions and proper motions must be aligned with the ICRS.

7 Solving for polarization

As said previously, the shift response is depending mainly on the source linear polarization parameters namely the polarization position angle of the polarization direction of the source with regards to the optical system axes. The instrument response can be expressed by formula 7.1 where $\Delta \eta_{POL}$ is the change in the instrument angle AL due to polarization and $P_{\text{source}}$ being the polarization vector of the source.

$$\Delta \eta_{POL} = \| P_{\text{source}} \| B_{rc}(\lambda) \cos 2(\chi_{rc} - \chi^0_{rc})$$ (7.1)

Its modulus is the polarization ratio of the source. $\chi_{rc}$ is the angle between the projection of the source polarization vector onto the FOV and the vertical direction parallel to the spin axis at the tip of $\vec{f}_P$ and $\vec{f}_F$ (Fig. 7). The angle is counted positive towards the East.
In the Scanning Reference System (SRS), for each viewing direction \( \vec{f}_P \) and \( \vec{f}_F \), the instrument angles \((\varphi, \zeta)\) are the spherical coordinates in the SRS of the observed (proper)direction \( \vec{u} \) towards the object.

\[ B_{rc}(\lambda) \text{ and } \chi^0_{rc} \text{ are depending on CCD row and column and are functions of the source wavelength. And } \chi^0_{rc} \text{ is the direction of maximum instrumental response to polarization in the FOV.} \]

If included in the astrometric model, polarization parameters could in principle be calculated. The formulation adopted for Gaia (Landi Degl’Innocenti et al. 2007) is based on the Stockes formalism and uses the framework adopted in 1973 by the International Astronomical Union (IAU) XVth General Assembly in Sydney, Australia. Linear polarization is expressed in terms of \( P_L \) and \( \theta \)

\[ P_L = \sqrt{P_Q^2 + P_U^2}, \]
\[ P_Q = P_L \cos(2\theta), \]
\[ P_U = P_L \sin(2\theta) \quad (7.2) \]

where \( P_L \) is the fraction of linearly polarized radiation, and \( \theta \) is the angle of maximum polarization, i.e., the angle that the major axis of the polarization ellipse forms with the x-axis of the reference system reckoned with the following convention: the frame of reference for the Stokes parameters is that of Right Ascension and Declination with the position angle of electric-vector maximum, \( \theta \), starting from North and increasing through East (Fig. 6 and Fig. 7).

From Eq. 7.2, we can calculate \( \theta \) as suggested in Landi Degl’Innocenti et al. 2007:

\[ \theta = \frac{1}{2} \text{sign}(P_U) \arccos\left(\frac{P_Q}{\sqrt{P_Q^2 + P_U^2}}\right) \quad (7.3) \]

The model comprises now seven parameters to be solved for each source: \( \alpha_0, \delta_0, \varpi_0, \mu_{\alpha_0}, \mu_{\delta_0}, P_Q, P_U \)
Fig. 7. For each viewing direction \( \vec{f}_P \) and \( \vec{f}_F \), the instrument angles (\( \zeta, \eta \)) are the spherical coordinates in the SRS of the observed (proper) direction \( \vec{u} \) towards the object. \( \theta \) is the polarization direction angle measured from the celestial North Pole.

Fig. 8. Convergence of error on Stockes parameter \( P_Q \) and \( P_U \) in the iterative solving of the astrometric solution.

8 First results

Astrometric simulations were made by Chris Skoog, master student at Lund University, with AGISLab. This software allows to simulate the astrometric solution in a lightweight processing framework but with all the properties of the real data processing system. In the case of sources of stellar M6V type at magnitude \( G = 13 \), Stockes parameter \( P_Q \) and \( P_U \) absolute error converged to \( \sim 0.01 \) for both 1% and 10% polarized (constant) sources (see Fig. 8). This means the observations will be sensitive to sources with greater than 1% linear polarization for M6V type at \( G = 13 \).

These simulations have been repeated for different magnitude values and reveal two different regimes. A bright star regime where polarization shift is dominating...
centroiding error and a faint star regime where centroiding error is the dominating contribution to the residuals. In the bright star regime, $P_Q$ and $P_U$ can be determined with an absolute error of 0.01 (see Fig. 9).

9 Which Objects can be calibrated?

A distribution of stellar polarization has been built from Heiles compilation (Heiles 2000) on a sample of about 9300 stars in a search for potential polarized sources visible from Gaia (Knude 2006). Stars are globally weakly polarized (see Fig. 10) and polarization comes mainly from the interaction of light with dust in the interstellar medium. Alignment of dust grains onto the galactic magnetic field results on polarization of Starlight and dust thermal emission. Individual stars have the potential to produce their own intrinsic polarization. Young stars have debris discs that, for certain line of sight orientations, may cause polarization. Cooler dwarfs like the M-type and dusty giant stars contain large amounts of dust and particulates in their atmospheres that can also contribute.

According to the same study (Knude 2006), QSOs with no variation (single measurements) typically have polarization level between 0.5 and 3% (see Fig. 11). Variable QSOs have polarization levels from about 5% to more than 10%. In addition Hutsemekers et al. 2005 showed that the polarization angle is not randomly distributed: it turns with redshift at a rate of 30 deg per Gpc.

Potential limitations to recover polarization parameters come from the fact that the instrumental response is a model that could be slightly different from the real instrument. However, the model could be calibrated from observations from the ground or included in the nuisance parameters and be recovered directly at the same time as the astrometric solution. This last point needs to be validated. Variability of the source polarization is also an issue especially for blazars which...
have the highest level of polarization. This issue needs to be addressed as well.

From these considerations, two directions of research have been considered. The first research aims at the Galactic magnetic field reconstruction and was carried by Chris Skoog master student at Lund University with D. Hobbs and L. Lindegren.

The second research topic aimed at studying the impact of QSO position errors on Gaia catalog alignment onto ICRF and was carried by the author in collaboration with G. Bourdat from Observatoire Bordeaux.

10 Galactic magnetic field reconstruction (by Chris Skoog from Lund University)

The interstellar medium provides a potential window into the galactic magnetic field (GMF) that can be explored by observing the light that has passed through the dust that resides there. The dust becomes detectable as a form of extinction when the observed starlight is dimmed via scattering by the dust, or when the

\[
\begin{array}{|c|c|}
\hline
P(\%) & \text{Fraction(\%)} \\
\hline
\geq 10 & 0.04 \\
\geq 7 & 0.27 \\
\geq 5 & 2.0 \\
\geq 4 & 5.4 \\
\geq 3 & 10.5 \\
\geq 2 & 19.7 \\
\geq 1 & 38.3 \\
\geq 0.5 & 50.5 \\
\hline
\end{array}
\]

Fig. 10. Distribution of stellar polarization among Heiles compilation.

\[
\begin{array}{|c|c|}
\hline
P(\%) & \text{Fraction(\%)} \\
\hline
\geq 1 & 62.9 \\
\geq 2 & 34.3 \\
\geq 3 & 23.9 \\
\geq 4 & 19.9 \\
\geq 5 & 15.8 \\
\geq 6 & 13.4 \\
\geq 7 & 11.9 \\
\geq 10 & 8.6 \\
\hline
\end{array}
\]

Fig. 11. Distribution of QSO polarization from Hutsemekers+ 2005 catalog (355 objects).
light is absorbed by the dust and emitted as infrared radiation. The interstellar
dust grains that create the extinction effect will also polarize the light that passes
through it if the dust particles are aligned. This effect increases with the amount
of aligned material it passes through. So if there is a general diffuse amount of
dust in the galactic disc, the extinction, and therefore the polarization, is thought
of as a property correlated with the line of sight distance. Using this knowledge
in combination with observational surveys, it is possible to build an fairly detailed
model of extinction. With sufficient knowledge of how galactic extinction affects
the polarization levels of a star at a certain distance, and having obtained the
distances to the sources by measuring their parallaxes, it is possible to construct
a three-dimensional image of interstellar dust clouds. The aligned dust grains in
these clouds trace out the magnetic field, providing a manner of which to learn
about the structure and topology of the GMF. These dust clouds and their as-
associated GMF-aligned particles could then be used to create a three-dimensional
mapping of the galactic magnetic field if one has a catalog with enough precision to
observe the polarization effects on the data as they trace the plane of the GMF-sky
projection.

Extinction levels can be calculated from color excess maps. For the purposes
of this study, an examination of the extinction levels at various points through
the sky is necessary to analyze the expected levels of polarization. The results
from the converted DIRBE-IRAS color excess maps (Fig. 12 a), along with the
calculated Stokes polarization magnitude maps (Fig. 12 b for the 1% threshold
limit and Fig. 12 d for the full threshold view) clearly show the influence of the
dust extinction in the plane of the galaxy. The $\theta$ angle (Fig. 12 c) is the angle
drawn between the celestial north pole and the plane of minimum polarization,
with the position of the DIRBE-IRAS data point at the vertex.

11 Alignment onto ICRF

11.1 Principle

Parameters $\vec{\epsilon}$ (orientation) and $\vec{\omega}$ (rotation) (see section 6) are determined by a
weighted least-squares solution, using as input the differences in positions and
proper motions for a subset of sources, between the AGIS results and a priori
data. At least three subset of sources could be used:

$S_{NR}$ : this subset of primary sources is used to define a kinematically non-rotating
celestial frame ($10^5$ to $10^6$ QSOs and point-like galactic nuclei). This subset
effectively determines $\vec{\omega}$.

$S_P$ : this subset of $S_{NR}$ has positions accurately determined with respect to the
ICRS independently of Gaia. These are optical counterparts of extragalactic
objects from radio interferometry (VLBI). This subset effectively determines
$\vec{\epsilon}$.

$S_{PM}$ : this is a subset of sources not belonging to the non-rotating subset but with
Fig. 12. The calculated all sky Healpix maps for the DIRBE-IRAS dust maps with the angle of minimum polarization located along the plane of $l = 77.4 \text{ deg}$. (a) E(B-V) color excess values obtained from DIRBE-IRAS dust maps. (b) Polarization magnitude values calculated from DIRBE-IRAS dust map extinction with a 1% threshold limit to emphasis the structure outside the galactic plane. (c) $\theta$ angle calculation using $l = 77.4 \text{ deg}$ and $b = 0.0 \text{ deg}$. (d) Polarization magnitude values calculated from DIRBE-IRAS dust map extinction with a full threshold range.

accurate positions and proper-motions determined independently of Gaia. It should be used for a consistency check.

11.2 Does polarization shift impact the estimation of $\epsilon$?

This study is based on a subset from the subset of the 201 QSOs from the ICRF2 catalog provided by G. Bourdat, obs. Bordeaux, for subset $Sp$. A polarization shift needs to be calculated for each source of the list depending on the observation scheme provided by the scanning law. However, once again, one can get a representative typical error by summing shifts for all CCDs and for a limited set of values covering the whole range of polarization vector orientations.

11.3 Model for QSO

As explained previously, the instrumental response to polarization depends on the spectrum of the polarized source. However availability of the ICRF2 QSOs
spectrum was limited. Consequently a generic spectrum has been used (from Telfer et al. 2002) and shifted according the redshift value of the source (see Fig. 13). This is a first order calculation that will need to be refined using more realistic data in order to differentiate at least highly polarized blazars from other QSOs.

Polarization information is missing for most of the entries and needed to be generated according to the distribution from Hutsemekers+ 2005 plotted on Fig. 13.

11.4 Result: impact on the ICRF

We can calculate the standard deviation of the centroiding by summing both the typical shifts (see Section 4) and the location error (in practice, the inverses of
Fig. 15. Comparison of location noise (centroiding error) and typical polarization shift for the 70 first sources of ICRF2 catalog assuming 700 observations per source.

Squares of errors should be summed) to get an idea of the weight of polarization for the initial 70 sources of ICRF2. A total value of $\sigma_{\text{tot}} = 37.1\mu\text{as}$ is obtained for the standard error including polarization shifts that can be compared to the value $\sigma_{\text{loc}} = 36.6\mu\text{as}$ for the error excluding polarization.

The numbers are very close. To understand this similarity, values of polarization shifts and centroid errors can be plot for each sources. In this case (see Fig. 15), out of the 70 sources, only 5 have a polarization shift value higher location error value. These are highly polarized objects (blazars).

Consequently, and as expected, it seems already from this step that polarization has no impact on the precision of the estimation of the parameters for the alignment onto the ICRF. Further work should quantify the accuracy to be expected on the determination of the parameter for the alignment onto the ICRF.

11.5 Calibration of QSOs polarization

Based on the 201 first sources of the ICRF2, we can do a quick and simple extrapolation based on the previous method, to estimate the number of calibrable QSOs. From the $\sim 500,000$ expected QSOs for magnitude $G < 20$, we can expect between 17,000 (where shift is higher than twice the error on location) and 32,000 (where shift is higher than the error on location) calibrated QSOs. This is a very small part of the QSOs population but would be still the largest catalog of polarization
so far.

11.6 Potential study

From Hutsemekers et al. 2005 based on the study of the set of 355 QSOs, the orientation of the polarization vector is not random. The mean polarization angle $\theta$ appears to rotate with redshift at the rate of $\sim 30$ deg per Gpc. This may be the signature of either dark matter or dark energy according to the study. Providing a large set of data could help refine this analysis.

12 Conclusion

Because of its weak instrumental response and the overall weak level of polarization of sources, polarization has a negligible impact on Gaia astrometry. However owing to the accuracy of the astrometric solution determination, polarization parameters can be calibrated for a few percent of the sources, which is still an unprecedented set. This would allow some science to be done.

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