Non linearity in CCD detection

Intermission on the way to Picard Sodism L1 products

J.-F. Hochedez

1. Successive restorative steps of instrumental correction

1. From the Level 0 to Level 1_{k+1} data products
2. The unwanted components in the signal of a pixel
3. Put the corrections in sequence!

From the Level 0 to Level 1_{k+1} data products

- Instrumental corrections:
  - Condition the scientific objectives
    - Especially in the fields of metrology/astrometry when accuracy and/or precision prevail
  - Bring instrumental diagnostics

- To convert Level 0 (= formatted & informed TM) into Level 1 products (= corrected for instrumental flaws), we must:
  1. Elaborate a correction method
  2. Compute its calibration elements
     - E.g. the parameters of a non-linearity function
  3. Process the data products provided by the previous correction stage

❑ The above cycle actually applies from Level 1_k to Level1_{k+1}, *i.e.* several times!

What are we talking about?

List of instrumental effects in the Picard Sodism solar space telescope

Additive

- Offset
- Dark signal
  - Hot pixels
- Cosmic ray hits
- Ghost images

Multiplicative

- Optical flatfield
  - incl. vignetting
- Detector flatfield
- Non linearity of the detection

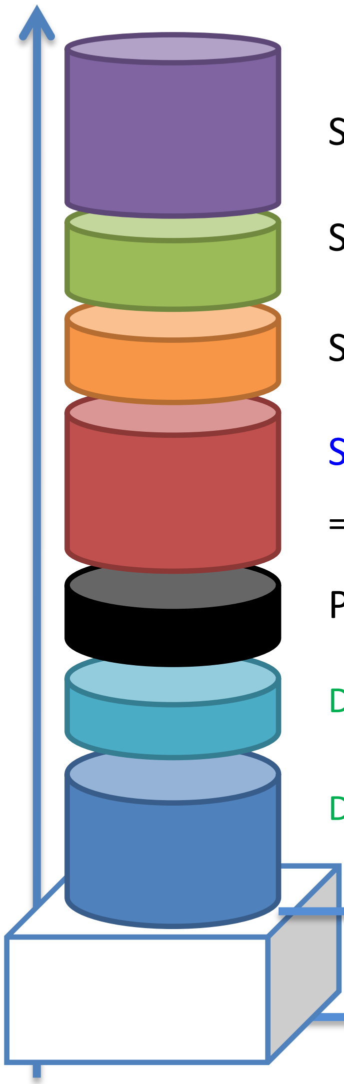
Convolutive

- PSF
  - Scattered light
  - Kinematic blur
  - Optical aberrations (defocus…)
- Persistence / hysteresis
- CCD charge transfer efficiency

Other

- Distortion (anamorphosis)

Components in the pixel signal



Signal due to cosmic ray hits

Signal due to parasitic reflections = ghost(s)

Signal due to the light scattered by the optical elements (window, mirrors, filters…)

Scientific signal (wanted!)

= G [DN/e-] × FlatField (x,y,t, previous image) [e-/ph] × **Non Lin Function** (Φ [ph_in]) × Exptime(x,y) [s]

Persistence

Dark signal (CO) generated in the CCD image zone (IZ), incl. IZ 'hot pixels'

Dark signal (CO) generated in the CCD memory zone (MZ), incl. MZ 'hot pixels'

Offset

0 DN

NB: Convolution by the PSF core not listed here

Put the corrections in the right sequence!

- The corrections ought to apply in "some" order…
- They must proceed from back to front
  1. DN or ADU ↵
  2. Detected e^- ↵
  3. Detected photons ↵
  4. Incident photons ↵
  5. *etc.*
- Typically, one cannot address optical effects with data that are still tainted by detection flaws.
  – In principle.
  – Might be OK for the spadework

Preferred sequence

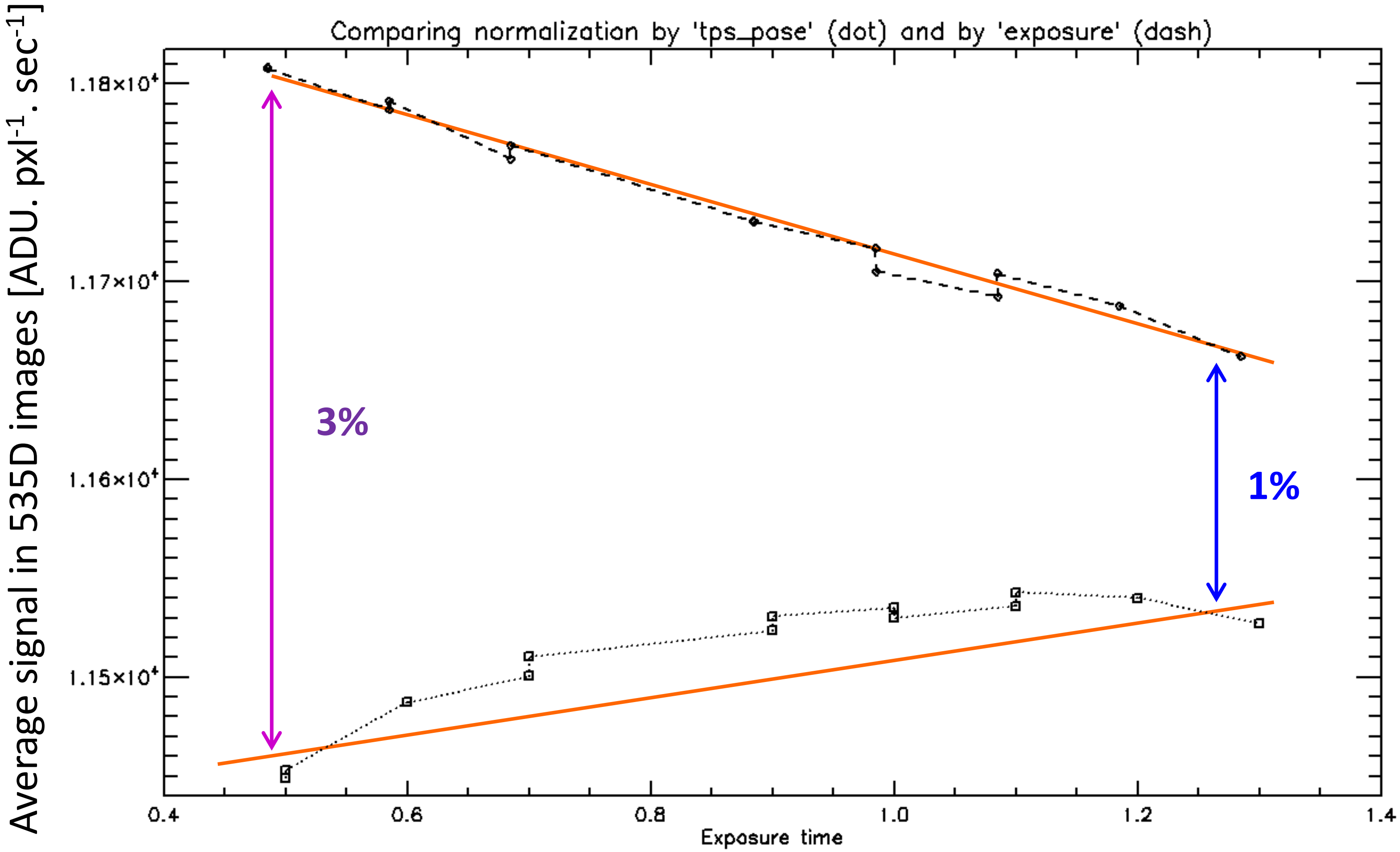
1. Offset
2. Cosmic ray hits
3. Dark signal and hot pixels
4. Non linearity
5. Detector flatfield
6. Persistence
7. Ghost
8. PSF (aberrations and scattered light)
9. Optical flatfield
10. Distortion
11. …

Sub-levels $L1_{k+1}$ after each

2. Non Linearity due to shutter kinematics

1. Evidencing the problem
2. Observational campaigns of exposure time variations
3. Modeling the shutter kinematics
   a. Parameterized modelization
   b. Inversion of the geometrical configuration

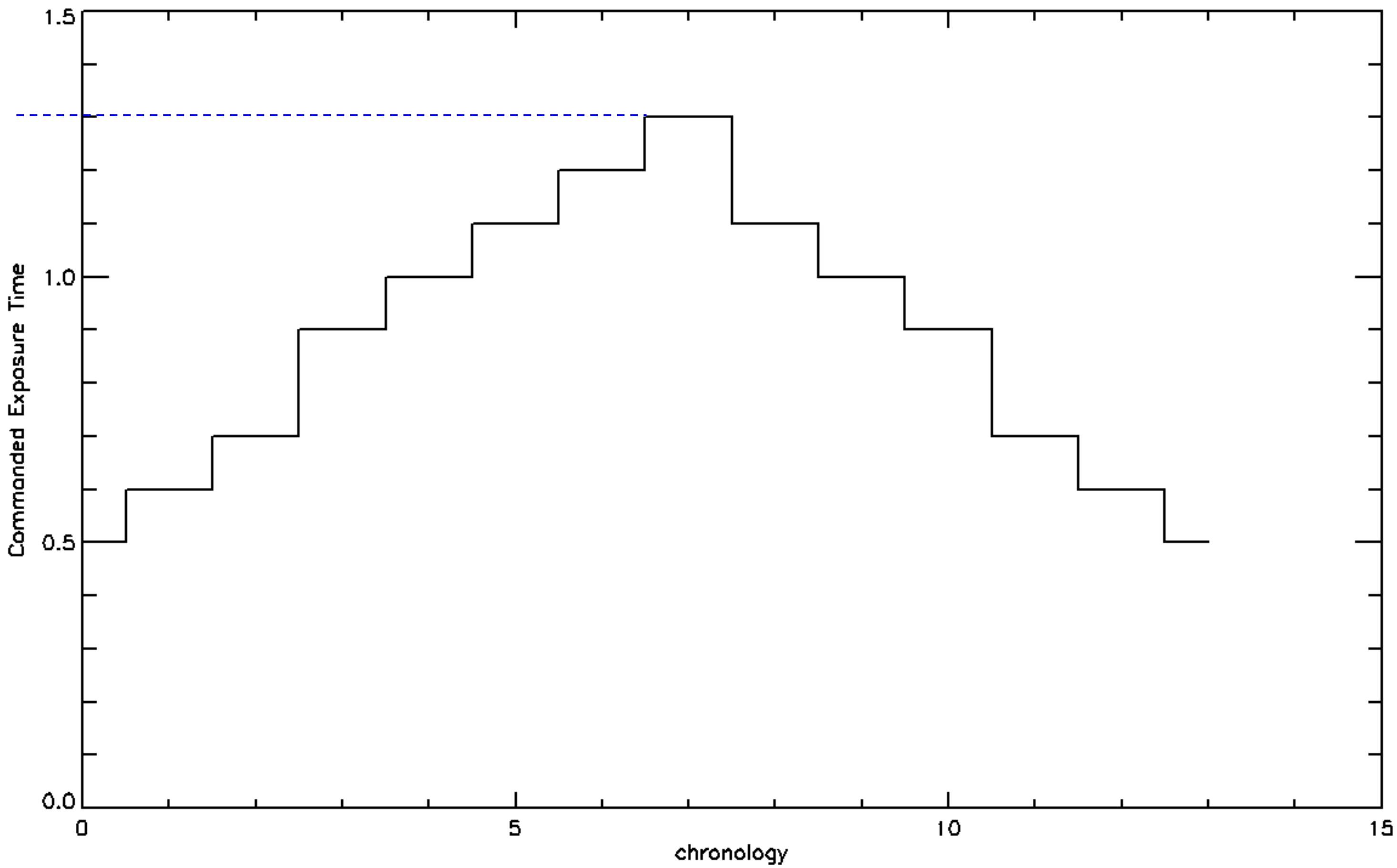
Non linearity seen during *exposure time variation campaigns*



Chronology of commanded exposure times

1.3 sec

0.5 sec



14 stages, from #0 to #13

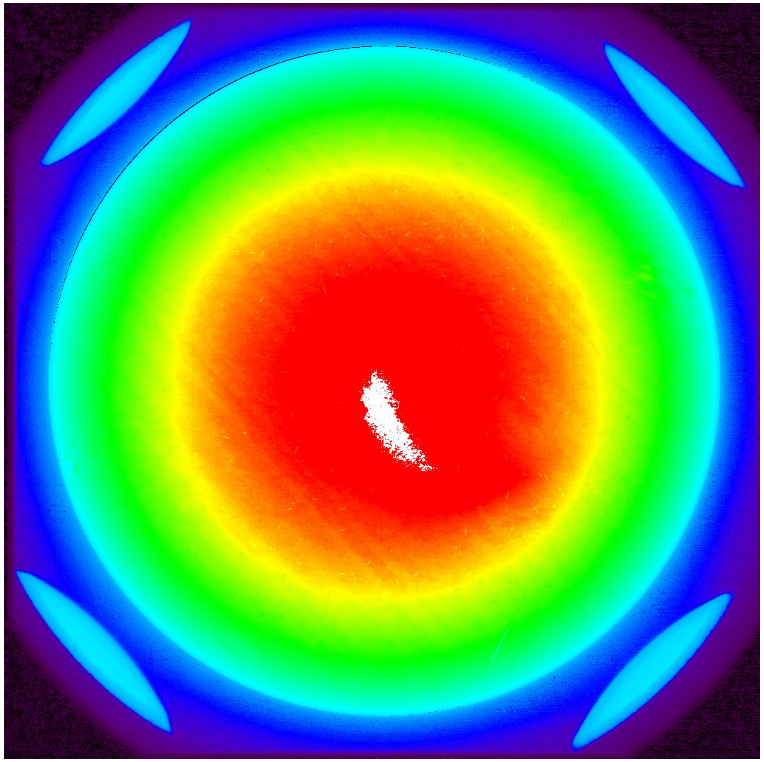
Exposure time variation campaign

March 22., 2011 @535D

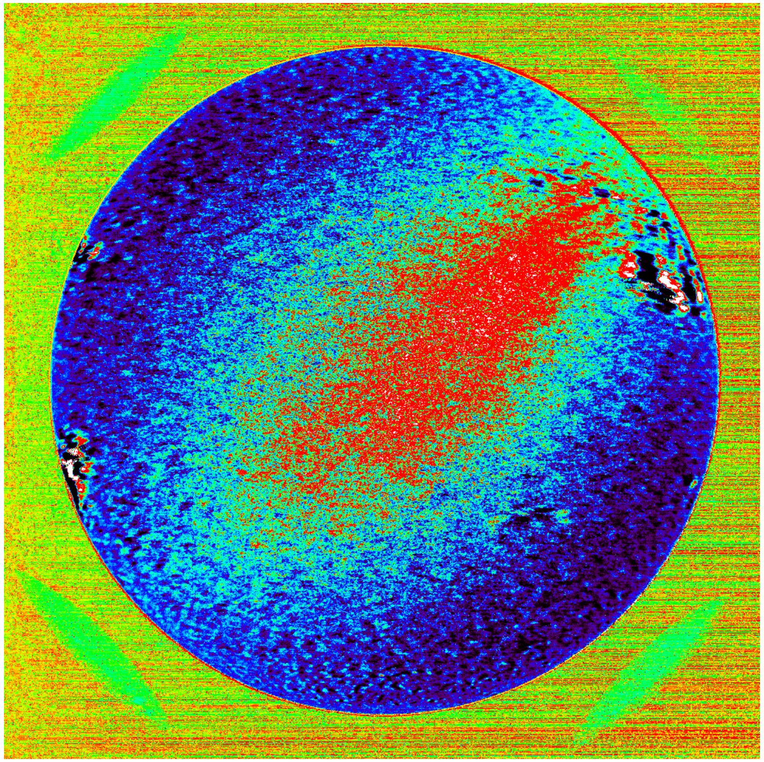
Let's first assume a fully linear model w.r.t. exposure time:

$$\boldsymbol{Signal}(pxl = i, Commanded\ exposure = T_j) = \boldsymbol{\varphi_i}\, \boldsymbol{T_j} + \boldsymbol{Offset_i}$$

φ_i and $Offset_i$ obtained by robust linear regression at each pxl

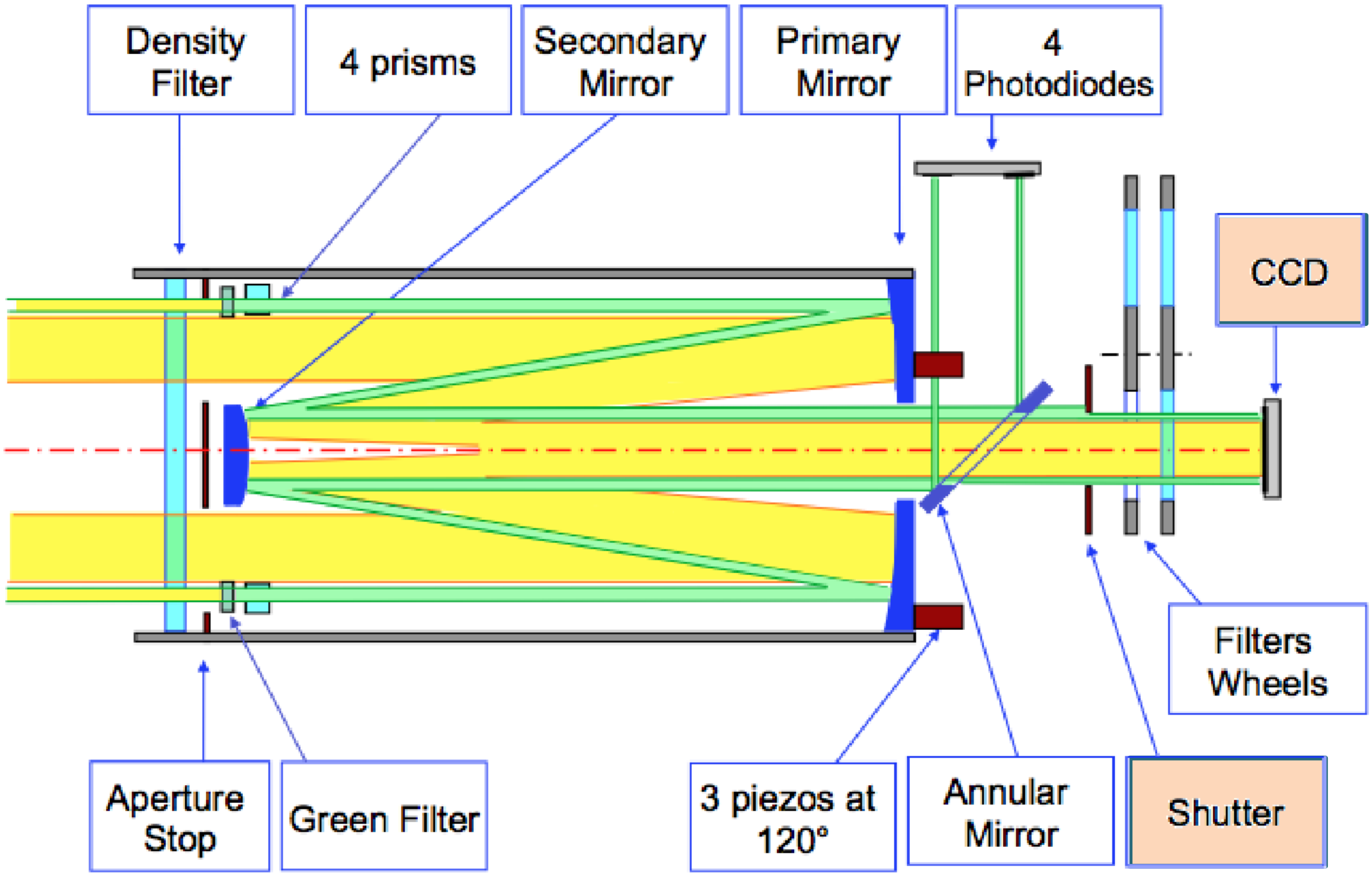


Flux image φ_i



Offset image

Optical scheme

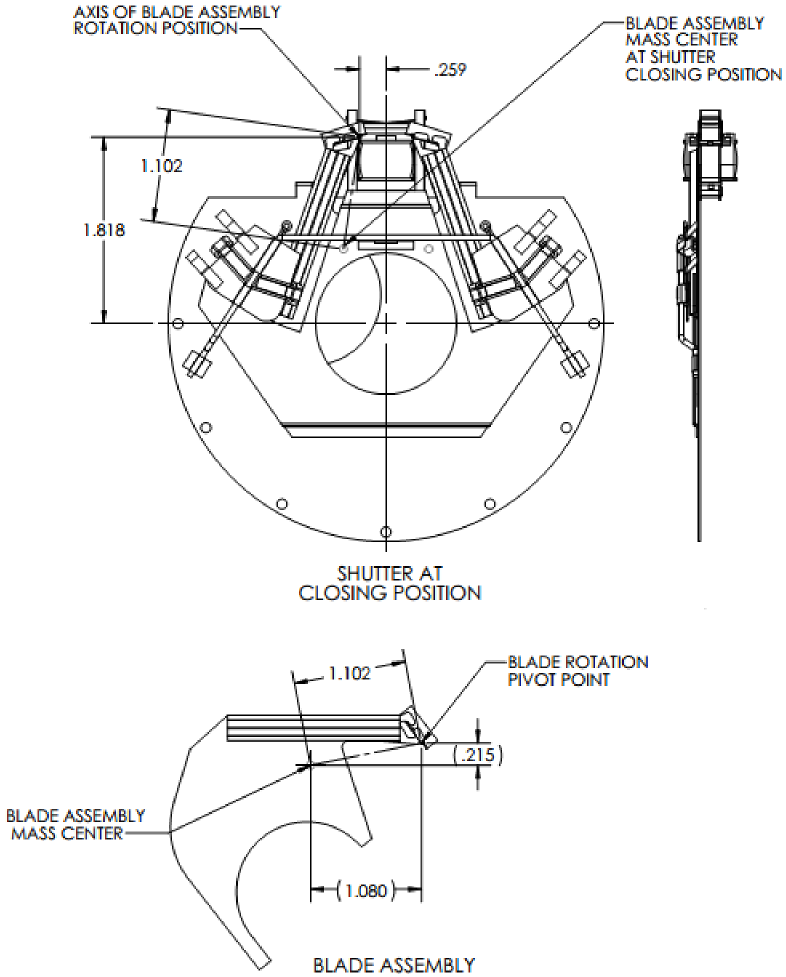


2.3 Modeling the shutter kinematics

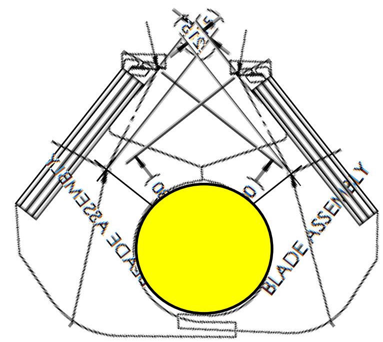
1. Exposure time is *non* homogeneous over the field
2. Six unknown parameters
3. Solution and result

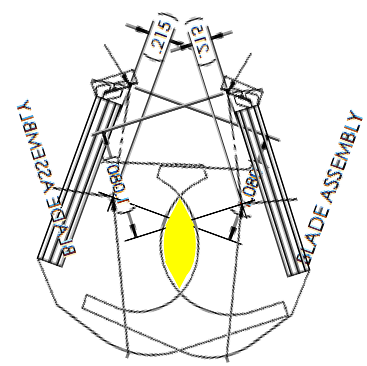
Effect of a not-so-swift electromechanical shutter

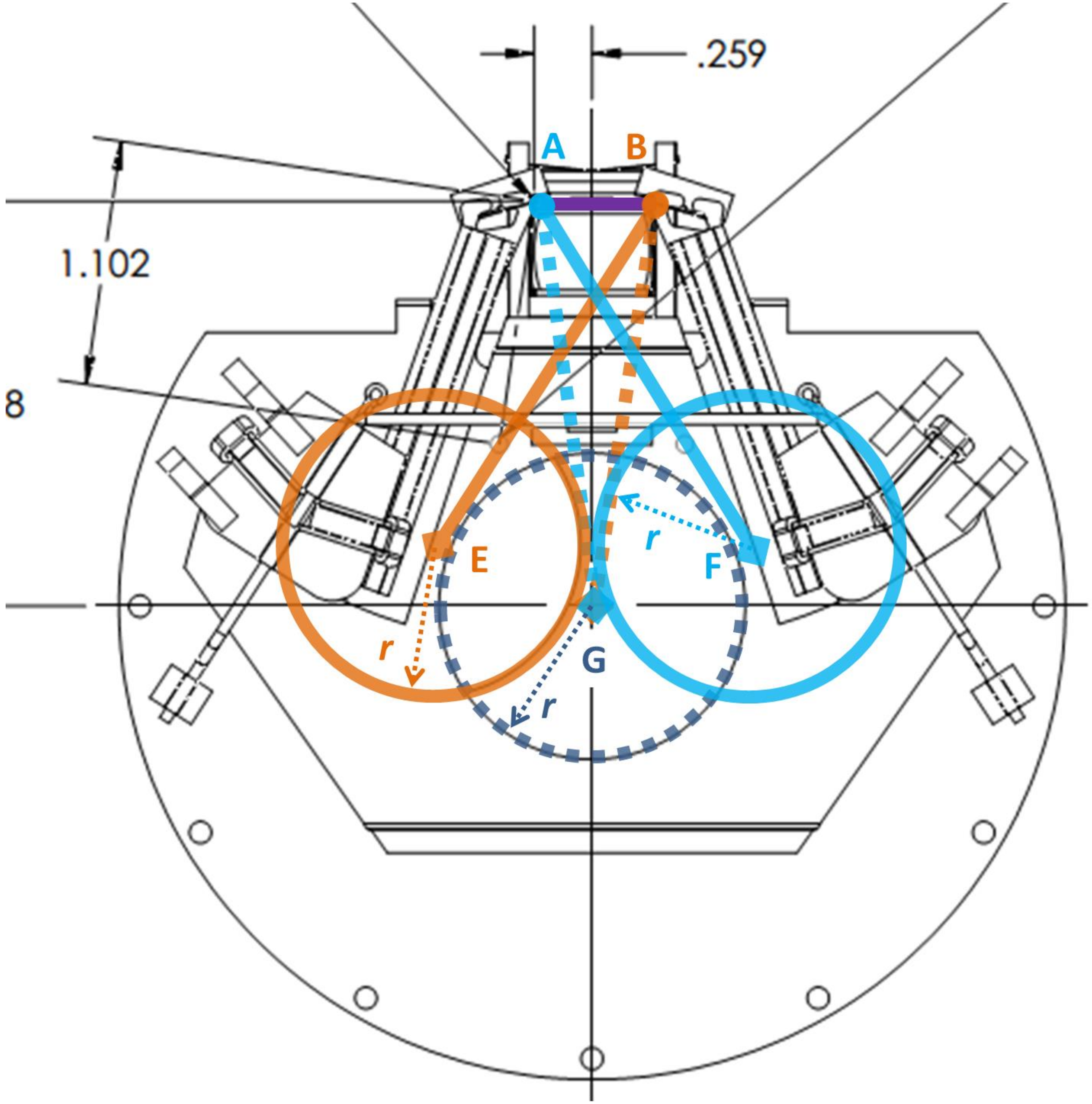
Most geometrical parameters are known

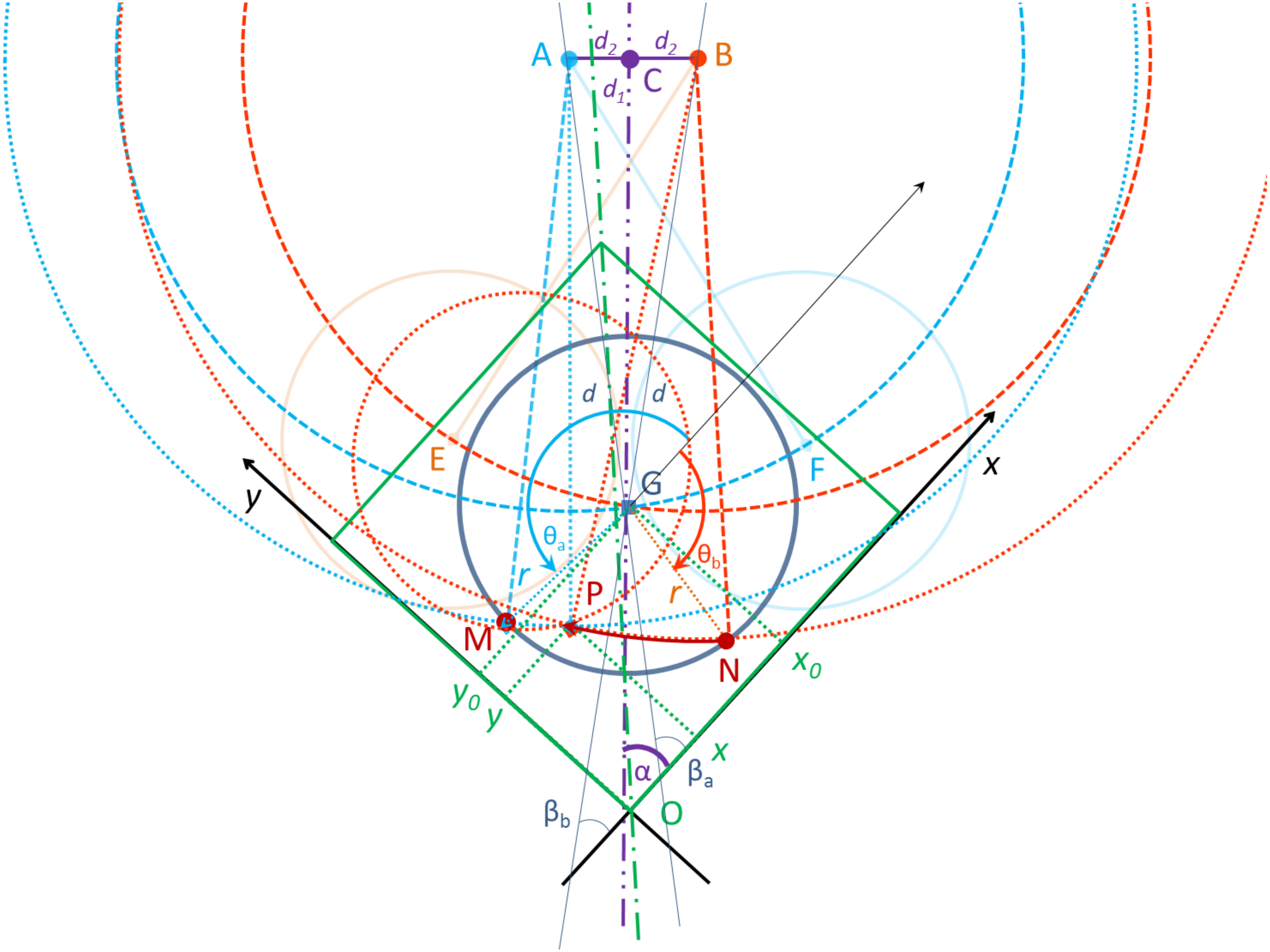


Much information resides in the Uniblitz/Vincent Associates drawings





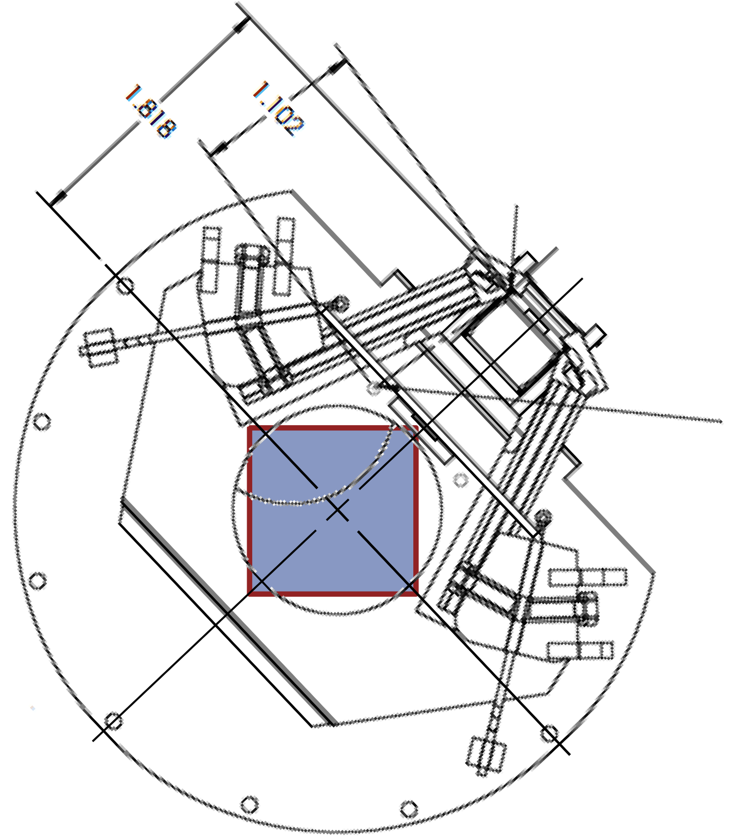

.259
A
B
1.102
8
E
F
G
r
r
r



A
B
C
d_2
d_2
d_1
d
d
E
F
G
θ_a
θ_b
r
r
P
M
N
x
y
x_0
y_0
y
x
α
β_a
β_b
O

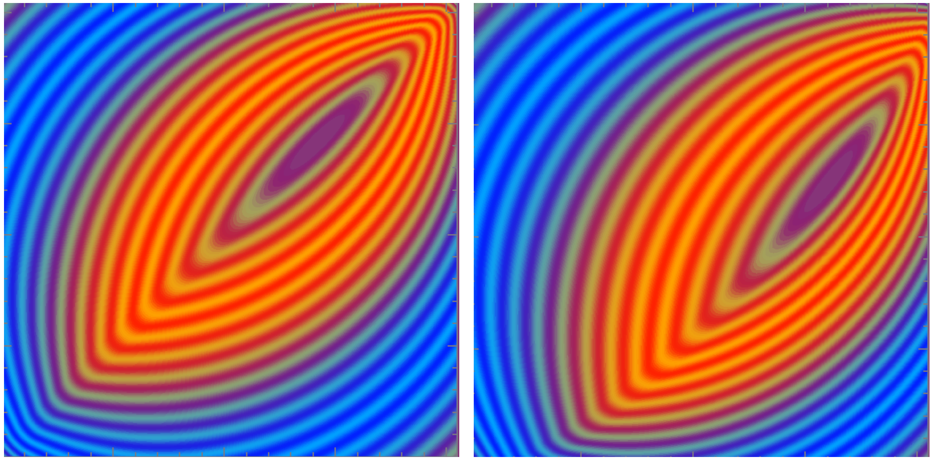
6 Unknowns parameters

- Relative centering of CCD *vs.* shutter
  - X_0 & Y_0
- Tilt of the overall shutter system
  - θ_0
- Speed of each blade
  - Reference blade : κ
  - Relative speed of the other blade : ζ
- Delay between header exposure time and actual motion
  - τ_0



Only 4 parameters needed to generate a map of extra exposure time

X_0, Y_0, θ_0, $\zeta \rightarrow \gamma_i$

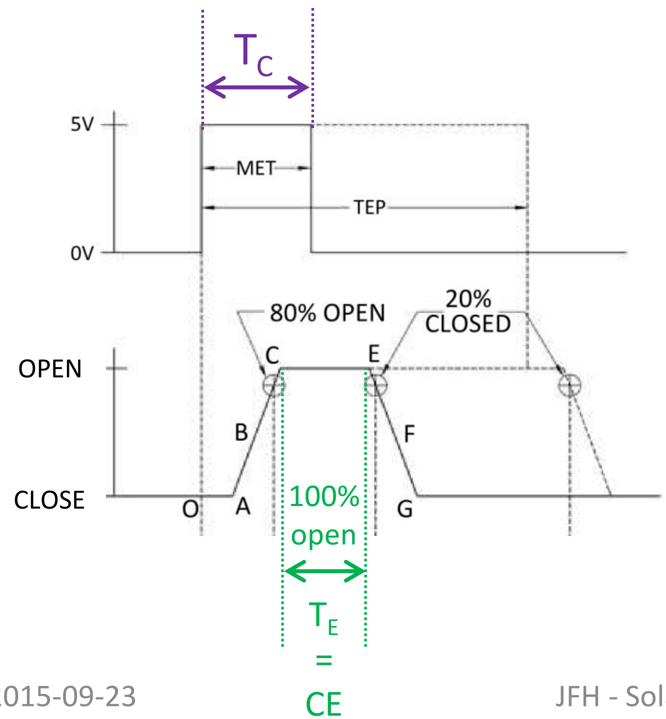


Estimation of the unknown geometrical parameters

$$\boldsymbol{Signal}(pixel = i, \boldsymbol{Commanded\ exposure = T_j}) = \varphi_i \times [T_j + \tau_0 + \kappa\, \gamma_i] = \boldsymbol{\varphi_i\, T_j + Offset_i}$$

$$\boldsymbol{Offset_i/\varphi_i = \tau_0 + \kappa} \times \boldsymbol{\gamma_i(X_0, Y_0, \theta_0, \zeta)}$$

(X_0, Y_0, θ_0, ζ, τ_0, κ) estimated by minimizing χ^2 in the above linear regression



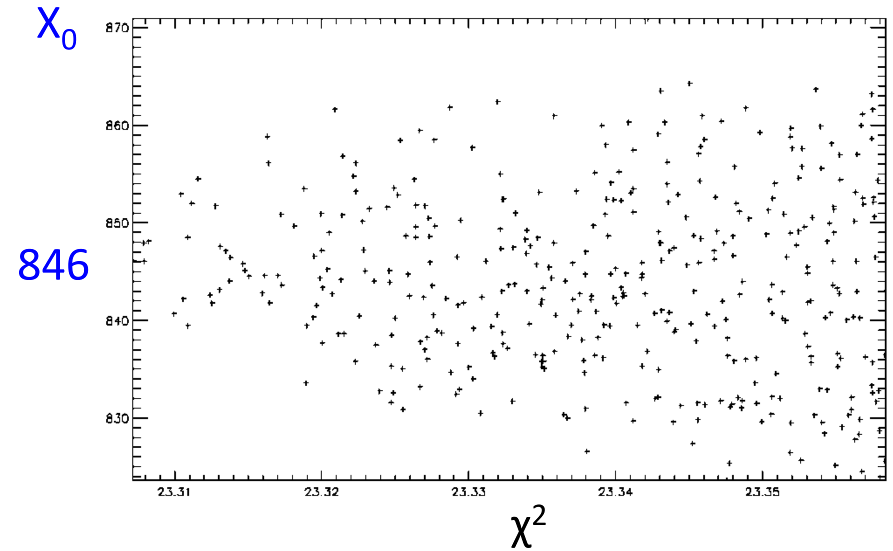
Origin of $\boldsymbol{\tau_0}$

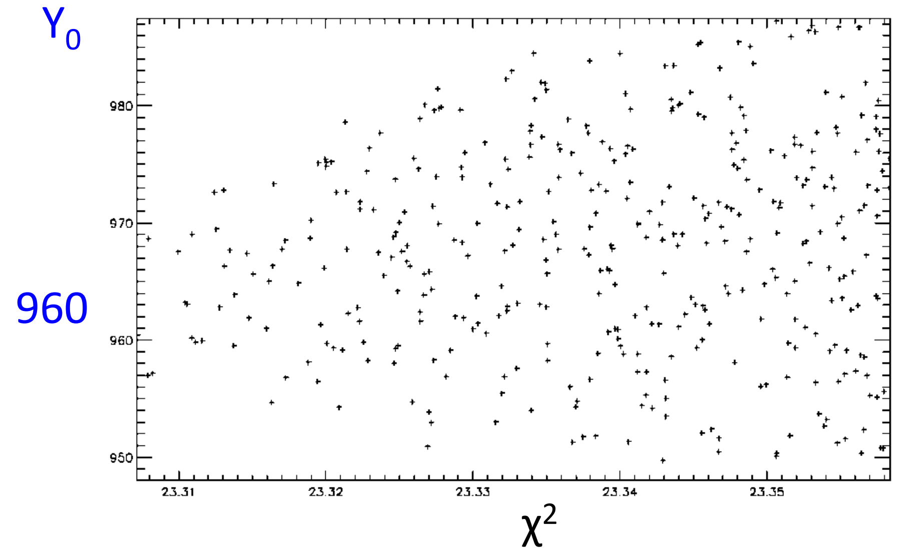
T_C = commanded exposure time

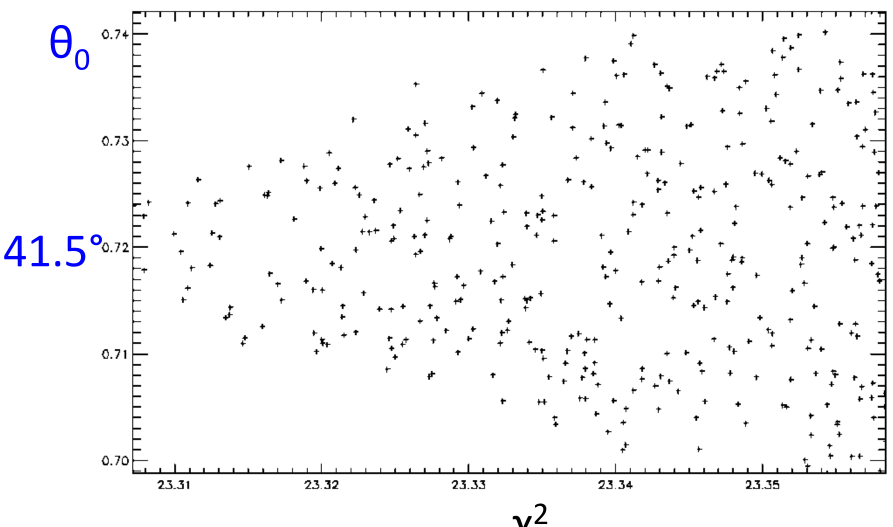
T_E = duration of the 100% open configuration

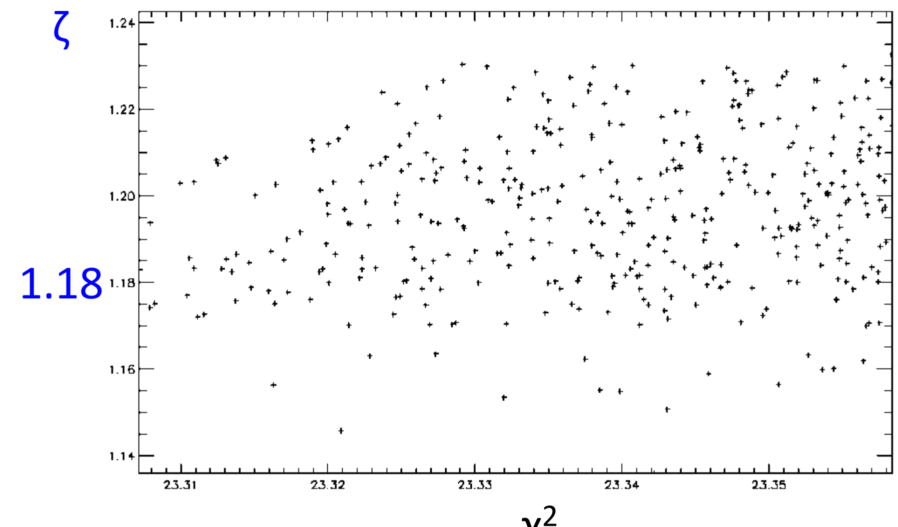
$\boldsymbol{\tau_0} = T_E - T_C$

Chi square minimization [1/2]

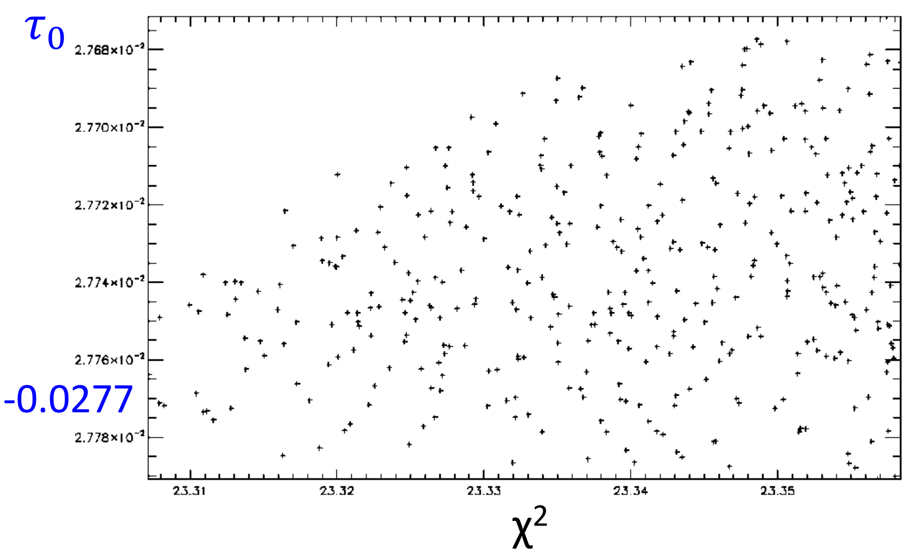


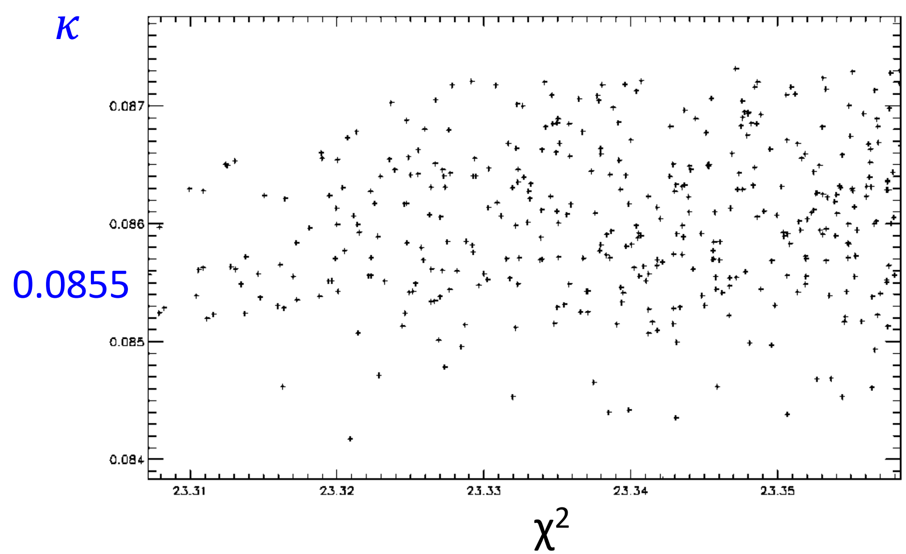






Chi square minimization [2/2]





$\theta_0 = 41.5°$

$X_0 =$ 846 pxl, $Y_0 =$ 960 pxl

κ = 85,5 ms.rad^{-1}

$1/\kappa$ = 11.7 rad.s^{-1} = 111.6 rpm

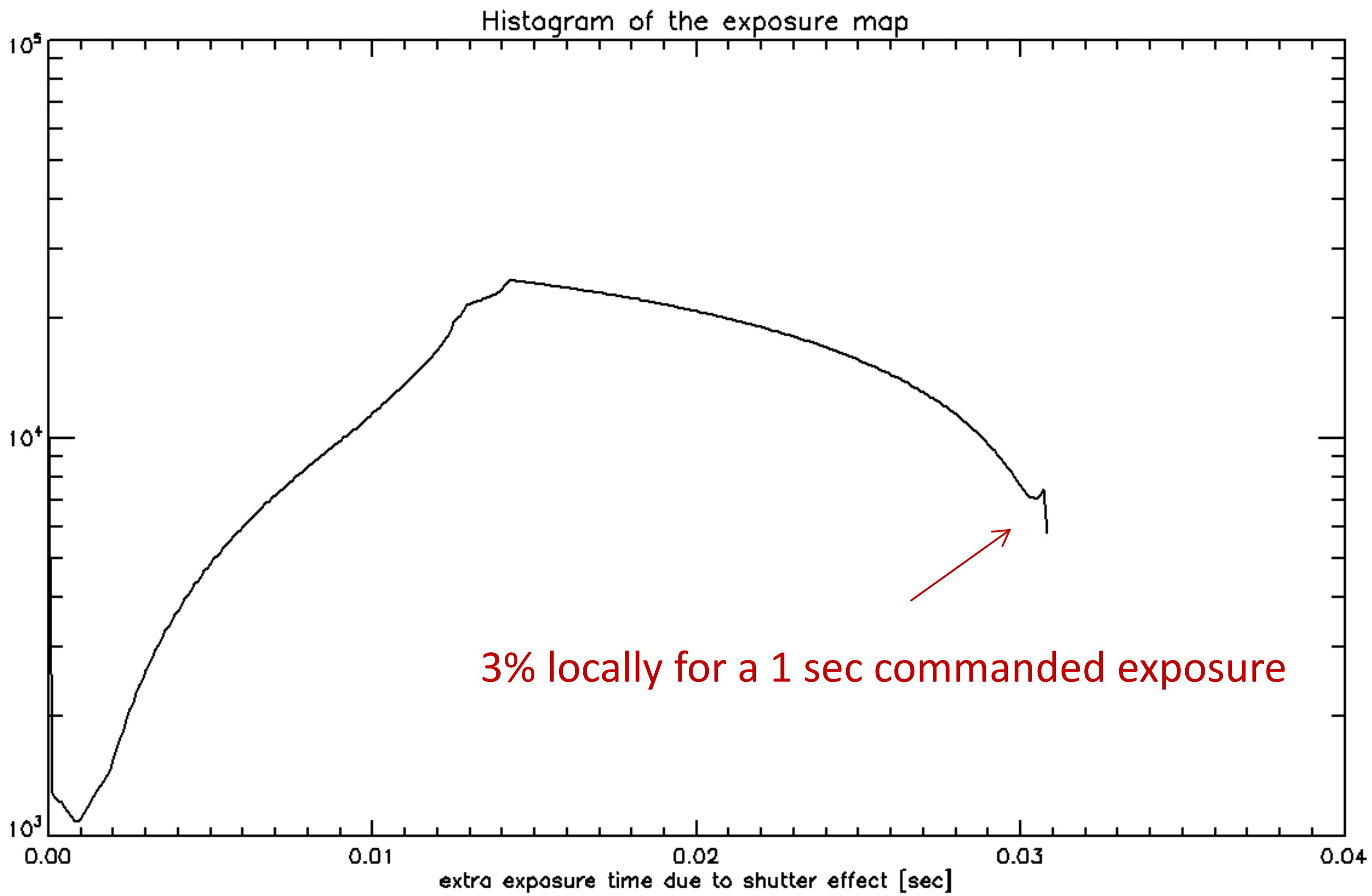
ζ = 1.18, *viz.* 2nd blade is 18% faster

τ_0 = -27.7 ms

LinearModel $= \varphi_i \times ExposureMap(i,j)$, with

$ExposureMap(i,j) = T_j + \tau_0 + \kappa\, \gamma_i$

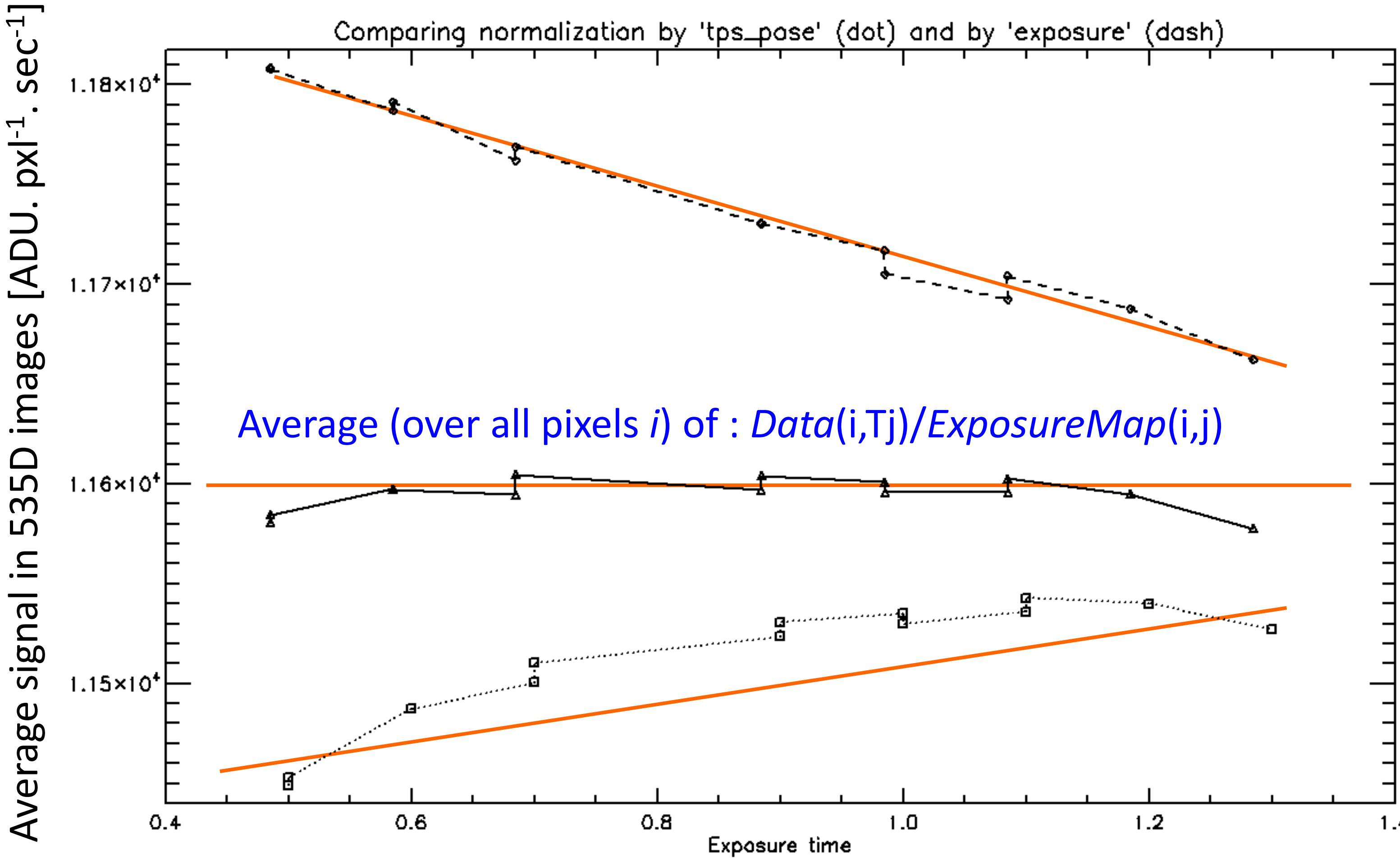
Extra exposure time due to the shutter



3. Residual non linearity

1. Dependency on exposure time - correct
2. Limits of the linear model
3. Model of the CCD non linearity

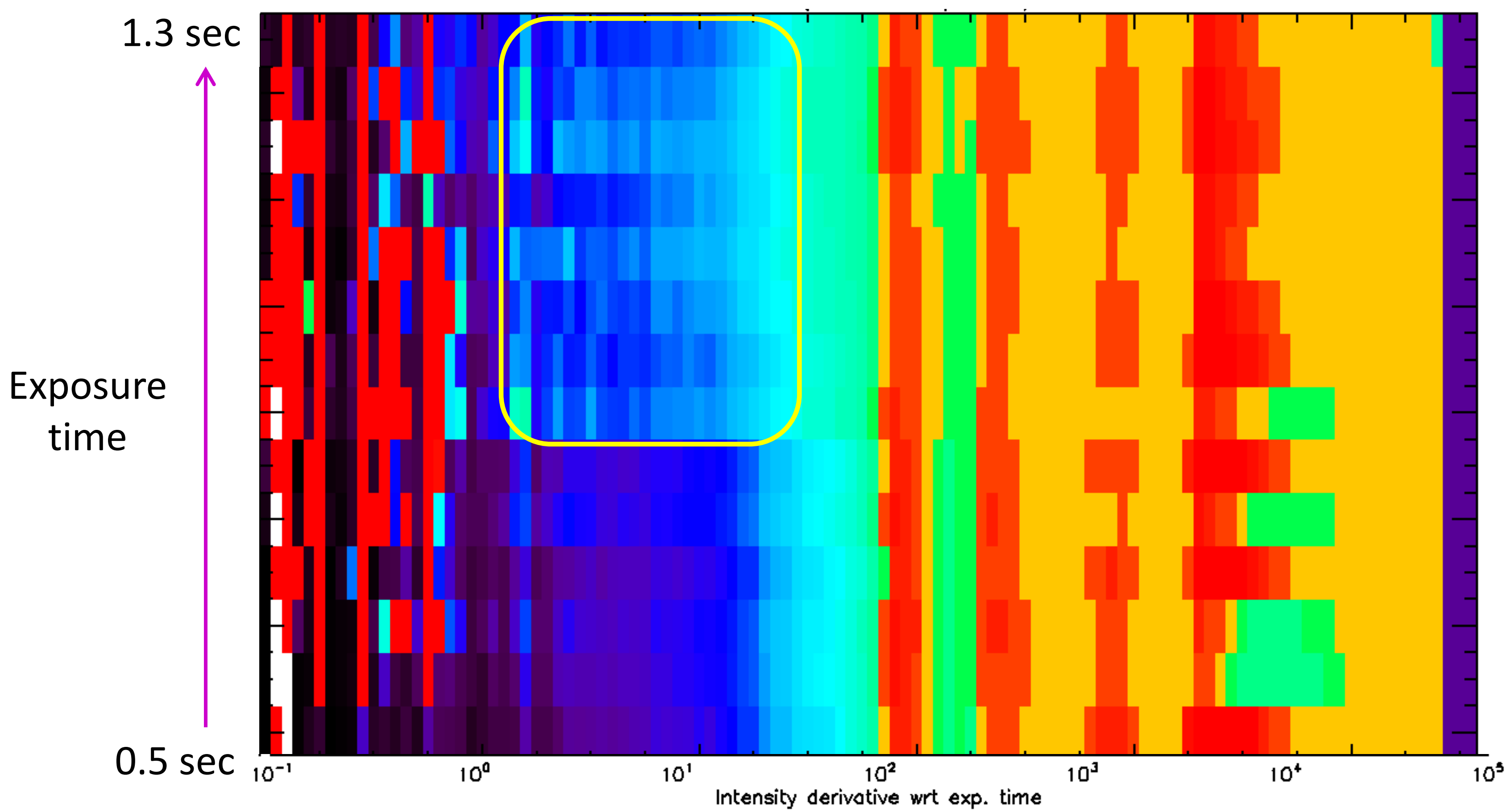
No more dependency on exposure time (almost)



☺

Observational data / Linear Model Ratio [1/4]

Histogram equalized ok, but should be flat & unstructured



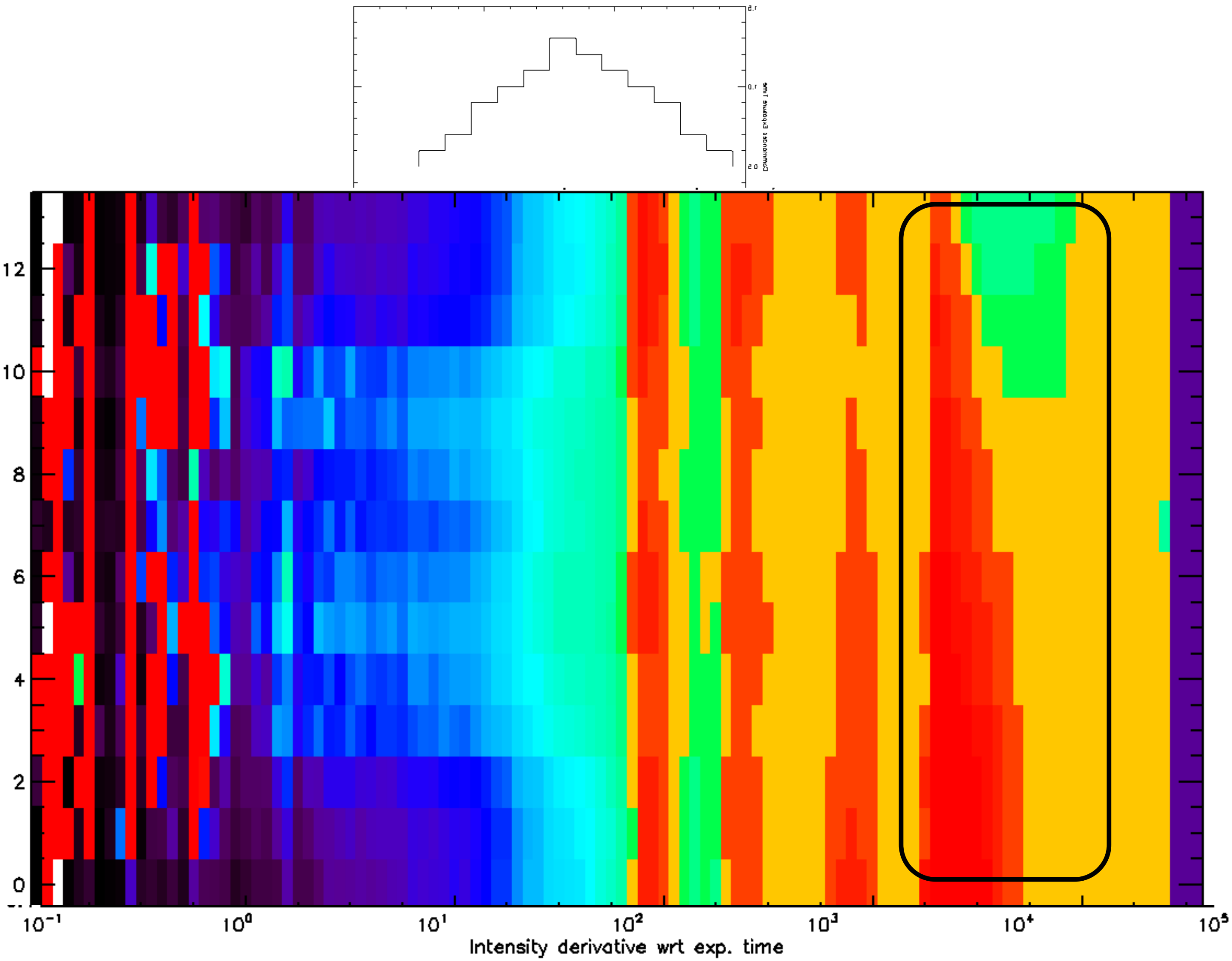
Observational data / Linear Model Ratio [2/4]

Chronology

0.5 sec

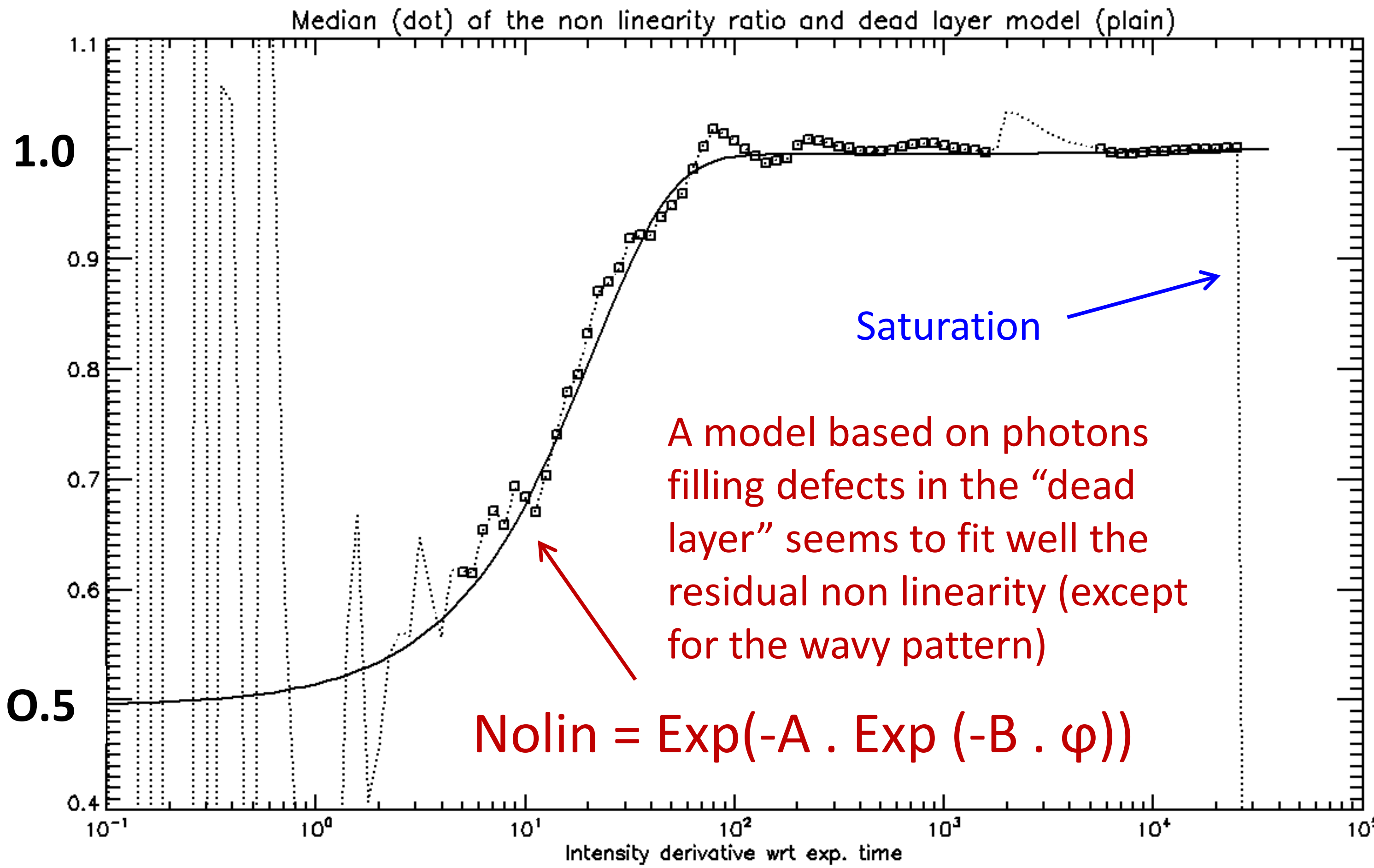
1.3 sec

0.5 sec



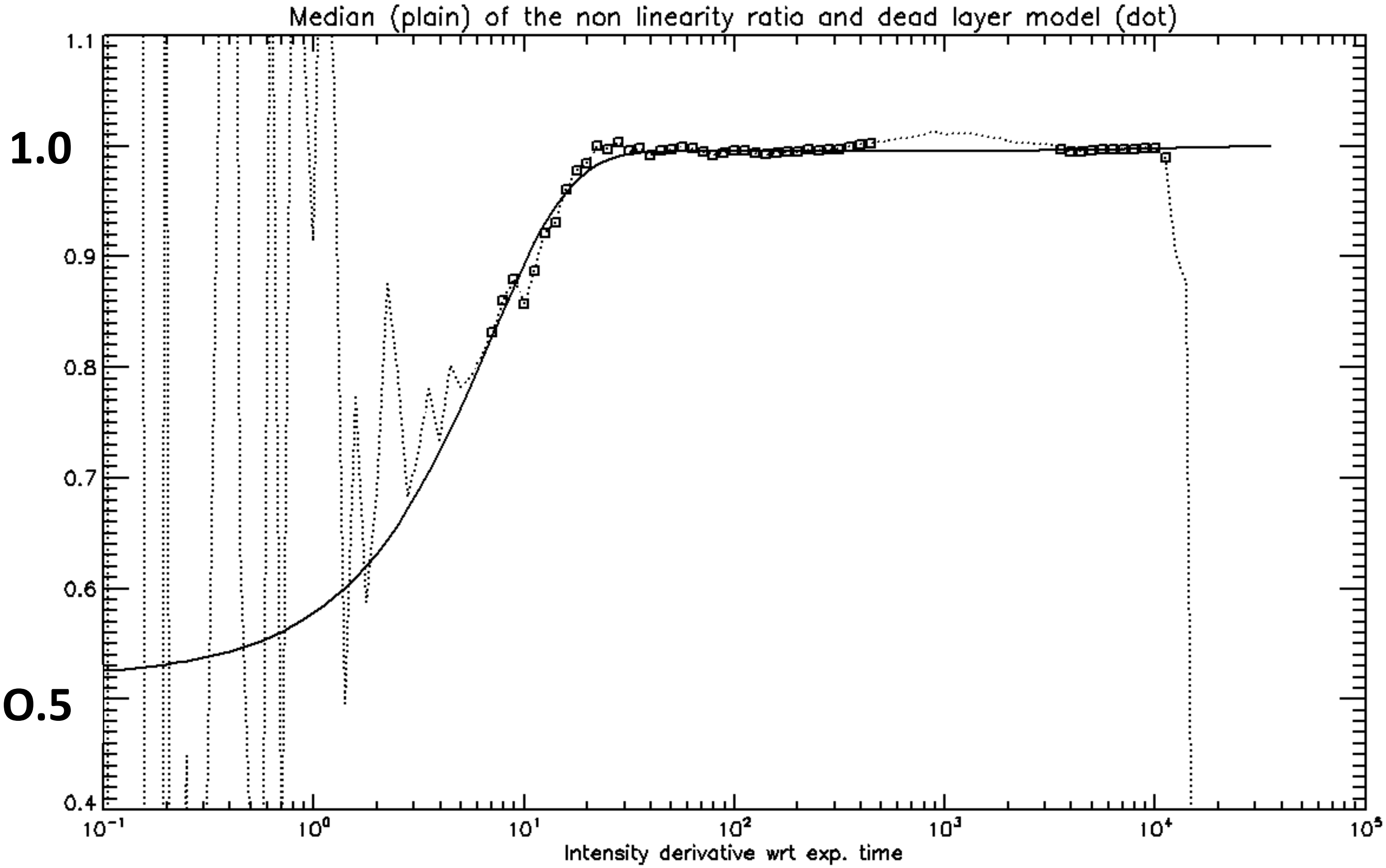
Observational data / Linear Model Ratio [3/4]

535nm (535D)



Observational data / Linear Model Ratio [4/4]

393



Conclusion

- Shutter effect
  - Needs to be corrected, as it otherwise adds false signal
    - 3% locally for a 1 sec commanded exposure
  - Especially important around solar disc center
  - Avoidable *via* CCD or CMOS-APS integration <u>within</u> shutter opening

- CCD non linearity
  - Critical effect below 100 ADU/s
  - Non linearity will affect
    - Scattered light removal
    - Estimation of the bottom part of the radial profile (esp. corner images)
  - Laboratory studies desirable (reality of waves) → EUV

- Do vary exposure in flight