Detection of Polarization Effects in Gaia Data

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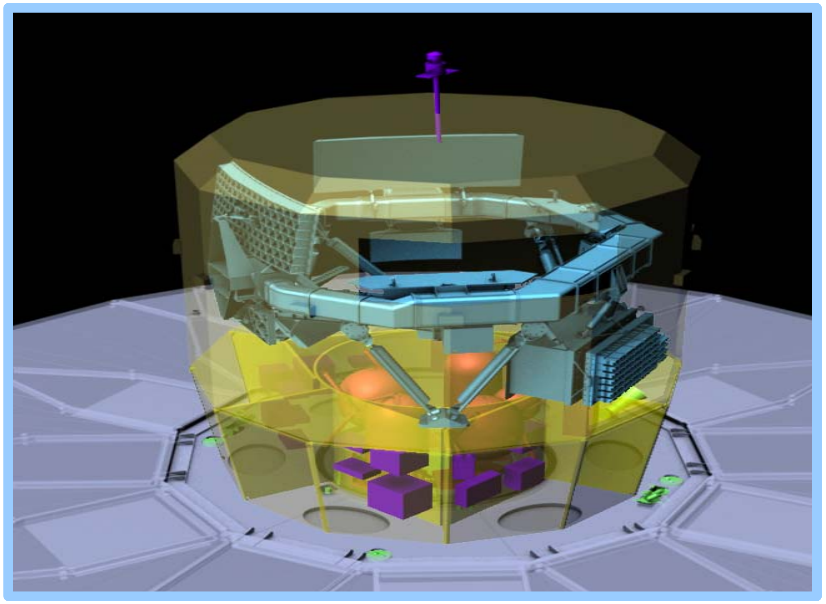
Introduction

- 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?



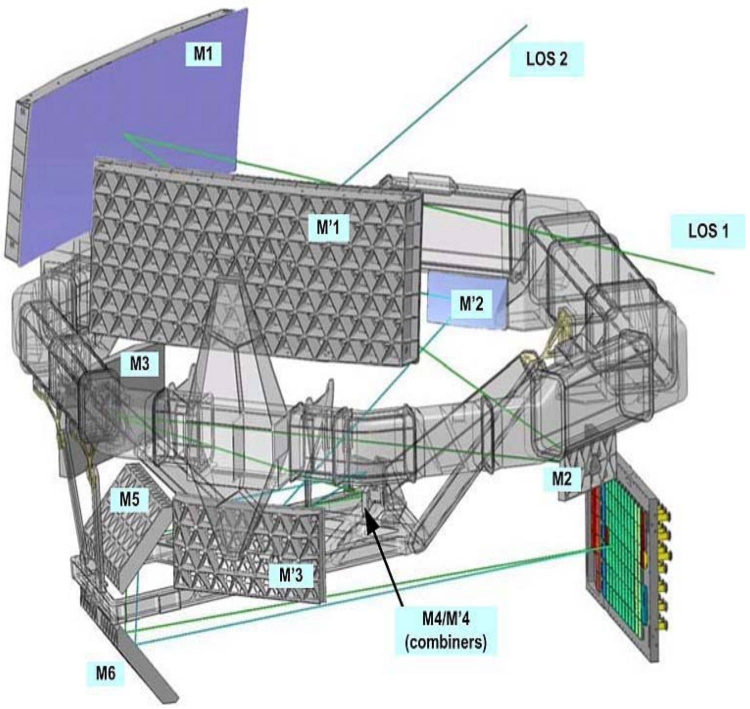
A: Gaia in few words

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

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

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

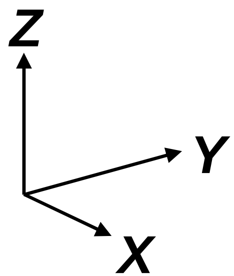
- Sources range from minor Solar System bodies (~250,000), supernovae and burst sources (~20,000) up to nearby galaxies and distant quasars (~ 500,000).



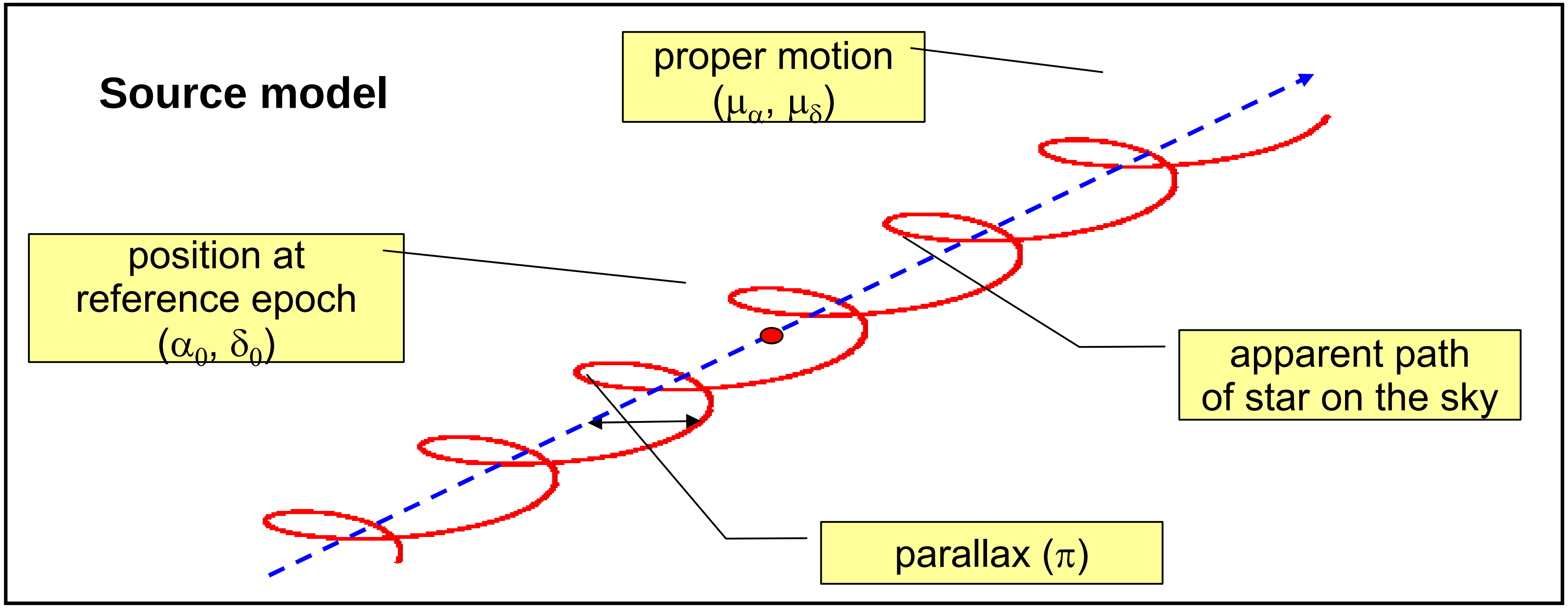
A: Astrometry

- 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

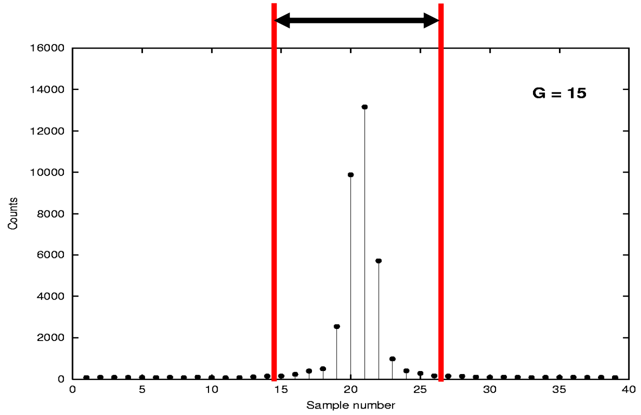


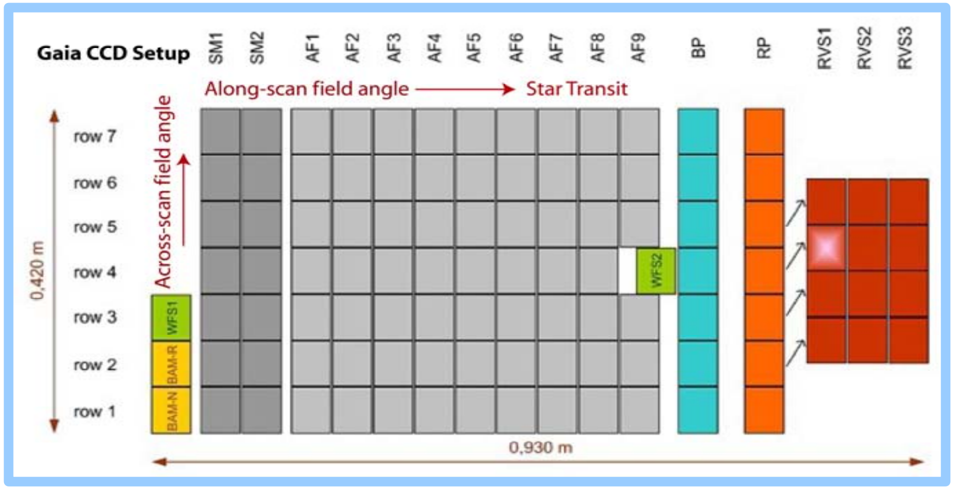
International Celestial Reference System (ICRS)



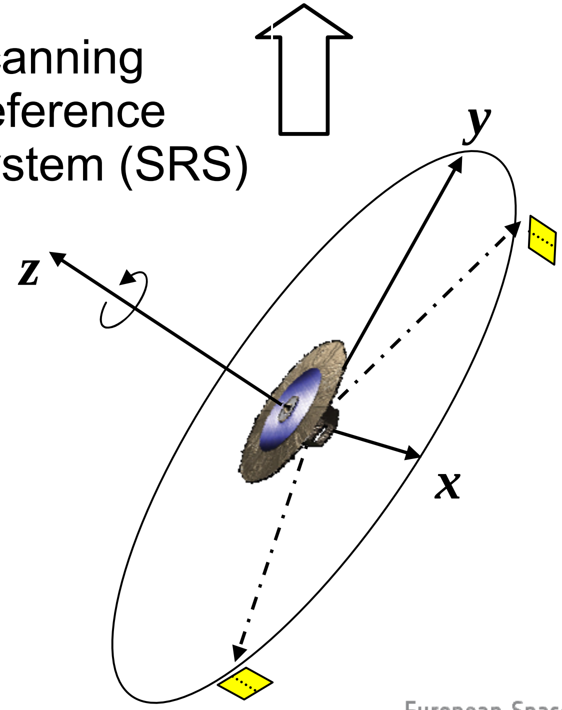
A: Measurements: time of centroids

window of 6-18 samples
transmitted to ground





Scanning Reference System (SRS)

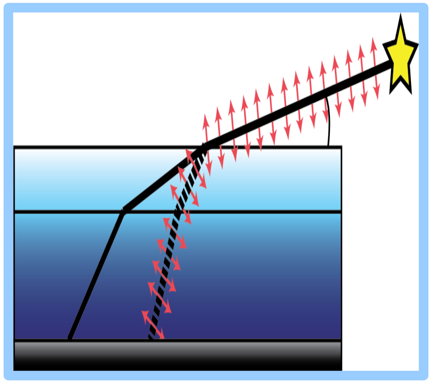


"Time of observation" for image centre relative to CCD

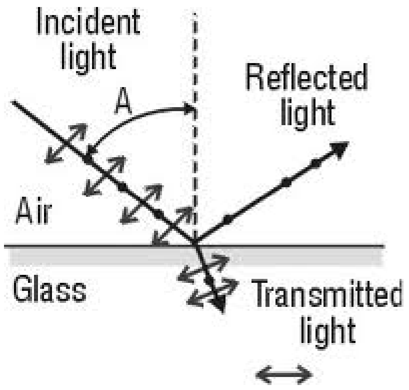
- determined to ~200 µas precision (magnitude 15)
- Some 700 such measurements per object in 5 years => 10^{12} observations

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:



Spectral type	σ [µas] @ 1% polarization
B1V	0.43
G2V	0.70
M6V	5.30



700 observations/source => this is within Gaia's resolving capabilities.

B: Astrometric solution

Predicted AL/AC obs: $m_L^{\mathrm{pred}} = f_L\,(\mathbf{s}_i, \mathbf{a}_j, \mathbf{c}_k, \mathrm{aux}) + \mathrm{noise}$

- 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

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

- 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 ($\boldsymbol{\omega} = [\omega_x, \omega_y, \omega_z]$) ...

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

- Need to align system of positions and proper motions with the ICRS.

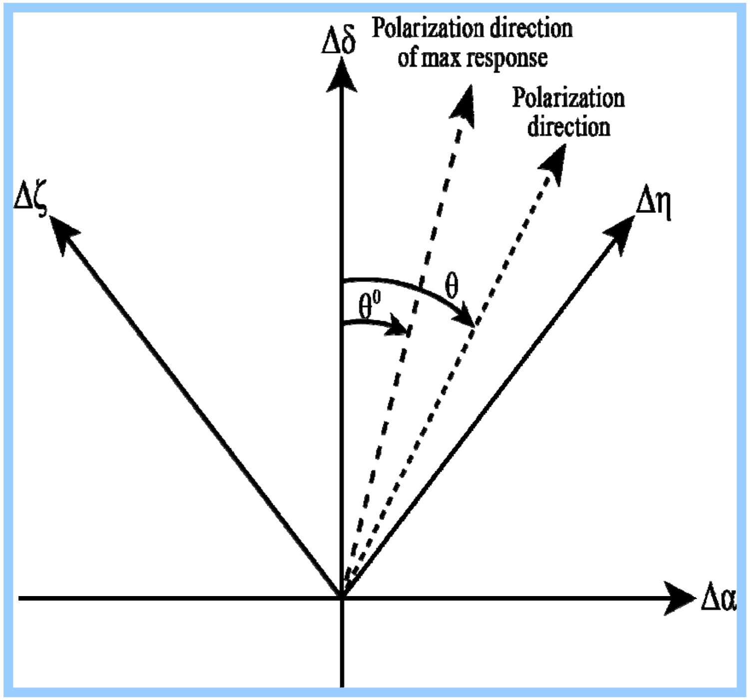
B: Solving for polarization

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

- Solving now for **7** parameters for each source:
  $\alpha_0, \delta_0, \mu_\alpha, \mu_\delta, \pi_0$,Pq,Pu

$$\begin{aligned} P_L &= \sqrt{P_Q^2 + P_U^2} \\ P_Q &= P_L\cos(2\theta) \\ P_U &= P_L\sin(2\theta) \end{aligned}$$

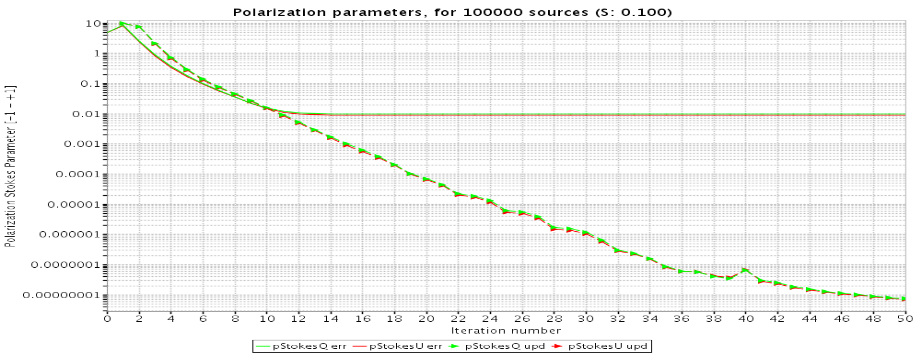
Stokes parameters describing linear polarization of light

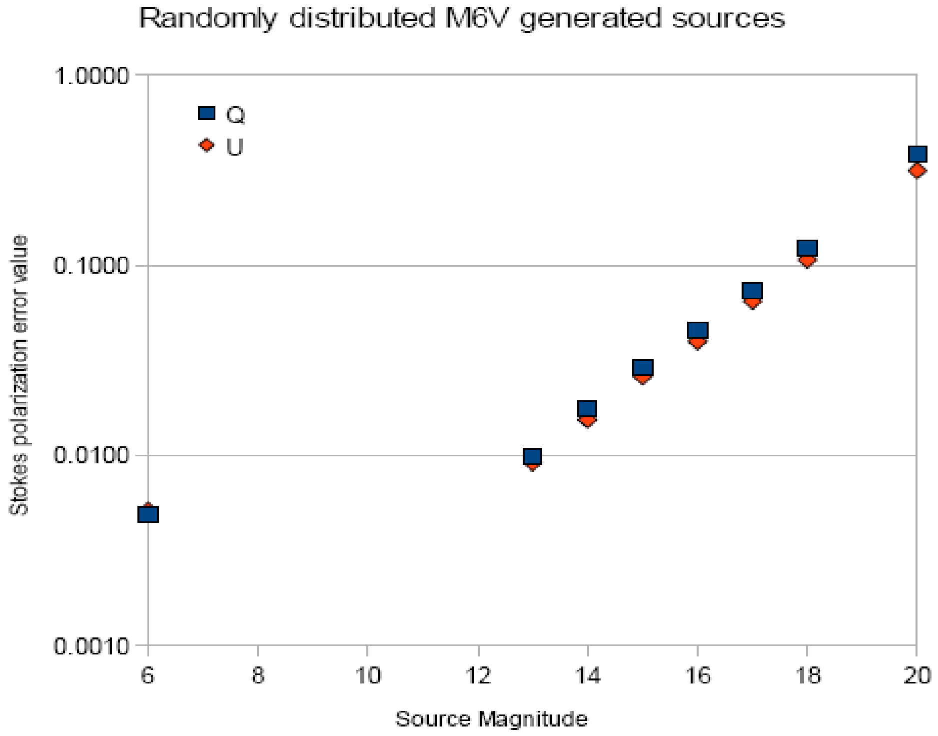


Δζ= Across-scan field angle
Δη= Along-scan field angle
Δδ= Declination
Δα= Right ascension

B: First results (M6V type @ G=13)

- Astrometric simulations were made by C.Skoog, Lund University, with AGISLab.
- Stockes parameter P_Q and P_U absolute error parameters converge to ~ 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)

P(%)	Fraction(%)
≥ 10	0.04
≥ 7	0.27
≥ 5	2.0
≥ 4	5.4
≥ 3	10.5
≥ 2	19.7
≥ 1	36.3
≥ 0.5	50.5

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

P(%)	Fraction(%)
≥ 1	62.9
≥ 2	34.3
≥ 3	23.9
≥ 4	19.9
≥ 5	15.8
≥ 6	13.4
≥ 7	11.9
≥ 10	8.6

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

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

Heiles, C. 2000 AJ 119, 923

Hutsemékers, D., Cabanac, R., Lamy, H., and Sluse, D. 2005 A&A 441, 915

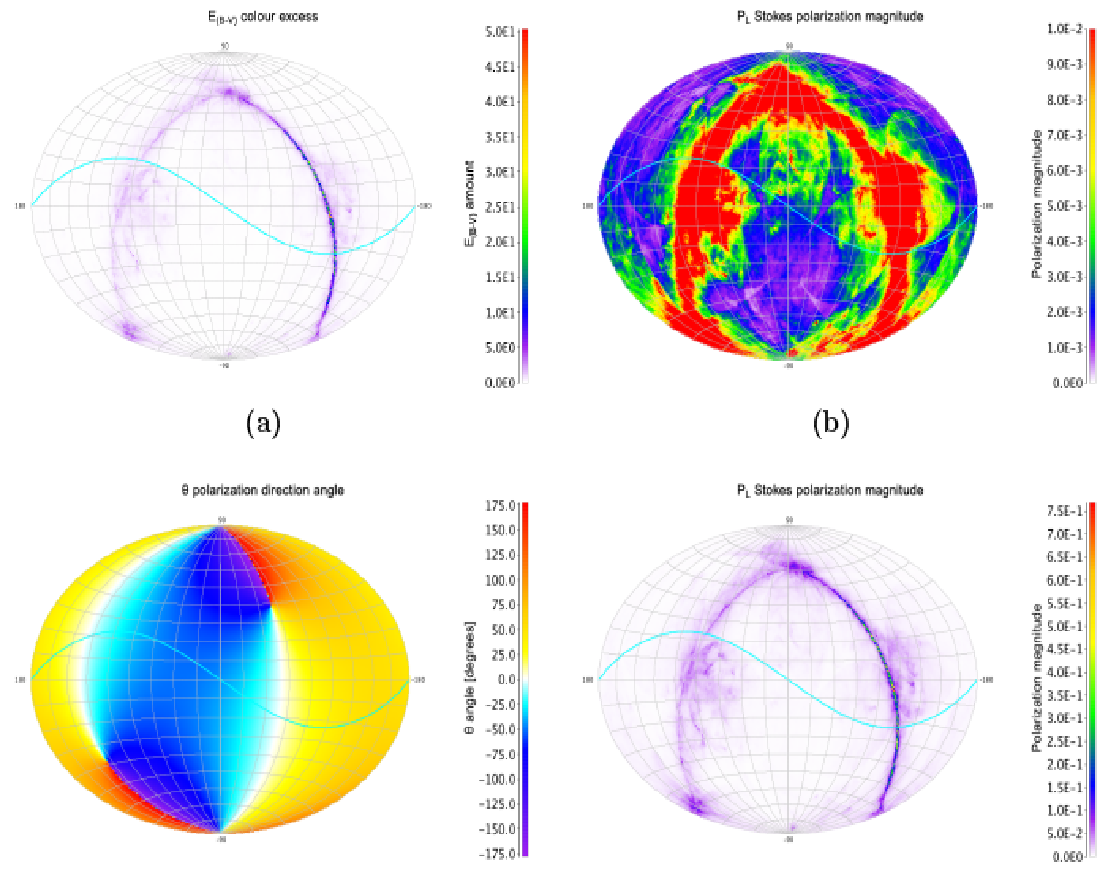
C: Directions of research

- Galactic magnetic field reconstruction: *C. Skoog, D. Hobbs, L. Lindegren, Lund University*.

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

Galactic magnetic field reconstruction *(C. Skoog, D. Hobbs, L. Lindegren, Lund University)*

- 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).



(a) (b) (c) (d)

Alignment on the ICRF: principle

- Parameters ε (orientation) and ω (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 ω.

- 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 ε.

- 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 ε?

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

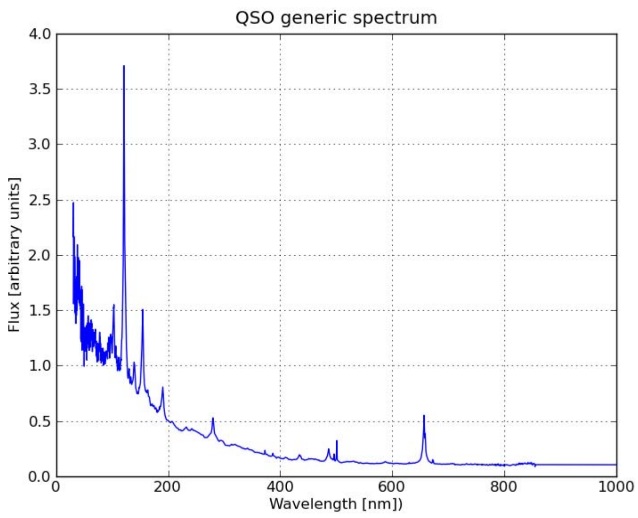
- A polarization shift is calculated for each source of the list: Pshift = $S_L(\lambda, \Delta\eta, \Delta\zeta, P_L, \theta, \theta_0)$

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

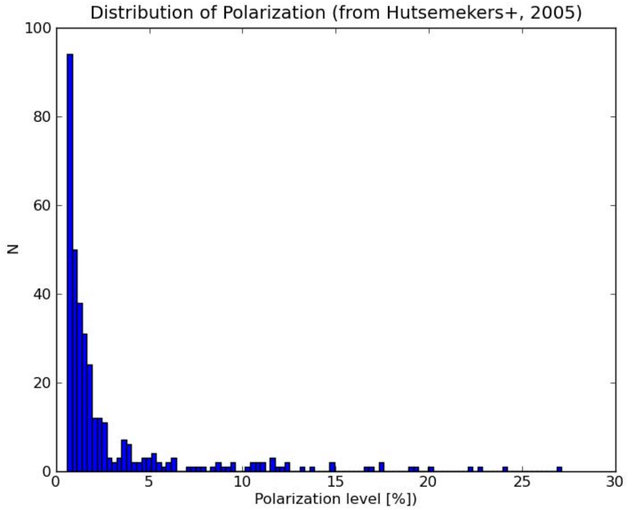
- But can get a representative typical error by summing shifts for all CCDs and for a limited set of values covering the range of orientations.

Model for QSO

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

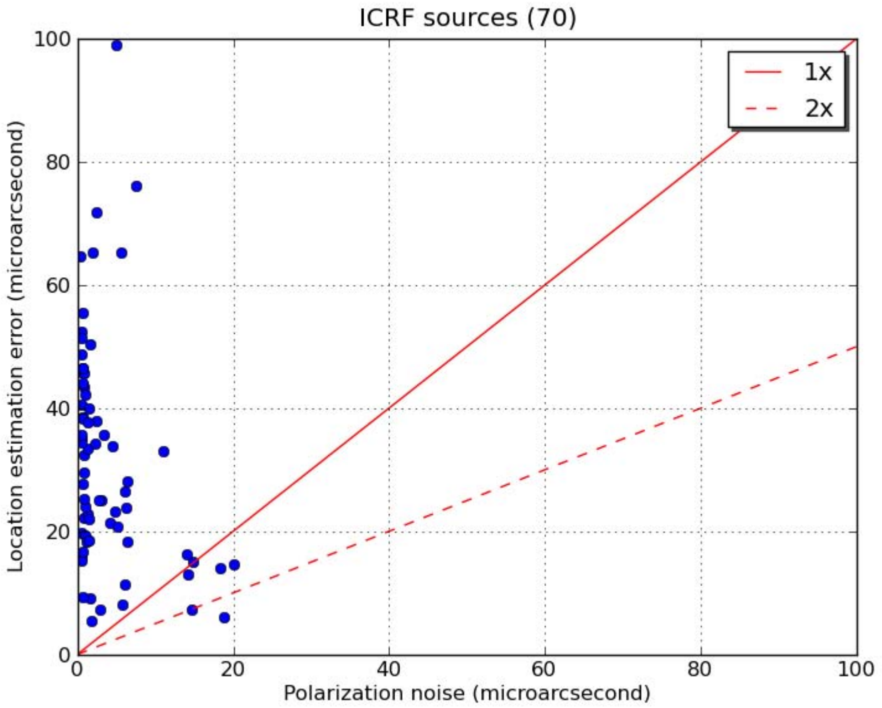


- Generate missing polarization information according to (Hutsemekers+, 2005)



Impact on the ICRF

- σ_{tot} =37.1 uas, σ_{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.



Calibration of QSOs polarization

- 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:

  Hutsemékers, D.; Cabanac, R.; Lamy, H.; Sluse, D., "Mapping extreme-scale alignments of quasar polarization vectors", 2005.

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 unprecedent set.

- Some science can be done.

Acknowledgment

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