Detection of Polarization Effects in Gaia Data

Frederic Raison

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Gaia is an astrometry mission using 2 telescopes.

The idea is to use Gaia as a polarimeter (low precision but unbiased global polarimeter).

This was not planned: we use an asymmetry of the optics to get more information from measurements.

After my first study of feasibility, Lund University joined.
Overview

A. How does Gaia work?
B. What is the polarization impact?
C. Which science can be done?
A: Gaia in few words

- Launch scheduled for summer 2013 for a 5-year mission at L2.

- **micro-arcsecond (μ as)** global astrometry for ~1 billion sources in the magnitude range G=[6, 20].

- One of the most comprehensive stellar catalogs to date when completed.

- Sources range from minor Solar System bodies (~250,000), supernovae and burst sources (~20,000) up to nearby galaxies and distant quasars (~500,000).
A: Astrometry

- 5 astrometric parameters: are assigned to all point sources: \( \alpha_0, \delta_0, \mu_\alpha, \mu_\delta, \pi_0 \)
- Want to determine their value for each source.
- Want to have a reference: ICRS

100 million primary sources means \( 5 \cdot 10^8 \) parameters
"Time of observation" for image centre relative to CCD

- determined to ~200 μas precision (magnitude 15)
- Some 700 such measurements per object in 5 years
=> $10^{12}$ observations
B: Impact of polarization on centroiding

- Mirrors coating sensitive to linear polarization and generate wave front error.
- Wave front error induces centroid displacement independent of magnitude, proportional to polarization.
- Can calculate a standard deviation from the shifts of N transits on random CCD raw on a single FOV:

<table>
<thead>
<tr>
<th>Spectral type</th>
<th>( \sigma [\mu \text{as}] ) @ 1% polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1V</td>
<td>0.43</td>
</tr>
<tr>
<td>G2V</td>
<td>0.70</td>
</tr>
<tr>
<td>M6V</td>
<td>5.30</td>
</tr>
</tbody>
</table>

700 observations/source => this is within Gaia's resolving capabilities.
Predicted AL/AC obs:

\[ m_L^{\text{pred}} = f_L (s_i, a_j, c_k, \text{aux}) + \text{noise} \]

- **Source parameters for star** \( i \)  
  \( (\alpha_0, \delta_0, \pi_0, \mu_\alpha, \mu_\delta) \)

- **Attitude parameters** for attitude interval \( j \)

- **Calibration parameters** for calibration unit \( k \)

- **Auxiliary data** (ephemerides, ..)

\( L \) = observation index  
\( i \) = source index  
\( j \) = attitude interval index  
\( k \) = calibration unit index

Database knows the mappings \( L \leftrightarrow i, L \leftrightarrow j, L \leftrightarrow k \)

**SOLVE**

\[ J(x) = \sum_L \left( t_L^{\text{obs}} - f_L (x, \text{aux}) \right)^2 \frac{w_L}{\sigma_L^2 + \varepsilon_L^2} = \sum_L R_L (x, \text{aux})^2 W_L \]

- **Sum over observations**
- **Residual (O–C)**
- **Statistical weight**
B: Solution is “non unique”

- Any small change in the orientation of the celestial reference system ($\varepsilon = [\varepsilon_x, \varepsilon_y, \varepsilon_z]$) ... 

- Any introduction of a small inertial spin of the system ($\omega = [\omega_x, \omega_y, \omega_z]$) ... 

- ... leaves observations invariant (differential measurements, no a priori information on sources).

- Need to align system of positions and proper motions with the ICRS.
B: Solving for polarization

- Instrumental response:
  - \( Shift = S_L (\lambda, \Delta \eta, \Delta \zeta, P_L, \theta, \theta_0) \)

- Solving now for 7 parameters for each source:
  \( \alpha_0, \delta_0, \mu_\alpha, \mu_\delta, \pi_0, P_q, P_u \)

\[
\begin{align*}
P_L &= \sqrt{P_Q^2 + P_U^2} \\
P_Q &= P_L \cos(2\theta) \\
P_U &= P_L \sin(2\theta)
\end{align*}
\]

Stokes parameters describing linear polarization of light

\( \Delta \zeta = \) Across-scan field angle
\( \Delta \eta = \) Along-scan field angle
\( \Delta \delta = \) Declination
\( \Delta \alpha = \) Right ascension
Astrometric simulations were made by C. Skoog, Lund University, with AGISLab.

Stockes parameter $P_Q$ and $P_U$ absolute error parameters converge to $\sim 0.01$ for both 1% and 10% polarized (constant) sources.

This means the observations will be sensitive to sources with greater than 1% linear polarization for sources for M6V type @ G=13.

2 regimes:
- bright stars for which accuracy on calibration is $\sigma=0.01$ on $P_Q$ and $P_U$ whatever magnitude
- faint stars for which accuracy depends on magnitude.
C: Which Objects can be calibrated?

- **stars:**
  - from Heiles compilation for about 9300 stars
  - Intrinsic polarization.
  - ISM (depending on Galactic magnetic field)

- **QSO:**
  - Non Variable: 0.5-3%
  - Variables: 5-+10%
  - Polarization angle turns with z

- **Potential limitations:**
  - Knowledge of the instrumental response.
  - (auto-)Calibrable? Observations from ground?
  - Variability (especially for high polarization). Model?

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**Sources:**

"Polarisation of the Gaia Sky" (GAIA-CA-TN-NBI-JK-001, 26 October 2006)

Heiles, C. 2000 AJ 119, 923


Impact of QSO errors on Gaia catalog alignment onto ICRF: F. Raison in collaboration with G. Bourdat (Obs.Bordeaux).
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.

(a) E(B-V ) colour excess values from dust maps.
(b) Polarization magnitude values calculated (1% threshold limit to emphasis the structure outside the galactic plane).
(c) angle calculation
(d) Polarization magnitude values (full threshold range).
Alignment on the ICRF: principle

- Parameters $\varepsilon$ (orientation) and $\omega$ (rotation) 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.

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

- Subset $S_P$ of $S_{NR}$ with positions accurately determined % ICRS independently of Gaia: optical counterparts of extragalactic objects from radio interferometry (VLBI). This subset effectively determines $\varepsilon$.

- Subset $S_{PM}$ of sources not belonging to non-rotating subset but with accurate position and proper-motion independently of Gaia. For consistency check.
Does polarization shift impact the estimation of $\psi$?

- Started from 201 QSOs from ICRF2 provided by G. Bourdat, obs. Bordeaux, for Subset $S_p$.

- A polarization shift is calculated for each source of the list: $\text{Pshift} = S_L (\lambda, \Delta \eta, \Delta \zeta, P_L, \theta, \theta_0)$

- Should calculate the error for each source depending on scanning law.

- But can get a representative typical error by summing shifts for all CCDs and for a limited set of values covering the range of orientations.
Model for QSO

- Available QSO spectra are limited: generic spectrum and use redshift (1rst order).

- Generate missing polarization information according to (Hutsemekers+, 2005)
Impact on the ICRF

- $\sigma_{\text{tot}} = 37.1$ uas, $\sigma_{\text{loc}} = 36.6$ uas

- Out of the 70 sources, only 5 (blazars) have a polarization error > location error

- No impact on the precision of the estimation of the parameters for the alignment onto the ICRF.

- Accuracy: ongoing work.
Can do a quick extrapolation to the observable set of the number of calibrable QSOs:

- ~500,000 expected QSOs for G<20
- Between 17,000 (error pol>2x loc) and 32,000 (error pol>1x loc) calibrated QSOs.
- = very small part of the QSOs population
- But would be still the largest catalog up to now.
Potential study

- Orientation of QSO polarization vector:

Conclusion

- Polarization has a negligible impact on Astrometry.

- Because of the accuracy of the astrometric solution determination, it can be calibrated for a few percent of the sources, which is still an unprecedented set.

- Some science can be done.
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