Astrometry with Gaia: what can be expected?

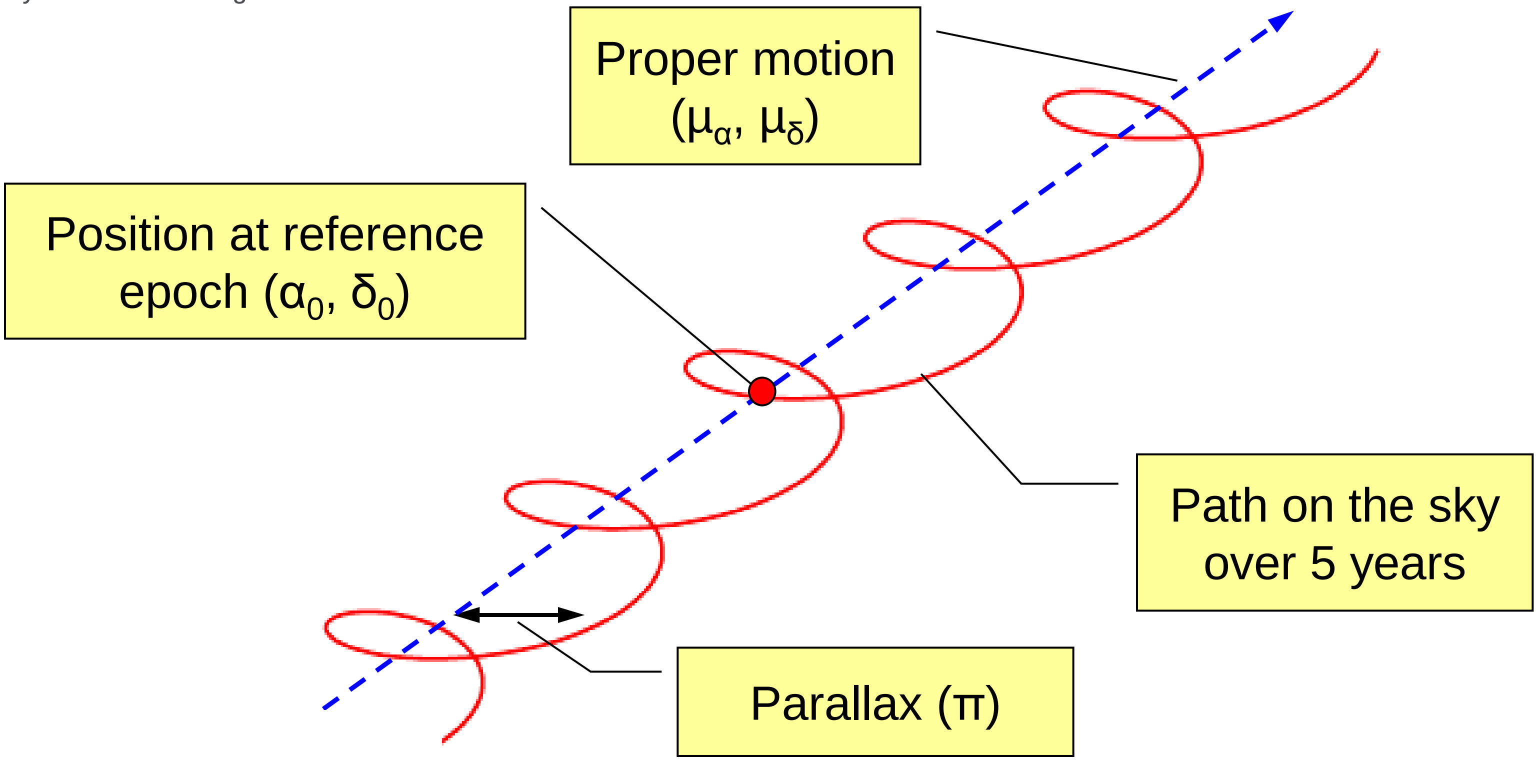
Jos de Bruijne

European Space Agency

www.rssd.esa.int/gaia

Gaia astrometry in one viewgraph

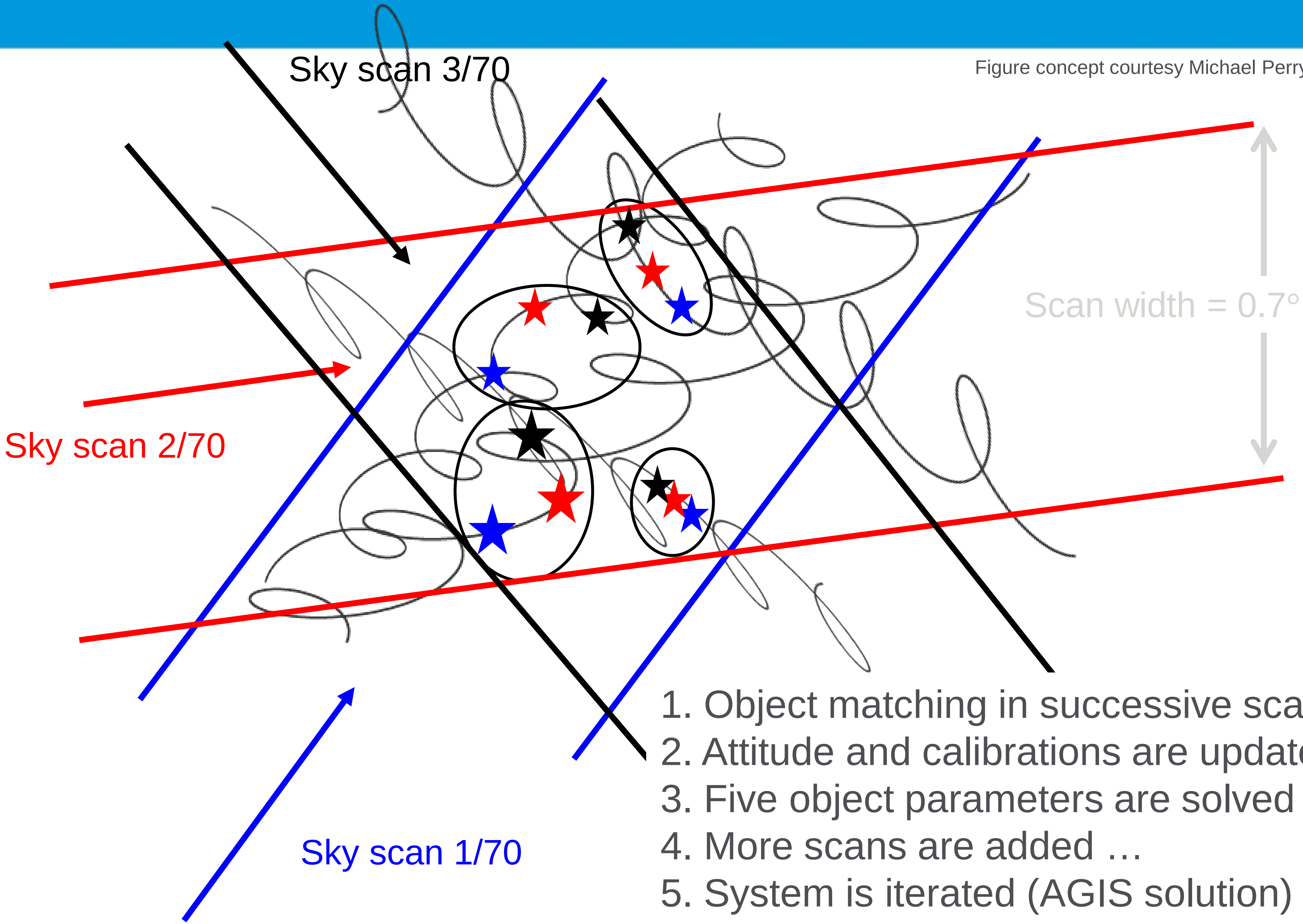
Figure courtesy Lennart Lindegren



Monitor this path for 10^9 stars during 5 years and fit, for each object, a 5-parameter model to retrieve reference position, proper motion, and parallax (for a “given” instrument calibration and attitude)

Well, actually two viewgraphs …

Figure concept courtesy Michael Perryman



1. Object matching in successive scans
2. Attitude and calibrations are updated
3. Five object parameters are solved
4. More scans are added …
5. System is iterated (AGIS solution)

Astrometry in one equation

End-of-mission parallax standard error:

$$\sigma_\pi \; [\mu\mathrm{as}] = m \cdot g_\pi \cdot \sqrt{\frac{\sigma_\xi^2 + \sigma_{\mathrm{cal}}^2}{N_{\mathrm{eff}}}}$$

m = scientific contingency factor (margin)

g_π = geometrical parallax factor (CCD to end-of-mission)

σ_ξ = single-CCD location-estimation (centroiding) error (μas)

σ_{cal} = residual calibration error (μas)

N_{eff} = end-of-mission number of detected CCD transits

Astrometry in one equation

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Scientific contingency factor *m*

A 20% science margin (m = 1.2) has been added to all calculations

- All estimates are for "perfect stars" (single, non-variable, non-crowded region, no background peculiarities, …)

- Covers residual "scientific calibration errors" (e.g., mismatch of the model PSF, sky-background-estimation errors, …)

Astrometry in one equation

End-of-mission parallax standard error:

$$\sigma_\pi \ [\mu\text{as}] = m \cdot \boxed{g_\pi} \cdot \sqrt{\frac{\sigma_\xi^2 + \sigma_{\text{cal}}^2}{N_{\text{eff}}}}$$

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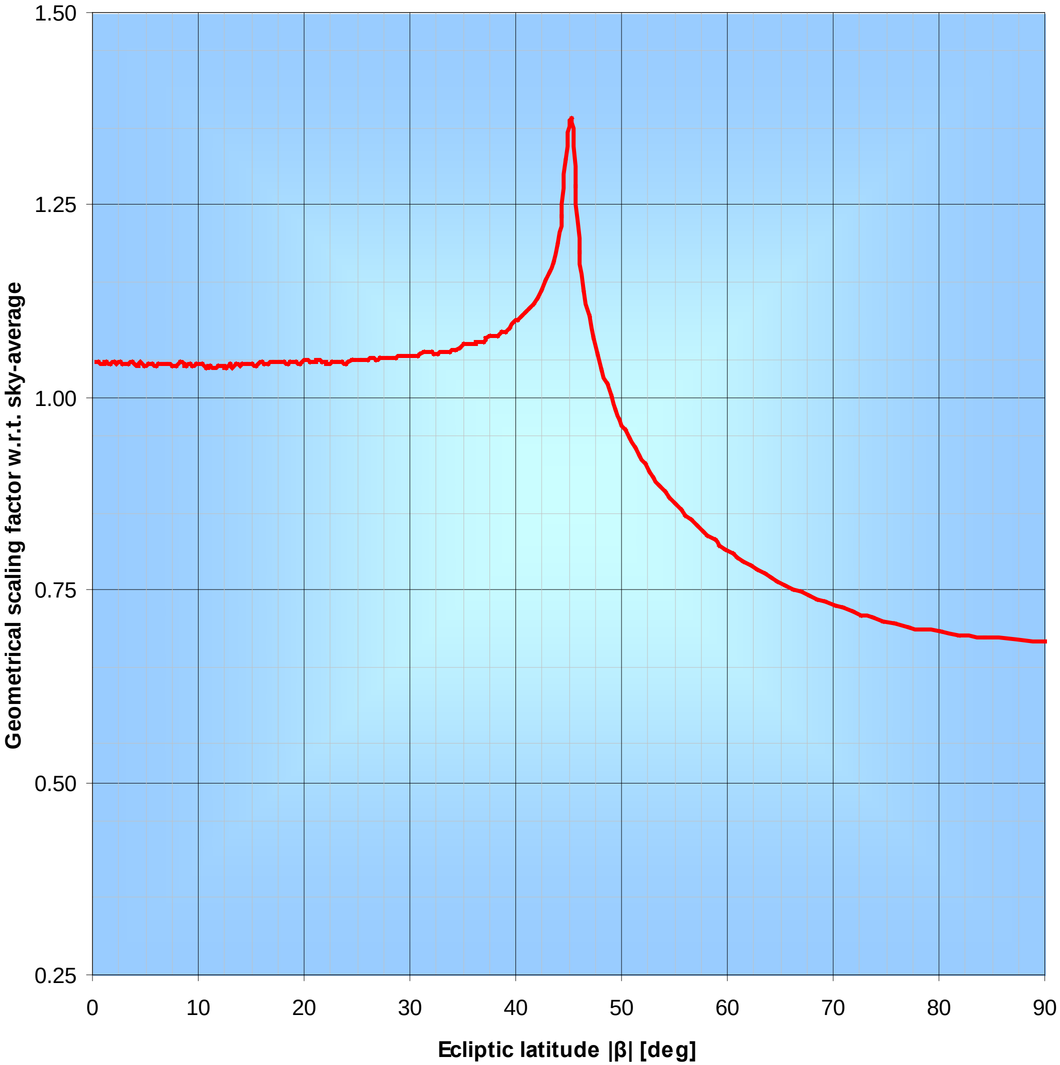
Geometric parallax factor g_π



The parallax factor g_π connects the along-scan centroiding and parallax signals

Optimum astrometry: make the solar-aspect angle ξ as large as possible and keep it constant (45° for Gaia)

Scanning-law simulations yield g_π = 2.08 for the sky-average factor

Figure from http://www.rssd.esa.int/index.php?project=GAIA&page=Science_Performance

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Single-CCD centroiding error σ_ξ

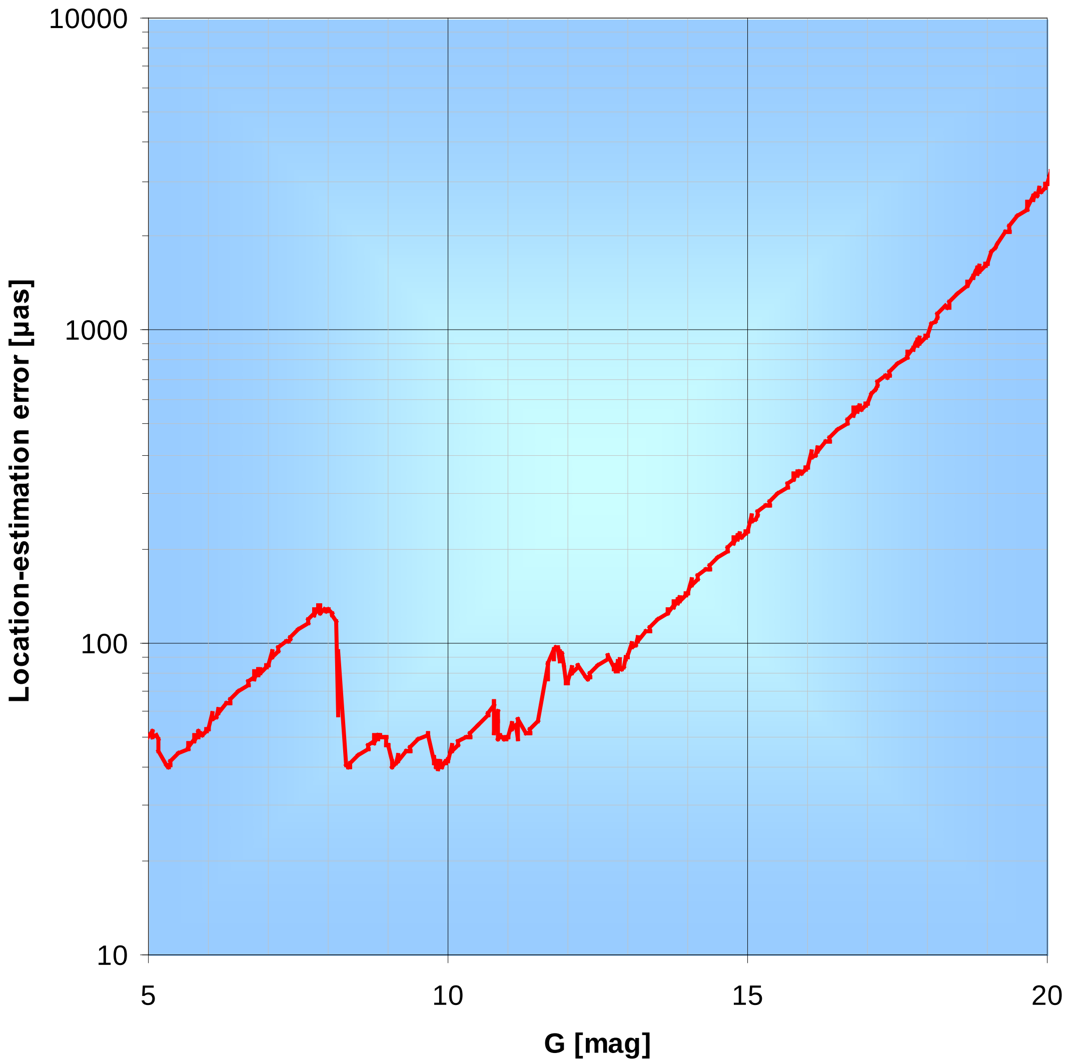

Figure from GAIA-CA-TN-ESA-JDB-053

Based on Monte Carlo simulations, including "everything", e.g., CCD QE + MTF, telescope wave-front errors + transmission + optical distortion, LSF smearing due to attitude jitters + TDI motion, CCD noise + offset non-uniformity, radiation-damage-induced charge loss + bias calibration, sky background, windowing / sampling, magnitude, extinction, spectral type, …

Astrometry in one equation

End-of-mission parallax standard error:

$$\sigma_\pi \ [\mu\text{as}] = m \cdot g_\pi \cdot \sqrt{\frac{\sigma_\xi^2 + \boxed{\sigma_{\text{cal}}^2}}{N_{\text{eff}}}}$$

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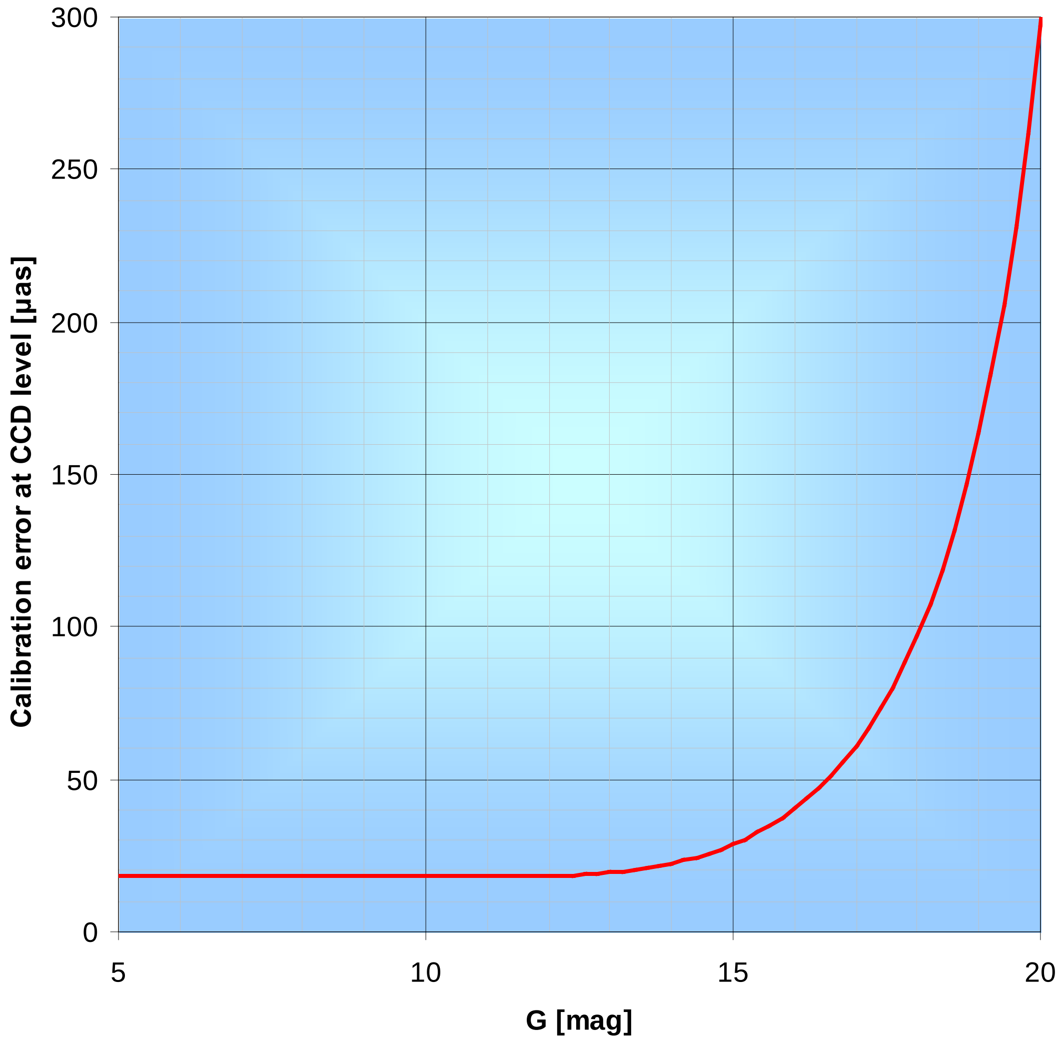
Residual calibration error σ_{cal}



Residual errors, including "everything", e.g., chromaticity calibration, geometrical transformation from focal plane to field coordinates, satellite attitude model, thermo-mechanical stability of telescope + focal plane, metrology errors associated with basic-angle monitoring, …

Small compared to random errors and relevant only for bright-star noise floor

Figure based on data from GAIA.ASF.RP.SAT.00005 (Science performance budget report)

Astrometry in one equation

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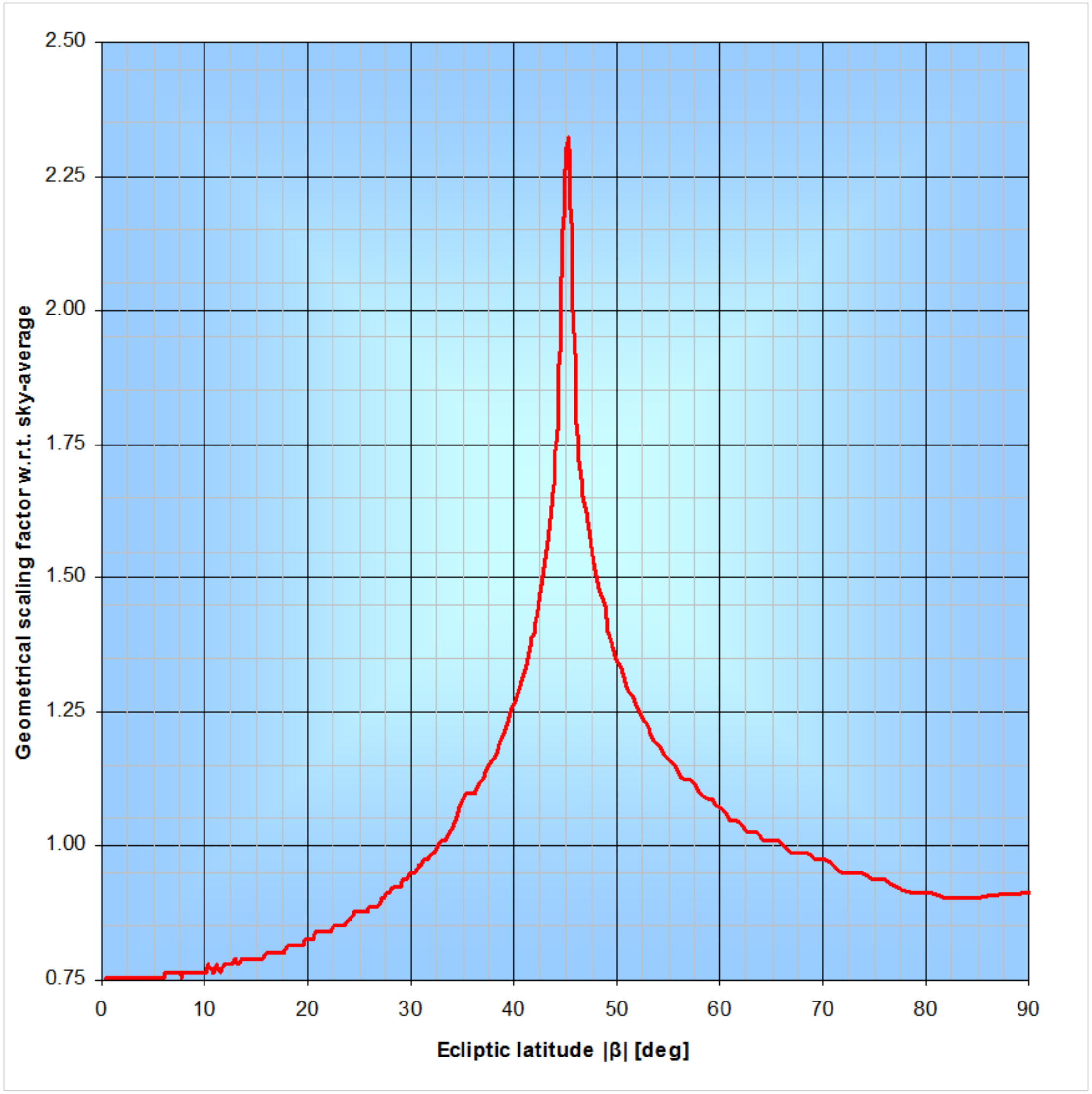
N_{eff} = end-of-mission number of detected CCD transits

Number of CCD transits N_{eff} (1/3)



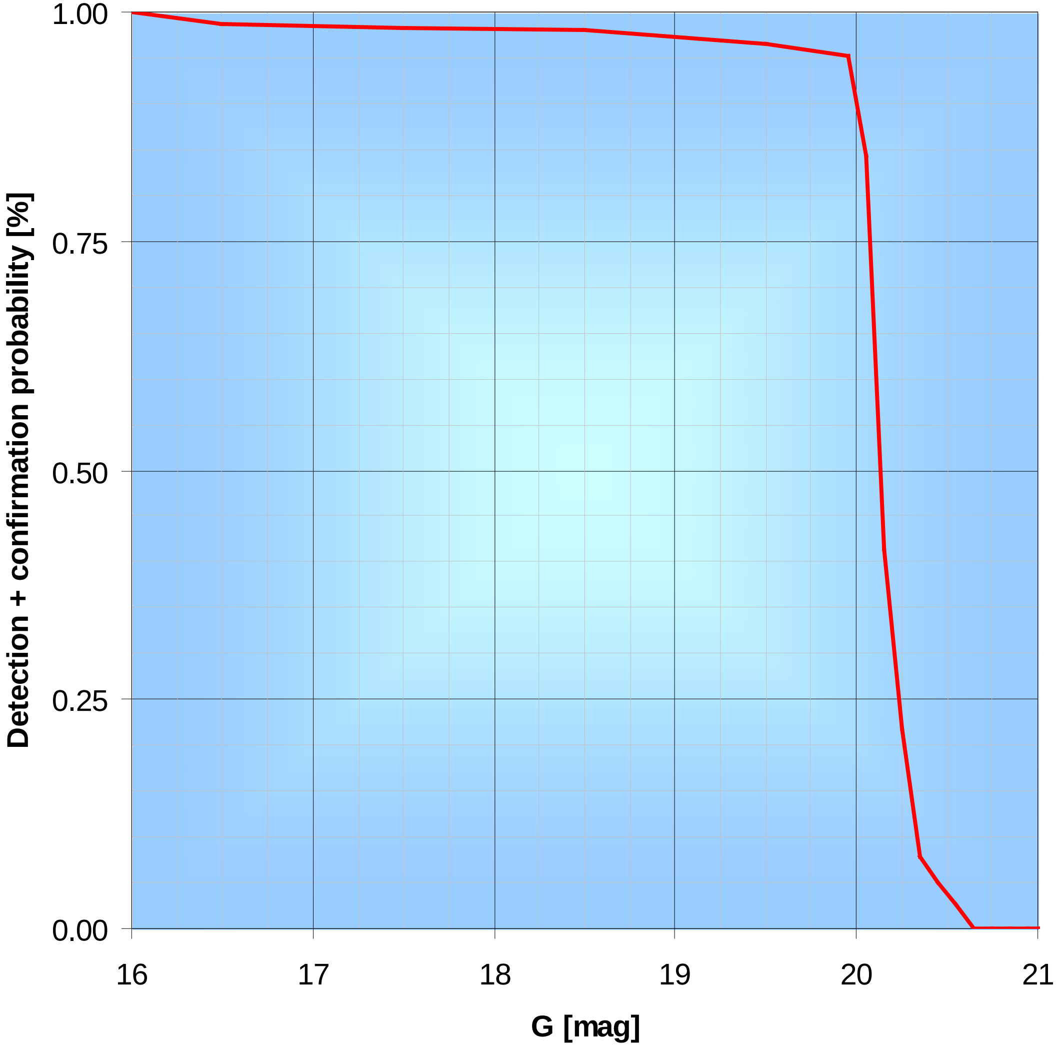
1: Number of focal-plane transits

The nominal scanning law during the 5-year mission introduces a non-uniform sampling of the sky

The sky-average number of transits is 86 (with 0% dead time) and varies mainly as function of ecliptic latitude

Figure from http://www.rssd.esa.int/index.php?project=GAIA&page=Science_Performance – Ecliptic coordinates

Number of CCD transits N_{eff} (2 / 3)



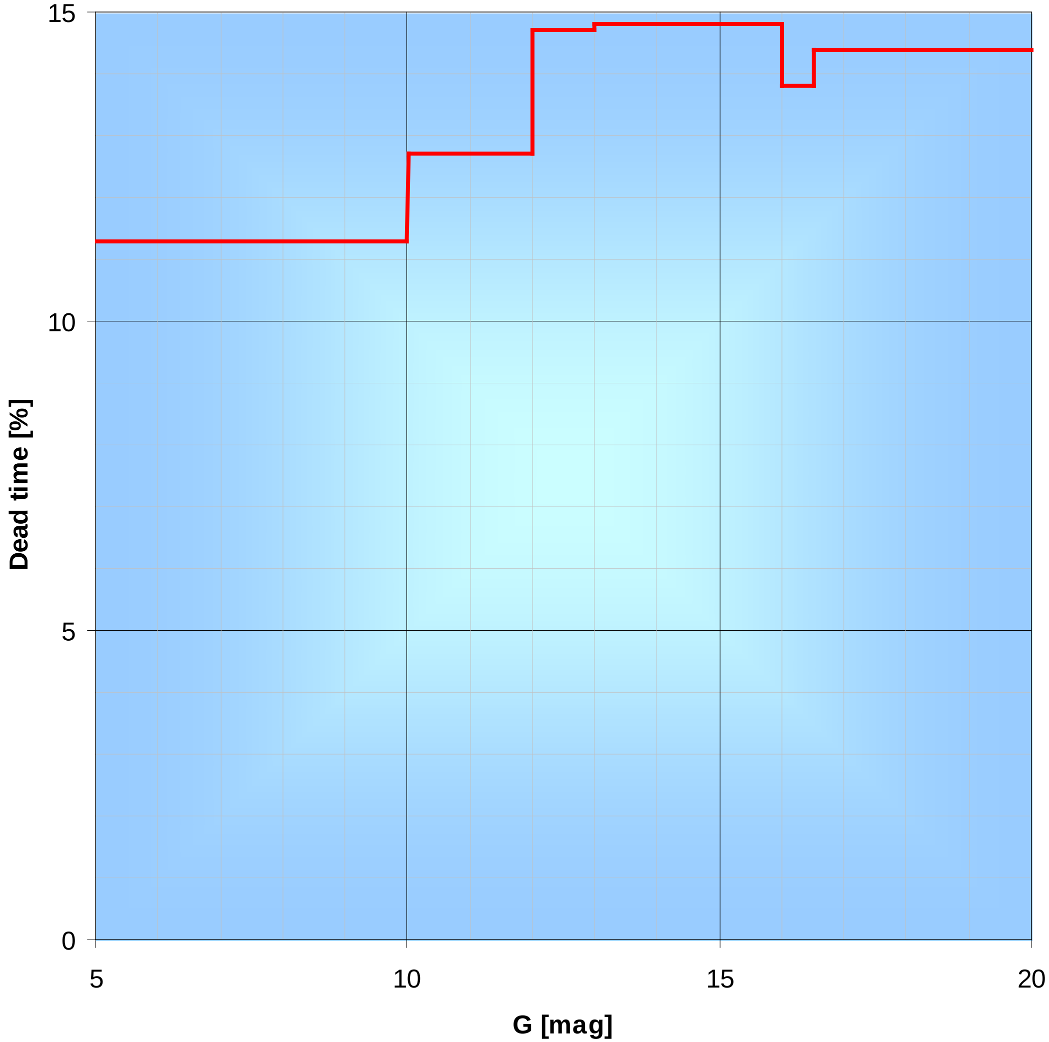
2: Detection + confirmation probability

At the faint end, the on-board object-detection and confirmation probability is finite

The design completeness limit is G = 20 mag

Figure based on data from GAIA.ASF.BG.PLM.00015 (Video processing unit software validation report)

Number of CCD transits N_{eff} (3 / 3)



3: Dead time

All (known) effects are accounted for, e.g., moon eclipses, orbit maintenance, cosmic rays, outages during solar eruptions, CCD cosmetic defects, pollution caused by charge injections and TDI gates, on-board memory overflow, micro-meteoroids, virtual objects, ...

Typical value < 15%

Figure based on data from GAIA.ASF.TCN.SAT.00133 (Dead-time report)

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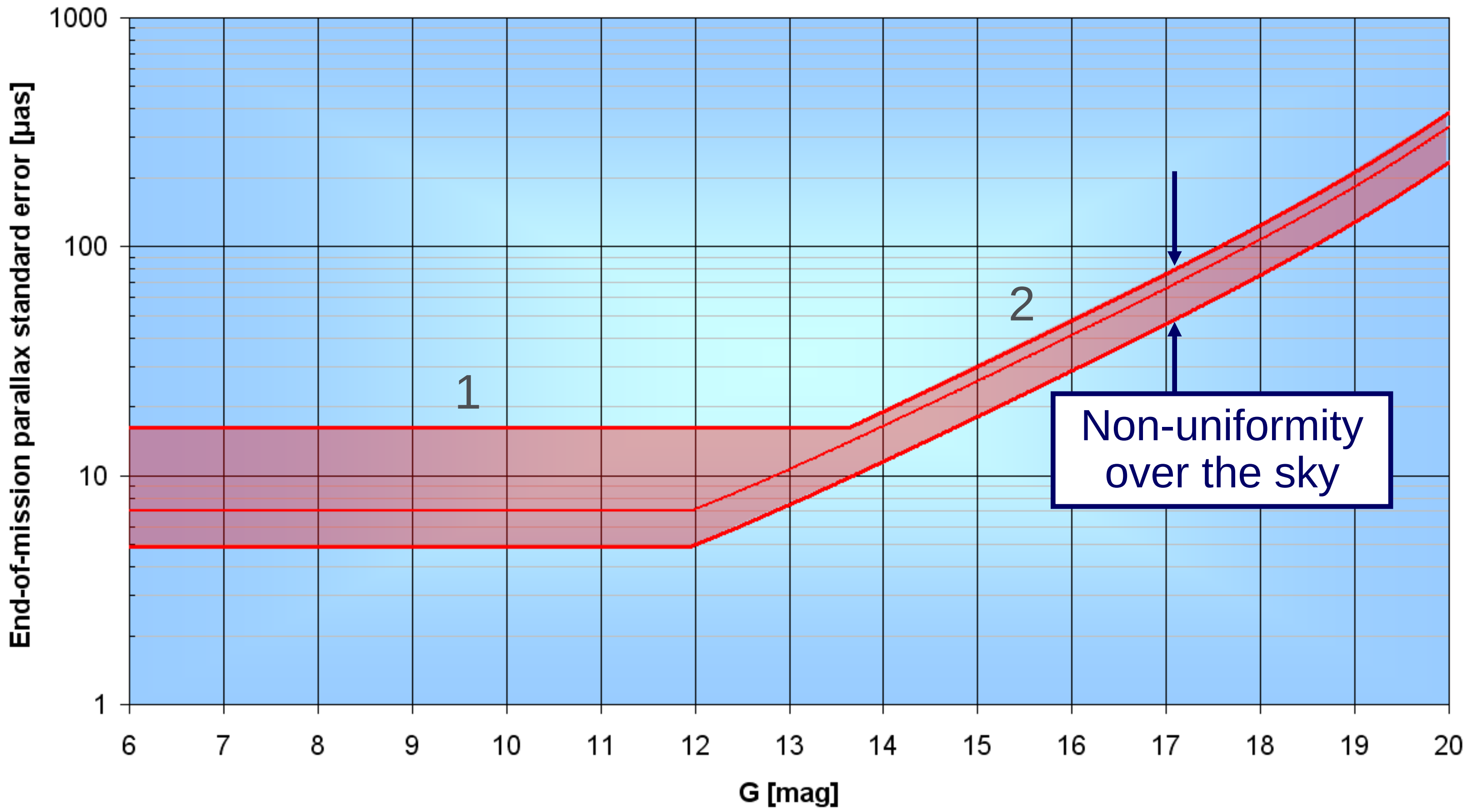
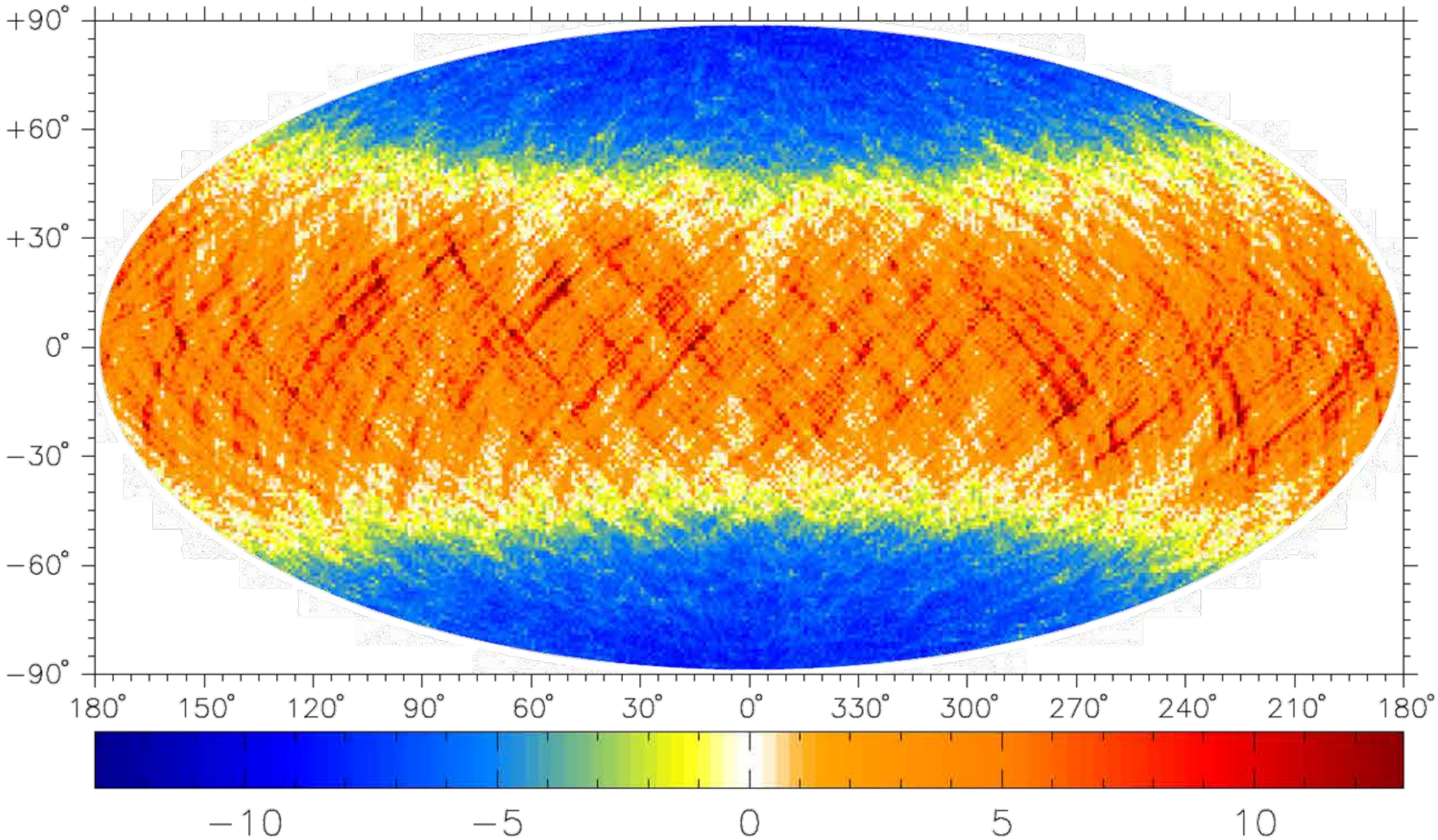
End-of-mission parallax standard errors



1. 6 < G < 12: bright-star regime (calibration errors + CCD saturation)
2. 12 < G < 20: photon-noise regime, with sky-background noise and electronic noise setting in around G ~ 20 mag

Figure from http://www.rssd.esa.int/index.php?project=GAIA&page=Science_Performance

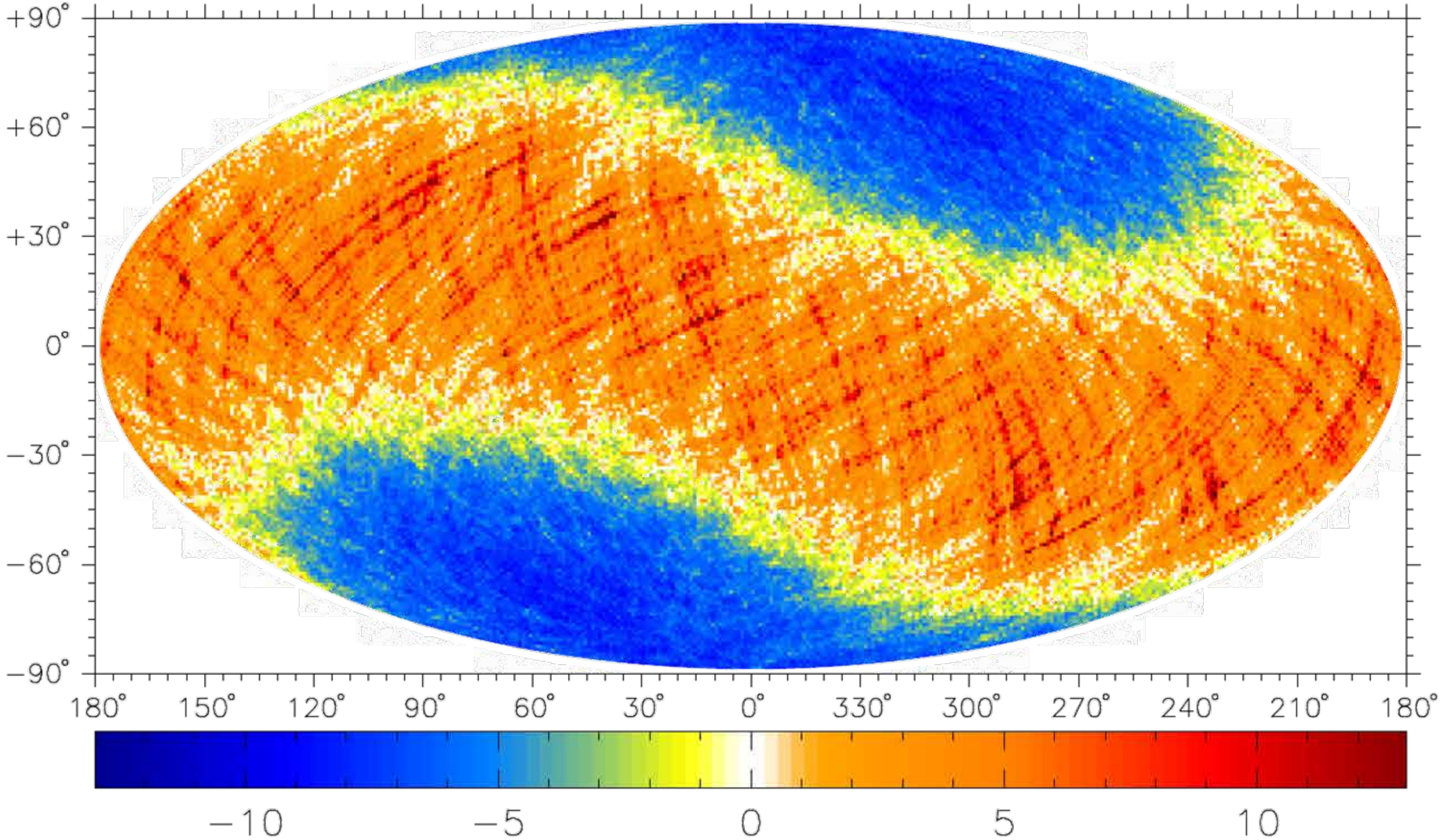
Parallax-error-variation map @ G=15 mag



Sky-average: σ_π = 25.8 µas

Figure from http://www.rssd.esa.int/index.php?project=GAIA&page=Science_Performance – ecliptic coordinates

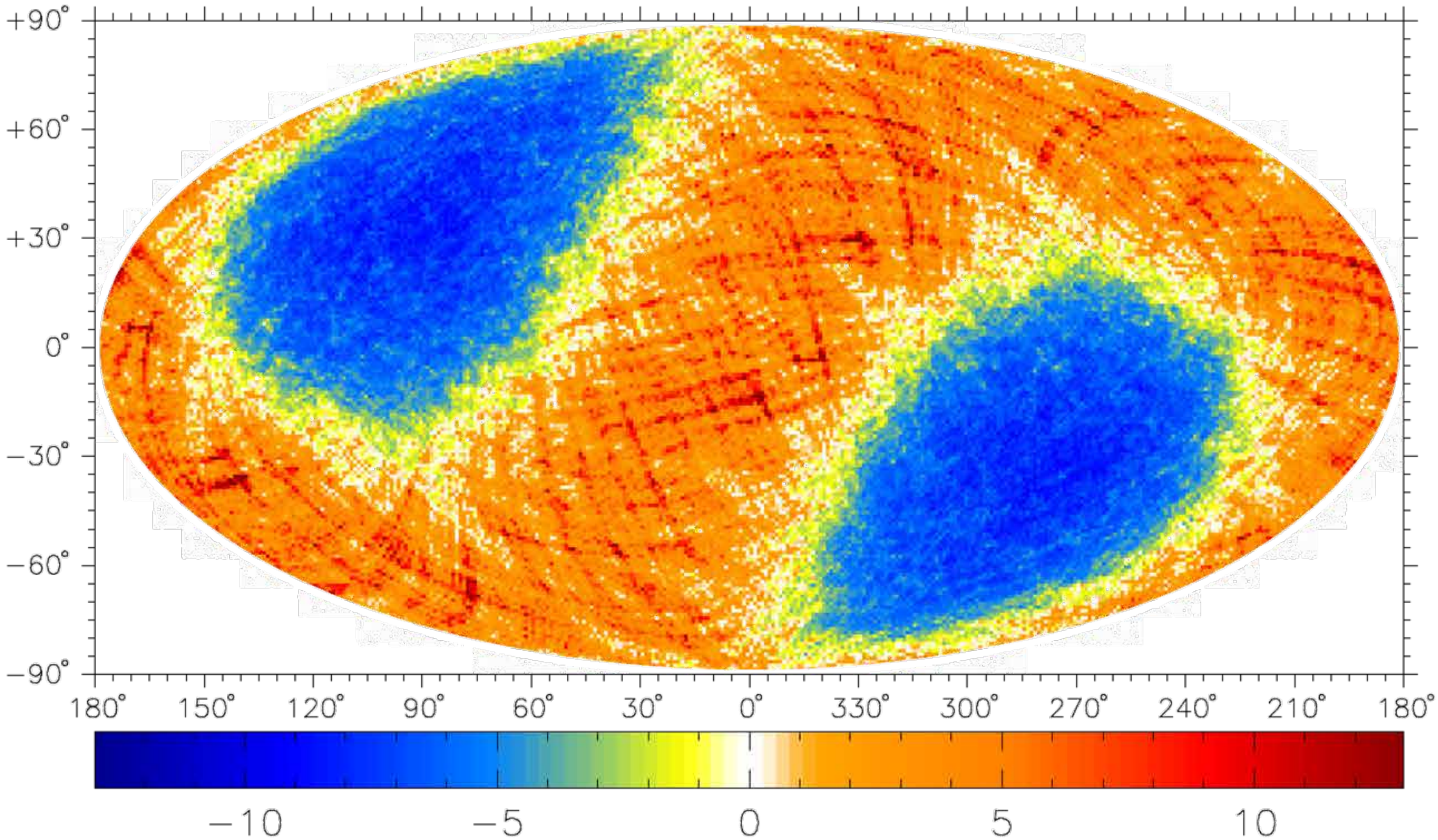
Parallax-error-variation map @ G=15 mag



Sky-average: σ_π = 25.8 µas

Figure from http://www.rssd.esa.int/index.php?project=GAIA&page=Science_Performance – equatorial coordinates

Parallax-error-variation map @ G=15 mag



Sky-average: σ_π = 25.8 µas

Figure from http://www.rssd.esa.int/index.php?project=GAIA&page=Science_Performance – galactic coordinates

End-of-mission astrometry

For a 5-year Gaia mission, sky-averaged position and proper-motion standard errors, σ_0 [μas] and σ_μ [μas yr^{-1}], are:

$$\sigma_0 = 0.743 \cdot \sigma_\pi$$

$$\sigma_\mu = 0.526 \cdot \sigma_\pi$$

For any given V magnitude and V-I colour index, the end-of-mission parallax standard error, σ_π [μas], averaged over the sky, is:

$$\sigma_\pi \text{ [μas]} = \sqrt{(9.3 + 658.1 \cdot z + 4.568 \cdot z^2)}\ [0.986 + (1 - 0.986)\ (V\text{-}I)]$$

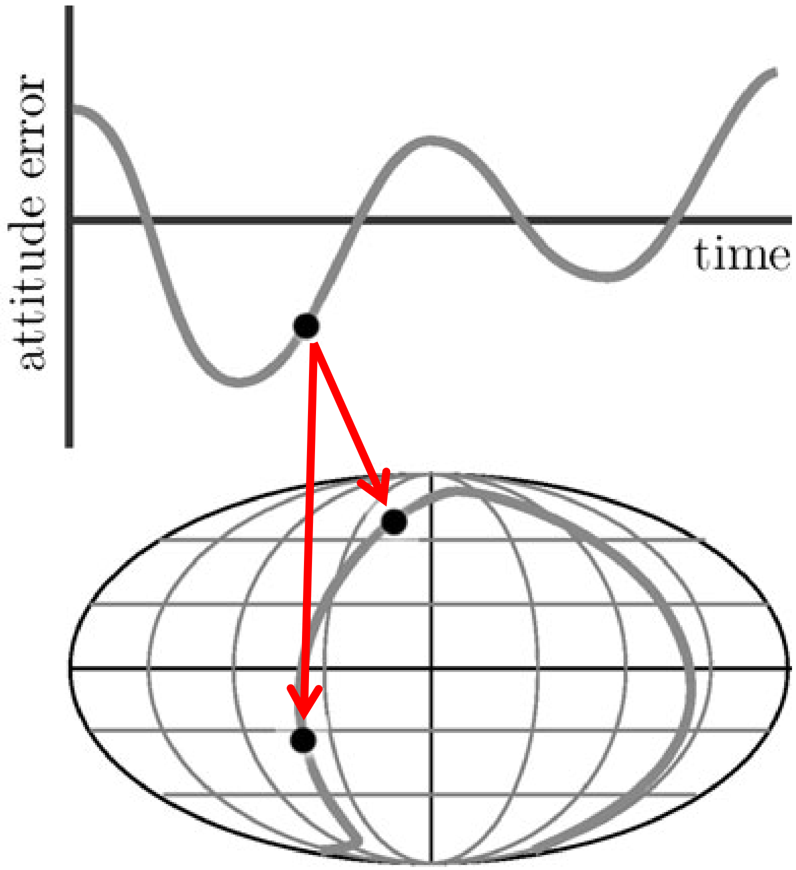
$$z = \mathrm{MAX}[10^{0.4\,(12 - 15)}, 10^{0.4\,(G - 15)}]$$

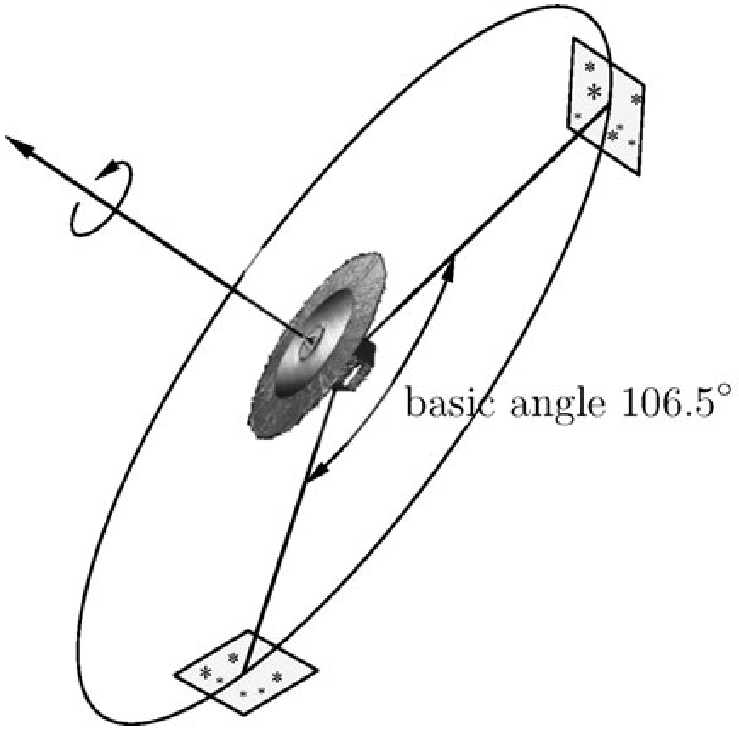
$$G = V - 0.0107 - 0.0879 \cdot (V\text{-}I) - 0.1630 \cdot (V\text{-}I)^2 + 0.0086 \cdot (V\text{-}I)^3$$

Equations and variations over the sky available on http://www.rssd.esa.int/index.php?project=GAIA&page=Science_Performance

What about correlations?

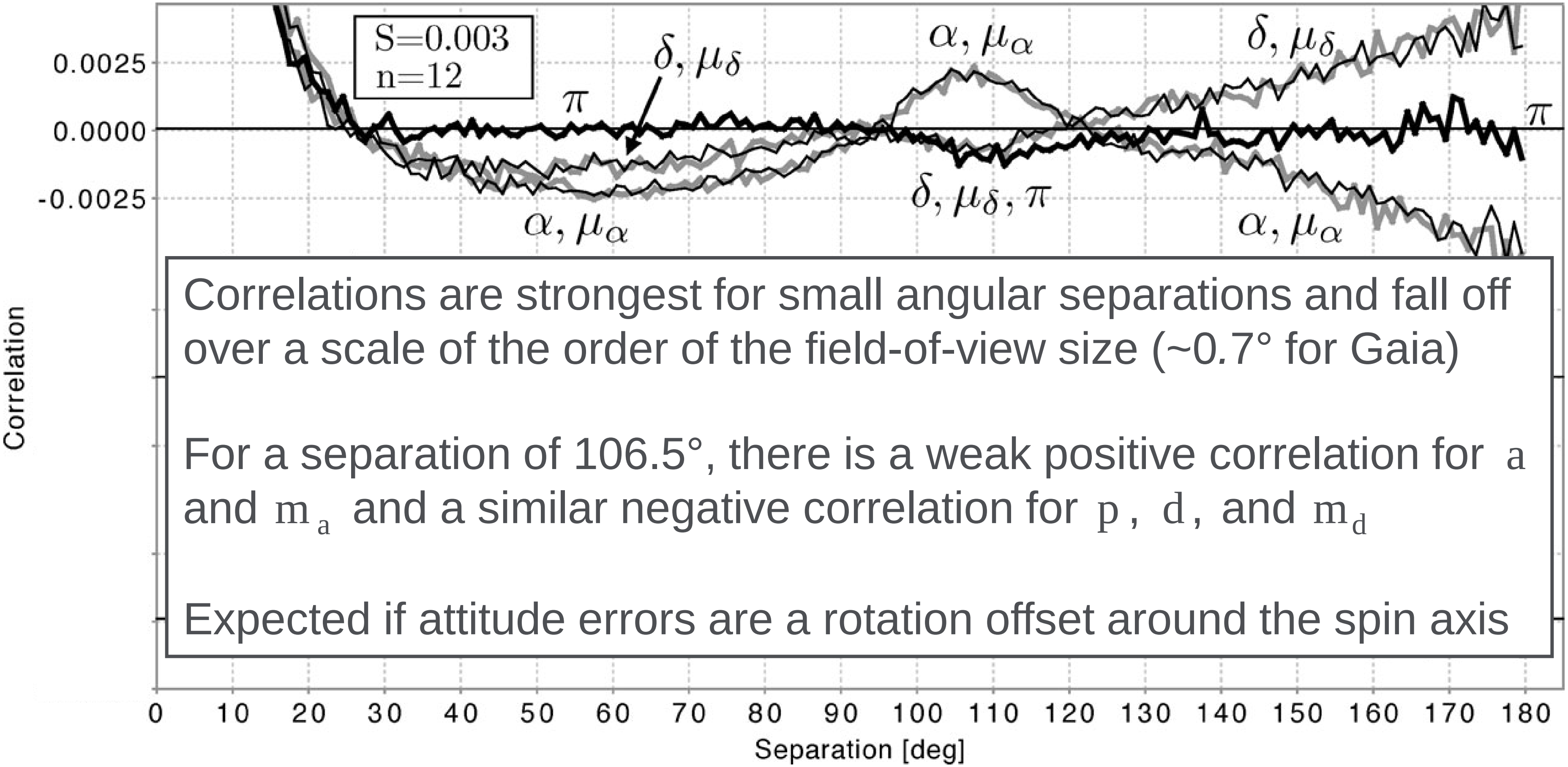
An error in the attitude at a particular time ‘biases’ all observations made at that time, in both fields → correlations between stars within each field as well as stars separated by the basic angle (106.5°)





Figures from Holl et al. (2010)

AGIS-Lab simulations of correlations



Correlations are strongest for small angular separations and fall off over a scale of the order of the field-of-view size (~0.7° for Gaia)

For a separation of 106.5°, there is a weak positive correlation for α and μ_α and a similar negative correlation for π, δ, and μ_δ

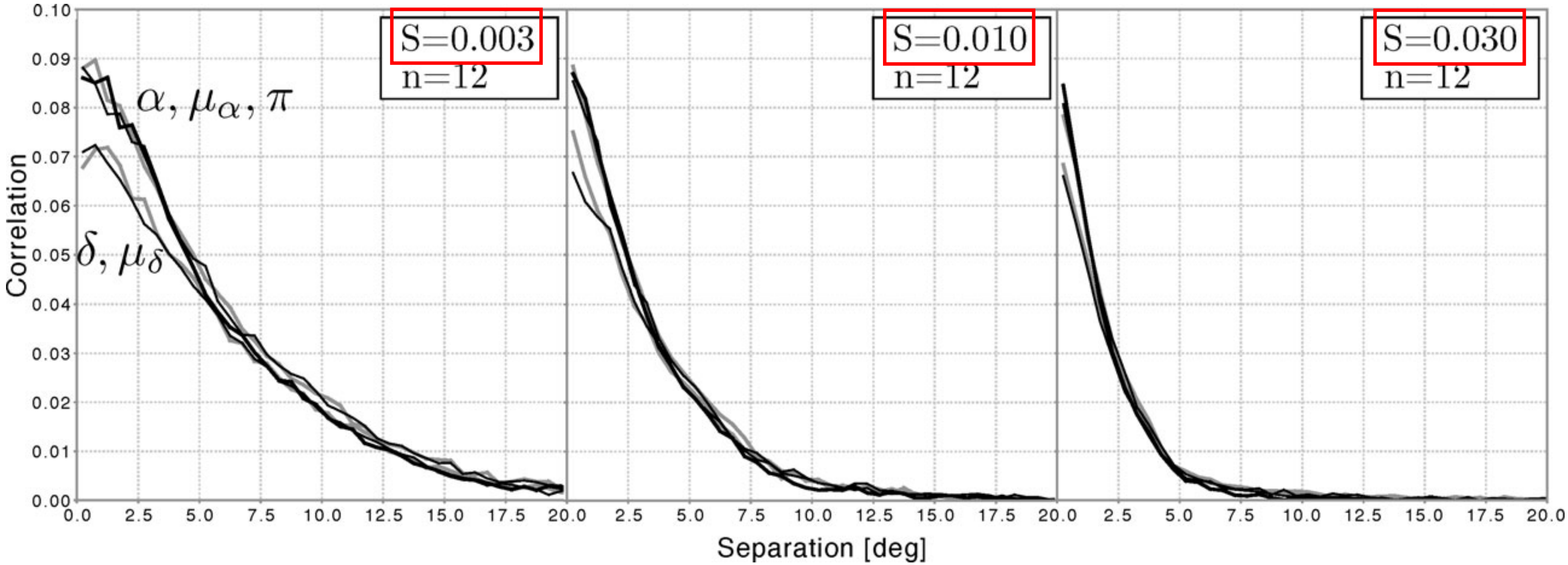
Expected if attitude errors are a rotation offset around the spin axis

Warning: the plot does not correspond to Gaia but a scaled version (*S* is an AGIS-Lab scaling parameter of the field-of-view size with *S* = 1 for Gaia)

gaia European Space Agency
www.rssd.esa.int/gaia

Figures from Holl et al. (2010)

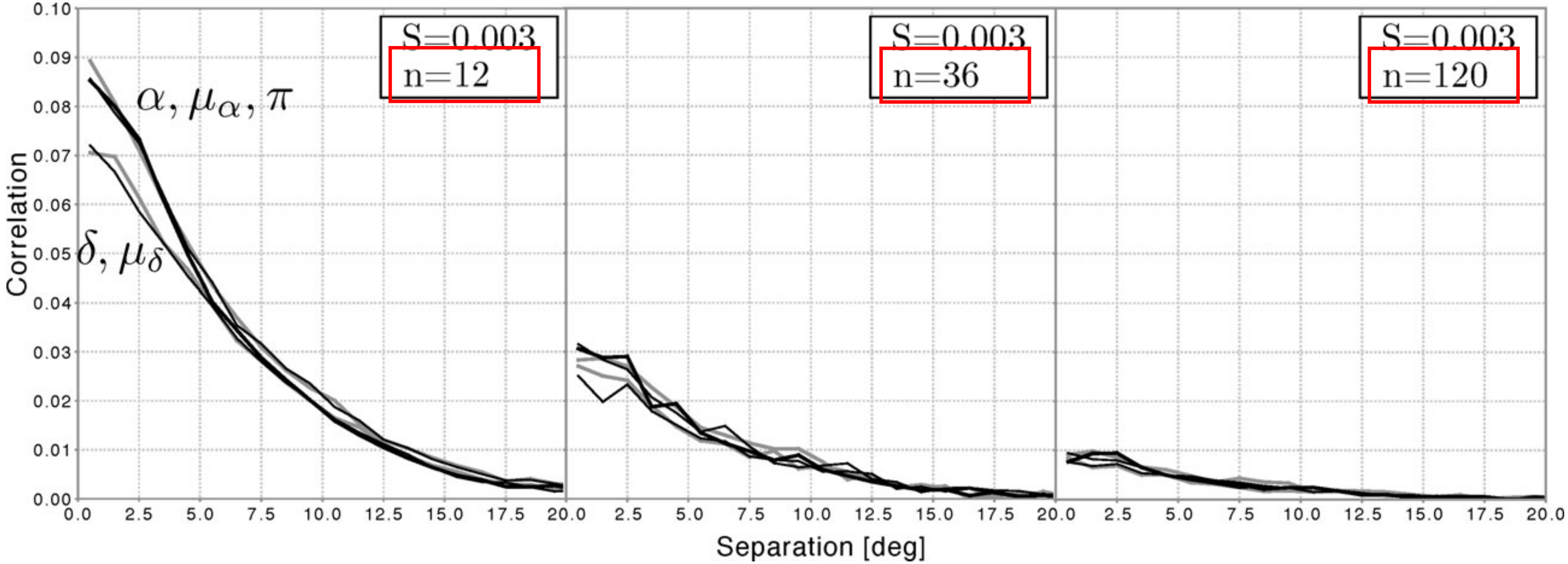
Influence of field-of-view size



The correlation half-length scales with the size of the field-of-view and equals ~0.3° for Gaia (0.4 ´ 0.7°)

Figures from Holl et al. (2010)

Influence of # stars in global solution



The maximum correlation depends on the number (and magnitude distribution) of stars used in the AGIS global solution

Using 100 million stars suggest that r_{max} ~ 0.005 for bright stars (V < 13 mag) and smaller for fainter stars

Figures from Holl et al. (2010)

Example: mean parallax of a cluster

$y = N^{-1} \sum_i x_i$ with N the number of stars in the cluster

$$\sigma_y^2 = \left(\frac{\partial y}{\partial \boldsymbol{x}}\right)' \mathrm{Cov}(\boldsymbol{x}) \left(\frac{\partial y}{\partial \boldsymbol{x}}\right)$$

$$= \sum_i \left(\frac{\partial y}{\partial x_i}\right)^2 \sigma_i^2 + \sum_i \sum_{j \neq i} \frac{\partial y}{\partial x_i} \frac{\partial y}{\partial x_j} \rho_{ij} \sigma_i \sigma_j$$

With $\sigma_i \simeq \sigma$ and $\rho_{ij} \simeq \rho > 0$, we find $\sigma_y^2 \simeq \sigma^2 \left(\frac{1}{N} + \frac{N-1}{N}\rho\right)$

$\sigma_y \longrightarrow \sigma N^{-1/2}$ without correlations

$\sigma_y \longrightarrow \sigma\sqrt{\rho}$ with correlations: accuracy is limited by averaging over some ρ^{-1} stars

Holl et al. (2010)

Degeneracies / correlations

Degeneracies / correlations exist between:

- The global parallax zero point
- PPN g of the Sun (relativistic light bending)
- Basic-angle variations (Sun-synchronous types)
- Gaia's *x* velocity in the BCRS (*x* bisects the field-centre directions)

Available data include:

- Astrometric data itself
- Basic-angle monitoring (BAM) data continuously collected on-board
- Gaia orbit from ESA/ESOC (Doppler, range, and/or DDOR)
- Periodic ground-based optical observations of Gaia itself (GBOT)
- Astrophysical constraints (e.g., mean QSO parallax or distance-ratio method)

Complex interplay between calibration and validation …

Outlook

Service module thermal vacuum testing completed

Payload module thermal vacuum testing in autumn 2012

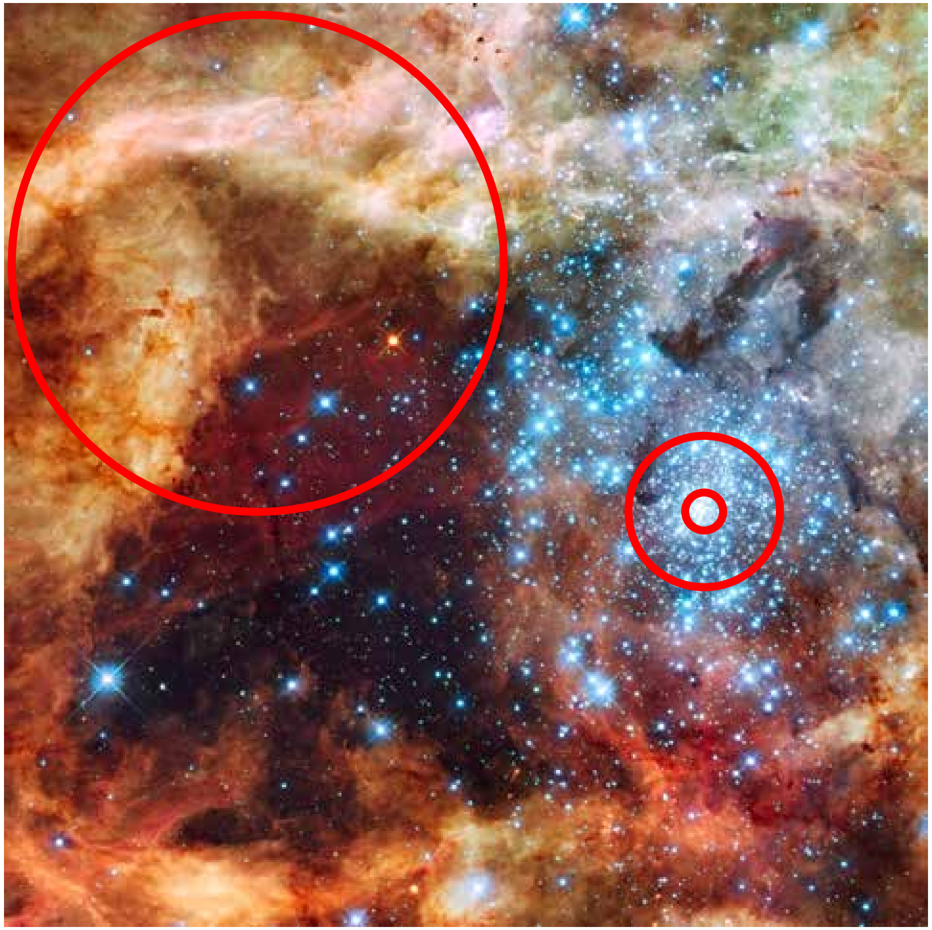
Launch in September 2013

First intermediate data late 2015

Figure courtesy EADS Astrium (payload status mid-August 2012)

How much time is left?

Case study of a dense region (R136)



162 arcsec (0.05°)

Crowding implies incompleteness at high densities and faint magnitudes

- The astrometric limit is ~1 million stars deg^{-2} over a full CCD (0.7°)
- Up to ~3 million stars deg^{-2} can be coped with by (temporarily) using a modified scanning law

R136 starburst in the LMC with HST:

- Field density is 350,000 stars deg^{-2} down to G = 20 mag
- Cluster density is ~10 million stars deg^{-2}
- Core density is ~40 million stars deg^{-2}

Figure from http://hubblesite.org/newscenter/archive/releases/2009/32/

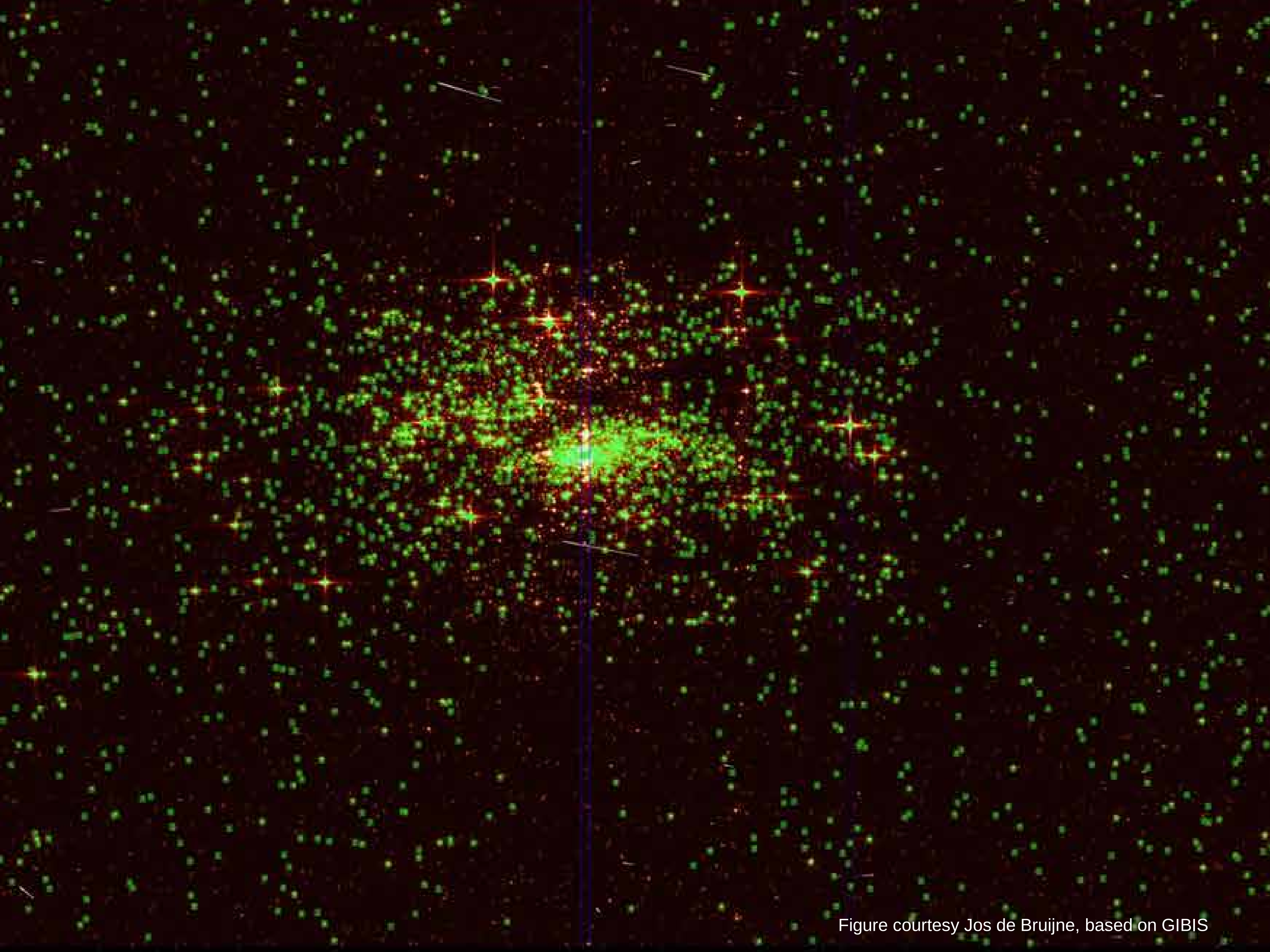


Figure courtesy Jos de Bruijne, based on GIBIS

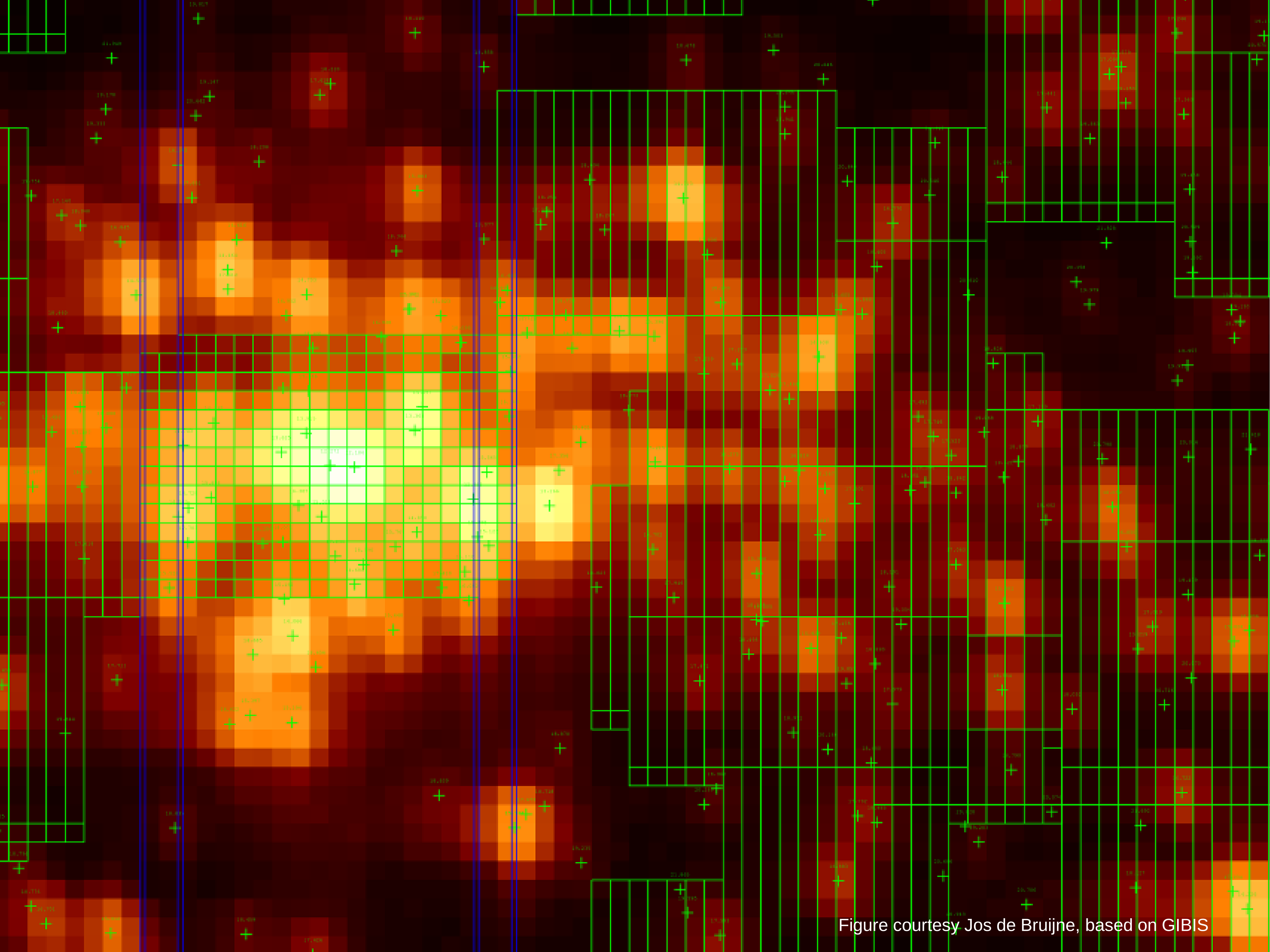
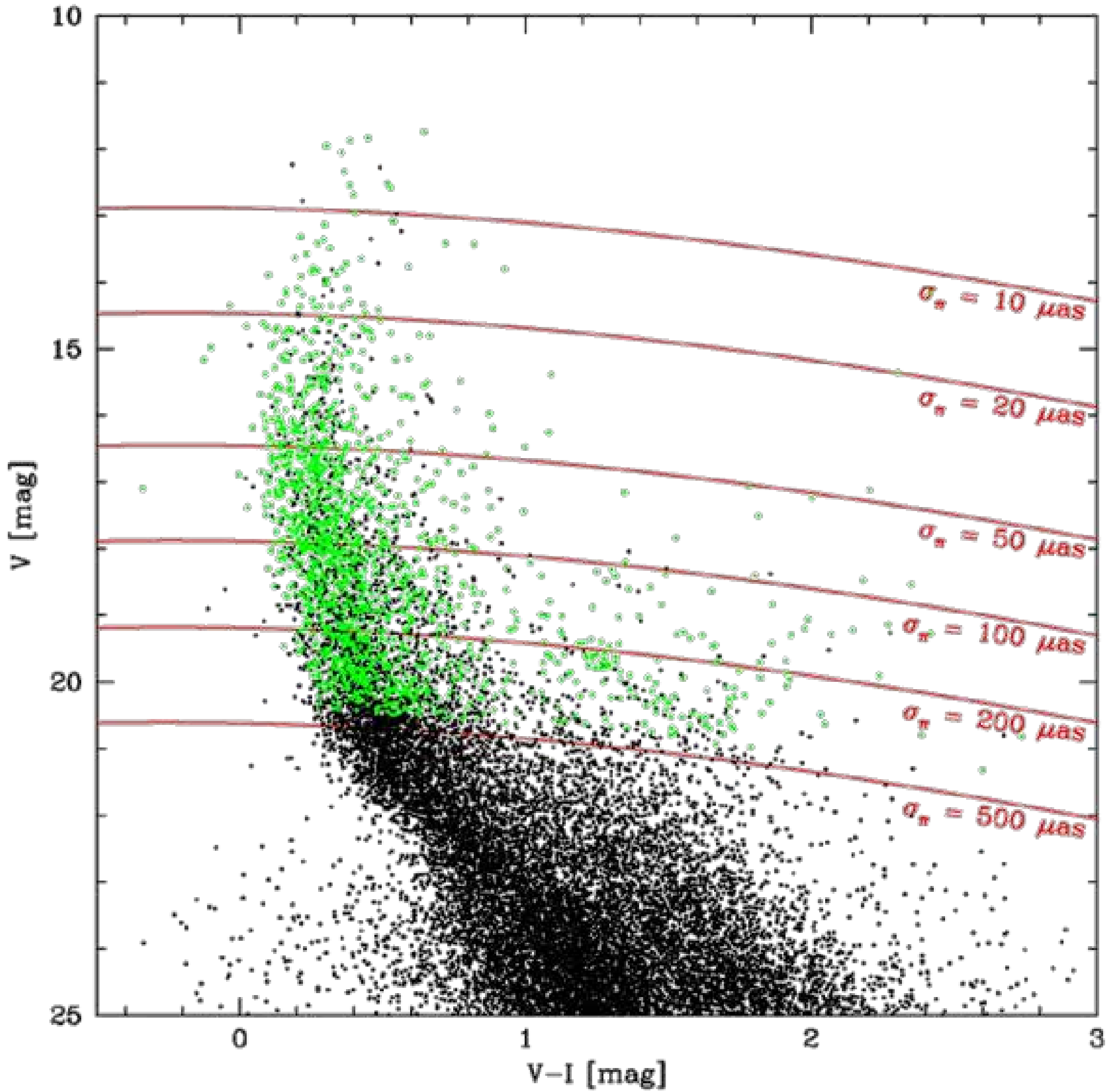


Figure courtesy Jos de Bruijne, based on GIBIS

Case study of a dense region (R136)



De Bruijne & de Marchi (2011)

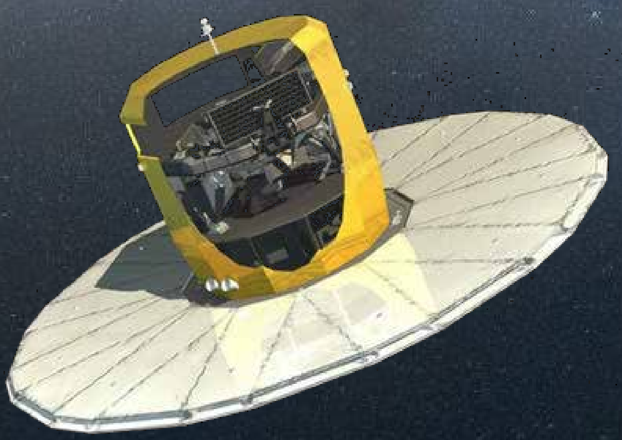
The cluster poses “no problems” to Gaia:

- Stars down to 20 mag are detected and observed
- The window overlap, however, is large and de-blending the data will be a challenge …

Black: HST input

Green: Gaia detection

Thank you for your attention



Figures courtesy EADS Astrium and Axel Mellinger

Background material

Gaia science-performance pages

http://www.rssd.esa.int/gaia

(click "Science performance" or simply Google for "Gaia science performance")

Gaia-performance pre-print

2012Ap&SS.tmp...68D

(de Bruijne, Astrophysics and Space Science, in press)

ESA / EADS Astrium / DPAC reports (limited distribution)

GAIA-EST-TN-00539 (= GAIA-JDB-022)

GAIA-CA-TN-ESA-JDB-053

GAIA-CA-TN-ESA-JDB-055

GAIA.ASF.RP.SAT.00005

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