The Gaia Basic angle: measurement and variations

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The Milky Way Unravelled by Gaia

Barcelona, 2014/12/02

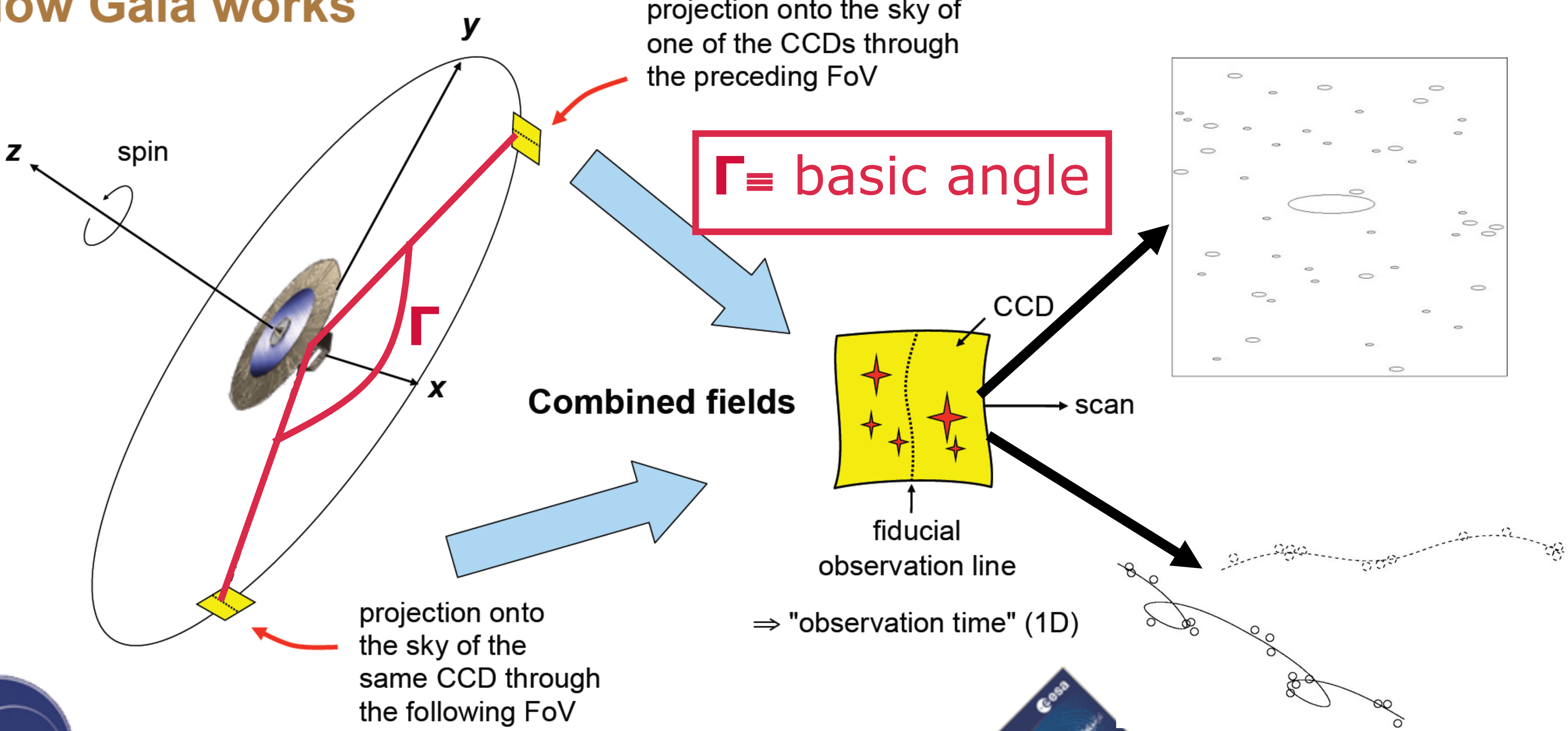
Outline

1. Preliminary results. Gaia still to be fully understood!
2. Basic angle: importance and instrument design
3. BAM data analysis
4. The real basic angle: in-orbit behaviour
5. Conclusions

2. Importance and instrument design

2.The Gaia basic angle

How Gaia works



Lindegren & Bastian: The astrometric solution of Gaia - a hard problem 3

European Space Agency

2. Basic angle variation: effects

- Gaia aims at global astrometry (reference frame, stellar motions and parallaxes) at µas accuracy
- The basic angle needs to be stable (or known) to corresponding precision
- Gaia is largely self-calibrating (calibration parameters estimated from observations)
- **Low frequency** variations ($f < 1 / 2P_{rot}$): eliminated by **self-calibration**
- High frequency random variations
  - Averaged during all transits, not so harmful
- Systematic variations synchronized with spacecraft spin
  - Only partially possible to eliminate by self-calibration
  - Residual variations could create systematic errors in astrometric results
  - Thus **high-frequency** variations need to be monitored by **metrology**

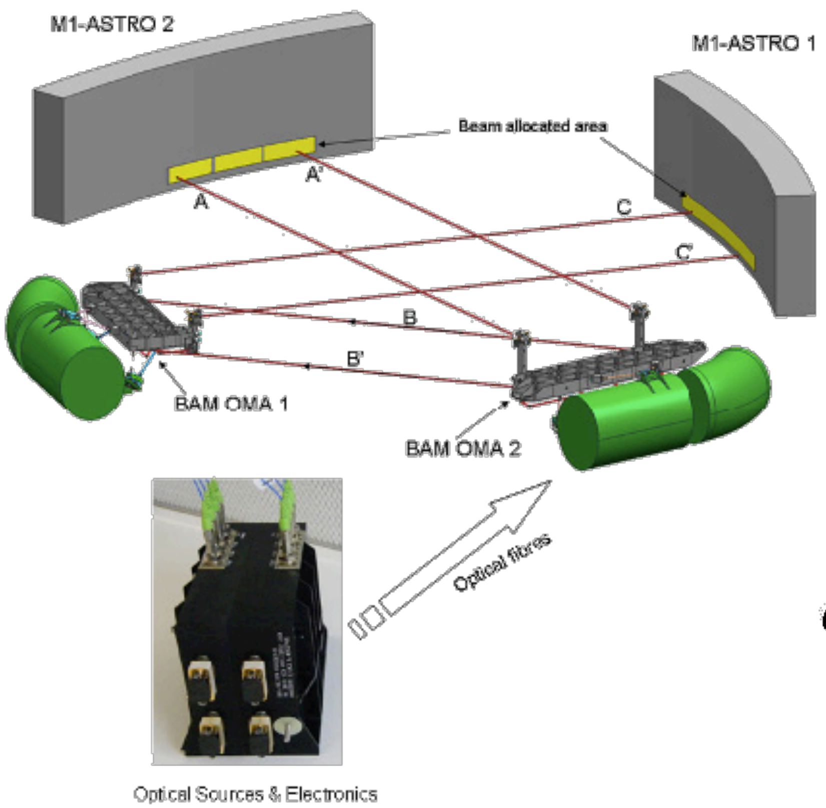
2. Basic angle measurement: BAM

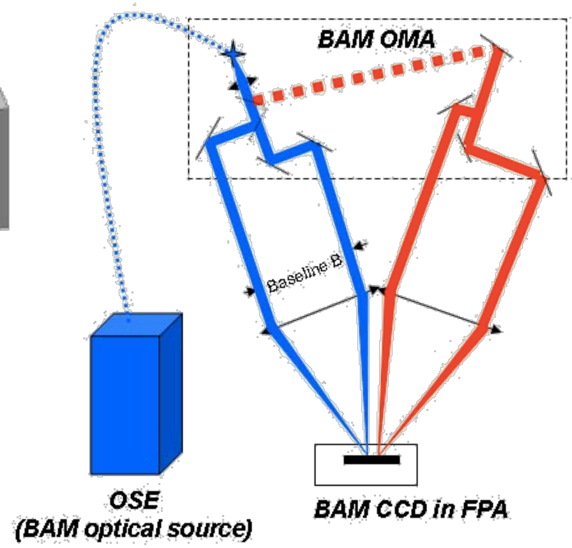
- One artificial fixed star per telescope needed
  - Collimated laser beams directed to the primary mirrors
  - Gaia telescopes generate the image
- Relative AL centroid displacement ➔ basic angle variation
- Single CCD AL centroid location precision
  - AF: Δy_{AL} ~ 40 µas single transit bright star limit
  - BAM: Δy_{AL} <0.5 µas in 10 min (differential measurement)
    - ~20s/frame ➔ $\Delta y_{AL,1frame}$ < 2.7 µas. ~15x better than bright stars!!
- Many photons and sharp LSF needed
  - Artificial stars are interferometric patterns

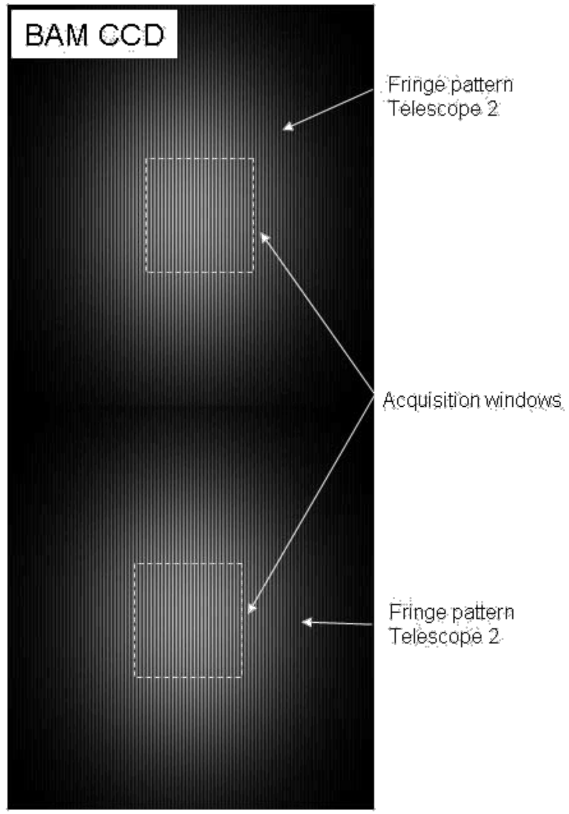
2. BAM working principle

0.5 µas = 2.4 prad = 3.6 pm = 0.66 µfringe

On ground state of the art: 1 milli-fringe







Courtesy: Airbus D&S

BAM measurement: differential interference pattern centroid

3. Data analysis

3. BAM data analsysis: strategies

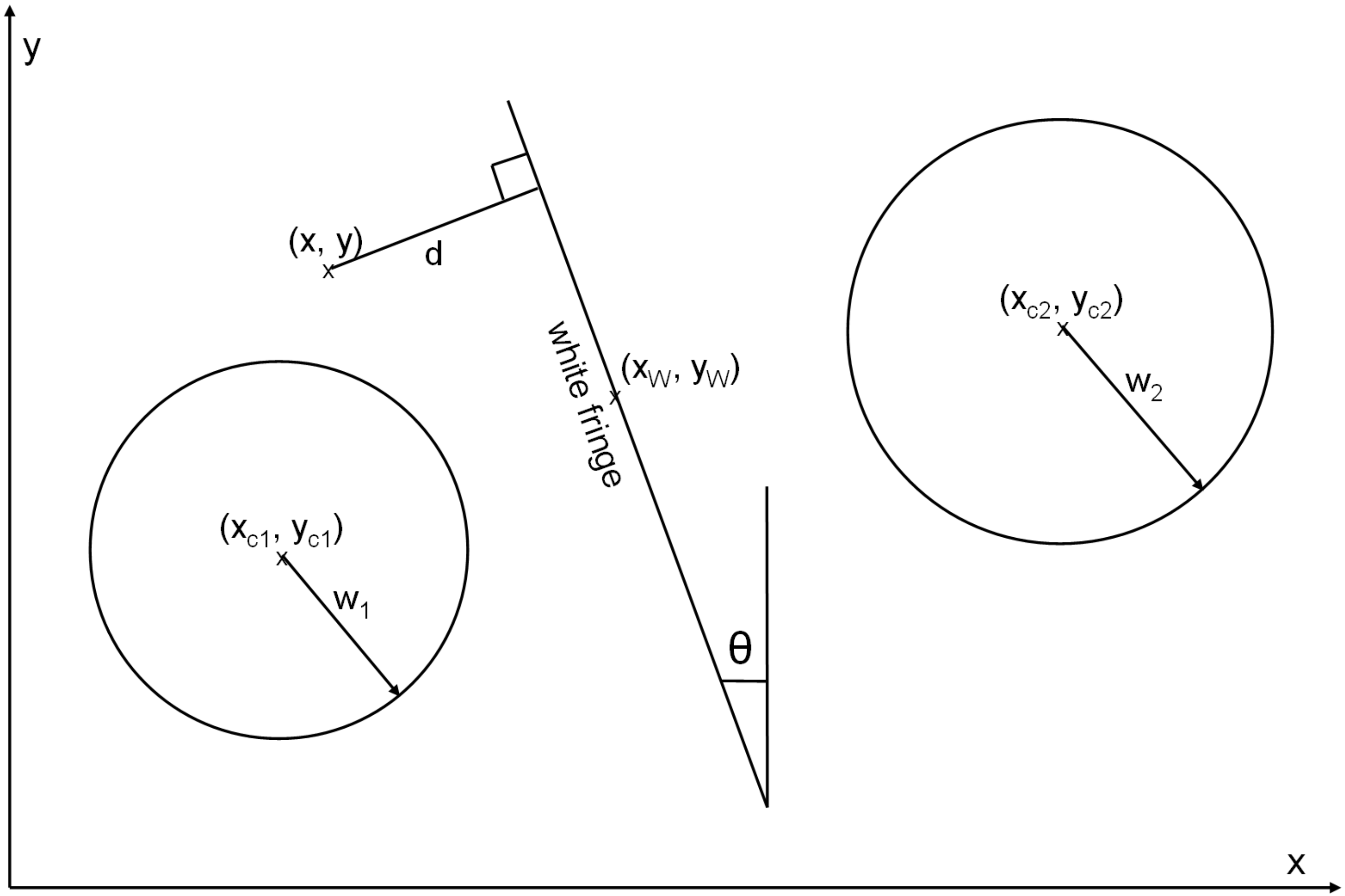
esa

- Cross-correlation
  - Pros: very fast, good precision, any template is OK
  - Cons: very high systematics, not customizable
- Fourier transform
  - Pros: fast, good precision
  - Cons: high systematics, not customizable
- Direct fit method
  - Pros: customizable ➔ low systematics for good model
  - Cons: slow, harder development

3. BAM analysis: direct fit model

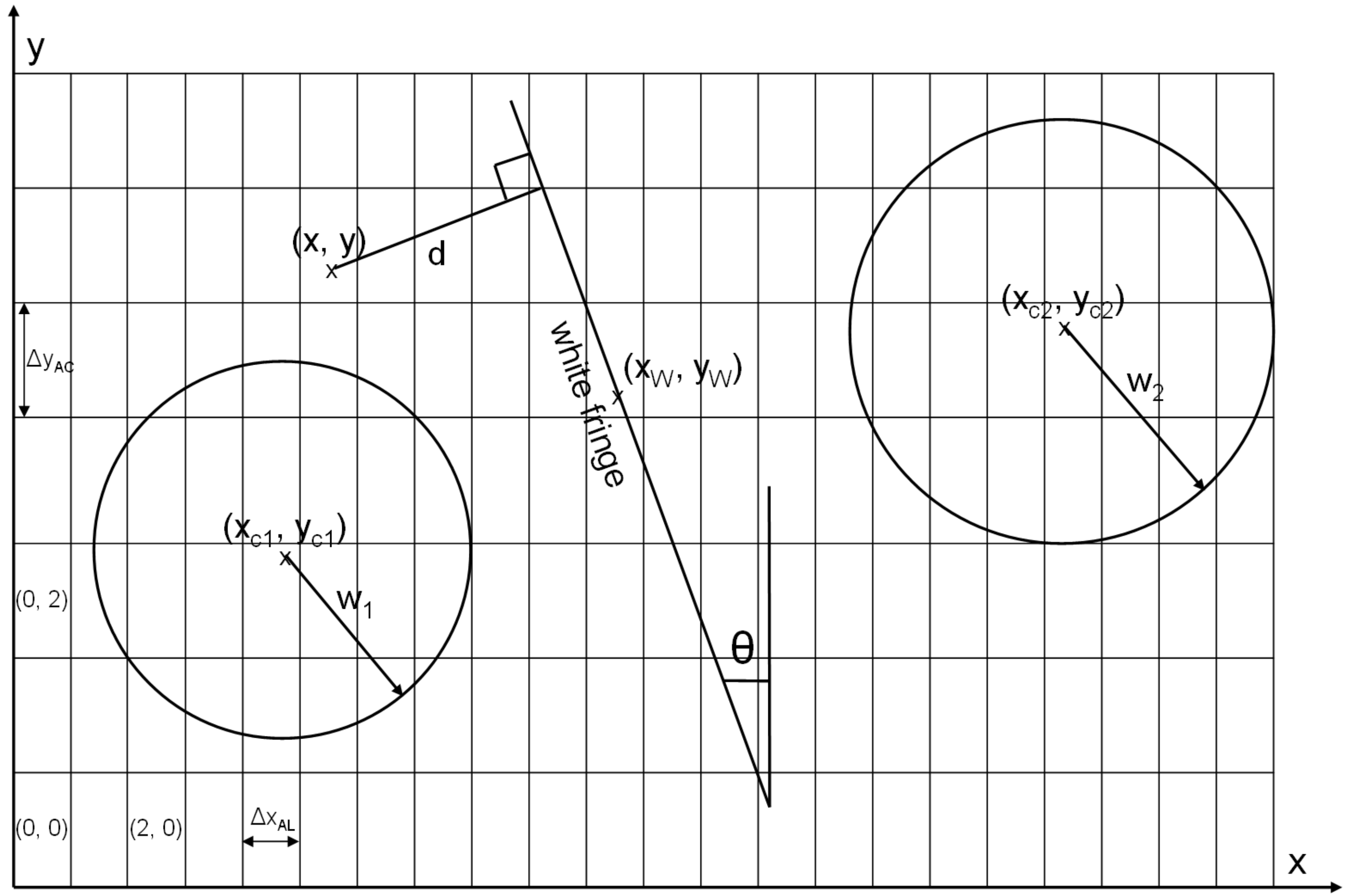
- Analytic model
  - Inspired by Airbus Defence and Space early studies
  - Reasonably fast computation
  - No optical aberrations considered
  - Derivatives ➔ parameter fit
- The image is a function of a few (12) variables
  - Gaussian peak, waist and x-y location
  - White light fringe: x-AL location and angle
  - Fringe period
  - Sky brightness
- Noise: Poisson shot noise and CCD read-out noise

3. BAM analysis: direct fit model



A. Mora, AMF-005

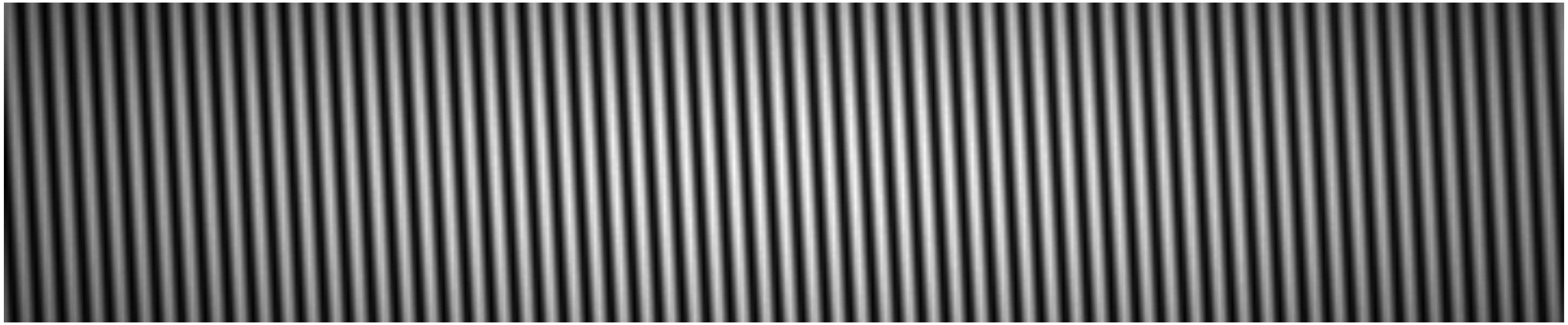
3. BAM analysis: direct fit model



A. Mora, AMF-005

3. BAM analysis: model example

- Interference pattern

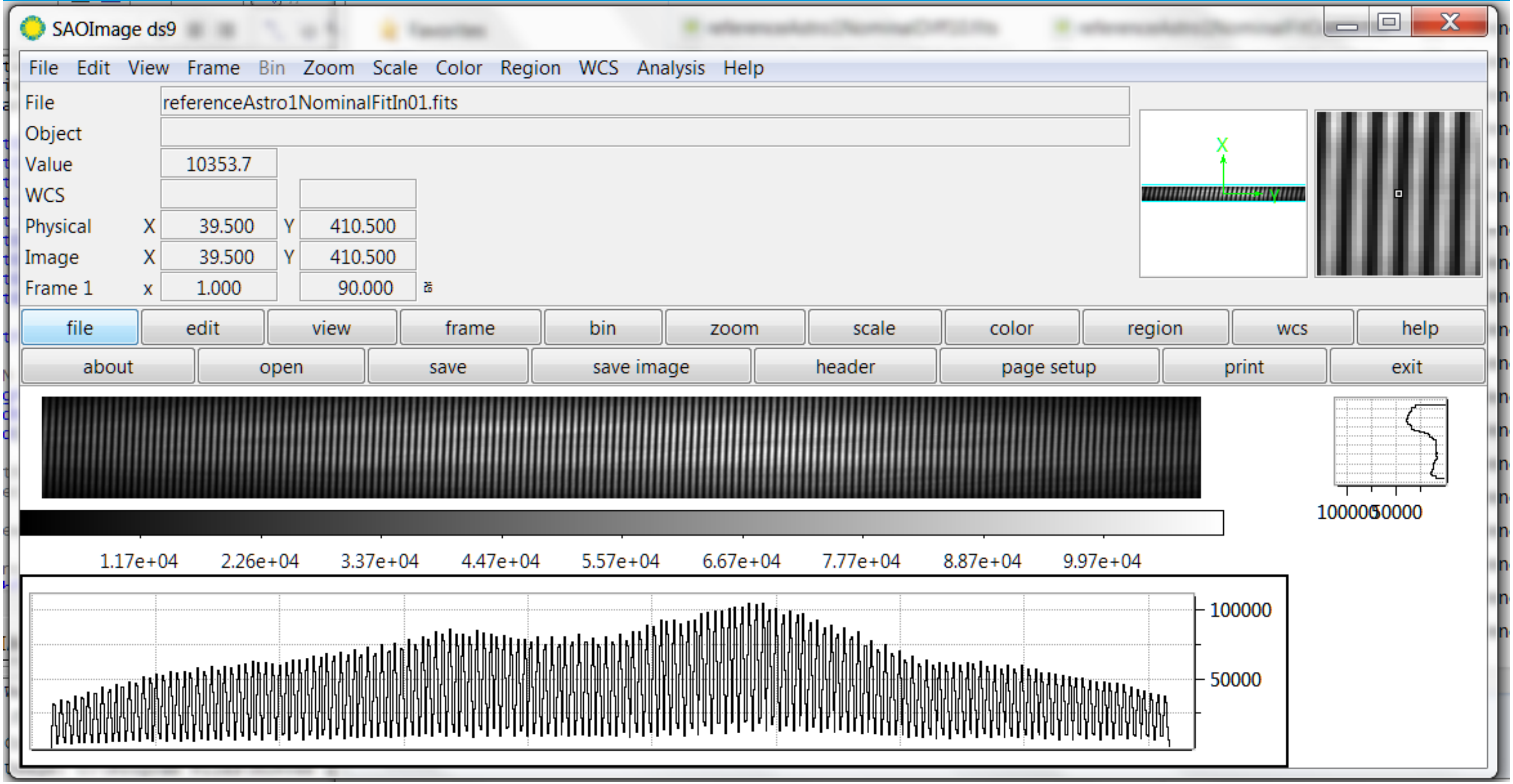


- Background (no shutter during CCD read-out)

A. Mora, AMF-005

4. The real BAM: in-orbit behaviour

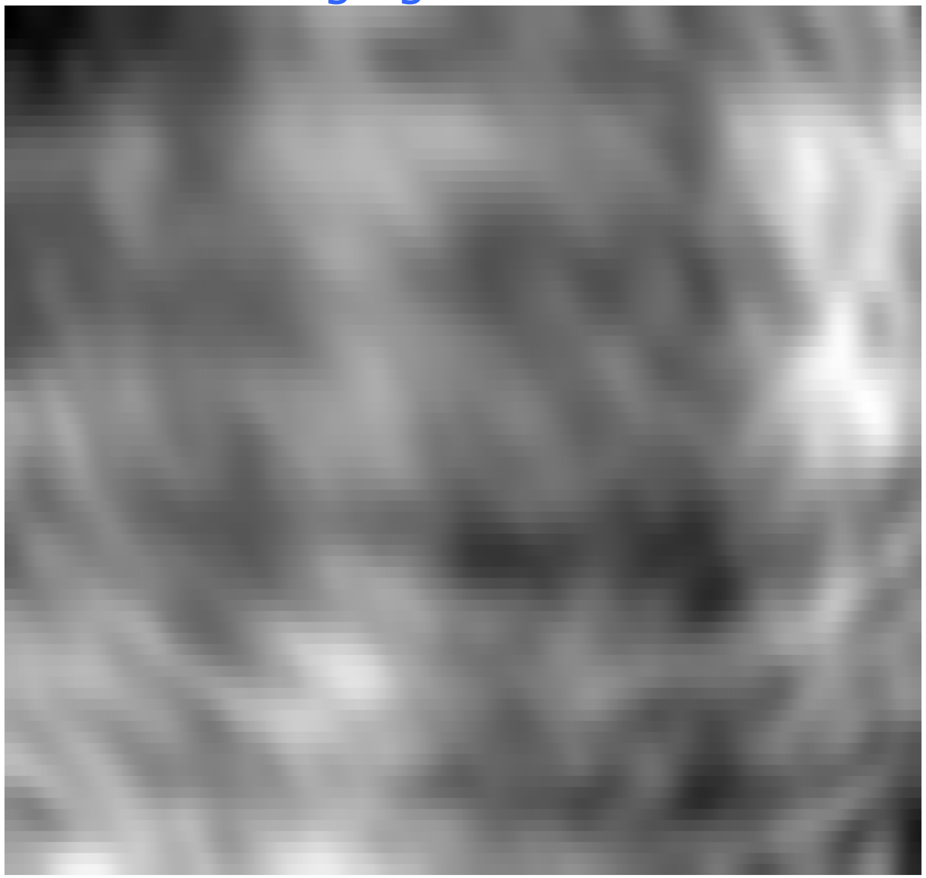
4. BAM (non-) Gaussianity

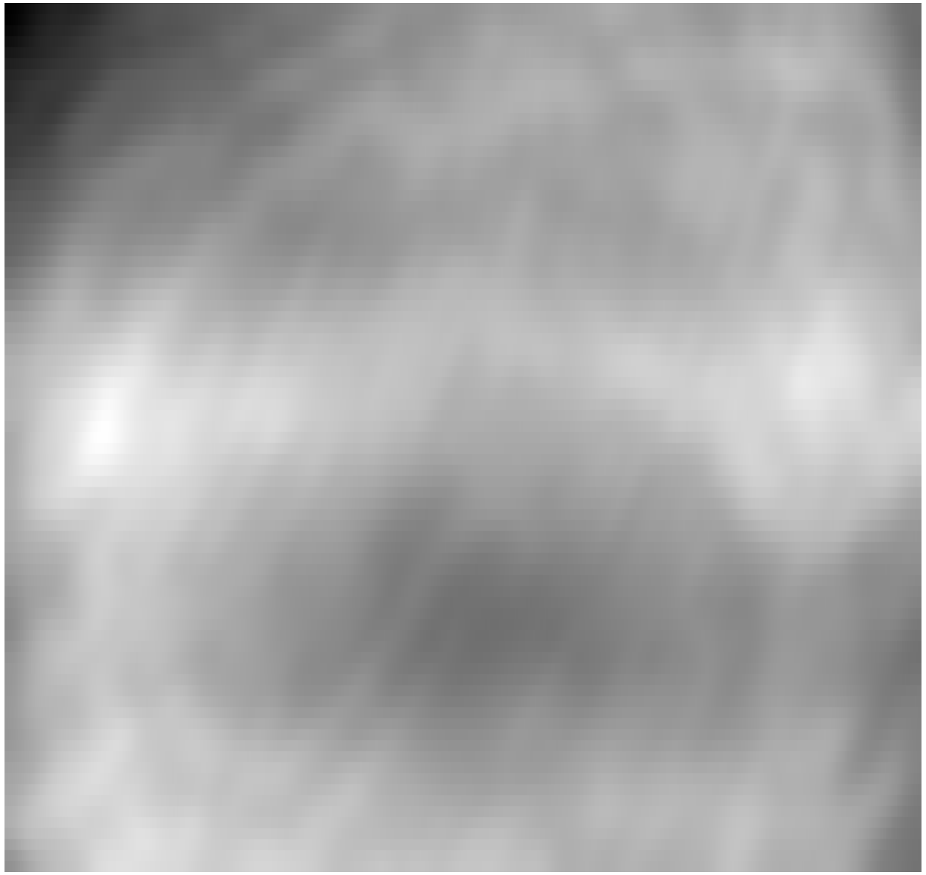


A. Mora, AMF-015
European Space Agency

4. BAM (non-) Gaussianity

- Additional overimposed low frequency interference pattern
  - Hypothesys: Accumulated aberrations in optical path
  - CCD fringing not an issue: ~2.9% prediction vs 20+% observed

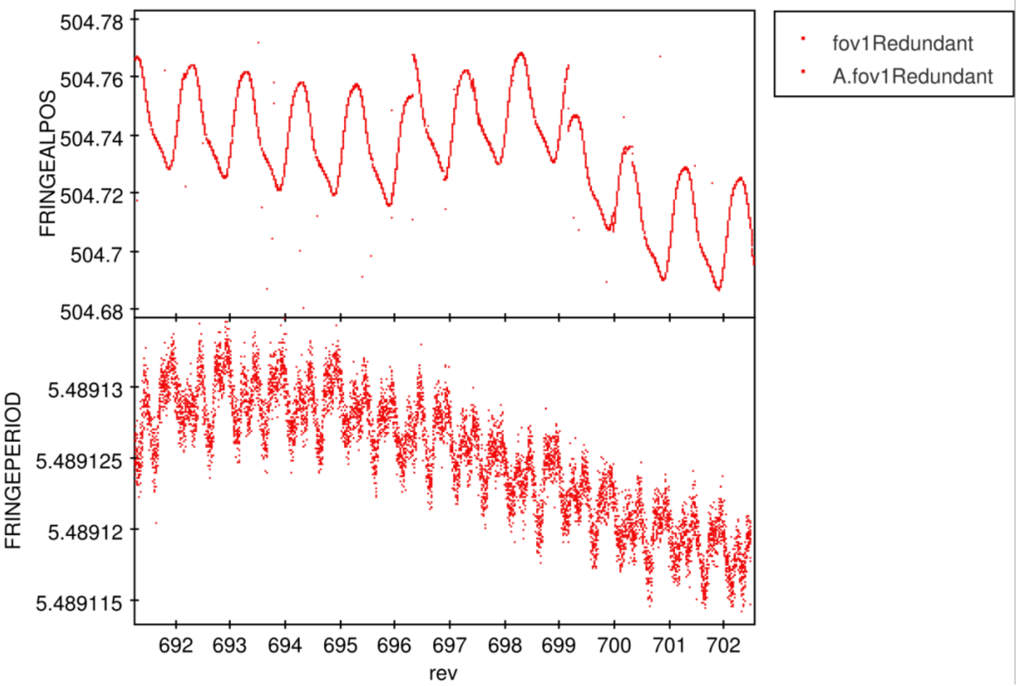


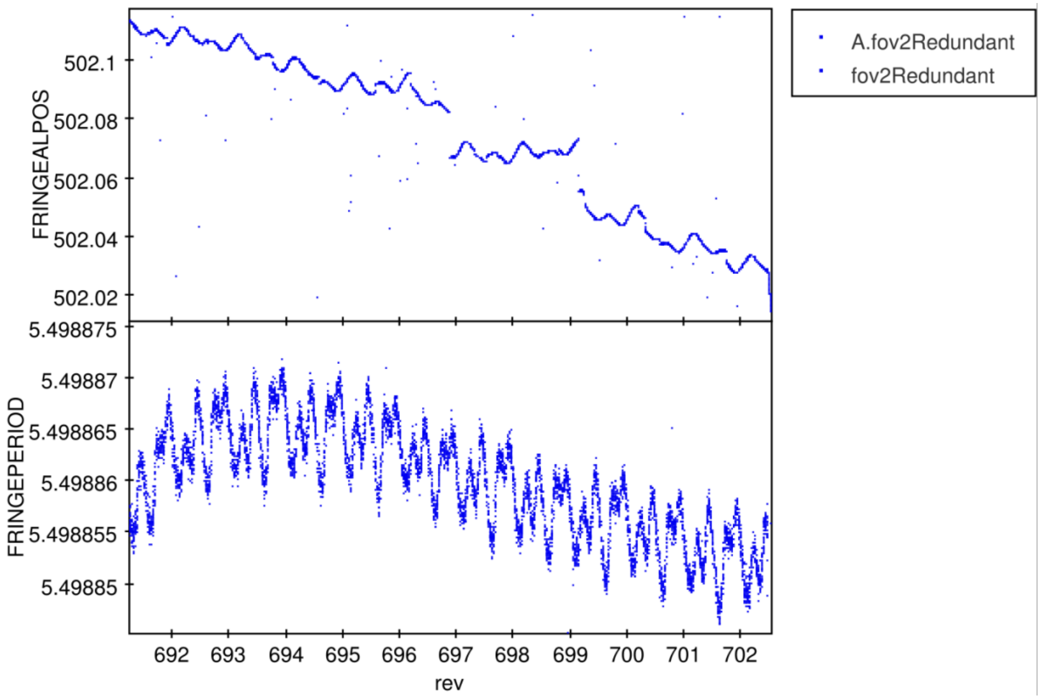


A. Mora, AMF-015

4. BAM phase and period variations

- Fringe phase periodic shift: Sun synchronous, ~1mas (nm stability!)
- Fringe phase discontinuities: several per day
- Fringe phase mid-long term evolution (real?)
- Fringe period variability

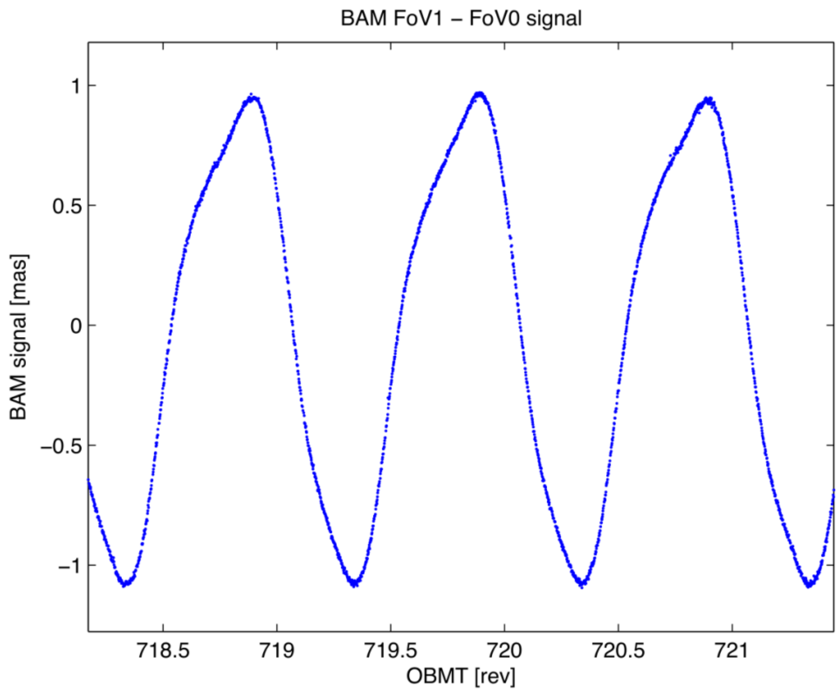


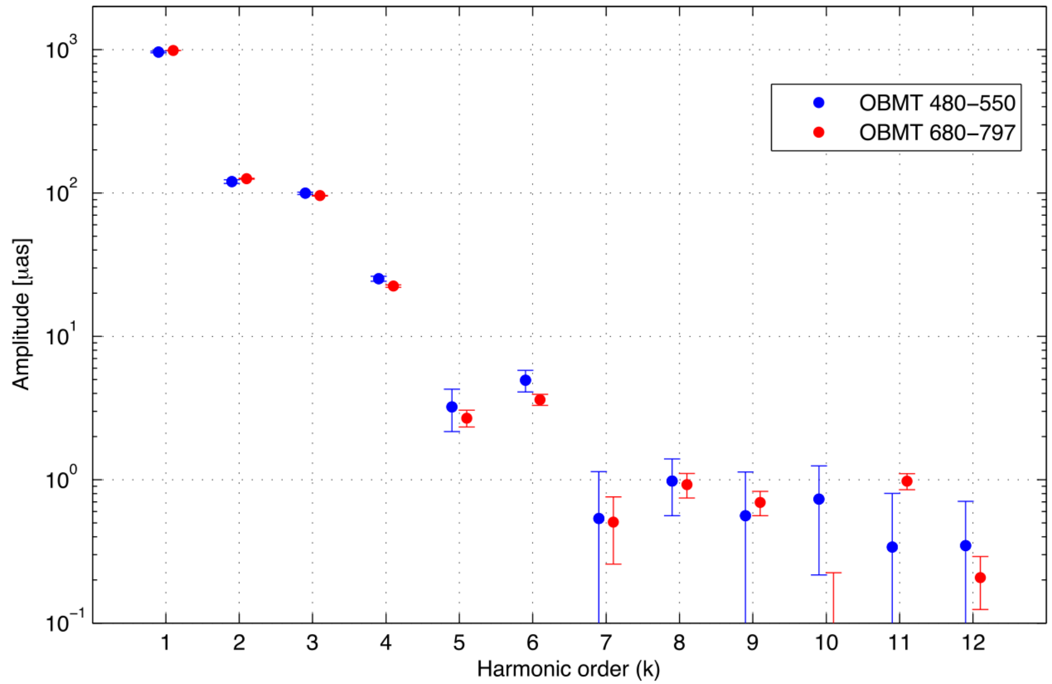


A. Mora, commissioning

4. BAM phase periodic component

- Periodic signal preliminar Fourier analysis
  - 6-12 harmonics of rotation period: mas ➔ µas
  - Slow temporal evolution + plenty of data ➔ can be characterised
- Can be a model input for the AGIS solution

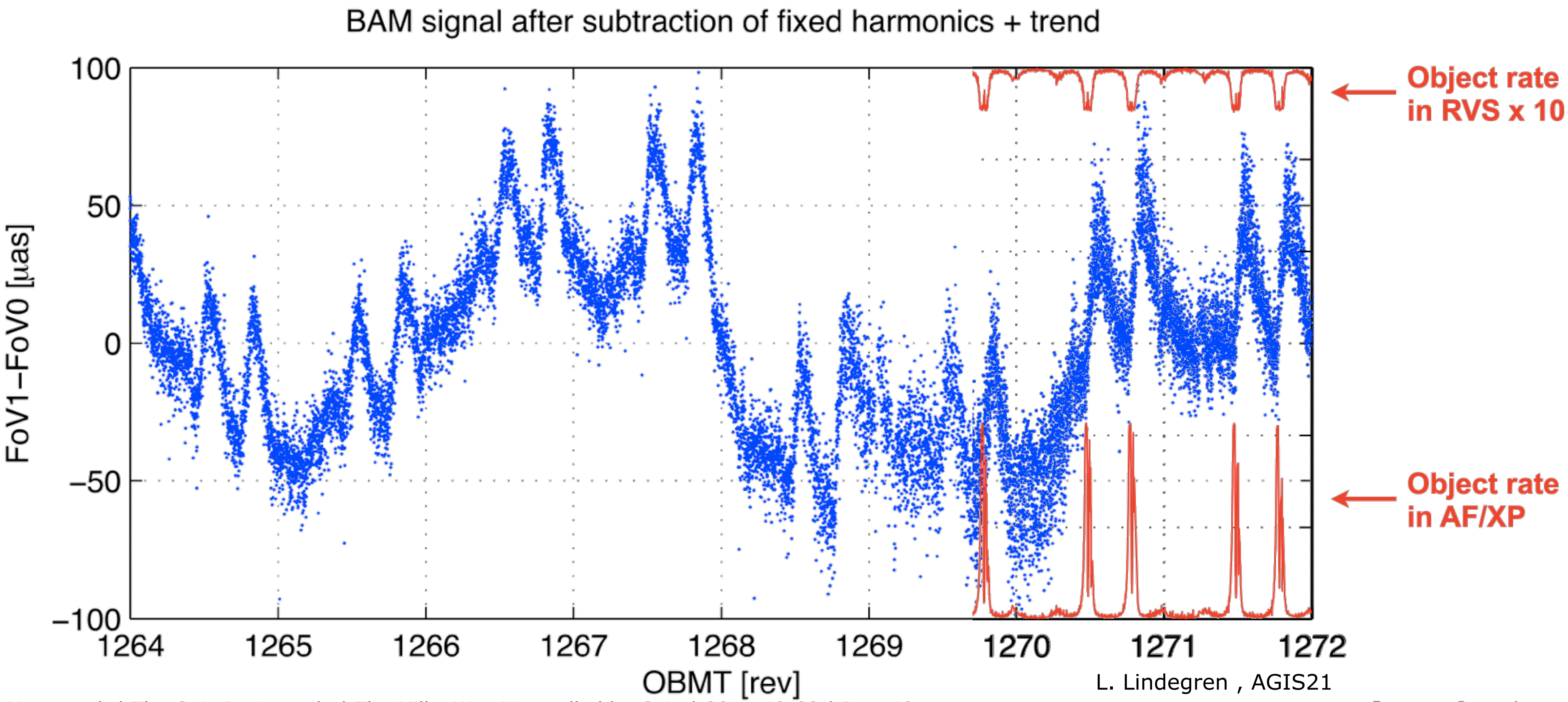




L. Lindegren, LL-105

4. BAM phase: Fourier fit residual

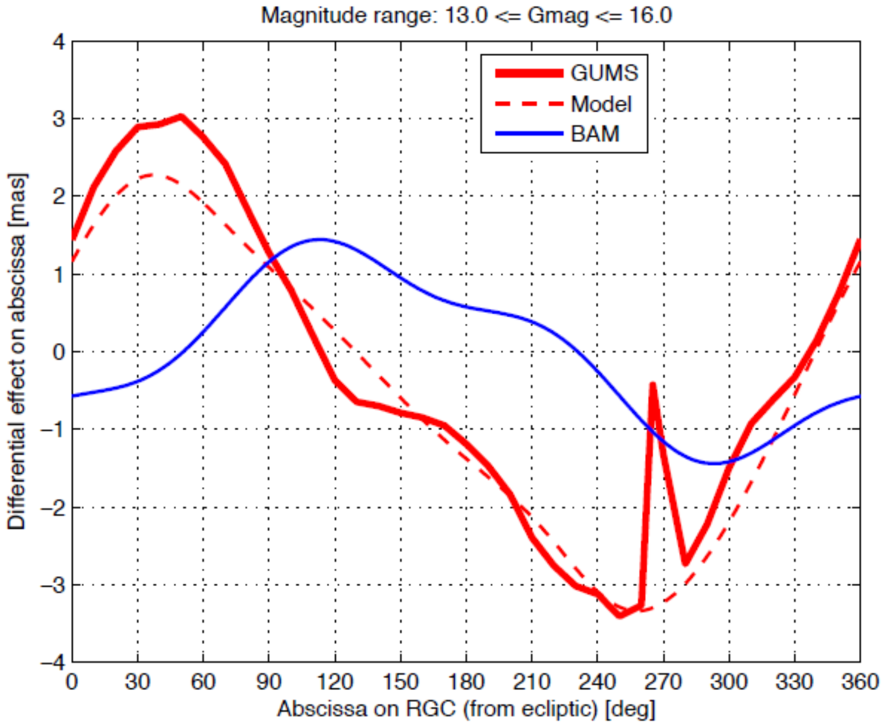
- 24 hr component: related to downlink (transponder + PDHU)
- Peaks for very high density sky (galactic plane, centre)
- Additional modeling required. House keeping temperatures and counters will help

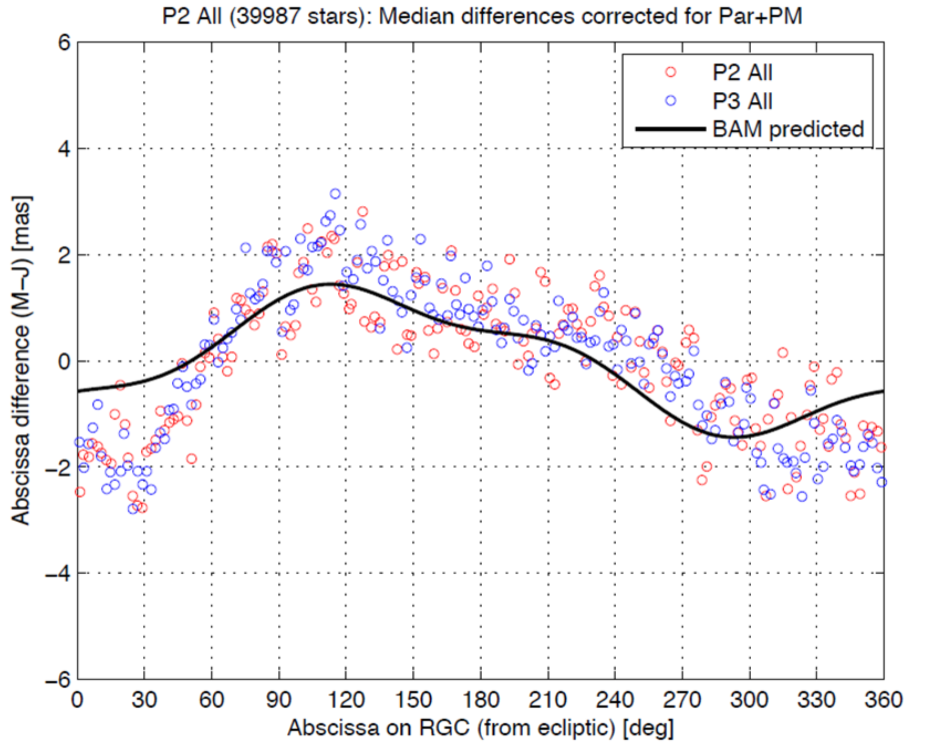


L. Lindegren , AGIS21

4. BAM vs stars: periodic component

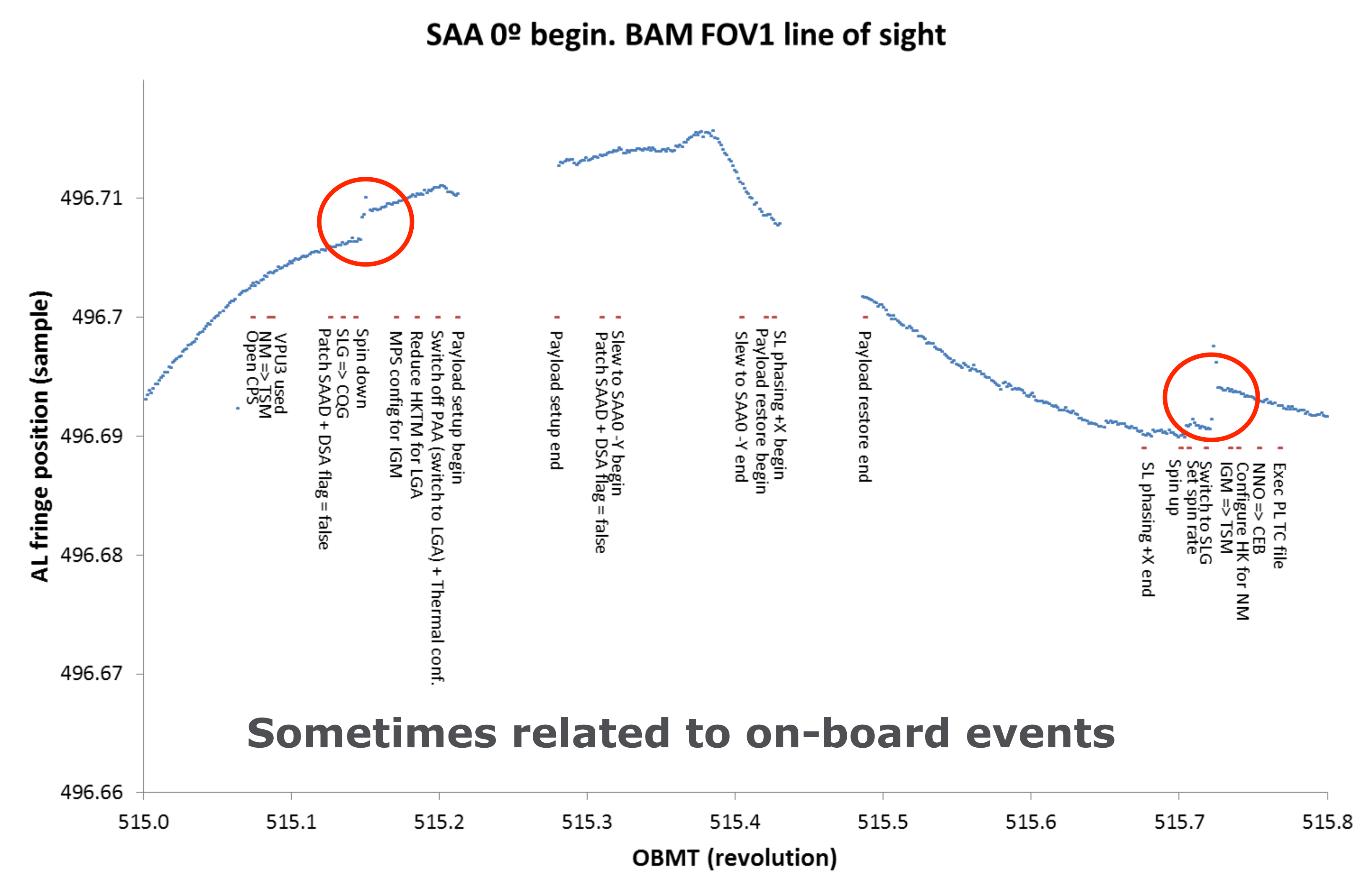
- Two same ring ODAS solutions with different epochs (Sun location)
- Parallaxes and proper motions model ➔ predictions on BAM data
- In-orbit data explained. Sun effect as expected, considering uncertainties
- More results expected after first AGIS solution





U. Bastian et al., FLS-036

4. BAM phase discontinuities

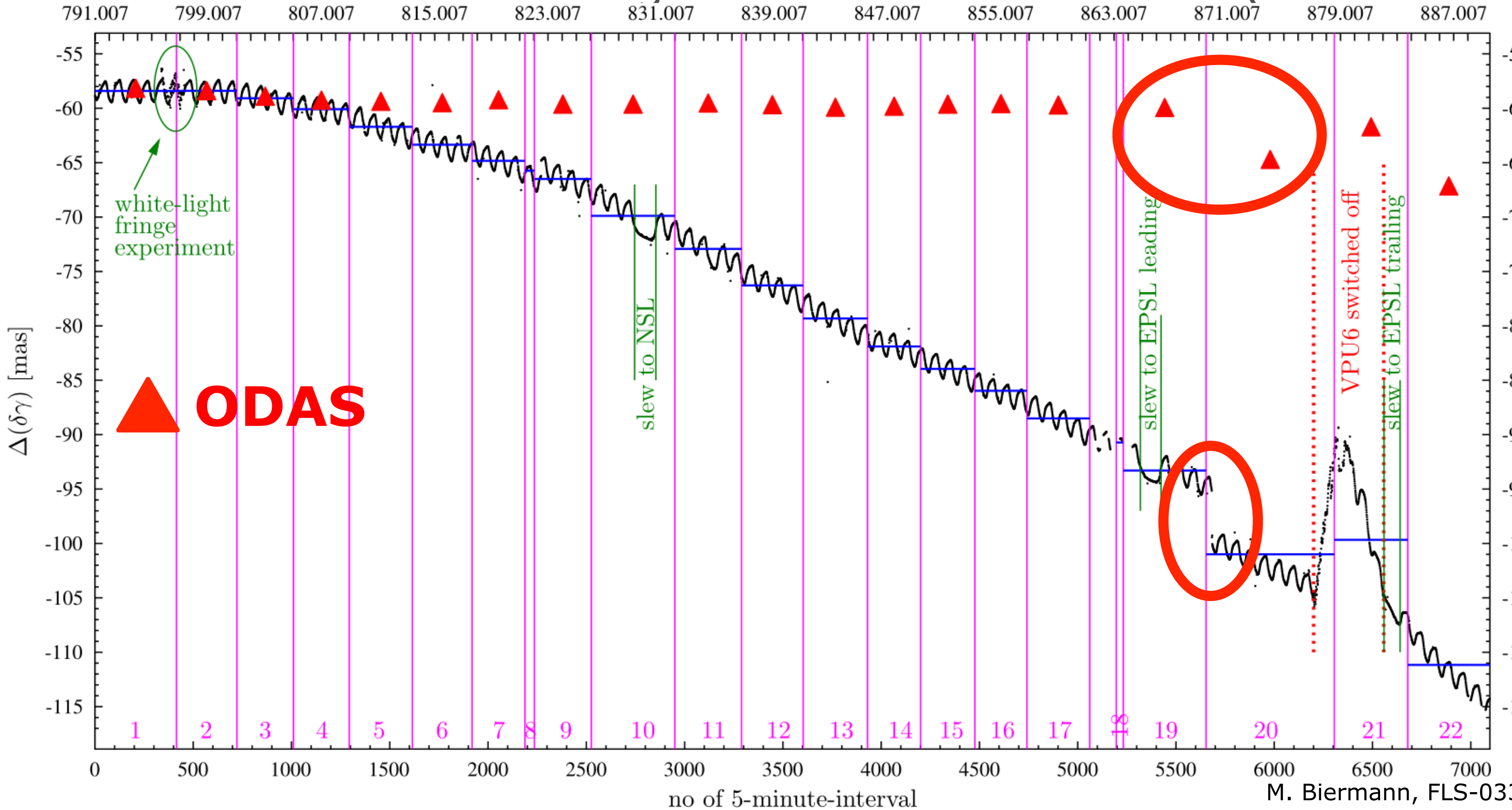


Sometimes related to on-board events

A. Mora, commissioning

4. BAM vs stars: discontinuities

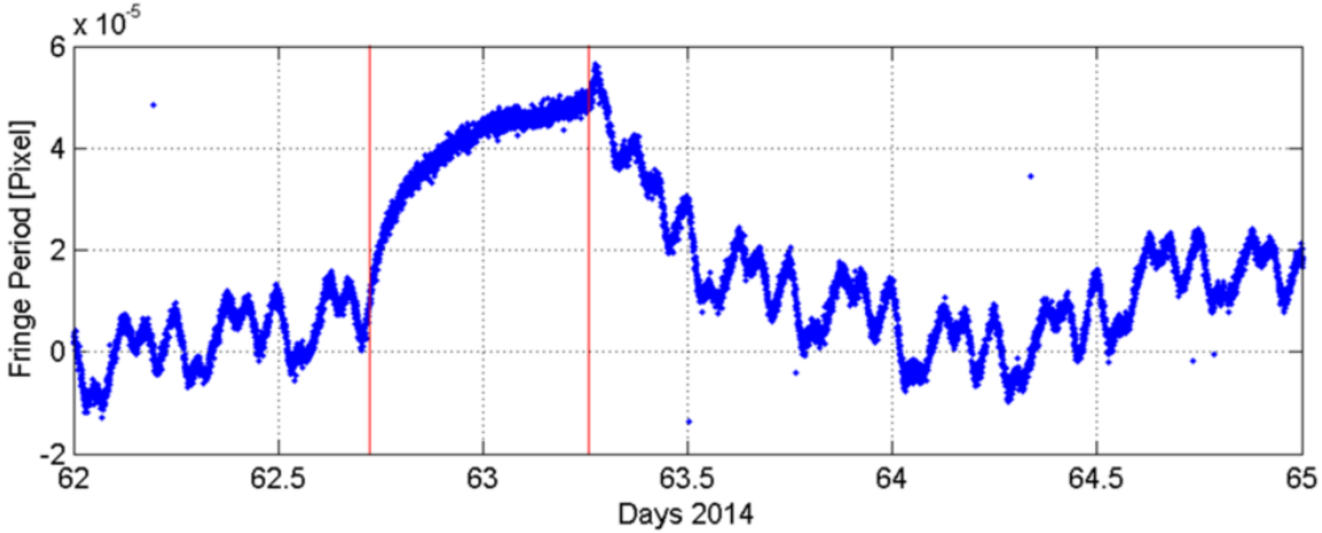
- One Day Astrometric Solution (ODAS): daily average (no periodicity)
- Discontinuities seem real. Long term evolution does not (but irrelevant)

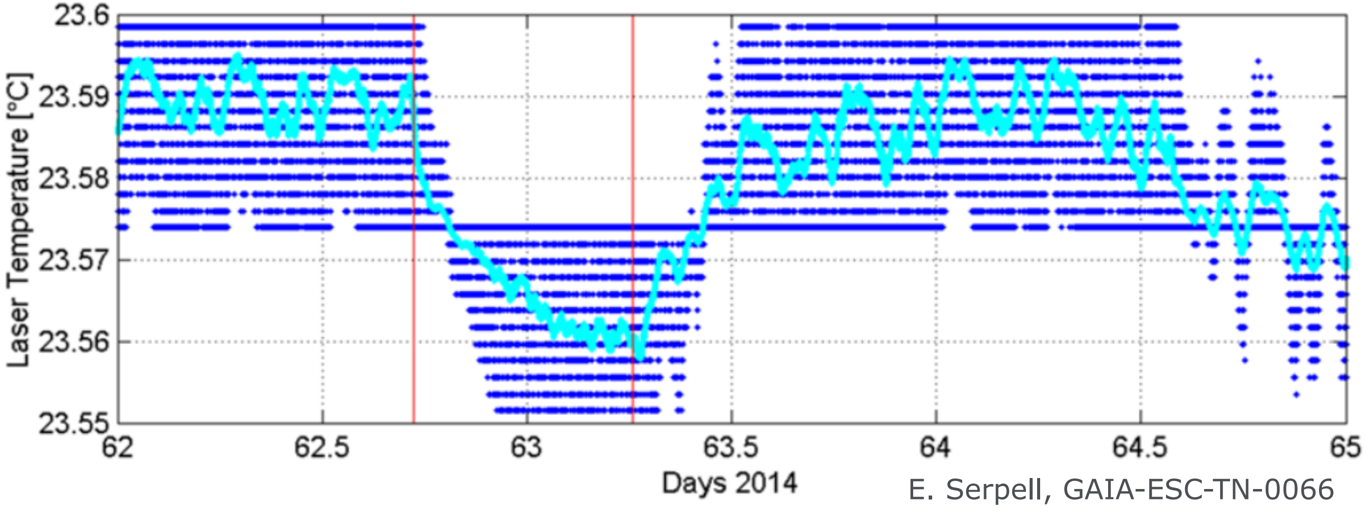


M. Biermann, FLS-033

4. BAM period variability

- ➢ Wavelength depends on laser temperature and current
- ➢ Focal plane array power consumption depends on the sky!
  - RVS LR-HR mode
  - VPU, PDHU power
- ➢ ±0.005 K ➔ stability ~1/250,000
- ➢ Mitigation schemes under study

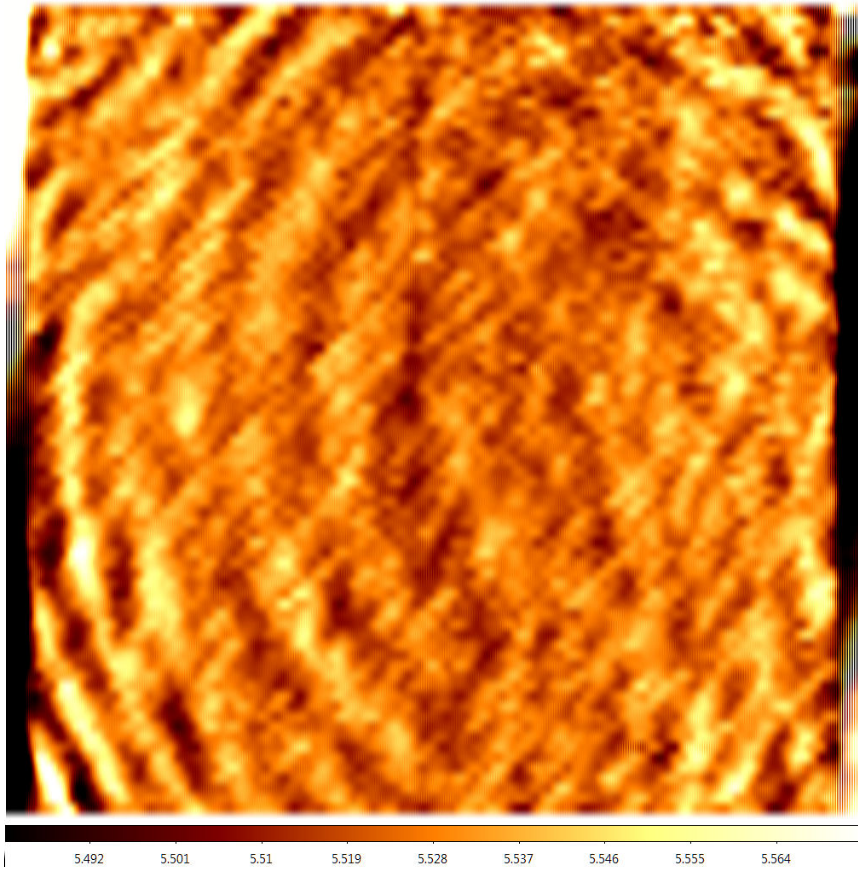


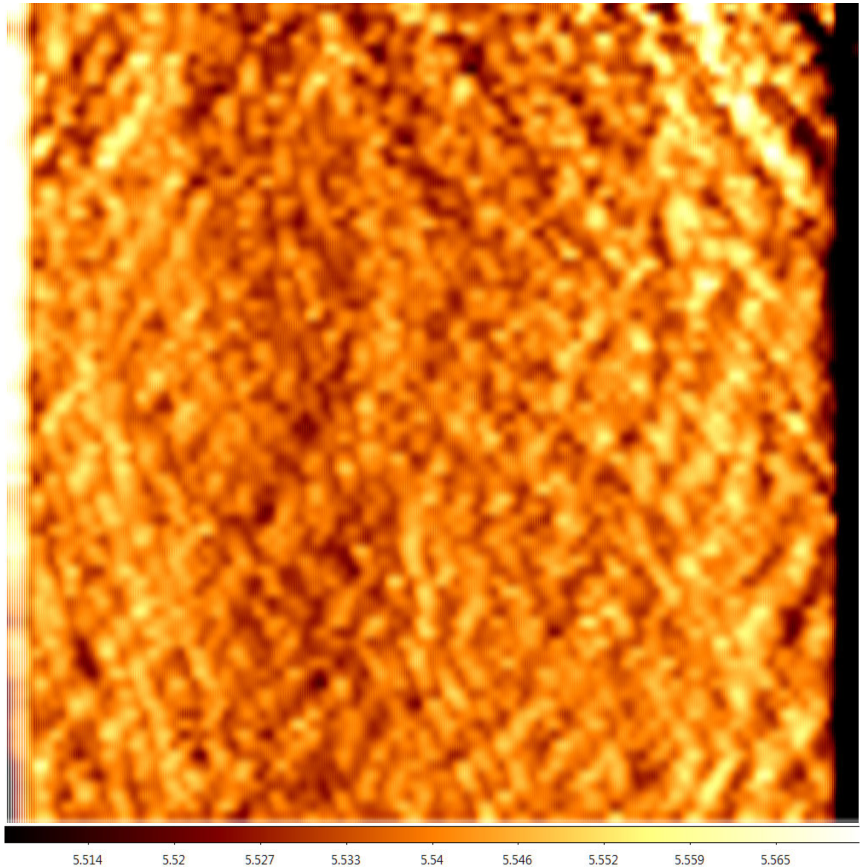


E. Serpell, GAIA-ESC-TN-0066

4. BAM period uniformity

- Wavelet analysis: constant fringe period does not exist
- Plane parallel fringe analysis ➔ works, but imperfect
- Better models required

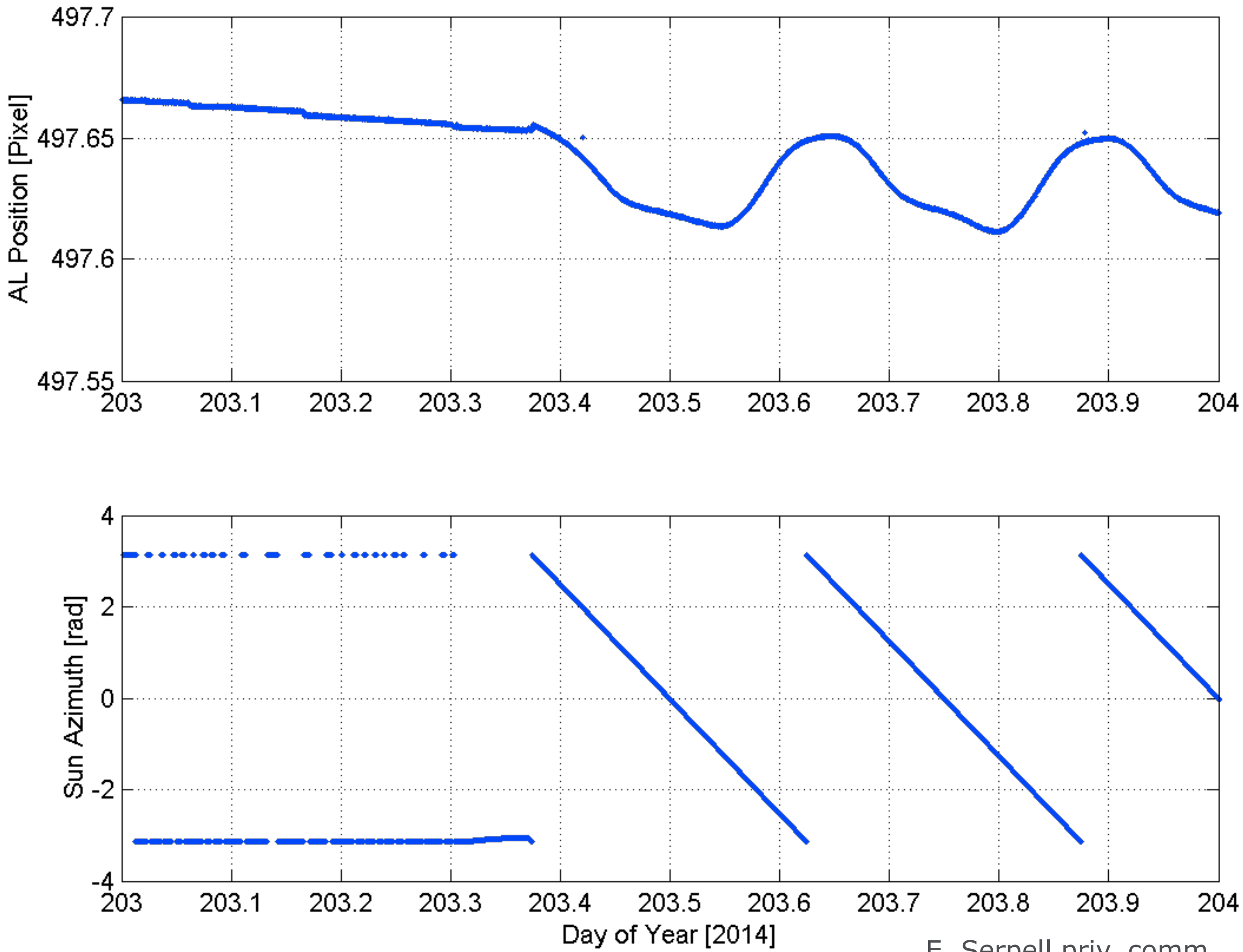




A. Mora, commissioning

4. BAM vs spin restart

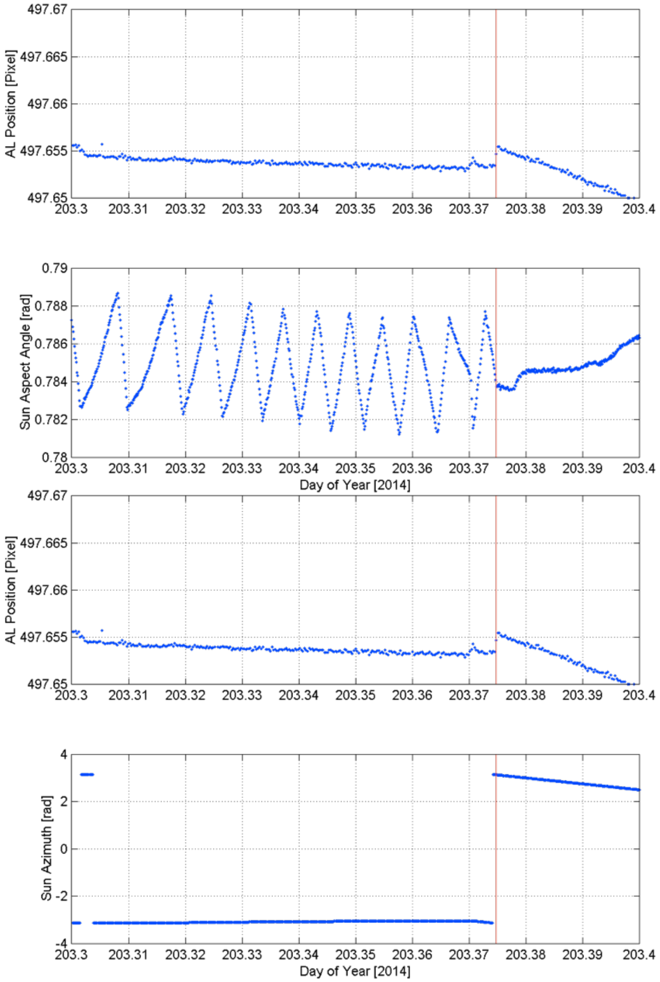
- Spin restart after safe mode: variations appear very soon: < 1 min

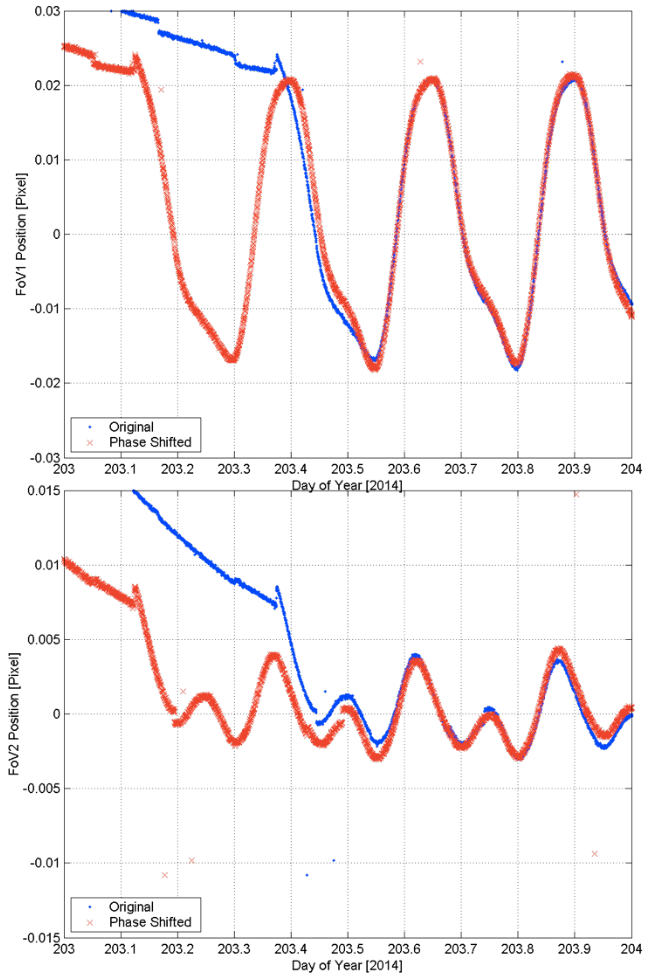


E. Serpell priv. comm.

4. BAM vs spin restart

- BAM signal: instantaneous periodic + transient ➔ Expected if thermoelastic

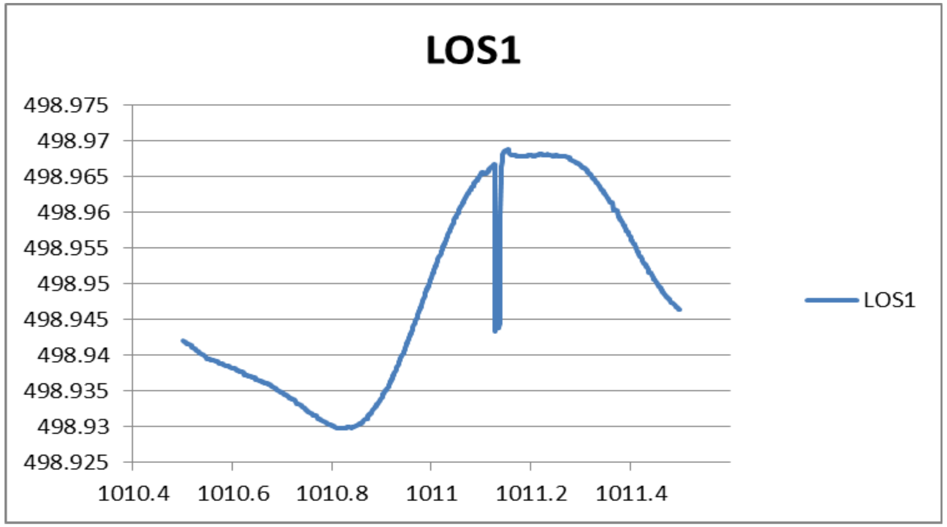


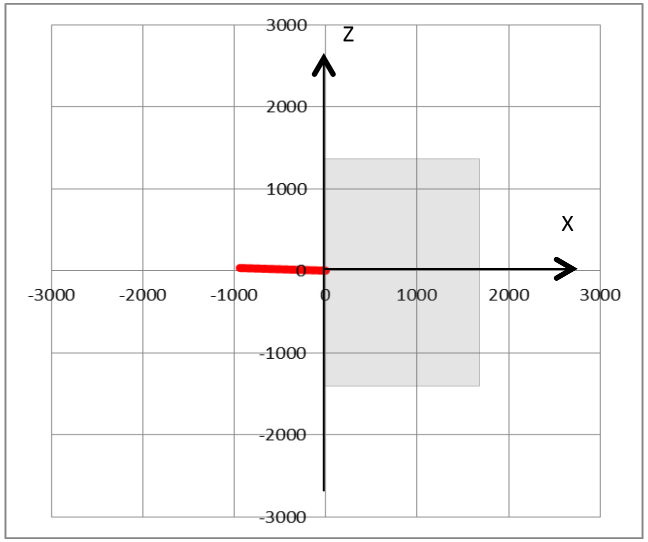


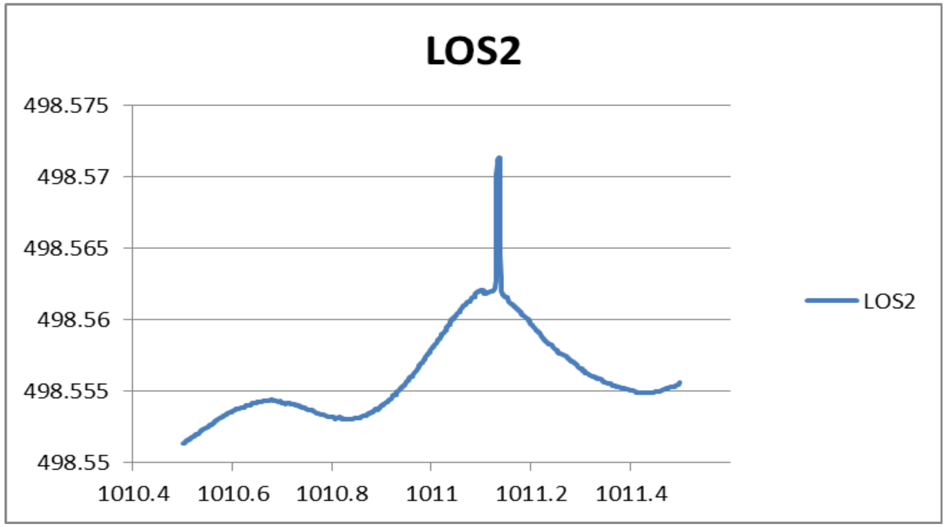
E. Serpell priv. comm.

4. BAM + spacecraft maneouvres

- Basic angle variations vs inertial forces
- Station keeping maneouvres
  - Chemical propulsion thrusters ~10 N
- Transient effect on the BAM
  - Good compatibility with Gaia opto-elastic model



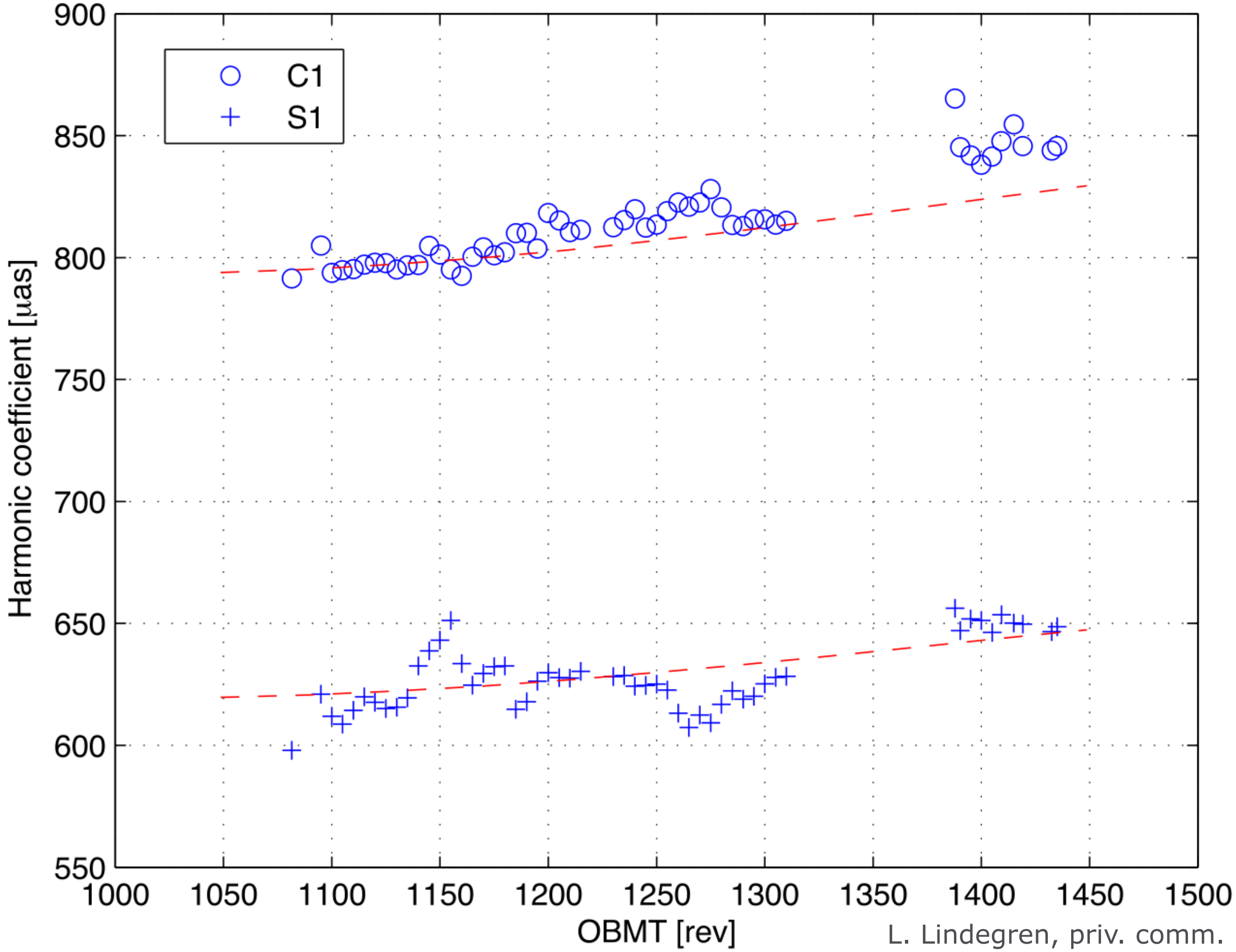




Courtesy: Airbus D&S

4. BAM vs Sun-Gaia distance

- Basic angle driven by the Sun? ➔ $1/r^2$ ➔ Approx. followed by first hamonics



L. Lindegren, priv. comm.

5. Conclusions

5. Conclusions

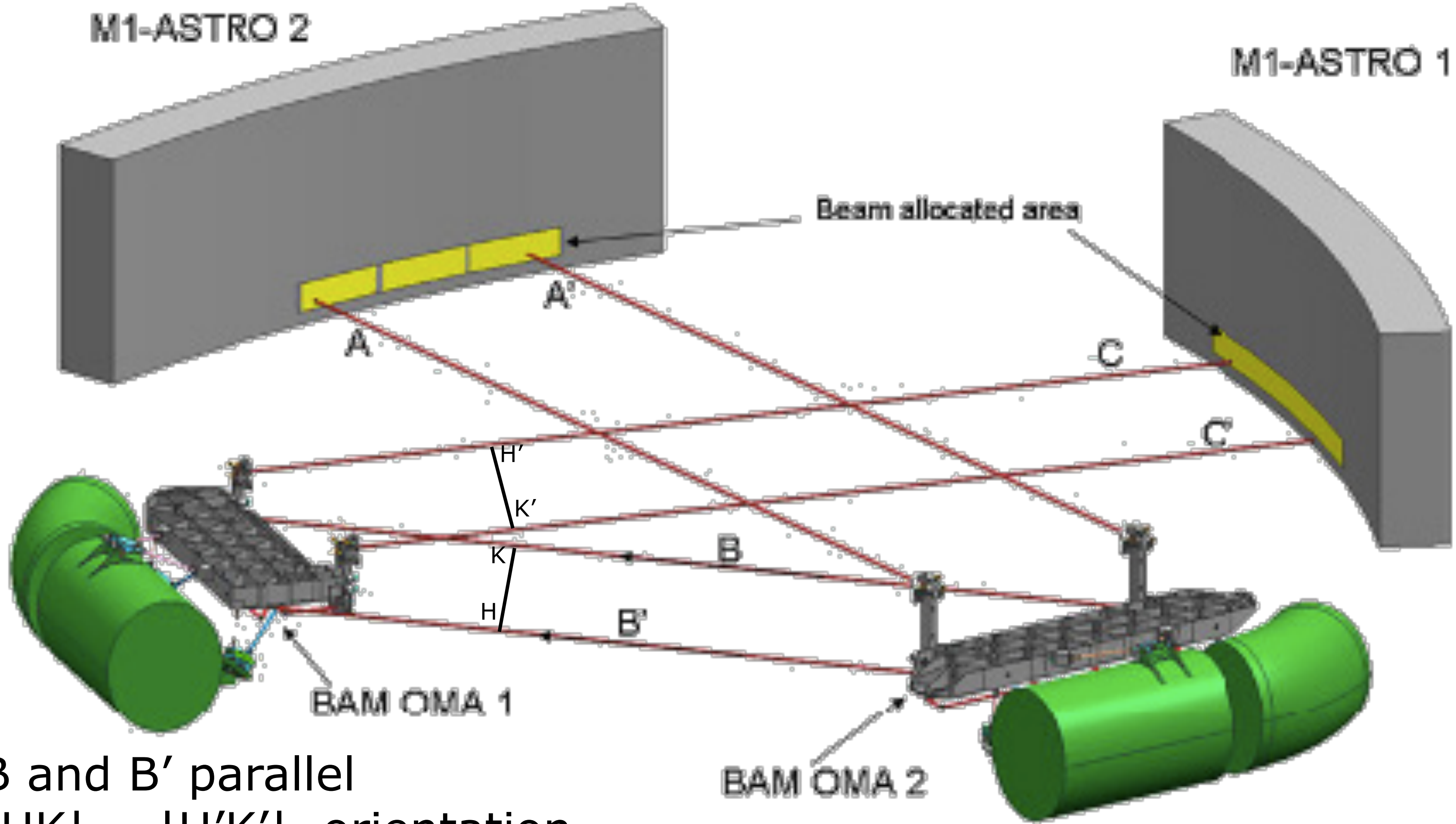
1. Basic Angle Monitoring device (BAM) is functional
    1. It measures real basic angle variations
2. Most precise interferometer ever flown
    1. Micro-fringe measurement precision, pm shifts!
3. ~1 year of data analysed. Reliable pipeline in place
4. Variations larger than expected: nm vs pm stability
    1. Driven by the Sun ➔ thermoelastic?
5. Further modeling being improved to achive μas accuracy

Additional material

2. The BAM is a retroreflector

- BAM design rules
- R1: Insensitive to translation of bar #1
  - The beams feeding bar #1 are parallel
- R2: Insensitive to to rotation of bar #1 along spin axis
  - Same input/output beam separation. Restrictions on orientation
- R3: Insensitive to different temperatures between bars
  - Adjust OPD to make input/output planes to bar #1 wavefronts
- R4: Insensitive to laser beam point source motions
  - Same light source for all beams
- R5: OPD ~ 0: white light fringe must be in the pattern
  - Adjust OPD of whole system.

2. Design rules

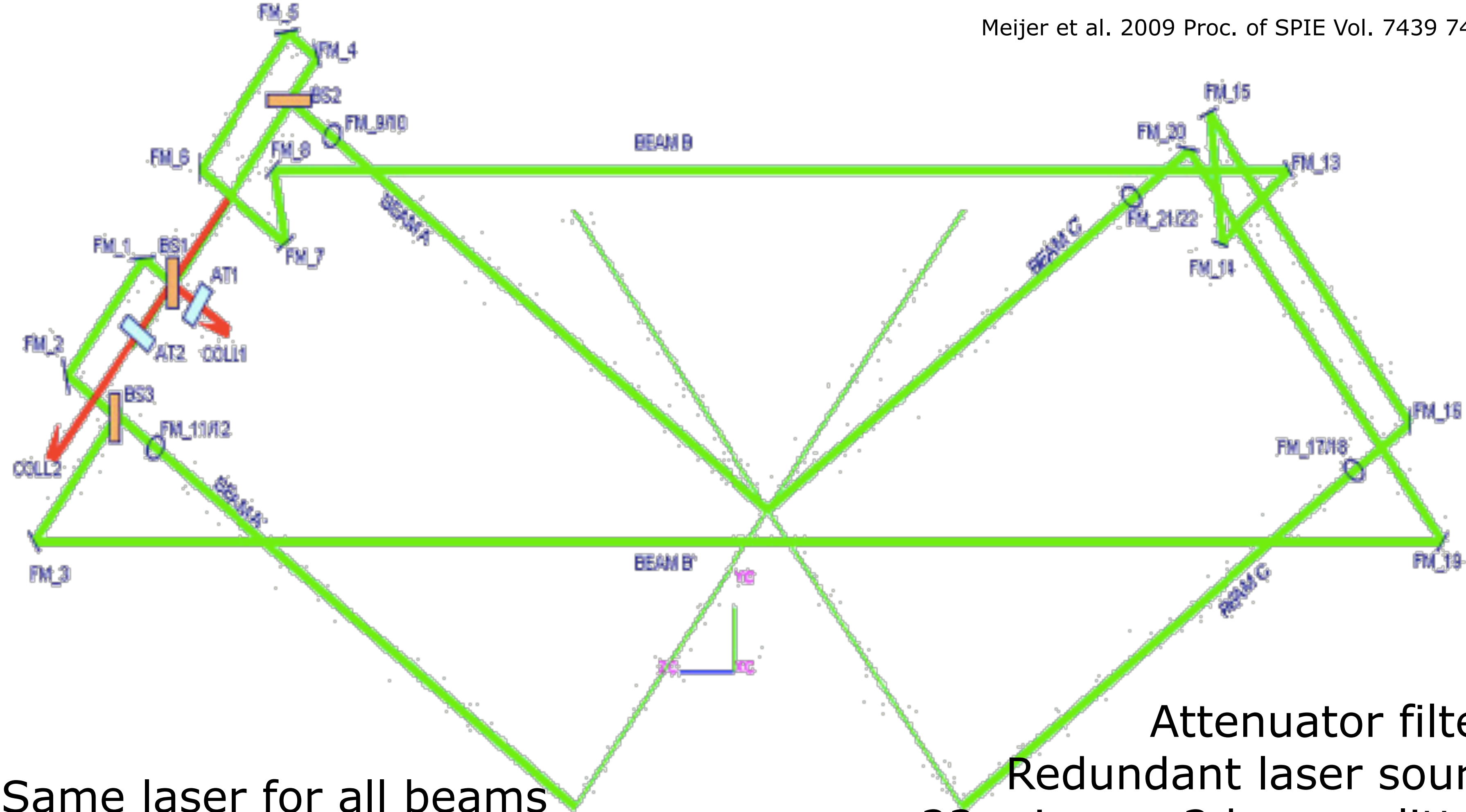


R1: B and B′ parallel
R2: |HK| = |H′K′|, orientation
R3: HK and H′K′ are wavefronts, adjust OPD

Courtesy: Airbus D&S

2. Design rules

Meijer et al. 2009 Proc. of SPIE Vol. 7439 74391



Attenuator filters
Redundant laser source
22 mirrors, 3 beamsplitters

R4: Same laser for all beams
R5: Adjust OPD in the whole system

3. BAM analysis: mathematics

- BAM image = interference pattern + background
- Interference pattern

$$N(i,j) = \frac{\Delta t_{\mathrm{BAM}} \mathrm{QE}}{h\nu} \int_{i\Delta x_{\mathrm{AL}}}^{(i+1)\Delta x_{\mathrm{AL}}} dx \int_{j\Delta y_{\mathrm{AC}}}^{(j+1)\Delta y_{\mathrm{AC}}} dy \left(I_{G1} + I_{G2} + 2\sqrt{I_{G1} I_{G2}} \cos\delta \right)$$

$$I_G(x,y) = I_0 \exp\left(-2 \frac{(x-x_c)^2 + (y-y_c)^2}{w^2} \right) \qquad \delta(x,y) = 2\pi\beta d = \frac{2\pi B_I d}{\lambda f}$$

- Background (TDI read-out + constant)

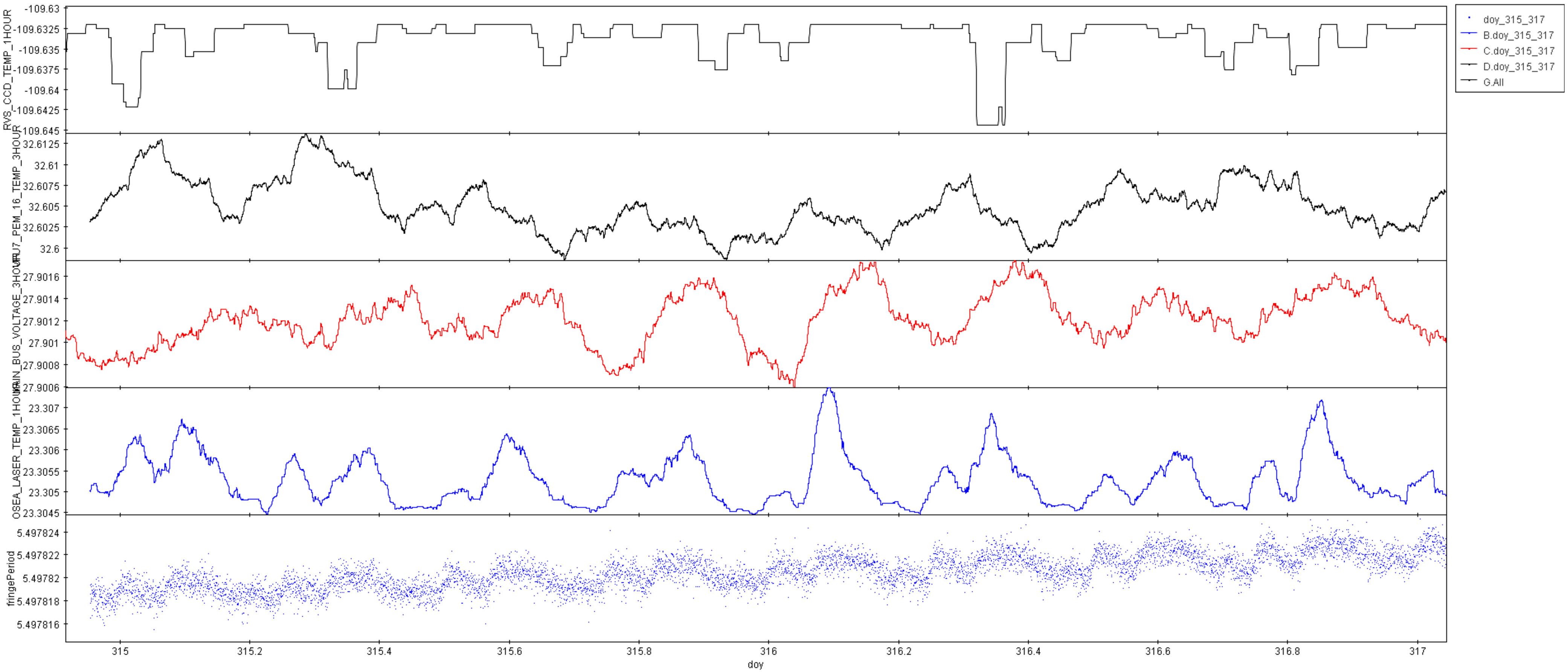
$$\begin{aligned} B(i,j) &= \mathrm{Sky} + \frac{\Delta t_{\mathrm{TDI}} \Delta y_{\mathrm{AC}} \mathrm{QE}}{h\nu} \sqrt{\frac{\pi}{2}} \\ &\times \left[w_1 I_{G1}(x_{c1}, (j+0.5)\Delta y_{\mathrm{AC}}) + w_2 I_{G2}(x_{c2}, (j+0.5)\Delta y_{\mathrm{AC}}) \right] \\ &= \mathrm{Sky} + B_1(i,j) + B_2(i,j) \end{aligned}$$

3. BAM analysis: MIT-IDT pipeline

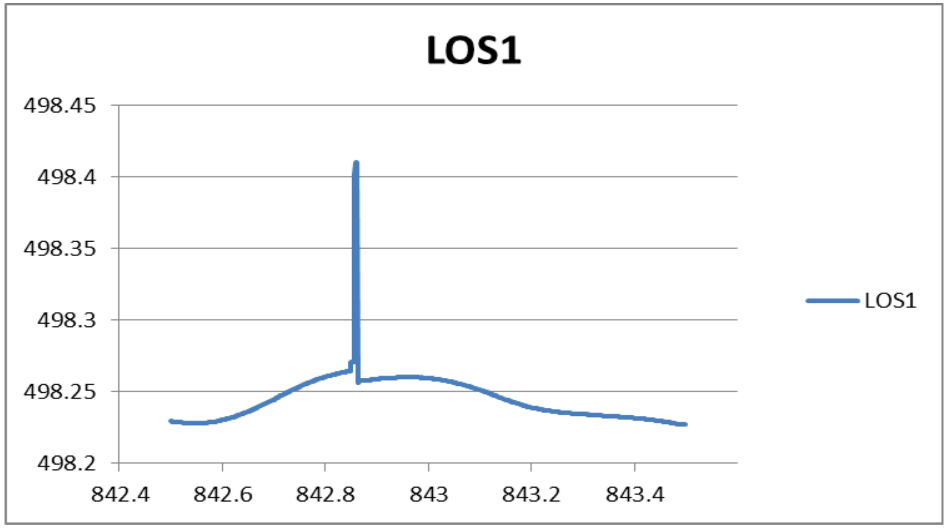
- MIT: MOC Interface Task (see Siddiqui et al. [9149-91])
  - TM stream ➔ BAM SP4 packets ➔ DB
  - Sequential processing (data assembly and integrity)
- IDT: initial data treatment
  - SP4 TM packet ➔ BamObservation ➔ BamElementary ➔ DB
  - Number crunching ➔ Parallel operations
- Fully automated Java pipelines. They are always active
  - One day of data is processed in a few hours
  - Manual operations: software and calibration (BamStatus) updates
- ESA-ESAC DPCE cluster. IDT typically runs on 8 nodes
  - 1 node = 2 CPU Intel X5550, 8 cores 2.66 GHz. 32 GB RAM

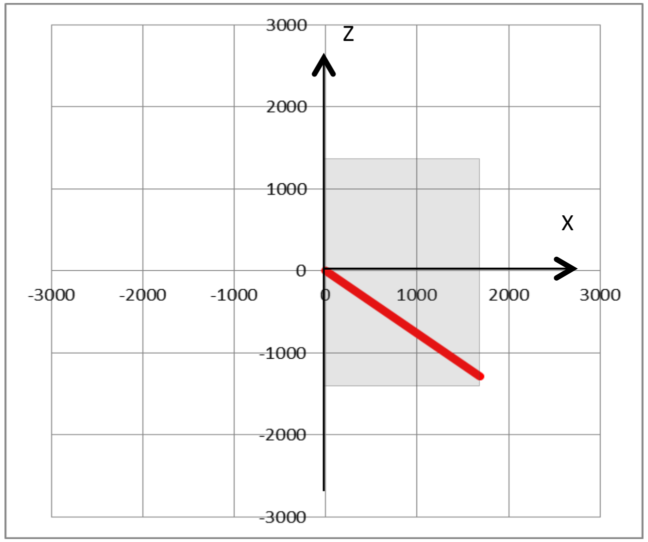
4. BAM period variability

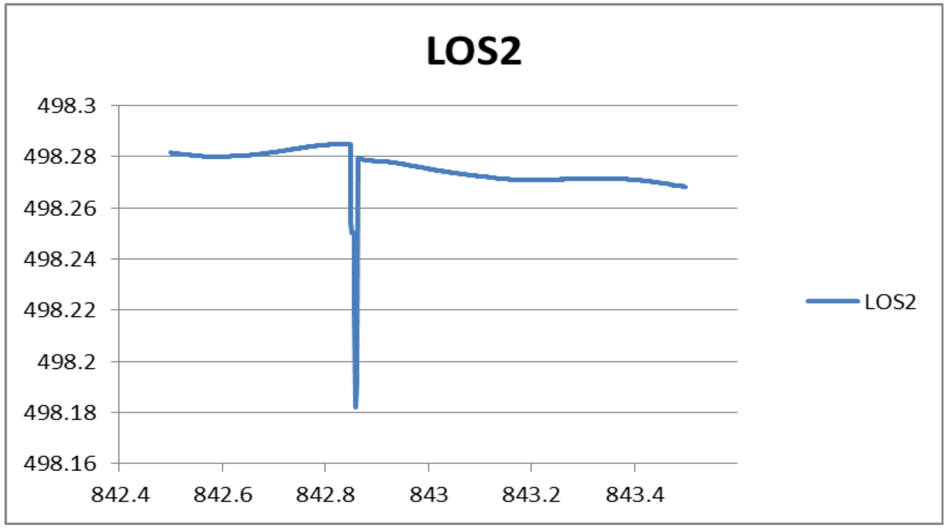
- Strongly correlated with BAM laser temperatures.
- Moderately correlated with main bus voltage (3 hr average) and RVS PEMs temperature
- House keeping data affected by quantisation



4. BAM + spacecraft maneouvres

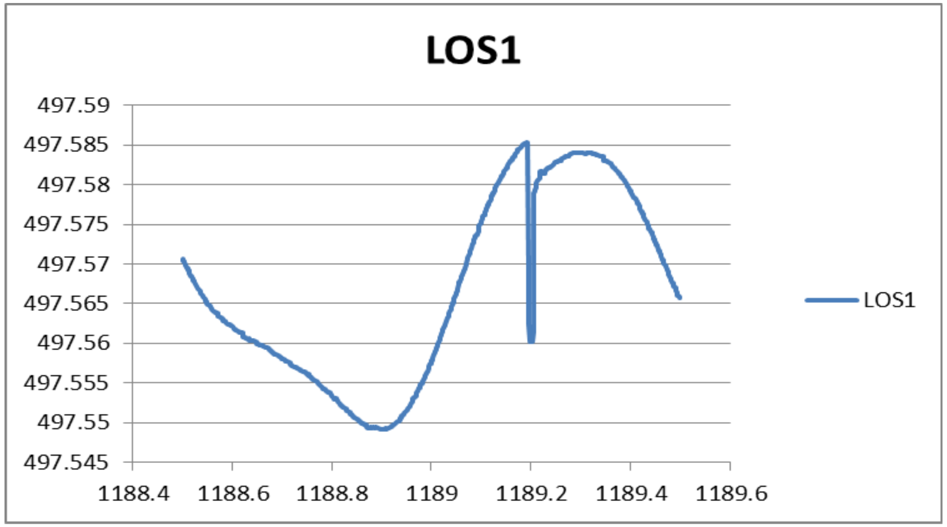


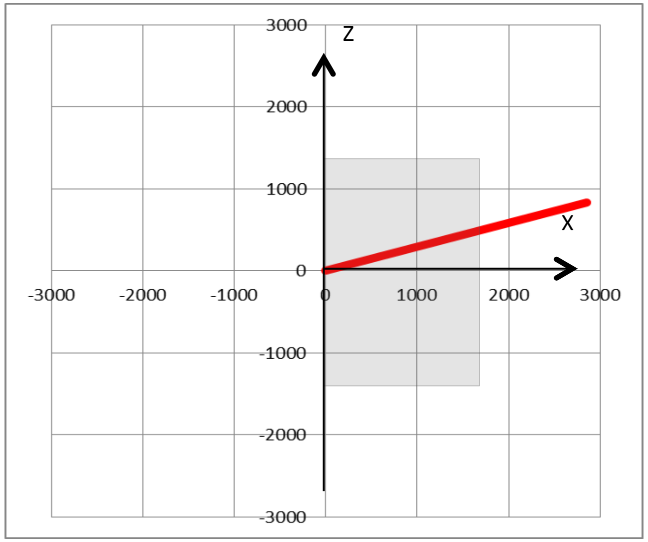


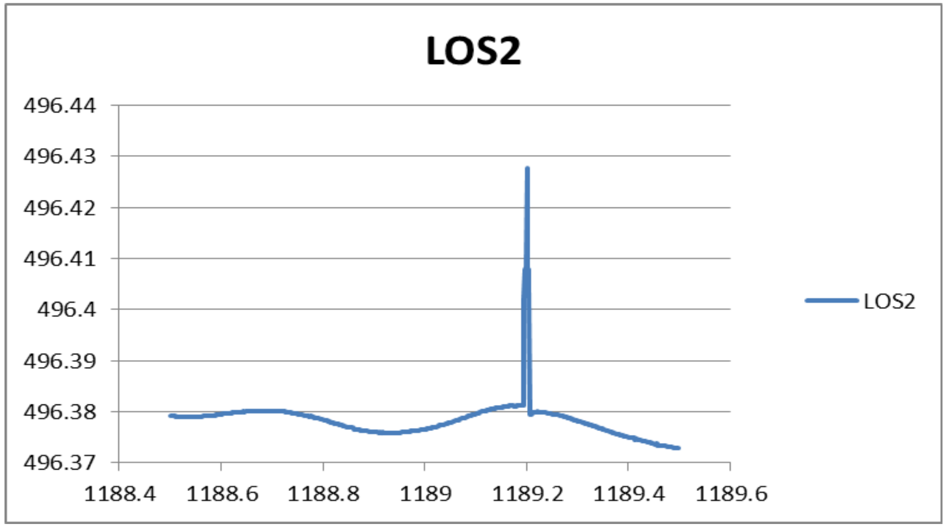


Courtesy: Airbus D&S

4. BAM + spacecraft maneouvres







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