The Gaia astrometric space mission and its deliveries

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on behalf of DPAC and GST
University of Barcelona, ICCUB-IEEC

Fig: ESA/Gaia-CC BY-SA 3.0 IGO

ESO Calibration Workshop 2017

Mission description

A&A special volum 595 (2016), the most relevant for this talk are:

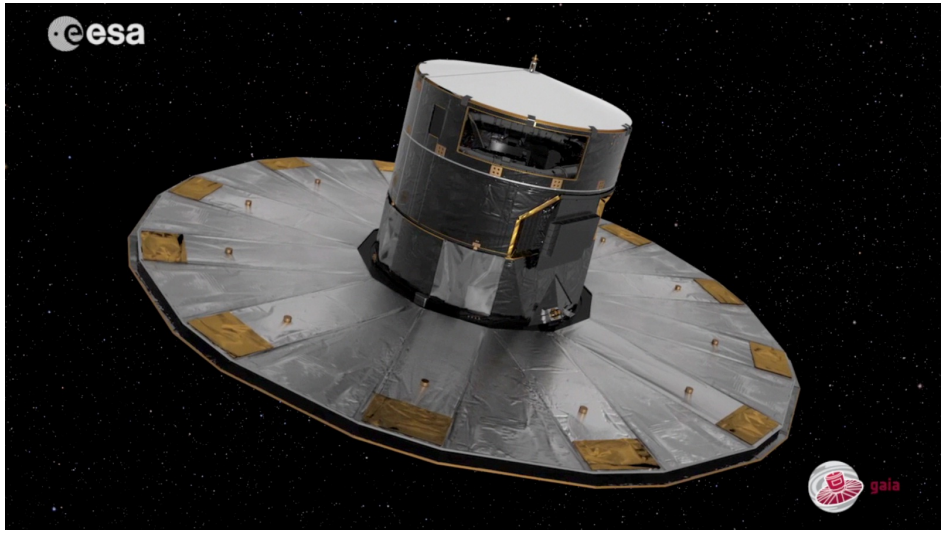
Gaia collaboration, Prusti et al, Mission description
Gaia collaboration, Brown et al, Gaia DR1 description

Fabricius et al, Pre-processing and source list creation
Lindegren et al, Astrometry
Mignard et al, Reference frame
Crowley et al, On-orbit performances of CCDs

See also:

G. Altavilla talk in this workshop
Website: http://www.cosmos.esa.int/web/gaia/
Animations in: http://www.cosmos.esa.int/web/gaia/media-gallery/videos

ESA's Mission



- Launch in Dec-2013
- Commissioning phase until mid Jul-2014
- Science operations started 25-Jul-2014
- First data release 14-Sep-2016

gaia DPAC Gaia esa

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Scanning law

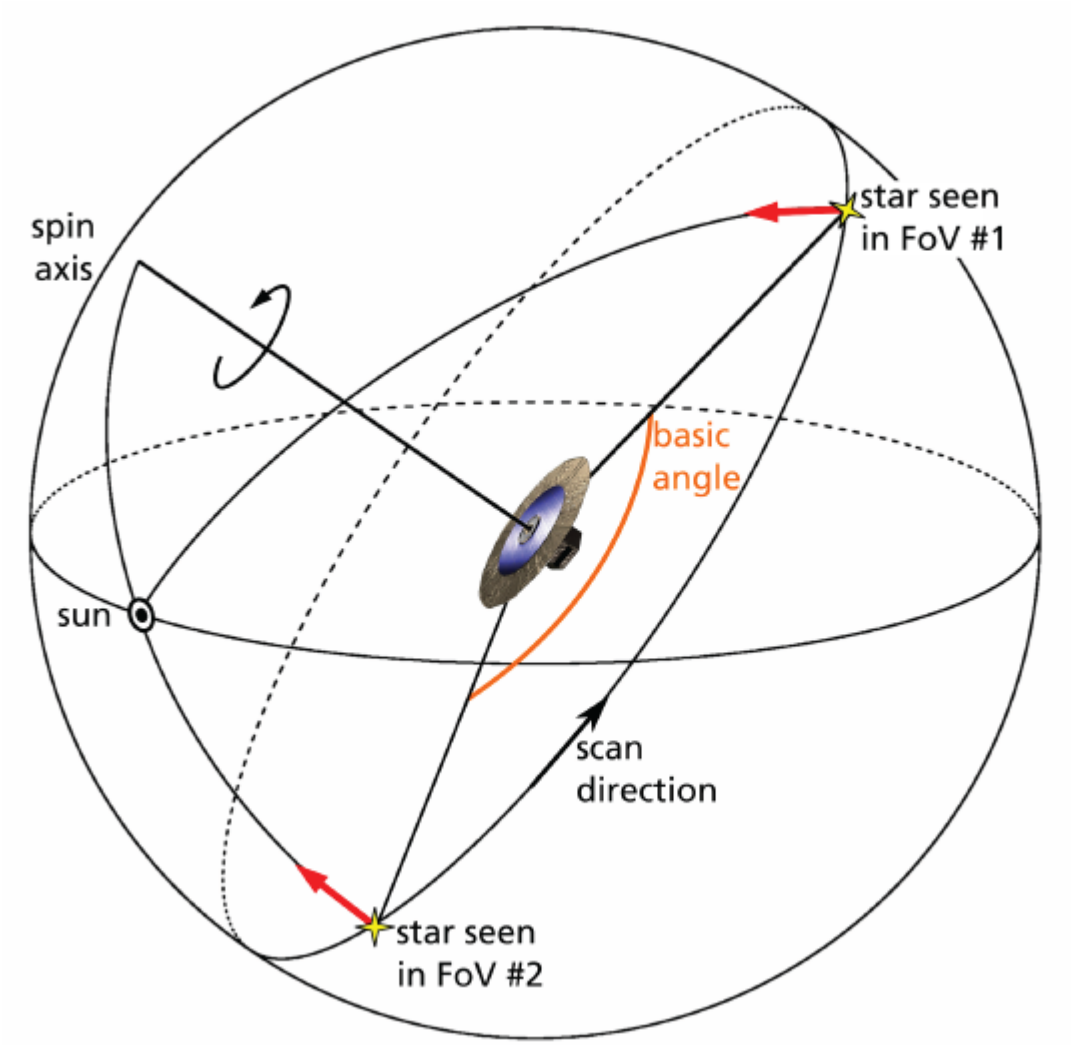


Figure: Lindegren & Michalik

Located at L2 point Earth-Sun:

Spin axis 6h

Precession at 45^{o} in 63 days

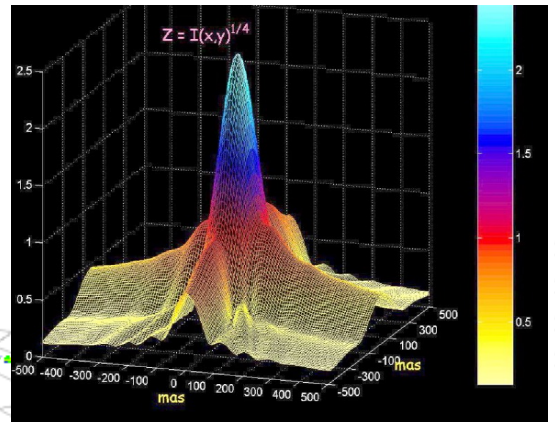
Revolution of 1 yr around the Sun

Daily scanning

70 million transits per day (in average)

- **637 million individual images**
- **140 million low-resolution spectra**
- **28 million high-resolution spectra**

Figures: DPAC/IDT



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The Gigapixel camera

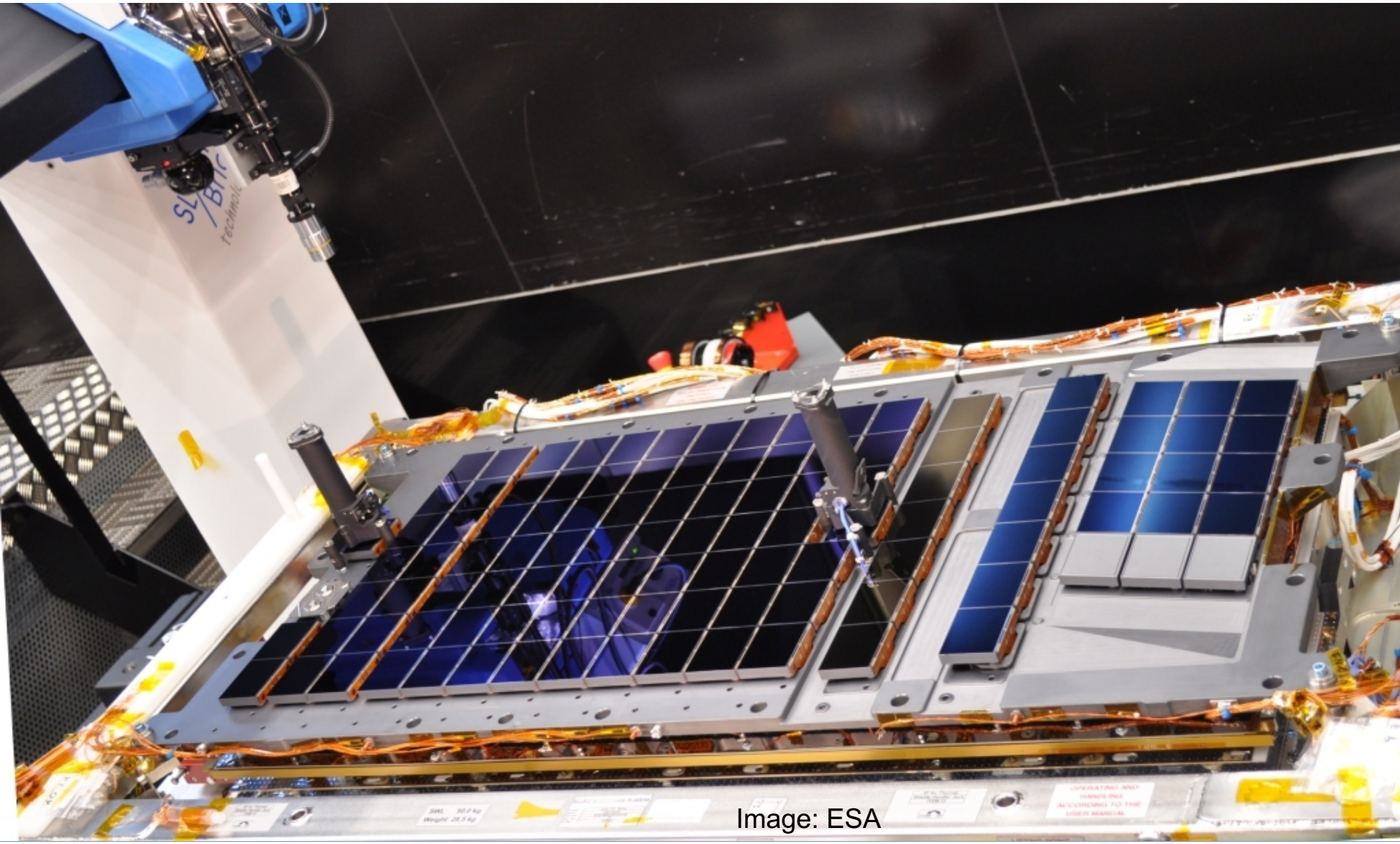

Image: ESA

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Astrometric section

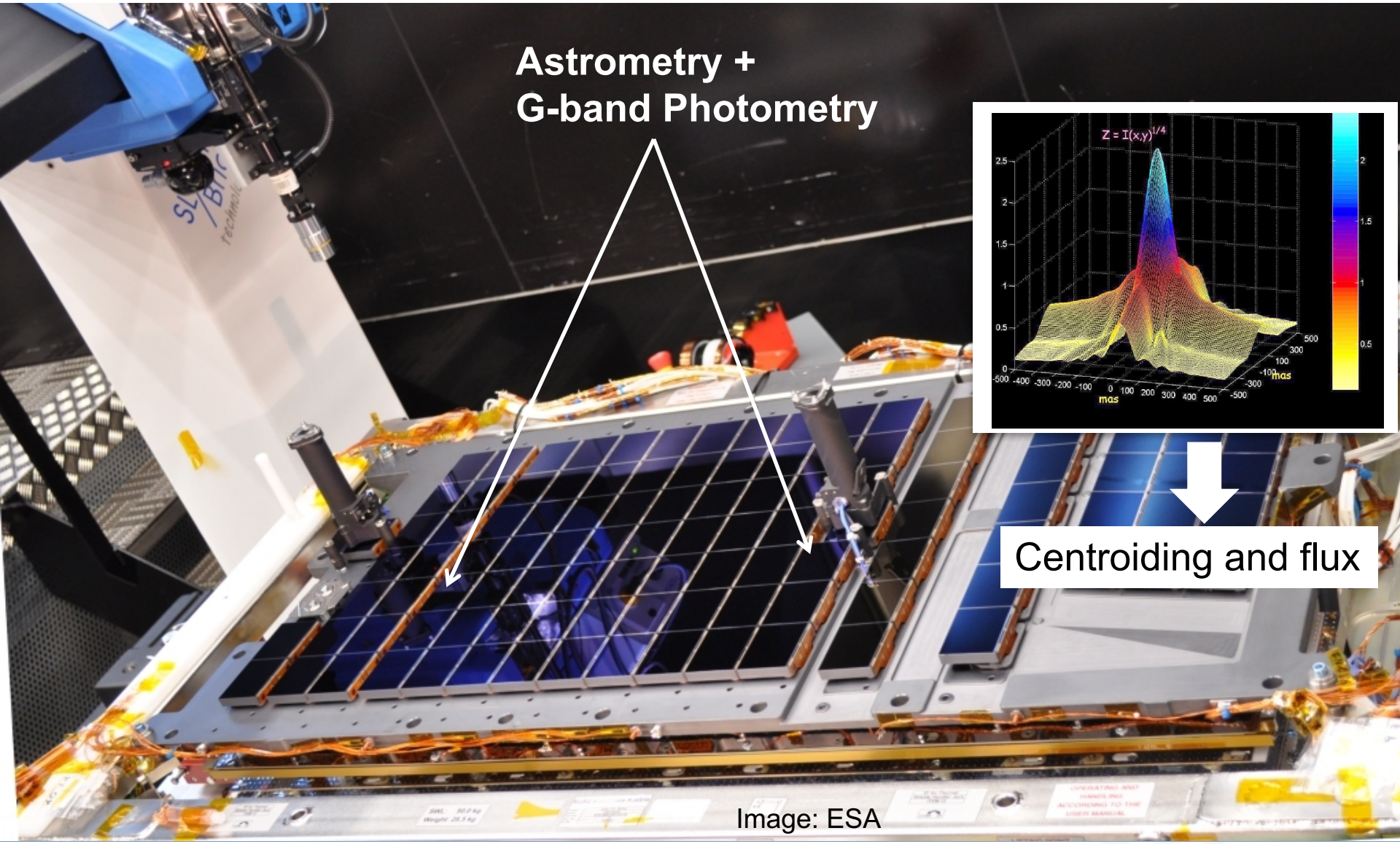

Image: ESA

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Data Processing and Analysis Consortium

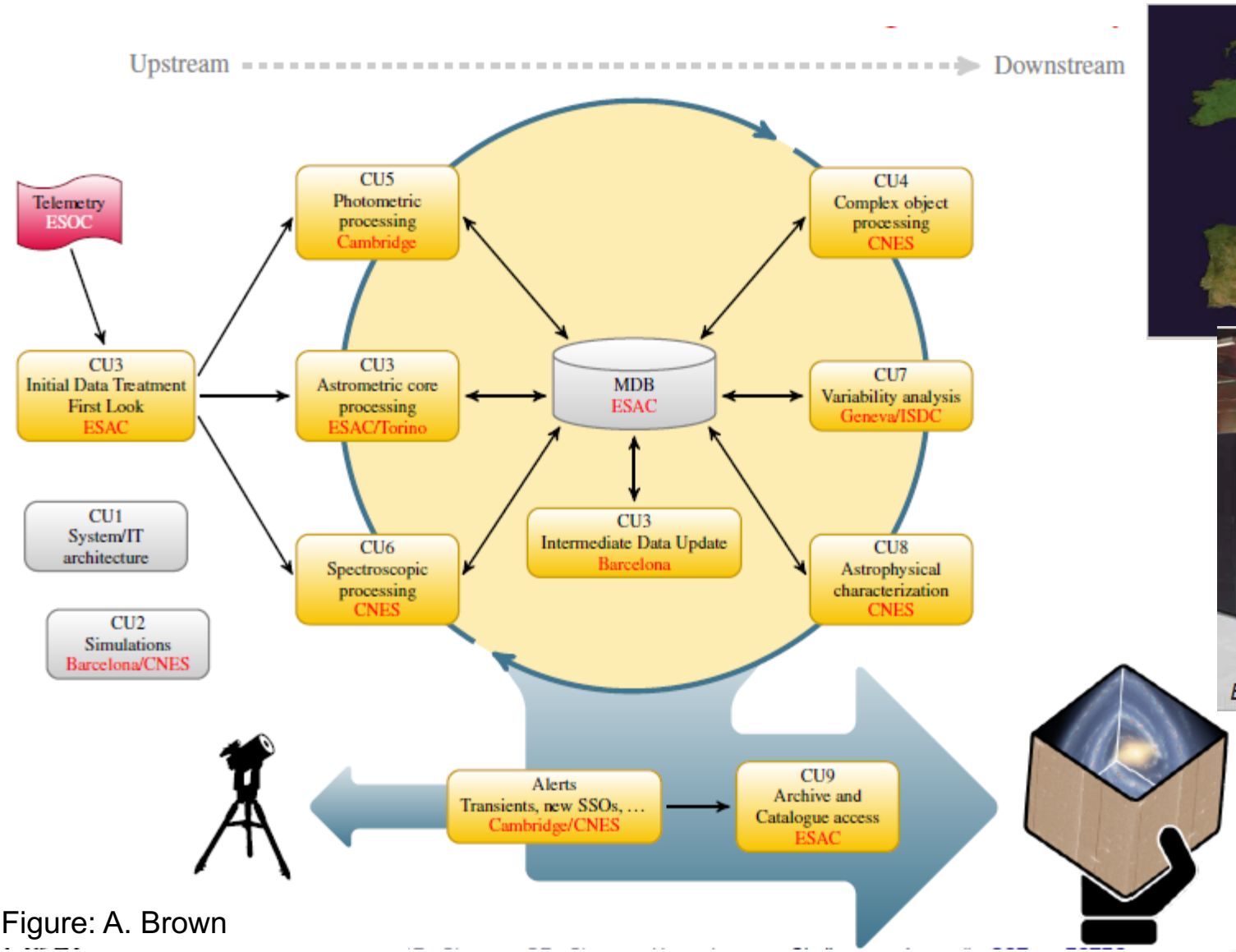
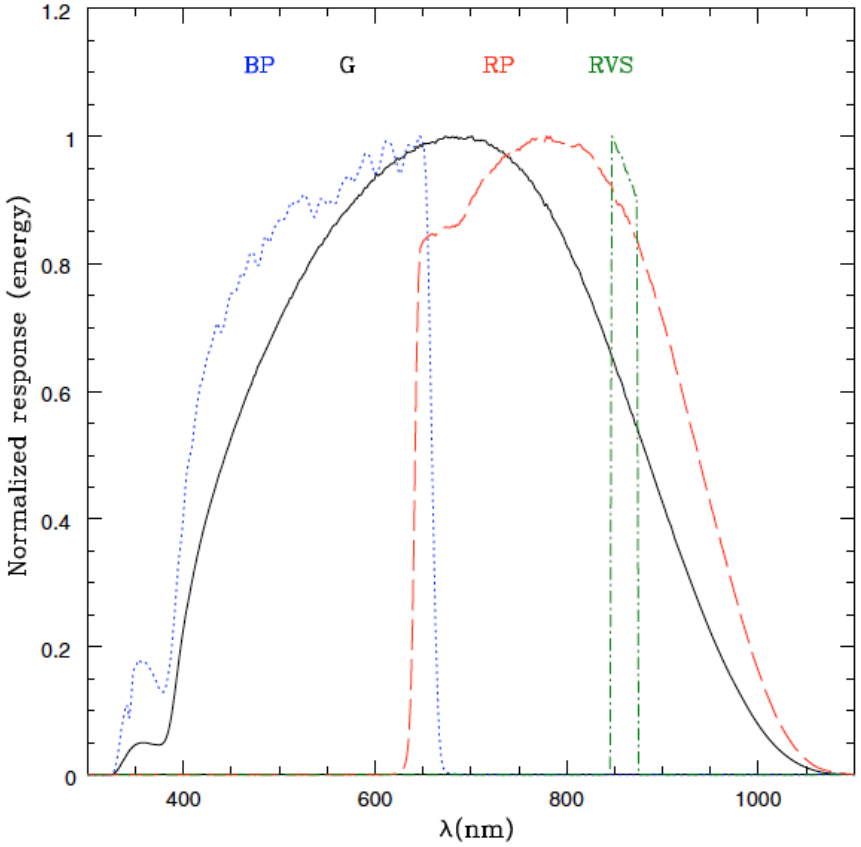
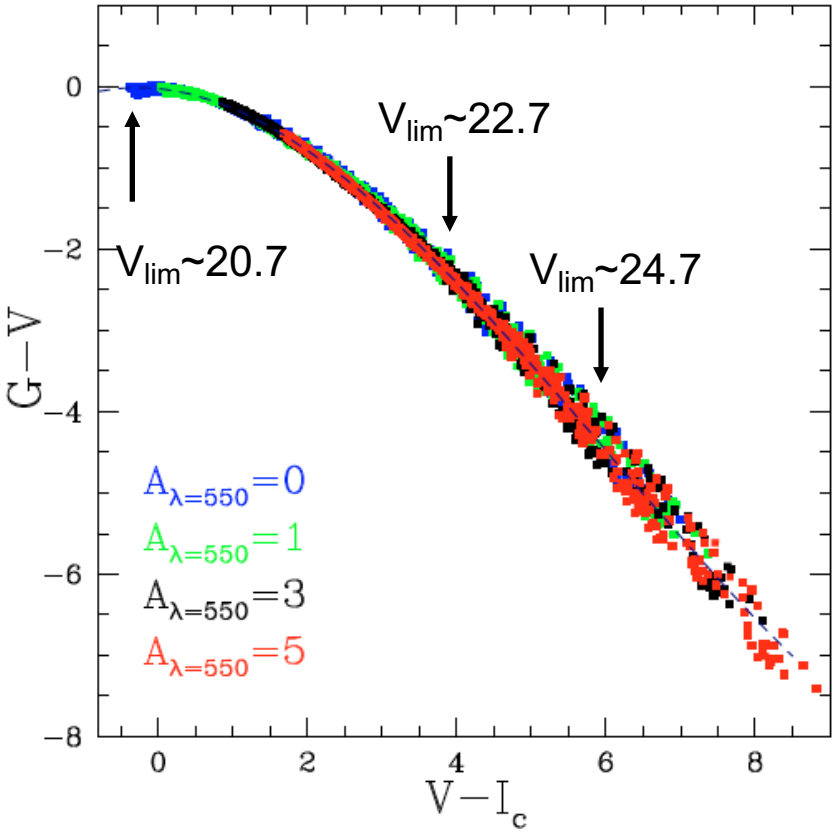


Figure: A. Brown

Gaia limiting magnitude

$G - V = 0.02266 - 0.27125 \cdot (V\text{-}I_C) - 0.11207 \cdot (V\text{-}I_C)^2$ (see, Gaia DR1 documentation)





Jordi et al, A&A 523, A48 (2010)

Status

- Gaia spacecraft, payload and ground stations are working in routine mode
- Daily monitoring confirms the health of all subsystems
- DPAC (CUs and DPCs) is working nominally (ingestion, daily treatment, health monitoring); astrometric, photometric and variability pipelines are being improved for the second release; other subsystems are facing real data
- Propellant can last for 5+5 yrs
  - mission extension has been proposed and is under discussion

Astrometry

Observations

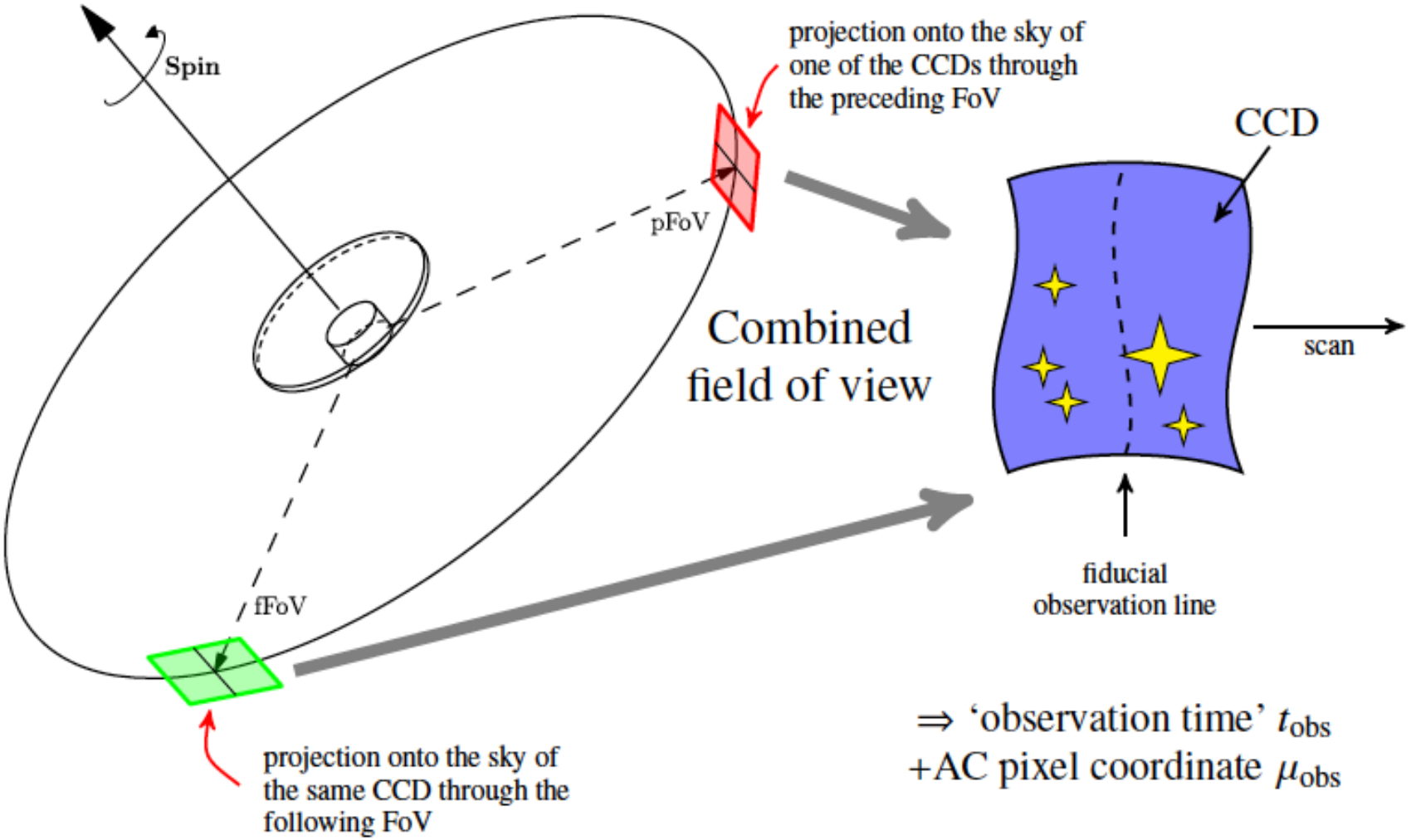


Figure: A. Brown

Basic concept: AGIS

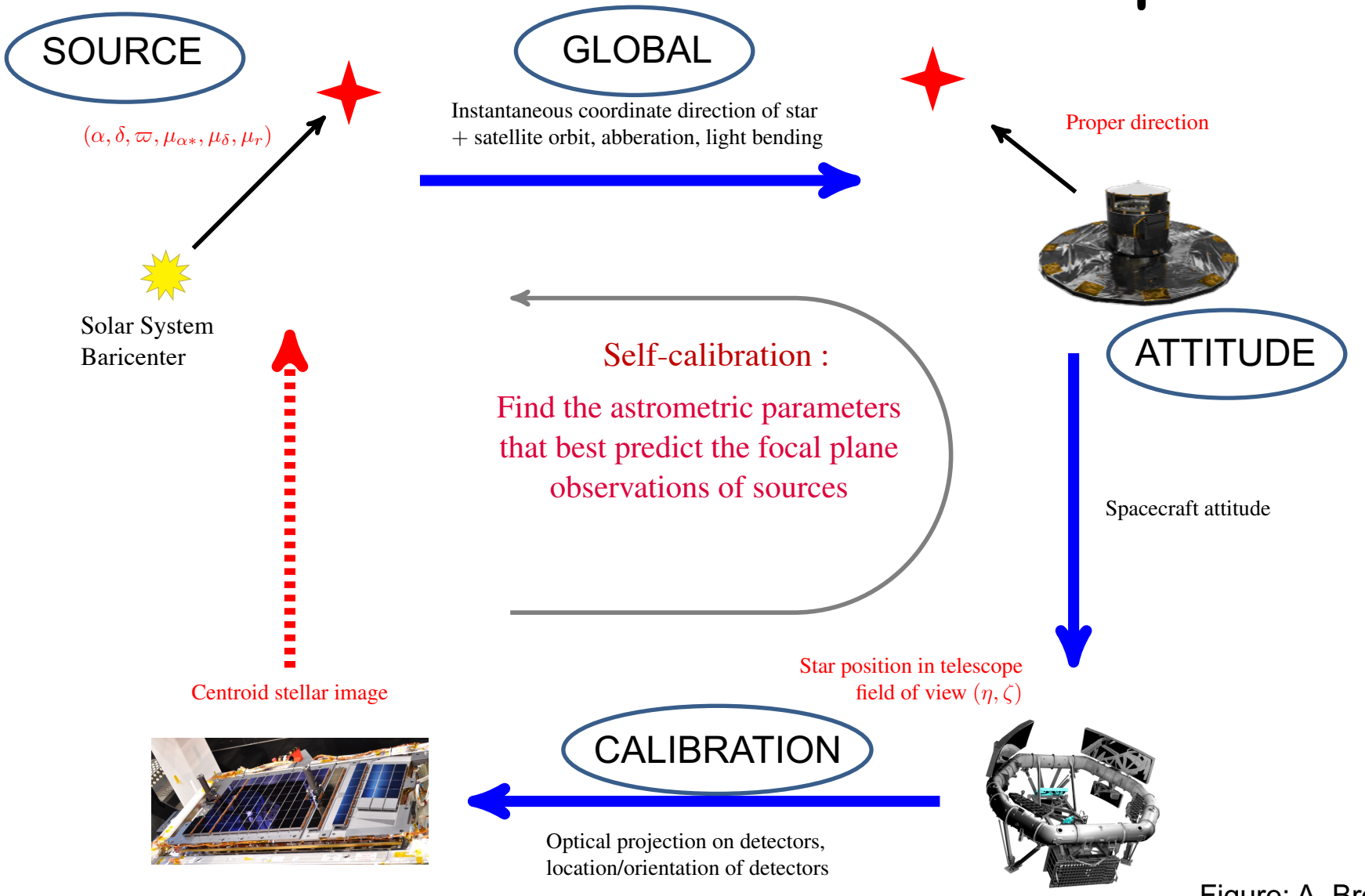


Figure: A. Brown

Whole processing: self-calibration

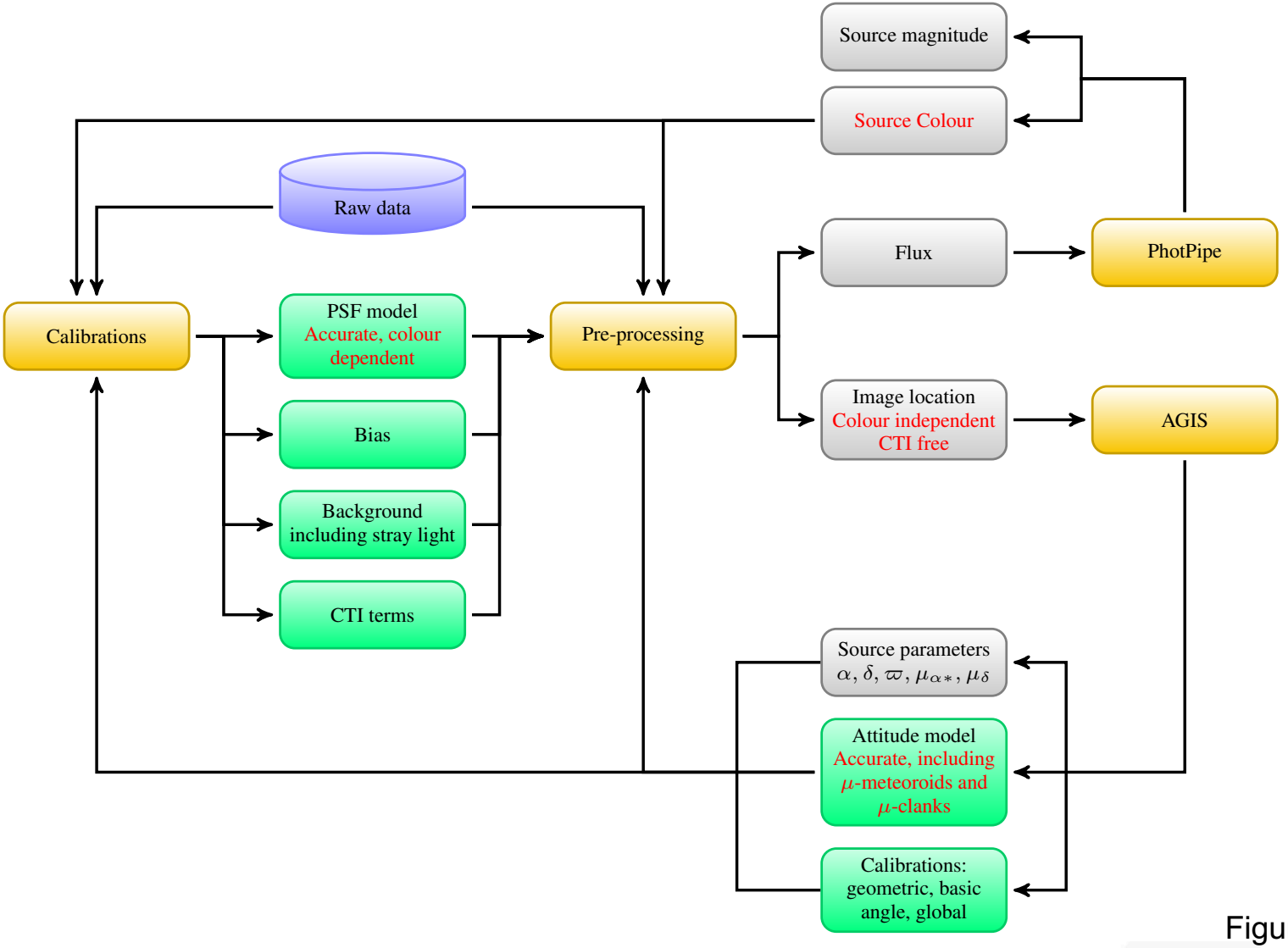
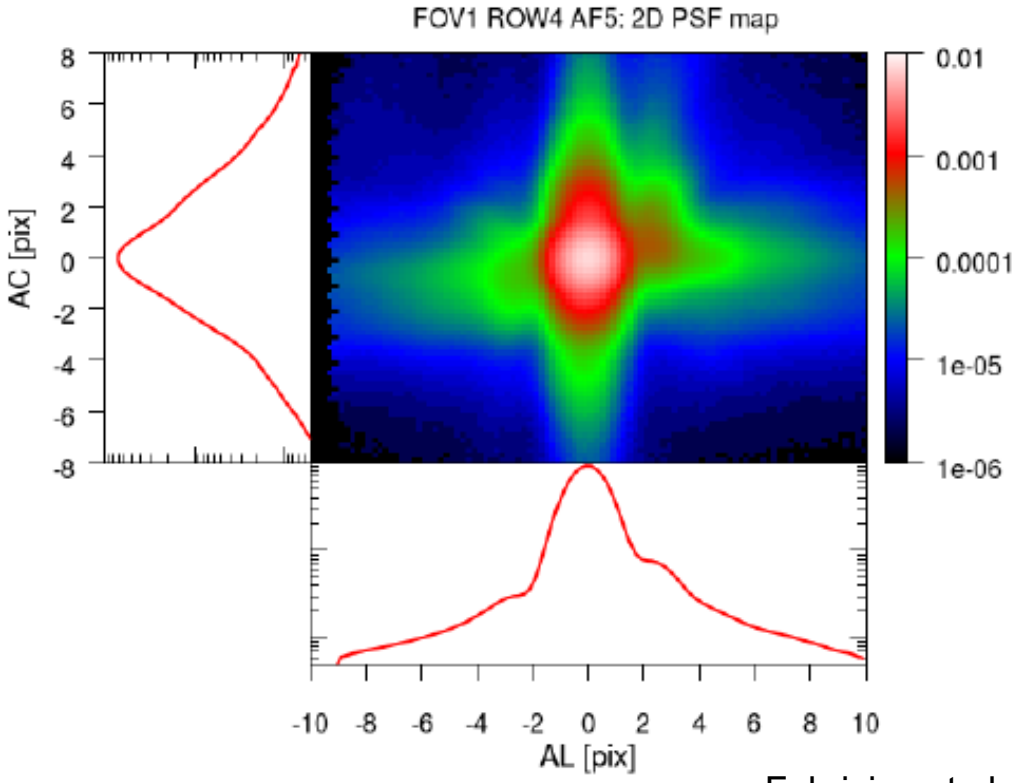


Figure: A. Brown

PSF/LSF calibration

PSF, LSF are modelled per [FoV + AC&AL position +gate + window class] combination and its variation is monitored daily

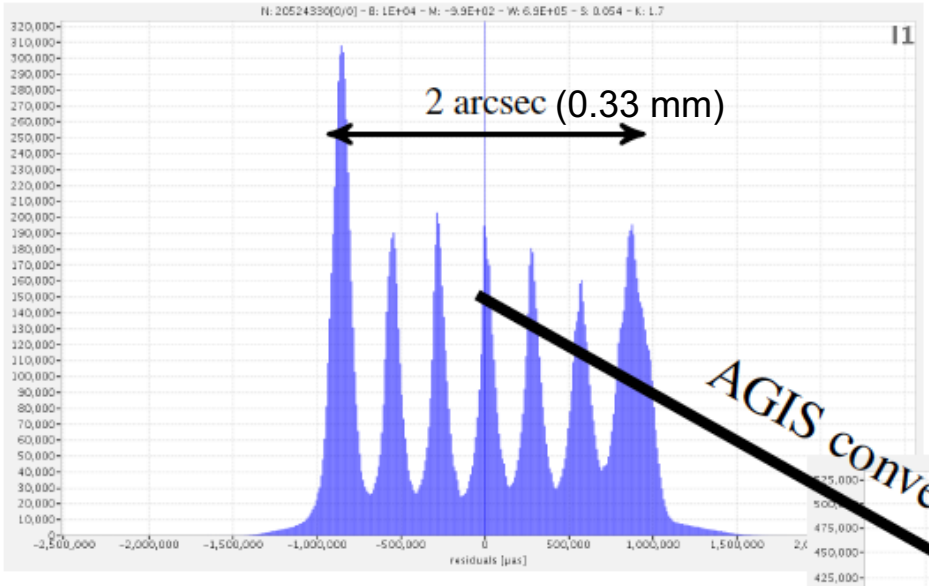
PSF, LSF include dependence with colour (chromaticity as well) and broadening due to the AC motion



Photometric information is needed

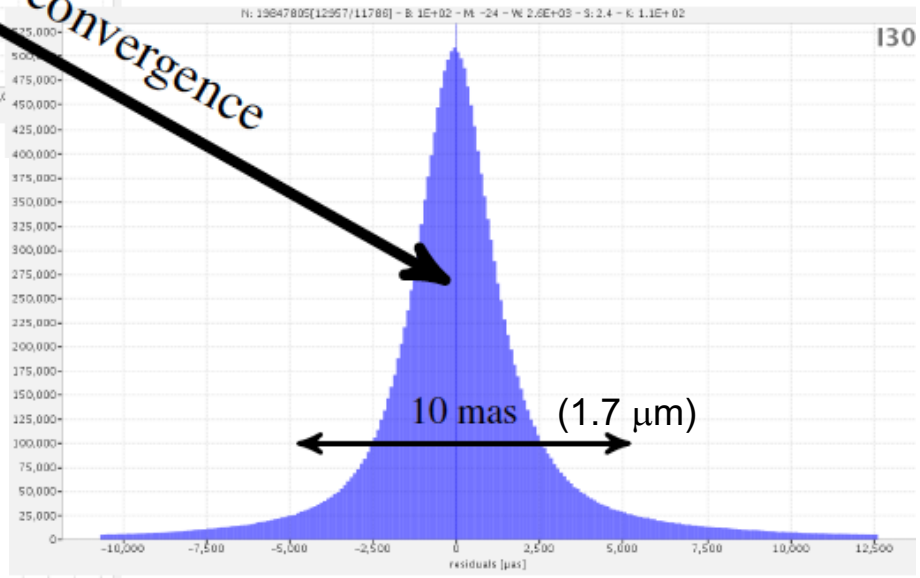
Fabricius et al, 2016

Geometry calibration



Initial Data Treatment

AGIS convergence



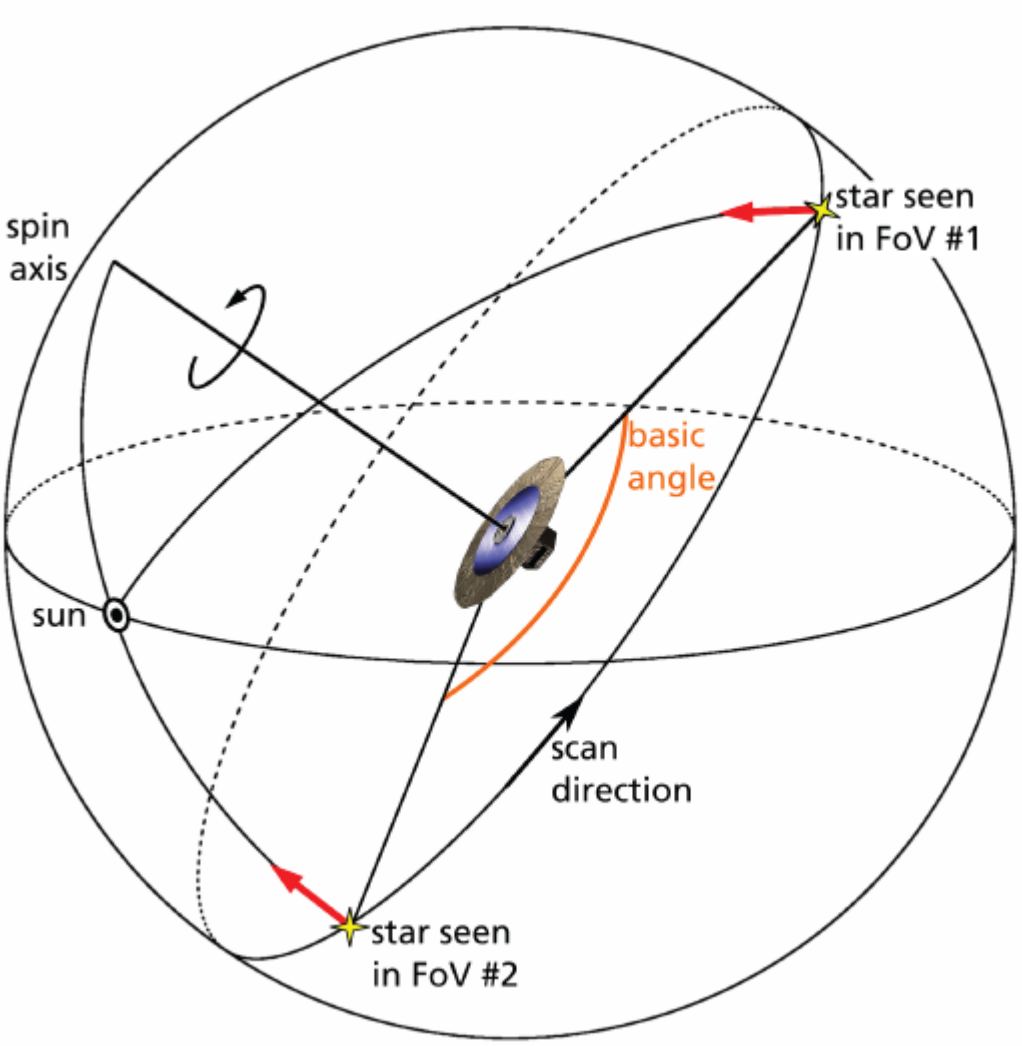
Calibration accounts for:
(x,y) position + rotation
and variation with time

FoV + CCD/stich blocks + gate

After geometry calibration

Figures courtesy DPAC/AGIS team, Airbus DS

Basic angle

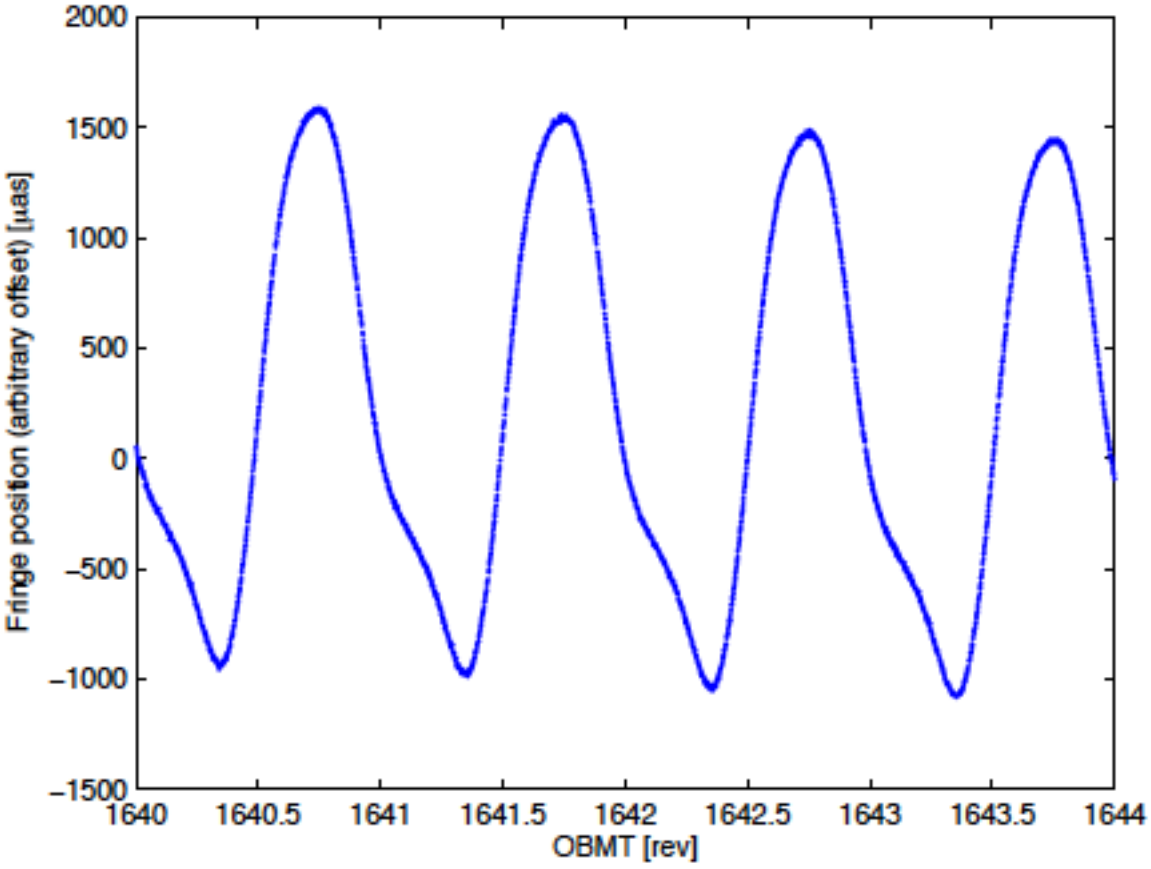


Basic angle must be very constant !

A special device Basic Angle Monitor checks for variations

Figure: Lindegren & Michalik

Basic angle variation



amplitude: ~1 mas
period: 1 revolution

It offsets the parallax zero point

Solution:
Apply measured variation

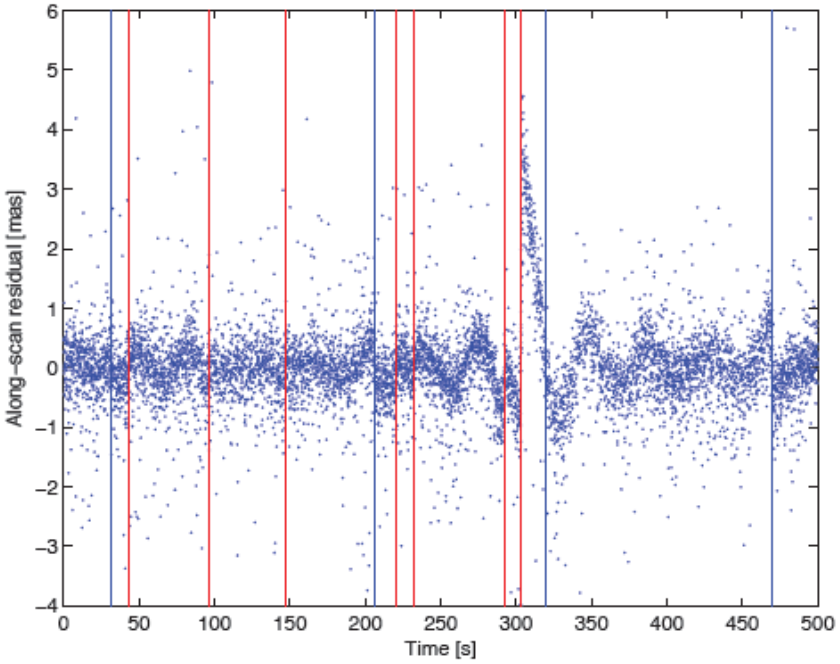
Validation needed and it is under study

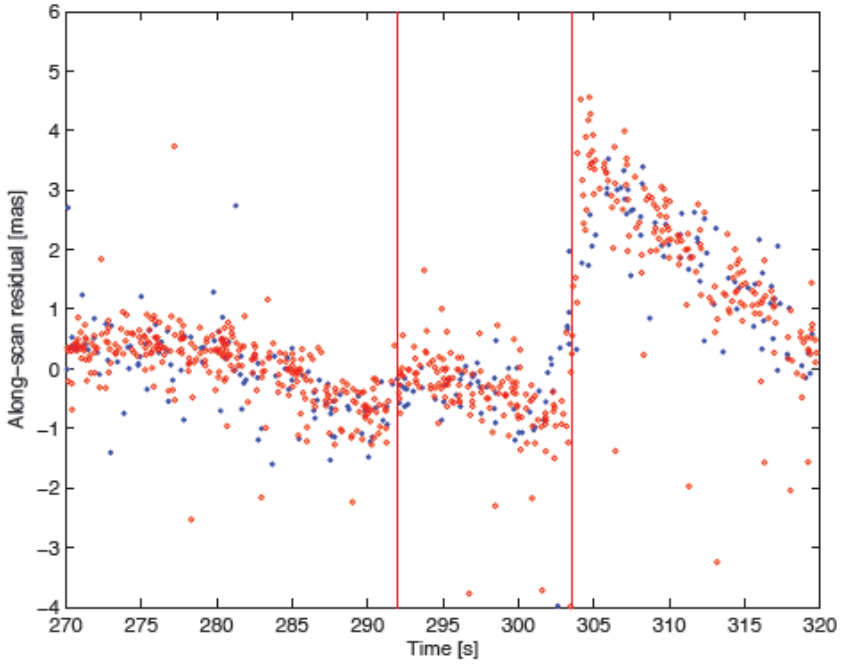
Lindegren et al, 2016

Attitude

Aims to determine position and orientation of the satellite

Major disturbances: Micrometeoroids impacts and micro-clanks
Modelled in the attitude calibration

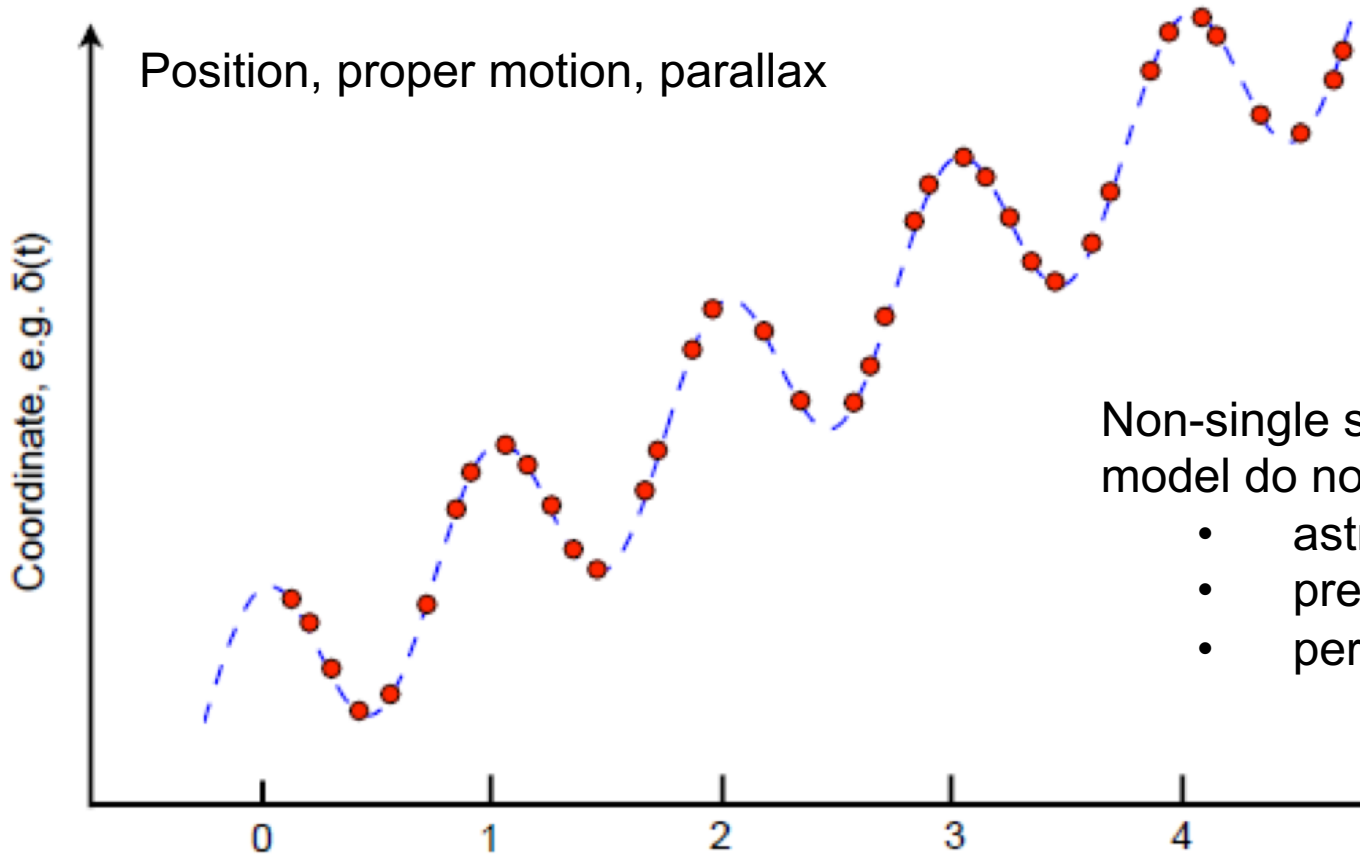




Effect of micro-clanks

Lindegren et al, 2016

Source updating



Non-single stars: 5-parameters model do not fit

- astrometric binaries
- presence of exoplanets
- perspective acceleration

Figure: D. Michalik

Iteration & convergence: AGIS

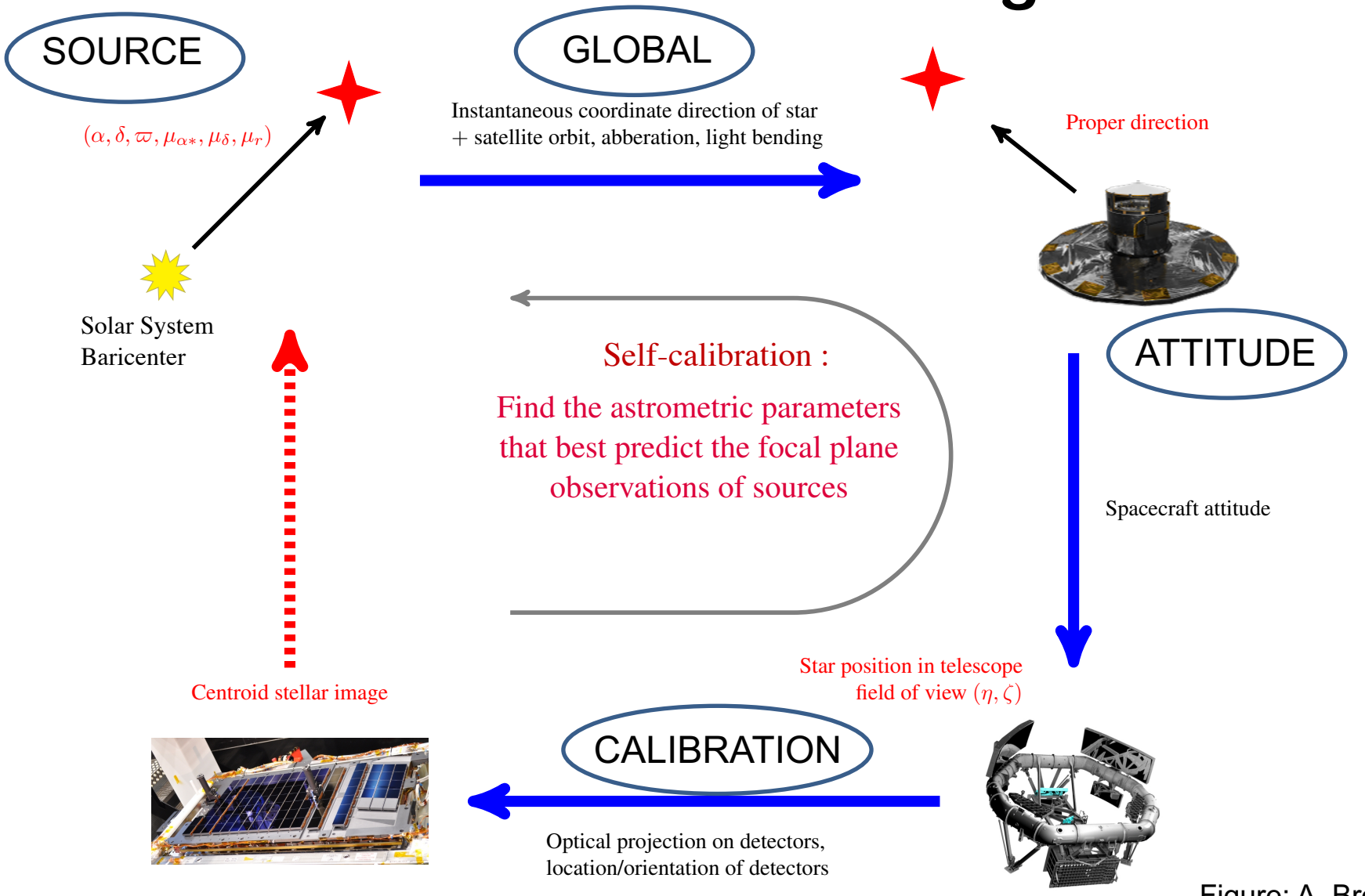
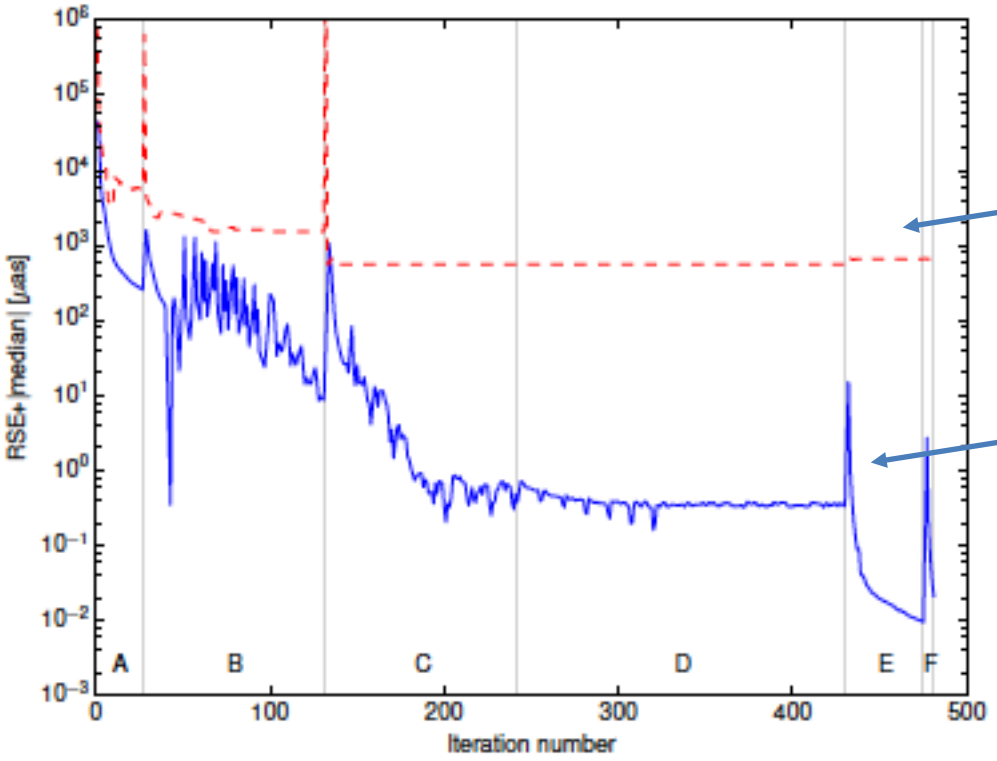


Figure: A. Brown

Convergence

Iteration process for Gaia Data Release 1



AL residual

Parallax updates

The several letters indicate main phases of the iterative scheme

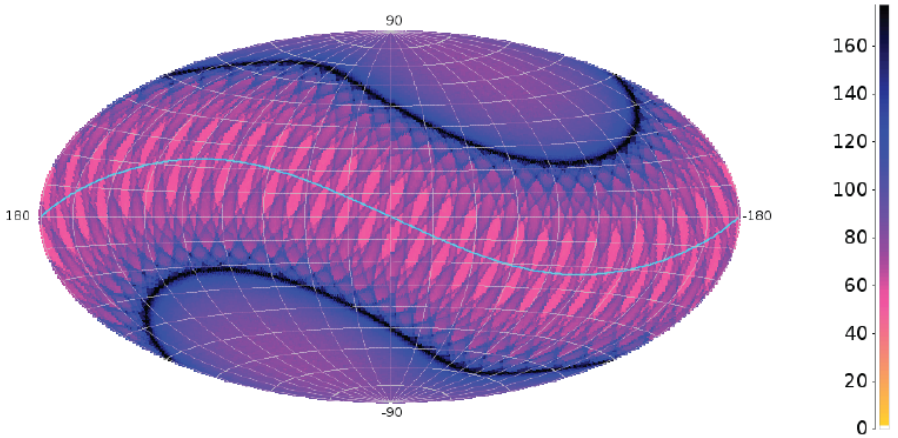
Lindegren et al, 2016

End-of-mission performance

End-of-mission performance

Precision depends on the SNR:

- number of observations (ecliptic latitude)
- magnitude



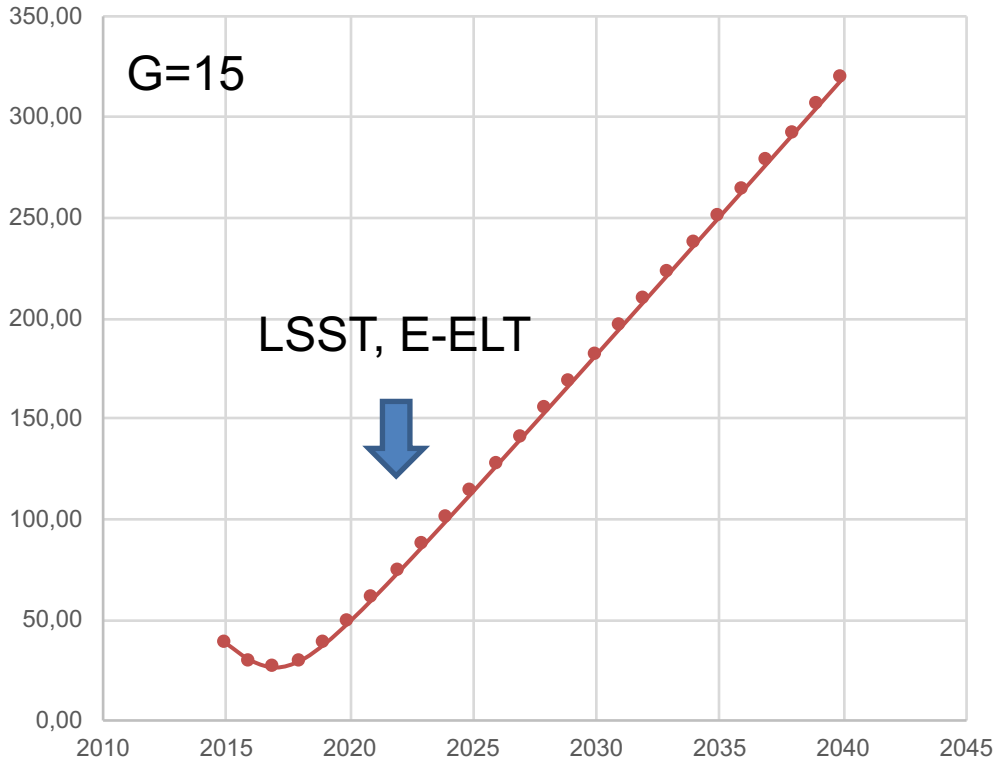
Precision of parallax. Precision of position scales with a factor ~0.74

	B1V	G2V	M6V
V-I_C [mag]	-0.22	0.75	3.85
Bright stars	5-16 μas (3 mag < V < 12 mag)	5-16 μas (3 mag < V < 12 mag)	5-16 μas (5 mag < V < 14 mag)
V = 15 mag	26 μas	24 μas	9 μas
V = 20 mag	600 μas	540 μas	130 μas

http://www.cosmos.esa.int/web/gaia/science-performance

Astrometry degradation with time

Position precision with time (μas)



Mission extension:

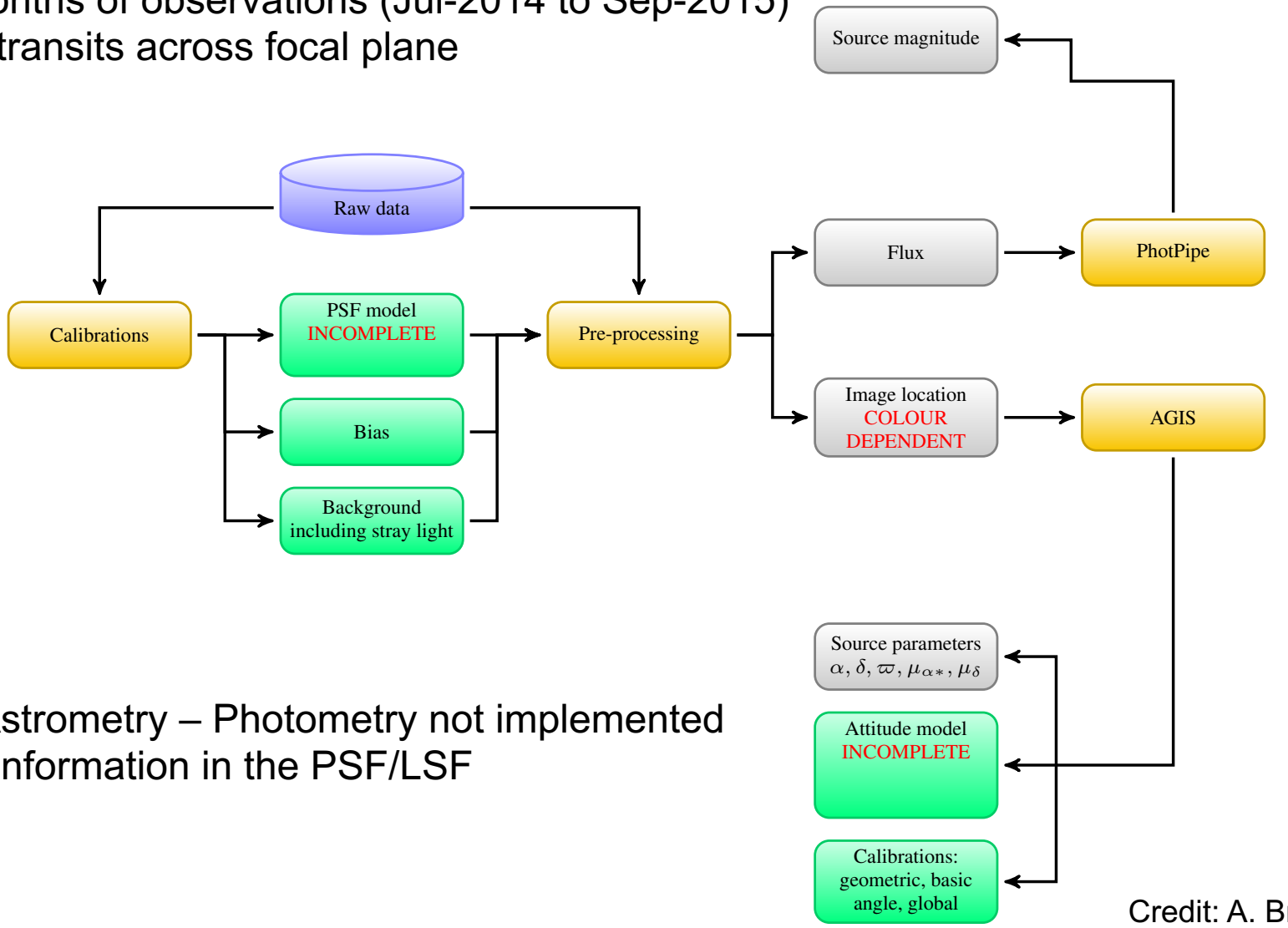
- Position, parallax, photometry & radial velocities precision scales with $t^{0.5}$
- Proper motion precision scales with $t^{1.5}$
- More complex systems scales with $t^{4.5}$

Gaia Data Release 1

Accessible from https://archives.esac.esa.int/gaia/

Implementation in GDR1

"Only" 14 months of observations (Jul-2014 to Sep-2015)
~ 2.3 × 10^{10} transits across focal plane



The loop Astrometry – Photometry not implemented
No colour information in the PSF/LSF

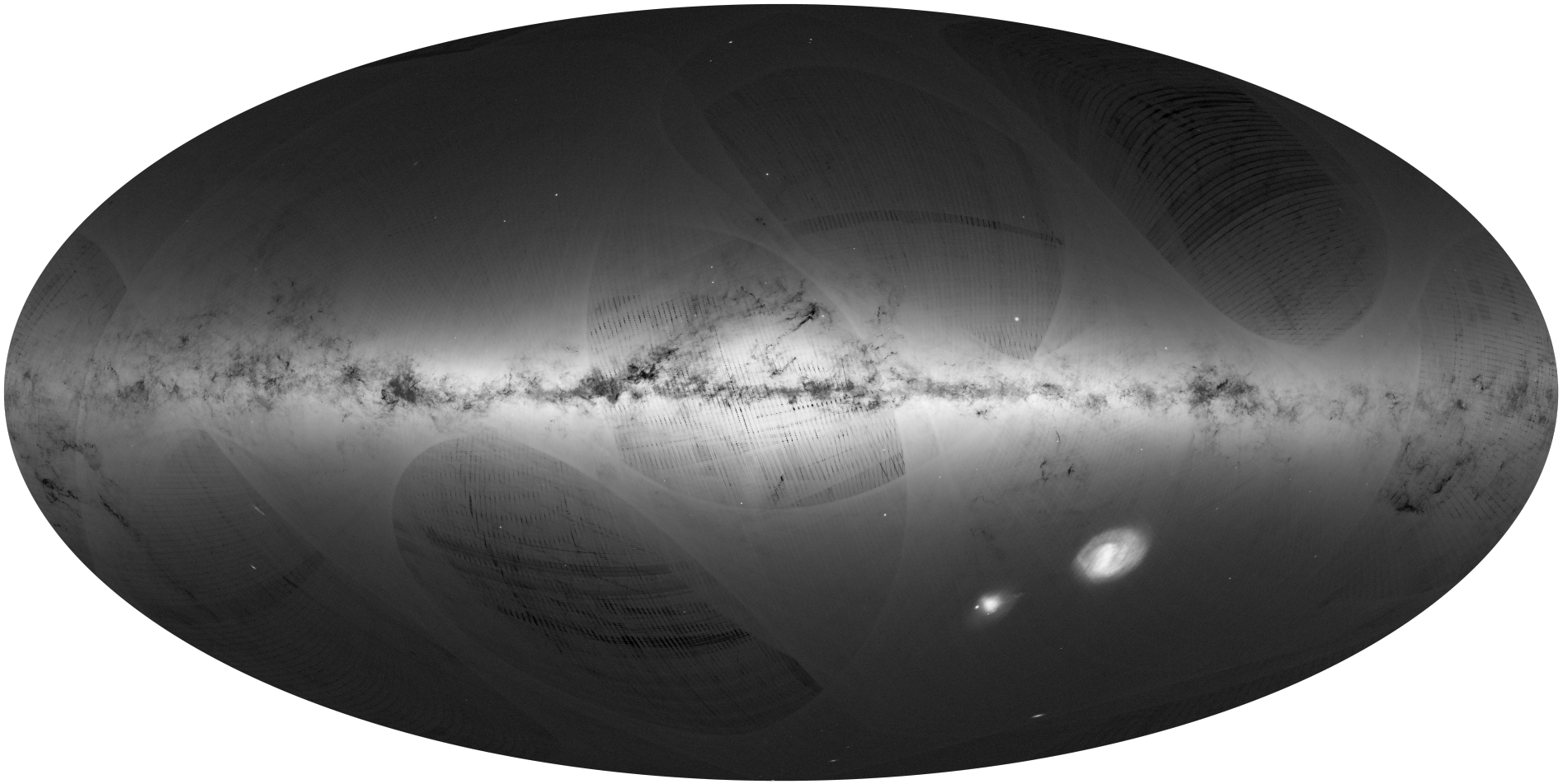
Credit: A. Brown

Gaia DR1: content

- 1.143 billion sources with mean (α,δ) and G
- 2 million sources with mean (α,δ) and G + proper motions and parallaxes
- 3194 light curves for RR Lyr and Cepheid stars
- Special solution for QSOs in ICRF2

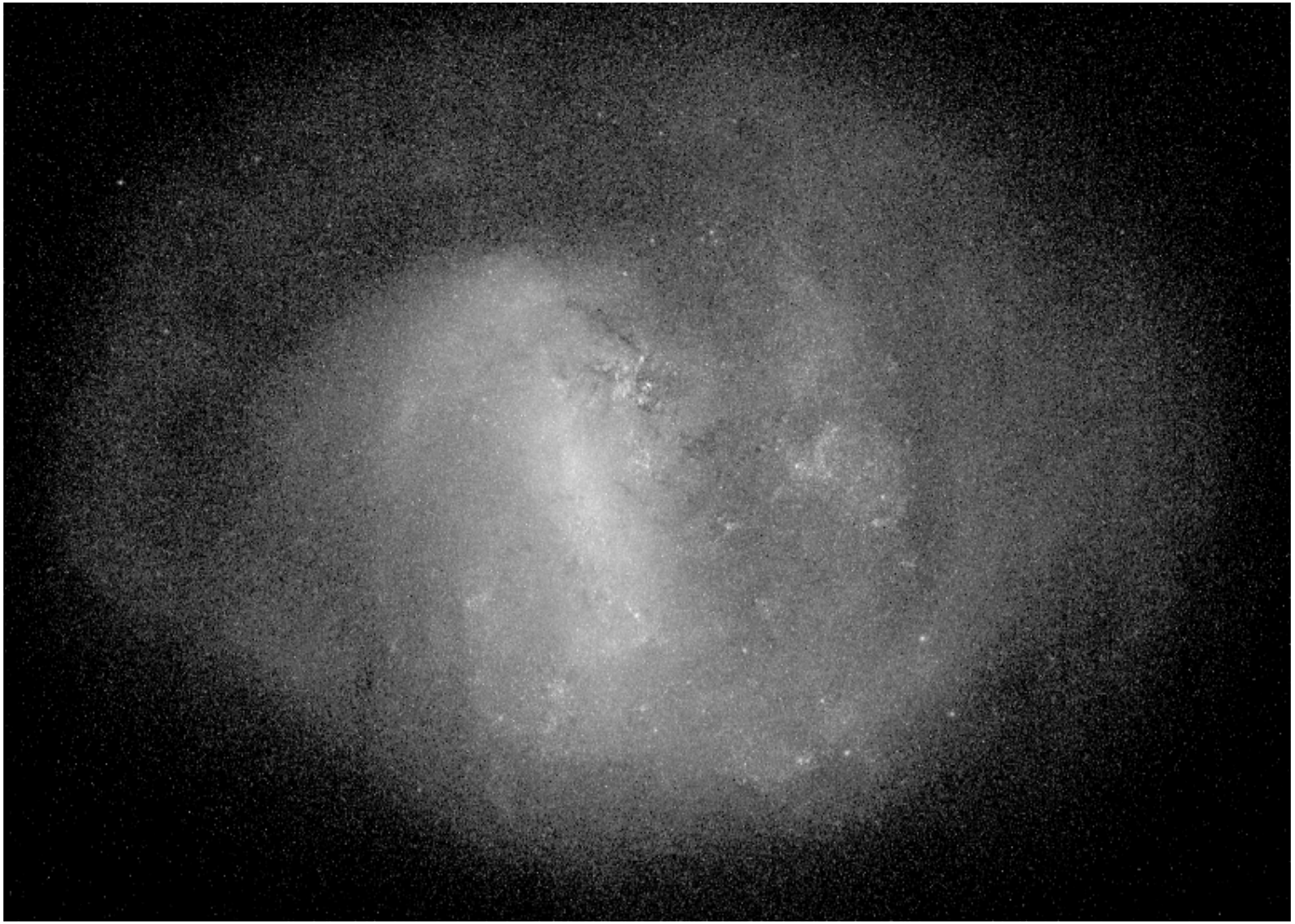
The first map of Gaia

(α, δ) for 1.143 billion sources to G = 20.7



ESA/Gaia/DPAC/André Moitinho & Marcia Barros (CENTRA - University of Lisbon)

LMC sources in Gaia DR1



ESA/Gaia/DPAC/André Moitinho & Marcia Barros (CENTRA - University of Lisbon)

Astrometric precision

Quantity (units of mas)	10%	50%	90%
Standard uncertainty in α ($\sigma_{\alpha*} = \sigma_\alpha \cos\delta$)	0.29	1.85	13.30
Standard uncertainty in δ (σ_δ)	0.26	1.62	11.67
Semi-major axis of error ellipse in position ($\sigma_{\mathrm{pos,max}}$)			
$G < 16$ (7% of the secondary data set)	0.11	0.27	5.27
$G = 16$–17 (7%)	0.18	0.50	12.10
$G = 17$–18 (12%)	0.28	0.77	12.40
$G = 18$–19 (21%)	0.48	1.45	13.66
$G = 19$–20 (30%)	0.93	2.76	16.61
$G = 20$–21 (22%)	1.90	6.75	21.45
all magnitudes (100%)	0.35	2.43	16.25

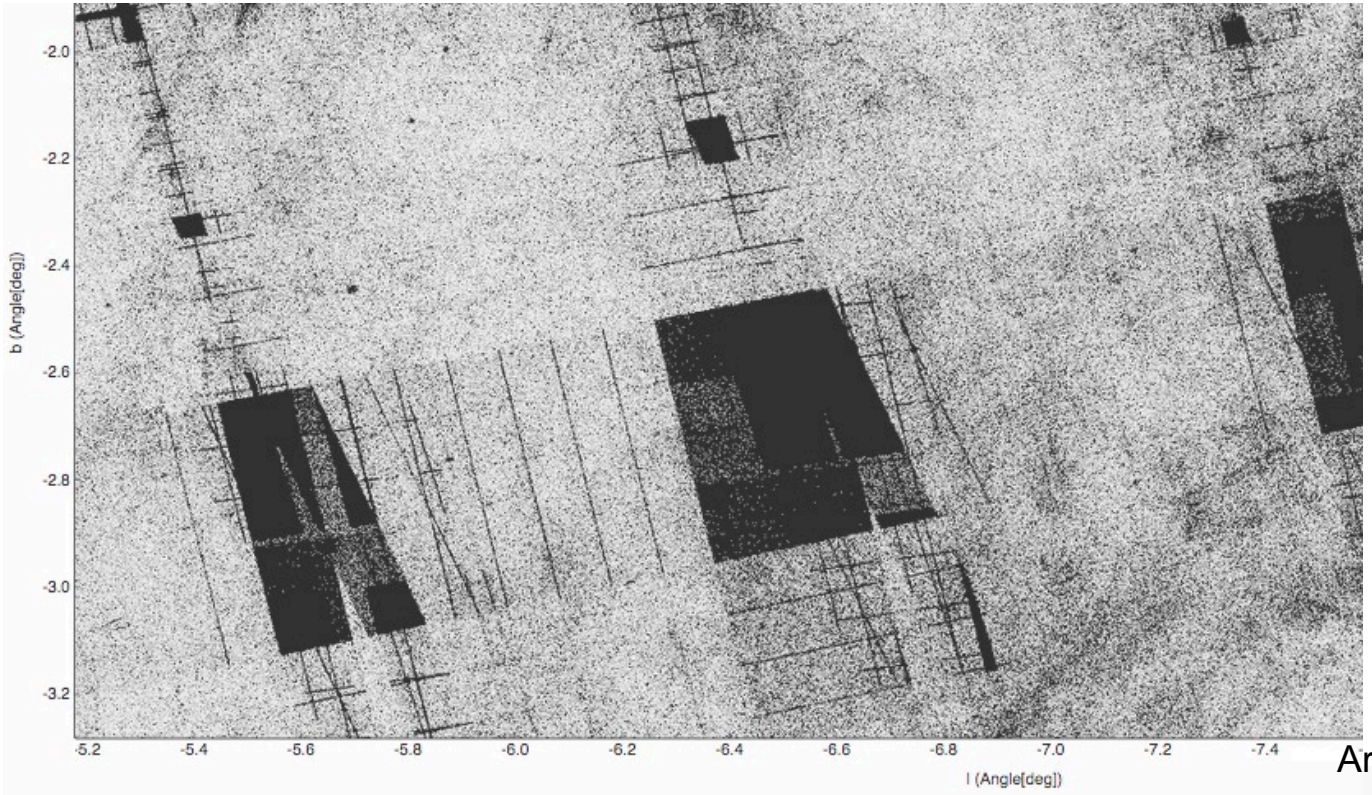
1.143 billion sources, the well behaved sources G < 20.7 mag

Lindegren et al, 2016

Completeness of GDR1

Completeness is not representative at all of the end-of-mission expectations

- Limited angular resolution: few double stars below 2” (4” in dense areas)
- Deficit of sources with extreme colours and faint stars in dense areas
- No very bright (G < 4.6 for TGAS)
- No stars with high proper motion: $|\mu| > 3.5$ arcsec yr $^{-1}$



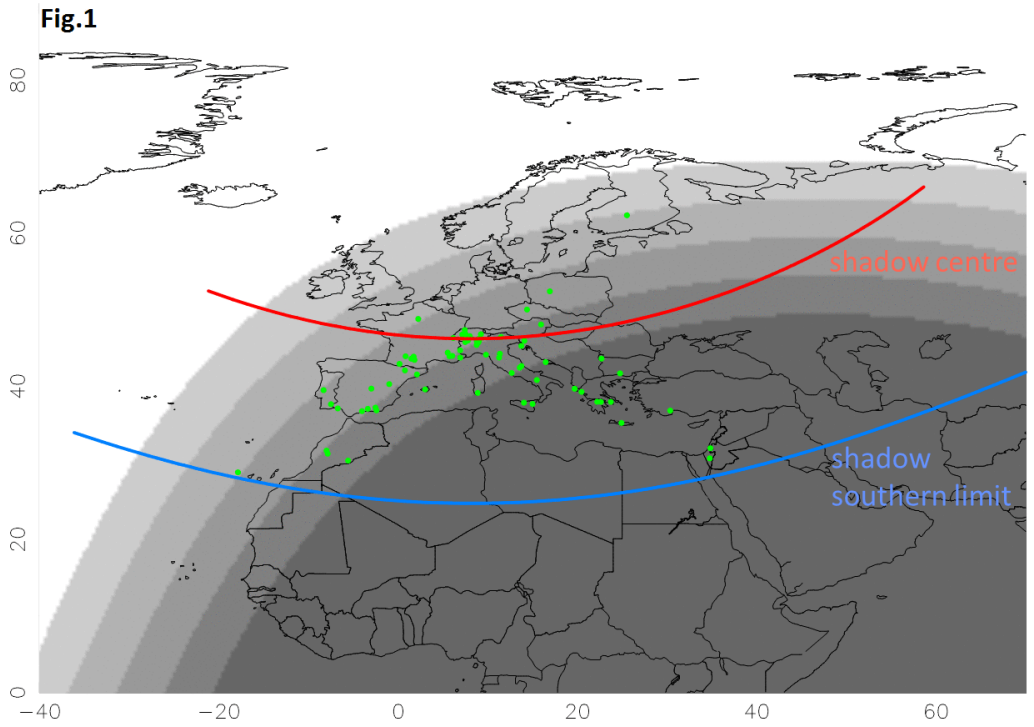
Arenou et al 2016

Examples

Occultation by Pluto

- UCAC4 345-180315, 14th mag
- observable from parts of Europe
- 19th of July 2016 around 20h 51m UTC

- pre-Gaia positions → 1500 km uncertainty
- Gaia positions → 100 km uncertainty



http://www.cosmos.esa.int/web/gaia/iow_20160914

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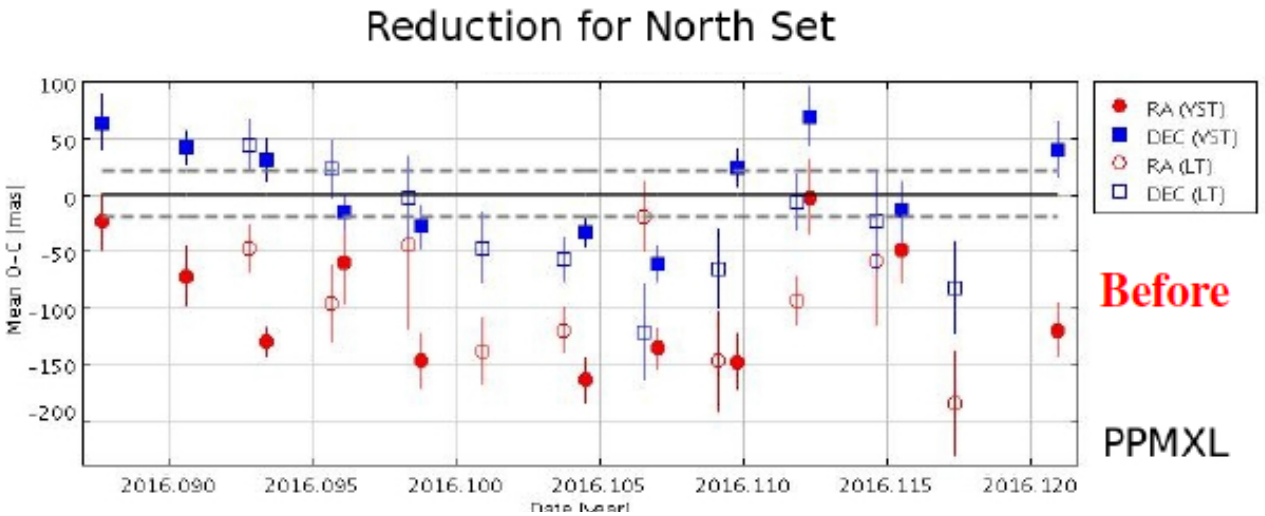
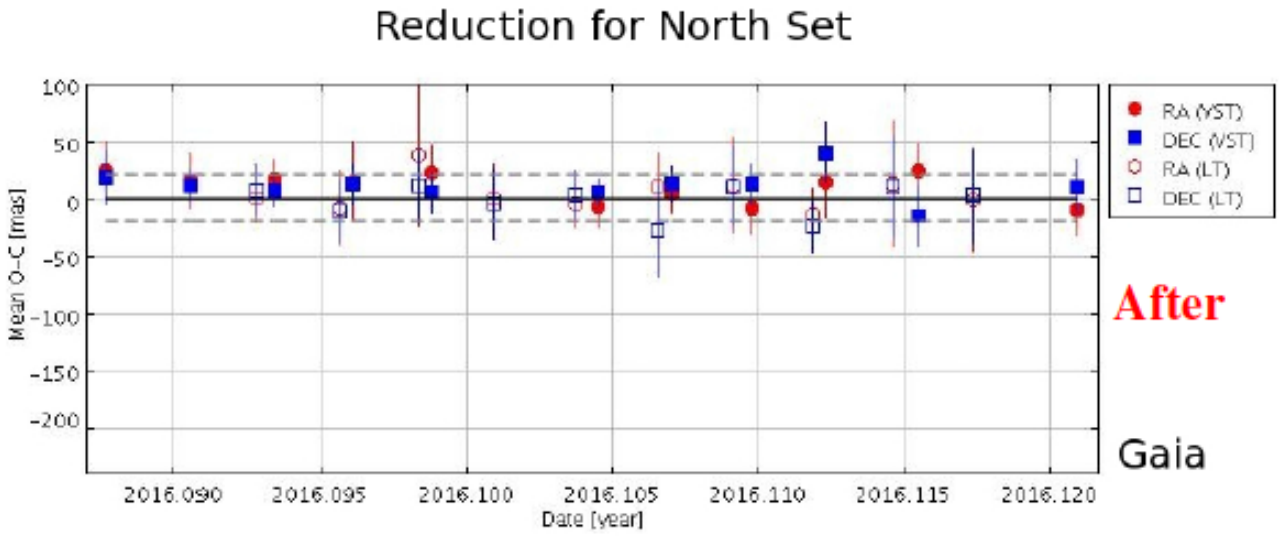
Improved astrometry





GBOT: Ground Based Optical Tracking

Rereduction of VST and LT observations

Credit GBOT/DPAC

Tycho-Gaia Astrometric Solution: TGAS

2 million sources with mean (α,δ) and G + proper motions and parallaxes

Gaia DR1: TGAS (Tycho-Gaia)

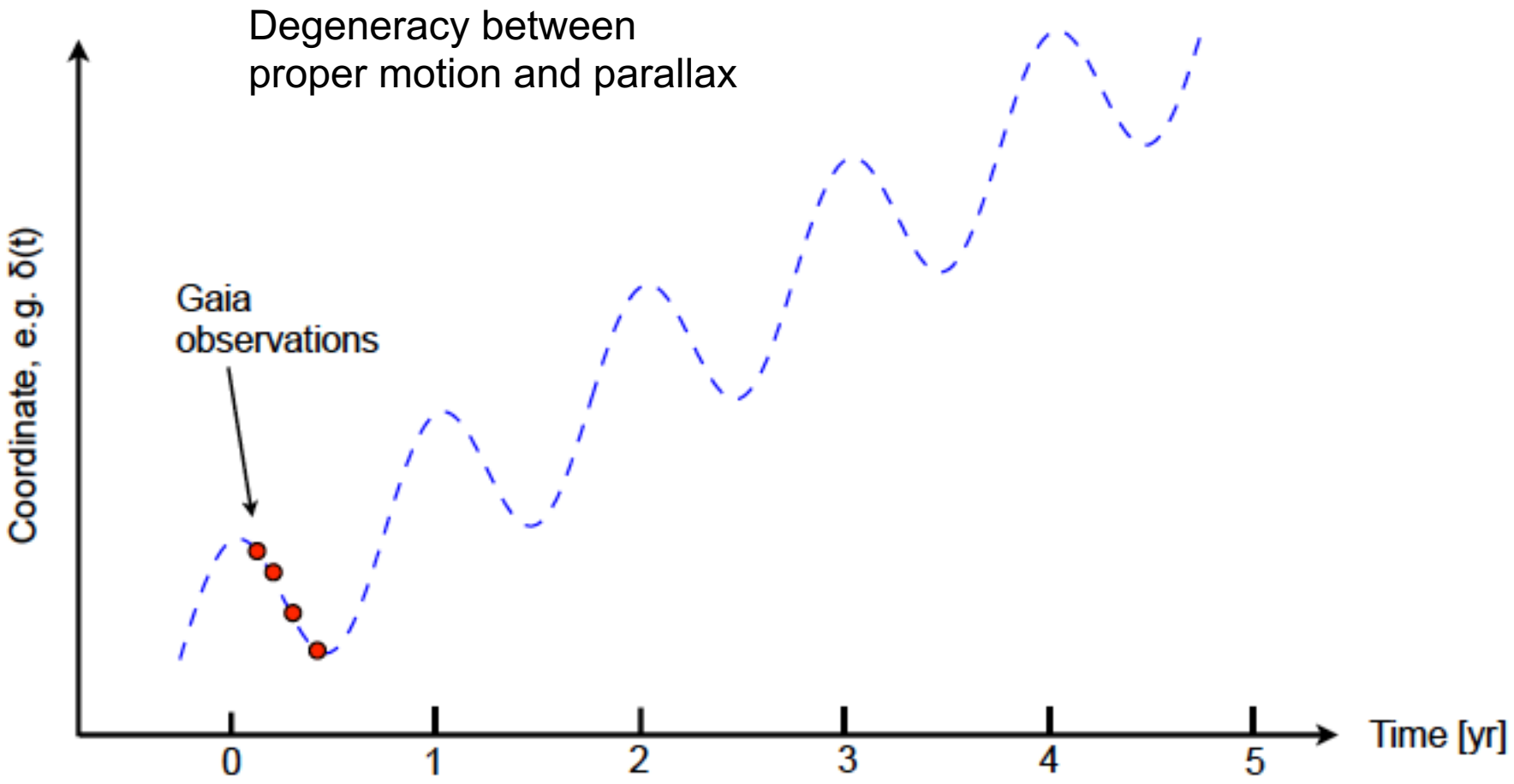


Figure: L. Lindegren

Gaia DR1: TGAS (Tycho-Gaia)

TGAS: The Tycho-Gaia astrometric solution
Michalik et al (2015), Lindegren et al (2016)

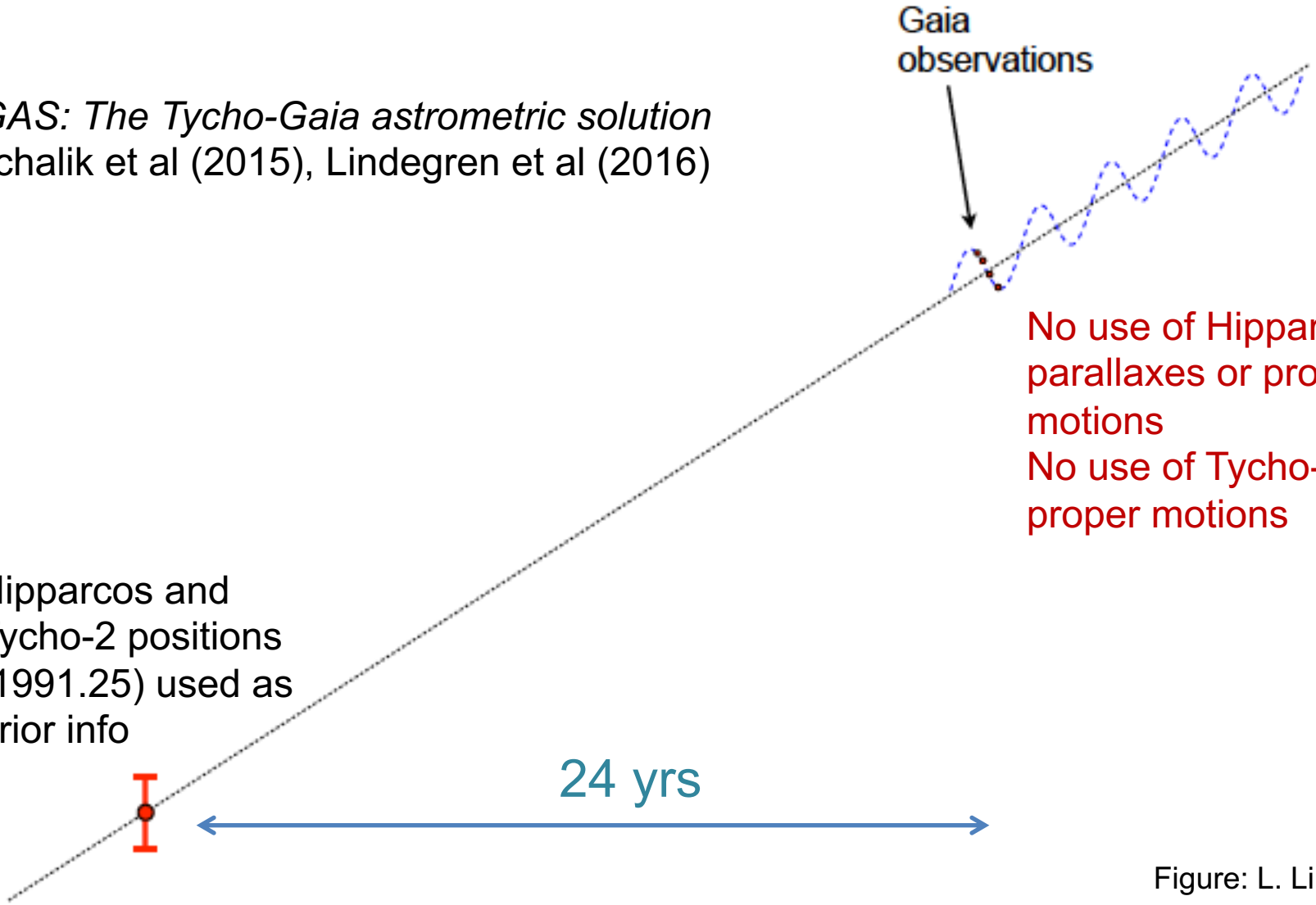


Figure: L. Lindegren

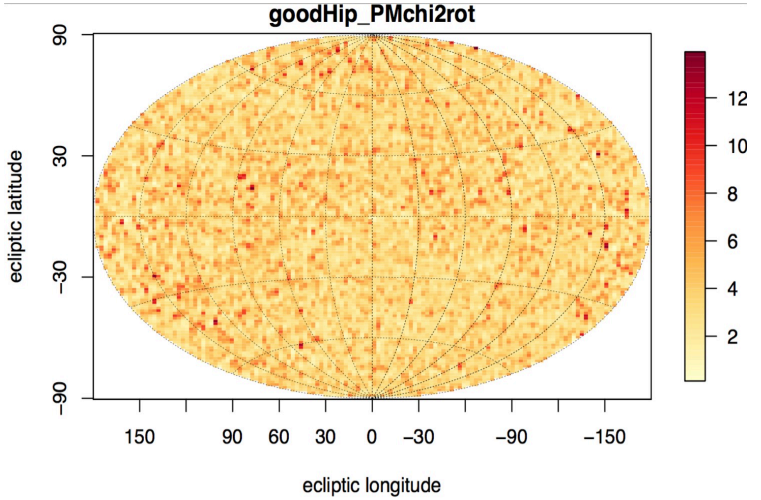
TGAS astrometric solution

Quantity (units of mas and mas/yr)	All primary sources 10%	50%	90%
Standard uncertainty in α ($\sigma_{\alpha*} = \sigma_\alpha \cos\delta$)	0.147	0.254	0.600
Standard uncertainty in δ (σ_δ)	0.139	0.233	0.530
Standard uncertainty in ϖ (σ_ϖ)	0.242	0.322	0.643
Standard uncertainty in $\mu_{\alpha*}$ ($\sigma_{\mu\alpha*}$)	0.503	1.133	2.670
Standard uncertainty in μ_δ ($\sigma_{\mu\delta}$)	0.443	0.867	1.956
Semi-major axis of error ellipse in position ($\sigma_{\mathrm{pos,\,max}}$)	0.203	0.319	0.752
Semi-major axis of error ellipse in proper motion ($\sigma_{\mathrm{pm,\,max}}$)	0.718	1.323	3.187

Lindegren et al, 2016

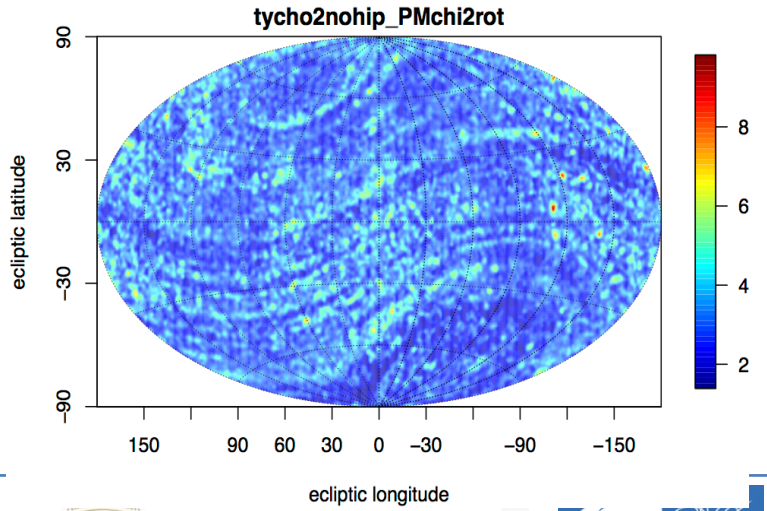
TGAS proper motions validation

- Compared to Hipparcos
  - Gaia - Hipparcos = 0 ±0.004 mas/yr
- Compared to Tycho-2
  - Hipparcos stars: -0.009±0.005 mas/yr
  - Non-Hip stars: 0.08±0.002 mas/yr
    - Little to infer, except Tycho-2 errors as a function of declination
  - Problems with Gaia, if any, second order only
- Compared to VLBI
  - OK: 0.008±006 mas/yr (36 stars)



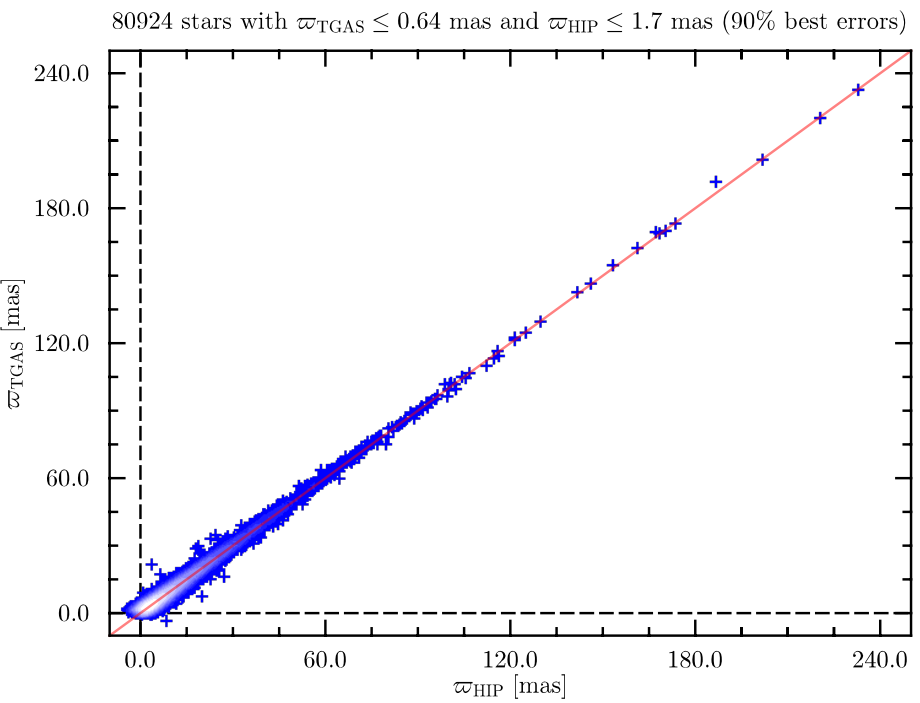
χ^2 of (Gaia – Hipparcos) proper motion

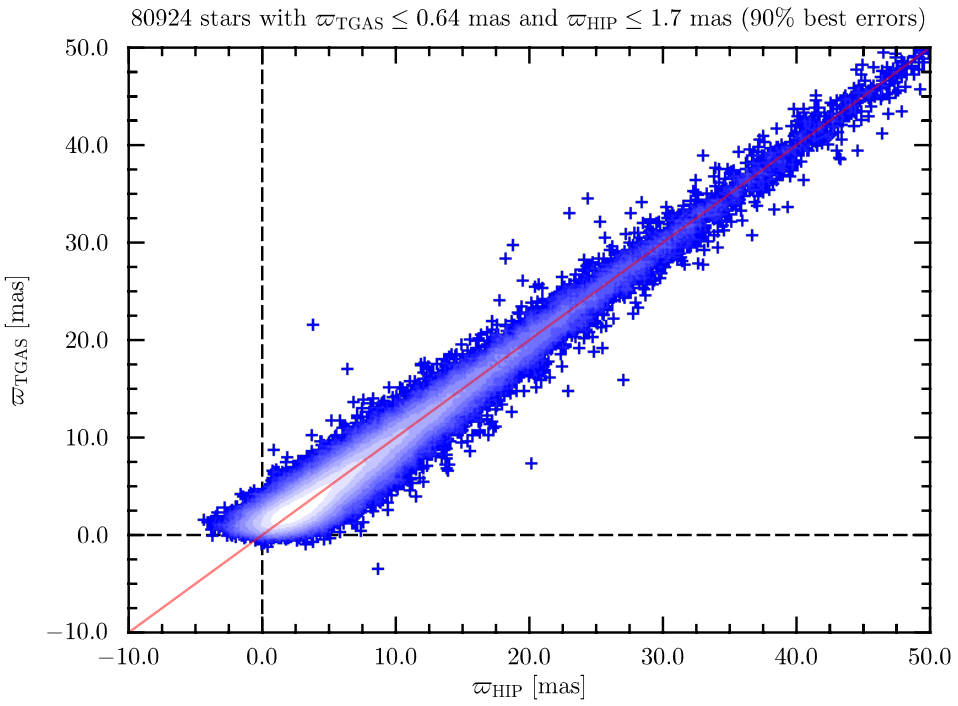
χ^2 of (Gaia – Tycho-2) proper motion



Credit: DPAC/CU9/C. Babusiaux

TGAS parallaxes validation



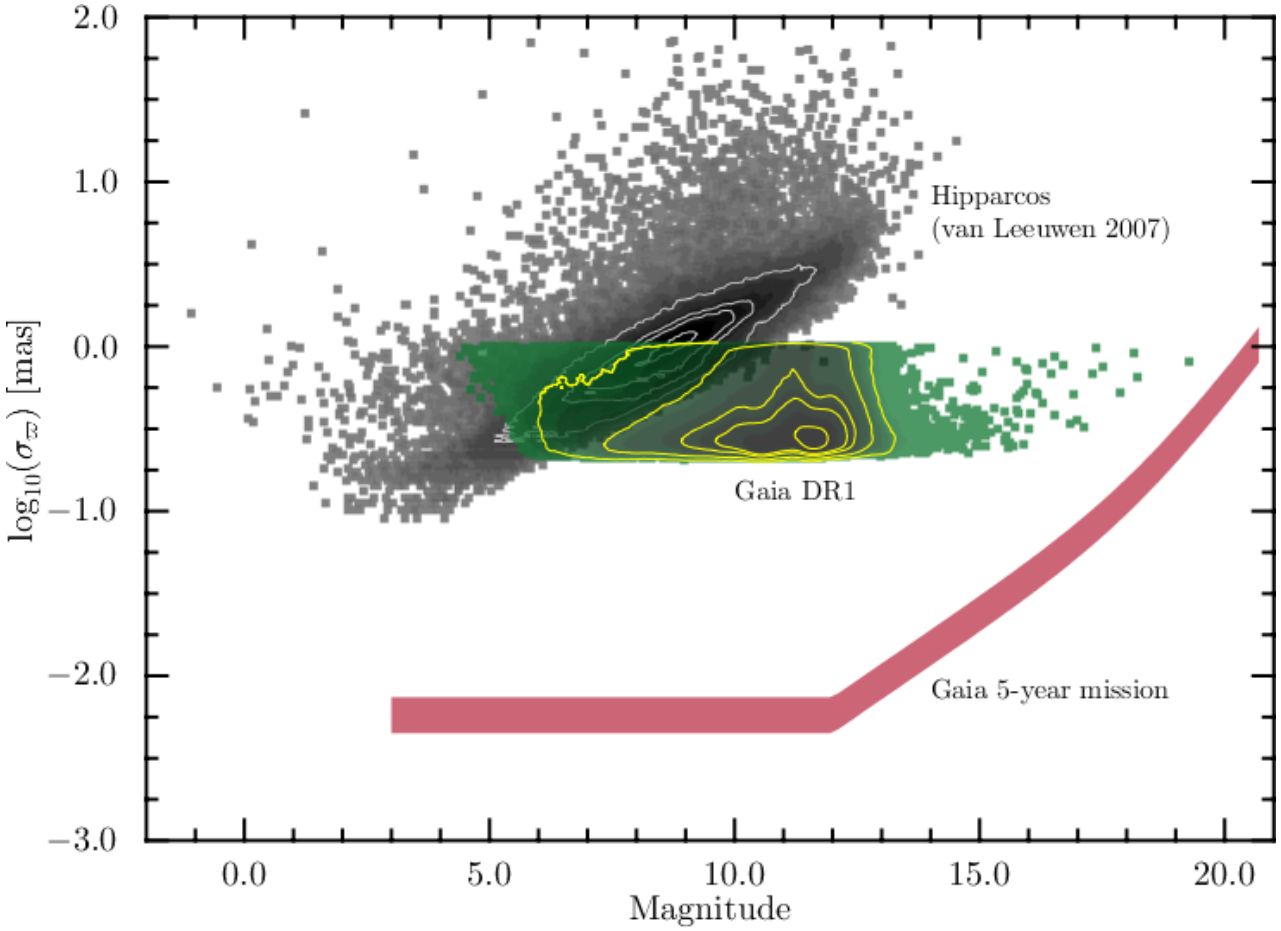


- Hipparcos and TGAS parallaxes are independent
- Global quality of Hipparcos and TGAS
- Errors in GDR1 are realistic

Slide by A. Brown

Credit: DPAC/CU3/AGIS

Parallax uncertainties



TGAS parallax precision compared to:

- Hipparcos parallaxes
- Gaia end-of-mission

Gaia collaboration et al, 2016

Potential of Gaia-DR1

- Validation of results demonstrates their high quality in spite of the weaknesses
- All-sky survey: the most accurate sky-map to date with 1.143 billion sources; position uncertainty ~ 5 - 20 mas
- 2 million TGAS sources with proper motion and parallax information: median uncertainty ~ 0.3 mas, ~ 1.3 mas yr^{-1}
- Much more accurate proper motions for Hipparcos stars: 0.07 mas yr^{-1}
- 3194 light curves of Cepheids and RR Lyrae near the South Ecliptic Pole (LMC)

Towards Gaia-DR2

A big step forward:

- GDR2 will include data to 23-May-16 → 14+8 months of data
- Positions, proper motions and parallaxes for well-behaved single-like sources to limiting magnitude of G=20.7
- G & integrated BP/RP photometry together with basic astrophysical parameter estimation (T_{eff}, A_v)
- Mean radial velocities for objects showing no radial-velocity variation and for which an adequate synthetic template could be selected

See “Data Release Scenario”: http://www.cosmos.esa.int/web/gaia/release

Conclusions

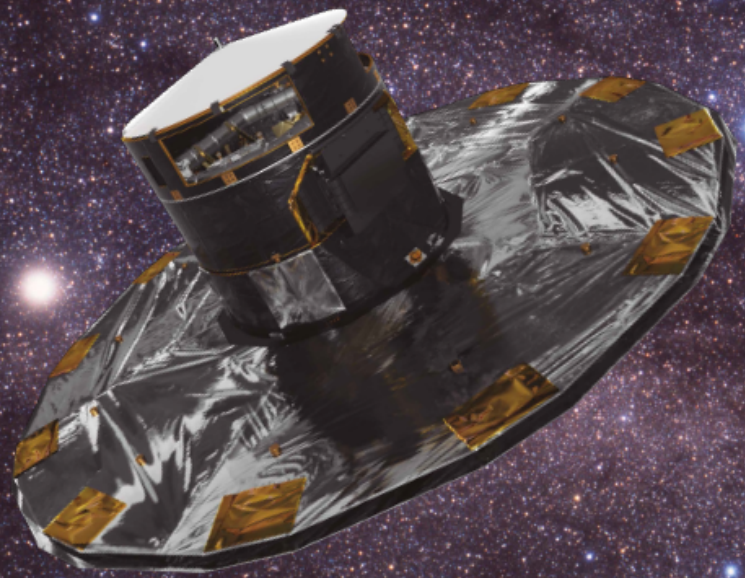
Gaia is (will be) unique

- Homogeneous all-sky coverage with G_{lim} ~ 20.7
- Micro-arcsecond precision + High Accuracy
- Inertial motions
- **The astrometric reference catalogue**
  - Photometric reference catalogue as well
  - Radial velocities
  - Astrophysical parameters

1,000,000,000 stars

Thanks

1,000,000,000 pixels



> 1000 people

> 10,000 scientists

1,000,000,000,000,000 bytes