# *Daily processing and calibration: AIM e BAM i sistemi di validazione del cuore astrometrico di Gaia*

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A nome del team AIM
e
del team BAM

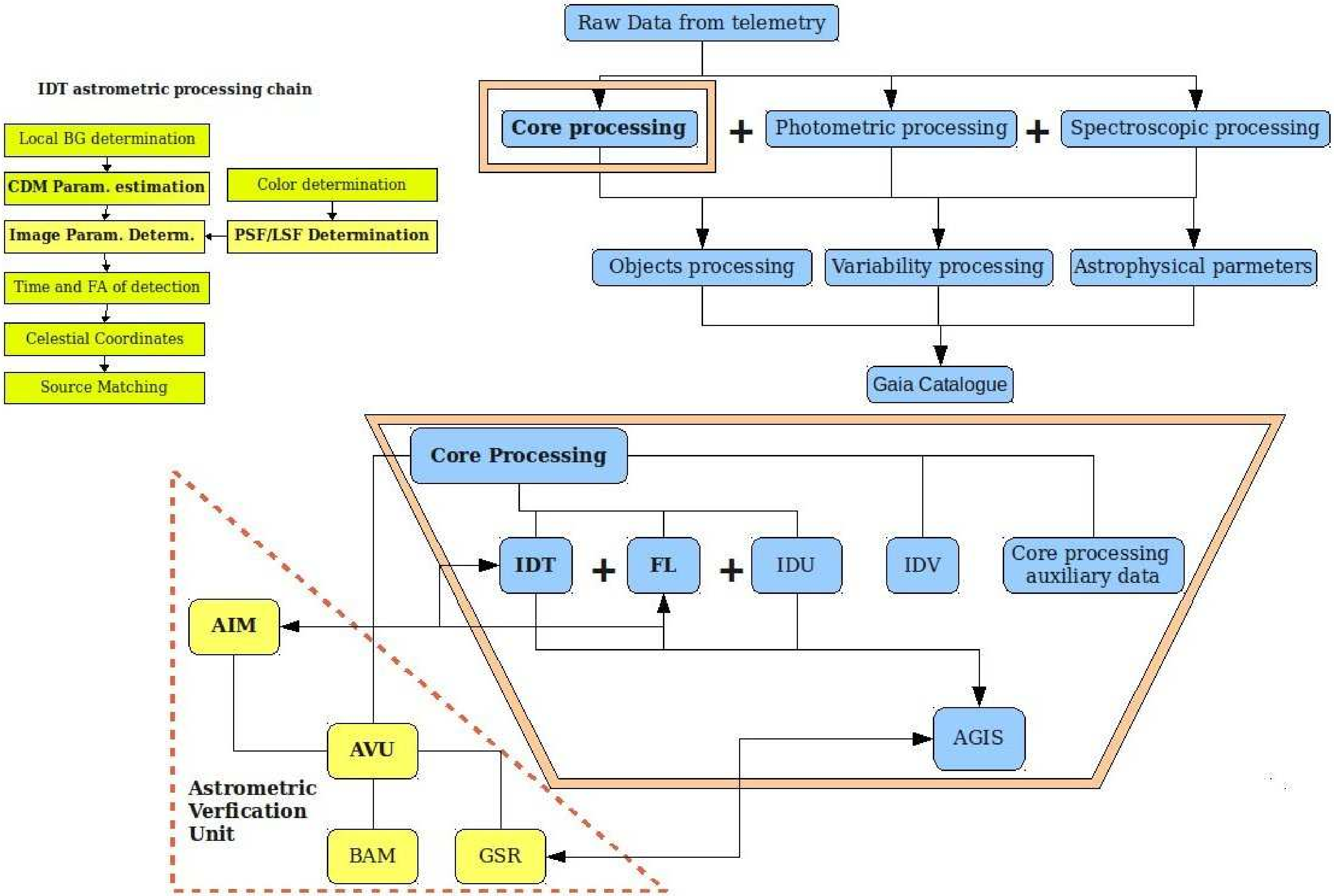
Cruciale per il buon fine della missione

- un effettiva comprensione del comportamento del payload,
- del suo impatto sulla qualità delle misure elementari
- ed eventuali conseguenze sulla qualità scientifica dei dati distribuiti

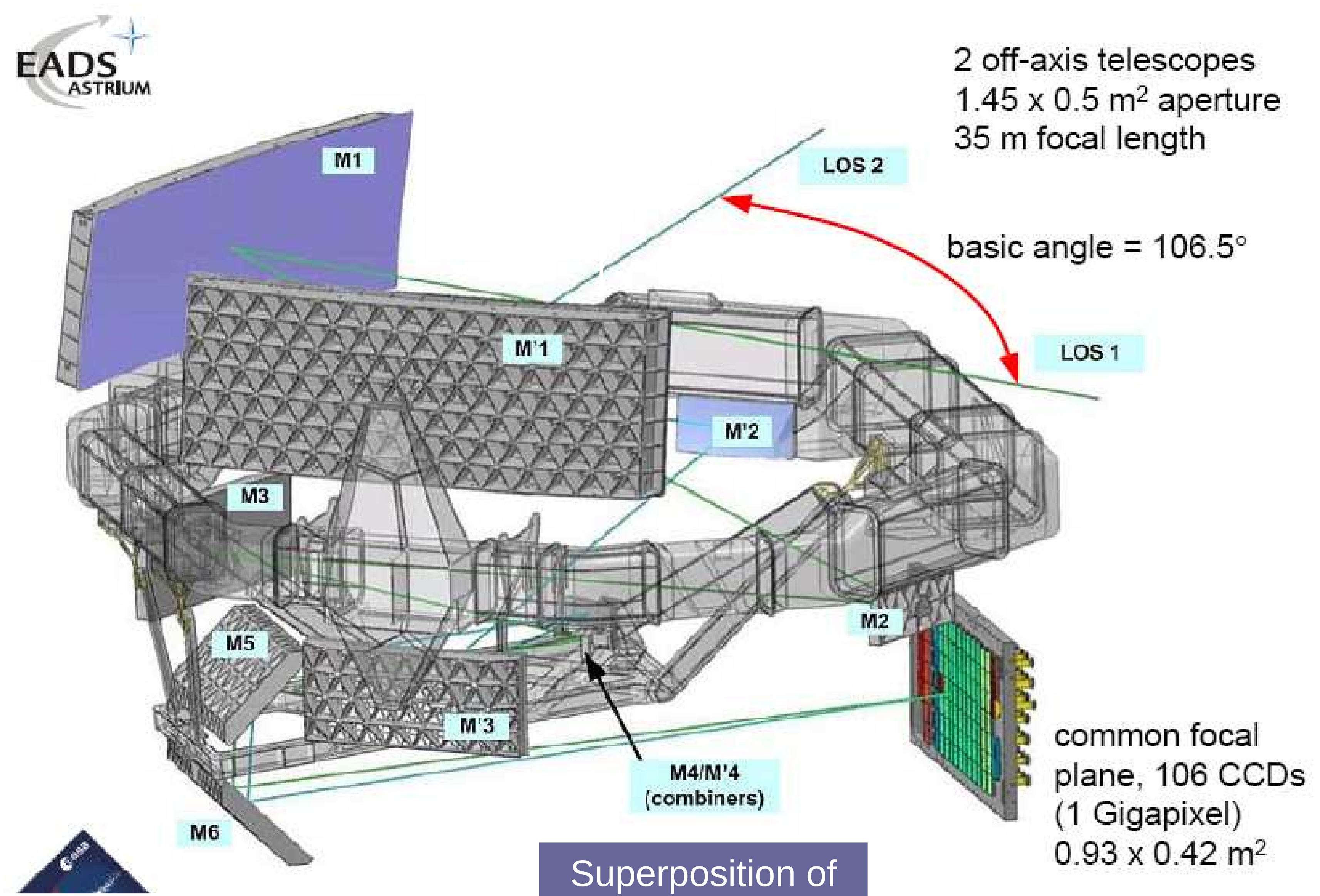
Sono considerati aspetti chiave:

- la distribuzione dell’errore random sul piano focale,
- i termini di errore sistematico dovuti ai diversi tipi spettrali, quale la cromaticità,
- le calibrazioni in volo e a terra durante il processamento.

# *Overview of the Gaia Processing chain*

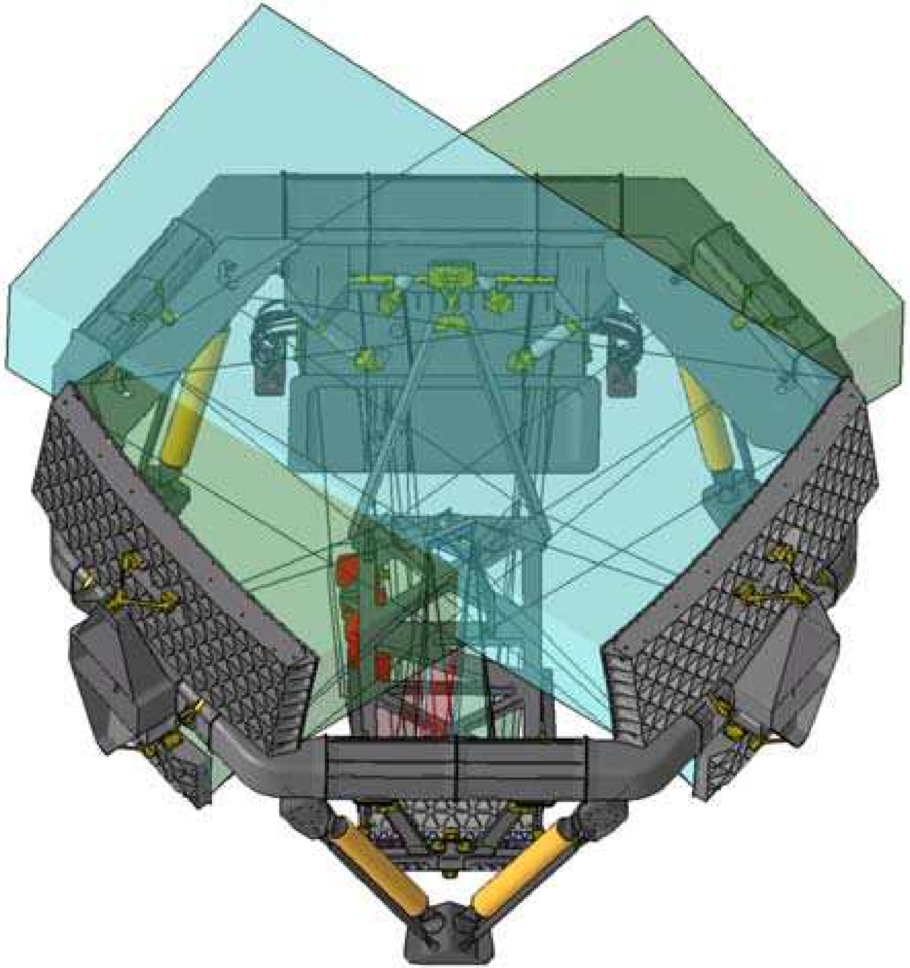


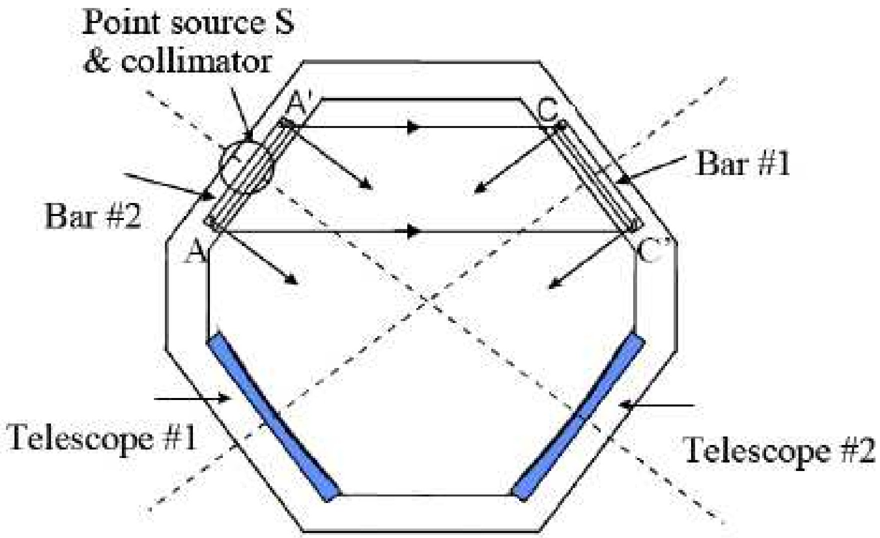
# Gaia's astrometric payload

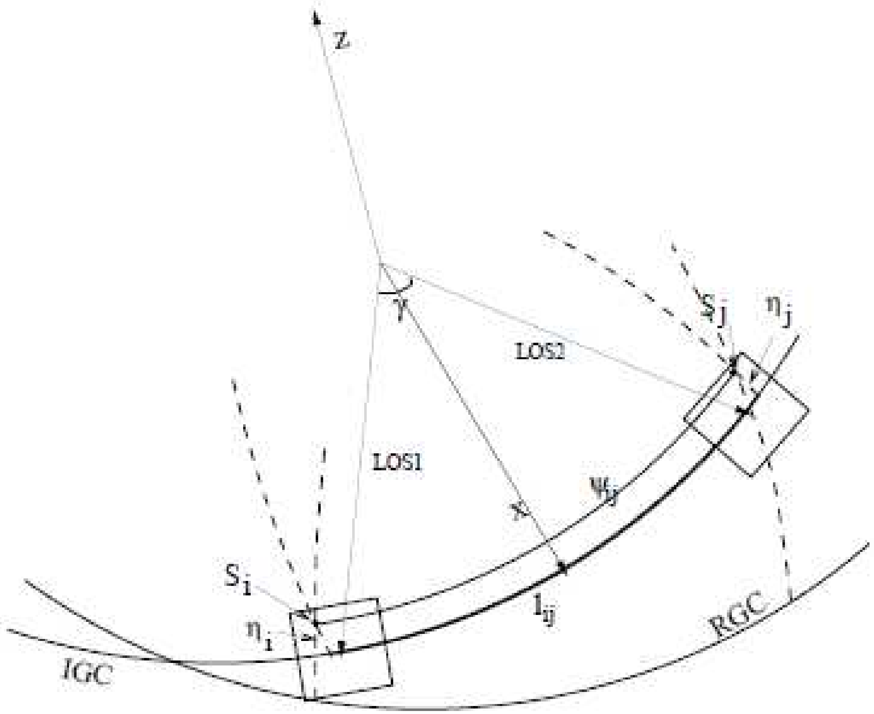



Superposition of two Fields of View (FoV)

# BAM device and concept





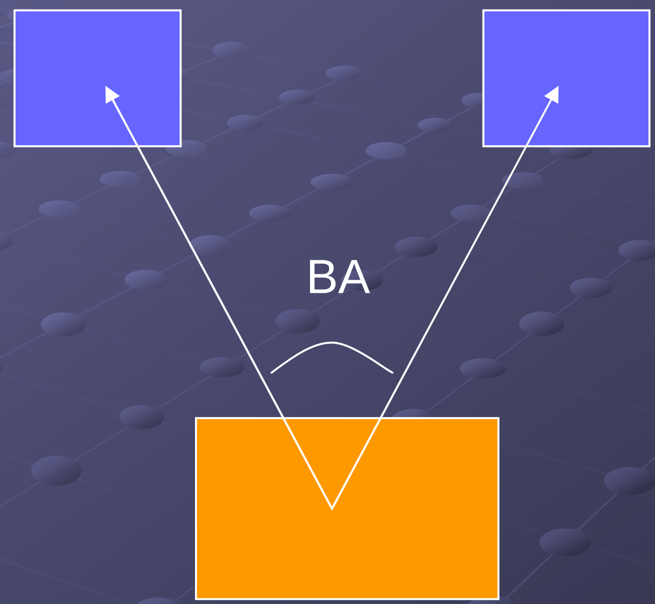

$$cos\psi_{i,j} = r_i \cdot r_j$$

## Angular coordinates

$\omega t = \phi(t)$ $\qquad$ $(\omega + \Delta\omega)t = \phi(t) + \Delta\phi$

$\xi + BA = \phi$ $\qquad$ $\delta\xi + \delta BA = \delta\phi$

$\xi = y/EFL$




$$\eta(1) = y \cdot os(1;x,y) = y/EFL(1;x,y)$$
$$\xi(1) = x \cdot os(1;x,y) = x/EFL(1;x,y)$$

$$\eta(2) = y \cdot os(2;x,y) + BA$$
$$\xi(2) = x \cdot os(2;x,y)$$

$$\delta BA(x,y) = \eta(2) - \eta(1) = y \cdot [os(2;x,y) - os(1;x,y)]$$

# The Focal Plane Assembly Layout

Gaia is designed to perform angular position measurements in their sensitive directions by centroiding their diffraction-limited images

Astrometric Accuracy goal: **few ten μas corresponding to $10^{-4}$ pixel size**

**Total field:**

- active area: 0.75 deg$^2$
- CCDs: 14 + 63 + 14 + 12
- 4500 x 1966 pixels (TDI)
- pixel size = 10 μm x 30 μm
  = 59 mas x 177 mas

**Sky mapper:**

- detects all objects to 20 mag
- rejects cosmic-ray events
- FoV discrimination

**Astrometry:**

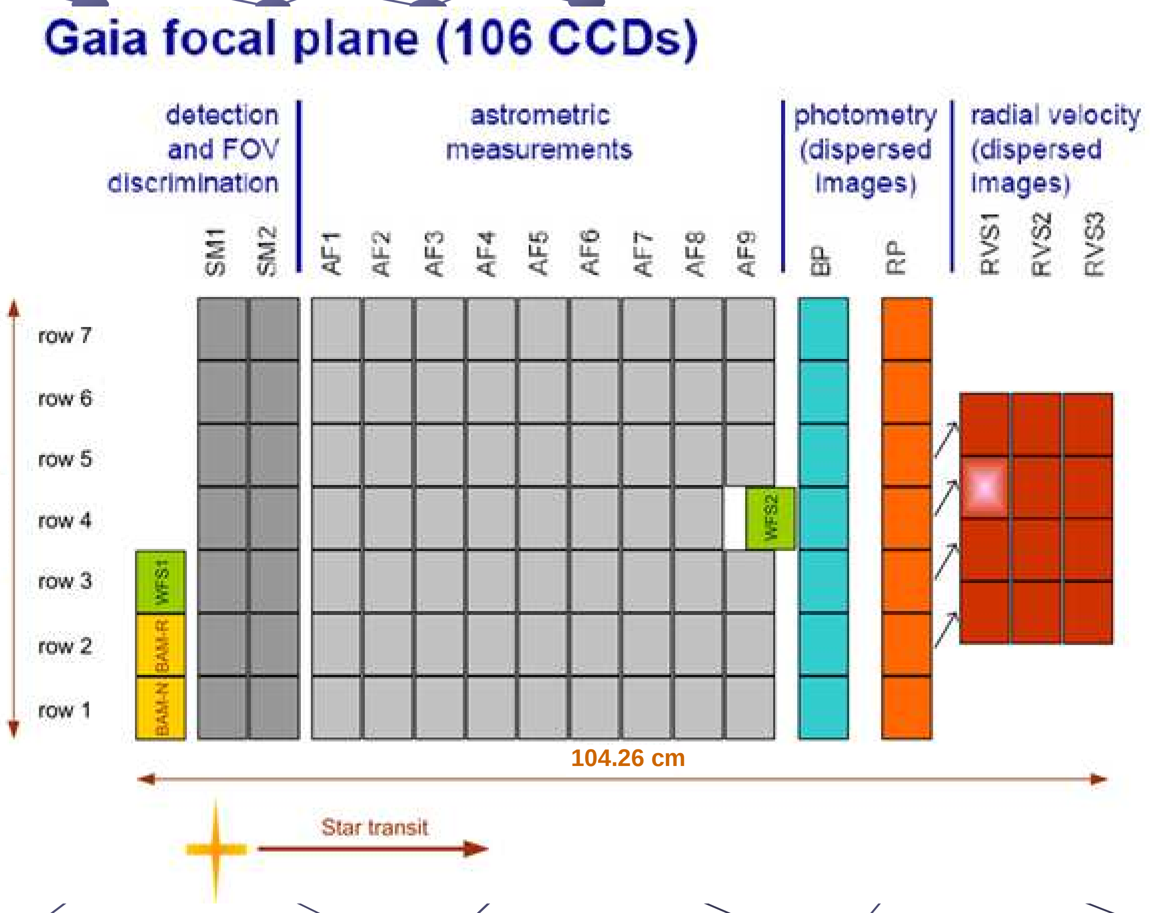
- total detection noise: ~6 e$^-$

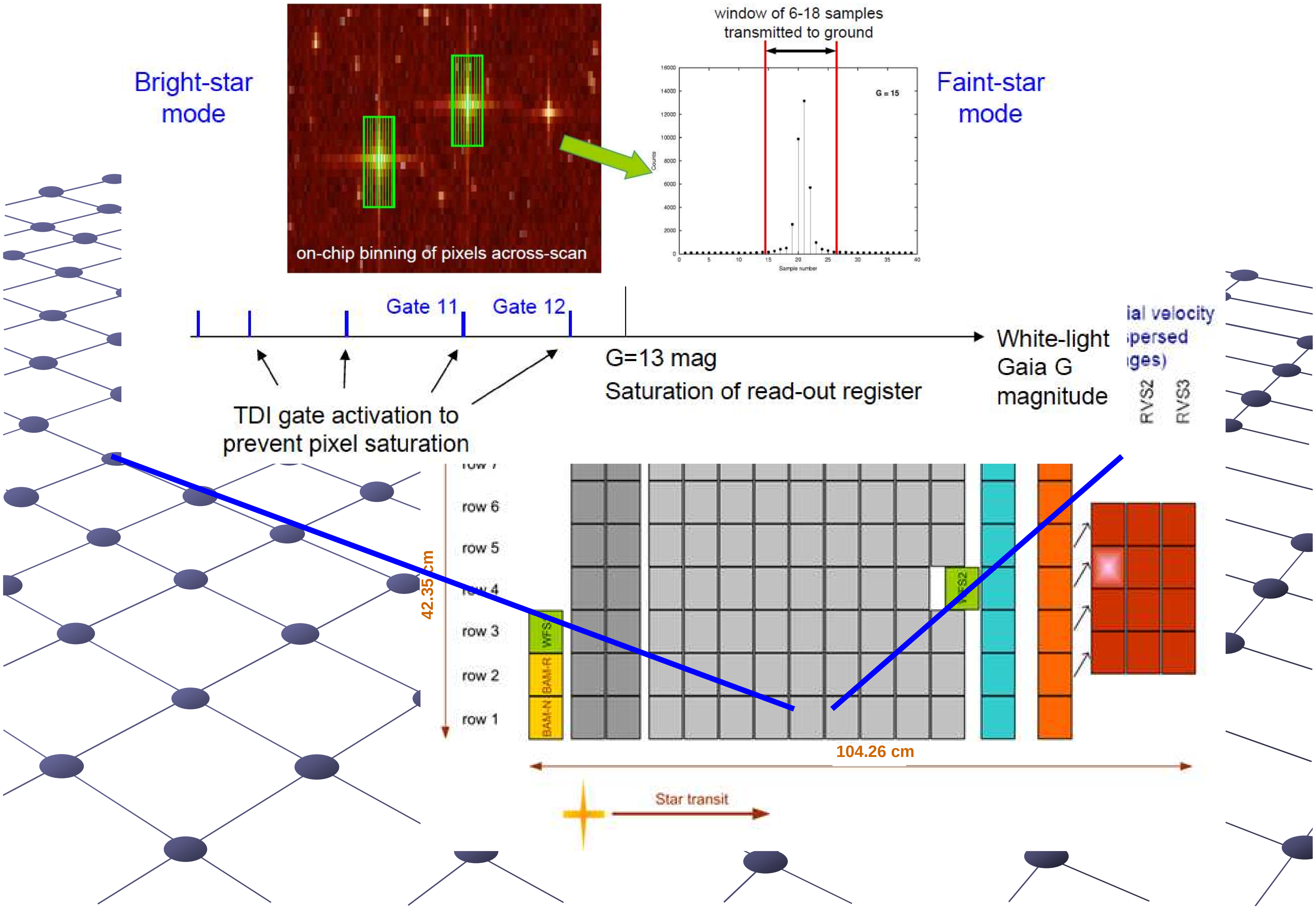
**Photometry:**

- spectro-photometer
- blue and red CCDs

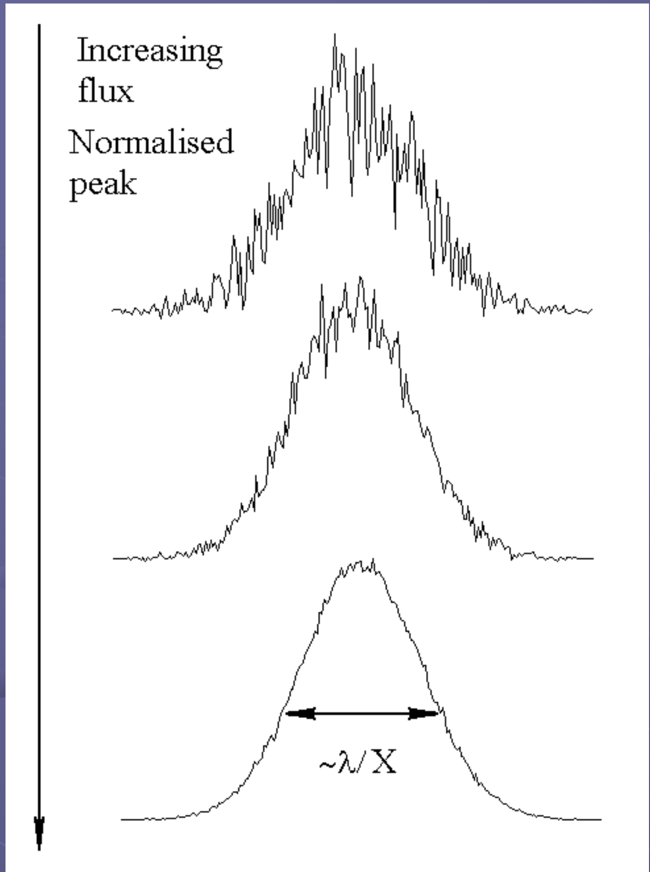
**Spectroscopy:**

- high-resolution spectra
- red CCDs




Bright-star mode
on-chip binning of pixels across-scan
window of 6-18 samples transmitted to ground
G = 15
Counts
Sample number
Faint-star mode
Gate 11
Gate 12
G=13 mag
Saturation of read-out register
White-light Gaia G magnitude
TDI gate activation to prevent pixel saturation
row 6
row 5
row 3
row 2
row 1
42.35 cm
WFS
BAM-R
BAM-N
RVS2
RVS3
104.26 cm
Star transit

# A fundamental limit to the location process is given by the Cramer-Rao bound




$$\sigma_x = \frac{\alpha \lambda}{4\pi X \, SNR}$$

$$SNR \leq \sqrt{N}$$

X = L/√12 for a rectangular pupil of size L in the x direction

$$\sigma_x = 0.8660 \frac{\lambda}{\pi L \sqrt{N}}$$

**σ**: Standard deviation of image location

**λ**: Effective wavelength of observation

**X**: The root-mean-square (rms) extension of the telescope entrance pupil in the high-resolution direction

**N**: Number of photons collected (noiseless detection, no background, …)

**α>1**: Instrumental factor of degradation (image quality, sampling resolution, location algorithm, …)

## A fundamental limit to the location process is given by the Cramer-Rao bound

| Quantity | Hipparcos | Gaia |
|---|---|---|
| photon flux | $10^4$ (10 mag) | $10^2$ (15 mag) |
| aperture size, $D_x$ | 0.25 m | 1.4 m |
| aperture area | 0.03 $m^2$ | 0.7 $m^2$ |
| EBW | 4 nm | 300 nm |
| total time on object | 500 s | 3000 s |
| no. of photons, $N$ | $6 \times 10^5$ | $6 \times 10^7$ |
| | 0.2 mas | 3 $\mu$as |

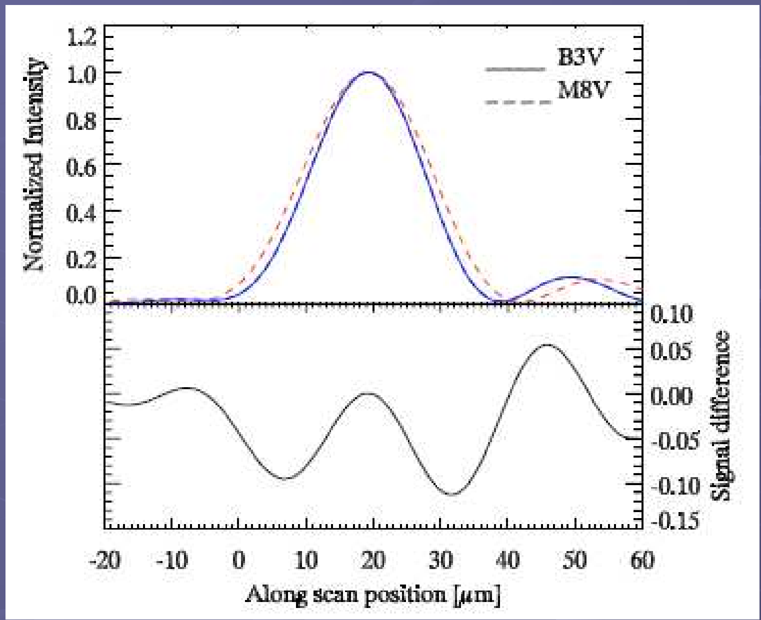
End-of.mission parallax standard error of order of 10 $\mu$as for G< 10 and 30 $\mu$as for G2V star of G=15. Stringent constraint on the accuracy of the location estimation on the CCD for each observation: **0.3 mas** ⟶ **0.005 pixels** for a G2V star at G=15

Critical parts for Gaia error budget which we need to calibrate:

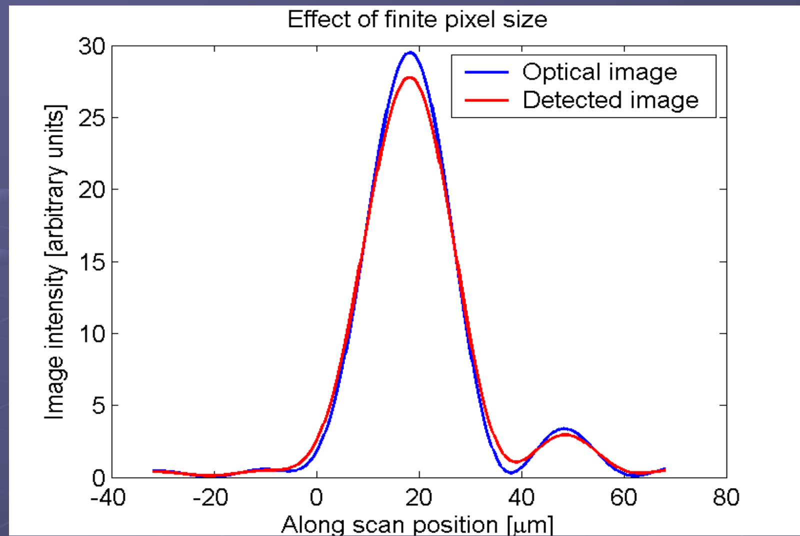
- Electro-optical response variation over the focal plane
- **Distortion**
- Blurring due to velocity mismatching
- **Chromaticity:** a color-dependent position variation, the same location on the sky is not uniquely mapped on the focal plane.
  It is an intrinsic property of all-reflective optical systems
- **Radiation Damage**

## Electro-optical response variation

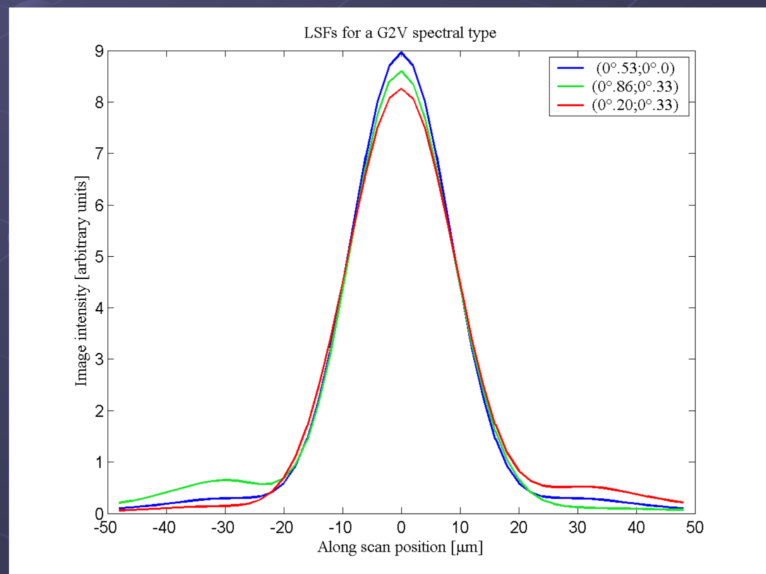
## Chromaticity:




*Impact of ideal CCD on monochromatic PSF:*




PSF in field position #3 @ λ=630 nm




Busonero et al. A&A 2006
Busonero et al. SPIE 2010

# Radiation damage

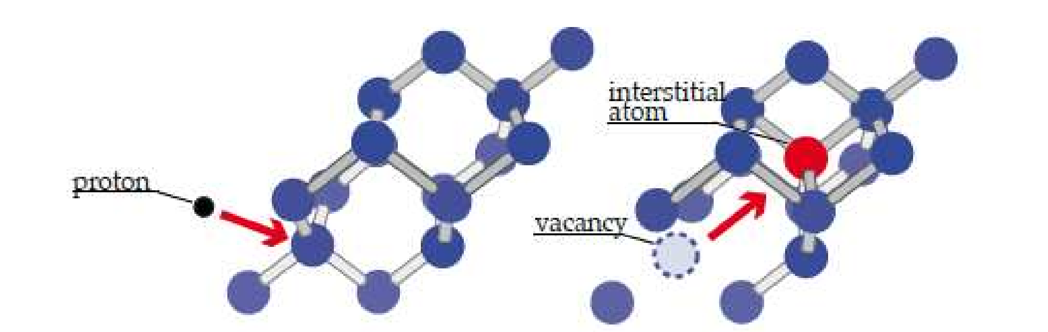
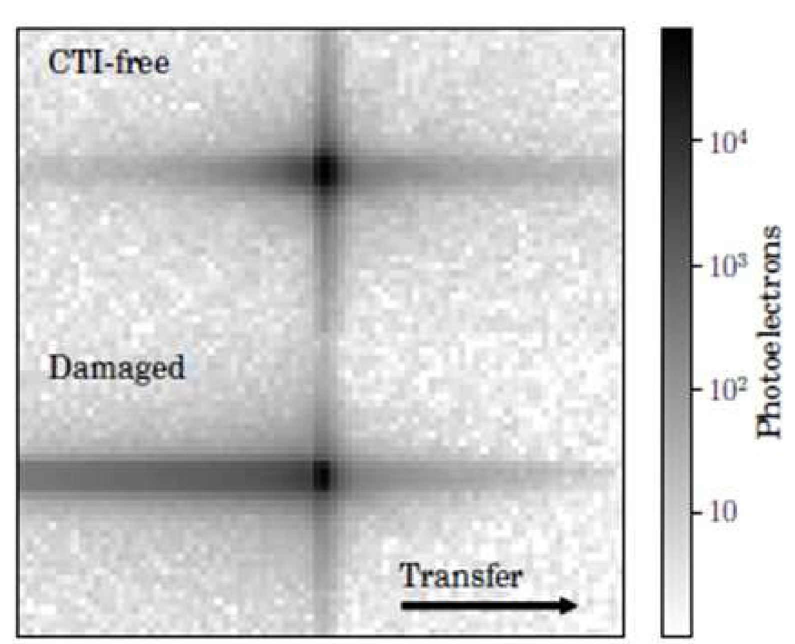
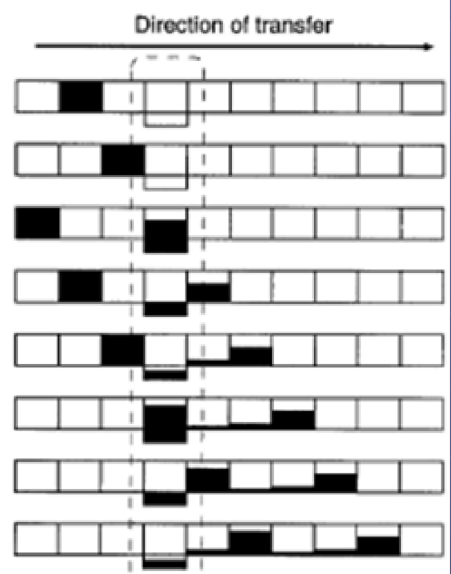
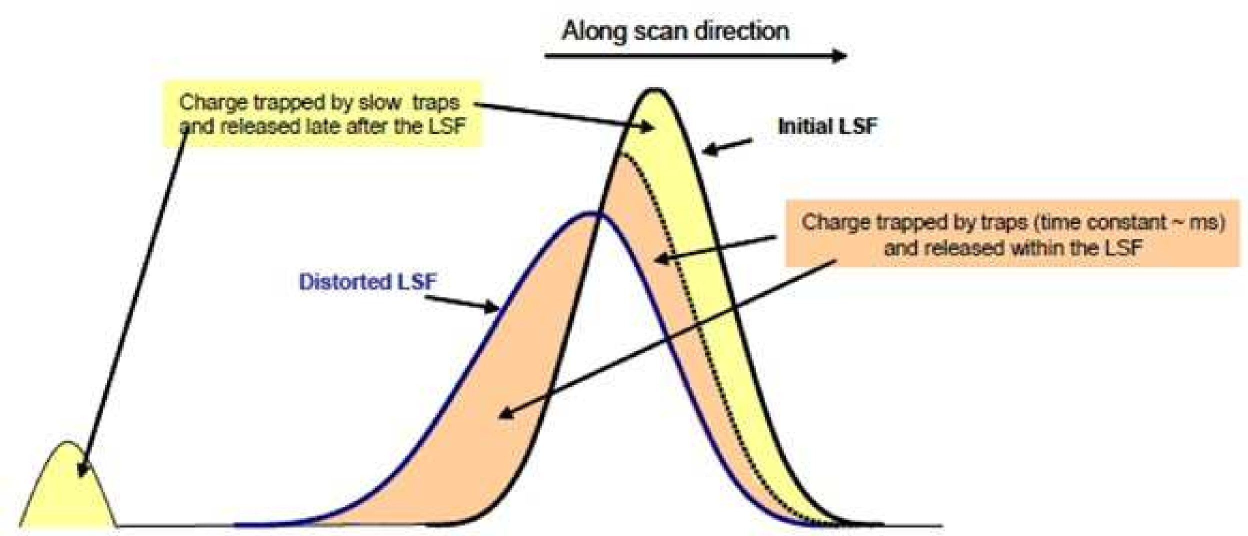



**Figure 1.10** — Displacement damage in the silicon lattice. An energetic proton collides with a silicon atom (left). The energy transferred by the proton to the target atom is enough to displace it into an interstitial location (requiring more potential energy than the normal lattice location of the Si atom), the lack of atom at the lattice location is called a vacancy: an interstitial atom-vacancy pair has been created (right). Vacancies can diffuse in the silicon lattice to bind with impurities and create bulk traps. Illustration adapted from G. Lucas and L. Pizzagali (LMP).



# *AVU/AIM*

- *AIM goals/ concepts*
- *Overview of the AIM scientific SW modules*
- *Briefing of the work in progress*

Busonero SPIE 2012
Busonero te al. SPIE 2010

# *AVU/AIM*

- Processing of the raw data coming from AF area of the focal plane in order to monitor and analyse the Gaia Astro instruments response (Astro1, Astro2 telescopes + FPA/AF area) and the astrometric data quality over the mission lifetime.

Fundamental:

•AIM implement and perform an instrument response monitoring and diagnostics independent of the baseline processing, so to compare the two results, and to report on possible alerts (daily and weekly reports).

•Different approach for assessing the astrometric instrument response during in-flight operations and image profile calibration procedure

# AIM system - Why

- ➢ Verification of the performance of specific parts identified as being critical to the astrometric error budget, of the IDT pipeline (i.e., psf modeling, location estimation, radiation damage..)
- ➢ Instrument monitoring during operation and diagnostic;
- ➢ Calibrations of the AF part of the focal plane;
- ➢ Understanding the parameter degeneration of the relation linking the observations to the instrumental behavior, and optimize the estimation process at the CCD and field-of-view crossing level.

✓ Critical for the system is the definition and maintenance of a physical instrument model fitting the science data, and able to accommodate non nominal configurations.

*Busonero, Loreggia, Riva 8449-57 SPIE 2012*

✓ Precise modeling of the astrometric response is required for optimal definition of the data reduction and calibration algorithms, and to ensure highest possible sensitivity to both the instrument and the astrophysical sources.

IDT/FL-ODC image profile modeling:

PCA approach:
75 coefficients each function

AIM image profile modeling:

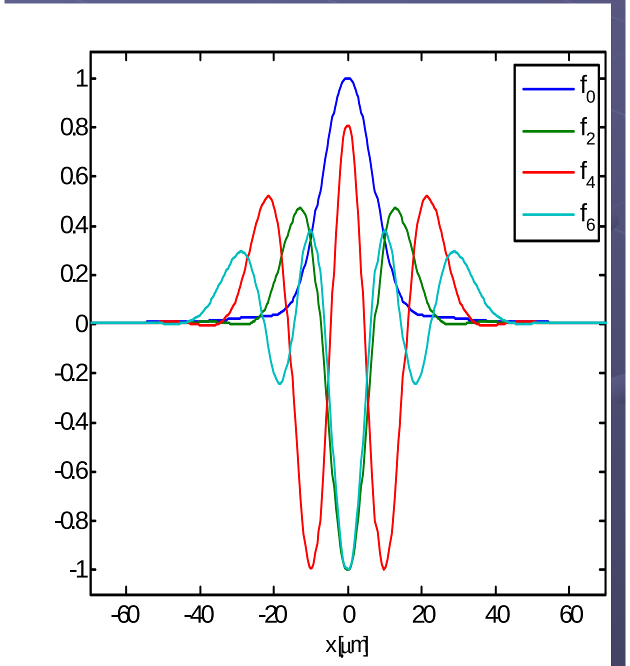
•for calibration
•and image parameter determination

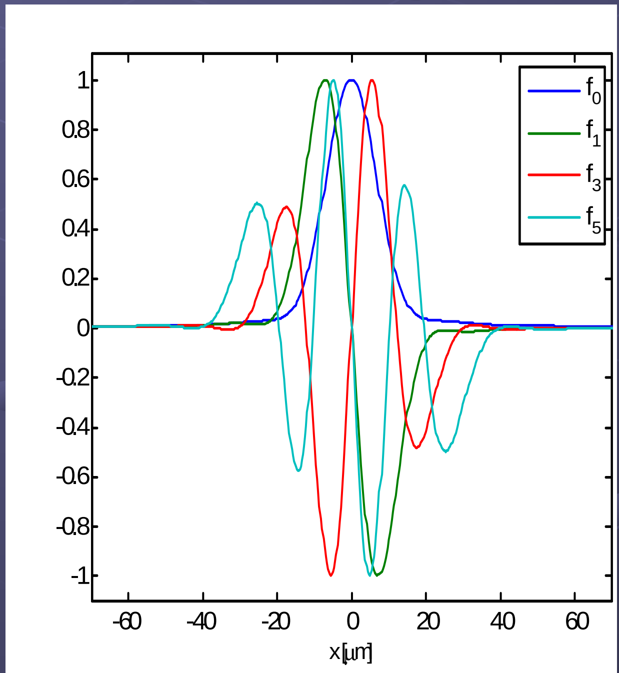
Parent function for generation of the monochromatic basis functions

$$\psi_0^m(x) = sinc^2\rho = \left[\frac{\sin\rho}{\rho}\right]^2 , \ \rho = \pi\frac{xL_\xi}{\lambda F} ,$$

Higher order functions: parent function and its derivatives

$$\psi_n^m(x) = \frac{d}{dx}\psi_{n-1}^m(x) = \left(\frac{d}{dx}\right)^n \psi_0^m(x) ,$$



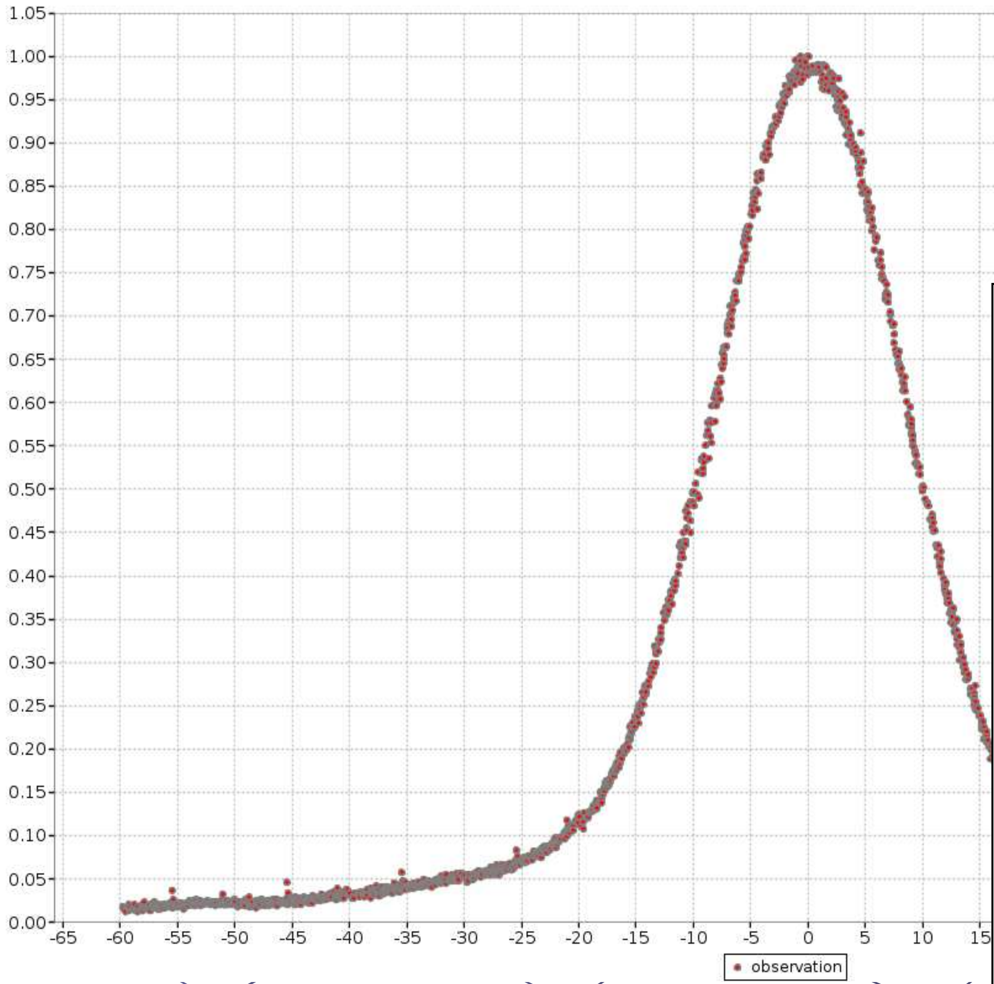




Common polychromatic function at T=6000 K

$$\psi_n(x) = \sum_l S_l \psi_n^m(x;l) .$$

# Calibration results

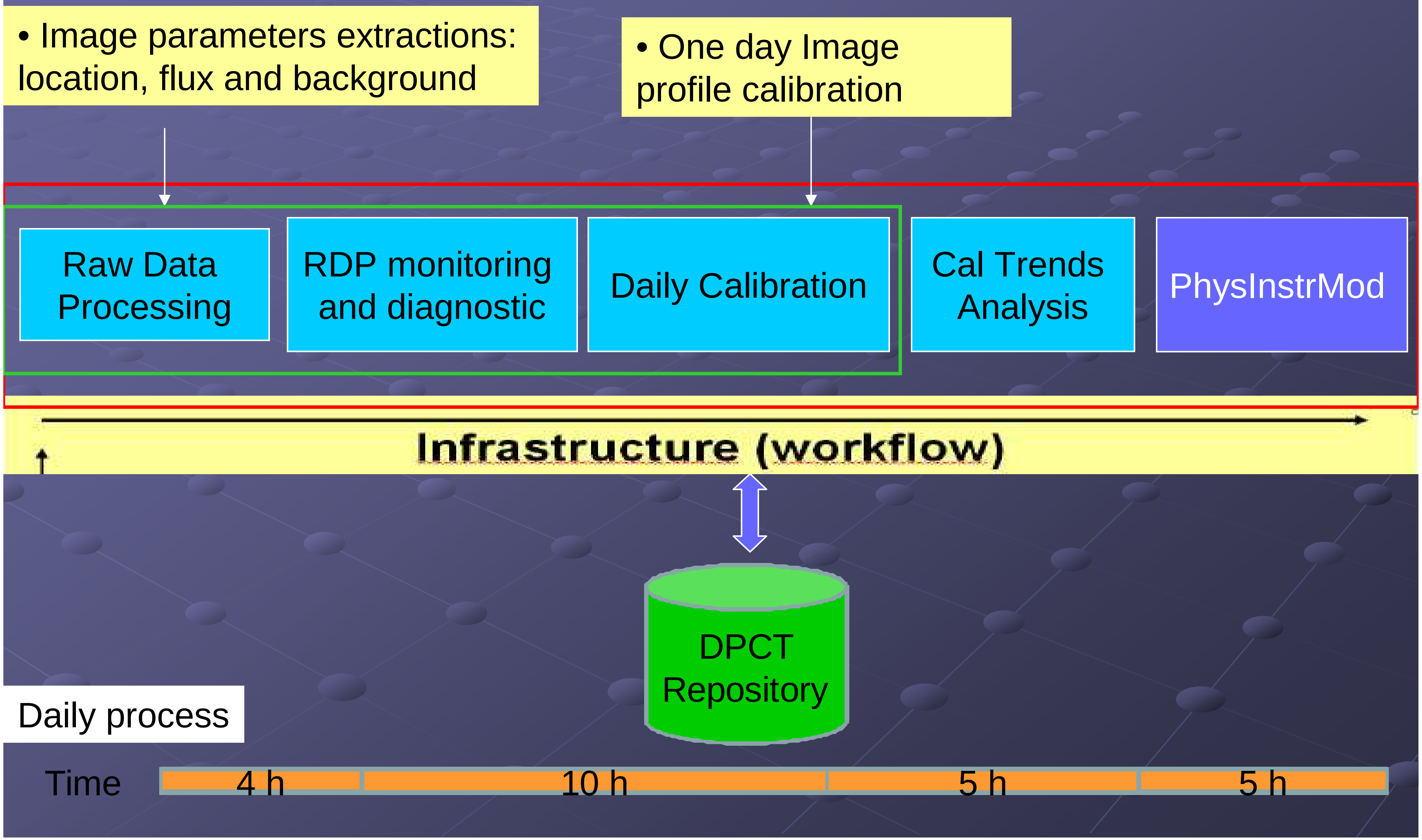
FOV=0
ccd_row=7
ccd_strip=2
N_obs = 200




********** BEST FIT **********
Best Fit Selection Method: WEIGHTED
Fit Time: 147 ms
Is Good Candidate: true
Is Candidate : true
OFFSET: 0.2
NTERMS: 11
TYPE : SAS_DATA
CENTRF :-1.4487062574410589E-5
PHOTOM :0.0010555261743935835
BIAS :-1.3195775231107141E-4
RESID :1.4411380861821676E-5

Gai, Cancelliere et Busonero MNRAS 2010
Gai, Busonero et Cancelliere PASP 2013

# *AVU/AIM scientific modules*

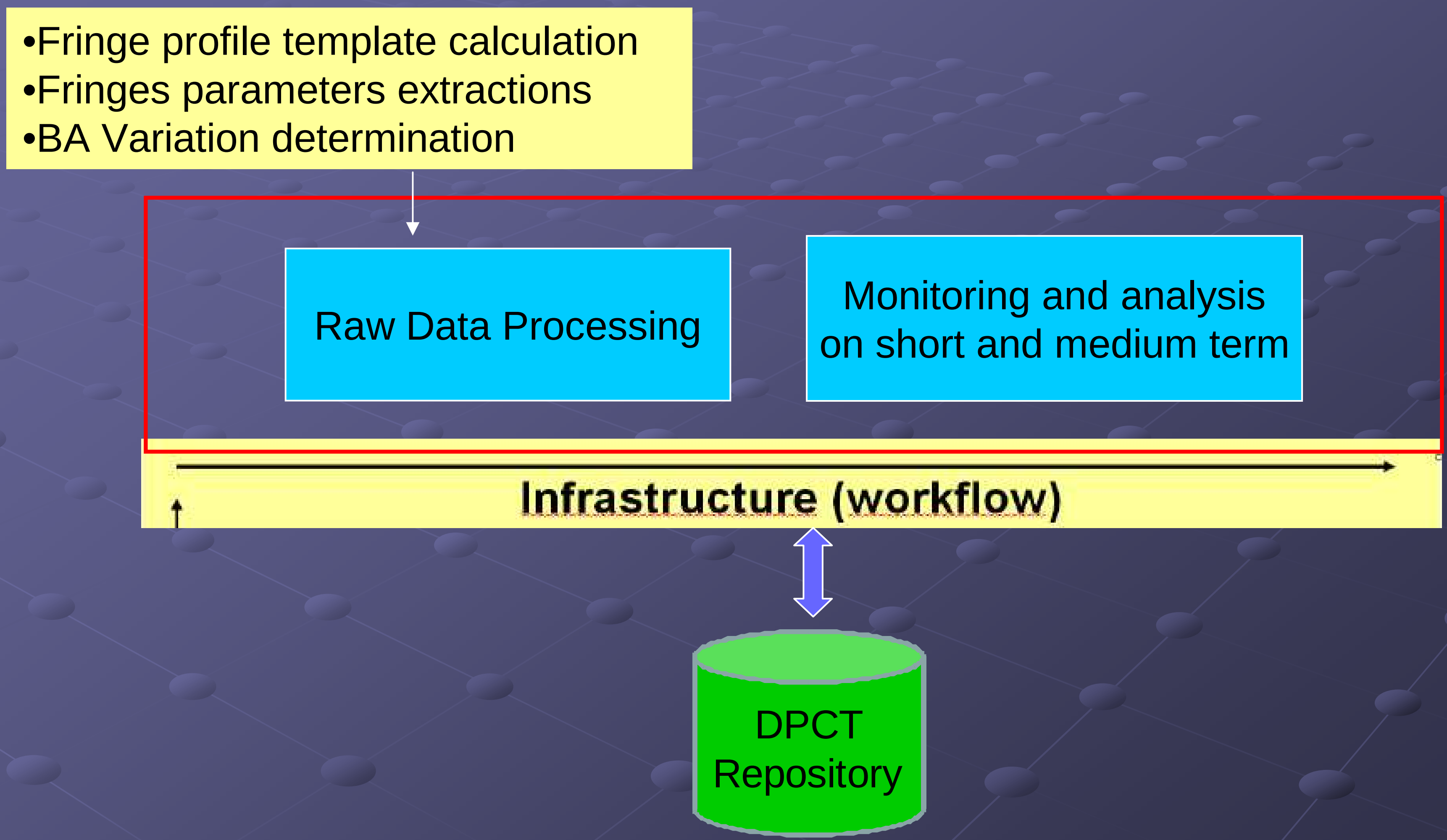


# *AVU/BAM*

The Basic Angle Monitoring (AVU/BAM) is the software in charge of processing the BAM Observations in order to monitor and analyse the BA behaviour, estimating the BA variation over the mission timeline

The Bam device produces a fringes set for each Line Of Sight
The variation of Base angle is proportional to the variation of the two fringes position

# *AVU/BAM scientific modules*



## *Operation Rehearsals*

- DPAC level tests *on daily processing*
- To test DPC procedures and to verify that the relevant DPCs are ready *for Commissioning* and Operations.
- To verify that relevant daily processing systems are ready *for Commissioning*.
- To verify the interfaces between DPCs needed for daily processing *during Commissioning*.
- Also used to define and test DPAC communication channels needed *for Commissioning*.
- 4 ORs are planned, with a possible post-launch OR#5 *only if absolutely necessary*.
- OR#4 may also test nominal operations procedures.
- No cyclic processing systems are involved.
- Uses several days of simulated telemetry, *with problems introduced* to test robustness of the procedures.
- AVU systems involved: **AIM and BAM**

**From Dec 4 through Dec 14 2012**, DPCT and the relevant AVU systems (AIM & BAM) successfully participated in OR#2, the first commissioning-like data processing exercise scheduled by DPAC under the supervision of the OCT.

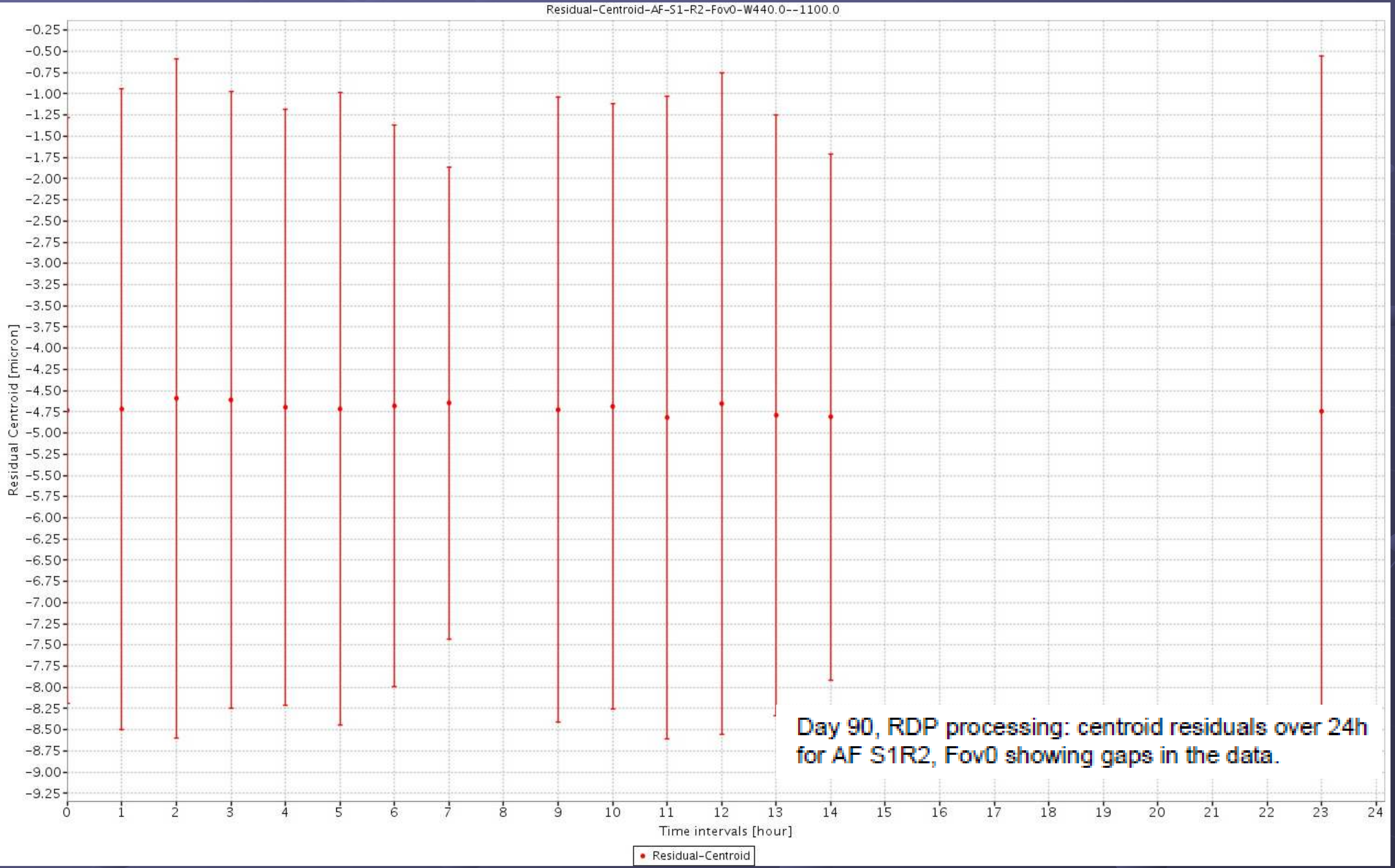
The test demonstrated readiness and consistency in routine processing of AstroObs and BamObs and ability to adapt to test conditions different from what anticipated (e.g., ‘continuous’ transmission mode from DPCE).

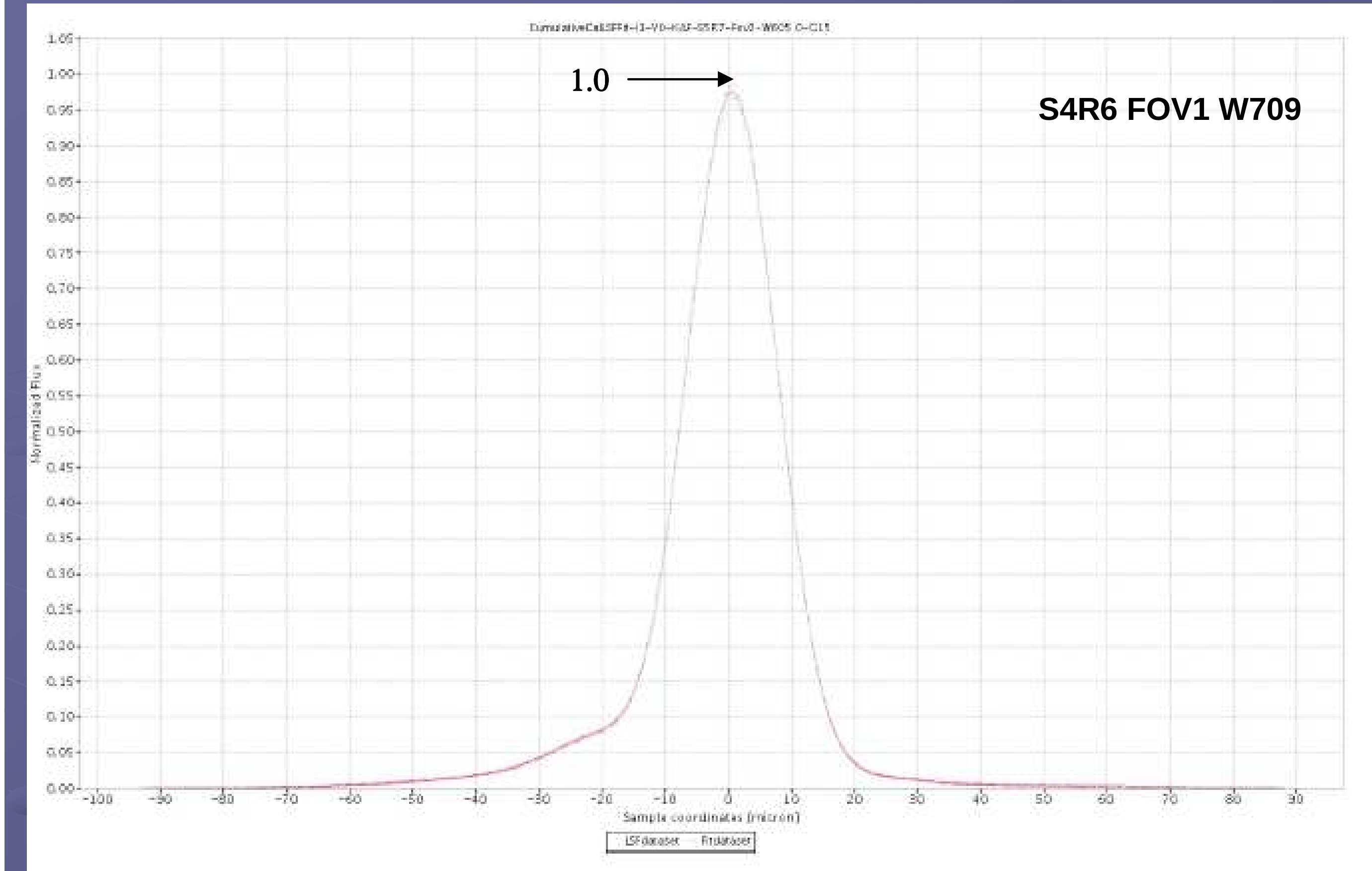
Reports assessing quality of results prepared and issued whenever possible throughout the test period.

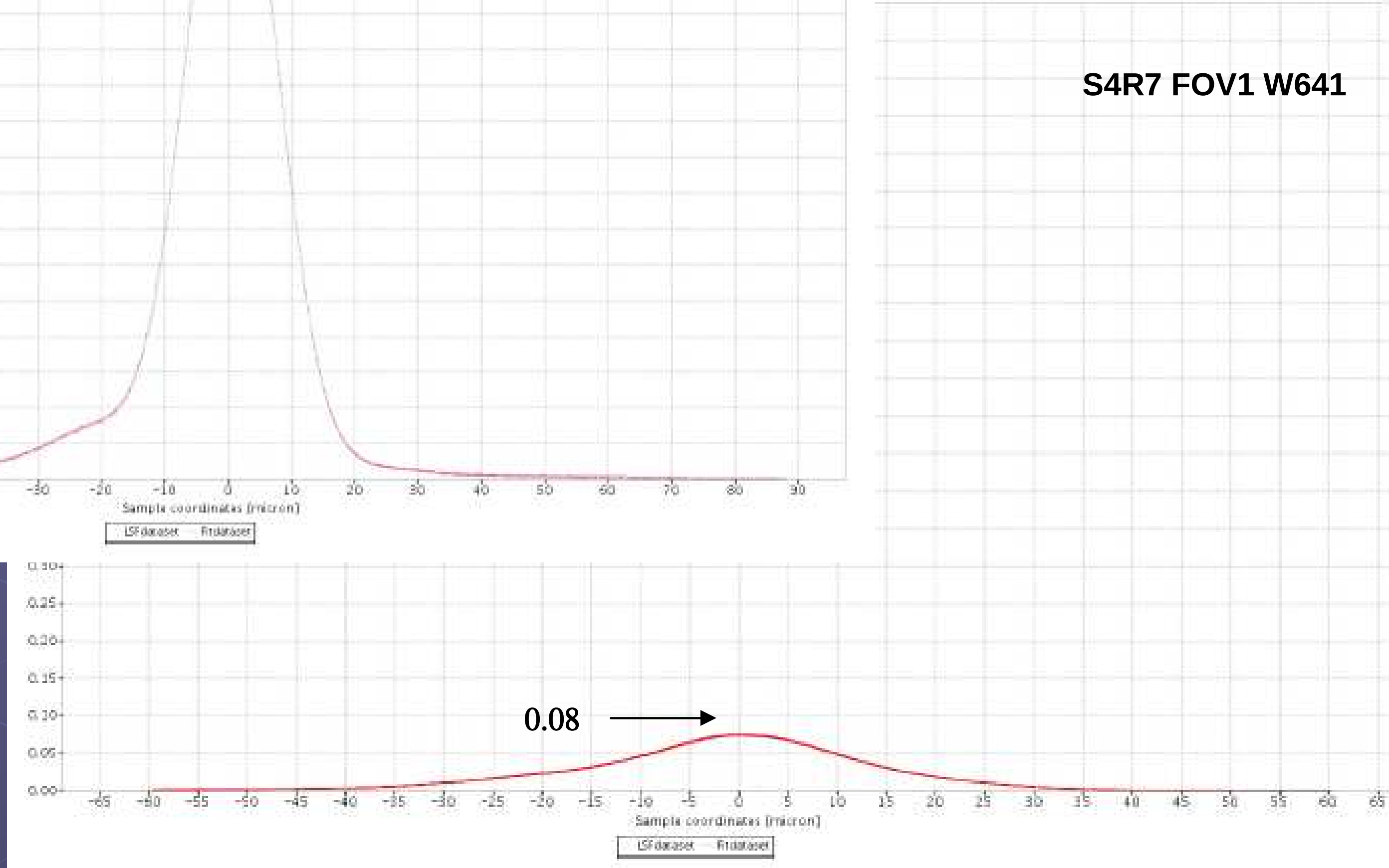
# OR2 @ DPCT (ALTEC, Turin) – Dec 4 – 14 2012

# AIM

- Able to operate all of integrated modules including the daily LSF calibration module;
- Results were consistent with quality of IDT data transferred



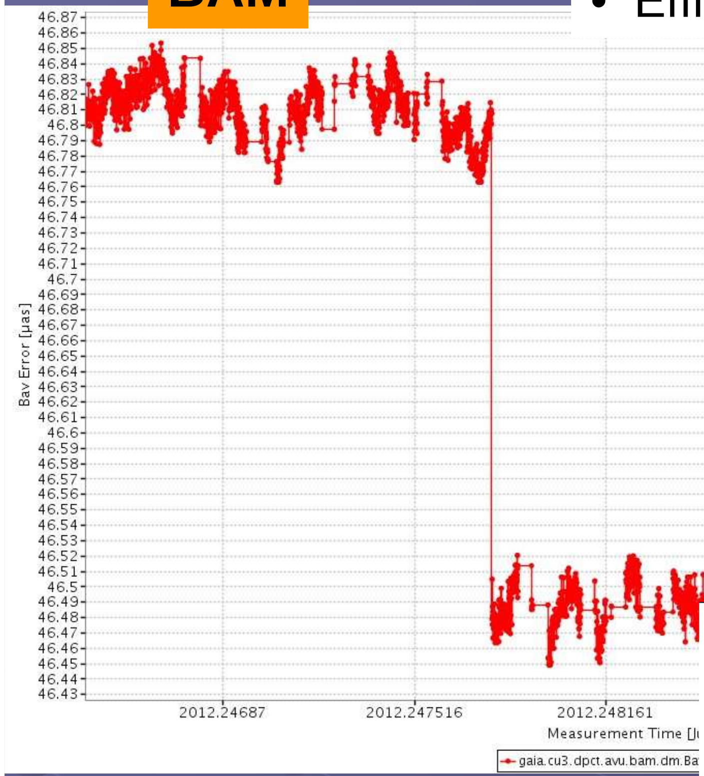


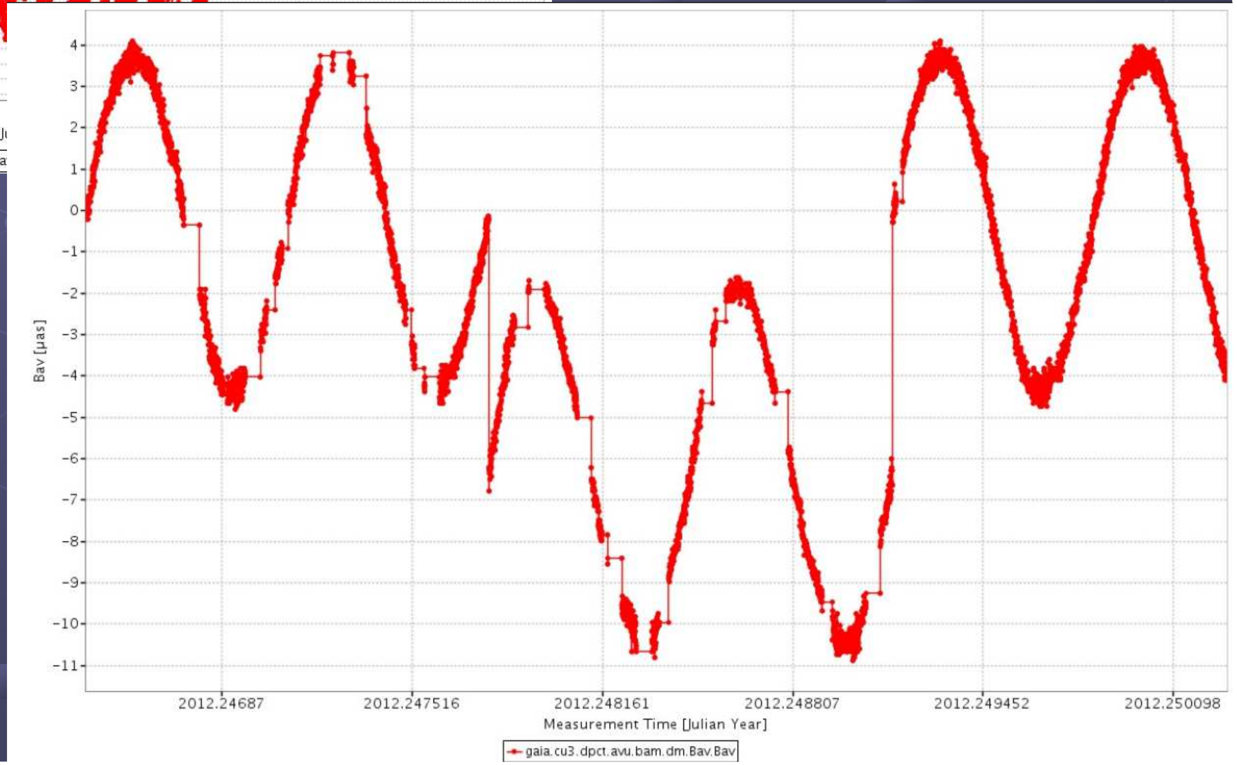

Results for daily LSF calibrations: left, calib. LSF for FOV1 S4R6, W709nm; right, failed calib. In FOV1, S4R7, W641nm (due to undetected anomalous intensity distribution in original pixels as shown by follow-up investigations).

**BAM**

- Efficient and robust pipeline throughout the rehearsal;




BAV Error Plot




BAV Plot

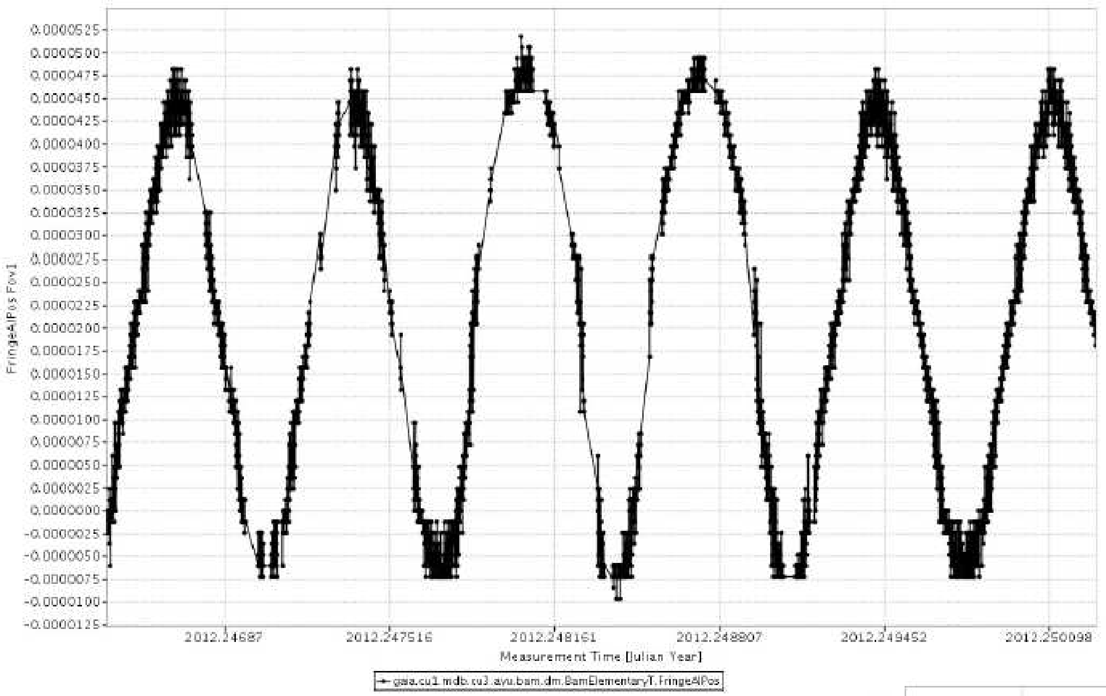



FIGURE 1: FOV 1 fringe position plot

variations of LOS 0 (left) and LOS 1 (right) with time (≈34h of data)

Sudden 'jump' of 7μas after the first 12h into Day 90.
The same discontinuity, but in the opposite direction (-7μas), appears at the end of Day 90.

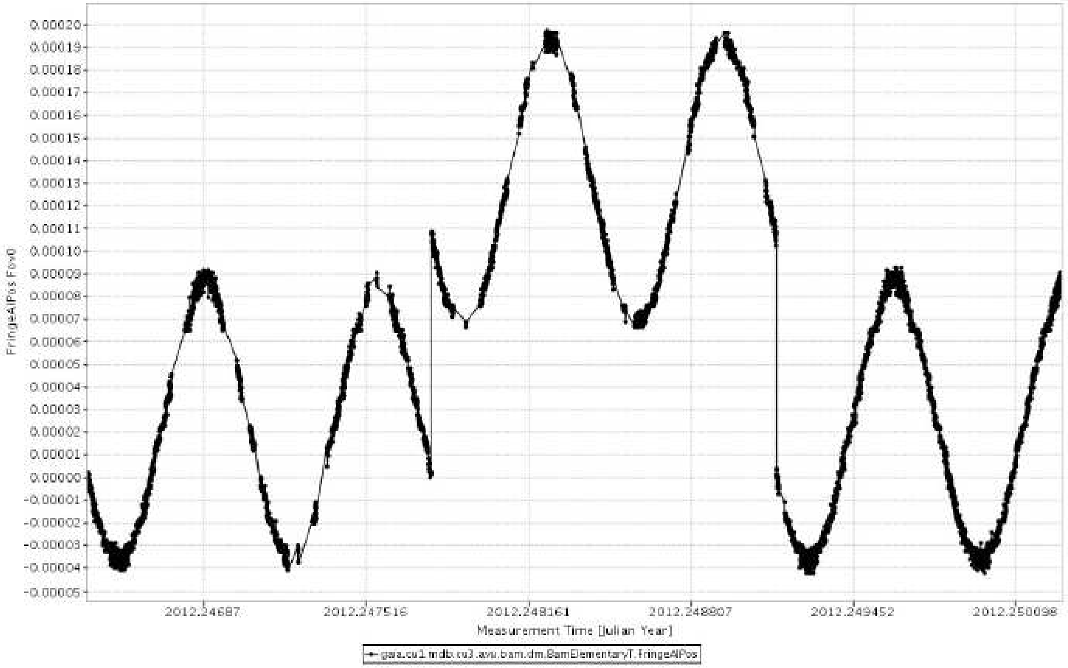



FIGURE 2: FOV 0 fringe position plot

# AIM, BAM and the mission timeline

Huge schedule compression

Getting ready for OR3 (end of April 2013):
SW systems deliveried from science team expected for end of March.

Getting ready for OR4 (September 2013):
SW systems deliveried from science team expected for end of August.

The SW systems shall be ready within August 2013

L + 3 months : Commissioning and early operations will start !!!

5 nominal + 3 extended years of mission length

## The legacy of AIM and BAM

- Full exploitation of the scientific potential of an astrometric experiment by identification and removal of systematic errors, either from astrophysical or instrumental origin, thus ensuring the science quality of delivered data.

- The experience suggests to us that a number of tools could be properly defined and deployed since the early design phase of future astrometric experiments, making the measurement concept intrinsically more robust.

- Development of conceptual and software tools for advanced calibration of future astrometric experiments, and specific subsets could be verified e.g. on the data from early Gaia operation

The development of AIM and BAM is a scientific effort that is involving the expertise of several people:

**AIM Team**

| | | |
|---|---|---|
| Deborah Busonero | 1.0 | TD |
| Enrico Licata | 1.0 | contrattista |
| Mario Gai | 0.2 | |
| Davide Loreggia | 0.3 | |
| M.G. Lattanzi | 0.1 | |

**BAM Team**

| | | |
|---|---|---|
| Alberto Riva | 1.0 | TD |
| M.G. Lattanzi | 0.2 | |
| Federico Russo | 0.8 | AR |
| Raffaella Buzzi | 0.5 | Borsista |
| Mario Gai | 0.2 | |

ALTEC: Rosario Messineo, Enrico Pigozzi, Angelo Mulone

Skills and expertise: location algorithm theory, advanced calibration for correcting the instrumental and astrophysical effects on astrometric signals, high level instrument response modelization, monitoring and diagnostic tools for instrument response, numerical algorithms, Java programming and system engineering

5 INAF people, for a total of 2.6 INAF FTEs
5 INAF people, for a total of 2.7 INAF FTEs