Experiences from the Gaia in-flight instrument modelling and suggestions for GaiaNIR

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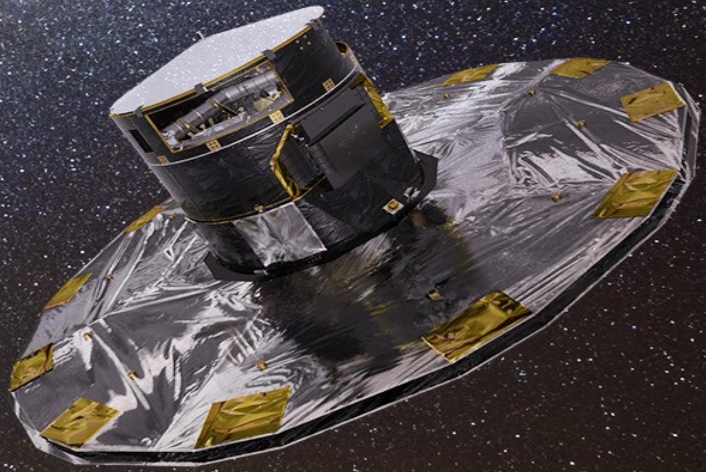


Lund Observatory

20th July 2023

Introduction

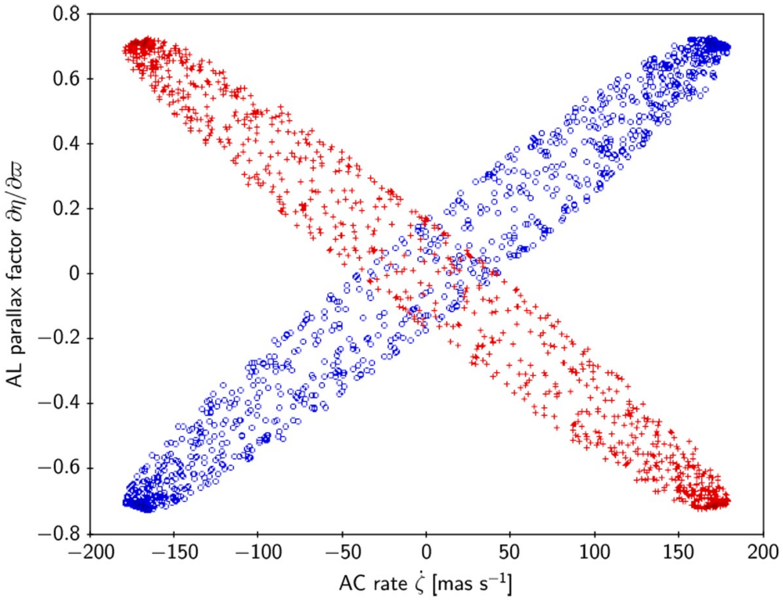
- Involvement of our Edinburgh group in the Gaia project
  - Within DPAC we are responsible for many low level CCD calibrations
    - Electronic bias, cosmetics, dark signal, saturation/nonlinearity, background/straylight, PSF
  - We also provide the algorithm for on-ground source detection and image parameter determination
    - Instantaneous positions and instrumental fluxes
  - Validation of core processing for cyclic data releases
  - Archive design and UK datamining platform

- We draw upon this to discuss some items of relevance to GaiaNIR

- These are mostly speculative ideas that require further study

Drift-scan related PSF distortions

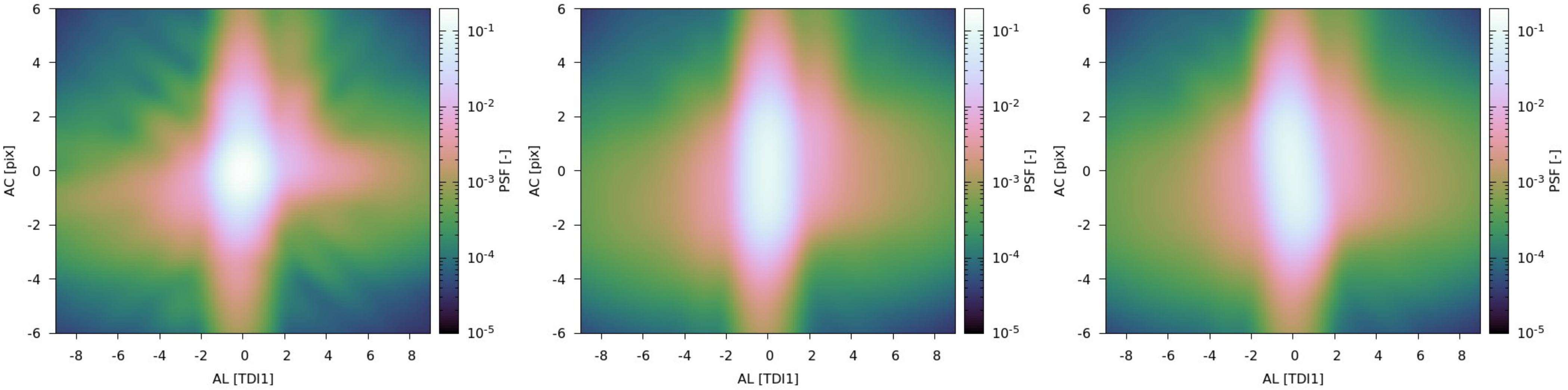
- TDI mode offers many advantages
- However its implementation in Gaia presents complications related to the scan law
- The precession induces a 6 hour modulation in the across-scan drift rate of stellar images relative to the (fixed) TDI rate
- This causes systematic periodic distortions in the effective PSF
- The major effect is a linear smearing of the PSF
- There is a secondary interaction with the detector spatial response variations that further complicates things
  - Along-scan variations in the detector spatial response are NOT marginalised out by TDI mode, contrary to expectations
- This is important because the across-scan drift rate correlates strongly with the along-scan parallax factor
- GaiaNIR will face the same issues



Lindegren et al. (2021)

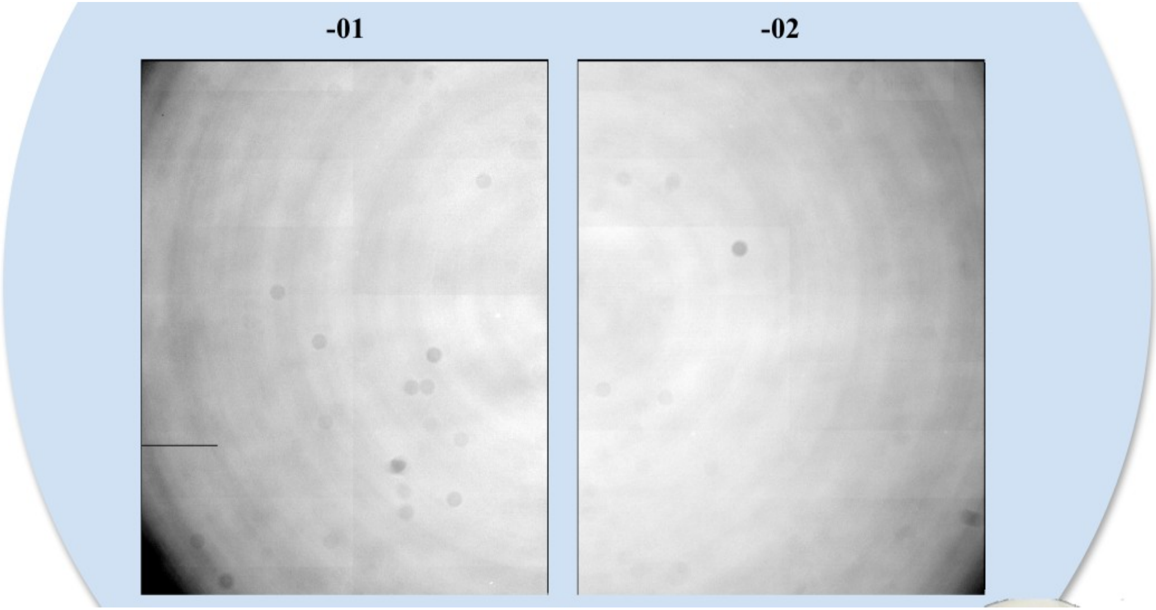
Drift-scan related PSF distortions

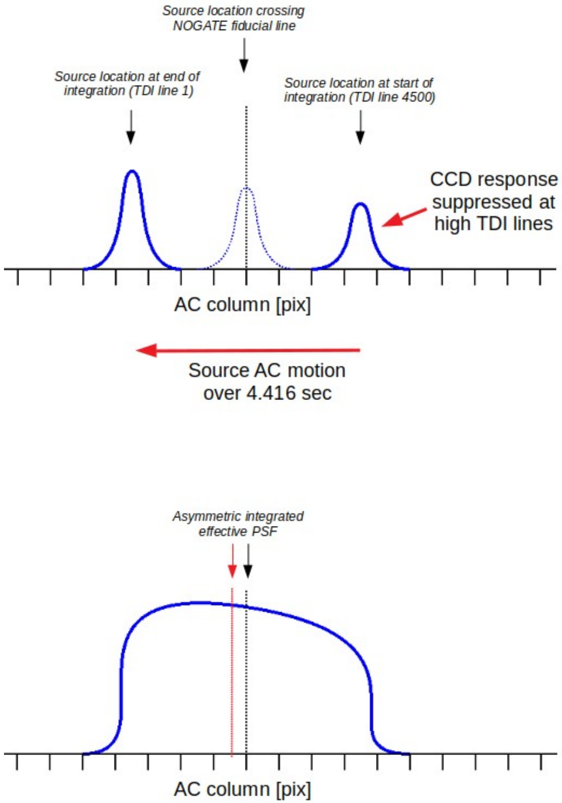
- Smearing effect of net AL/AC motion
  - Relative motion of stellar image and integrating charge is ~constant during 4.416s integration
  - Effect is well approximated as a convolution with a top hat of appropriate width and orientation
  - This requires a calibration of the along-scan pixel angular scale, available serendipitously from the geometric calibration of different CCD gates



Drift-scan related PSF distortions

- Gaia's CCDs have a systematic spatial variation in response at up to 10% level
- The impact this has on observations depends on the AC rate
- Accurate modelling requires calibration of detector response in 2D
  - TDI mode doesn't 'hide' the AL detector inhomogeneity

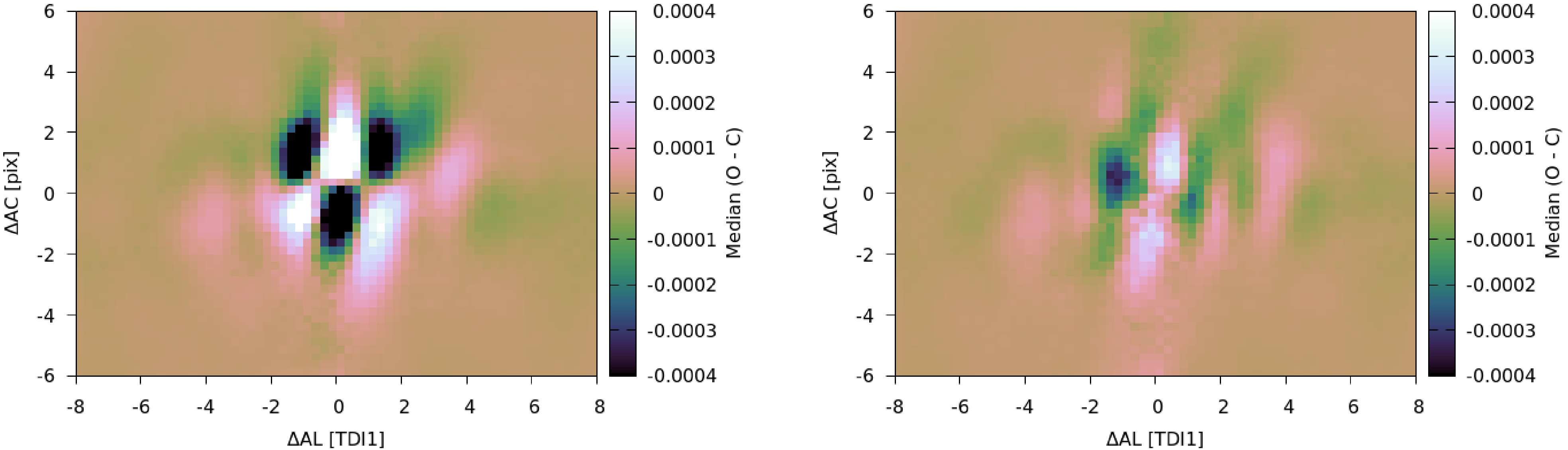




Credit: Ralf Kohley, DPAC internal documentation

Drift-scan related PSF distortions

- This has been included in the PSF modelling for DR4 → increased parameterisation and execution time
  - details will be published in a future paper
- Residuals to PSF model incorporating only AL/AC drift (left) and including CCD response variations (right)
- Modelling of spatial response variations reduces PSF reconstruction error from ~1% to ~0.5%



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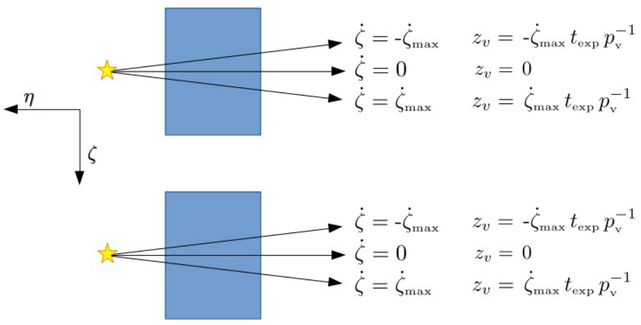
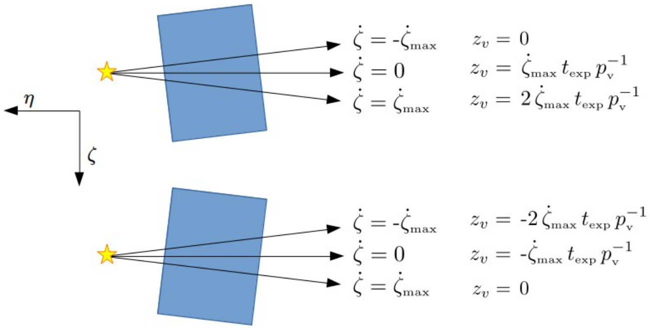
Gaia DPAC

Drift-scan related PSF distortions

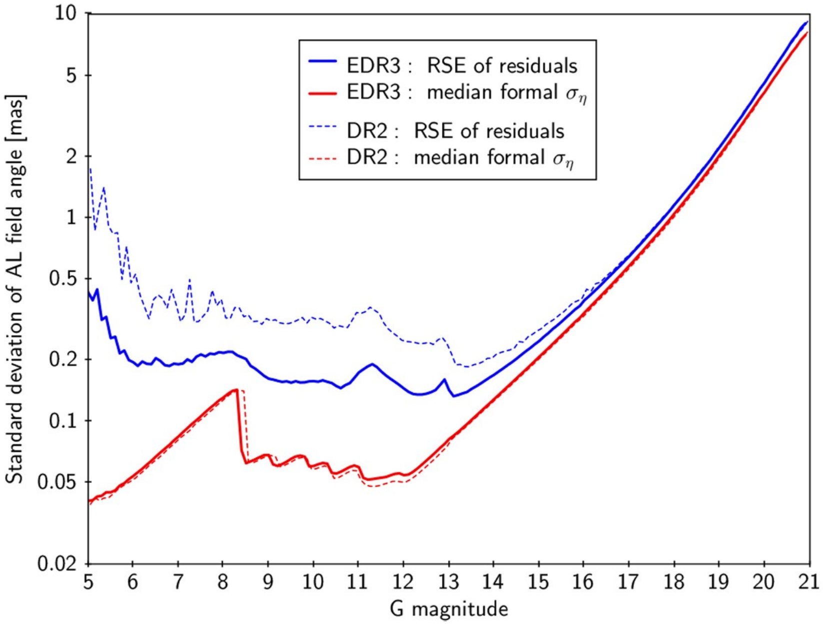
- Drift-scan related PSF distortions will manifest in GaiaNIR
- Possible mitigation strategies:
  - Do nothing - model it in the PSF, ensuring auxiliary calibrations are available
  - If TDI mode is implemented in onboard processing, could correct for stellar drift to some extent
  - Marginalise all observations to 1D AL profiles
    - However, 2D centroid is necessary for attitude and geometric calibrations
    - ...and 1D marginalised observations also have a dependence on AC rate due to windowing
  - Rotate devices in the focal plane to reduce AC smearing effect





On-board processing of faint stars

- Astrometric uncertainty for faint stars is dominated by photon noise
- Centroiding using parameterised PSF model fitted to observed samples may be overkill
- This could be exploited to optimise the telemetry budget
- Could instead perform centroiding onboard using a carefully chosen scheme and telemeter only the measured centroid
  - Tukey biweight used successfully in Gaia bootstrapping
- Systematic errors that depend on stellar colour etc could be corrected statistically during astrometric solution
- For some fraction of faint stars the samples could be telemetered, to allow a comparison between the onboard-measured centroid and a full on-ground calibrated PSF fit
- Precedent for this in Gaia → 'calibration faint stars'



Lindegren et al. (2021)

On-ground processing / system design

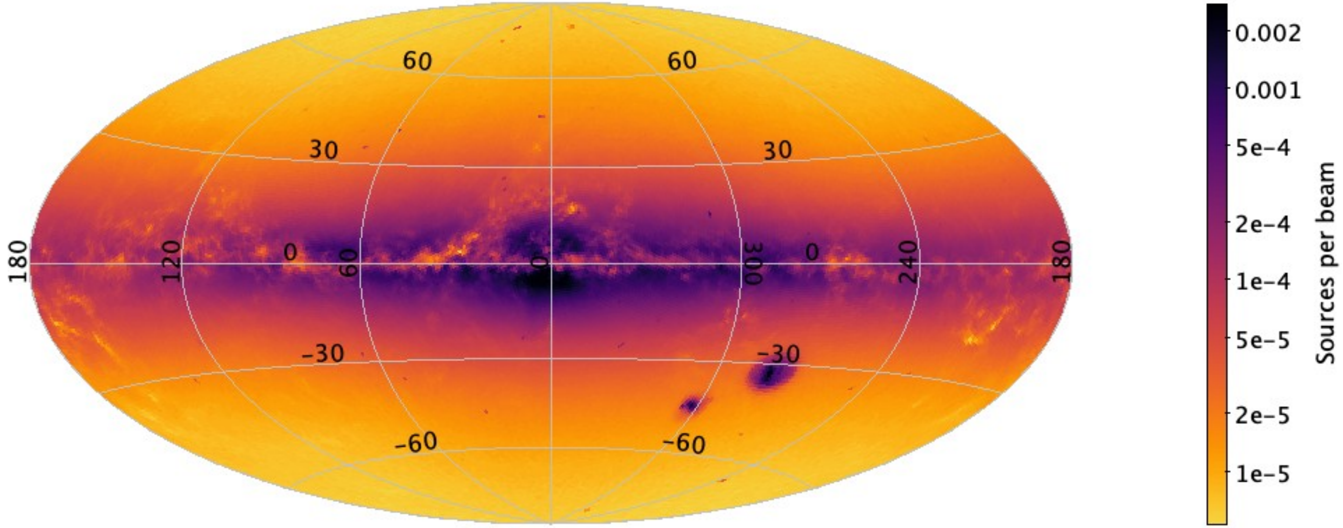
- Collection of instrument calibration data
  - Should be considered from the start
  - Interleaved with science data to avoid disturbance to payload
  - Ability to control individual devices e.g. to put into full-frame imaging mode for analysis of far PSF
  - Enable calibration of detector effects not anticipated or fully understood pre-launch
  - Ensure calibrations can be adapted to physical reality of in-flight spacecraft

- Tight integration of teams working on closely related topics
  - Avoid reinvention of the wheel, artificial distinctions/boundaries
  - Promote a sense of working together on the same thing
  - System-level continuous integration would help to coordinate different groups

- Ensure simple access to & interaction with realtime data & systems
  - Must be easy to add new diagnostics and access data for analysis
  - Data should be structured in a simple way that can be built upon

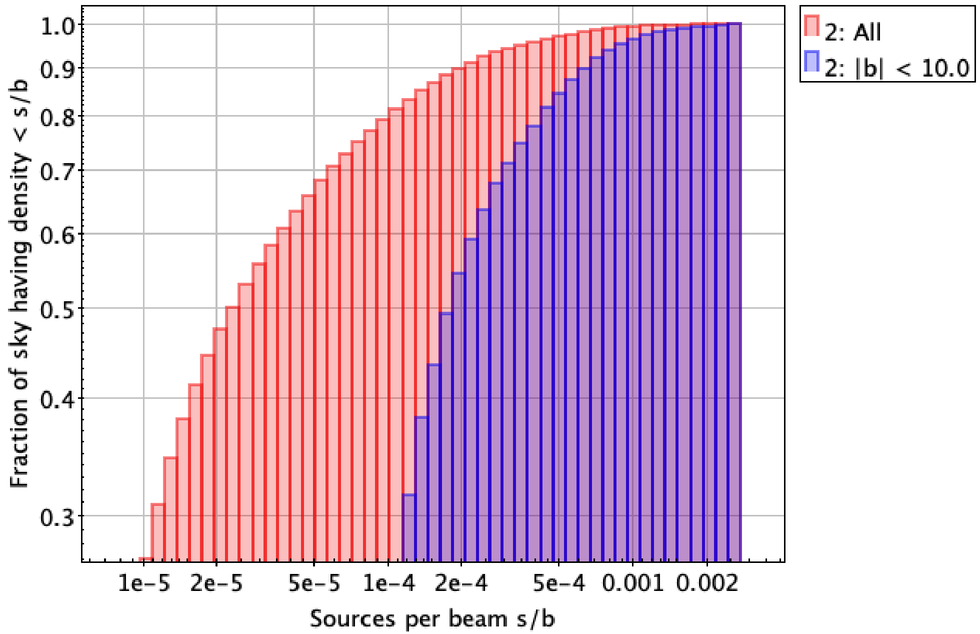
Source density considerations

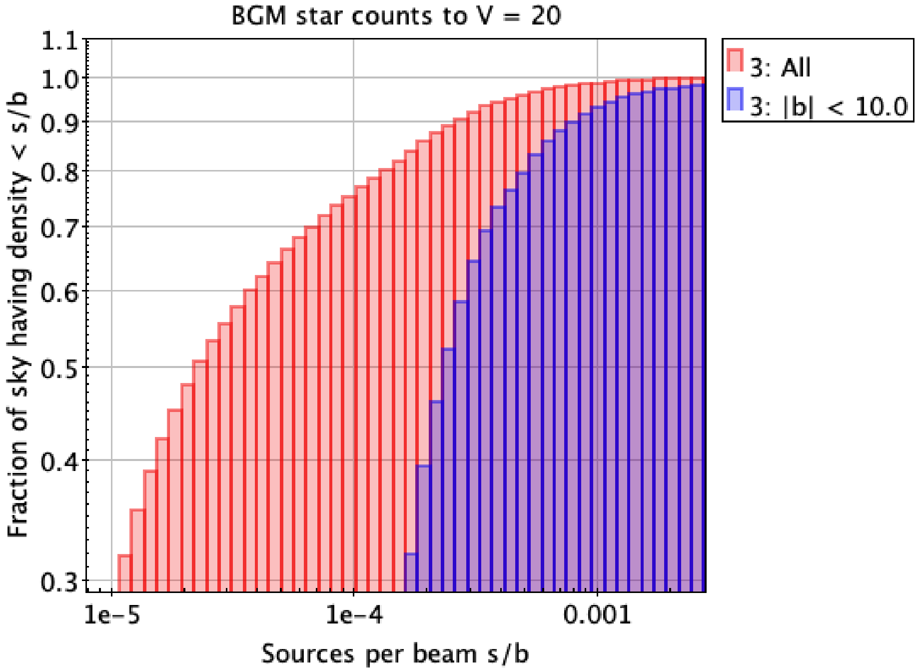
- IR sky towards inner regions of Galaxy will look very different to Gaia
  - Source density is extreme in exactly the regions that GaiaNIR intends to probe
  - Confusion limit will depend on long wavelength cutoff
- Source density over the sky as seen by Gaia
  - Elliptical 'beam' size approximated using a simplistic λ/d Rayleigh criterion for $\lambda = 0.6\mu$m and $d = 1.45$m AL and 0.5m AC



Source density considerations

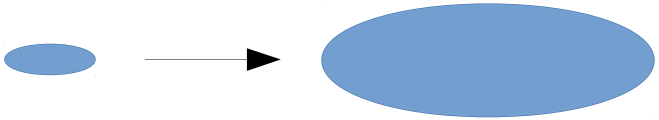
- For low latitude sky ($|b|$ < 10) most of the sky ($\gtrsim$95%) has sources per beam < 0.001
- Observed histograms agree well with BGM star count predictions in the optical
  - Johnson V < 20, transformed from (G, BP – RP)



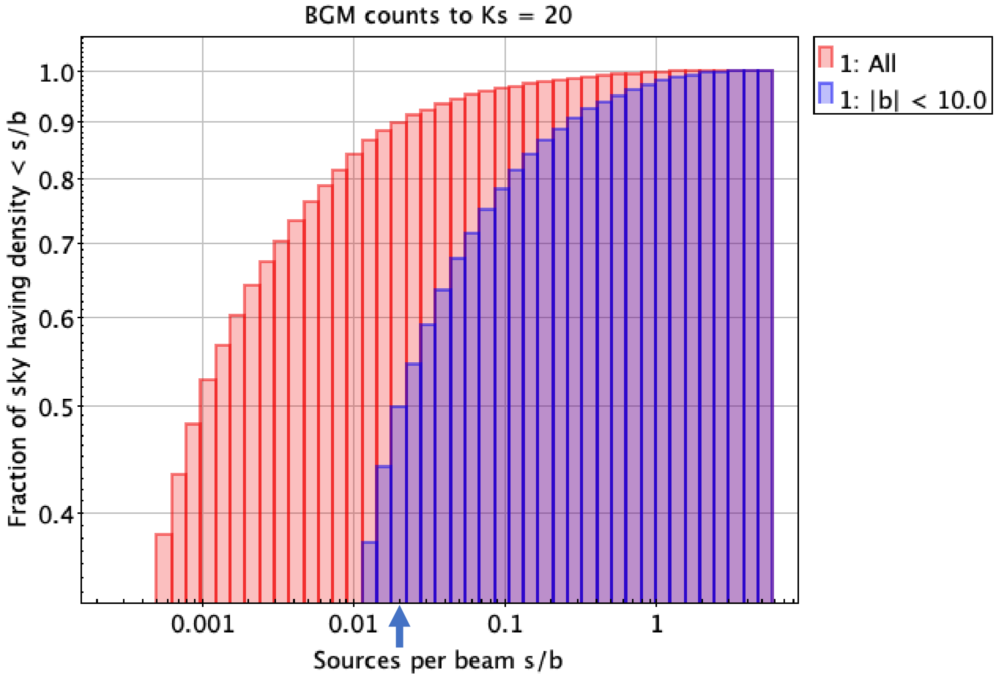


Source density considerations

- What about in the near-infrared for GaiaNIR?
- Again use BGM, but 2MASS Ks < 20 predictions
- Assume same M1 dimensions, but $\lambda = 2.2\mu$m



- Sources per beam is now much higher
  - IR beam size is larger
  - Extinction is lower
- Now ≈ 50% of the low-latitude sky has s/b ≳ 0.02
- This is the point at which crowding-induced scatter in astrometry and photometry becomes significant (e.g. D. Hogg, astro-ph/0004054)



Even an optimistic prediction suggests that for near-infrared N(m) counts, the worst 10% of positions are scattered by HWHM of the beam size (∼100 mas!) at s/b ≈ 0.06 … that's around 25% of the low-latitude sky.

Source density considerations

- Resolution will be better for a broad passband
  - but not for high reddening and/or red SEDs
- Simplifying assumptions include perfect knowledge of PSF and full 2D fitting
  - situation worse for 1D marginalised observations
- This analysis only considers one FOV
  - Source density in focal plane could be up to double during Galactic plane scans
  - Both FOVs are affected by confusion when either is pointed at dense regions
  - May be difficult to determine corresponding FOV for sources (lack of SM)
- Effective beam width is larger in AC direction due to scan-law induced broadening by ~0.8 arcsec

- Careful simulations including subtle instrumental effects are required in order to derive accurate performance predictions, trade off sensitivity & long wavelength cutoff, and define processing (on-board and ground segment) requirements