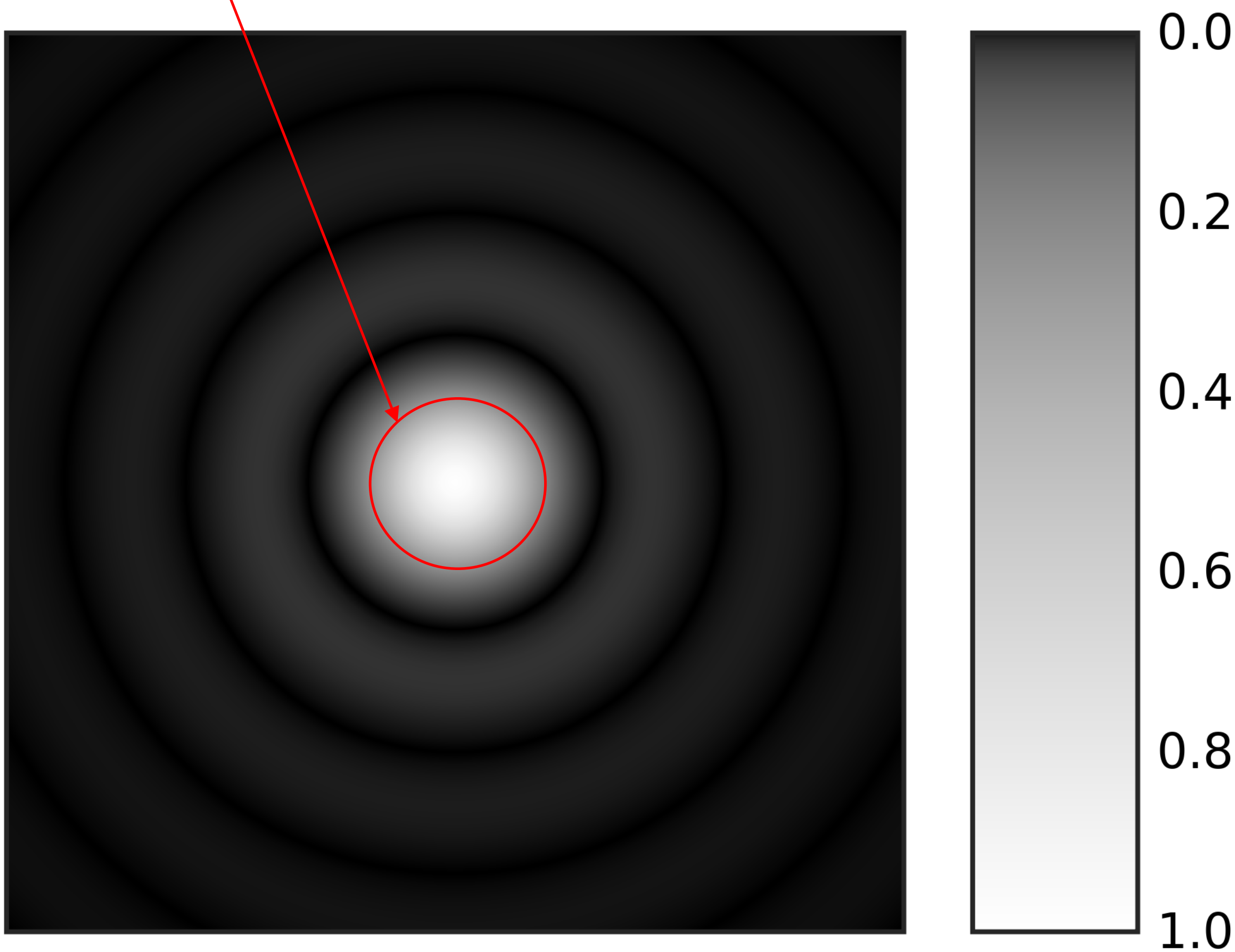
Nulling data analysis and how to interpret results

D. Defrère
University of Liège

HOSTS team meeting -- Carnegie – Washington (September 5-6, 2018)

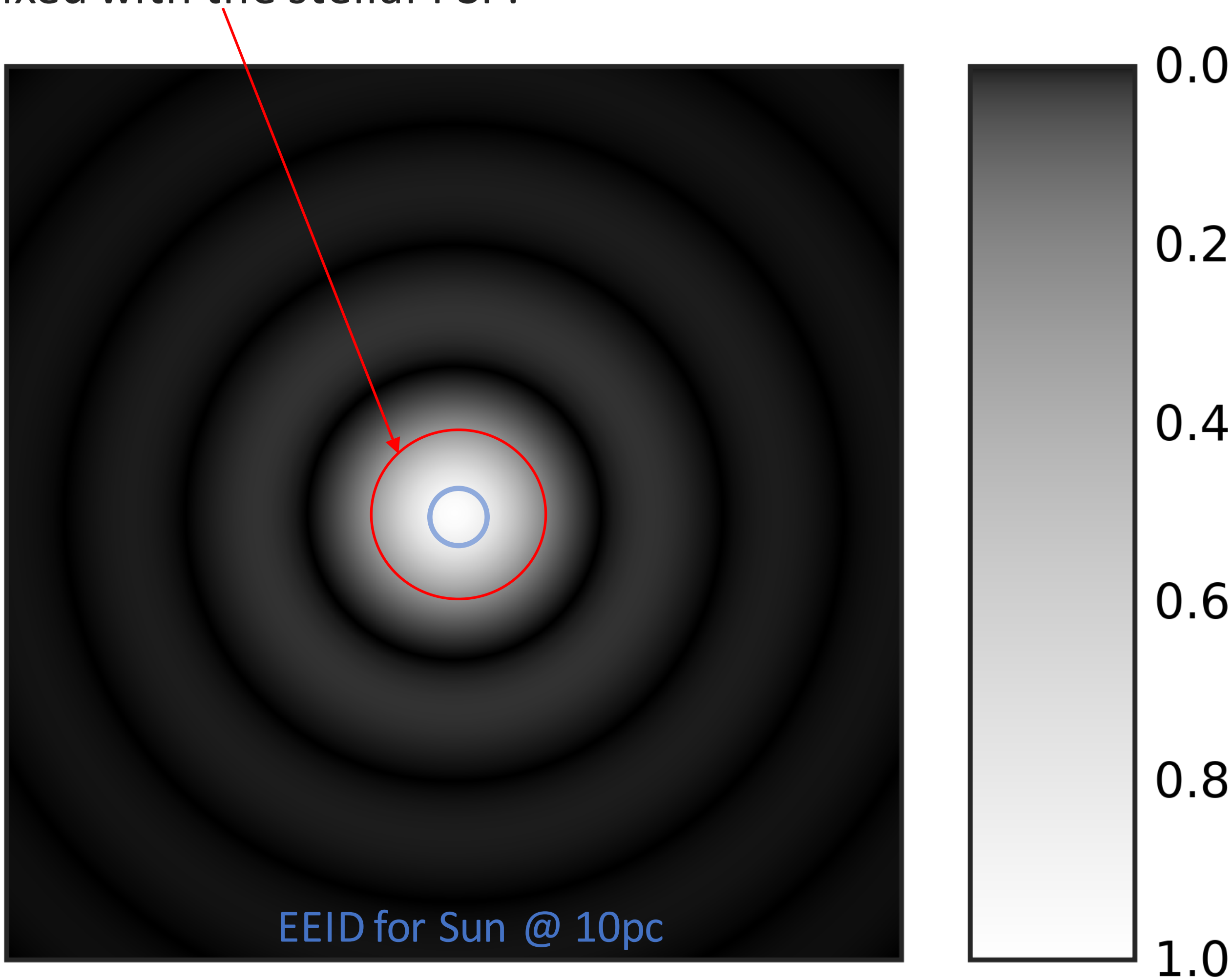
Observing challenge

- 1 zodi around a 2-Jy star is ~**1 million times** dimmer than the background and **~20000 times dimmer** than the star
- Signal mixed with the stellar PSF!



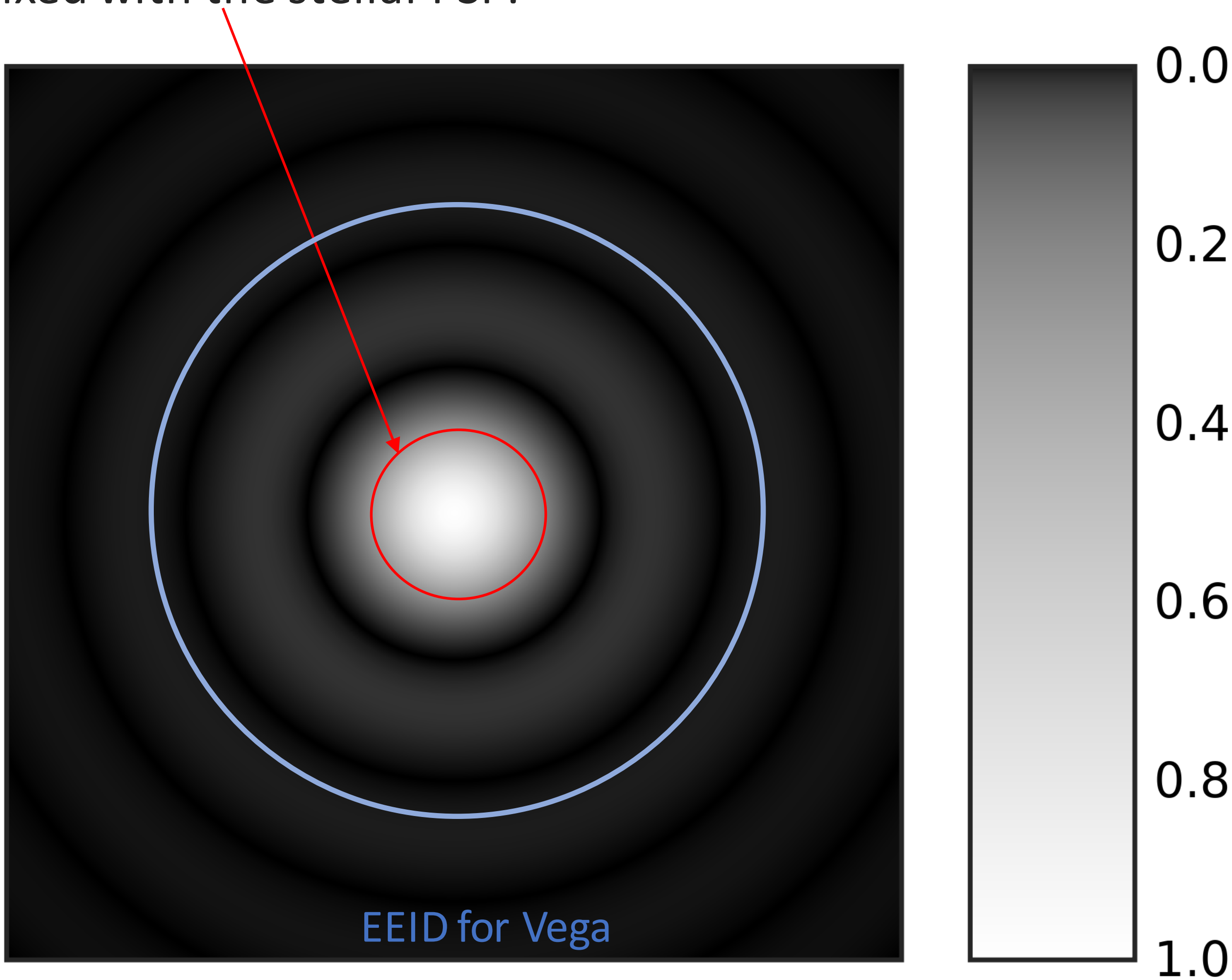
Observing challenge

- 1 zodi around a 2-Jy star is ~**1 million times** dimmer than the background and **~20000 times dimmer** than the star
- Signal mixed with the stellar PSF!



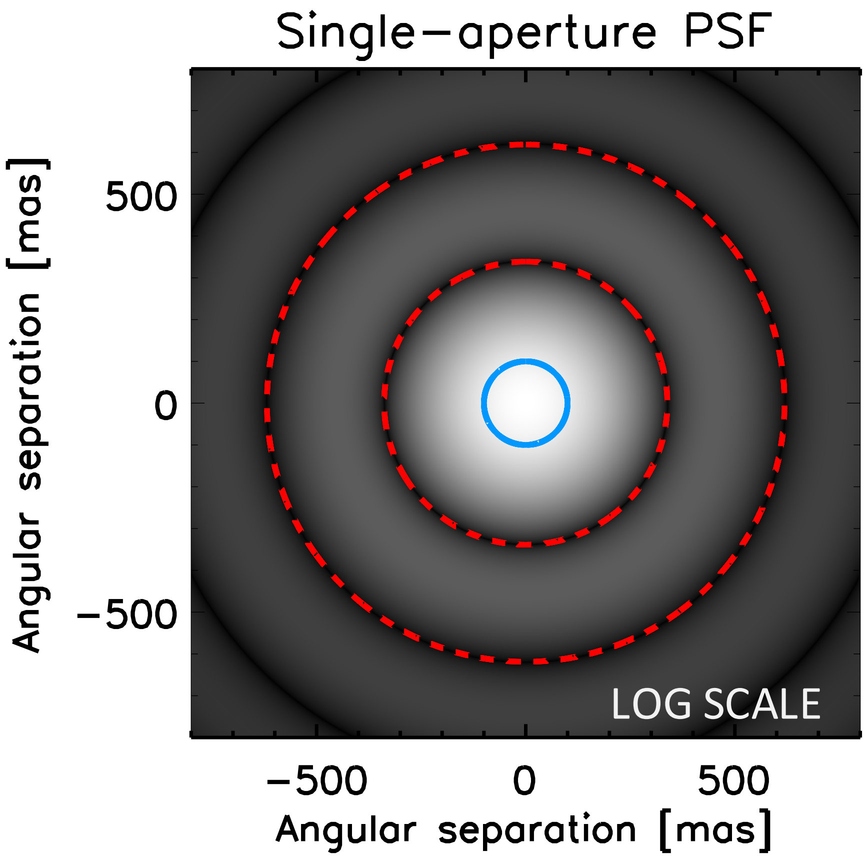
Observing challenge

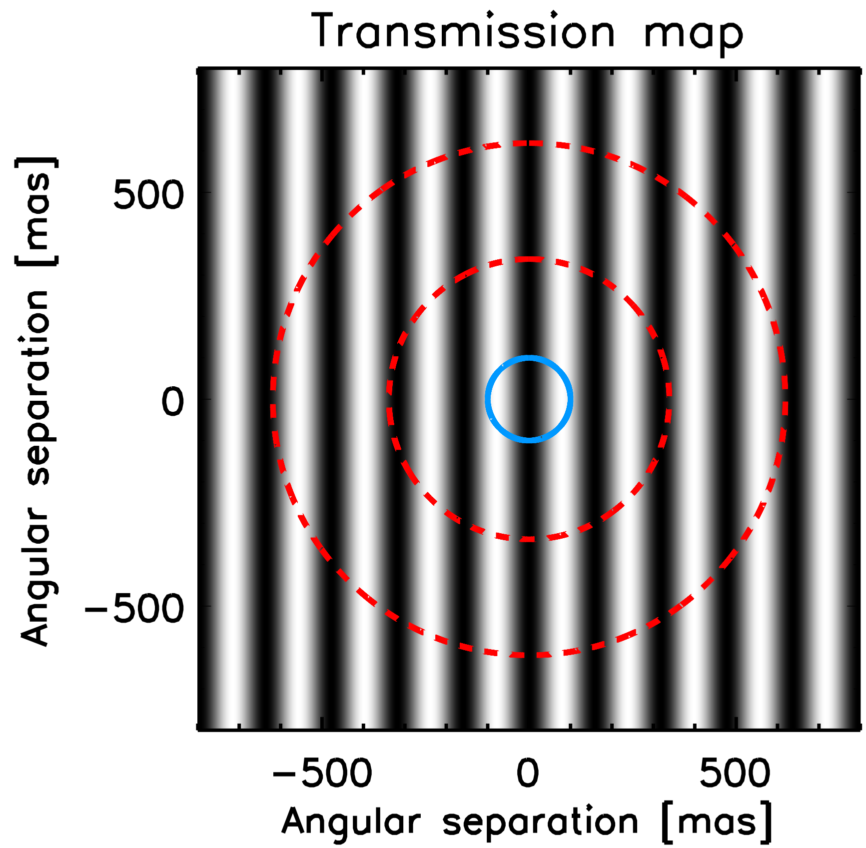
- 1 zodi around a 2-Jy star is ~**1 million times** dimmer than the background and **~20000 times dimmer** than the star
- Signal mixed with the stellar PSF!



How does it work?

- Exploit the instrumental response of the interferometer:





How does it work?

- Exploit the instrumental response of the interferometer:

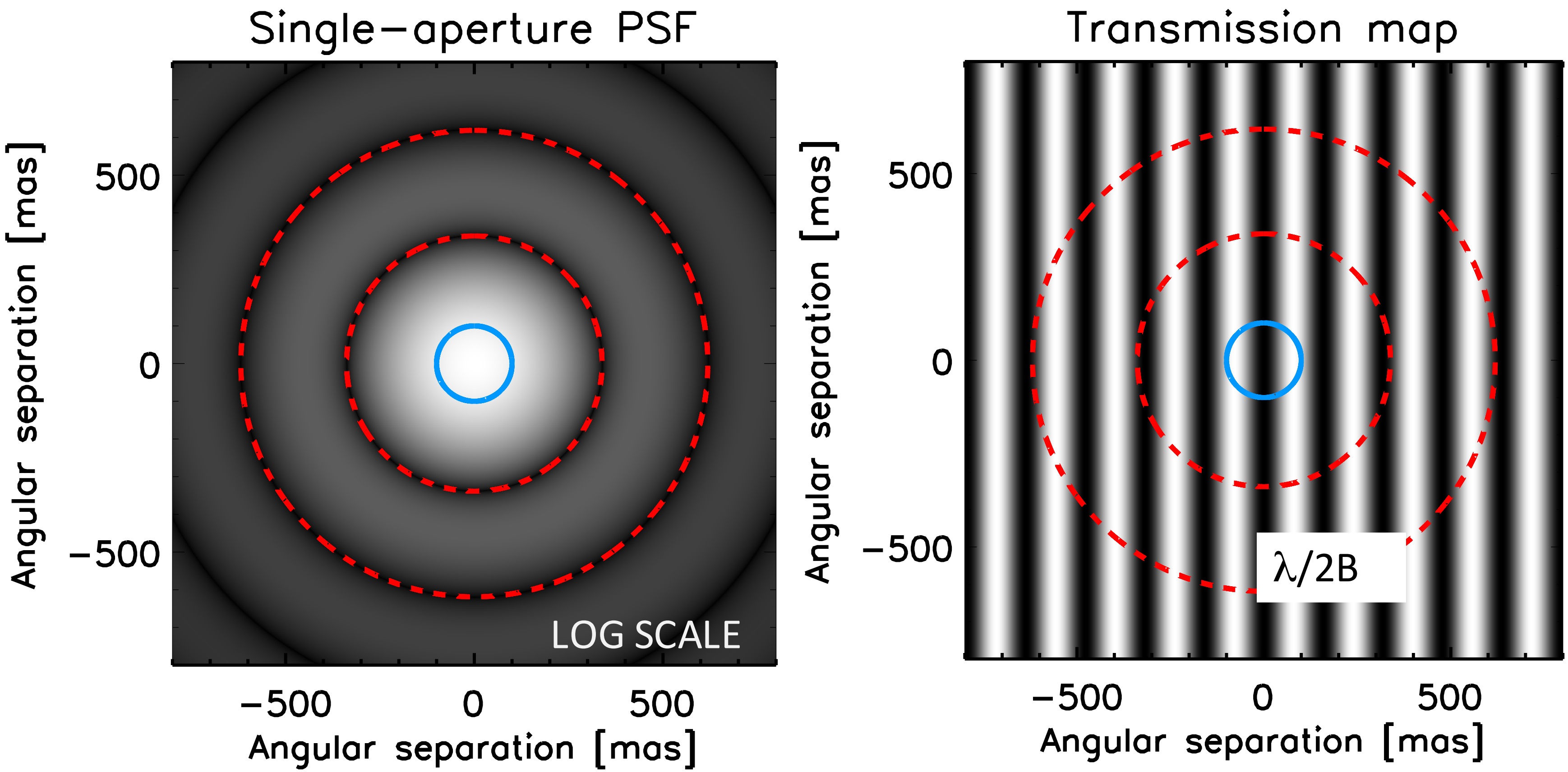


Illustration with a binary

- Observations of gam per: G8III+A3IV binary system:
  - Angular separation: 250 mas
  - Estimated contrast at N band: 3.55% +/- 0.22%.

- Data obtained on December 2013 (coarse fringe tracking)

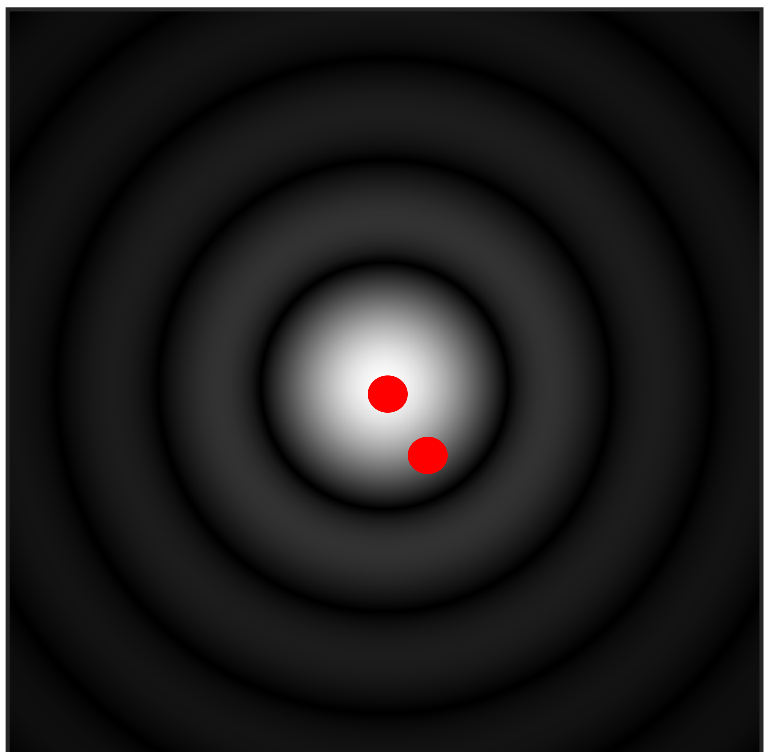


Illustration with a binary

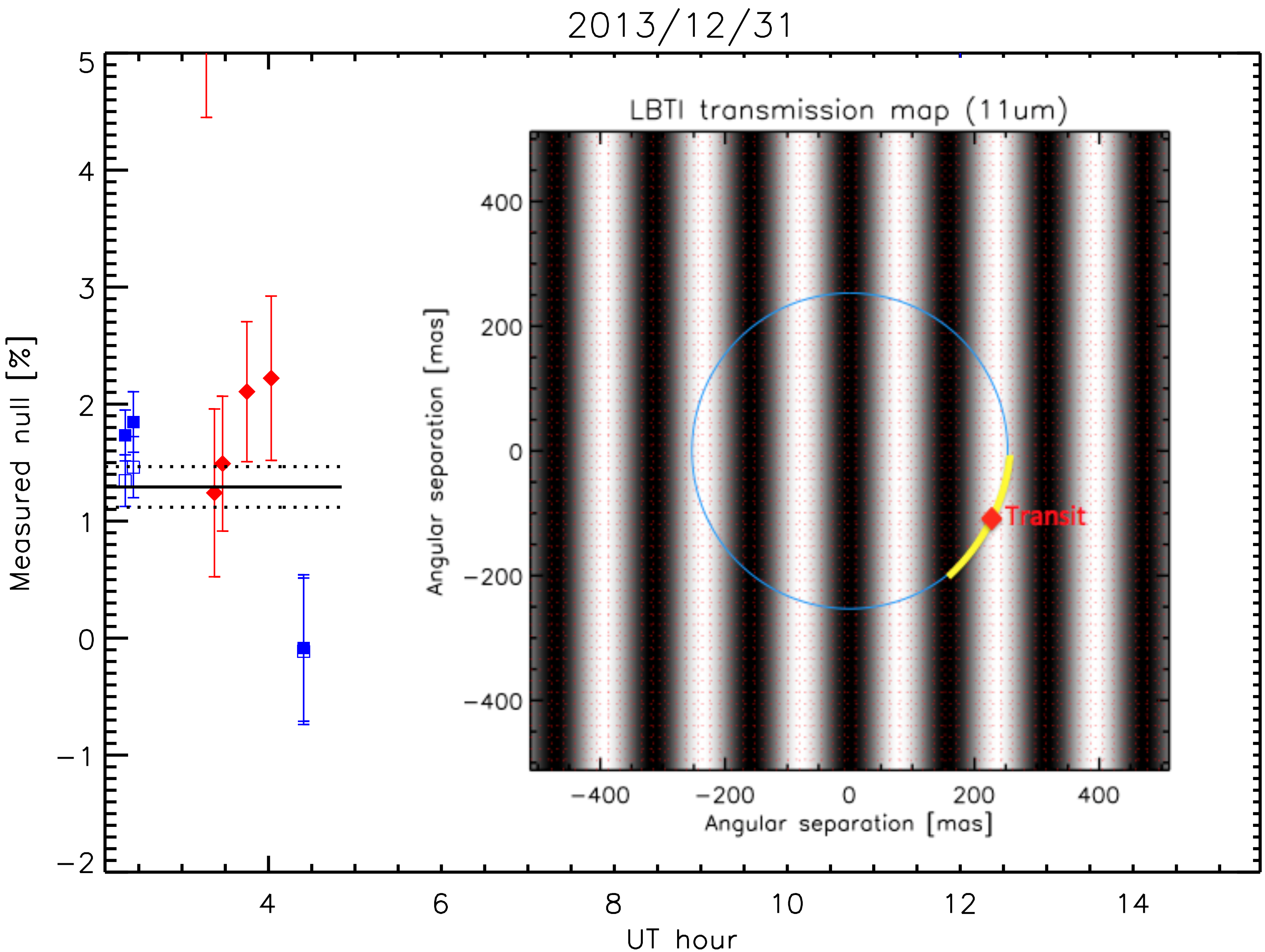


Illustration with a binary

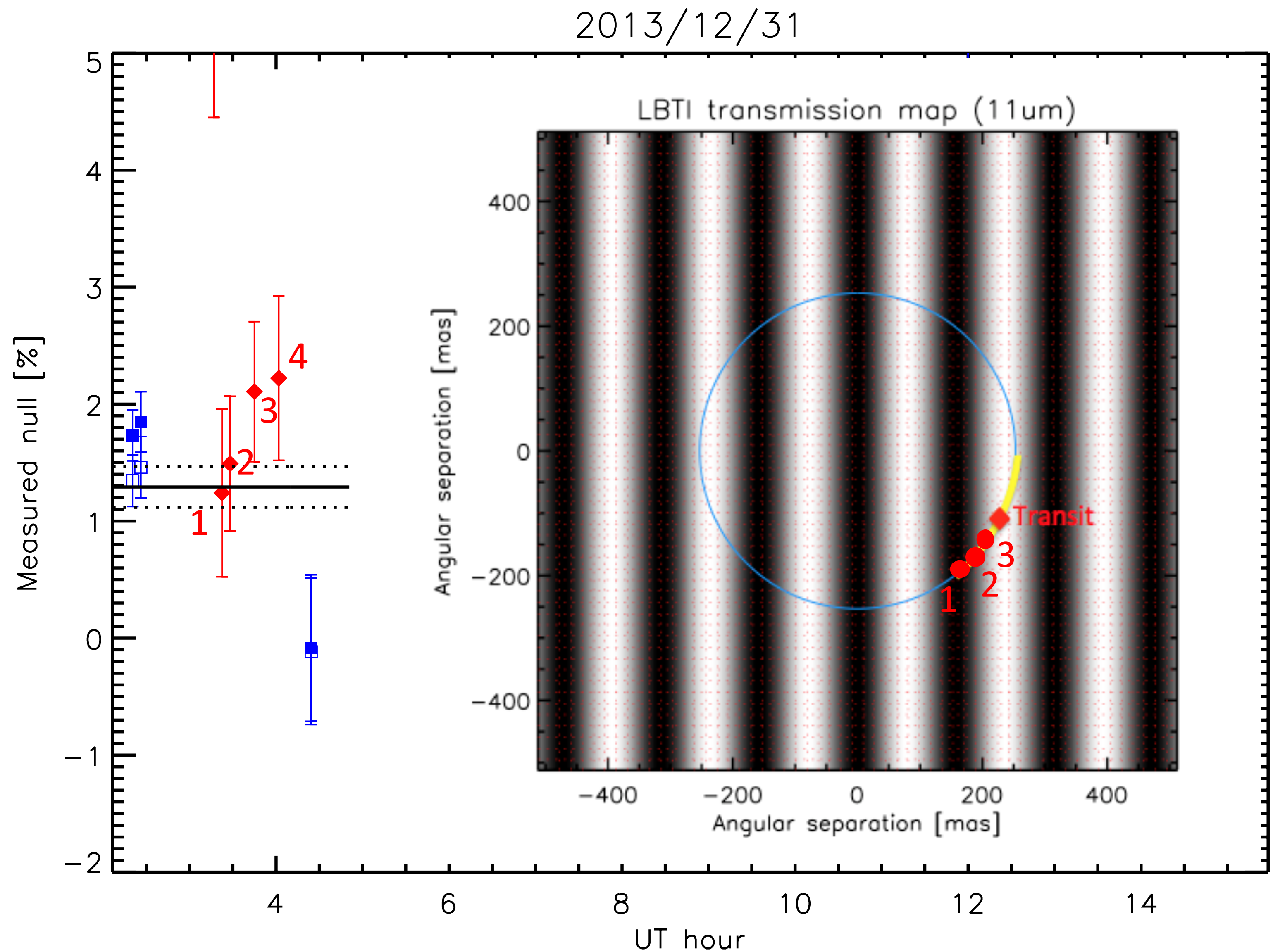


Illustration with a binary

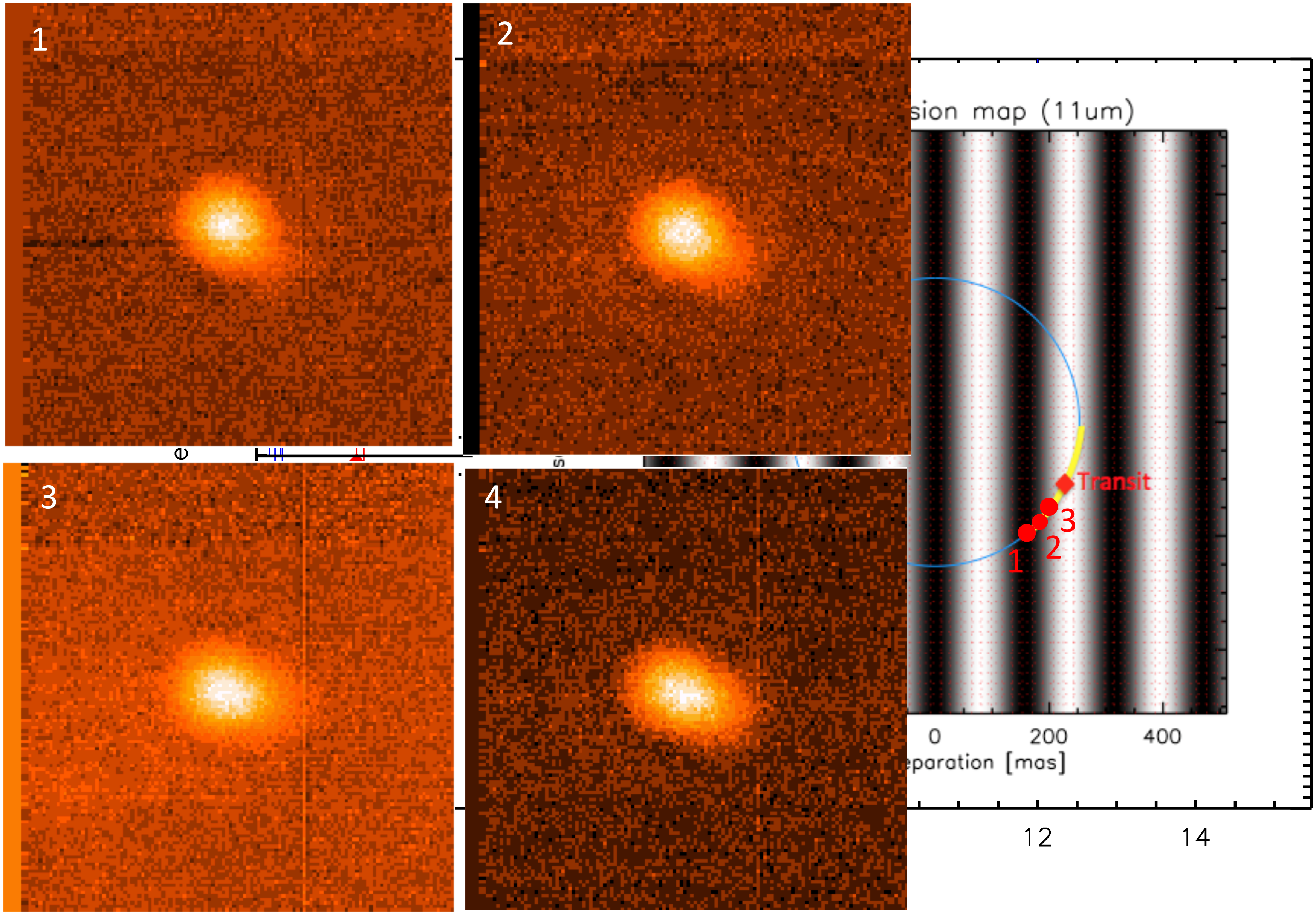
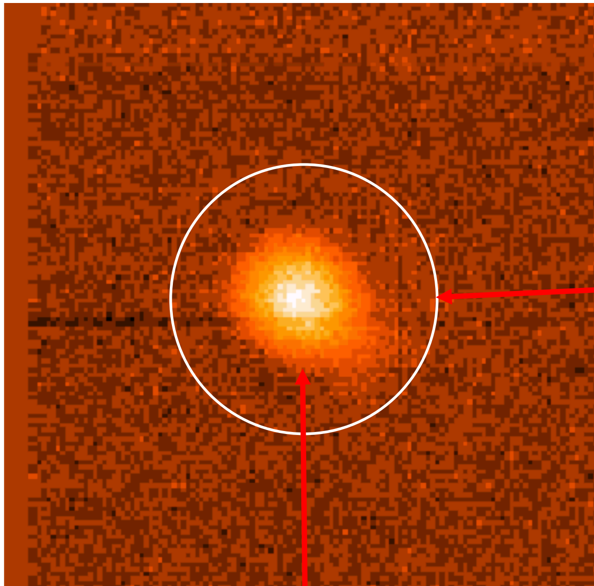


Illustration with a binary



Flux in given aperture can be modelled (same for exozodis)

Central star not perfectly suppressed => need for calibrators

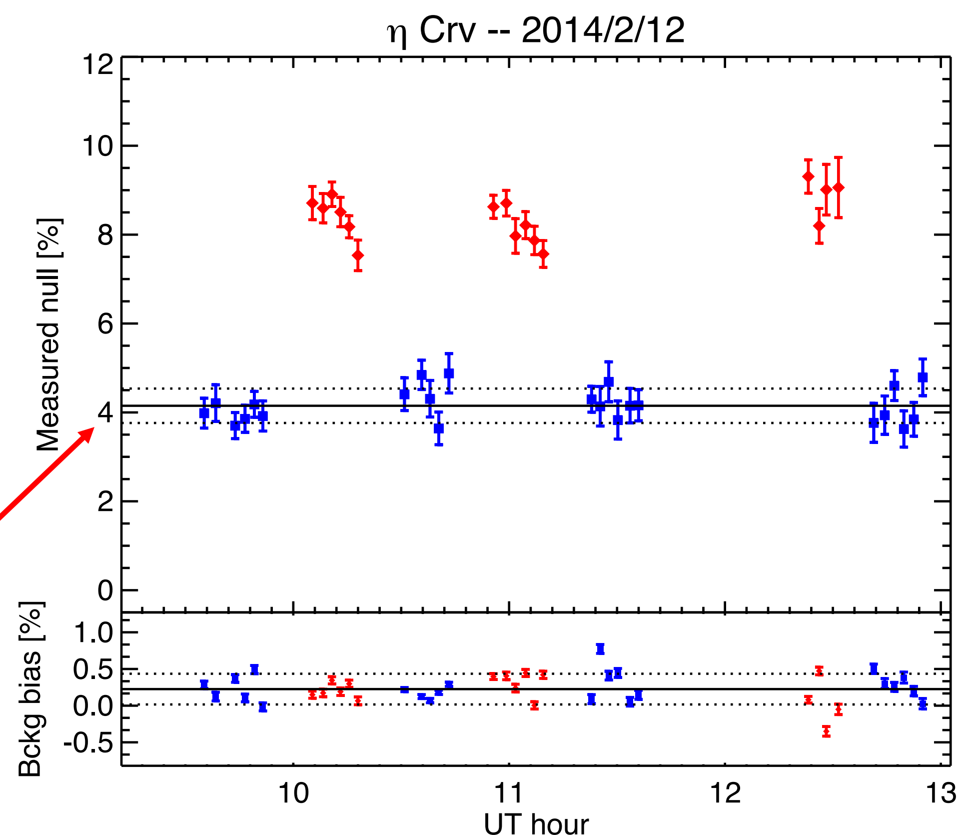
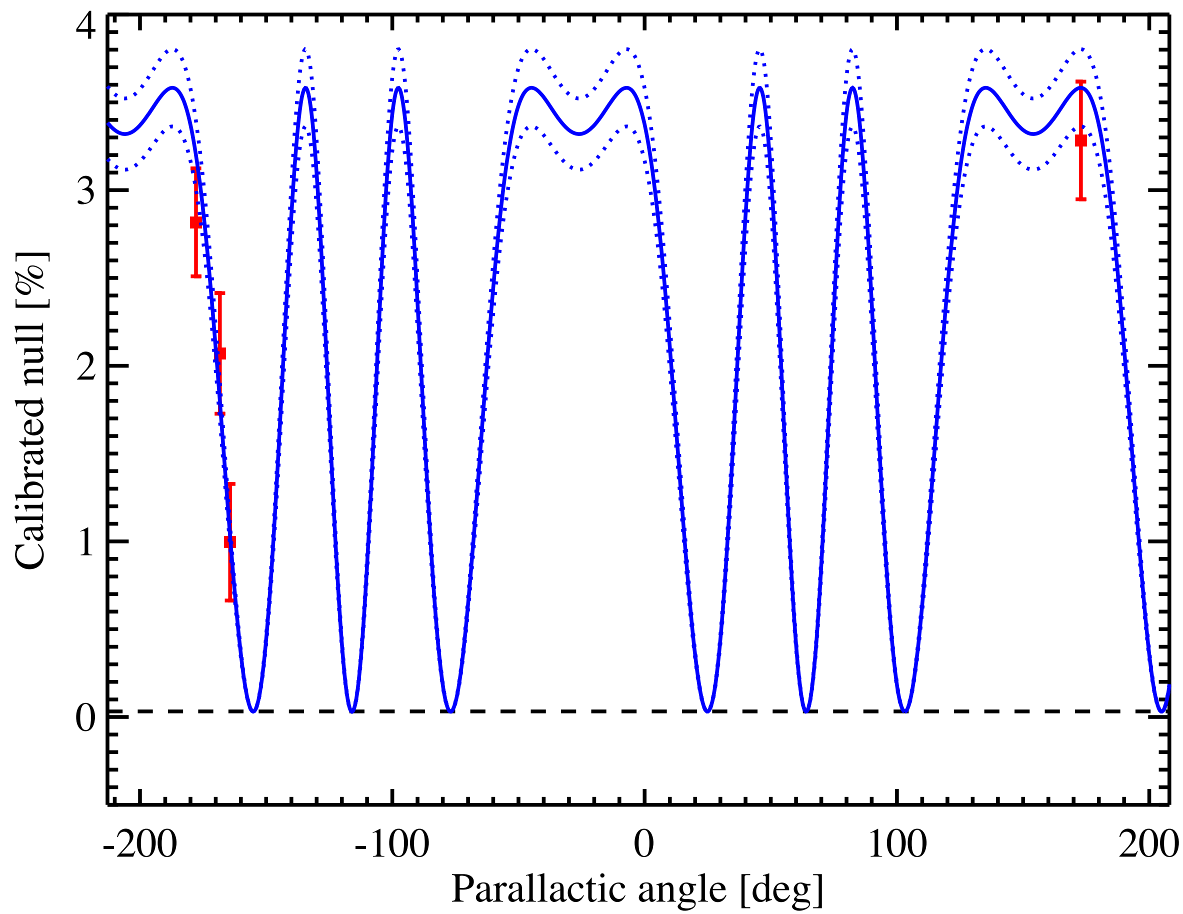


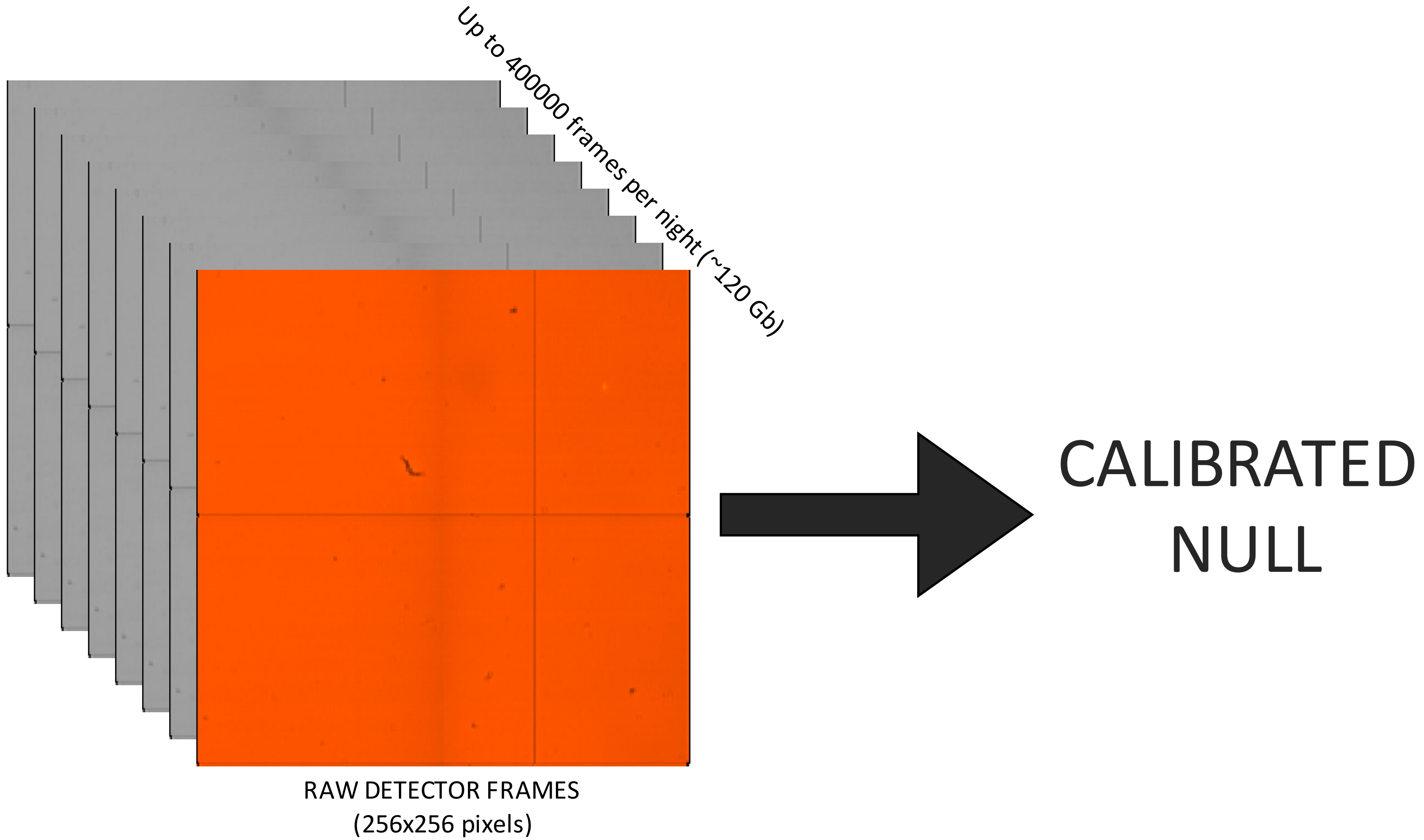
Illustration with a binary

- Measured contrast: 3.25% +/- 0.40%.
- Estimated contrast at N band: 3.55% +/- 0.22%.

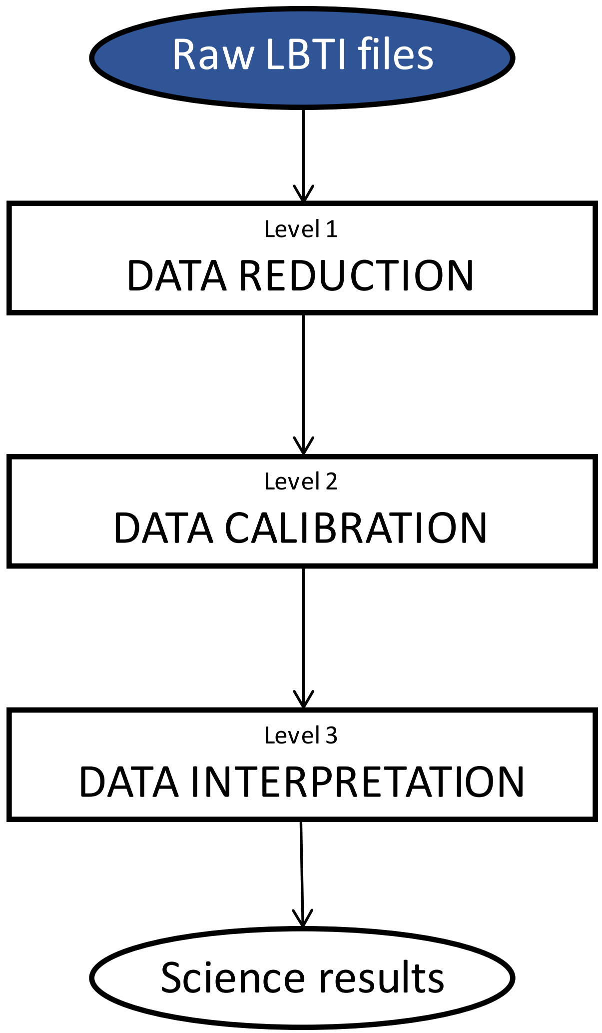


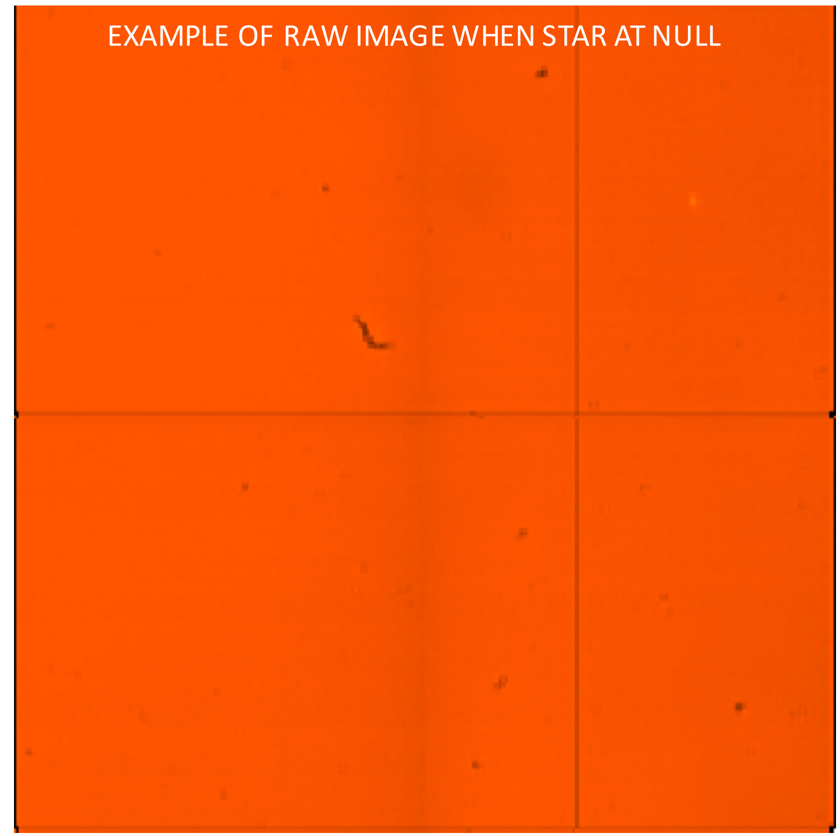
Data analysis

Data analysis overview



Data analysis overview





Data analysis overview

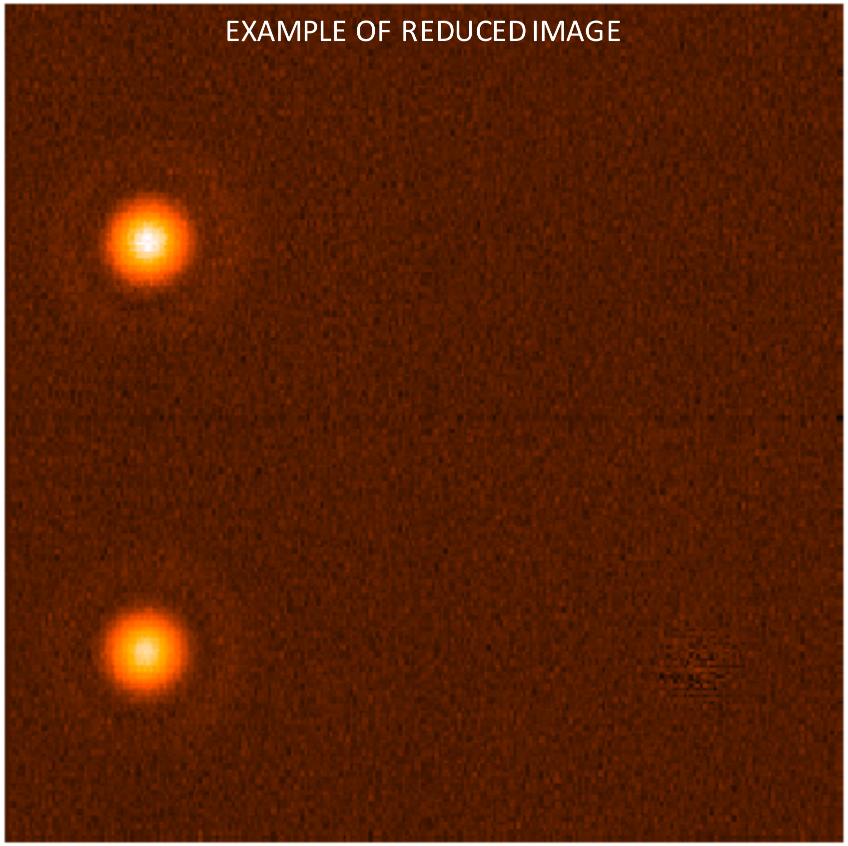
Raw LBTI files

Level 1
DATA REDUCTION

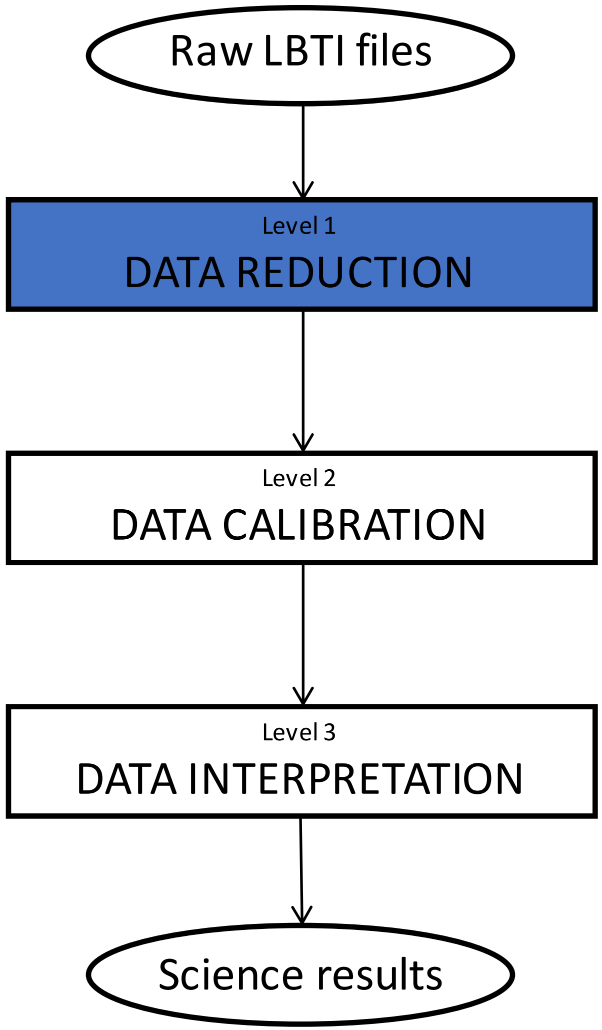
Level 2
DATA CALIBRATION

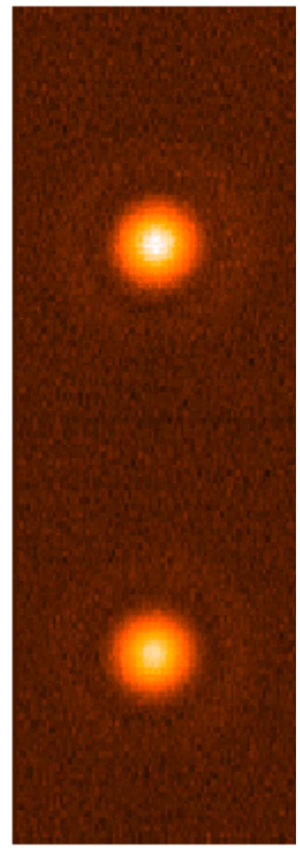
Level 3
DATA INTERPRETATION

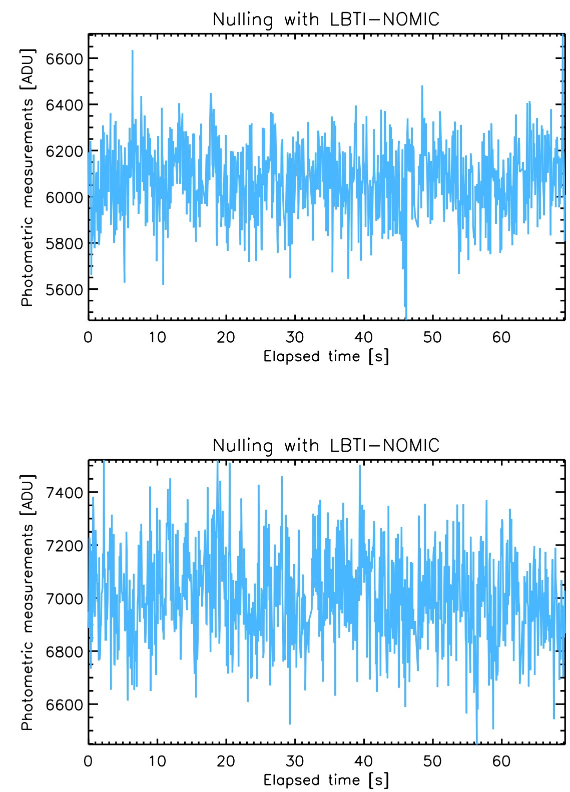
Science results



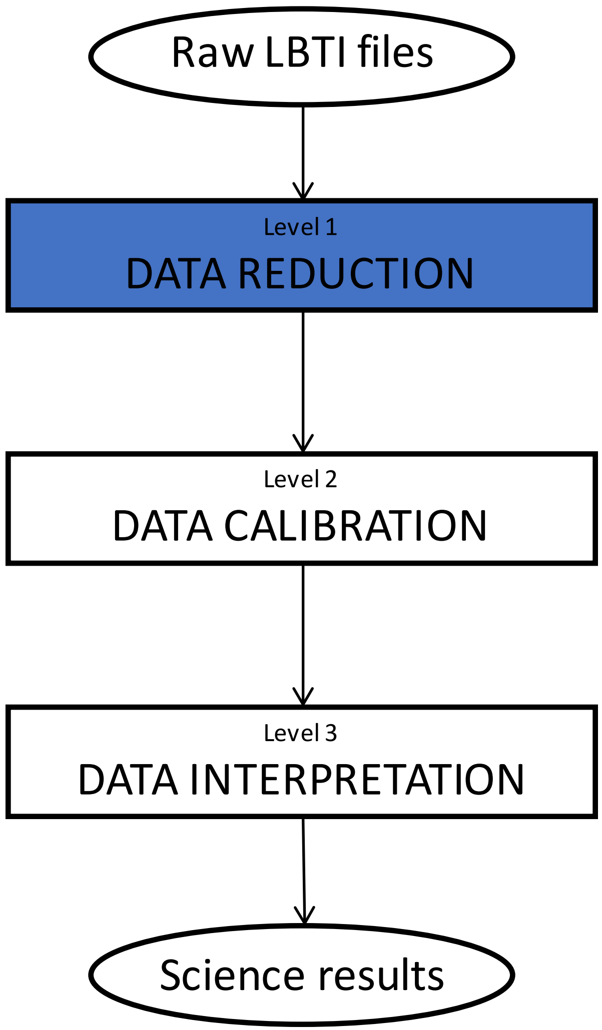
Data analysis overview

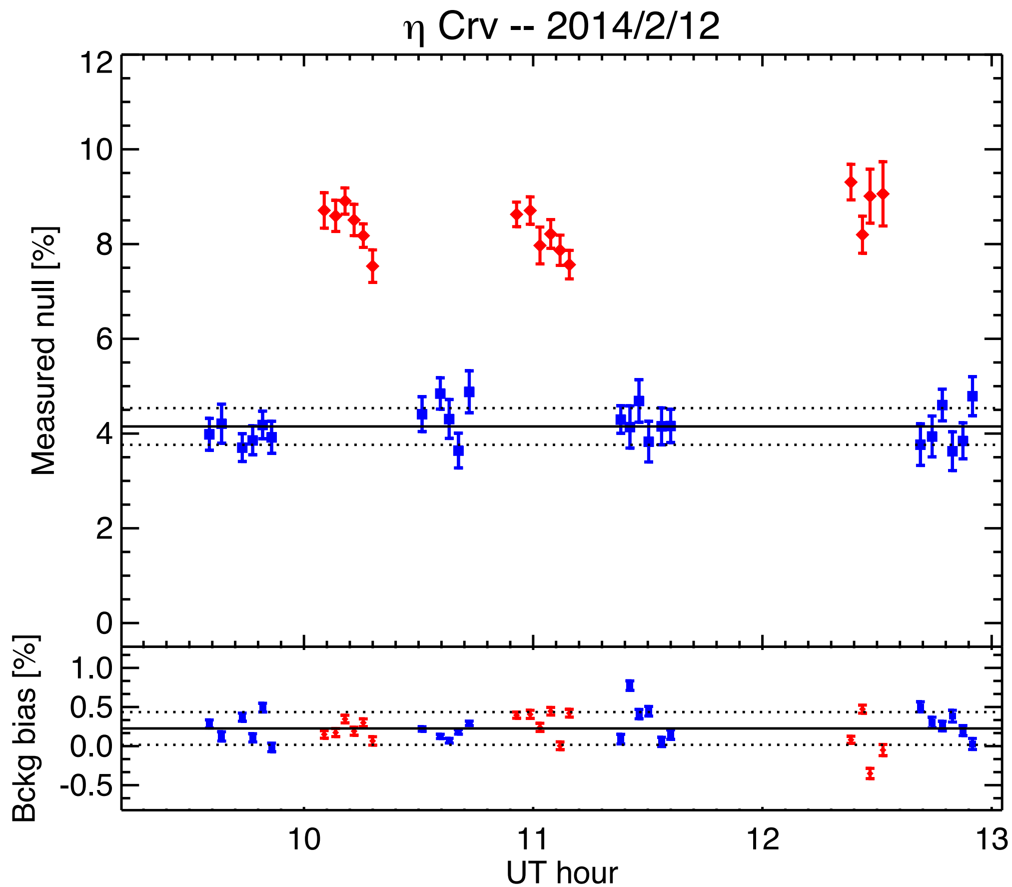




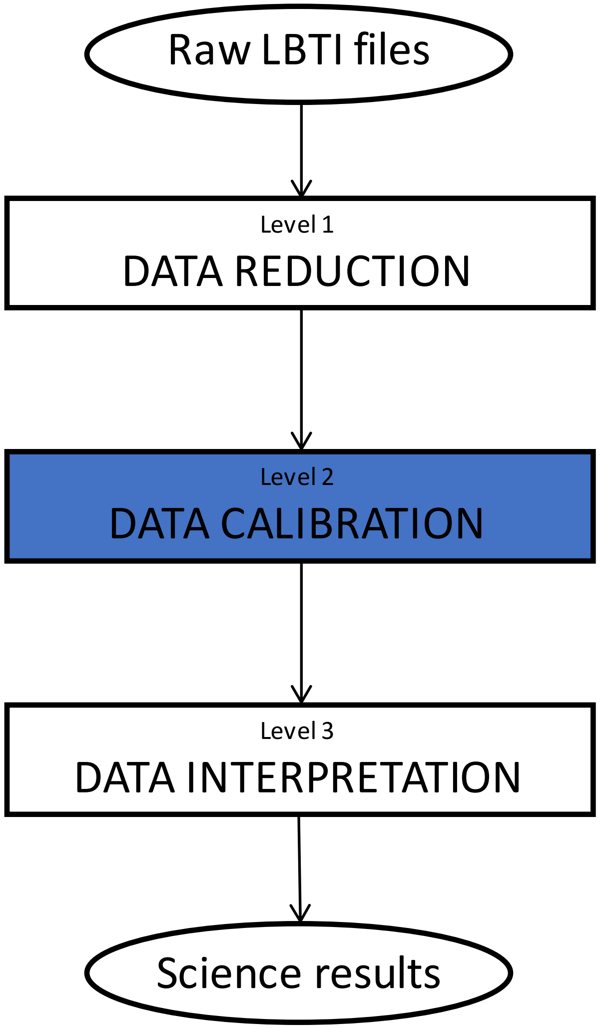


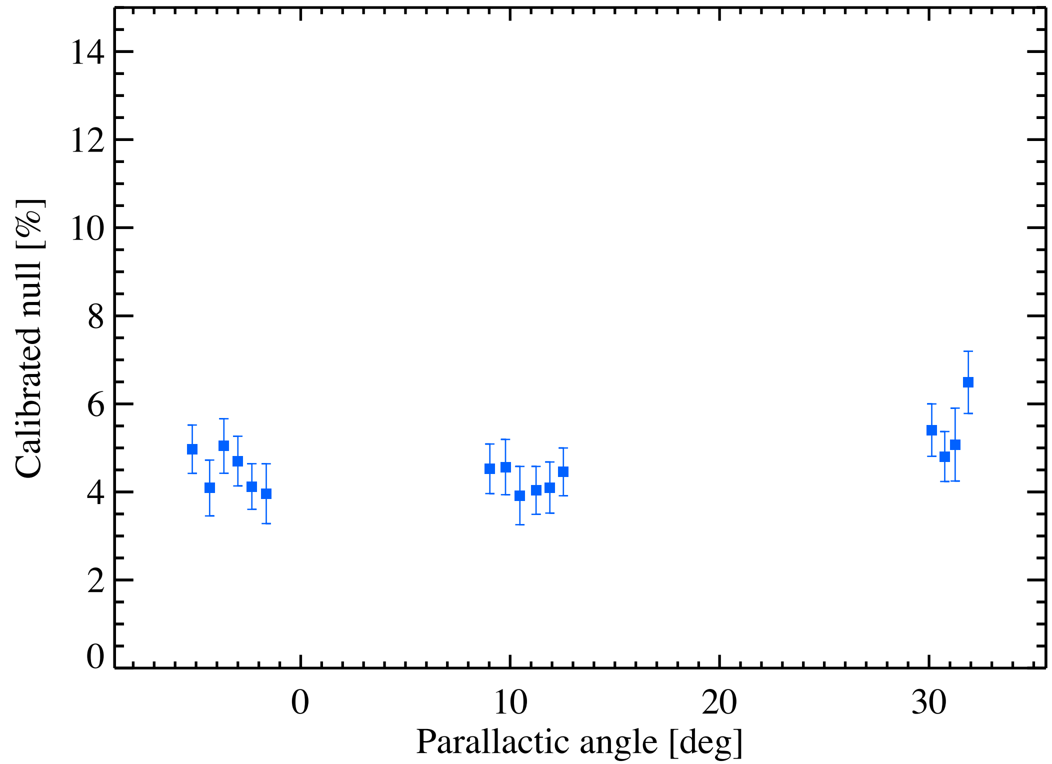
Data analysis overview



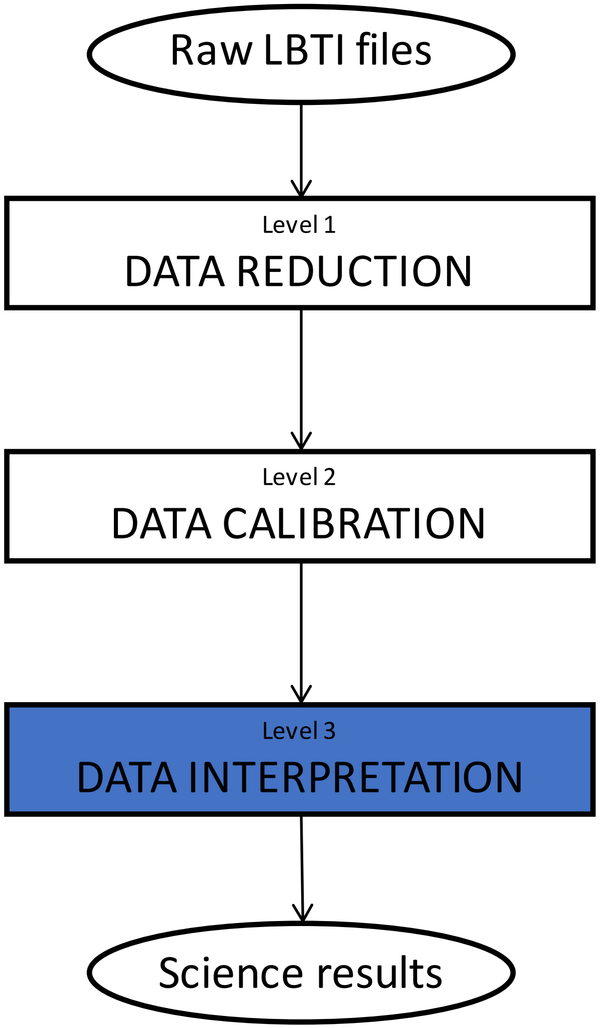


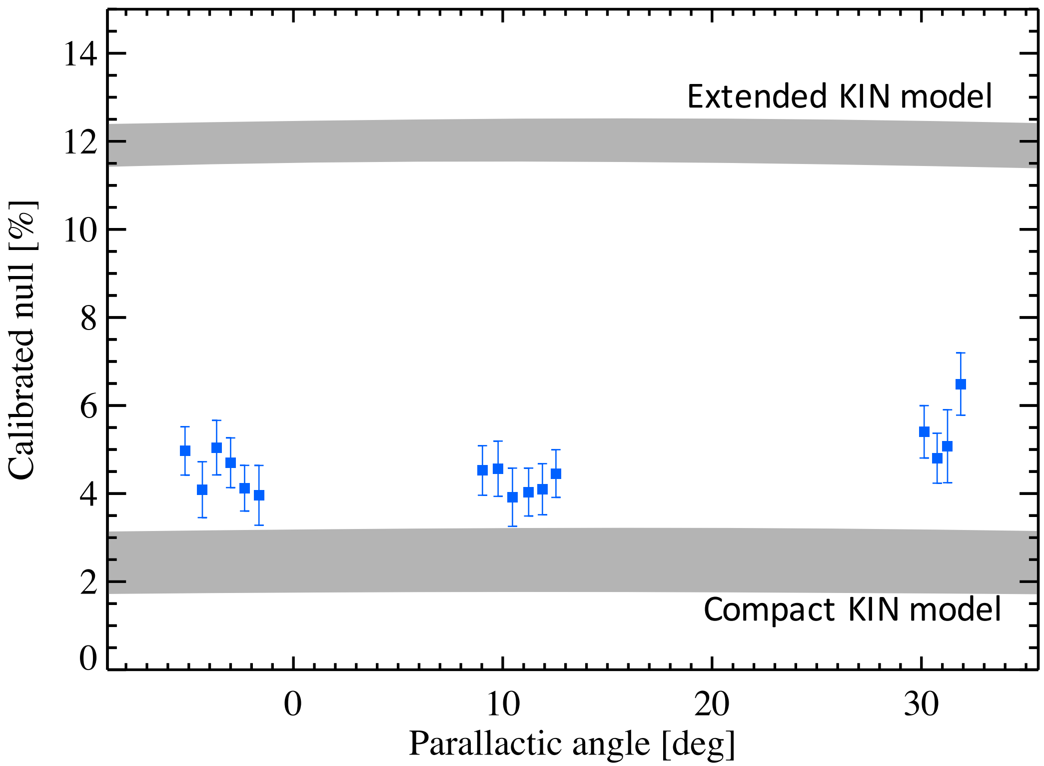
Data analysis overview



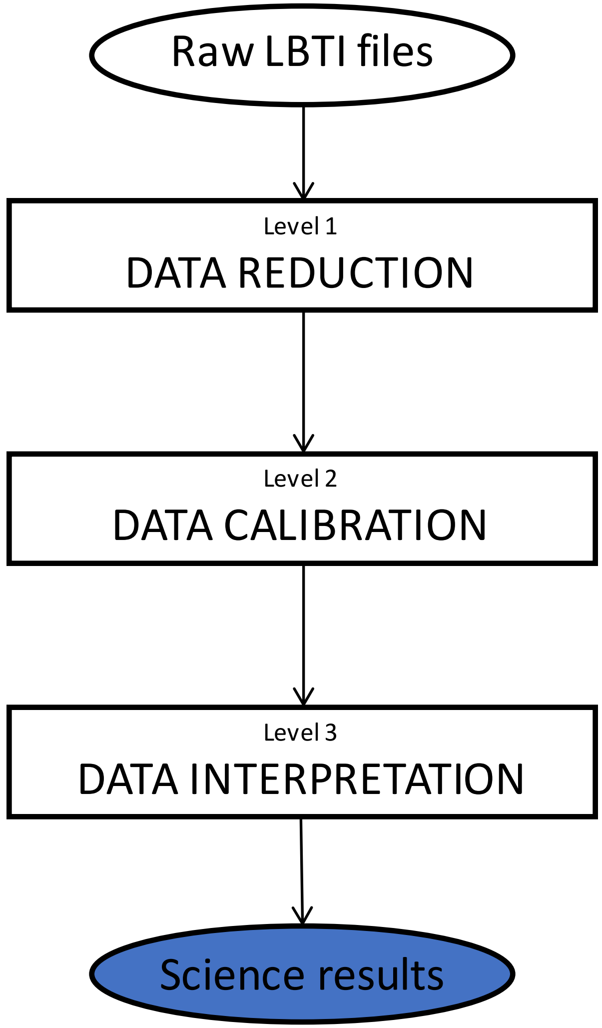


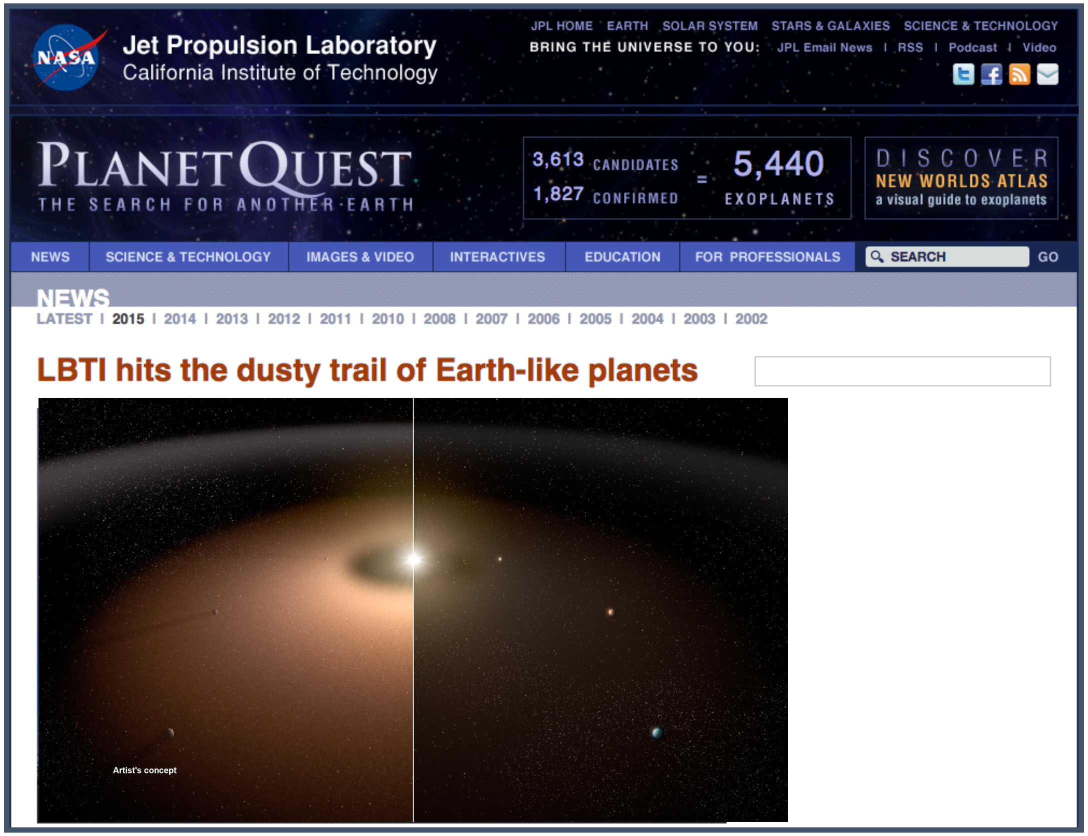
Data analysis overview

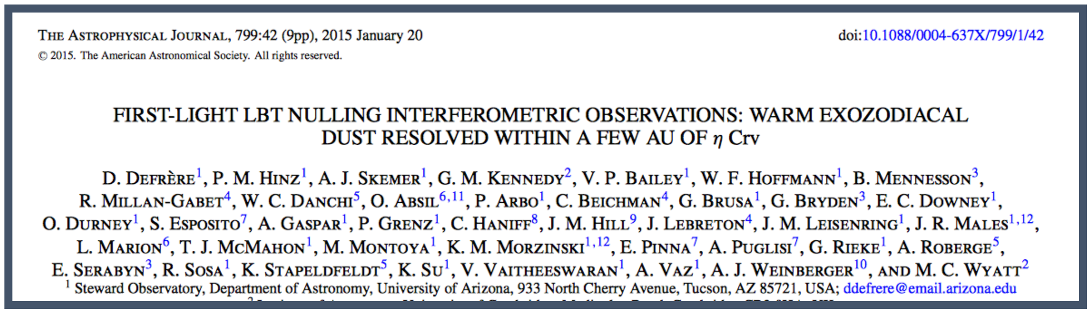




Data analysis overview





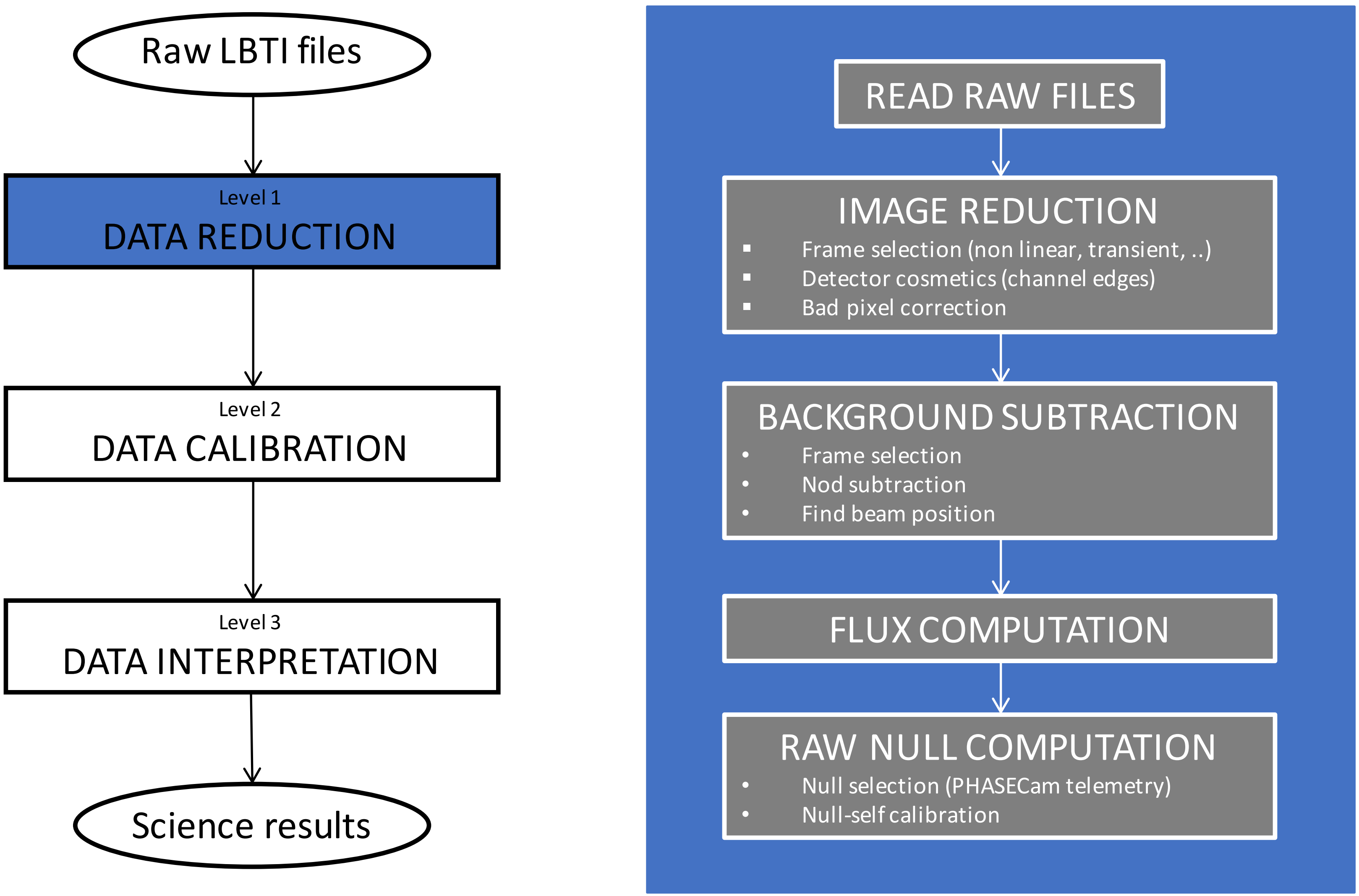


The Astrophysical Journal, 799:42 (9pp), 2015 January 20 doi:10.1088/0004-637X/799/1/42

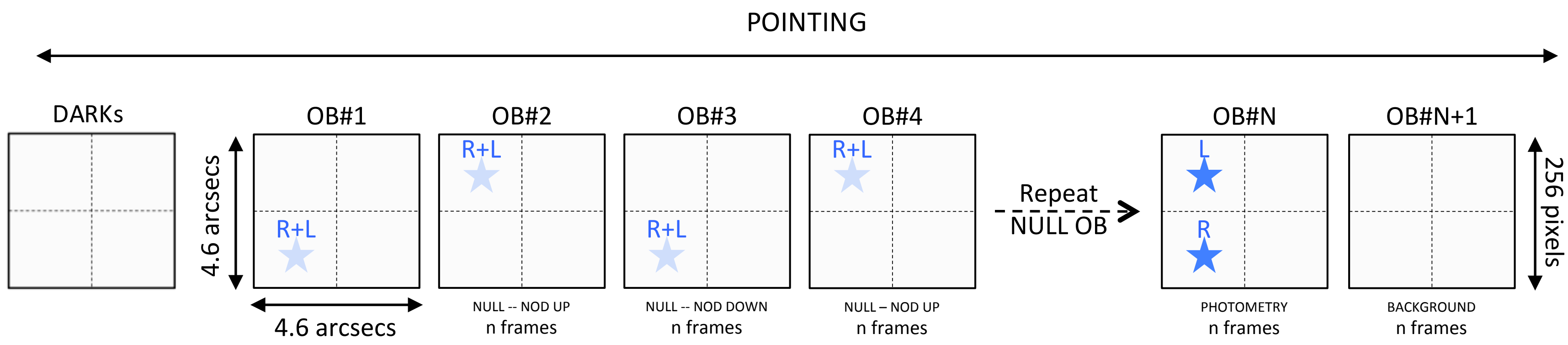
FIRST-LIGHT LBT NULLING INTERFEROMETRIC OBSERVATIONS: WARM EXOZODIACAL DUST RESOLVED WITHIN A FEW AU OF η Crv

D. Defrère[1], P. M. Hinz[1], A. J. Skemer[1], G. M. Kennedy[2], V. P. Bailey[1], W. F. Hoffmann[1], B. Mennesson[3], R. Millan-Gabet[4], W. C. Danchi[5], O. Absil[6,11], P. Arbo[1], C. Beichman[4], G. Brusa[1], G. Bryden[3], E. C. Downey[1], O. Durney[1], S. Esposito[7], A. Gaspar[1], P. Grenz[1], C. Haniff[8], J. M. Hill[9], J. Lebreton[4], J. M. Leisenring[1], J. R. Males[1,12], L. Marion[6], T. J. McMahon[1], M. Montoya[1], K. M. Morzinski[1,12], E. Pinna[7], A. Puglisi[7], G. Rieke[1], A. Roberge[5], E. Serabyn[3], R. Sosa[1], K. Stapeldfeldt[5], K. Su[1], V. Vaitheeswaran[1], A. Vaz[1], A. J. Weinberger[10], and M. C. Wyatt[2]
[1] Steward Observatory, Department of Astronomy, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721, USA; ddefrere@email.arizona.edu

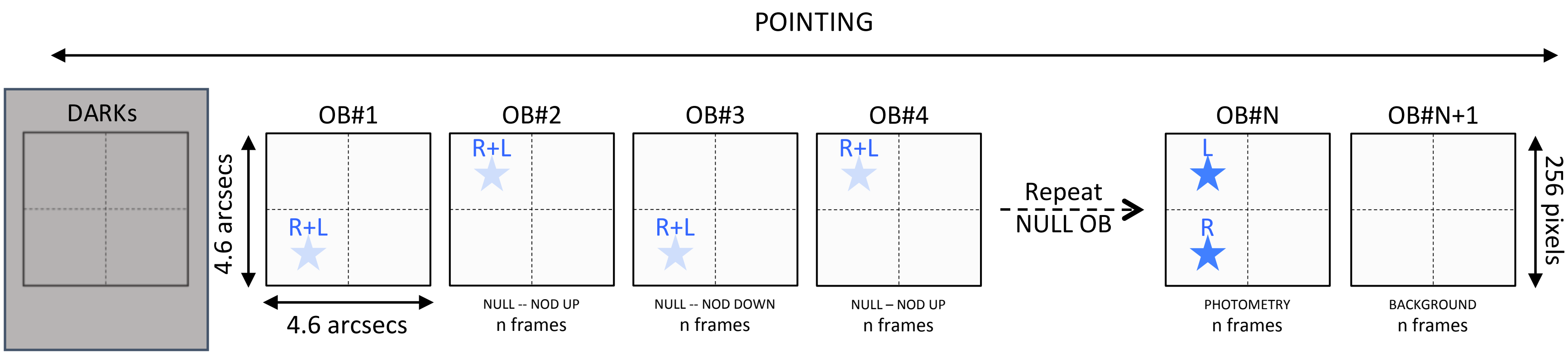
Data analysis overview



Observing strategy

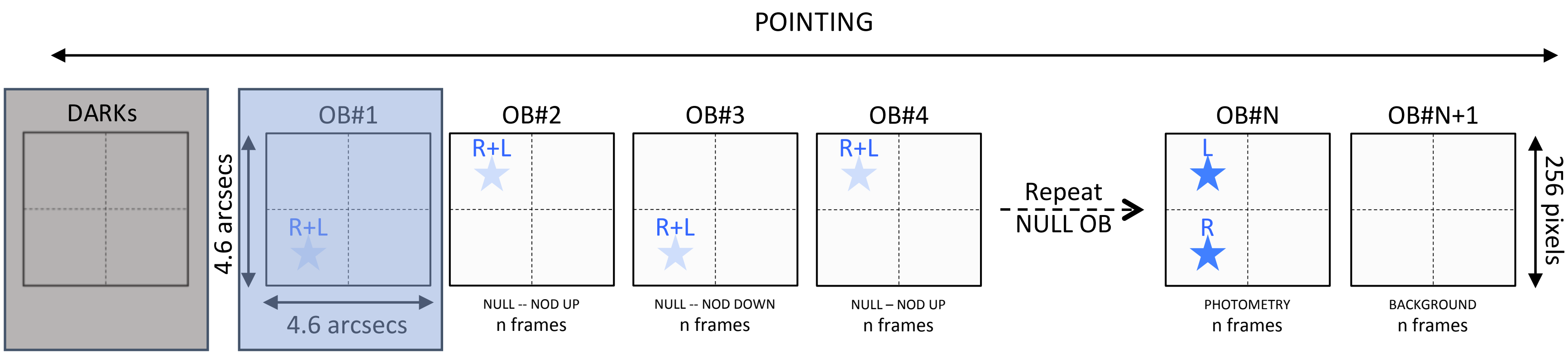


Observing strategy



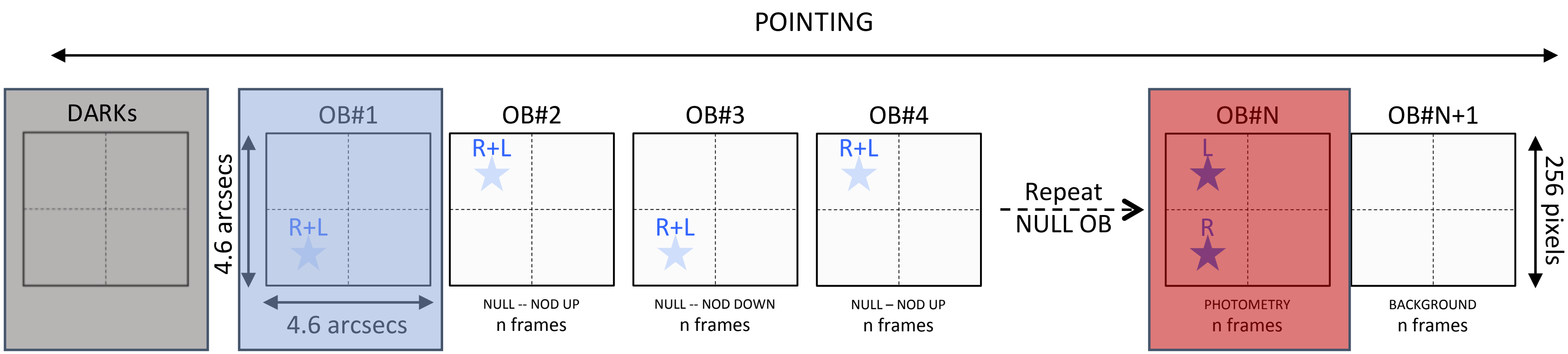
- DARKS: used for hot bad pixel identification

Observing strategy



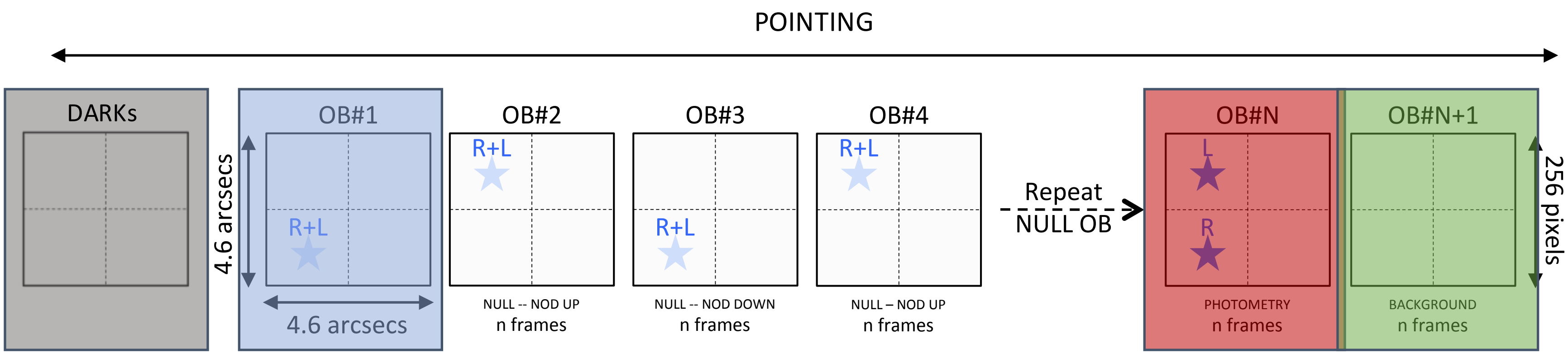
- DARKS: used for cold bad pixel identification
- NULL observing block (OB): overlapped beams in phase opposition.

Observing strategy



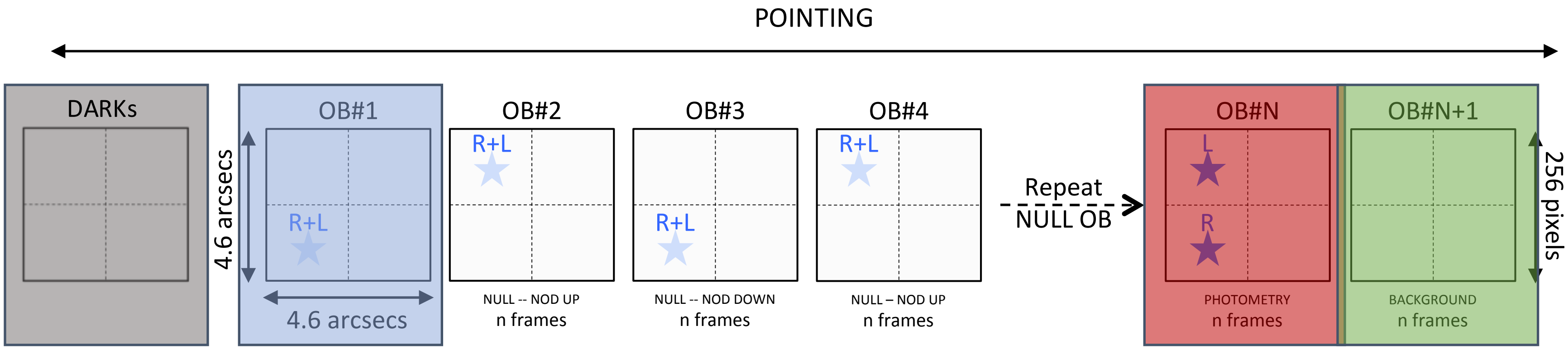
- DARKS: used for hot bad pixel identification
- NULL observing block (OB): overlapped beams in phase opposition.
- PHOTOMETRY OB: separated beams, used for normalization

Observing strategy



- DARKS: used for hot bad pixel identification
- NULL observing block (OB): overlapped beams in phase opposition.
- PHOTOMETRY OB: separated beams, used for normalization
- BACKGROUND OB: used for flat fielding and cold bad pixel identification

Observing strategy

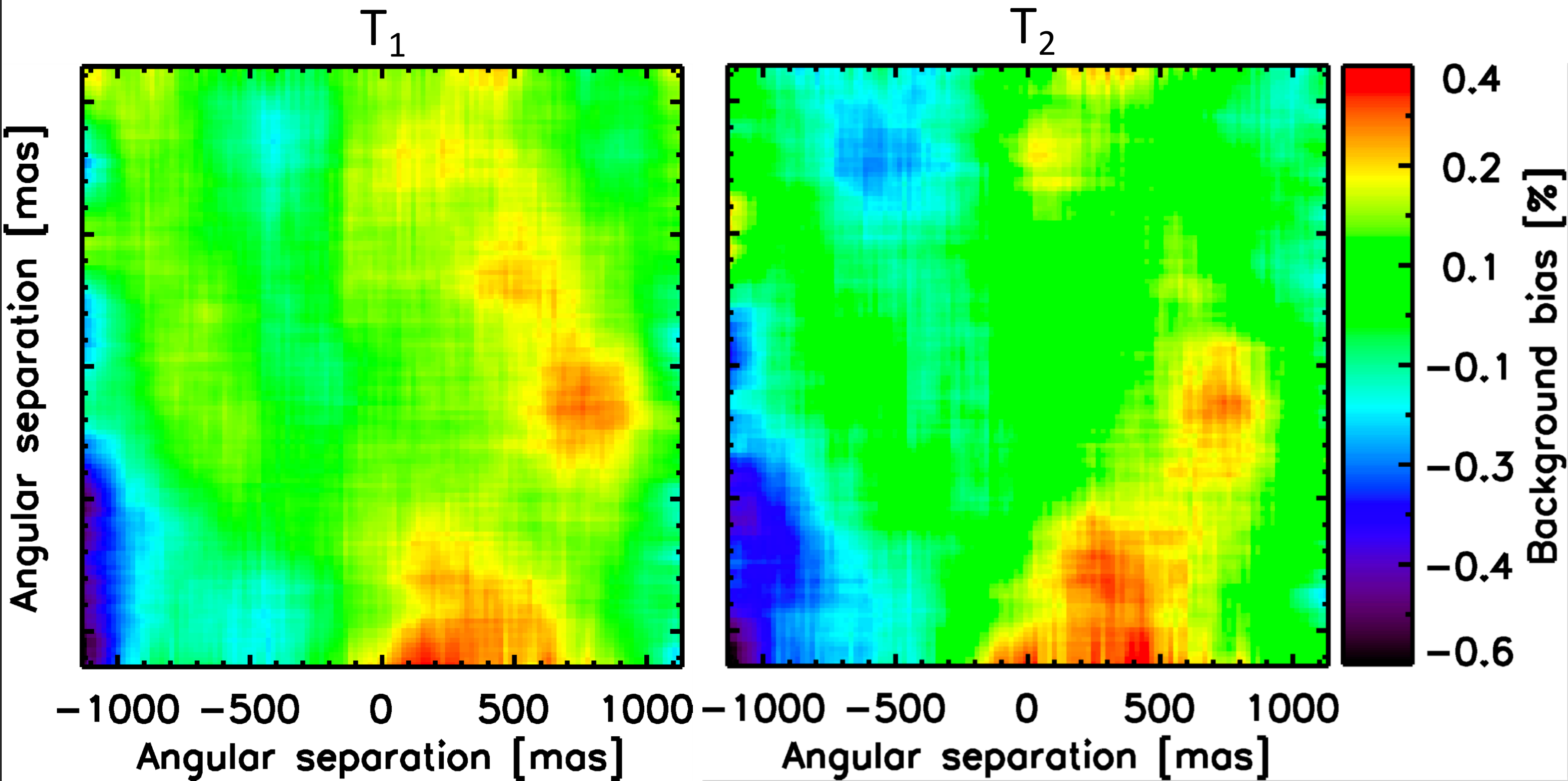


<u>IMAGE HEADER</u>

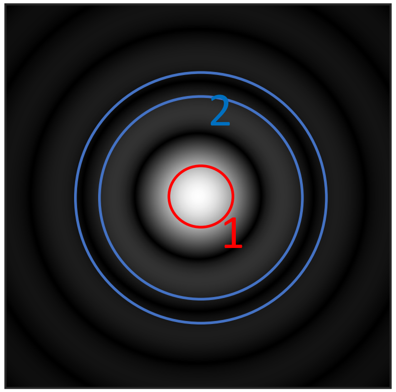
- Target info (e.g., name, RA, DEC, …)
- Telescope telemetry (e.g., elevation, …)
- Detector and filter configuration (e.g., DIT, mode, filter position, …)
- AO telemetry (e.g., loop status, loop frequency, loop gains, …)
- PHASECam telemetry (e.g., loop status, SNR, speed, OPD RMS, tip/tilt RMS, …)
- Weather information (e.g., seeing, PWV, wind, …)

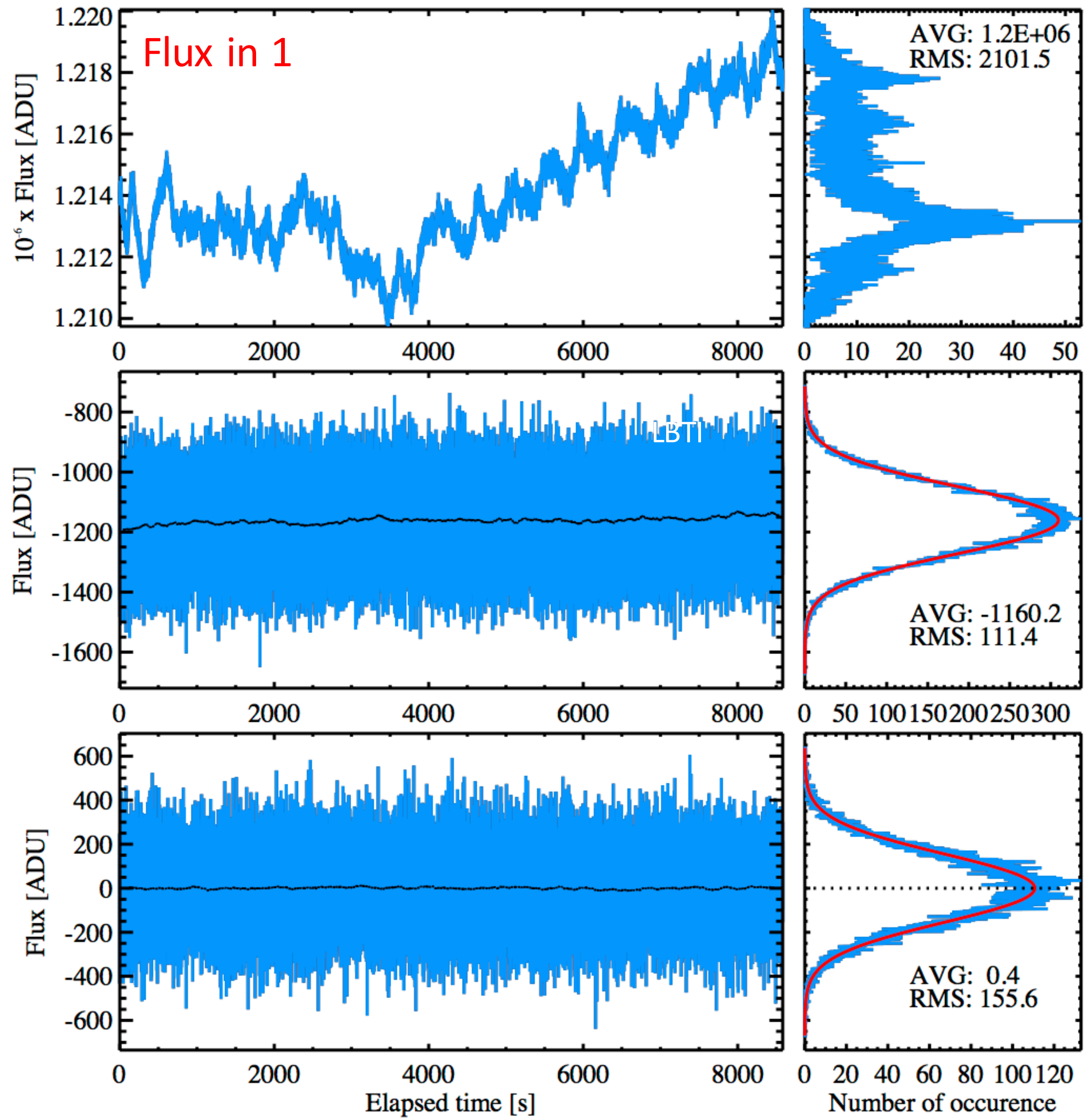
Background subtraction

- Complex spatiotemporal fluctuations
- Flux-dependent detector behavior
- Temporal and spatial noise correlation
- Must be corrected for accurate null measurements



Background subtraction



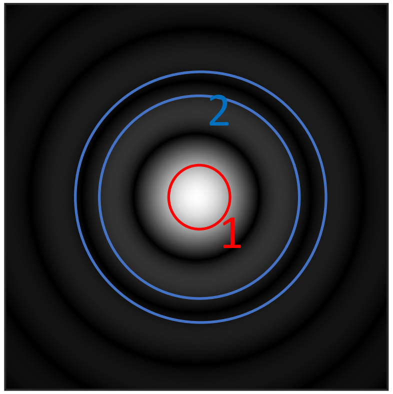


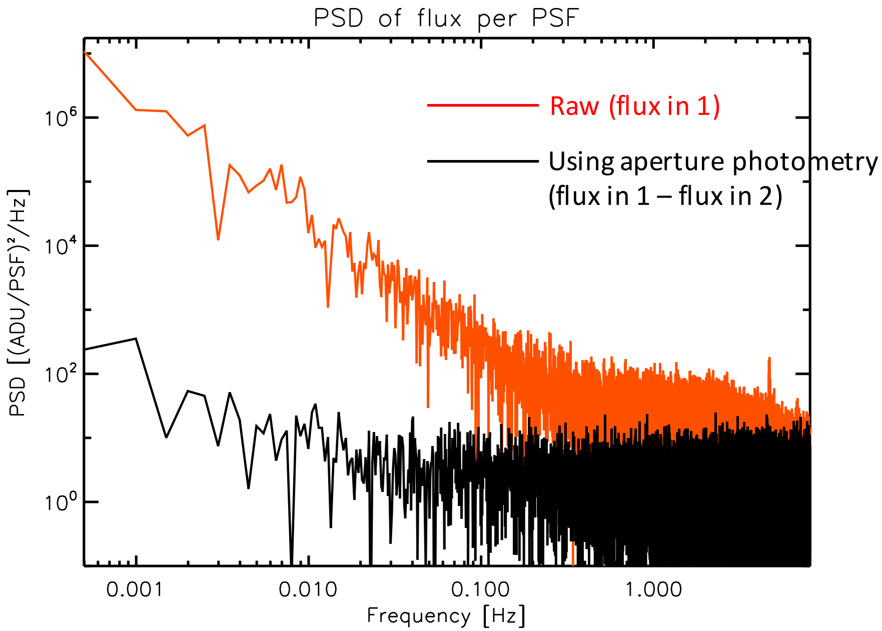
<u>Flux in region 1 – region 2</u>
Large variation corrected
Large offset
Slow drift

<u>Flux in region 1 – region 2 - (estimate in next nod)</u>
Offset corrected
Slow drift removed

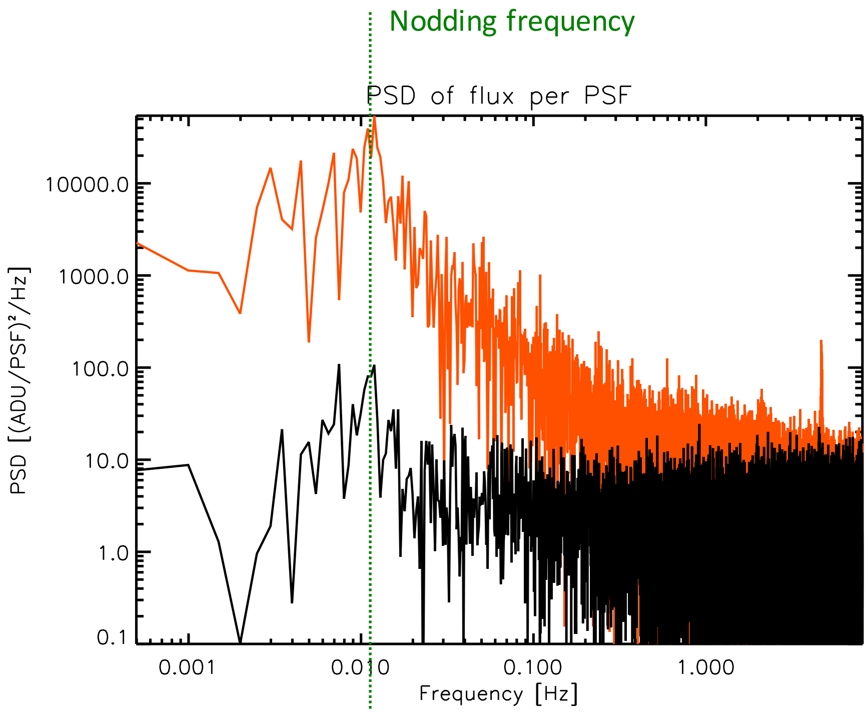
Background subtraction

- High nodding frequency!



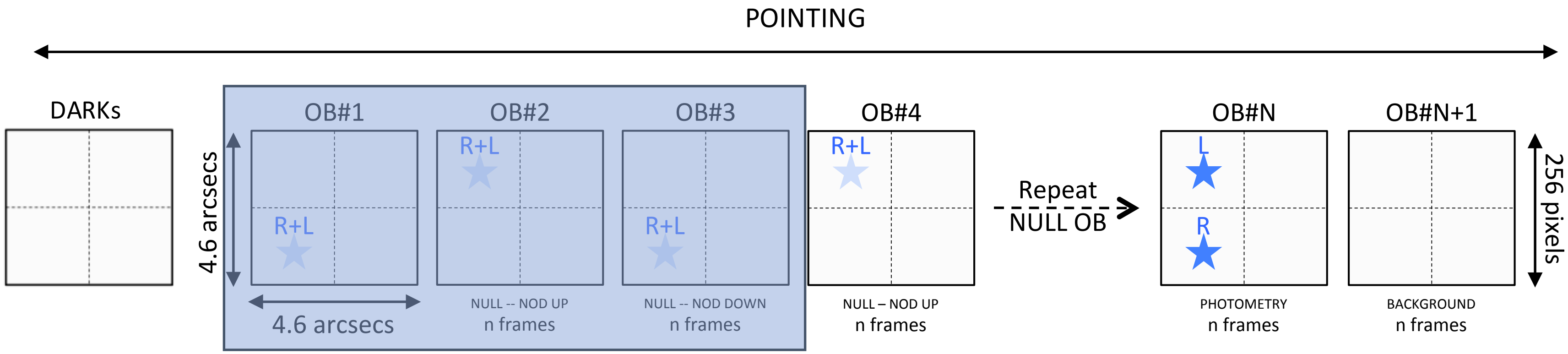


WITHOUT NODDING SUBTRACTION



WITH NODDING SUBTRACTION

Observing strategy

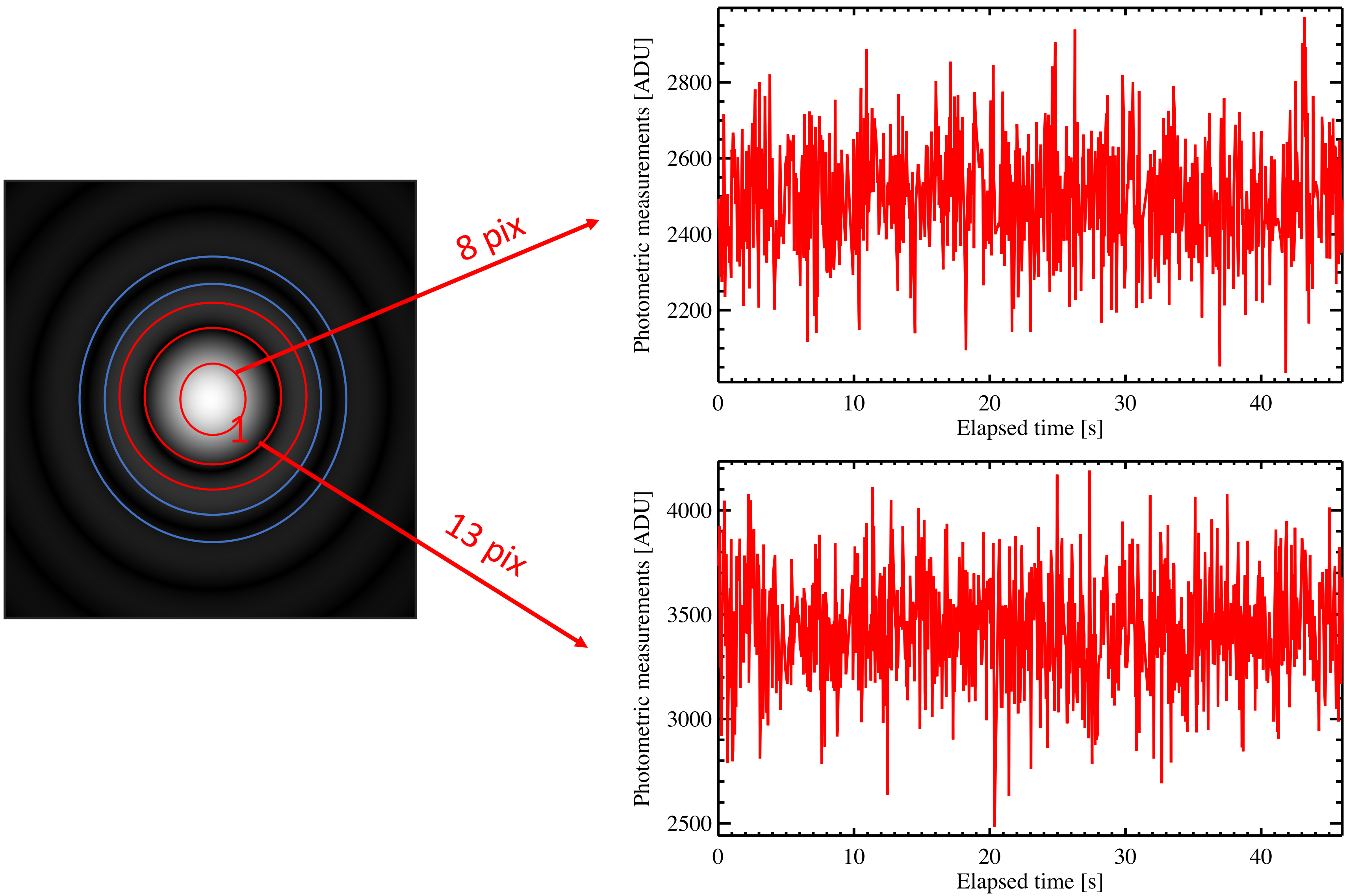


- Two-step approach:
  1. SPATIAL ESTIMATOR (simultaneous, different position): aperture photometry
  2. TIME ESTIMATOR (different time, same position): median of frames in neighboring nods

- Frame selection is critical:
  - Several possibilities: proximity in time, flux, elevation, …
  - Weighted-combination (e.g. Bottom et al. 2017)?

Flux computation

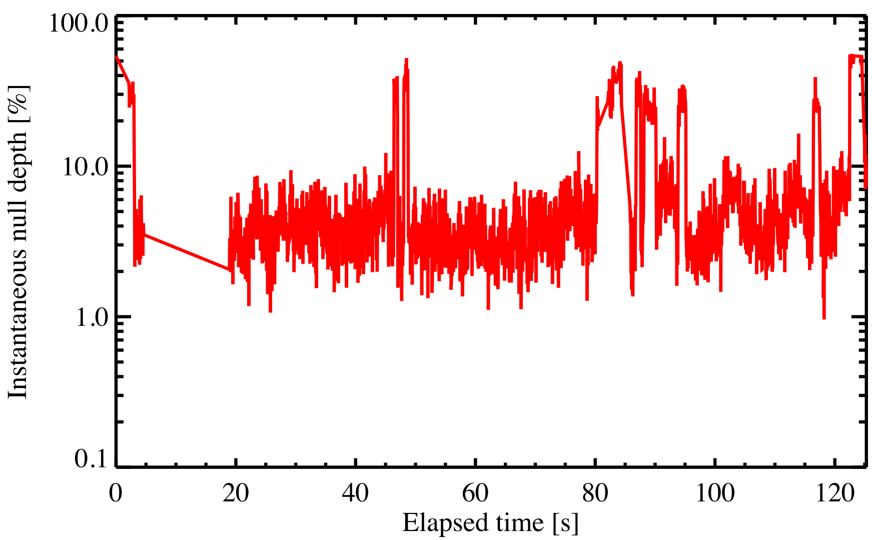
- Performed by aperture photometry over different aperture radii

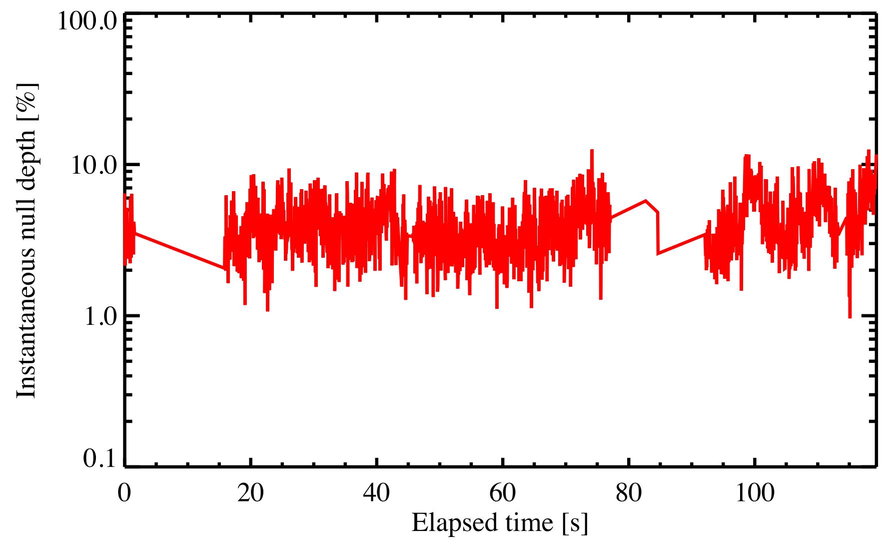


Null computation

Step 1: frame selection

- Reject open-loop frames (AO and phase)
- Reject fringe jumps
- Reject frames associated to low-quality 2-μm fringes
- Reject frames associated to high phase noise (measured by PHASECam)
- Keep only nulls in the [-0.02,0.95] range





Null computation

<u>Step 2</u>: convert flux measurements at null of each OB to a single null value

- Assume Gaussian phase ϕ (μ ; σ), adjust (μ,σ,V) to build fake data set and match observed distribution:

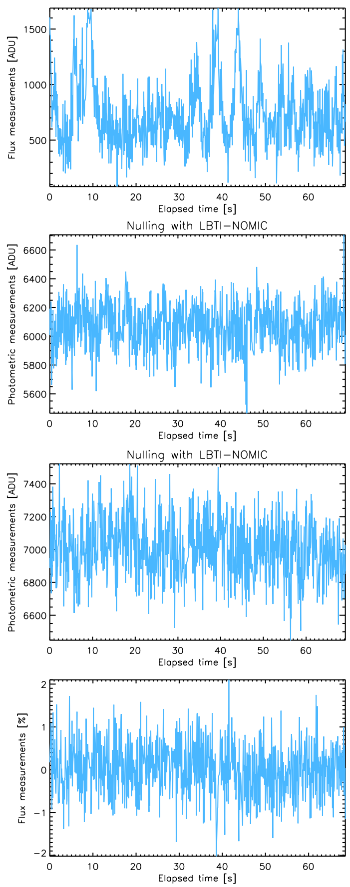
$$N_1 = I_1 + I_2 + 2|V|\sqrt{I_1 I_2} < \cos\phi(t) > + B$$

FLUX AT NULL

PHOT1

PHOT2

BCKG



PHASECam OPD telemetry

Nulling Self Calibration*
(NSC, Mennesson et al., ApJ 743, 2011)

*improved and adapted for LBTI:
- 2D images (vs 1 pixel);
- N band (vs K band);
- Account for high-frequency phase noise;
- Bayesian approach to compute error bars.

Null and error bar
(per OB)

Null Self Calibration

- The average measured null (or visibility) is NOT the best observable !! The analysis of the distribution provides a much better and more robust estimator
- Deconvolution of instrumental effects (piston and intensity mismatch) making use of *whole* dataset
- Can work with average nulls as bad as 10% and fluctuating by the same amount, and still measure underling astro nulls < 0.001 with a few 10^{-4} accuracy
- Works as well on resolved objects, measuring accurate visibilities (tested on archival KI FT data)
- Single-mode monochromatic assumption for the interferometric signal:

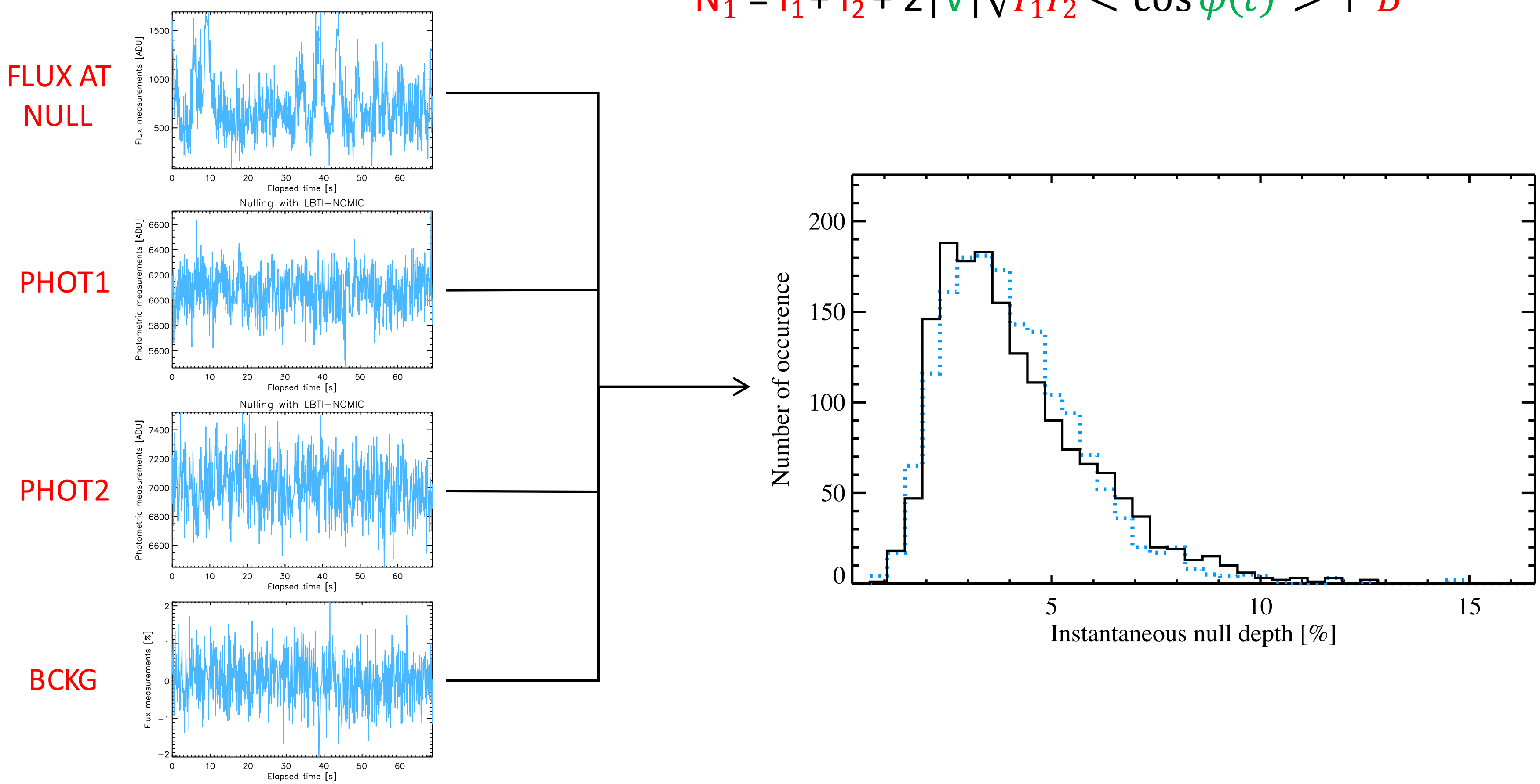
$$= I_1(t) + I_2(t) + 2|V|.\sqrt{I_1(t)I_2(t)}.cos(\phi(t) + \phi_V) + D(t)$$

Null computation

Step 2: convert flux measurements at null of each OB to a single null value

- Assume Gaussian phase ϕ (μ ; σ), adjust (μ,σ,V) to build fake data set and match observed distribution:

$$N_1 = I_1 + I_2 + 2|V|\sqrt{I_1 I_2} < \cos\phi(t) > + B$$

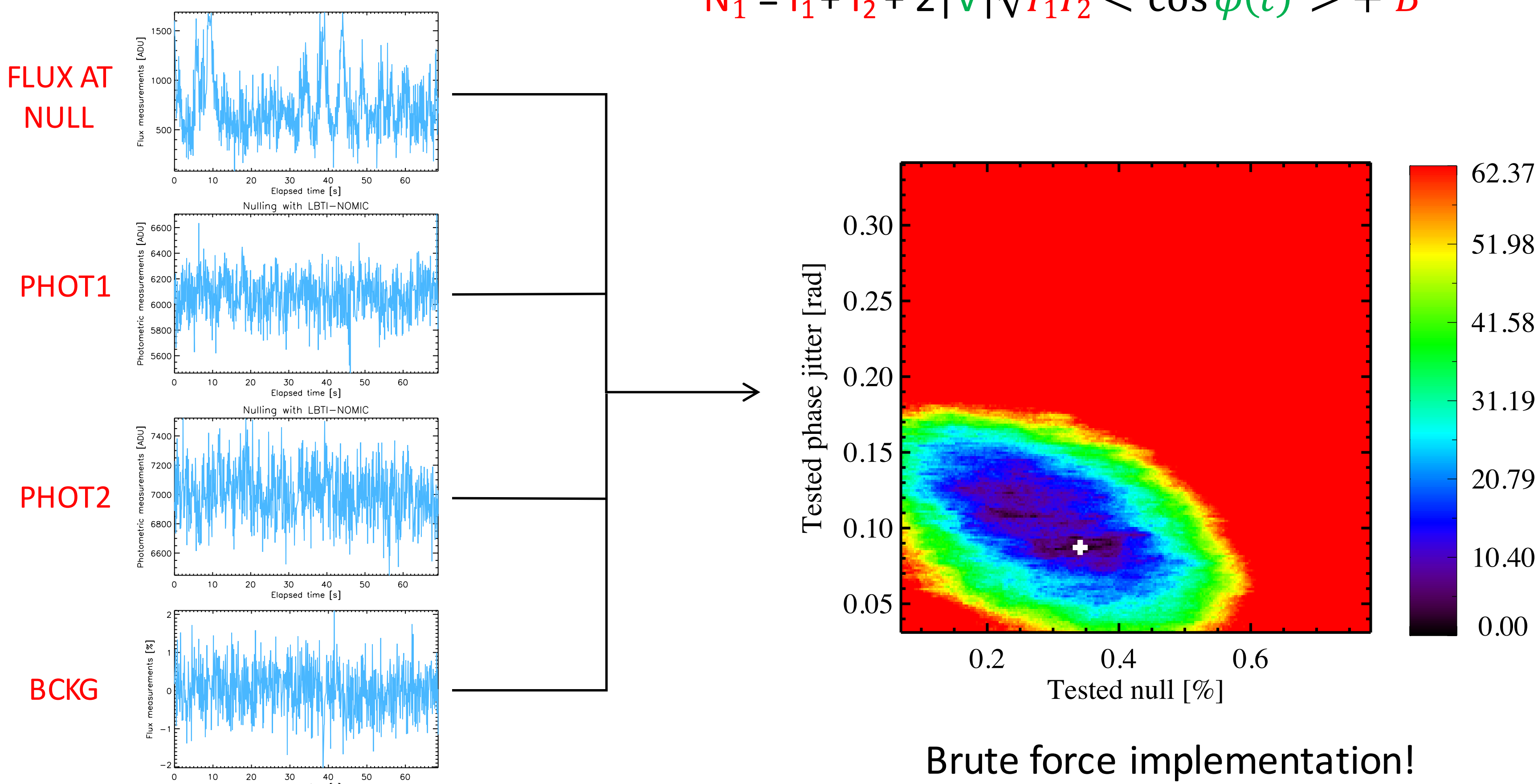


Null computation

<u>Step 2</u>: convert flux measurements at null of each OB to a single null value

- Assume Gaussian phase ϕ (μ ; σ), adjust (μ,σ,V) to build fake data set and match observed distribution:

$$N_1 = I_1 + I_2 + 2|V|\sqrt{I_1 I_2} < \cos\phi(t) > + B$$



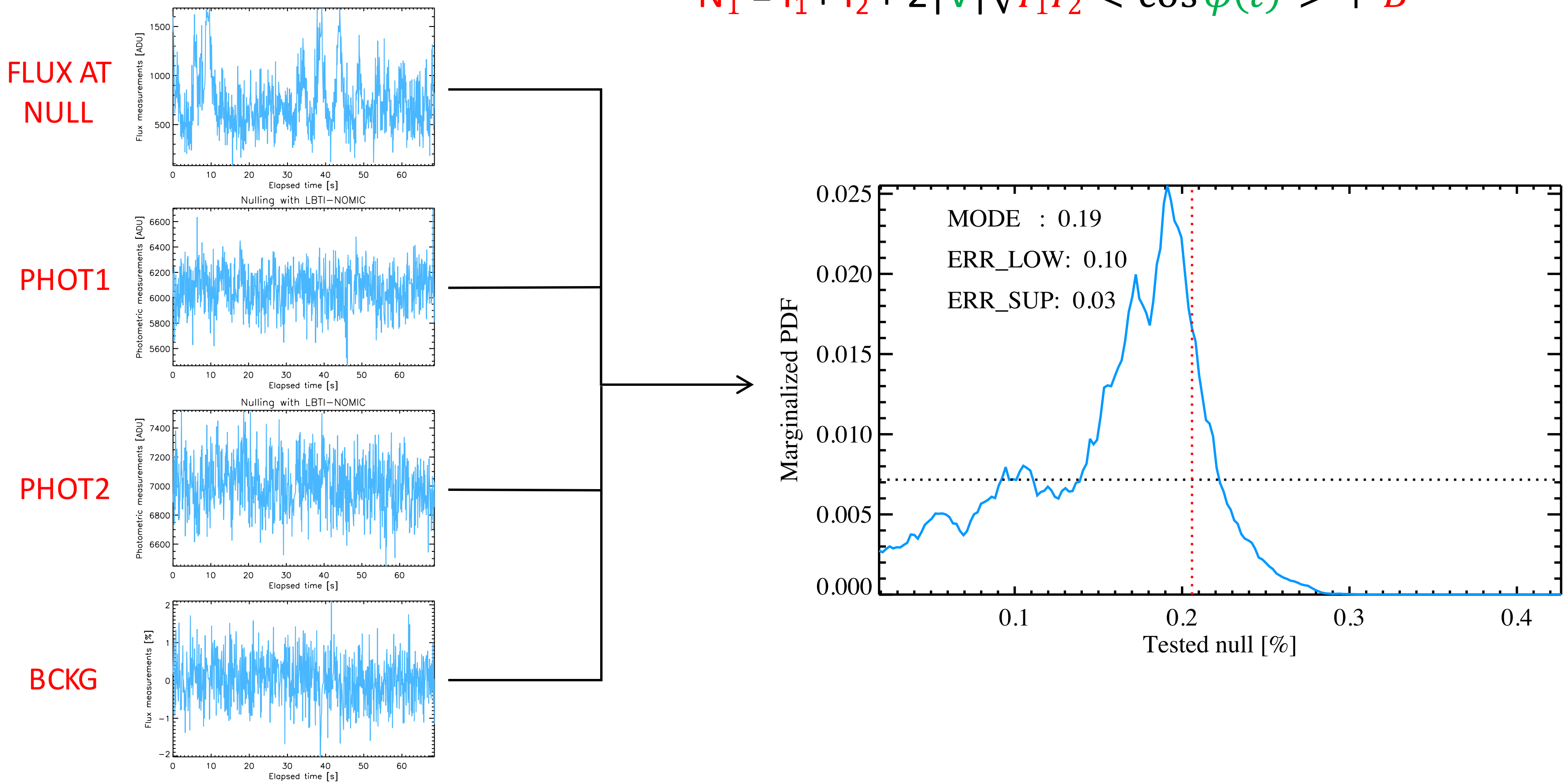
Brute force implementation!

Null computation

<u>Step 2</u>: convert flux measurements at null of each OB to a single null value

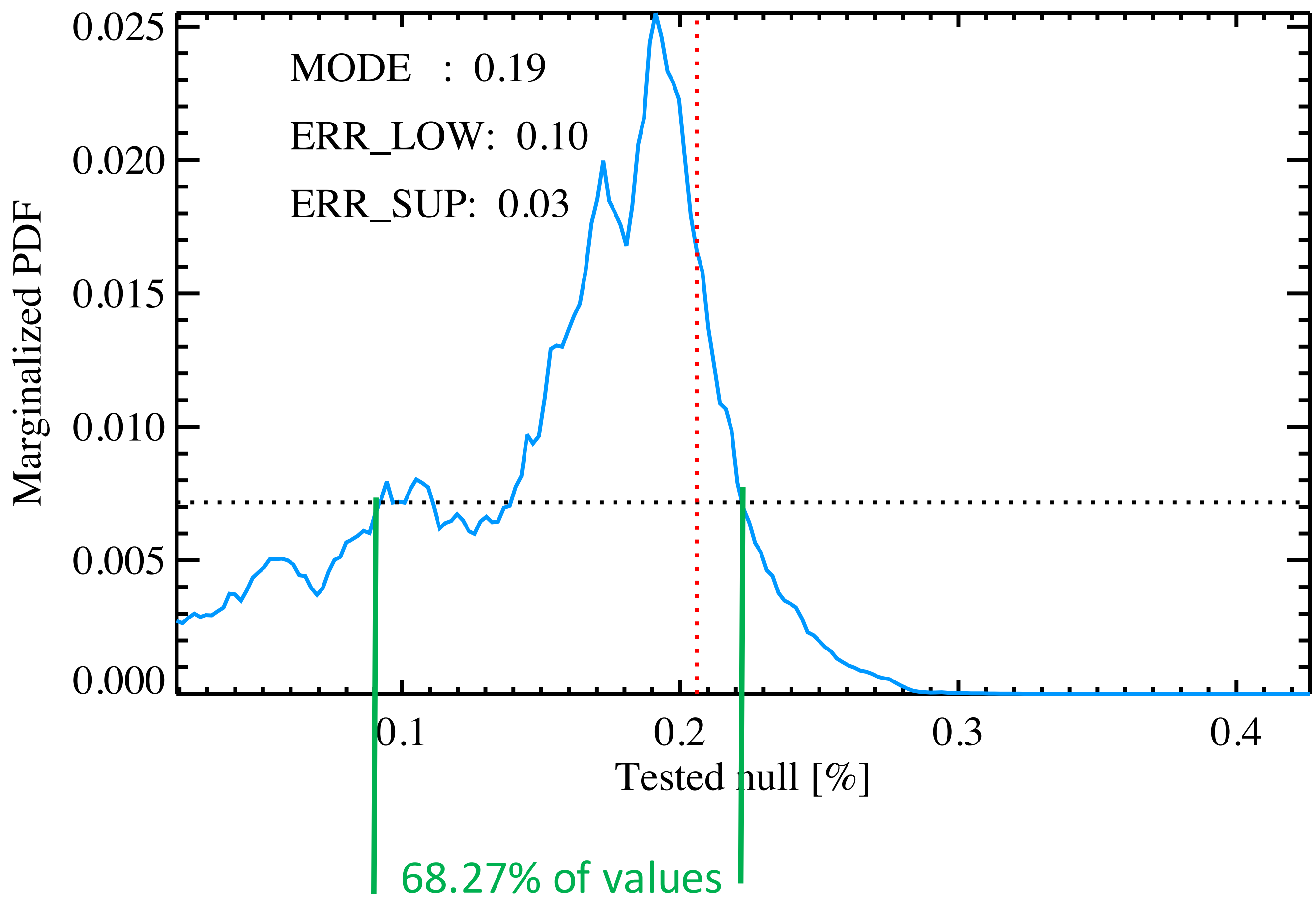
- Assume Gaussian phase ϕ (μ ; σ), adjust (μ,σ,V) to build fake data set and match observed distribution:

$$N_1 = I_1 + I_2 + 2|V|\sqrt{I_1 I_2} < \cos\phi(t) > + B$$

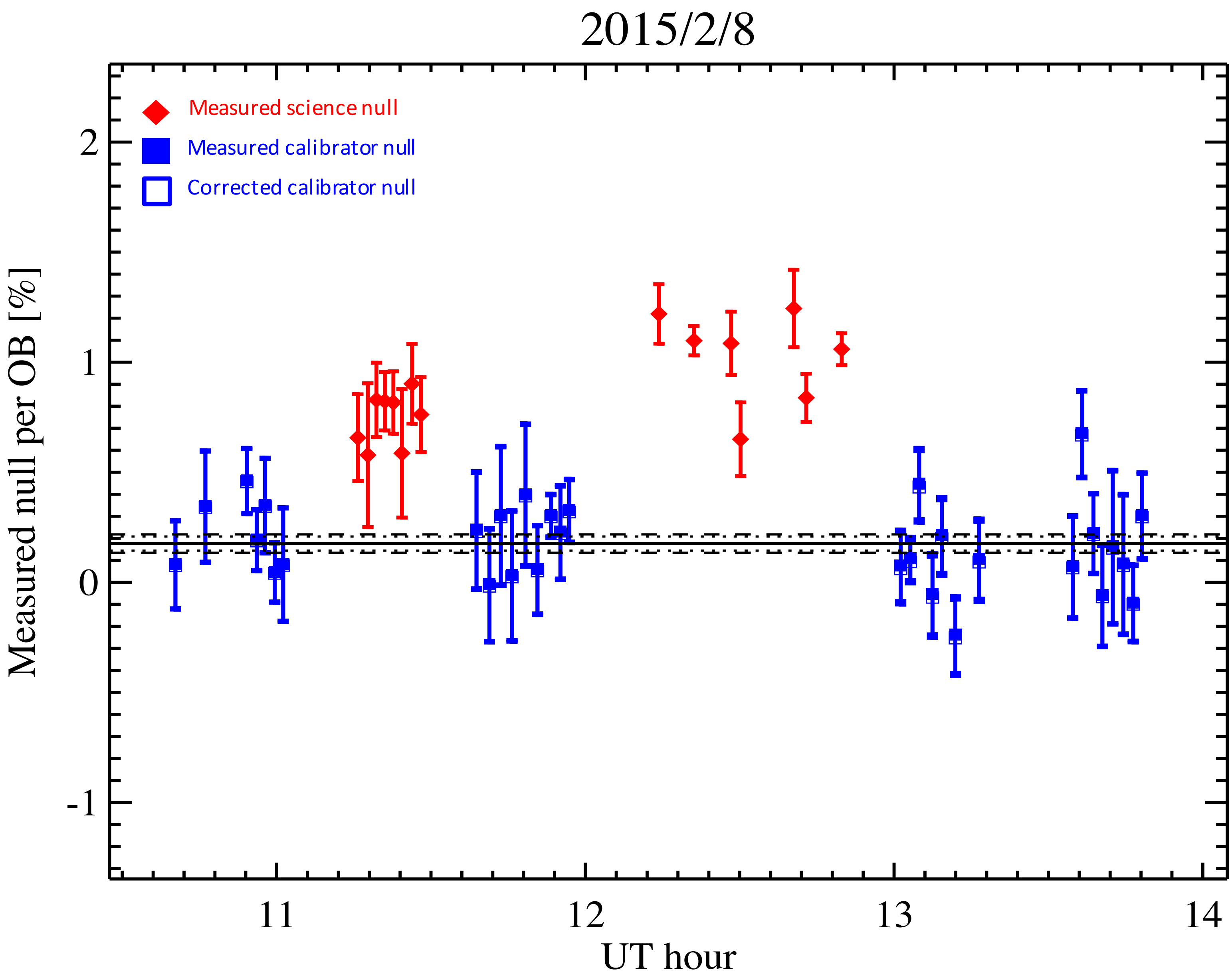


Null computation

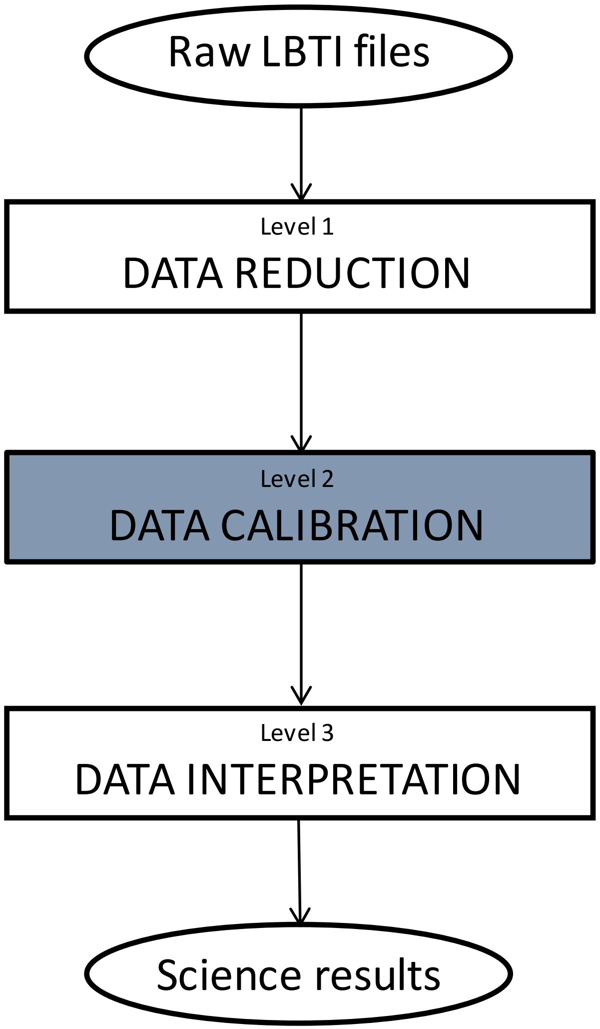
- Error bar computed using high-density regions described by Hyndman, R. J. 1996, The American Statistician, 50, 120:

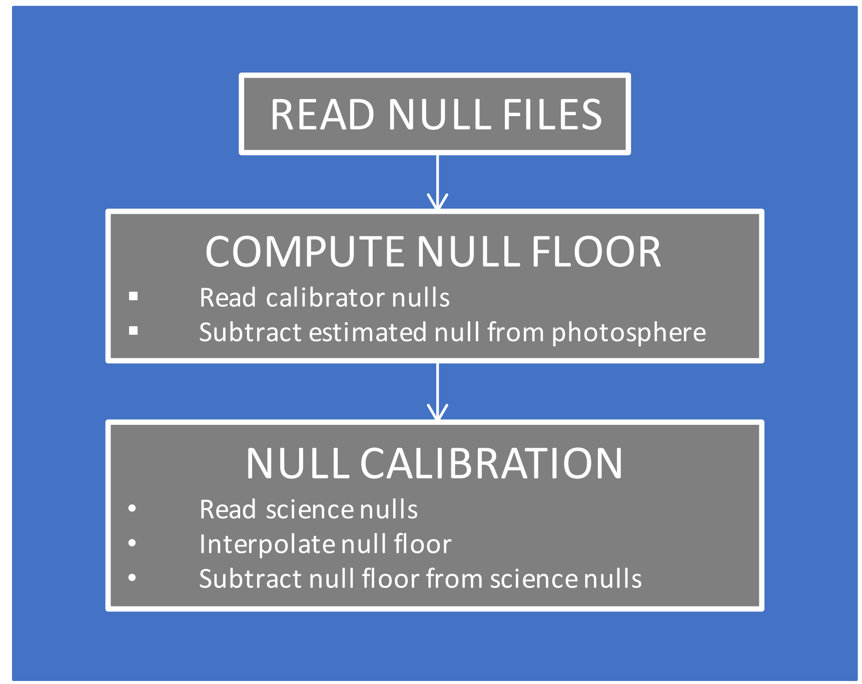


Null computation

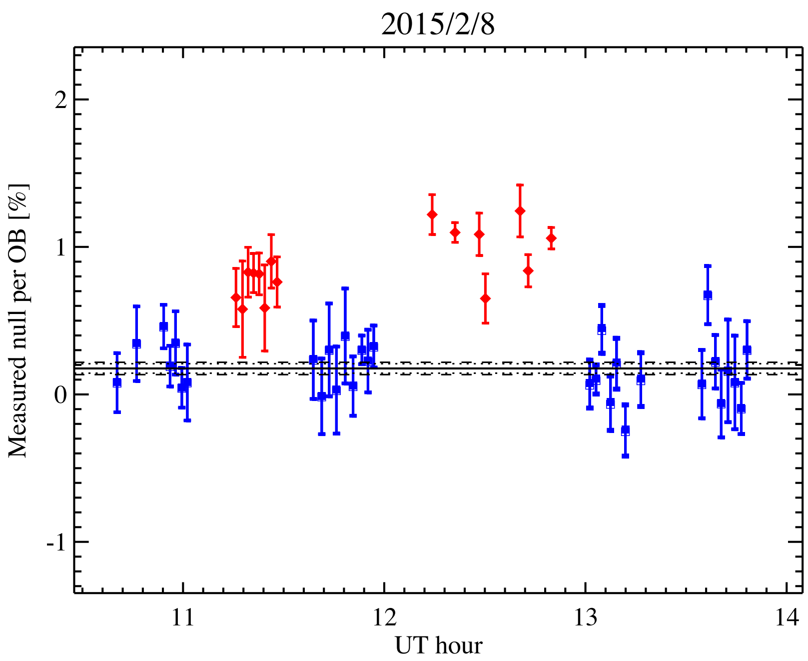


Null calibration





Null calibration



READ NULL FILES

↓

COMPUTE NULL FLOOR

- Read calibrator nulls
- Subtract estimated null from photosphere

↓

NULL CALIBRATION

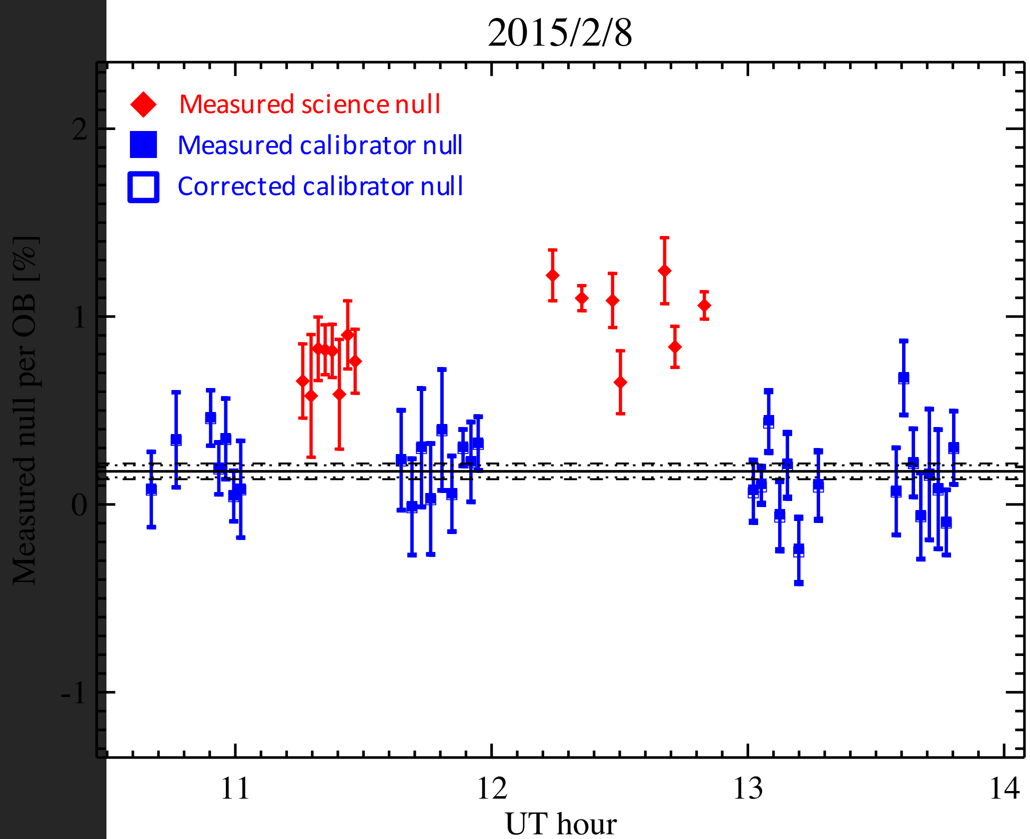
- Read science nulls
- Interpolate null floor
- Subtract null floor from science nulls

Analysis and pipeline limitations

- Need to test more advanced nod-subtraction techniques (e.g. parameter weighted approach, gain of ~20%, see Bottom et al. 2017)
- Replace brute-force computer-intensive NSC approach by MCMC
- Asymmetric error bars not propagated (only the maximum of the 2)
- Implement and test null calibration using images rather than fluxes

Data calibration

NOTATIONS AND ERROR BARS



Weighted mean transfer function (TF, cal. only):

$$TF = \frac{\sum_i n_i/\sigma_i^2}{\sum_i 1/\sigma_i^2}$$

1-σ propagated statistical error on mean TF (cal. only):

$$\sigma_{stat} = \frac{1}{\sqrt{\sum_i 1/\sigma_i^2}}$$

1-σ unbiased weighted error on the weighted mean:

$$\sigma_{sys} = \sqrt{\frac{\sum_i 1/\sigma_i^2}{\left(\sum_i 1/\sigma_i\right)^2}\,\frac{\sum_i (n_i - TF)^2/\sigma_i^2}{\frac{(N-1)}{N}\sum_i 1/\sigma_i^2}}$$

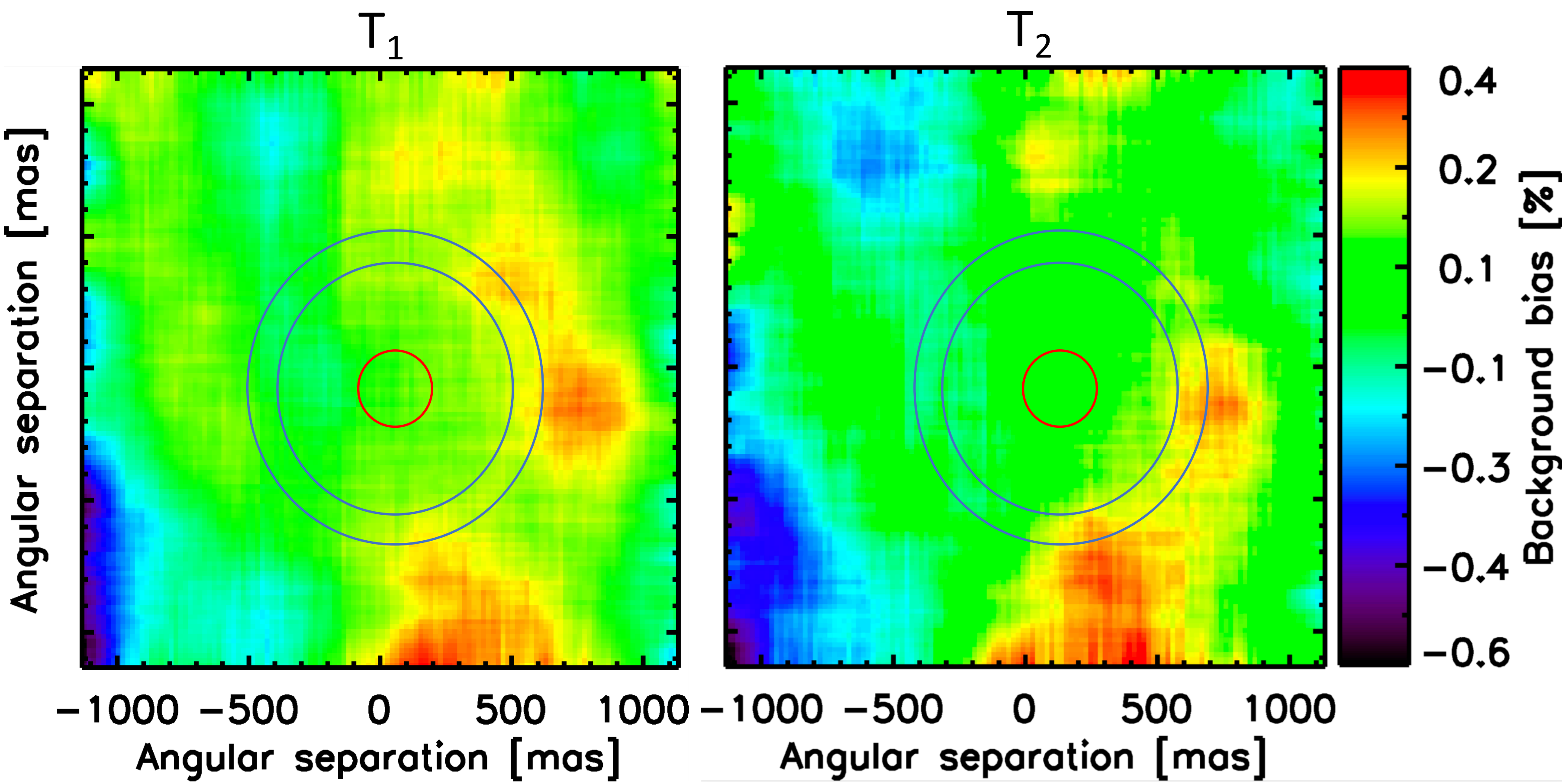
+ error due to diameter uncertainty (generally negligible)

LBTI's nulling performance limitations and prospects

D. Defrère
University of Liège

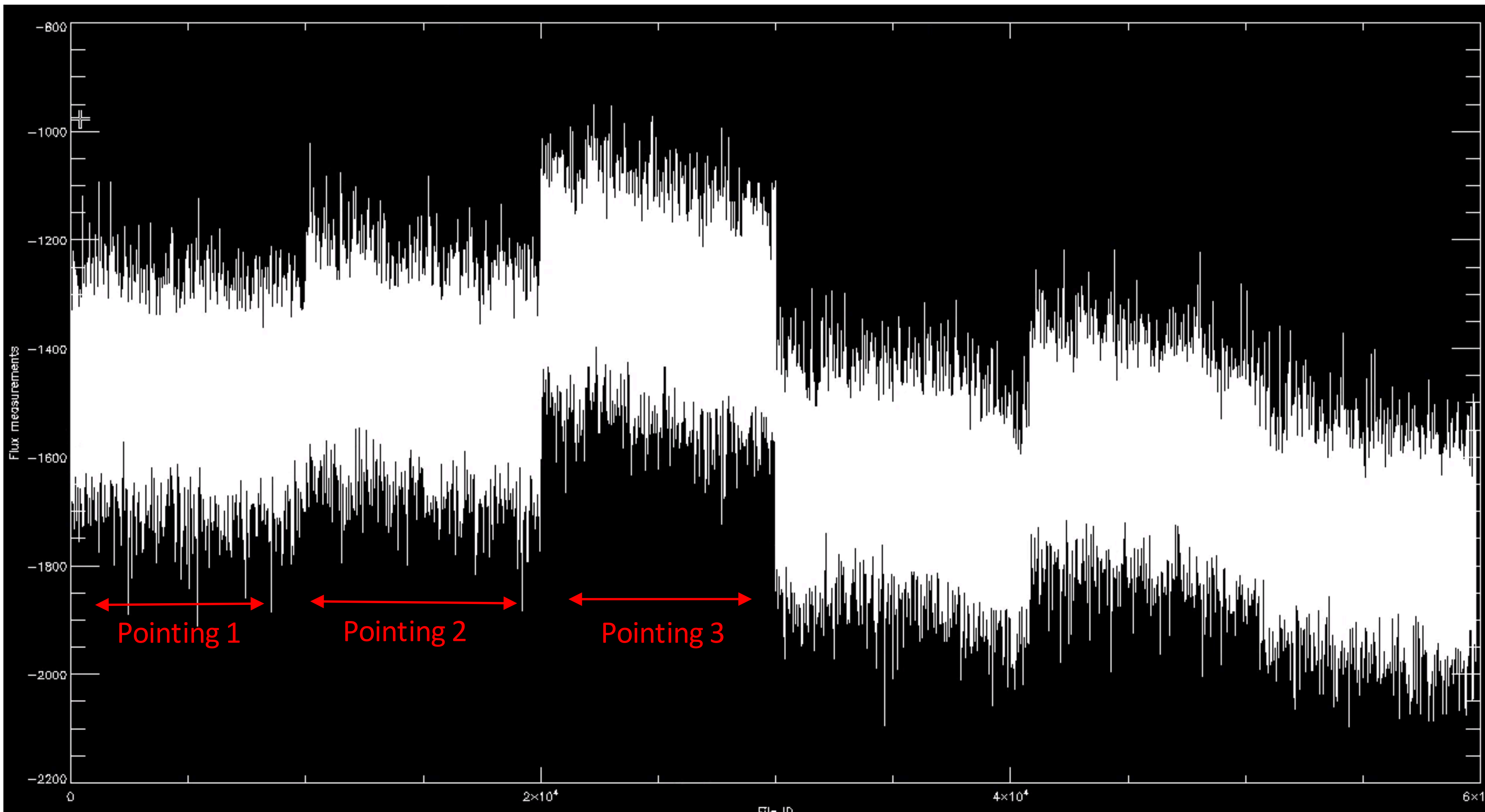
Background bias

- Empty region of the detector at two different times:



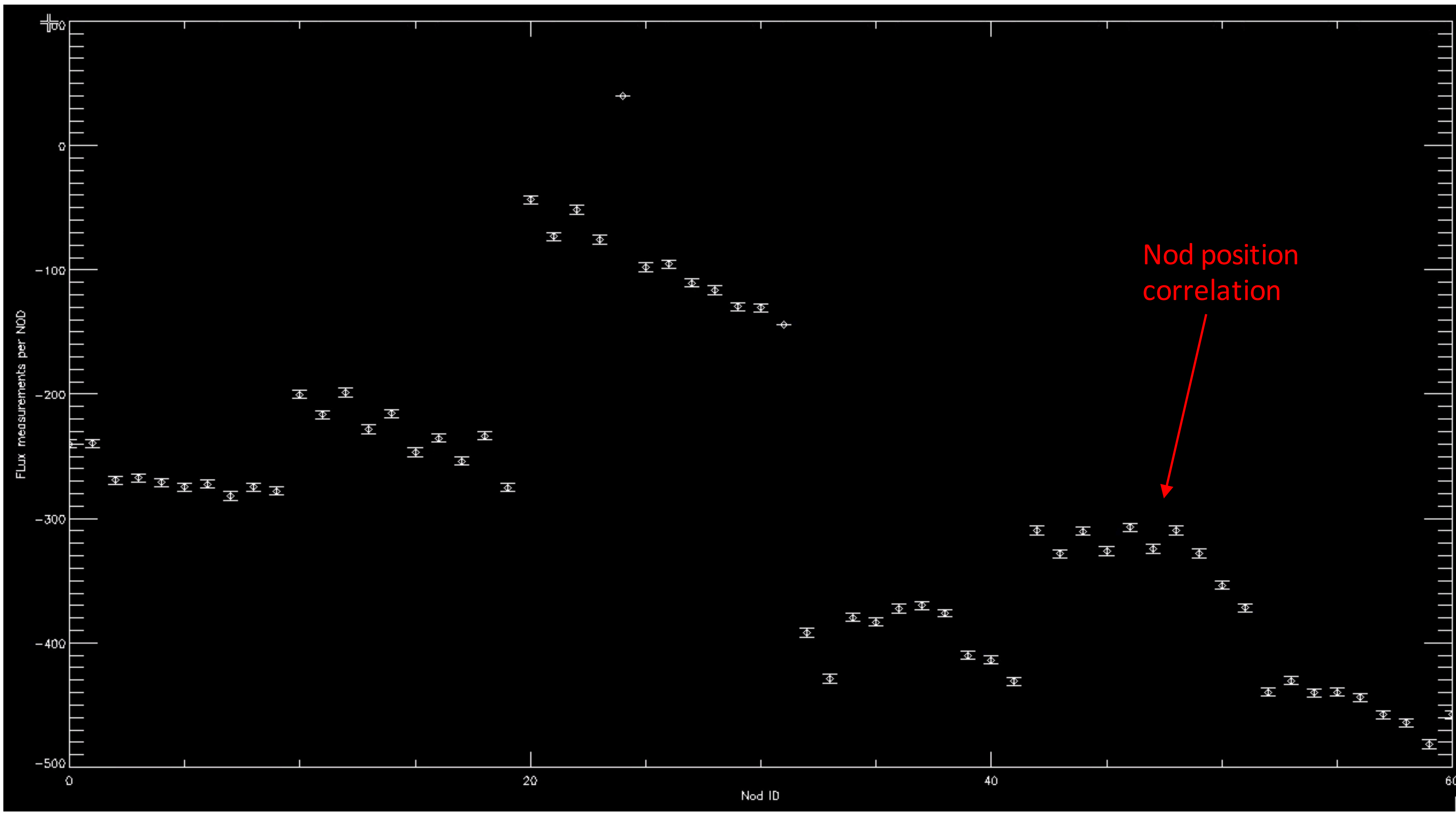
Example of nulling sequence

- The plot below shows the background bias looking at **an empty region of the sky** (60000 frames).
- Each pointing can be clearly identifies by a jump in background bias.



Example of nulling sequence

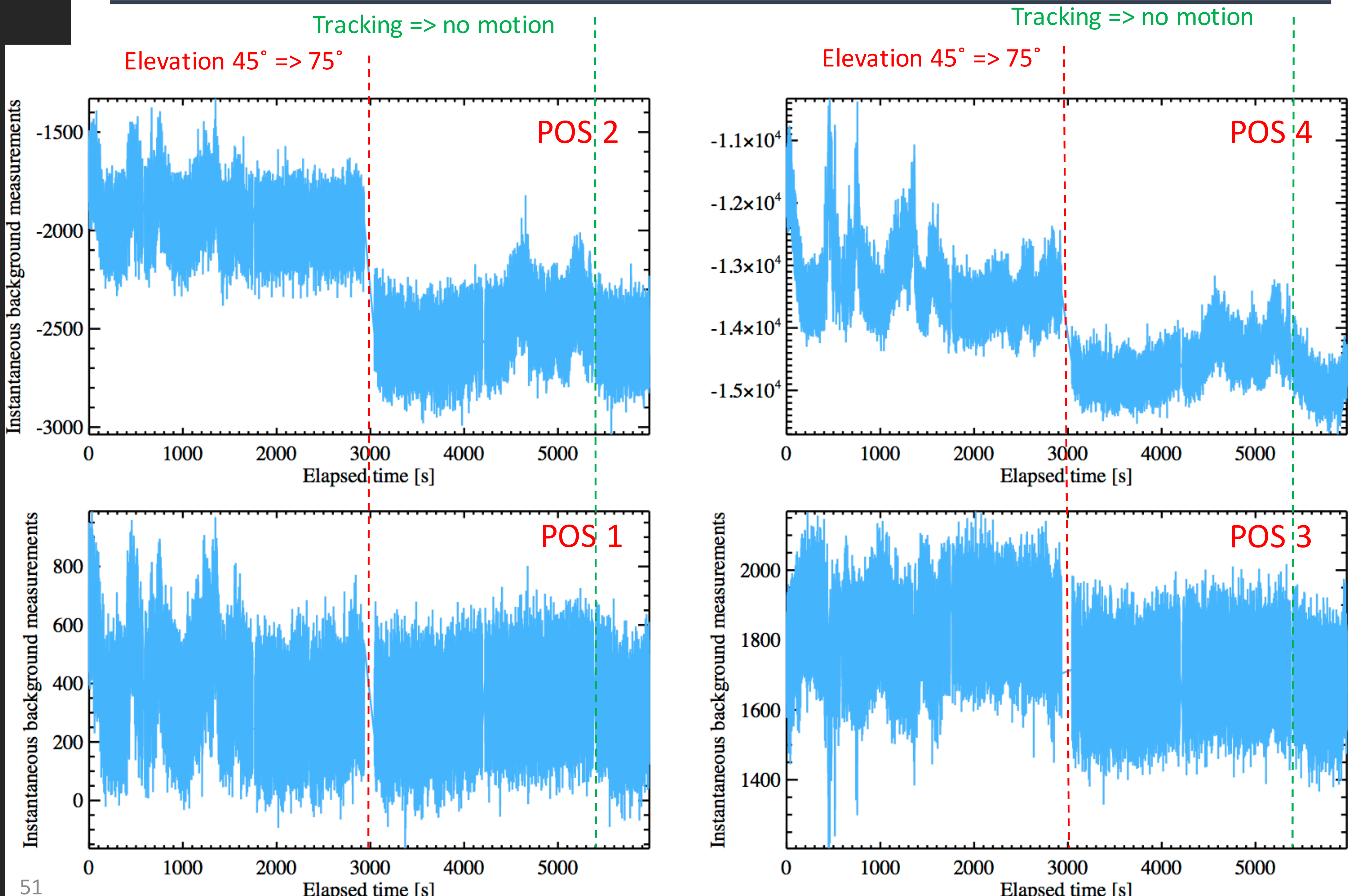
- Within each pointing, the flux measurements are not stable and are often correlated by NOD position (but not always!).
- The difference in flux per NOD for successive NODS within a given pointing can be as large as 20 ADU **or 0.2% of beta Leo** flux over the same aperture! (~10000 ADU)



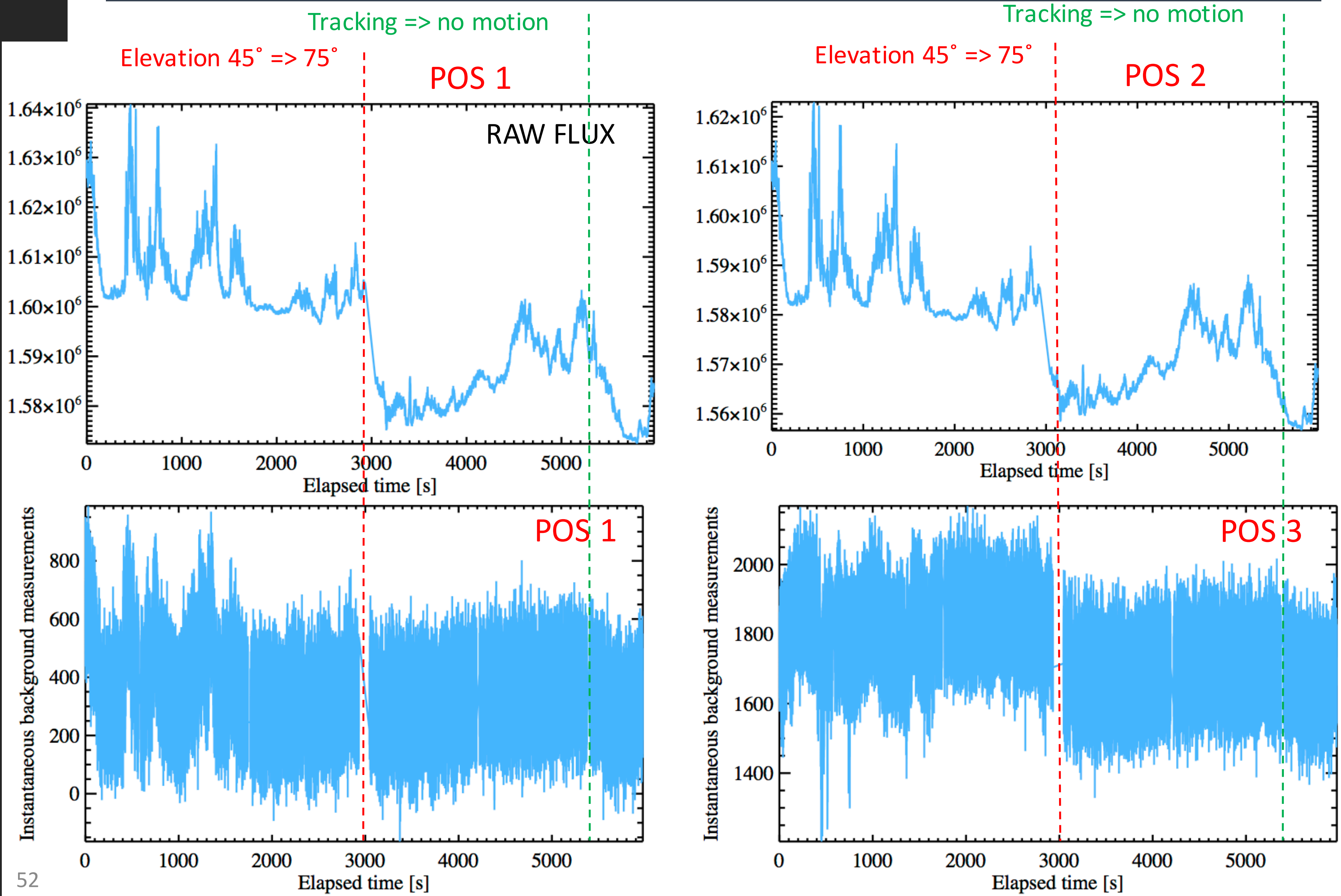
Origin of the background bias?

- Based on data from March 9th 2016 and March 26th data;
- Approach follows default procedure of nulling pipeline, i.e. a photometric aperture of 8 pixels in radius and a background annulus which has an inner radius of 31 pixels and the same number of pixels as the photometric aperture;
- Following slides show the results for 4 different positions on the array (corresponding to the middle of each channel of the default 256x256 sub-array). **POS1 and POS2 are default for nulling;**
- The background bias is defined as the offset between the flux measured in the photometric aperture and that estimated from the background annulus;

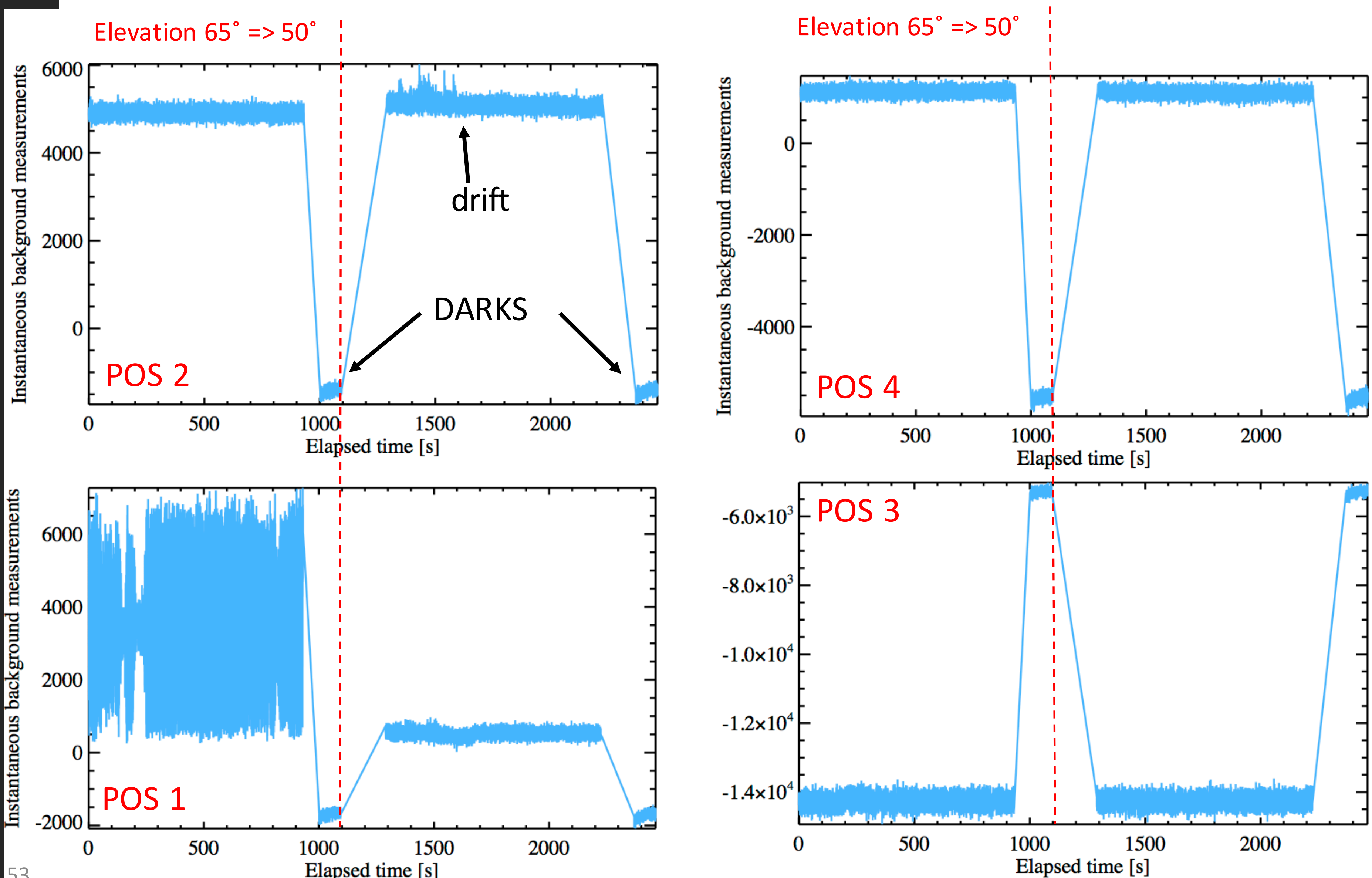
Origin of the background bias?



Origin of the background bias?

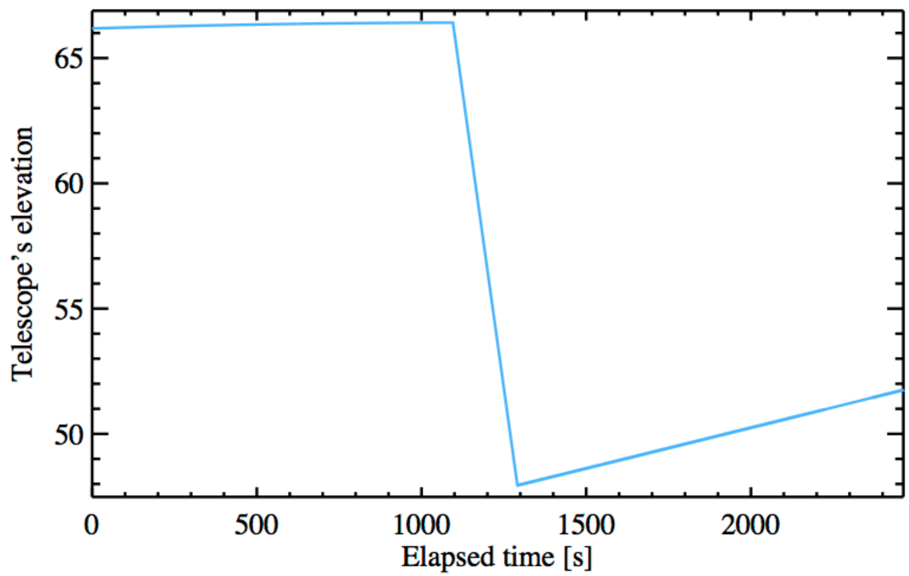


Origin of the background bias?

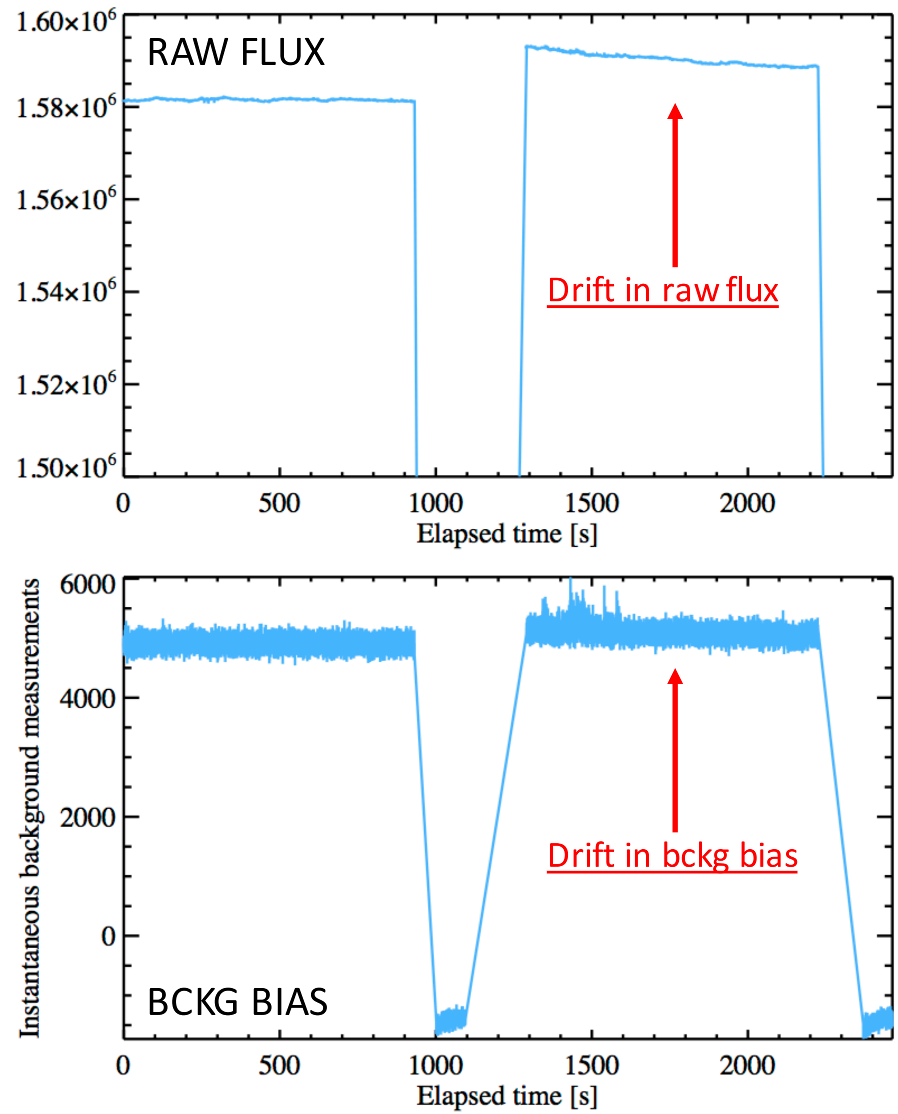


Origin of the background bias?

Drift in raw flux related to elevation changes

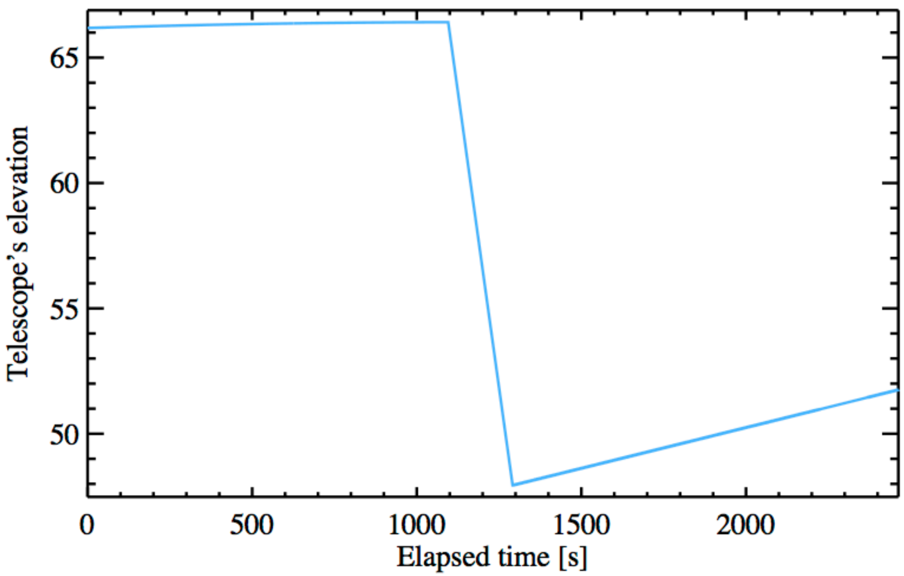


POS 2

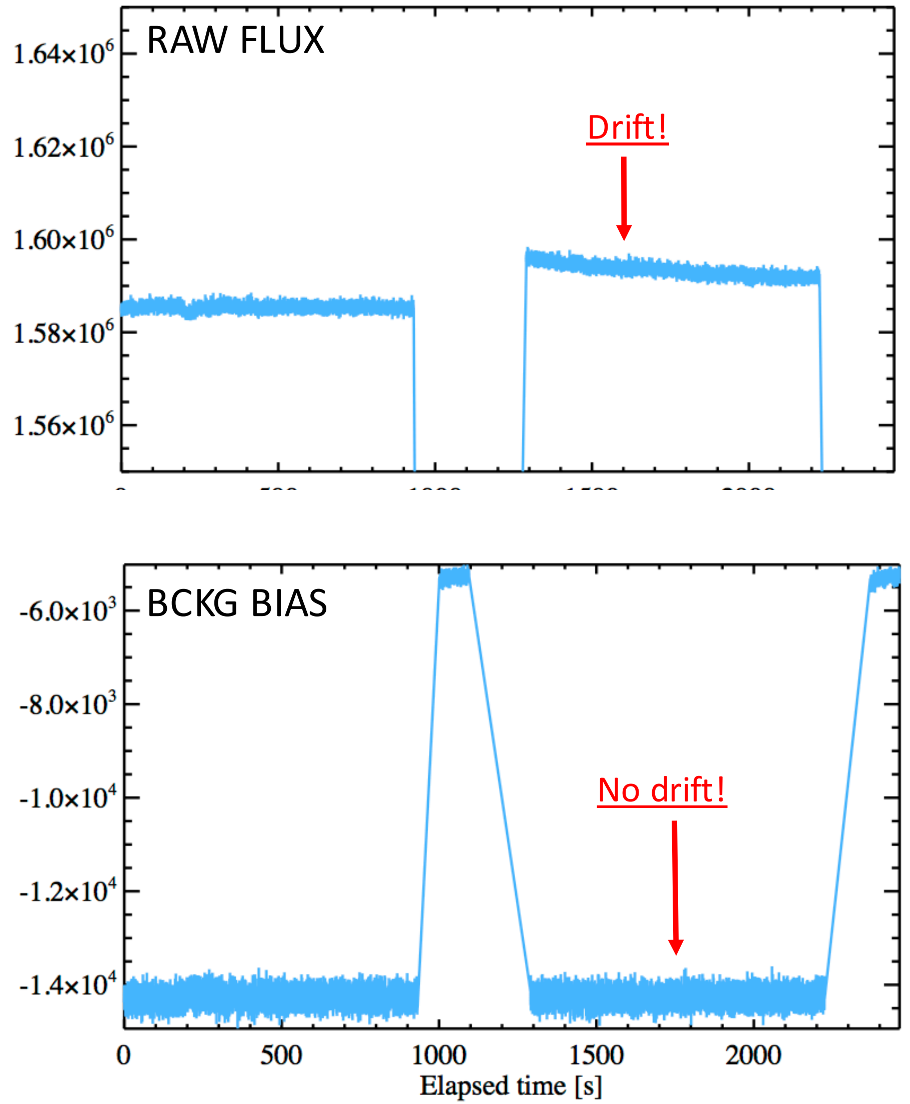


Origin of the background bias?

But this doesn't always produce a drift of the background bias, e.g. POS 3



POS 3



Conclusion on background bias

- The background bias depends on raw flux, but not always! (e.g., POS1 at ~3000s for March 9th data)

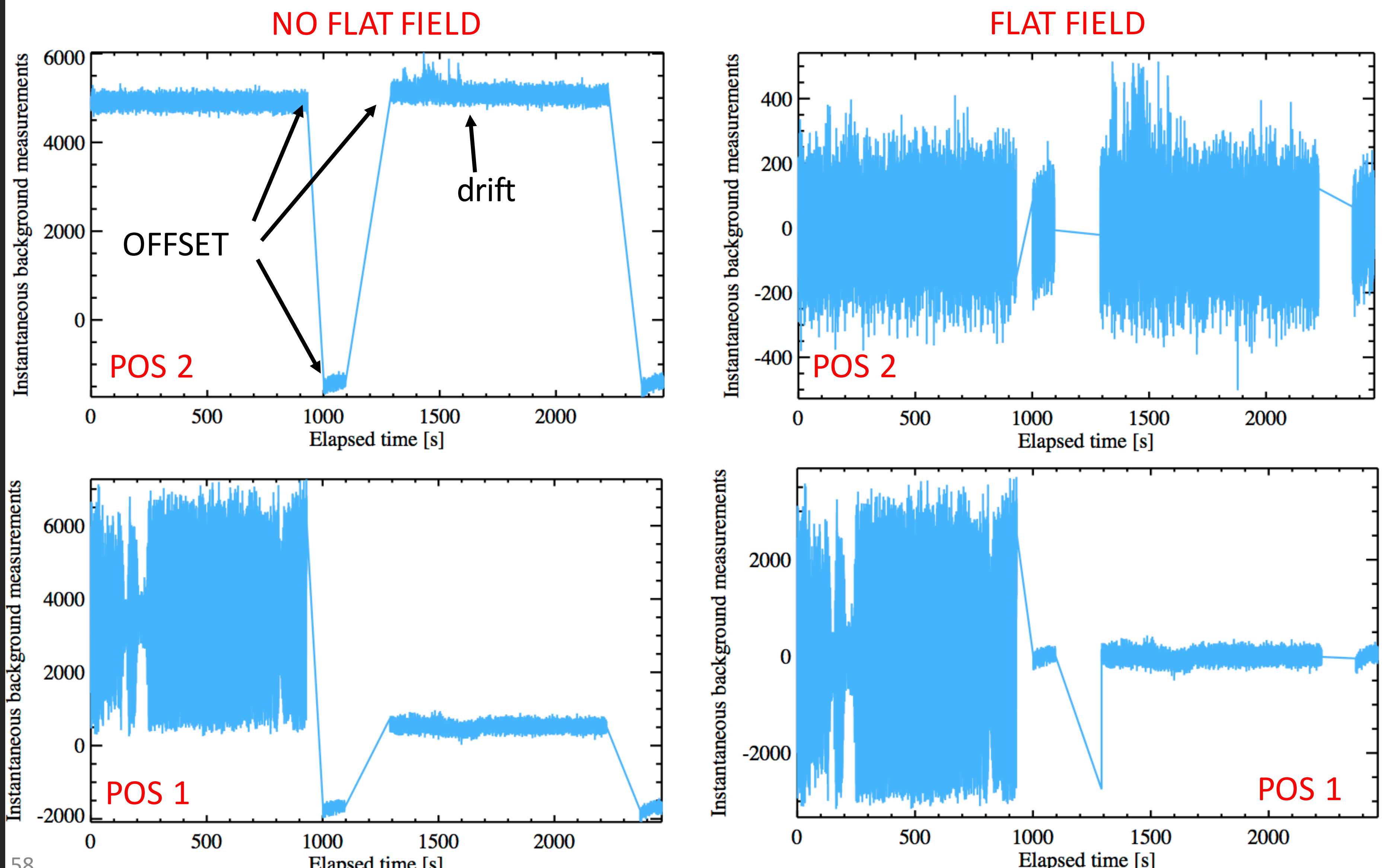
- The raw flux depends on elevation and, therefore, the background bias depends on the elevation, but not always!! (e.g., POS3 for March 26th data)

- Some channels show excessive noise at a given elevation (e.g., POS1 on March 26th). This problem goes away at a different elevation with similar raw flux levels. This points to temperature problems but needs to be checked.

- **These points suggest that NOMIC has a significant pixel-to-pixel differential flux response but also an elevation/temperature-dependent flux response per pixel!**

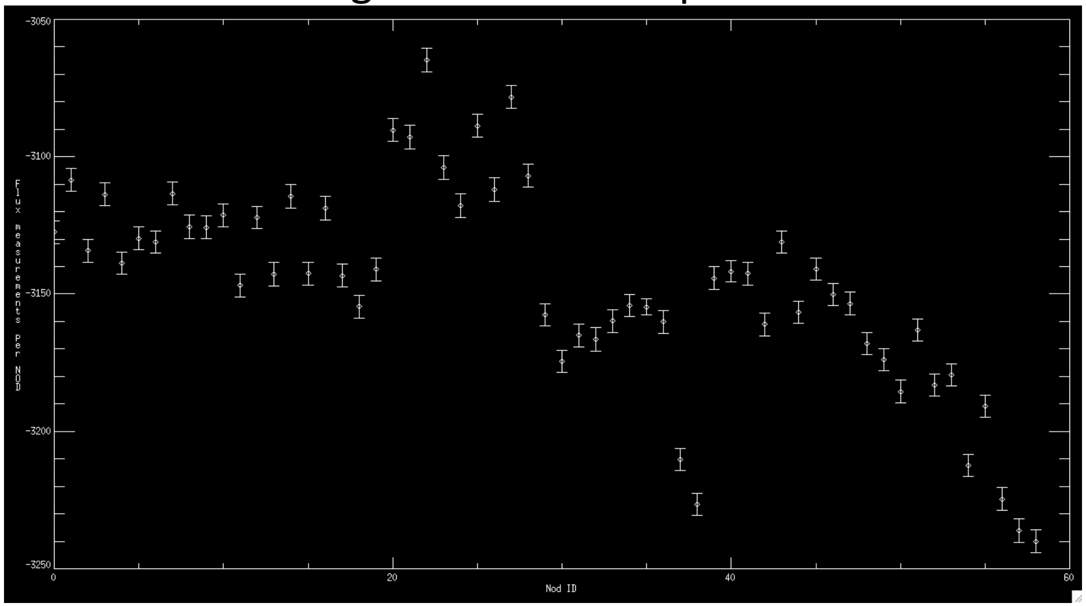
Removing the background bias

Approach 1: flat fielding



Approach 1: flat fielding

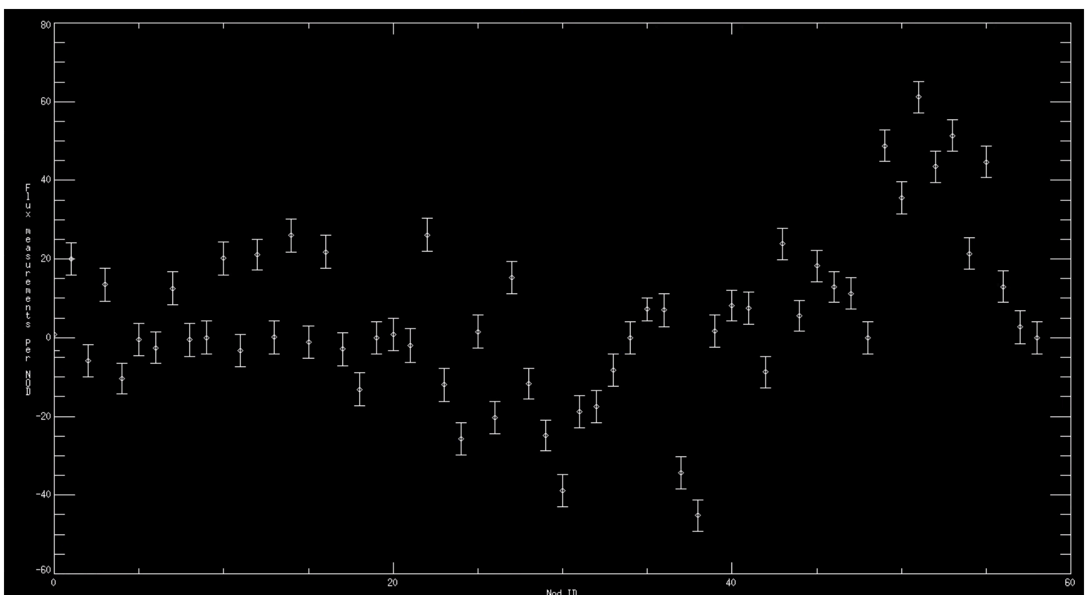
Background estimate per nod



No flat fielding

RMS of background estimates: 38 ADU

Expected RMS: 4 ADU



Flat fielding

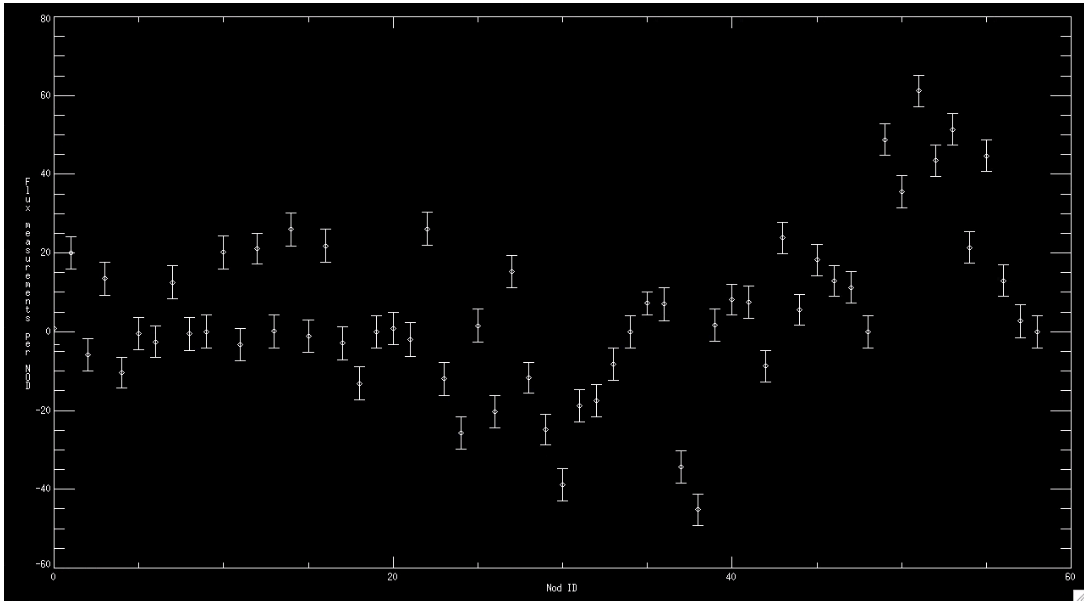
No offset

RMS of background estimates: 21 ADU

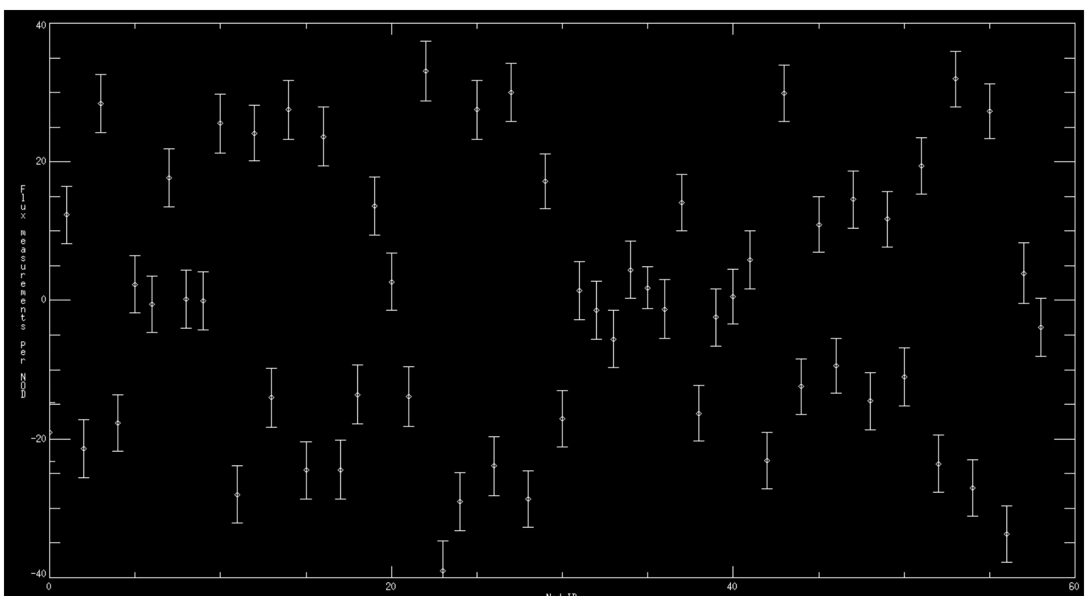
Expected RMS: 4 ADU

Approach 2: nod subtraction

Background estimate per nod



Flat fielding
No offset
RMS of background estimates: 21 ADU
Expected RMS: 4 ADU

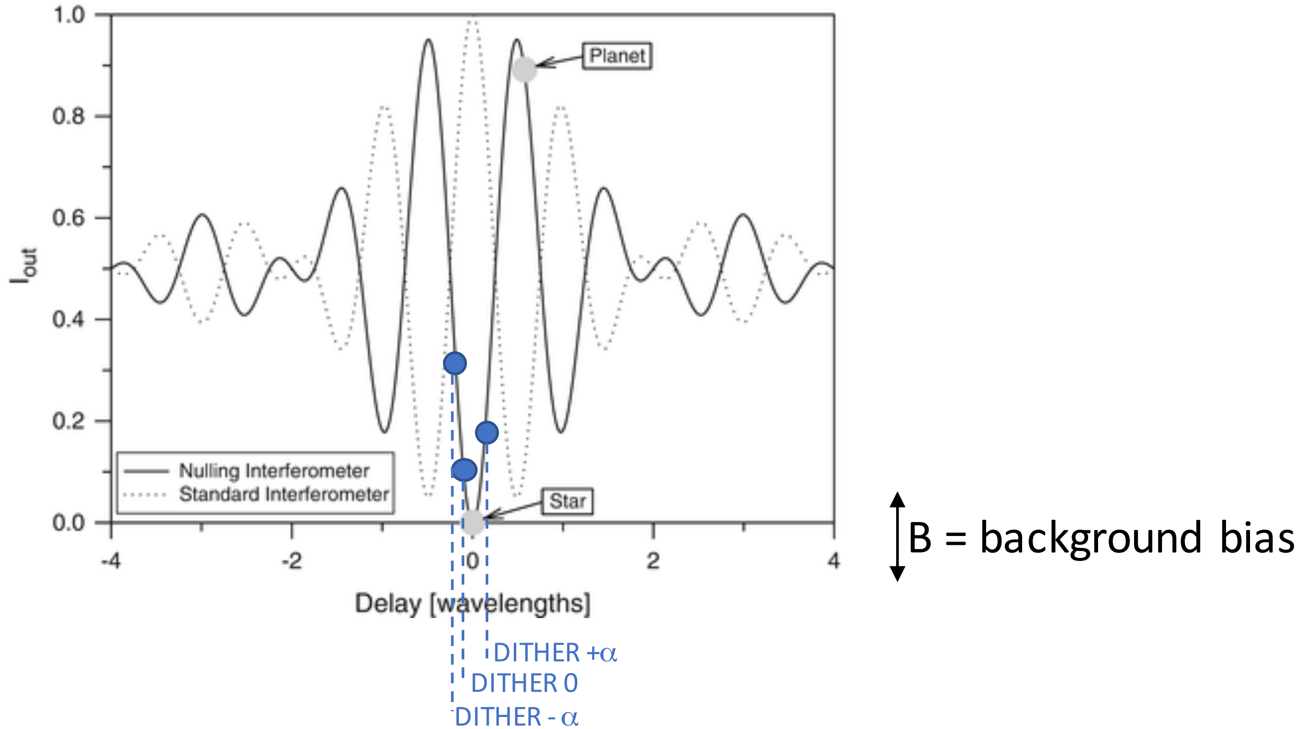


Nod subtraction
No offset
RMS of background estimates: 19 ADU
Expected RMS: 4 ADU

Conclusions

- Flat fielding helps but nod subtraction gives slightly better results
- With current approach, error on background estimate **~5x larger** than based on pure photon noise
- New idea: fast dithering

Fast dithering principle

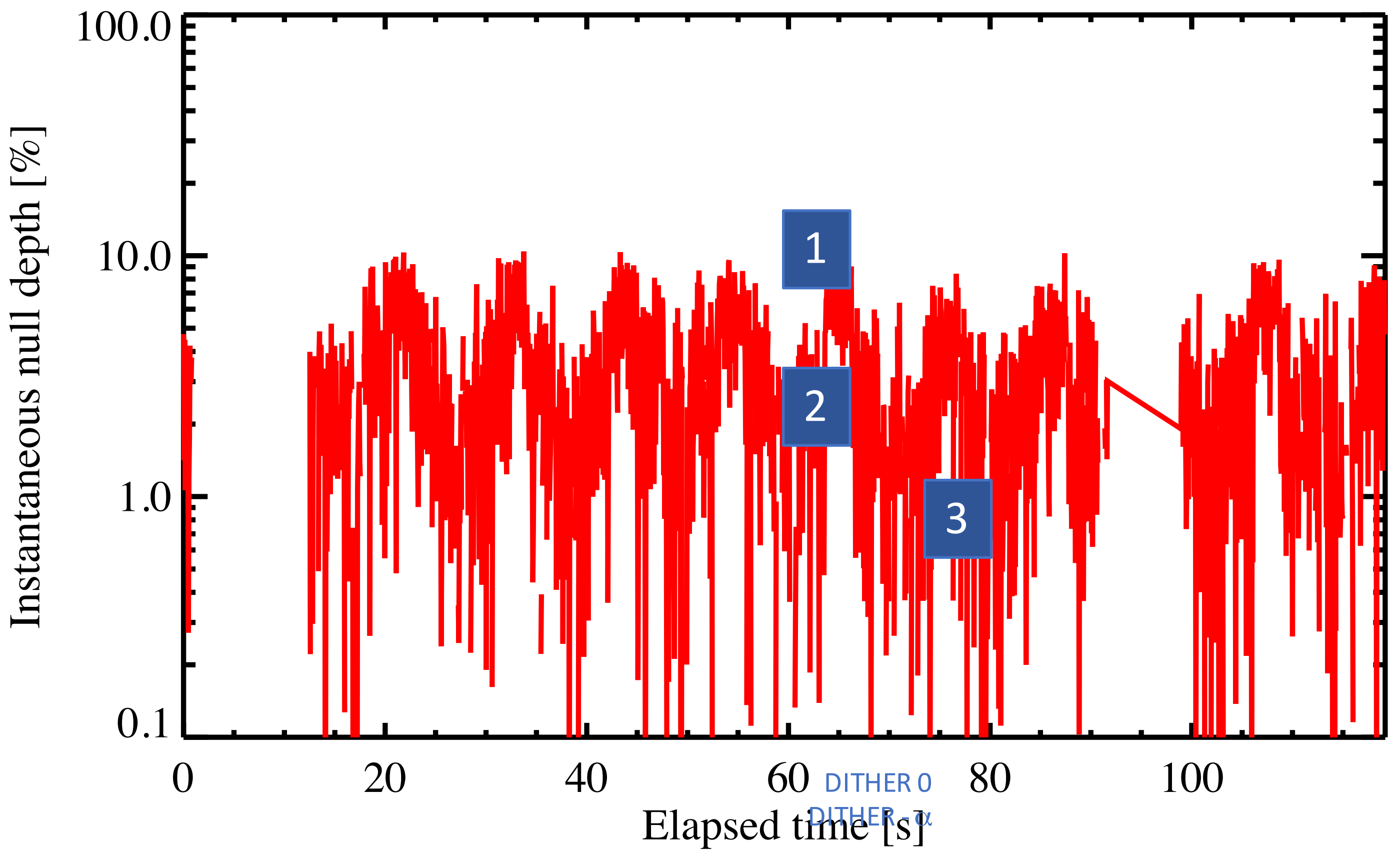


$$N_1 = \langle I_1(t)\rangle = I_1 + I_2 + 2|V|\sqrt{I_1 I_2} < \cos\phi_1(t) > +B_1$$

$$N_2 = \langle I_2(t)\rangle = I_1 + I_2 + 2|V|\sqrt{I_1 I_2} < \cos(\phi_2(t) + \alpha) > +B_2$$

$$N_3 = \langle I_3(t)\rangle = I_1 + I_2 + 2|V|\sqrt{I_1 I_2} < \cos(\phi_3(t) - \alpha) > +B_3$$

Fast dithering principle



$$N_1 = \langle I_1(t)\rangle = I_1 + I_2 + 2|V|\sqrt{I_1 I_2} < \cos\phi_1(t) > + B_1$$
$$N_2 = \langle I_2(t)\rangle = I_1 + I_2 + 2|V|\sqrt{I_1 I_2} < \cos(\phi_2(t) + \alpha) > + B_2$$
$$N_3 = \langle I_3(t)\rangle = I_1 + I_2 + 2|V|\sqrt{I_1 I_2} < \cos(\phi_3(t) - \alpha) > + B_3$$

Fast dithering principle

$$N_1 = \langle I_1(t)\rangle = I_1+I_2+2|V|\sqrt{I_1 I_2} < \cos\phi_1(t) > +B_1$$
$$N_2 = \langle I_2(t)\rangle = I_1+I_2+2|V|\sqrt{I_1 I_2} < \cos(\phi_2(t)+\alpha) > +B_2$$
$$N_3 = \langle I_3(t)\rangle = I_1+I_2+2|V|\sqrt{I_1 I_2} < \cos(\phi_3(t)-\alpha) > +B_3$$

$$\phi_1 = s_1 + \varepsilon_1$$

- Fit the null equation to null measurements at 3 dither positions:

⇒1 null estimate per dither cycle

⇒Average nulls per dither cycle to get 1 null per OB

- Assumptions:

1. Background bias constant between 3 dither positions (B_1=B_2=B_3);
2. Phase setpoint constant between 3 dither positions (s_1=s_2=s_3);
3. Stable high-frequency phase jitter between the 3 dither positions (ε_1=ε_2=ε_3);

- Analytical solution:

$$B = \frac{N_1+N_2-2\cos\alpha\ N_1}{2(1-\cos\alpha)} - (I_1+I_2)$$

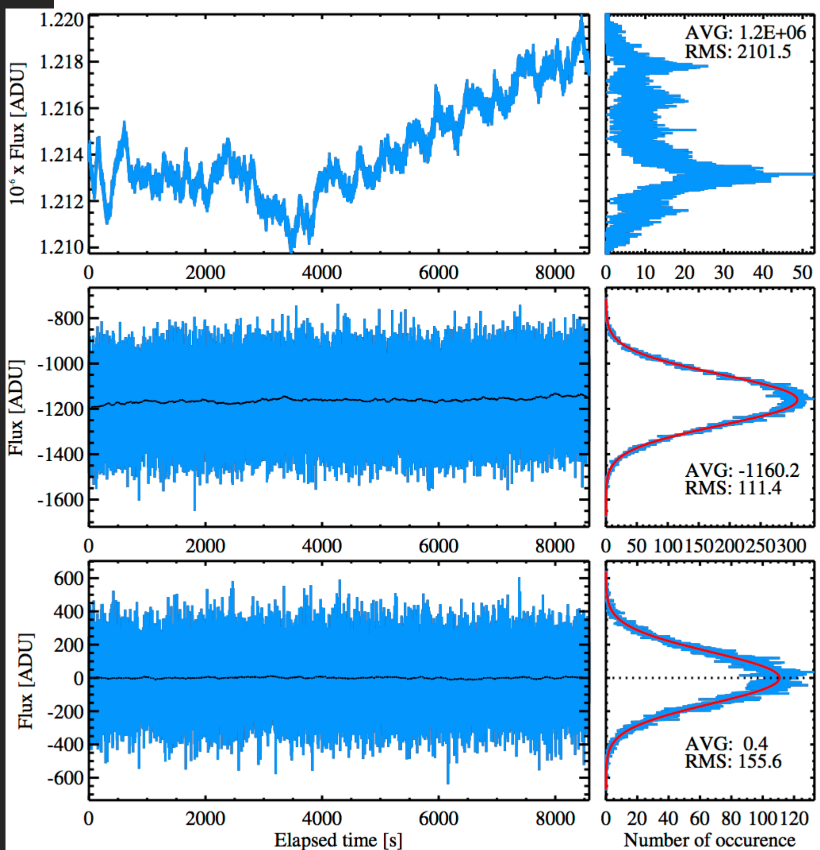
$$\tan\phi = \frac{N_2-N_3}{2(N_1-I_1-I_2-B)\sin\alpha}$$

$$|V| = \frac{N_1-(I_1+I_2)-B}{2\cos\alpha\sqrt{I_1 I_2}}$$

Fast dithering principle

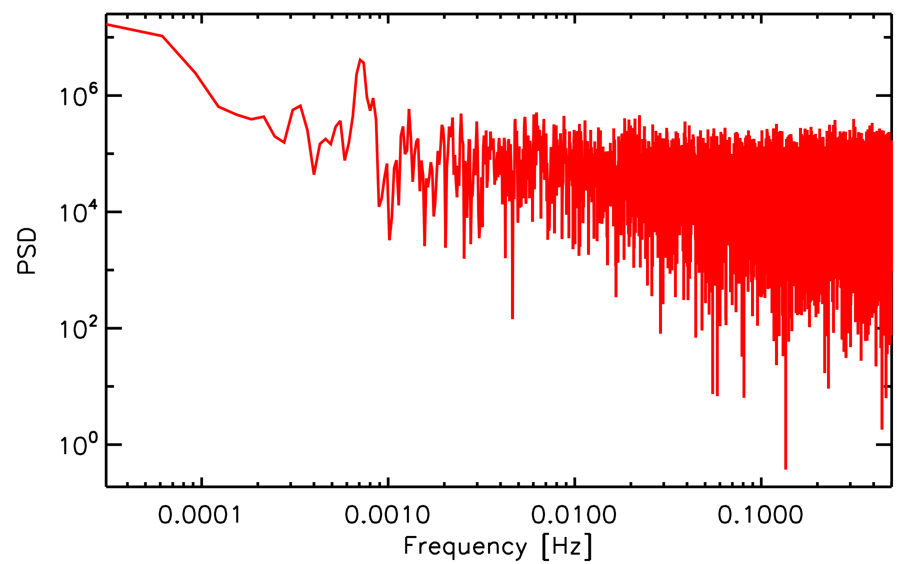
- Assumption 1: background bias constant between 3 dither positions

One example



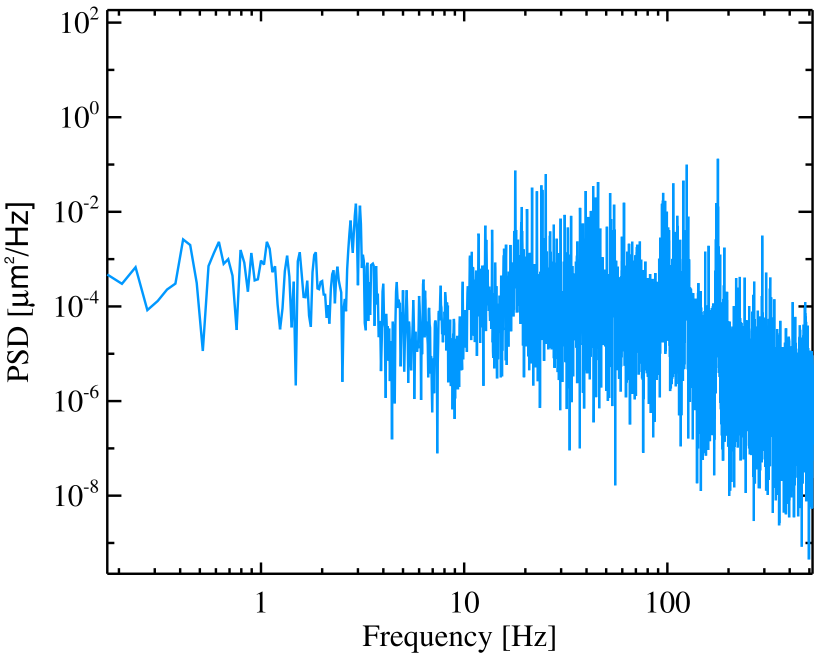
Uncorrected background bias

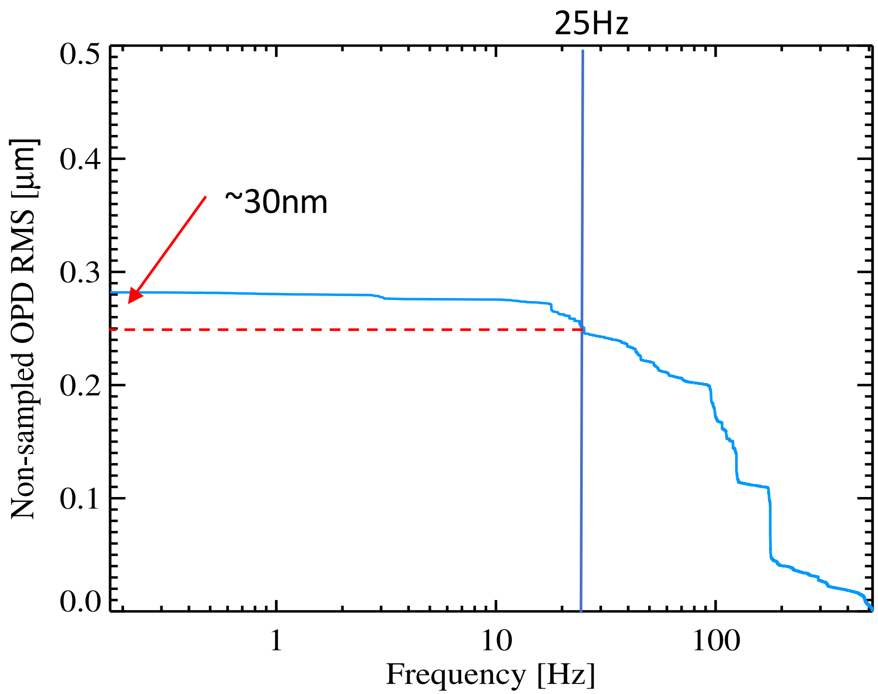
Mostly low frequency



Fast dithering principle

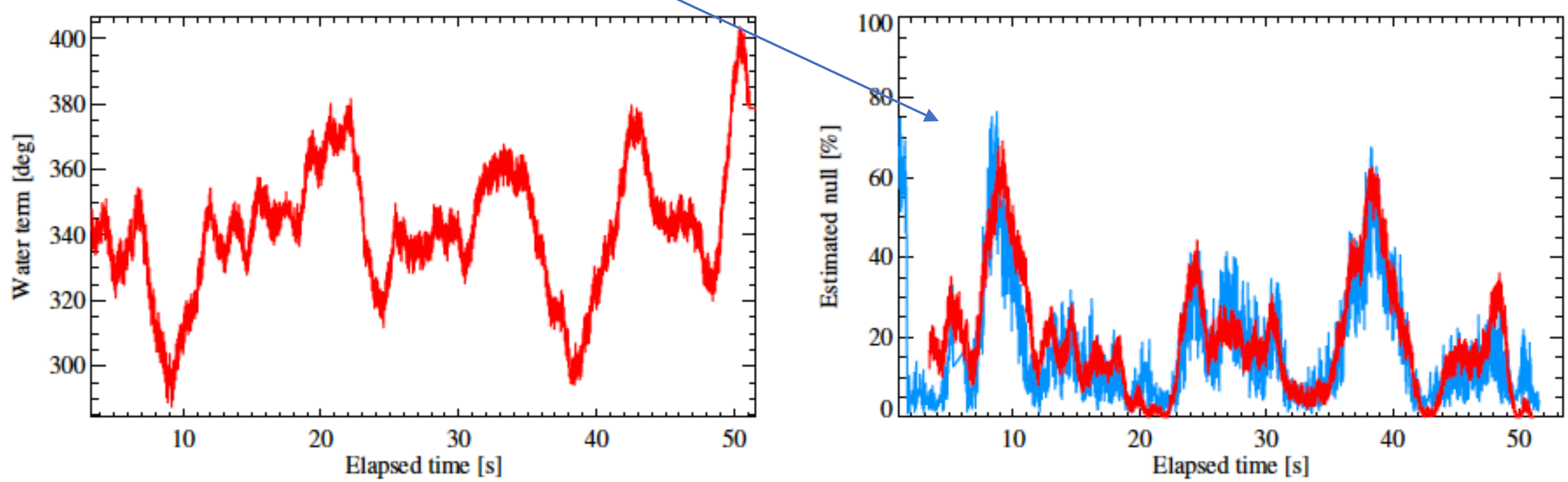
- Assumption 2: Phase setpoint constant between 3 dither positions
- Phase drift between measurements < 30nm or 0.02rad or ΔN~100ppm





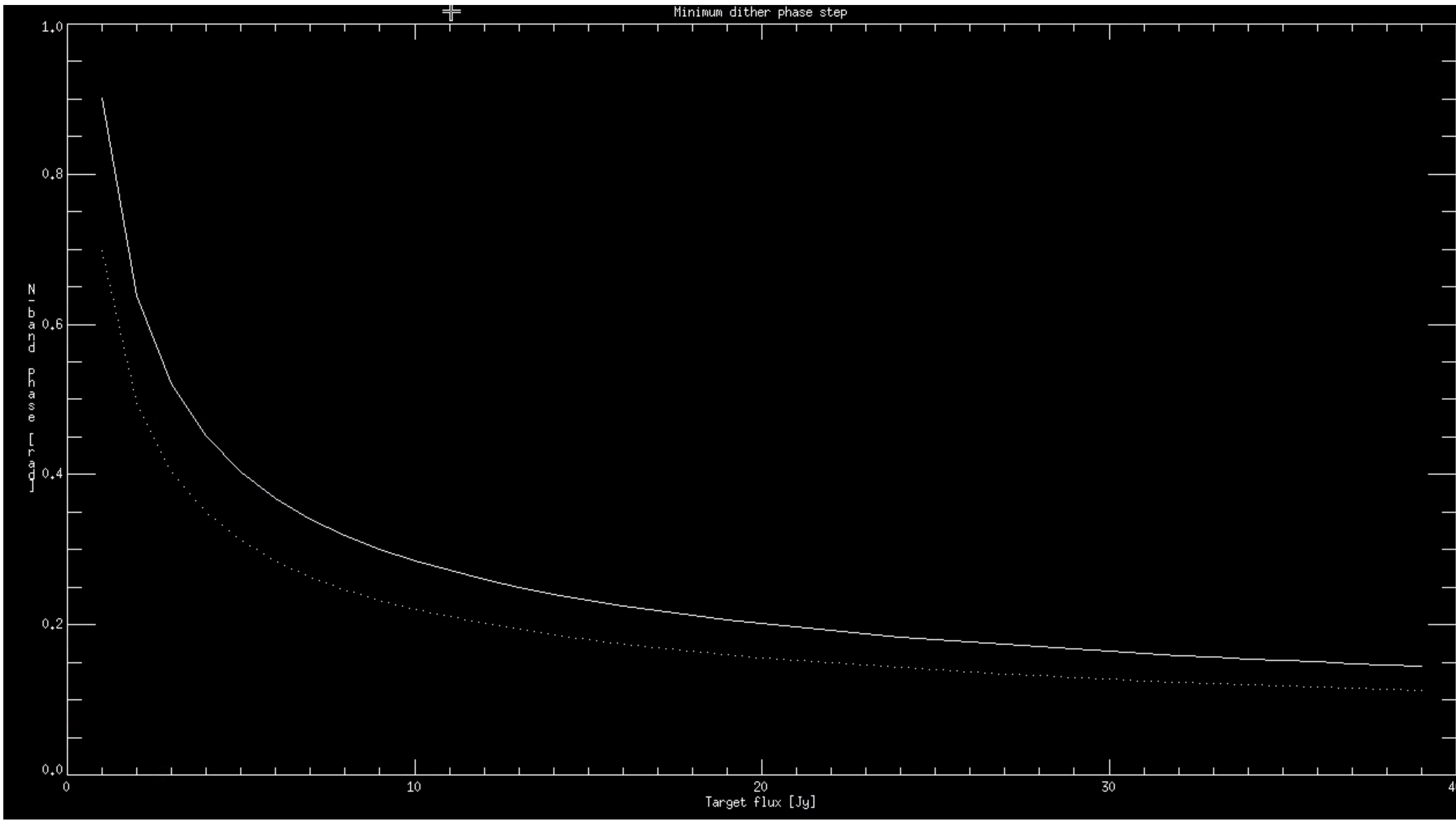
Fast dithering principle

- Assumption 2: Phase setpoint constant between 3 dither positions
  - What about PWV?
  - Null can vary by 70% in 3sec…This is ~1% in 40ms!! => <u>must be taken into account in post-processing for high PWV nights </u>(can we rely on H-K phase?) or can still use th NSC in case of problem.



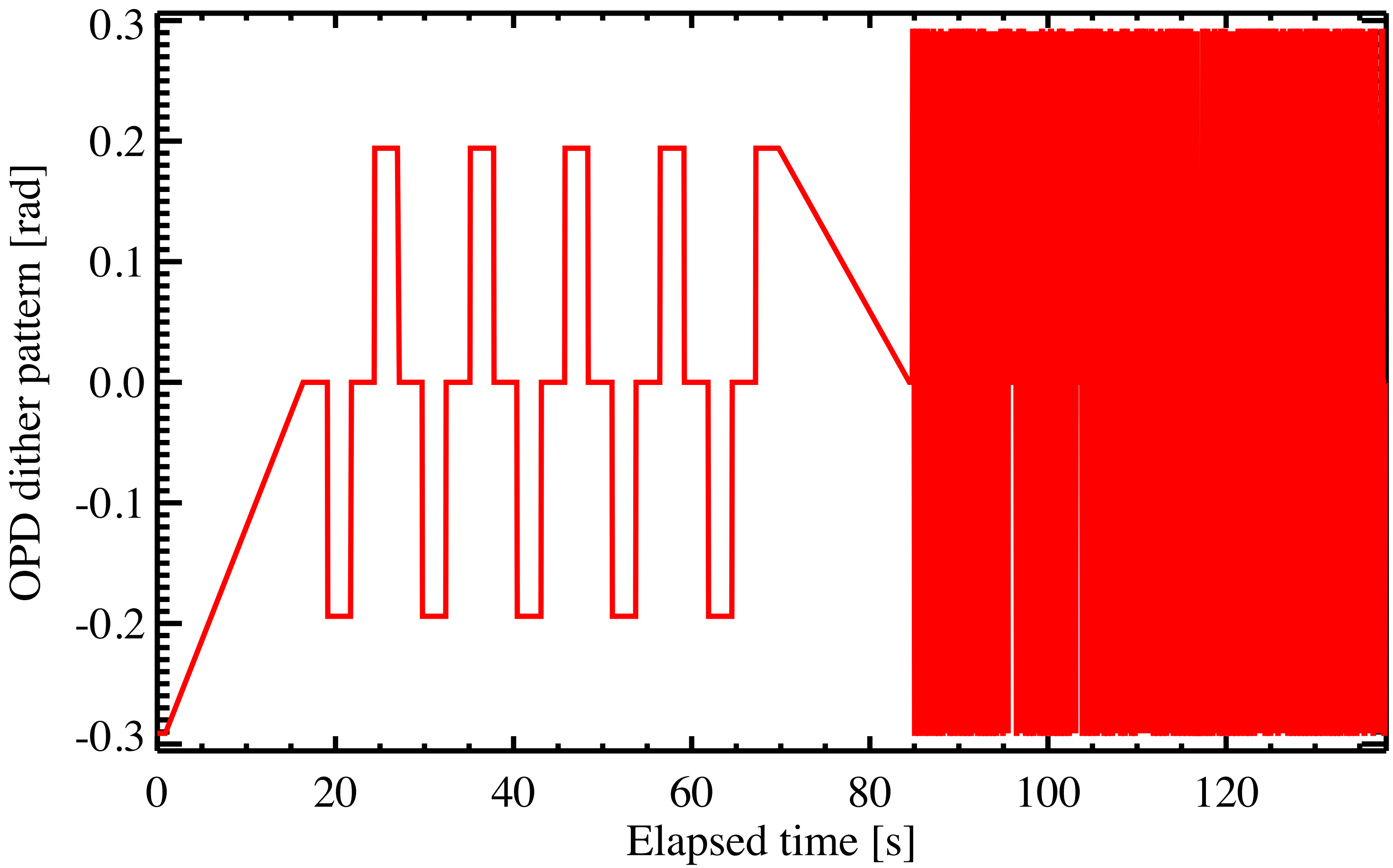
Dithering amplitude matters

- Minimum N-band phase steps as a function of target flux (3 and 5-sigma > background RMS) :



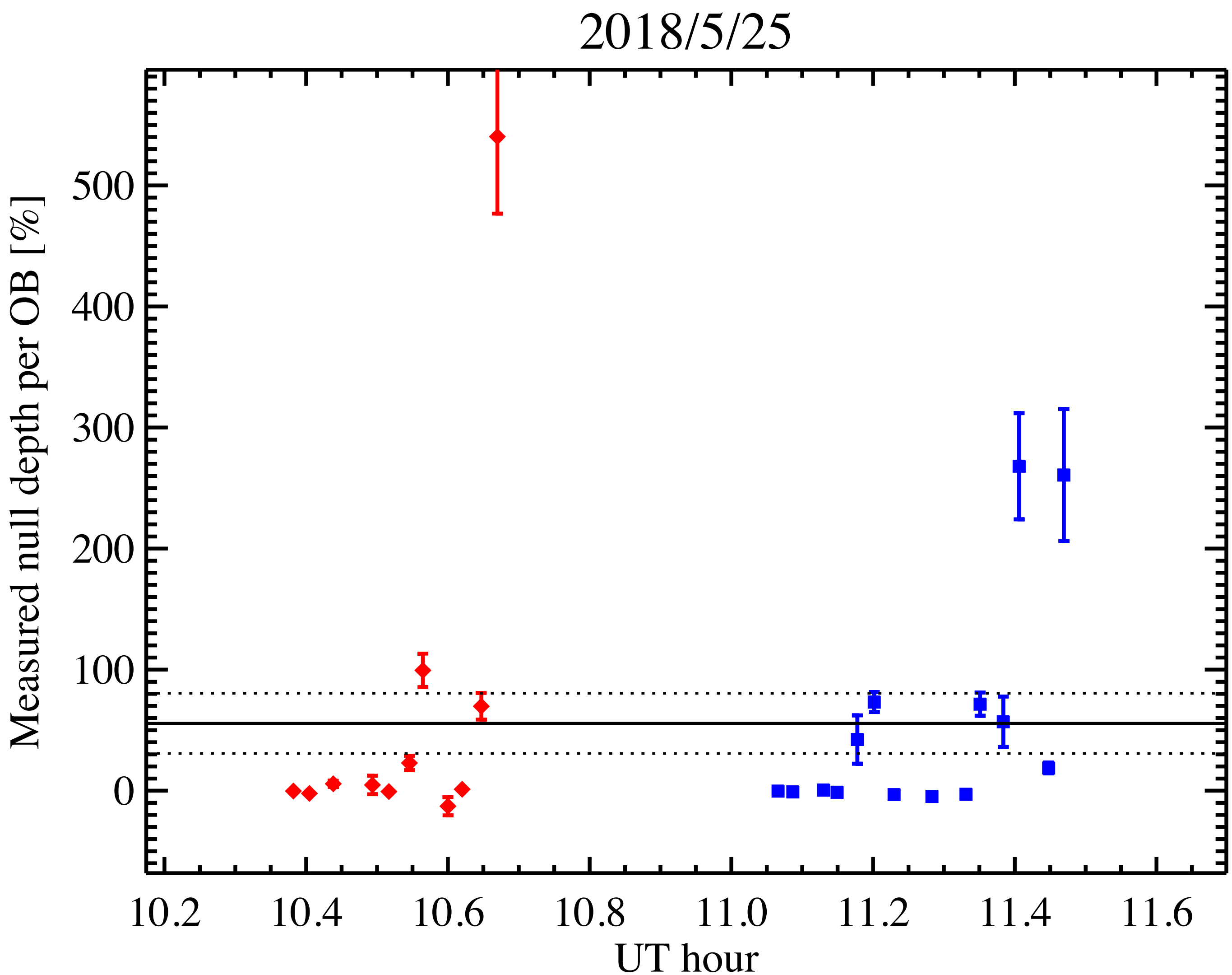
Results of fast dither approach

- Data obtained on May 25, 2018 on 61 Cyg A (4 Jy) and calibrator
- Each OB divided in one slow and one fast dither sequence:



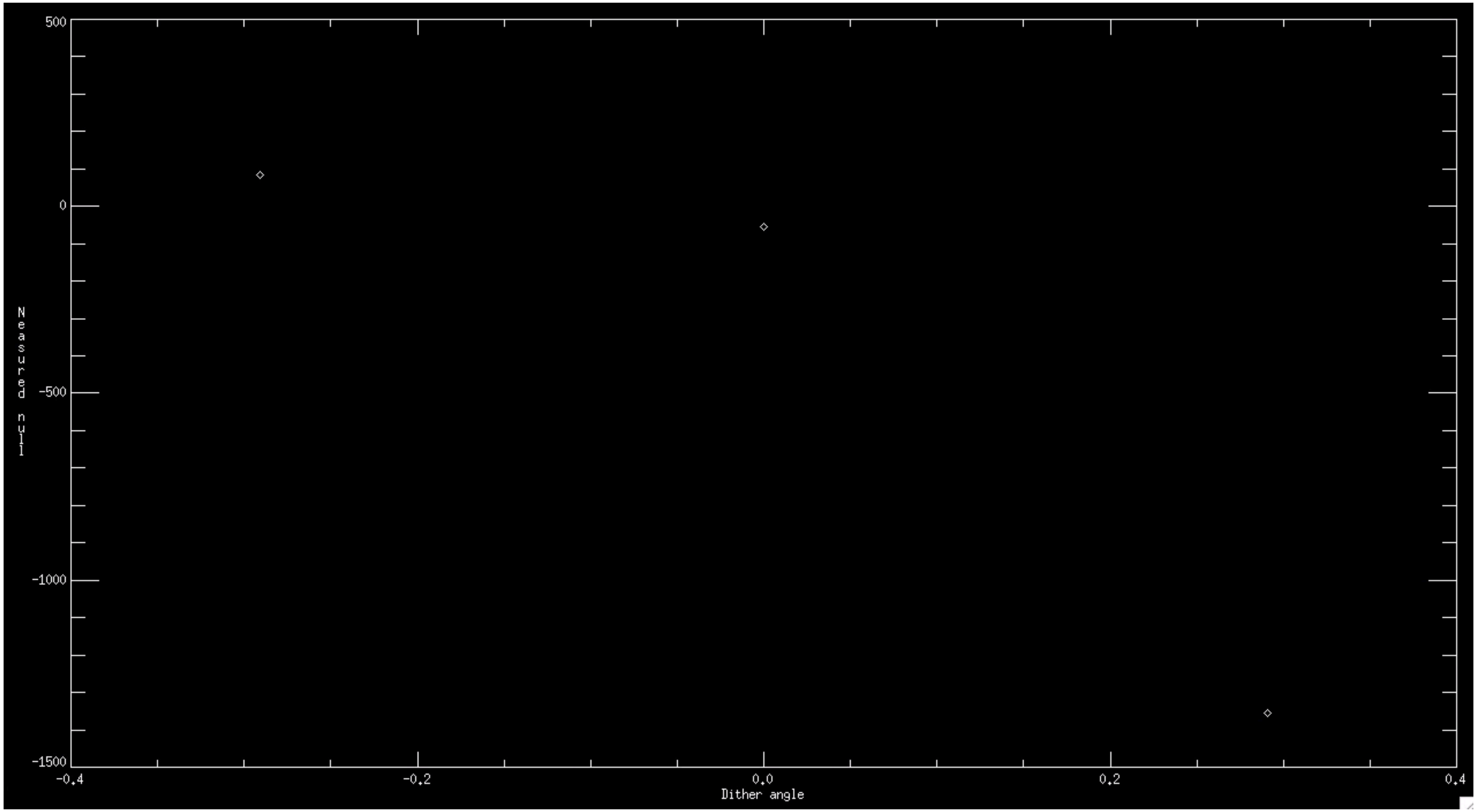
Results of fast dither approach

- Method doesn't work (so far)



Results of fast dither approach

- Dither pattern not apparent in the null measurements??



Results of fast dither approach

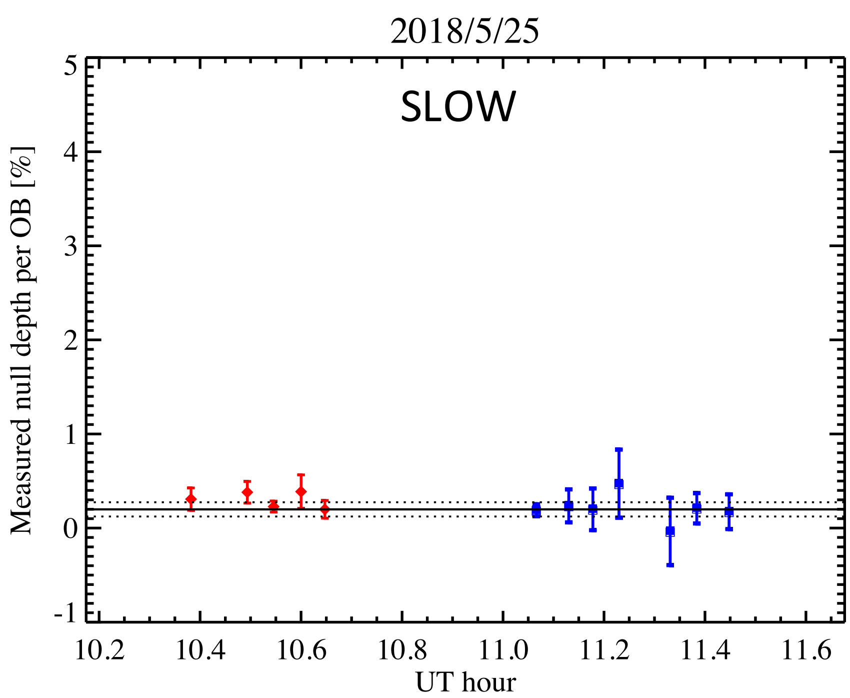
- Using default NSC for both, fast-dither data show smaller error bars

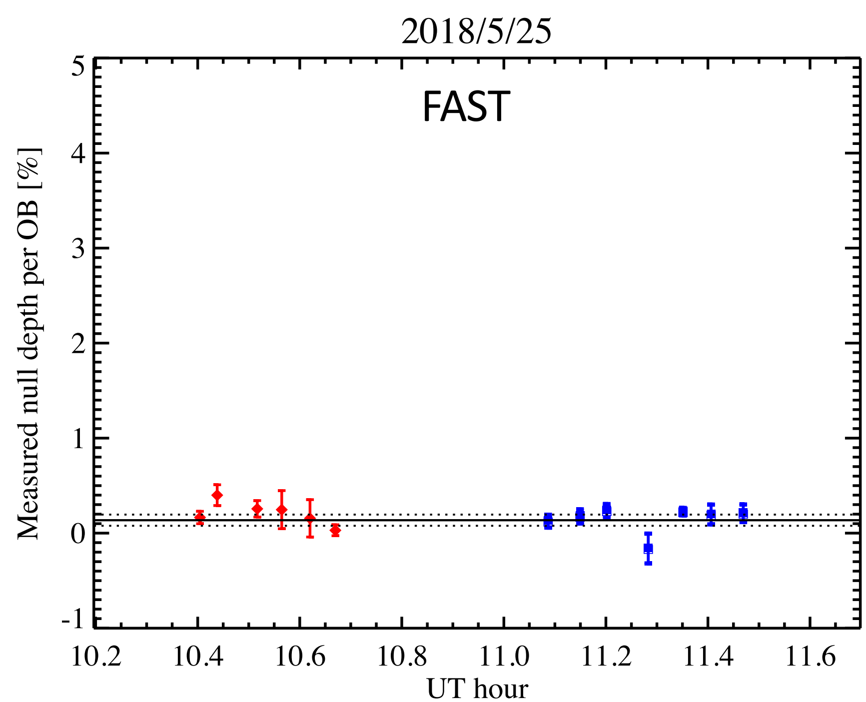
MEAN ERROR PER OB
0.18%

CALIBRATED NULL
0.094% +/- 0.098%

MEAN ERROR PER OB
0.10%

CALIBRATED NULL
0.065% +/- 0.081%





Summary and conclusions

IMMEDIATE ACTION

- Using a larger dither amplitude will improve the null uncertainty (at least 0.3 rad or more, to be tested)

ANALYSIS NEEDS

- Test more advanced background subtraction or flat fielding strategies on existing data (pipeline still uses very basic, but fine tuned, approach)
- Test null calibration using images rather than fluxes

PIPELINE DEVELOPMENTS

- Replace brute-force computer-intensive NSC approach by MCMC
- Asymmetric error bars not propagated (only the maximum of the 2)