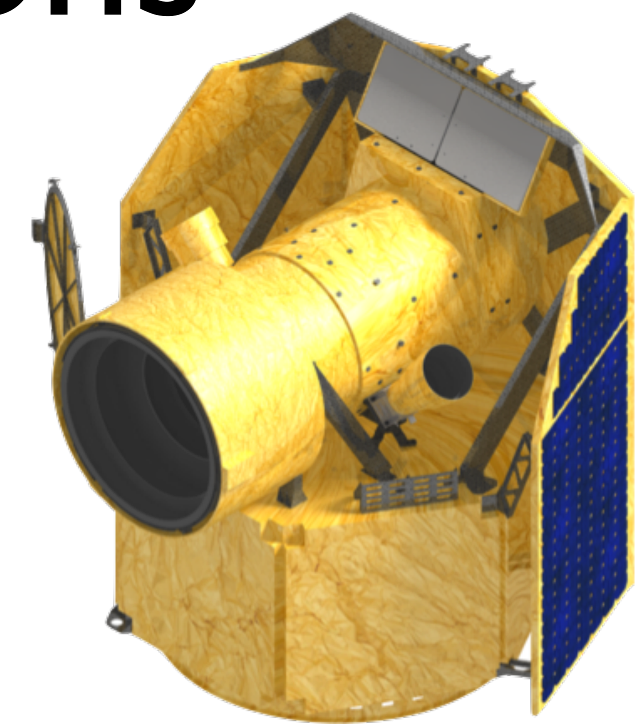
CHEOPS Instrument: Design & Operations



Andrea Fortier
CHEOPS Instrument Scientist

University of Bern

Overview

- Instrument design
- Spacecraft accommodation

Design

- Instrument Schedule

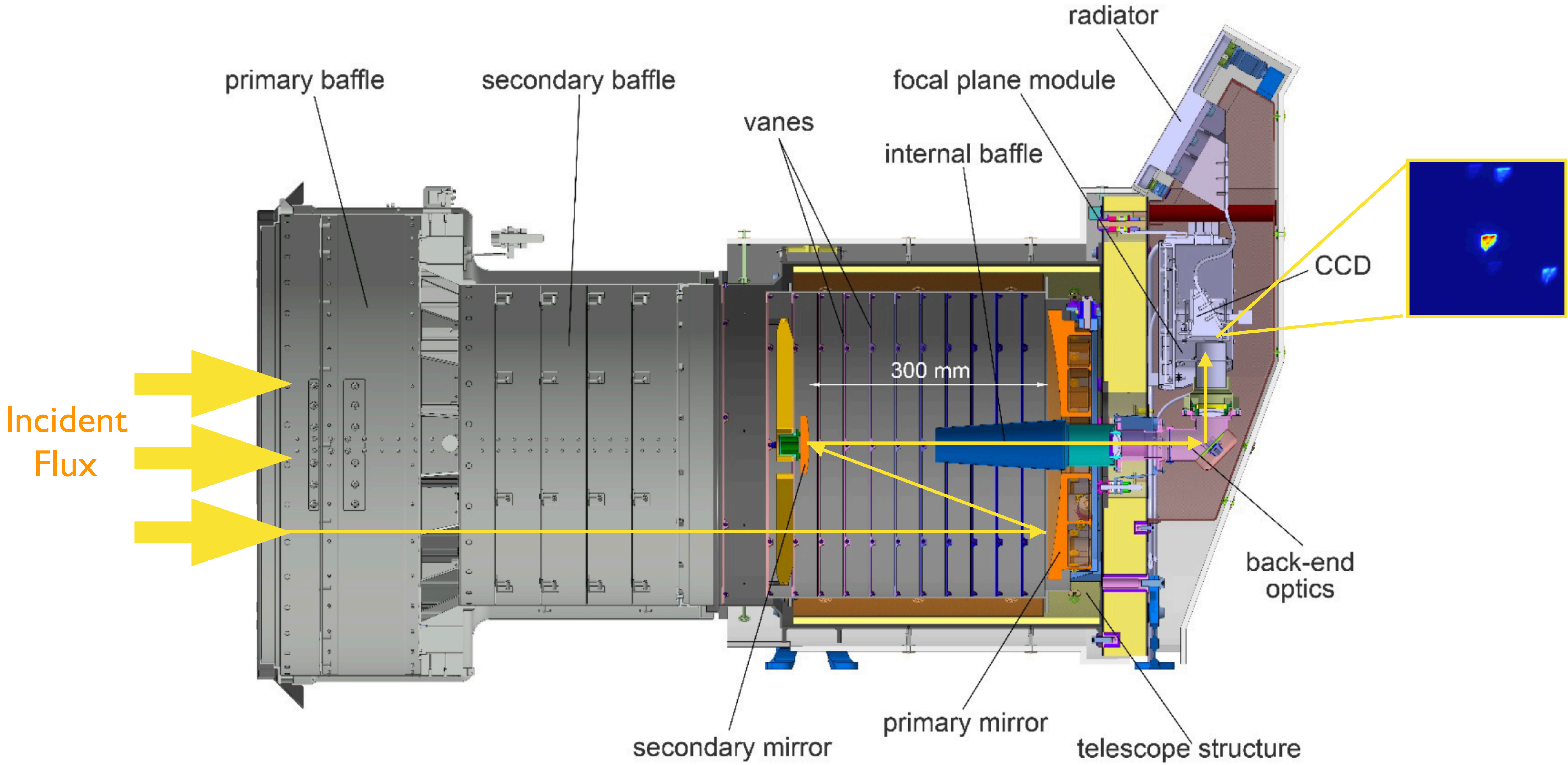
- Focal plane and CCD
- PSF + pointing jitter + flat field
- CHEOPS passband
- Field rotation

Characteristics

- Instrument operations
- CHEOPS science data format

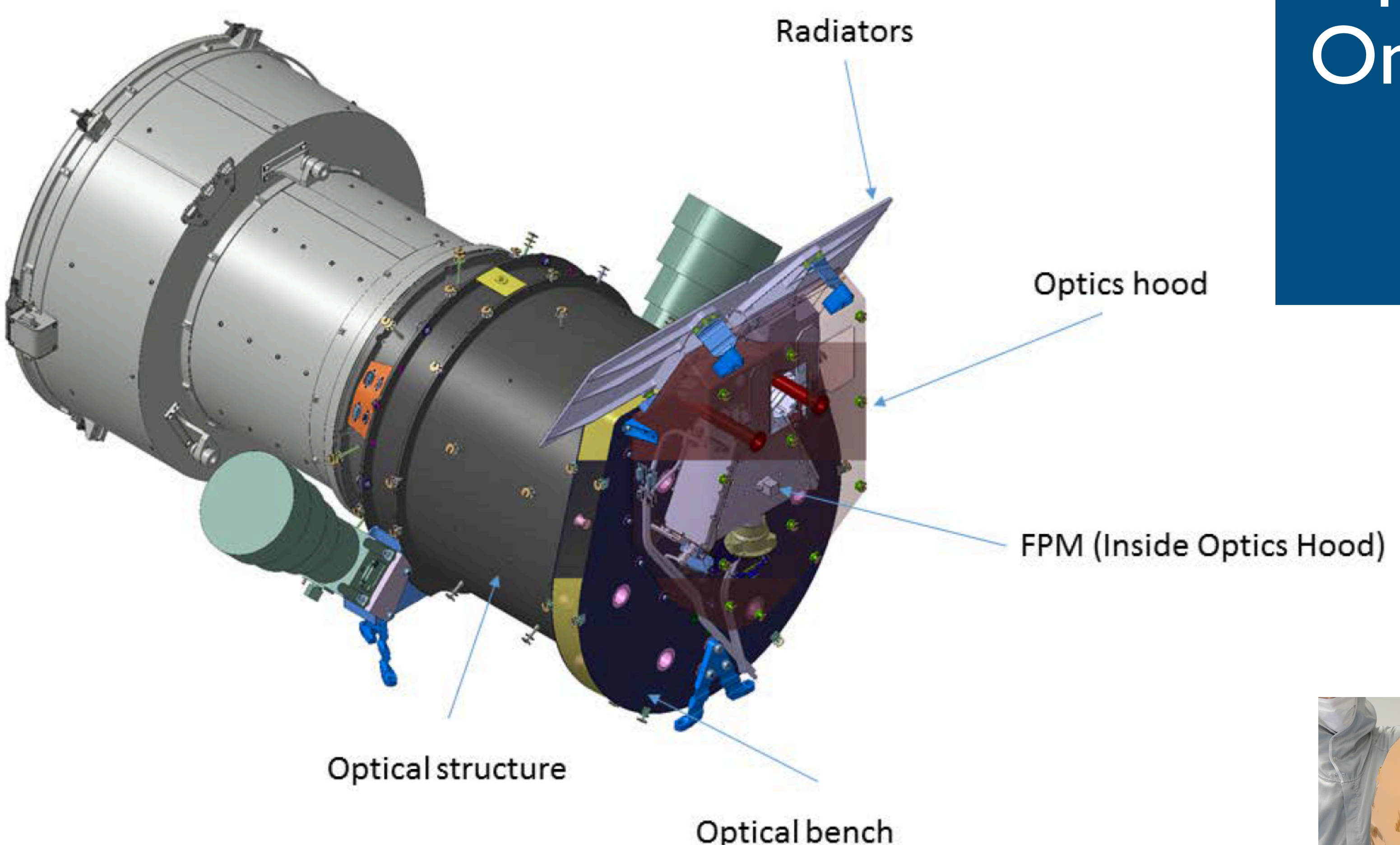
Operations

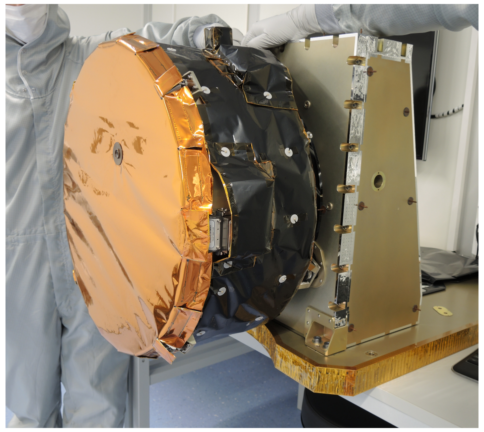
Payload description

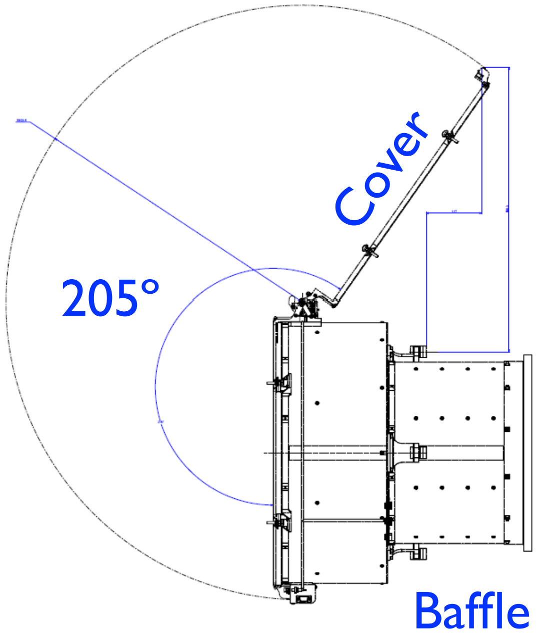


Payload Description

Ritchey-Chretien telescope
30 cm effective aperture
Optical bandpass 330-1100 nm
On-axis carbon fiber structure
Defocused PSF
Payload mass 60 kg

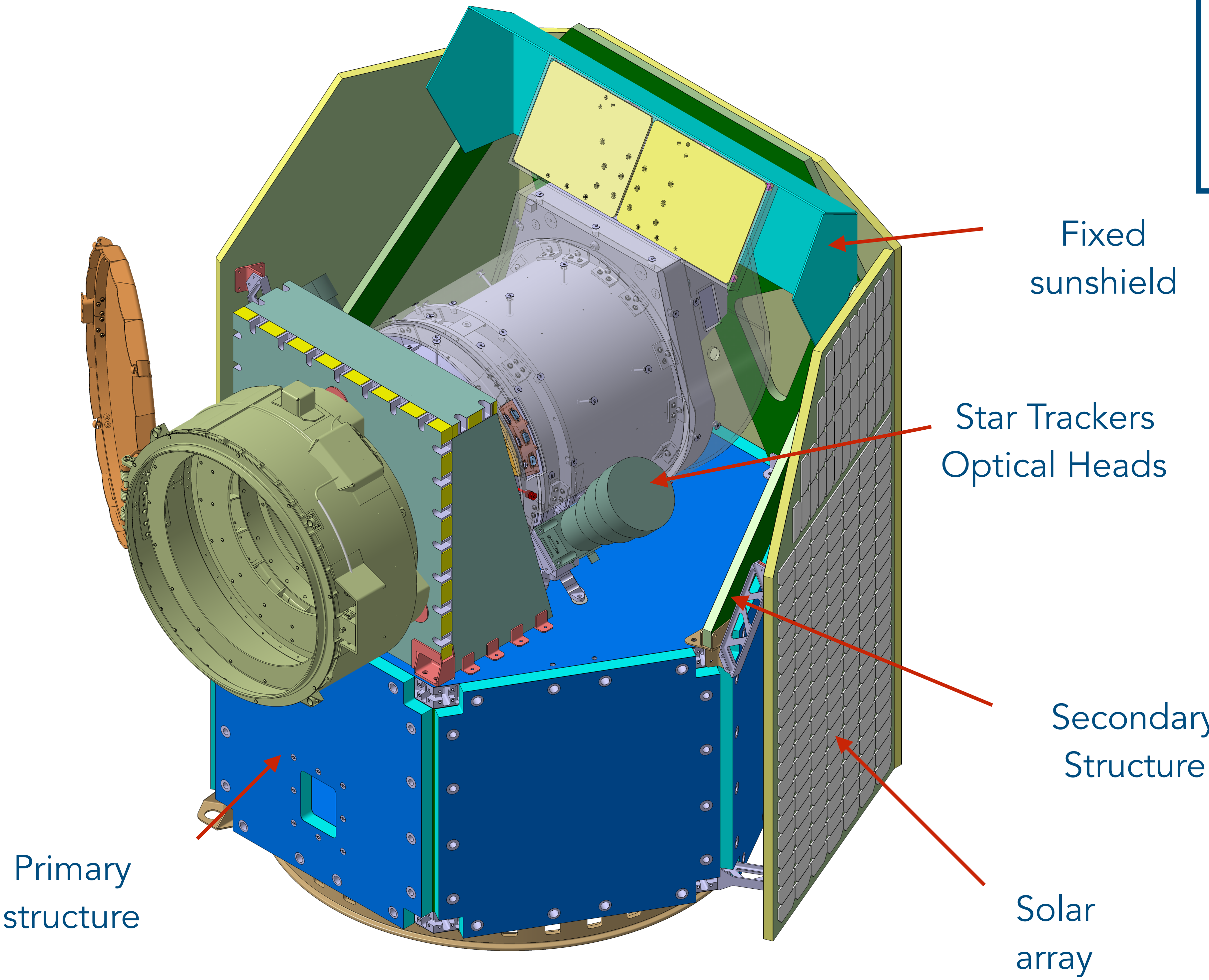


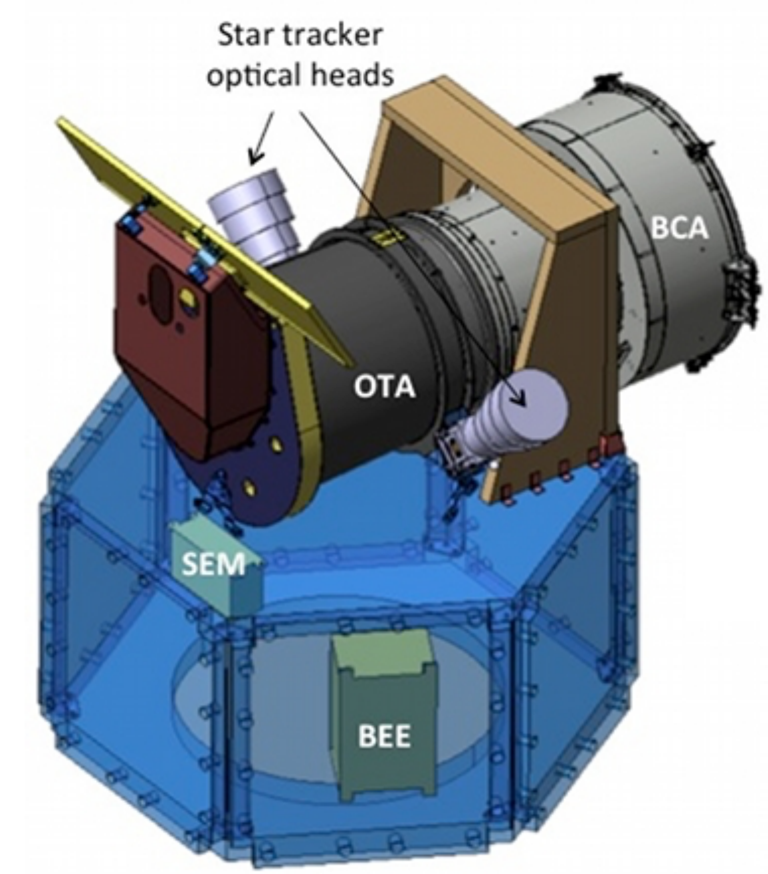




Spacecraft Accommodation

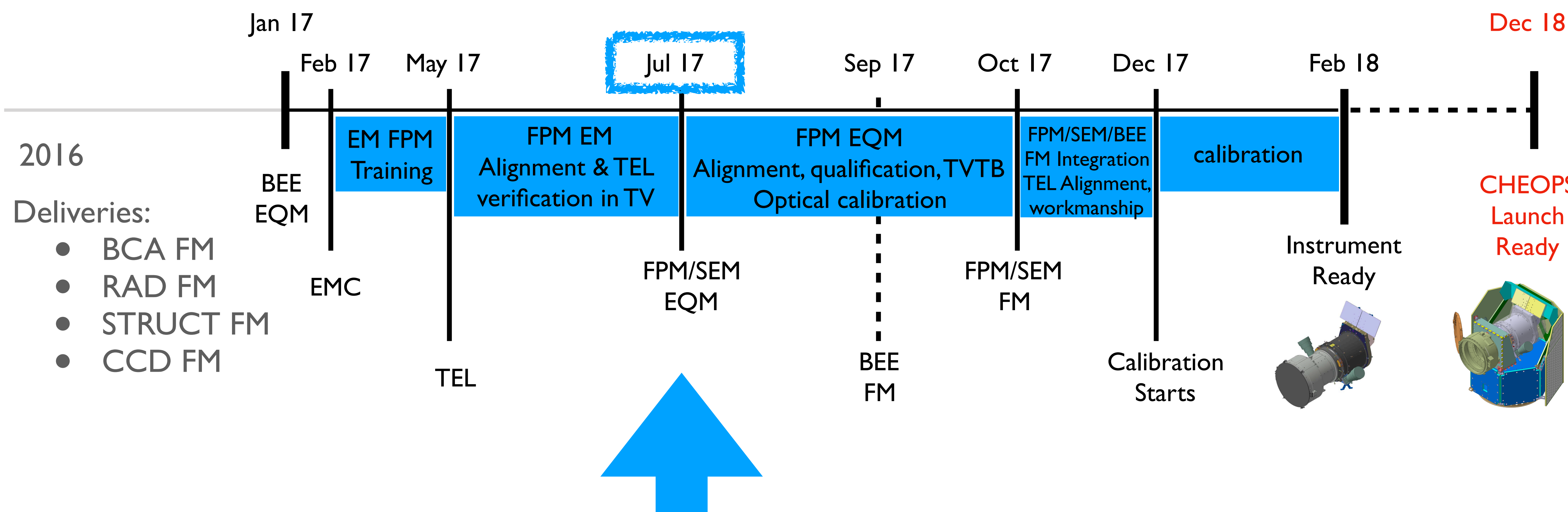
S/C contractor: ECE-CASA
Total satellite weight: 280 kg
Telemetry: 1.2 Gbit/day (S-band)
Pointing precision: 4”rms





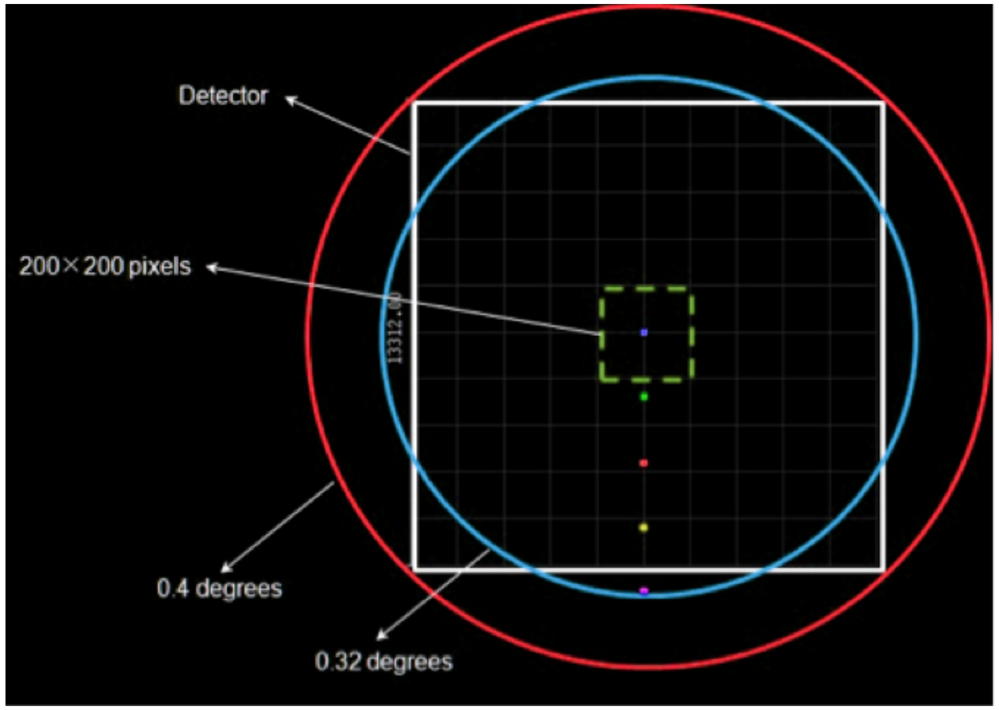
Instrument Schedule

2017-2018

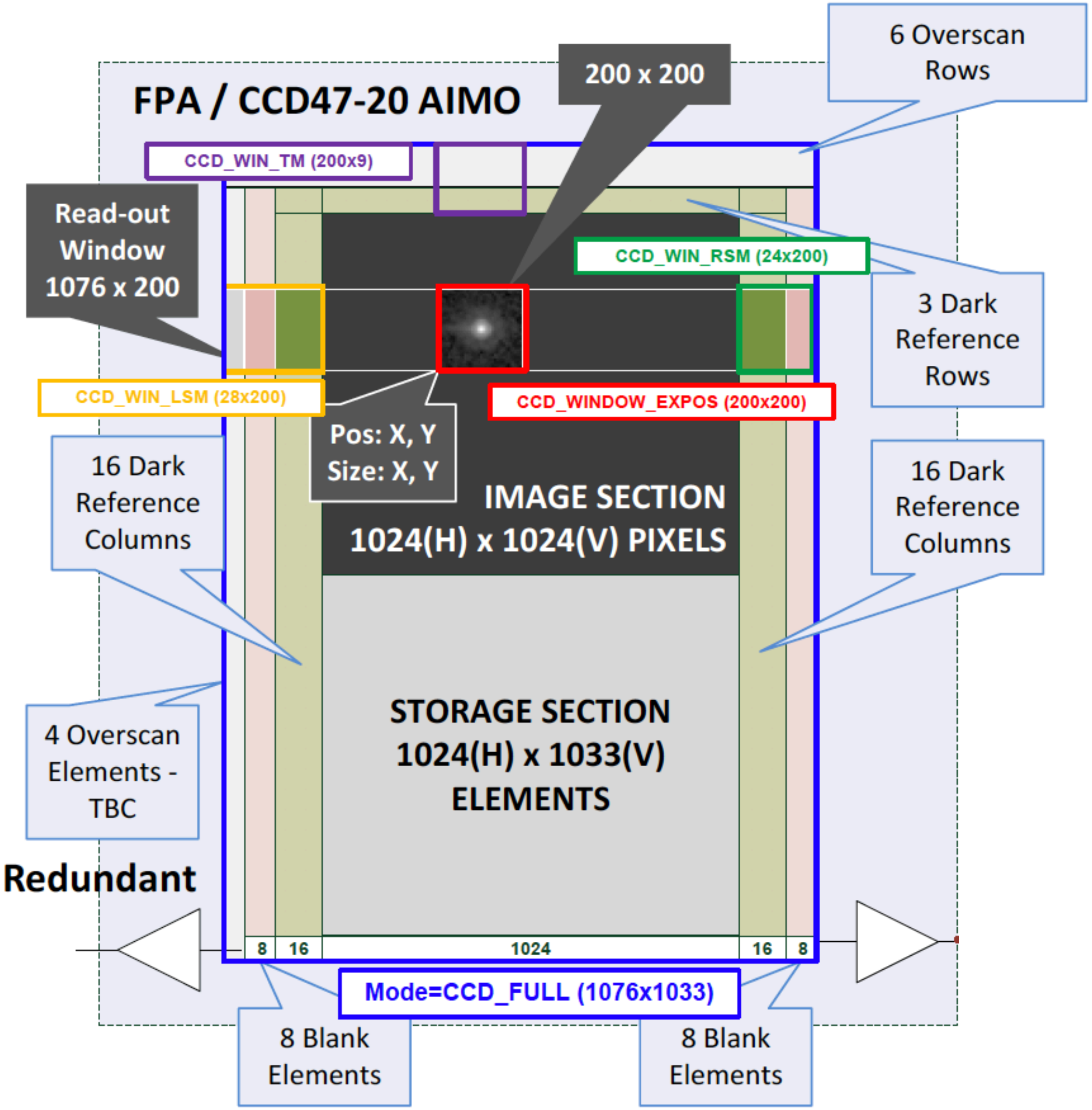


BCA: Baffle and Cover Assembly
BEE: Back End Electronics Box
EM: Engineering Model
EMC: Electromagnetic Compatibility Test
EQM: Engineering Qualification Model
FM: Flight Model
FPM: Focal Plane Module
RAD: Radiators
SEM: Sensor Electronics Module
STRUCT: Telescope Structure
TEL: Telescope (Optics + Structure)

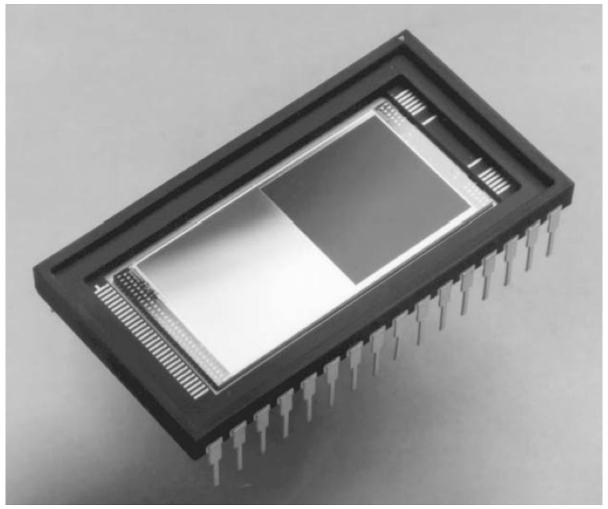
Focal Plane and CCD



CHEOPS Field of View: 17′×17′
plate scale: 1 arcsec = 1 pixel
CCD image section = 1024×1024 px



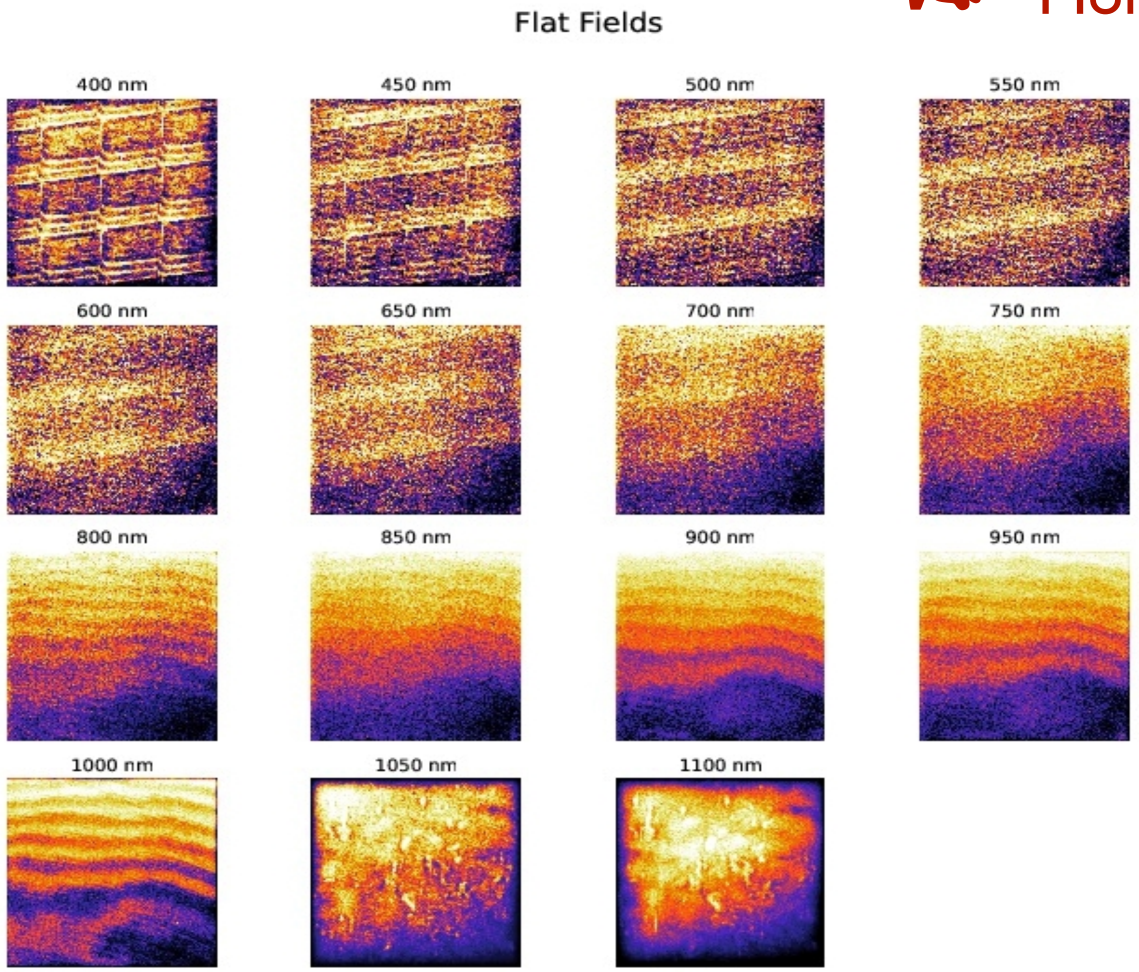
Frame-transfer CCD,
e2v CCD47-20 AIMO



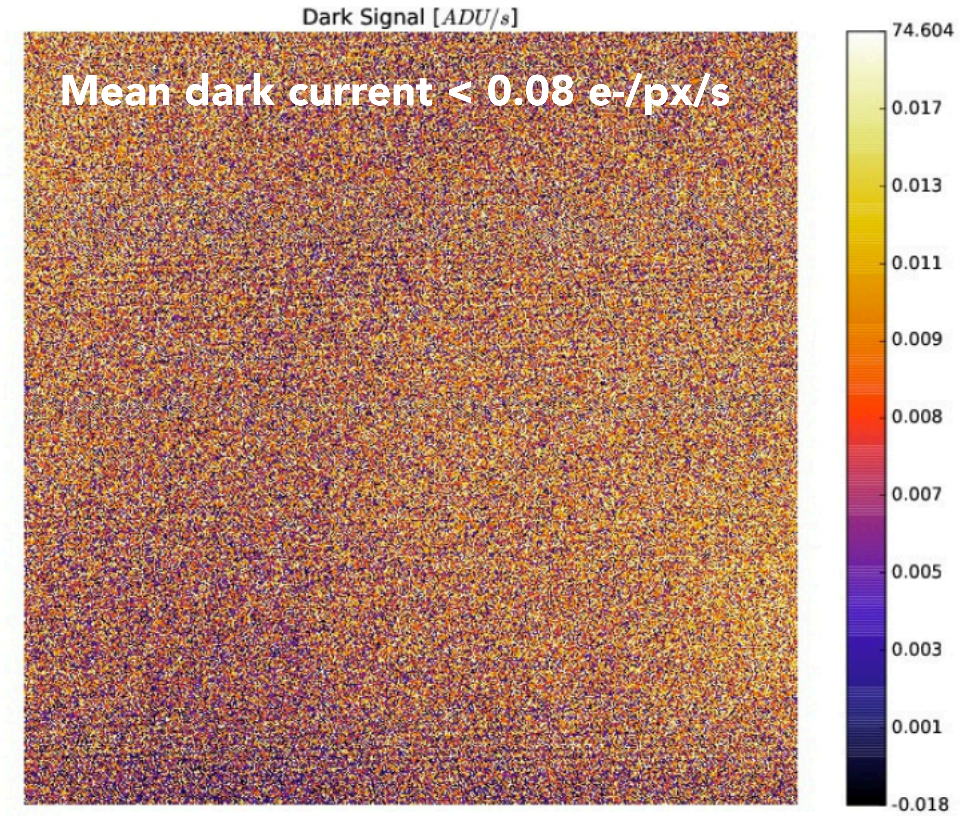
Stabilized @ -40°C to 10 mK

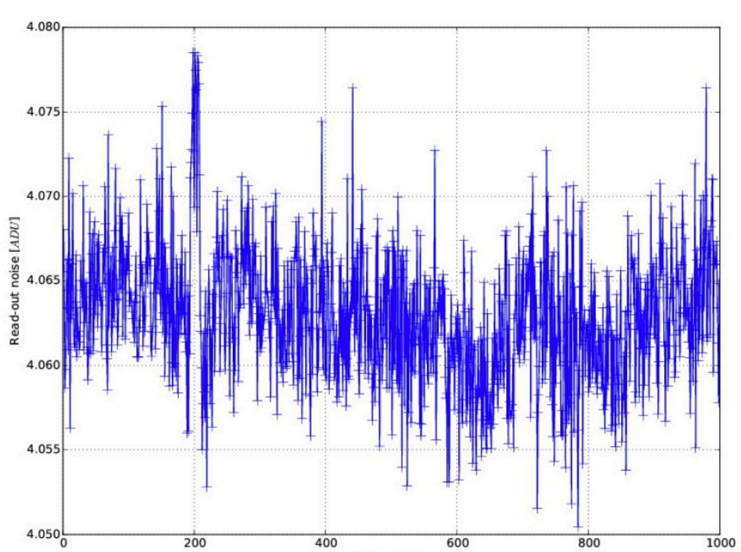
CHEOPS Flight detector characterisation completed

More in A. Deline's talk



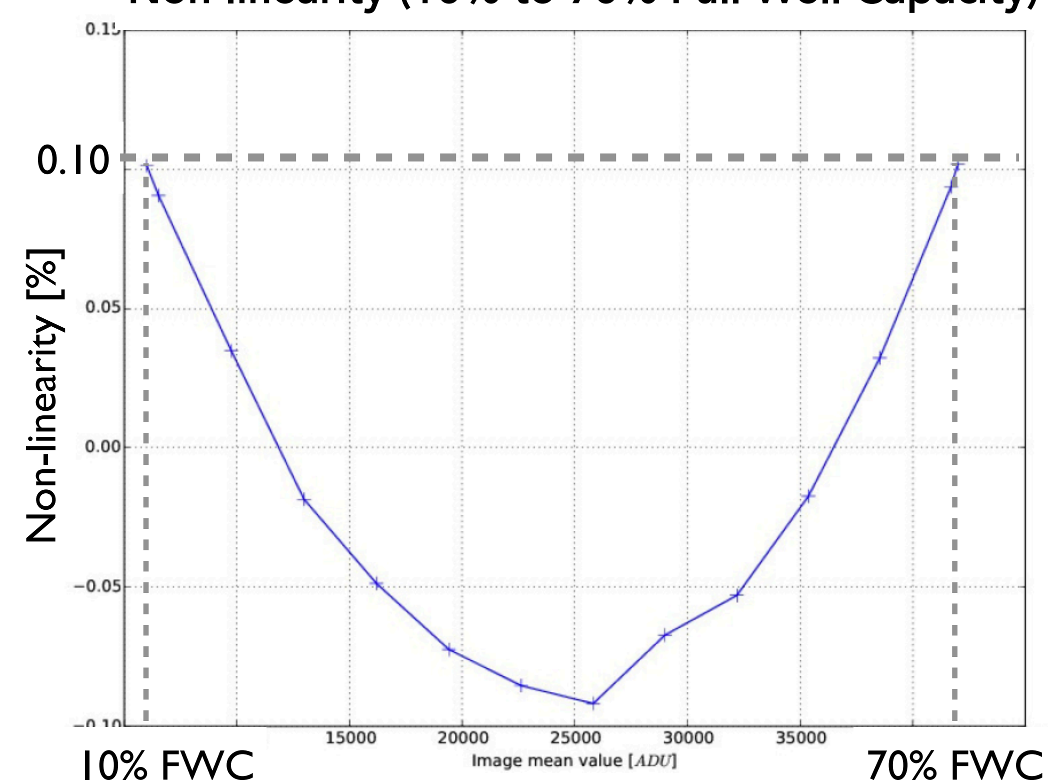
Flat field knowledge better than 0.1%





Detector read-out noise < 10 e-/px

Non-linearity (10% to 70% Full Well Capacity)



Detector non-linearity.

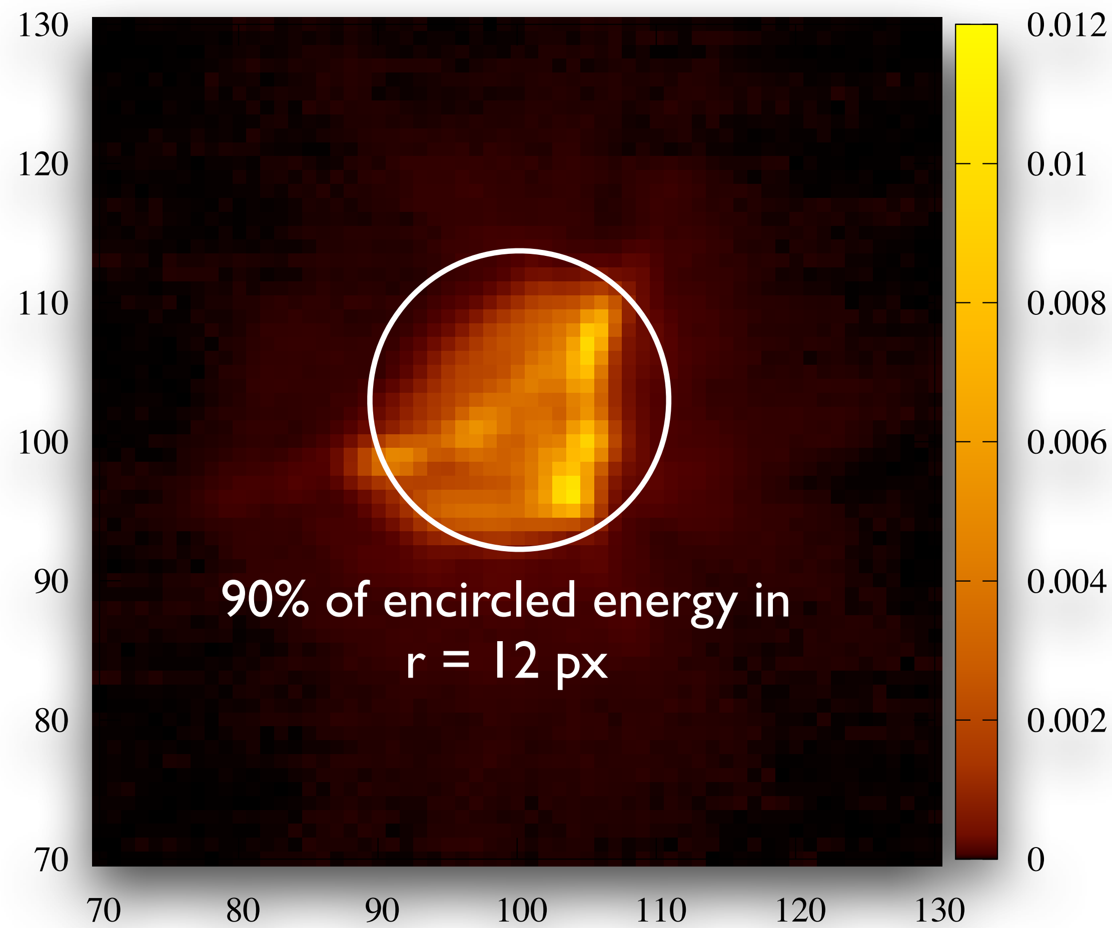
FWC of FM CCD ~132'000 e-/px

CHEOPS

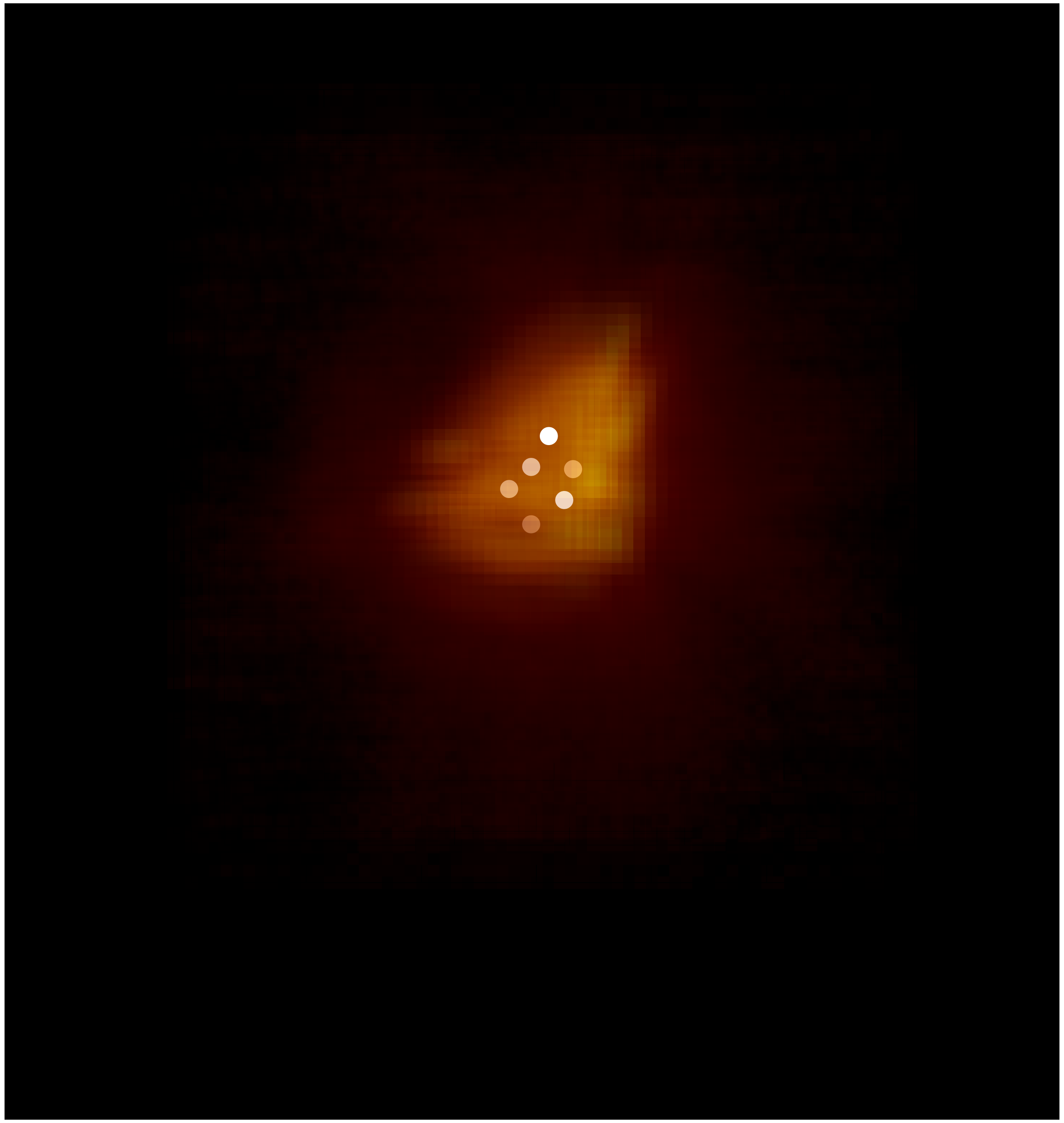
PSF, pointing jitter and flat field

esa

Defocused PSF

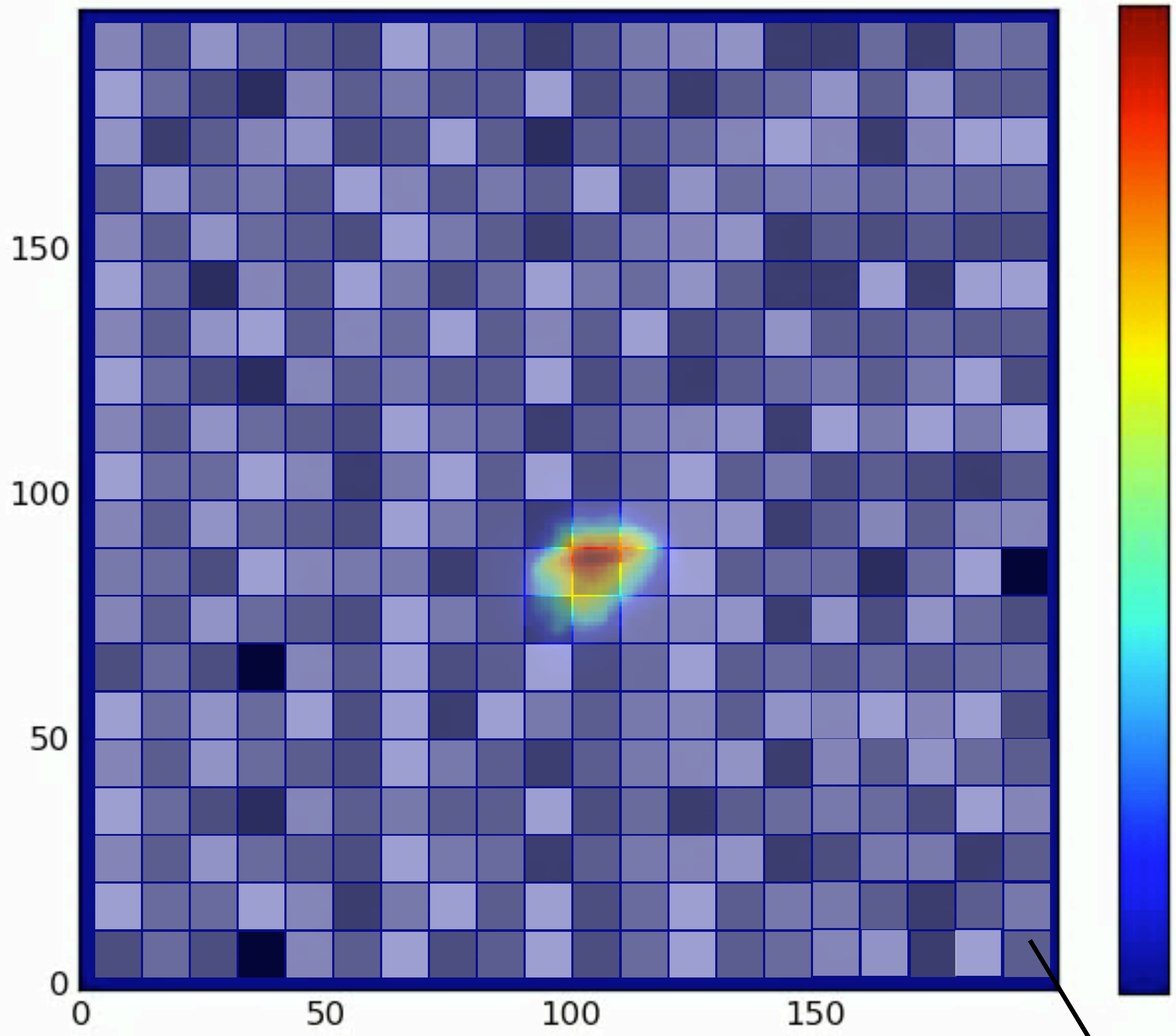


Jitter effect



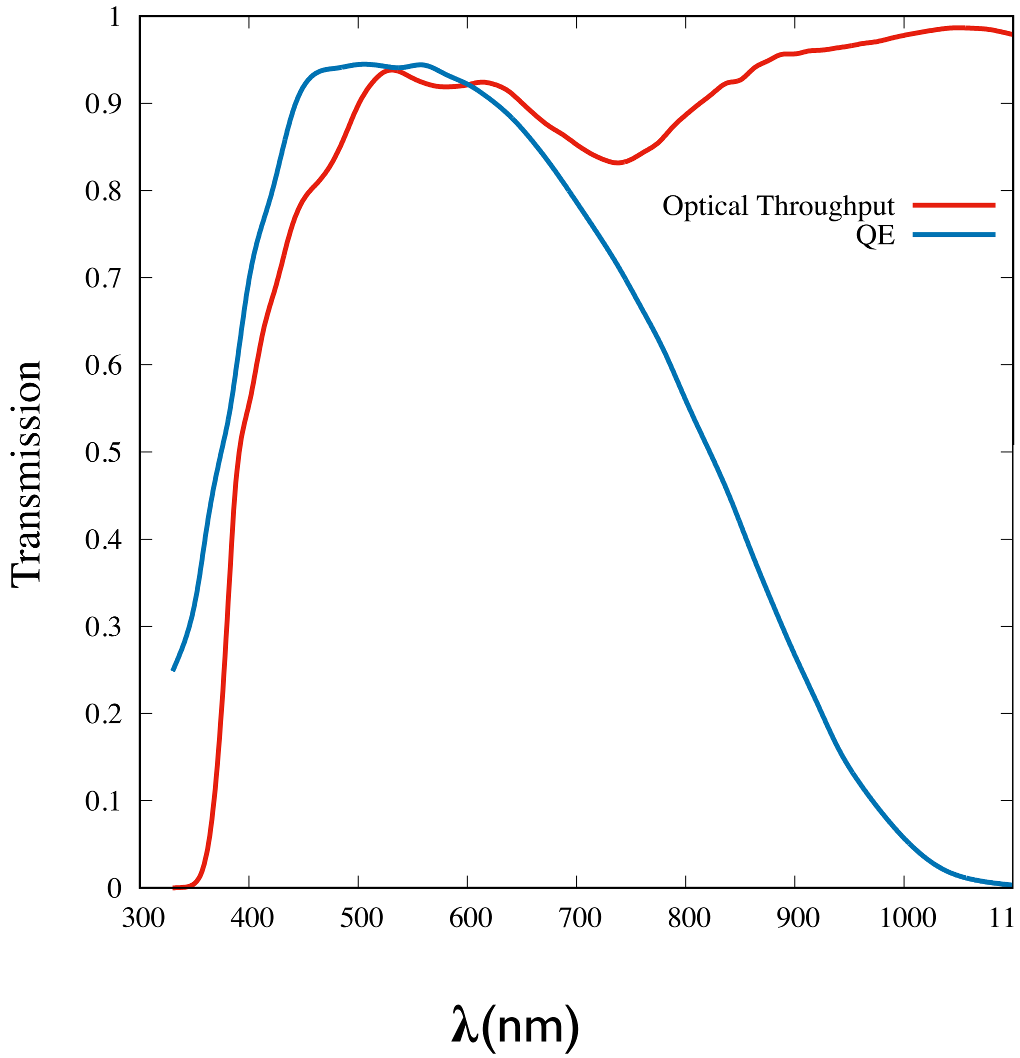
PSF, pointing jitter and flat field

Defocused PSF to mitigate the noise produced by the combination of pixel response non-uniformity and pointing precision.

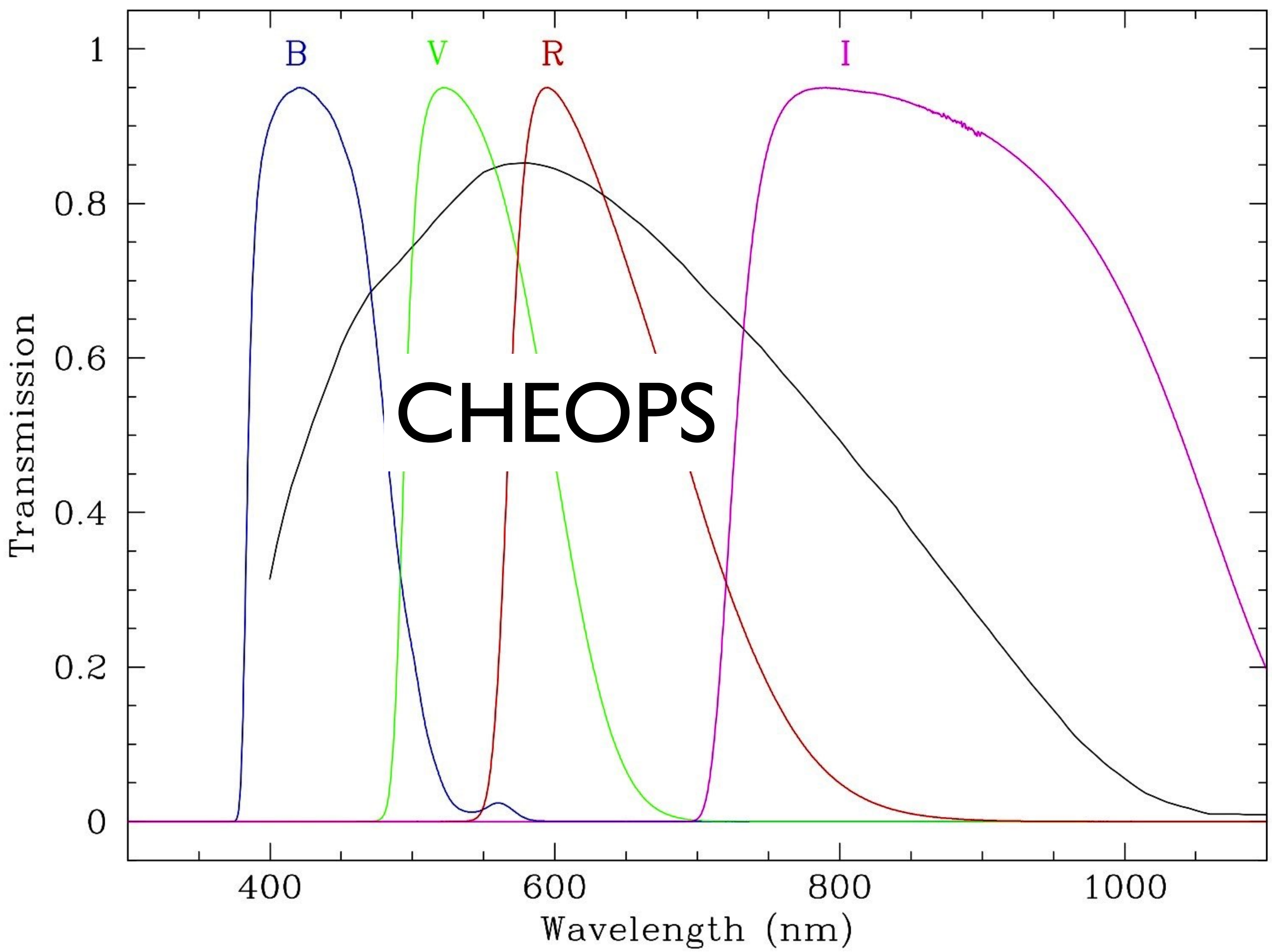


1 ■ = 10 px

Passband and global transmission

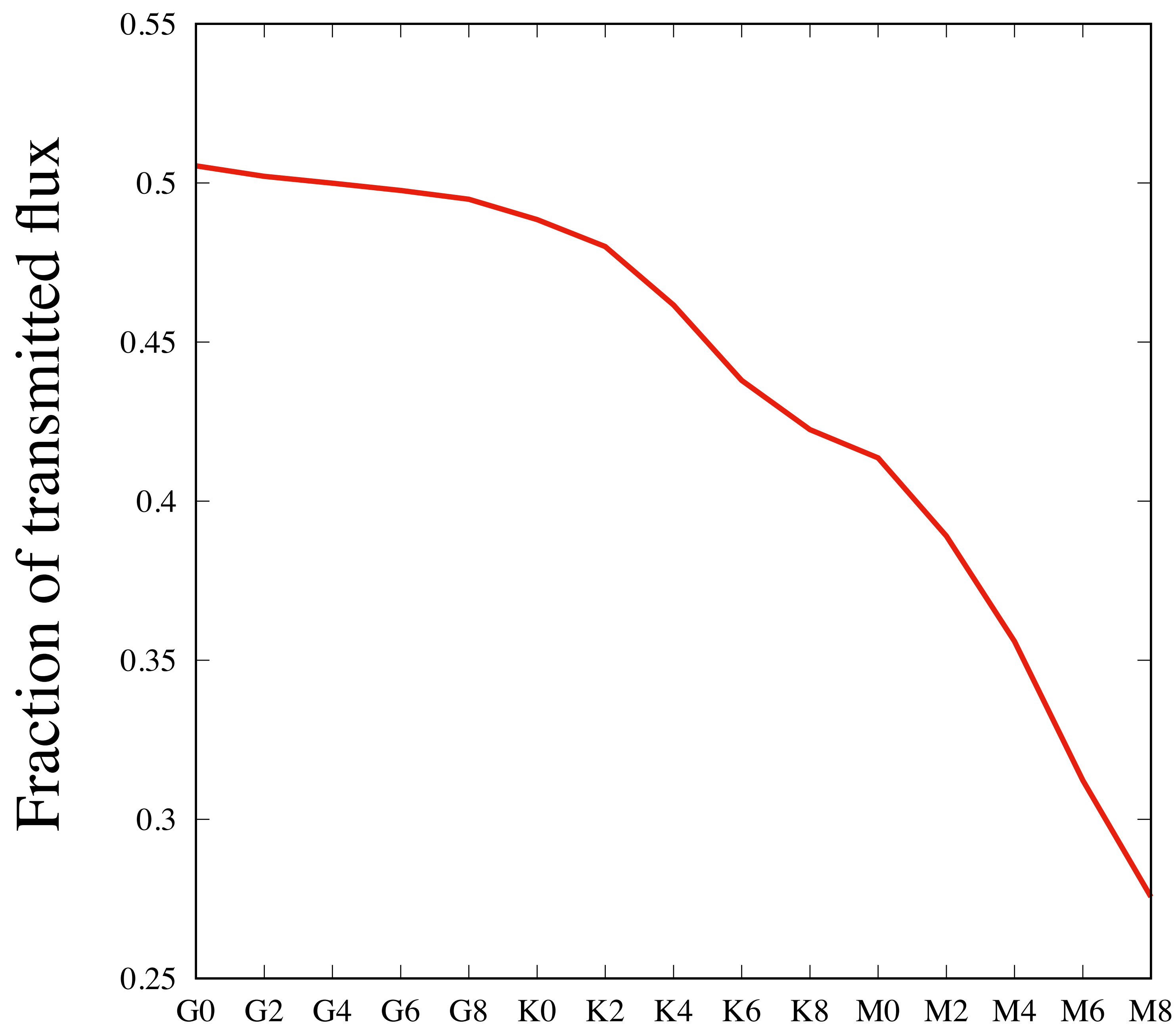


Johnson's filters B,V, R, I as reference



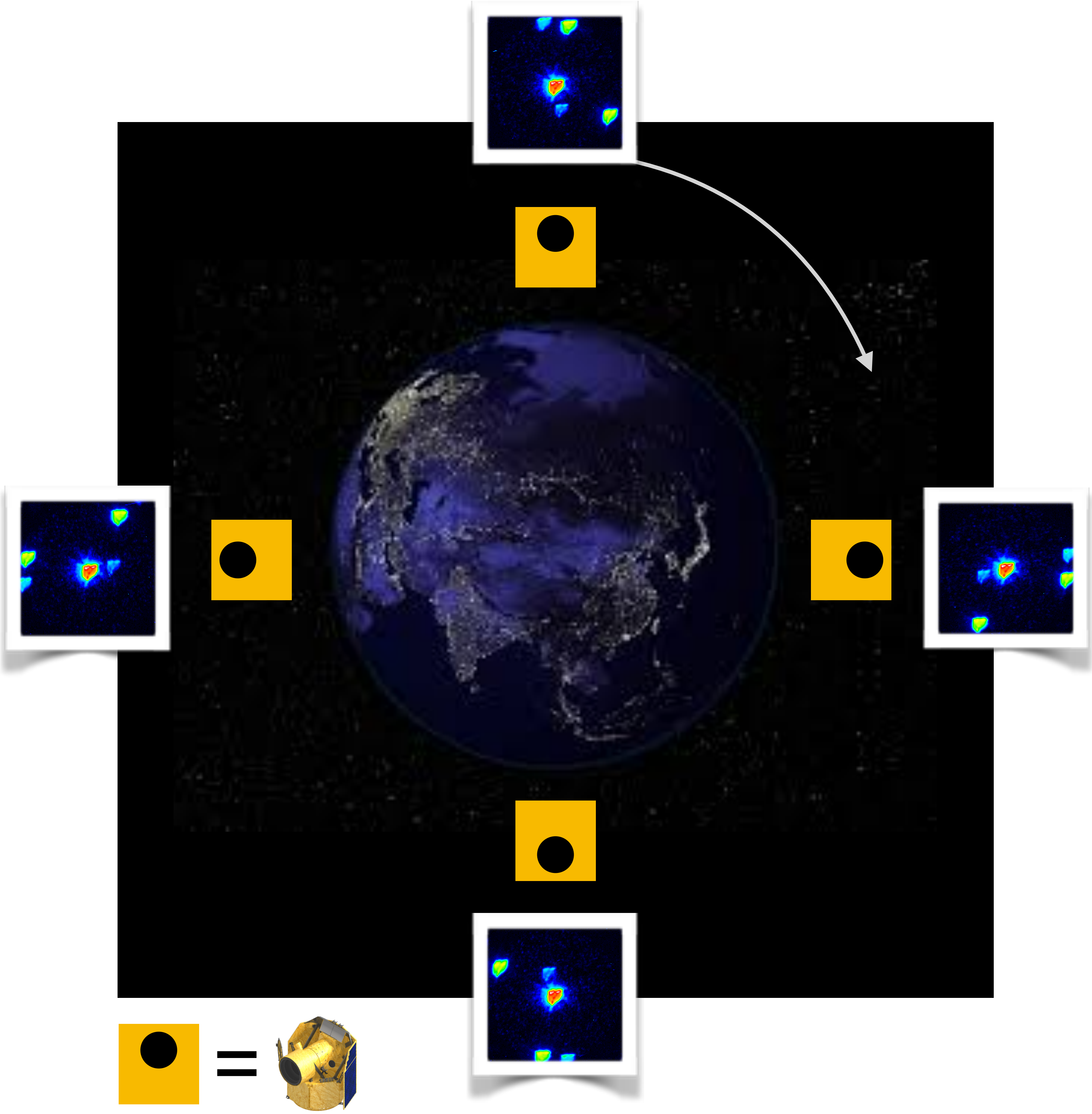
Passband and global transmission

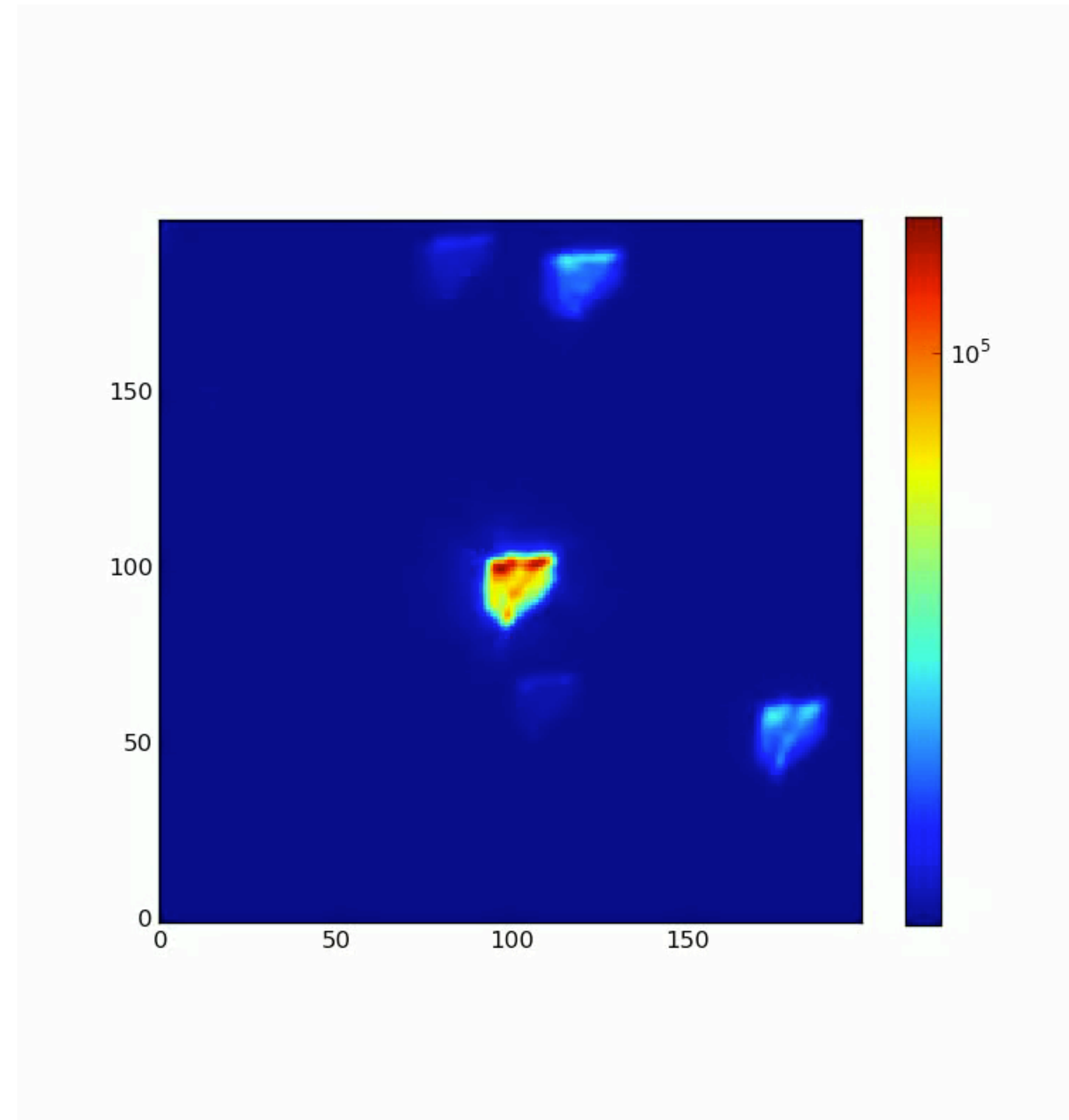
Global Transmission as a function of the stellar spectral type.



Field Rotation

Field Rotation





For thermal stability the radiators are always opposite to the Earth

CHEOPS Data Rate

SciReq 5.1 **Temporal resolution of the measurements (L1)**

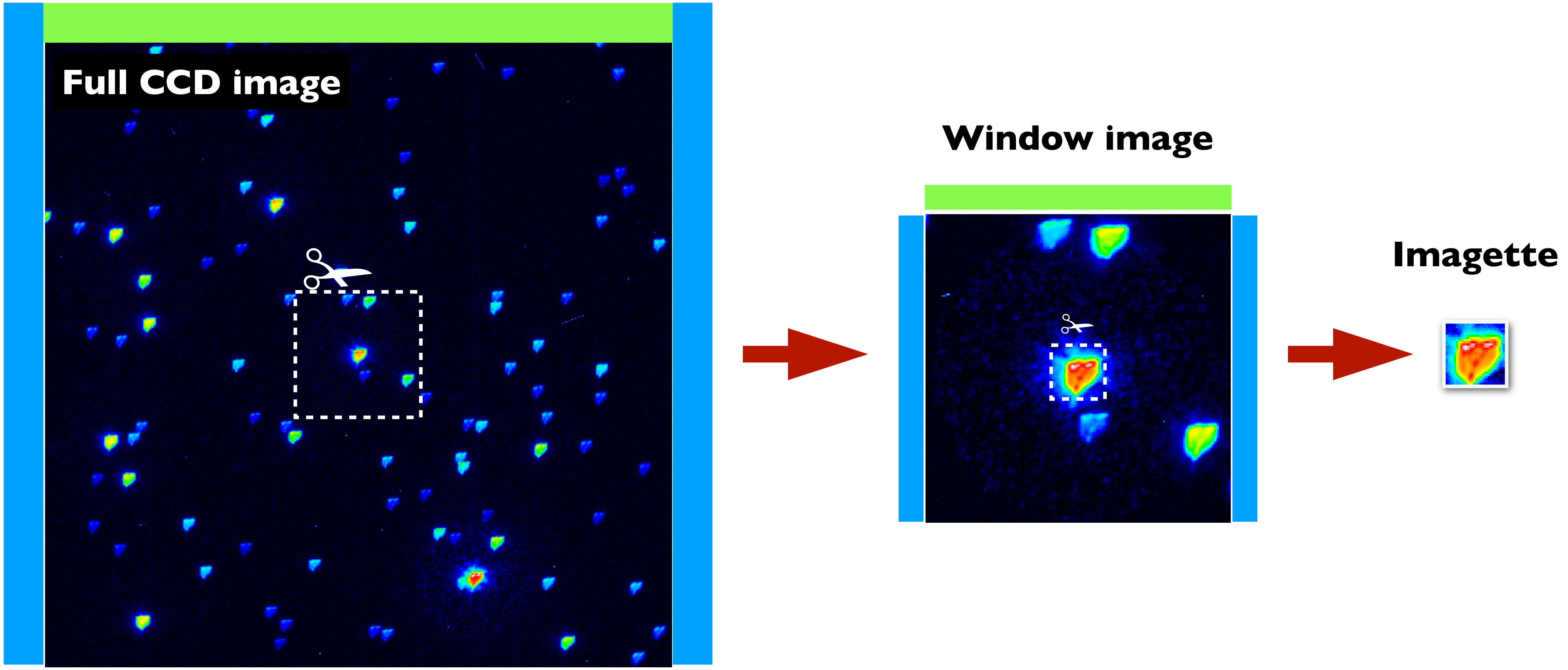
CHEOPS shall be able to provide one photometric measurement per minute (goal: one per 30 seconds) in order to characterise the transit light curves of Neptune-size planets (SciReq 1.2).

In particular, this requirement will enable the ingress and egress phases to be temporally resolved, which will in turn lift the degeneracy between the impact parameter and the transit duration.

CHEOPS

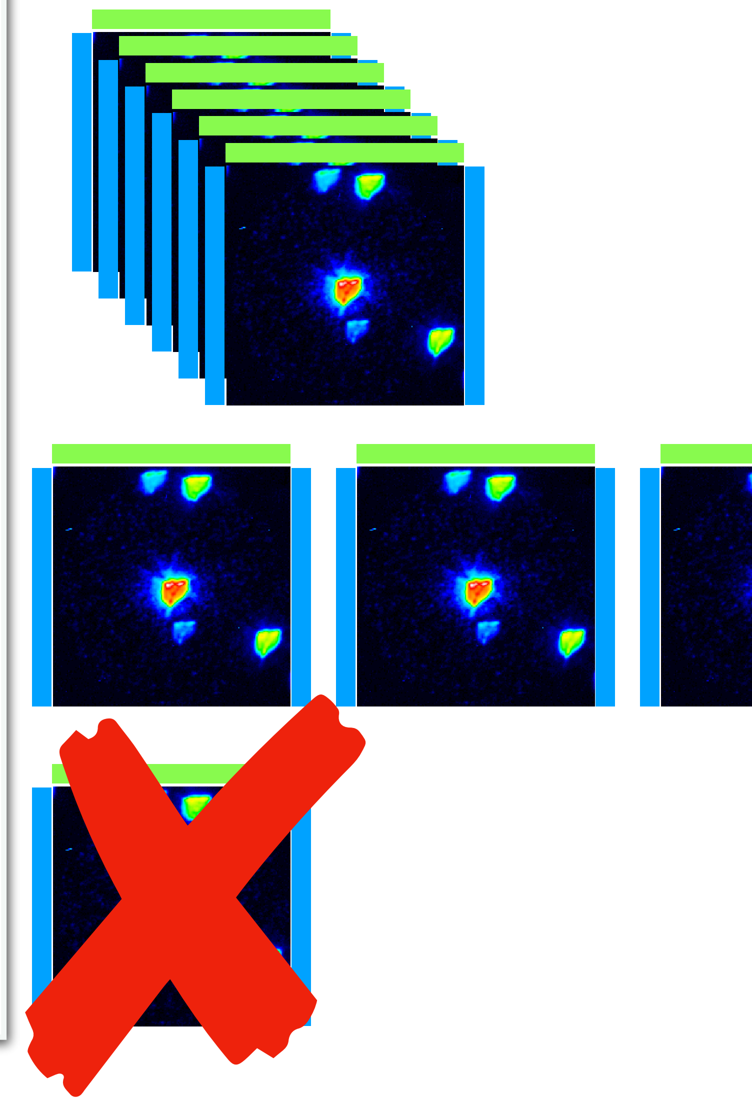
Image types

Image types	Description
Window image	
Exposed window	Selected section of the CCD image. In the nominal case, it contains the exposed target star in its centre. The shape, size and location in the CCD are configurable parameters.
CCD side margins	Section of the dark, blank and overscan columns that are in the same CCD stripe of the exposed window.
CCD top margin	Section of the dark and overscan rows that correspond to the exposed window columns.
Full CCD images	Full-frame image: exposed section plus CCD margins (1076×1027 pixels)
Imagette	Small window image that contains only the PSF

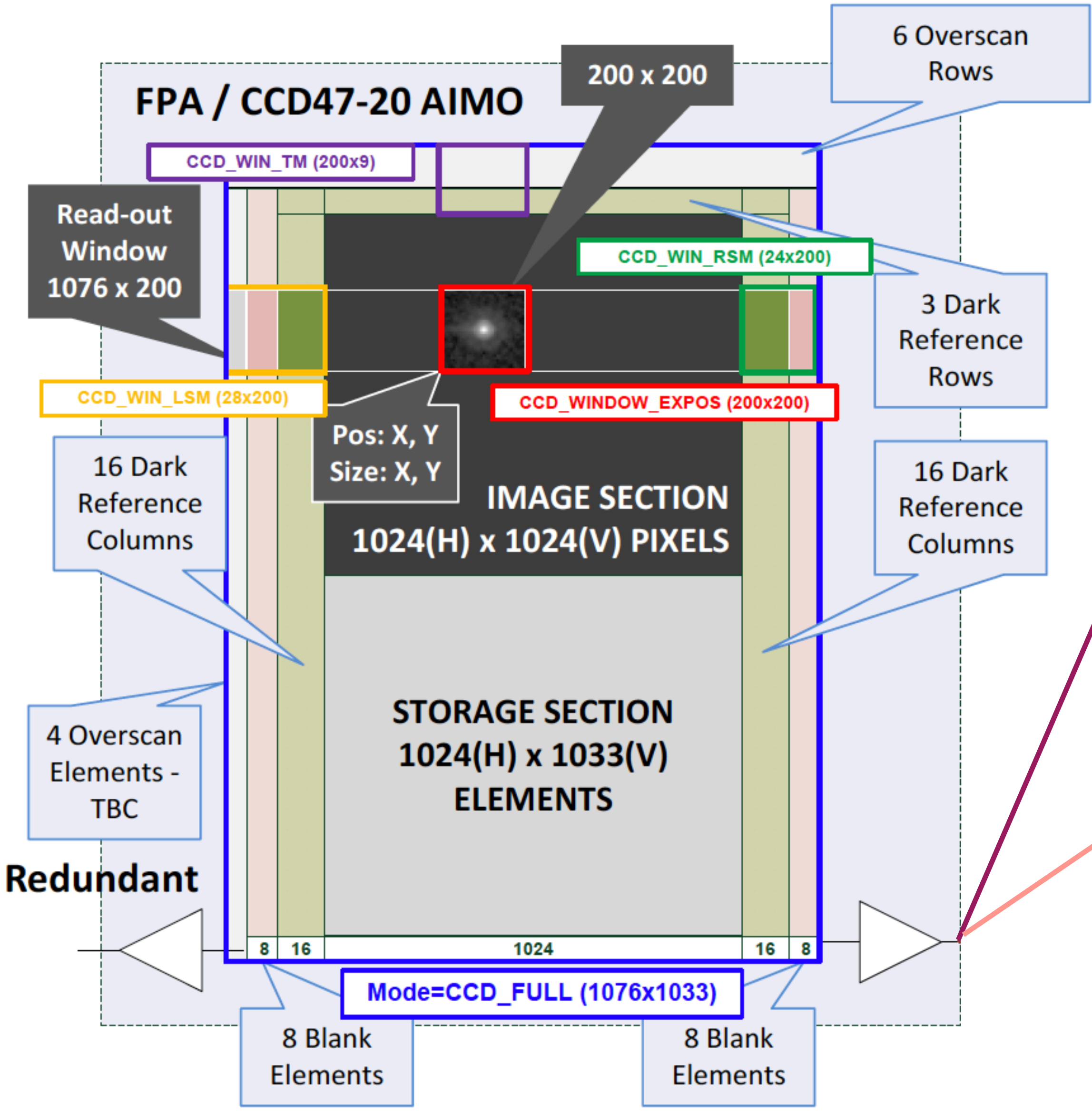


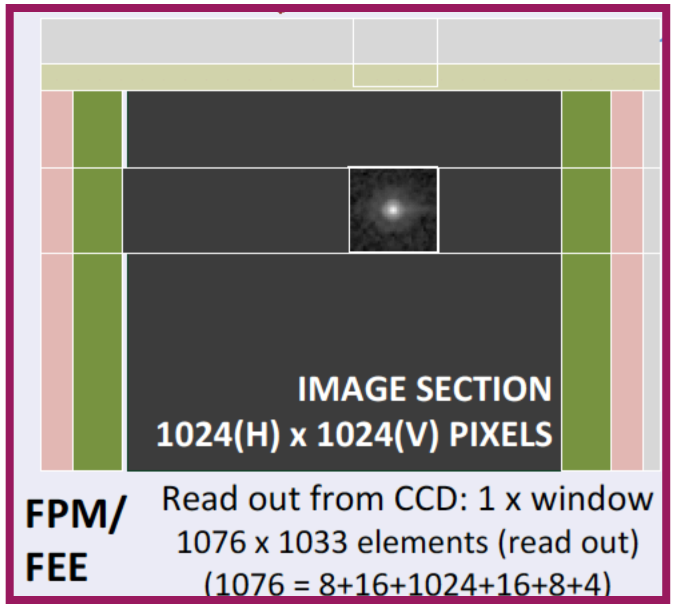
On-board image processing methods

On-board image processing methods		
1	STACK	In STACK mode, individual exposures are COMBINEd into one single image that is downloaded to the ground. Before being COMBINEd, each exposure is processed by one or more science algorithms. Note that, in general, an imagette of the PSF is saved and download to the ground for each individual exposure, before combination.
2	SNAP	In SNAP mode, individual exposures (images with an exposure time t_{exp}) are all saved and downloaded to the ground.
3	DROP	In DROP mode, individual exposures (images with an exposure time t_{exp}) are used for specific functions (e.g. centroid generation) but not stored and/or downloaded to the ground. These images are DISCARDed.



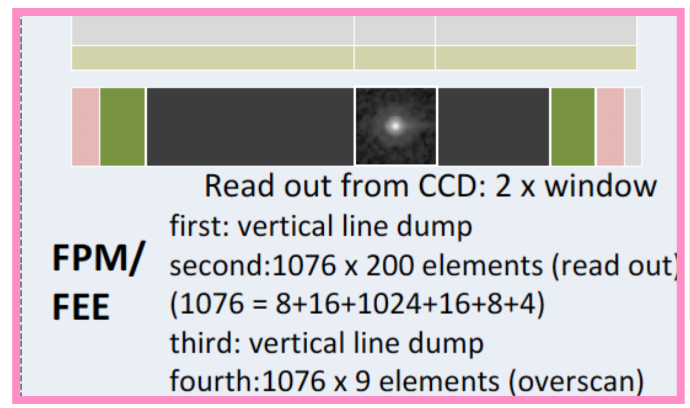
Read Out Modes





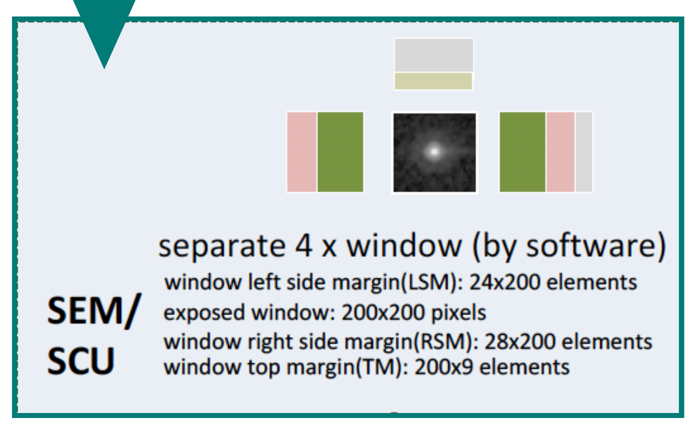
CCD Full:
0.001 ≤ Exposure time [s] ≤ 60
Read Out complete CCD= 5 s
Read Out clock= 230 kHz

CCD Window Faint:
12 ≤ Exposure time [s] ≤ 60
Read Out complete CCD= 12 s
Read Out clock= 100 kHz
Exposure and Read Out in parallel



CCD Window Bright:
1 ≤ Exposure time [s] ≤ 12
Read Out complete CCD= 1 s
Read Out clock= 230 kHz
Exposure and Read Out in parallel

CCD Window Ultrabright:
0.001 ≤ Exposure time [s] ≤ 1
Read Out complete CCD= 1 s
Read Out clock= 230 kHz
Read Out after exposure

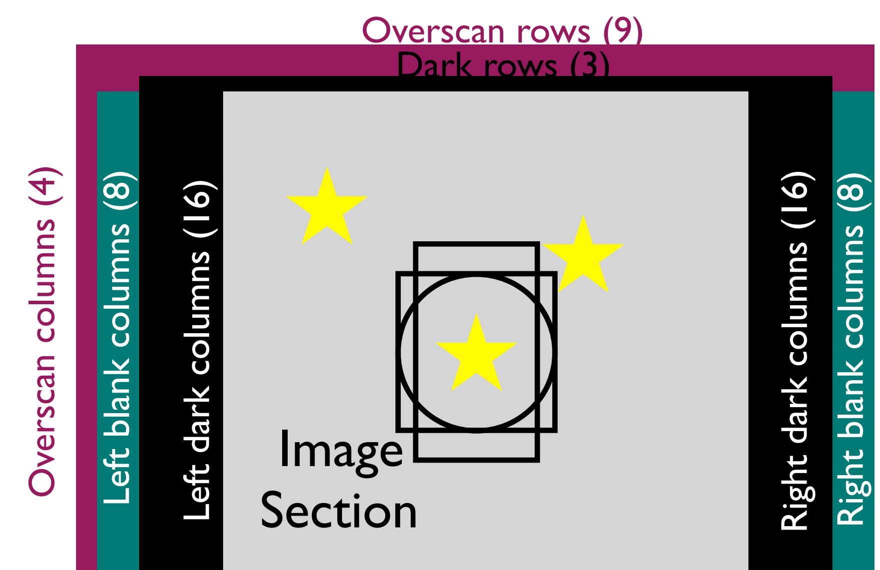


To DPU

Flexibility:

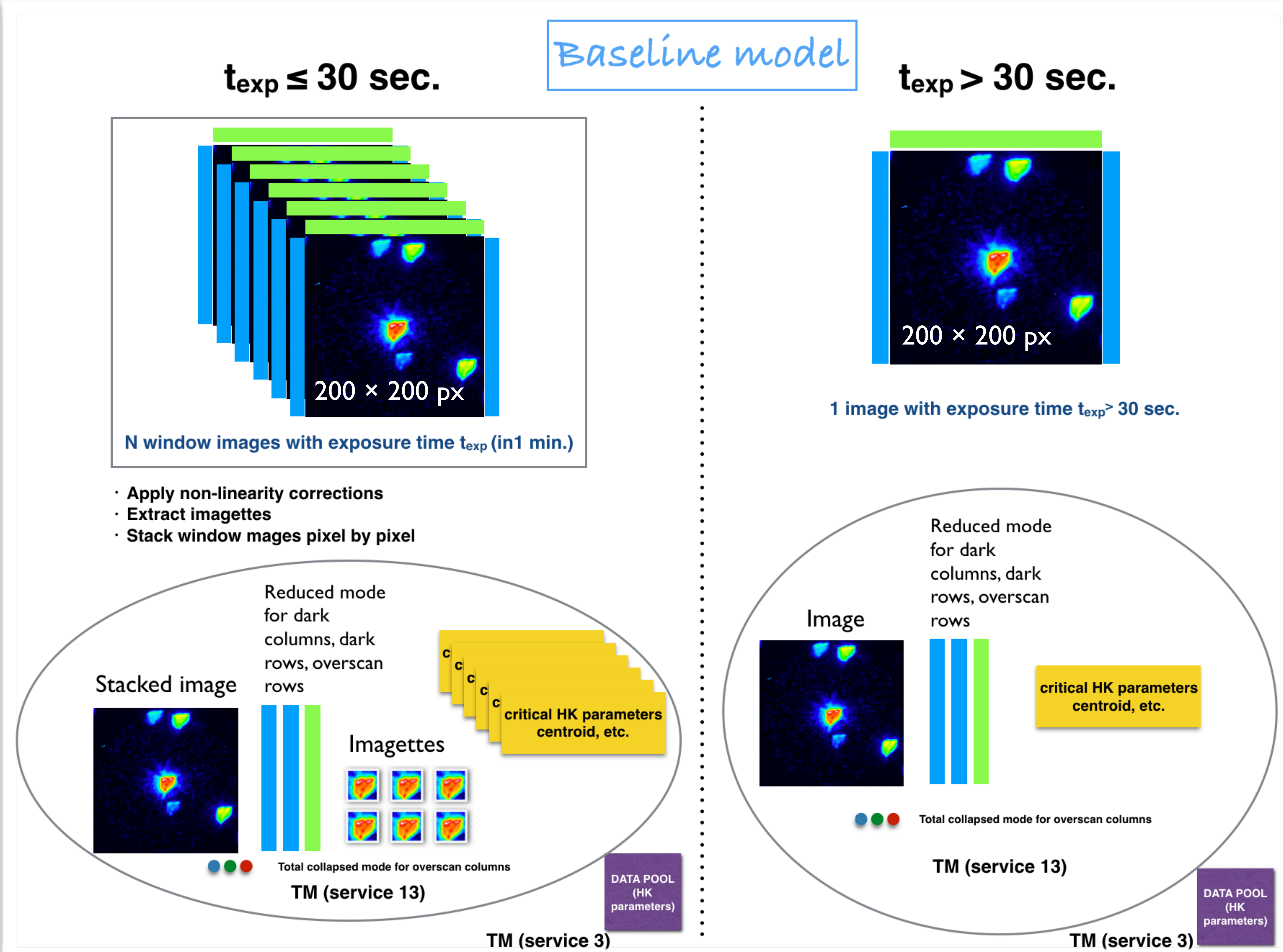
- The target star can be placed anywhere in the CCD
- Window shape: square, rectangle, circle*
- Window size: customisable
- Imagette size: customisable
- Imagette frequency: one per exposure if t_{exp} < 5 s, otherwise stacked to get one every 5 s.
- Window margins:
  - "image mode"
  - "reduced mode"
  - "total collapse mode"

Combination	Dark Right	Blank Right	Dark Left	Blank Left	Overscan Left	Dark Top	Overscan Top
image mode	16 * X pixel	8 * X pixel	16 * X pixel	8 * X pixel	4 * X pixel	Y * 3 Pixel	Y * 6 pixel
reduced mode	3 values per row	no data	3 values per row	no data	3 values in total	Y * 3 Pixel	3 values per column
total collapsed mode	4 values	4 values	4 values	4 values	4 values	4 values	4 values

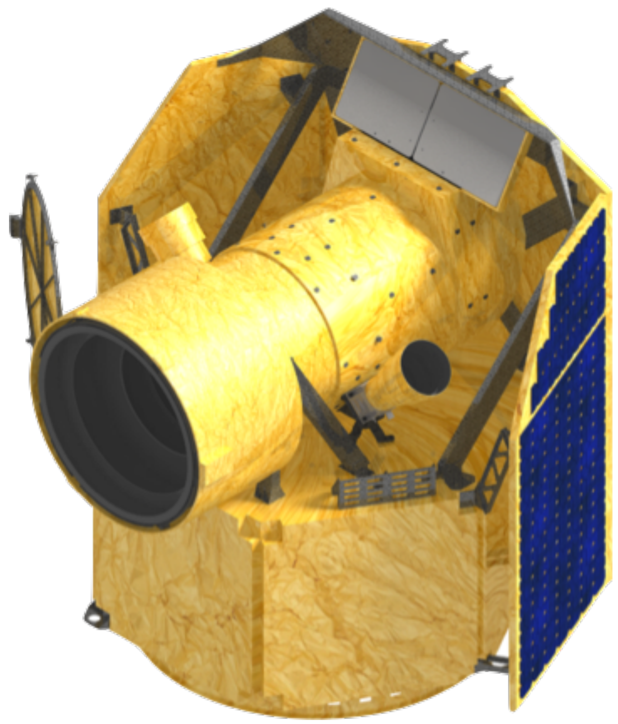


CHEOPS Data

CHEOPS data baseline model as a function of the exposure time. Minimum cadence 1 image/minute.



CHEOPS Instrument: Performance



Andrea Fortier
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Science Data

Ground Station
INTA- Spain

<u>Example:</u>
Target star: V9
t_{exp} = 10 s
Image cadence: 1stacked image/min
Visit duration: 48 hours

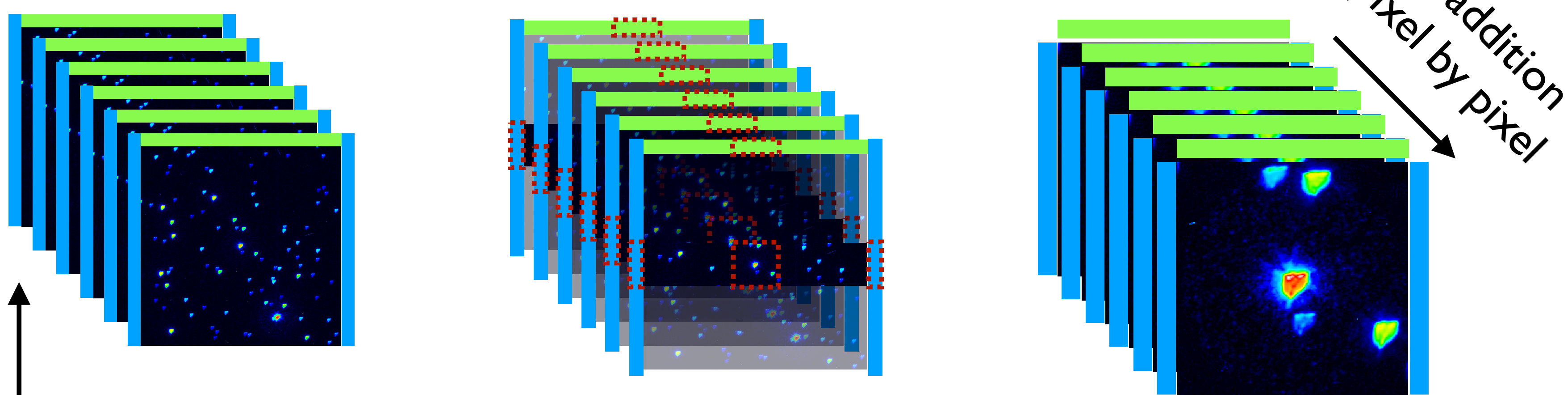
Ground Station
INTA- Spain

Science Data

raw exposures → **read-out & window generation** → **SW operations**

compression →

Co-addition pixel by pixel

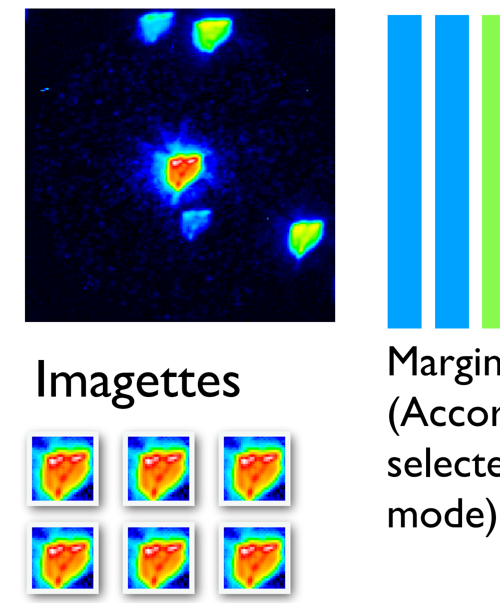


"Windowing" (by SEM)

For each exposure (by on-board SW):

- Imagette extraction
- Centroid
- Quick photometry
- Non-linearity corrections (TBC)
- Science housekeeping parameters (temperatures and voltages)

Stacked image



Imagettes

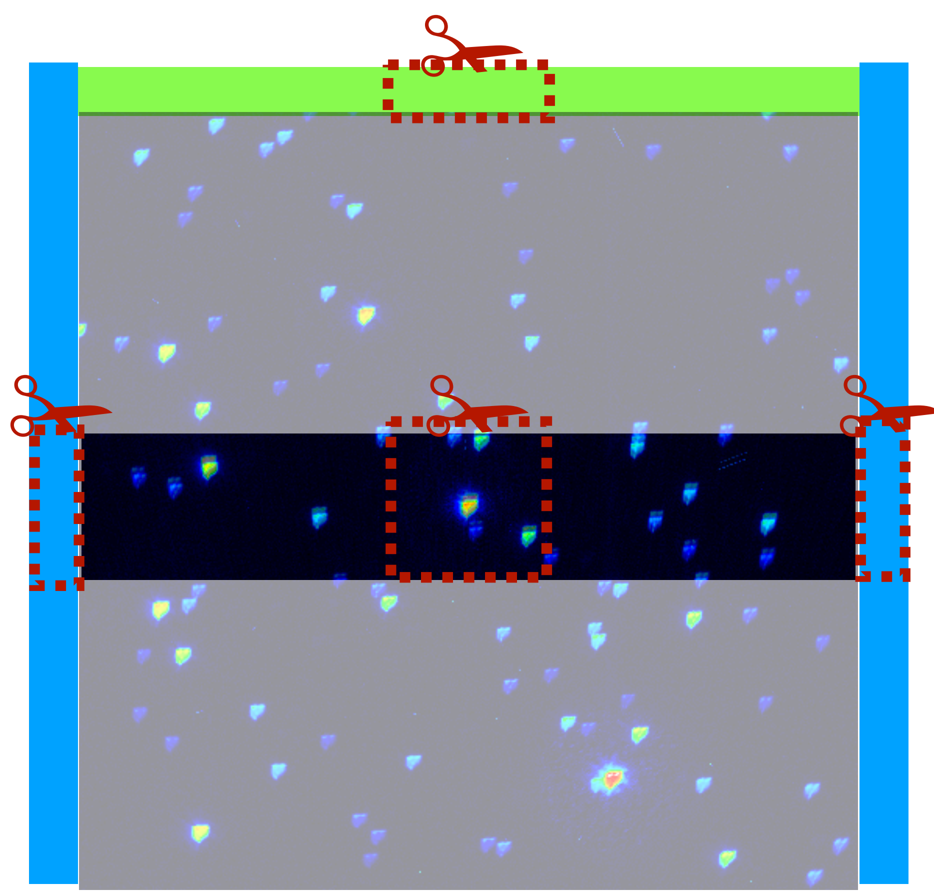
Margins (According to selected mode)

- Science Data
- "Science" HK parameters
- Critical HK parameters

Compression entity

Telecommands

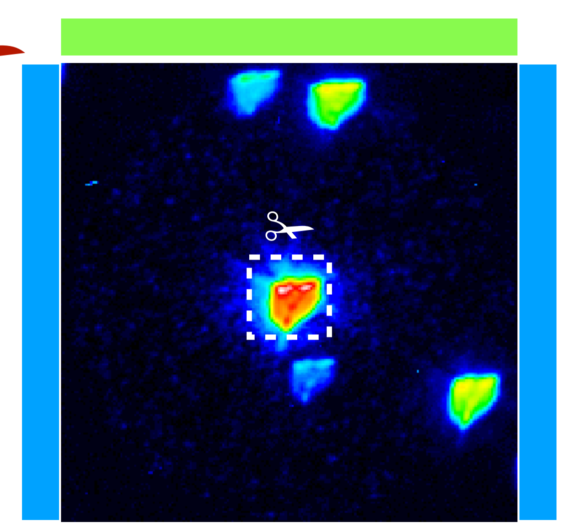
Ground Station INTA- Spain



Telemetry

Ground Station INTA- Spain

More in M. Beck's talk



(Performance) Science Requirements

SciReq 1.1

- Earth-size planets
- G5 dwarfs (T = 5500 K)
- $6 \leq V \leq 9$
- Transit depth = 100 ppm
- Photometric precision ≤ 20 ppm in 6 h of integration time

SciReq 1.2

- Neptune-size planets
- K dwarfs (T = 4500 K)
- $V \leq 12$
- Transit depth = 2500 ppm
- Photometric precision ≤ 85 ppm in 3 h of integration time

Noise Contributors

Noise categories

Random noises (white noise)

The noise will then decrease as:

noise associated to one image

$$\mathcal{E} = \frac{\varepsilon}{\sqrt{N}} \propto \frac{1}{\sqrt{t}}.$$

number of images

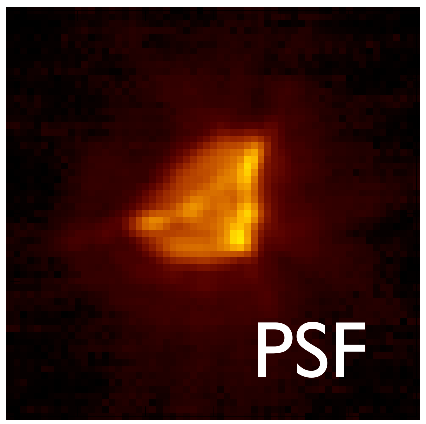
Systematic/correlated noises

Noise sources

- Astronomical/science noise
  1. Shot (photon) noise,
  2. Sky background (zodiacal light),
  3. Cosmic ray effects,
  4. Stray light contributions (Earth, Moon, stars; for the moment we consider only the Earth contribution).
- Instrument noise
  1. Jitter + Flat Field (+ Breathing) noise
  2. Read-out noise (CCD alone)
  3. Dark current variation with temperature
  4. CCD gain variability
  5. Analog electronic stability
  6. Quantum Efficiency variation with temperature
  7. Timing error
  8. Quantization noise of the FEE
  9. Analog chain random noise
  10. Bad pixels

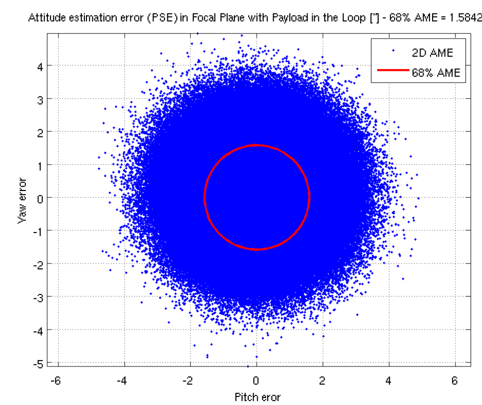
Noise Budget

PSF, jitter and flat field



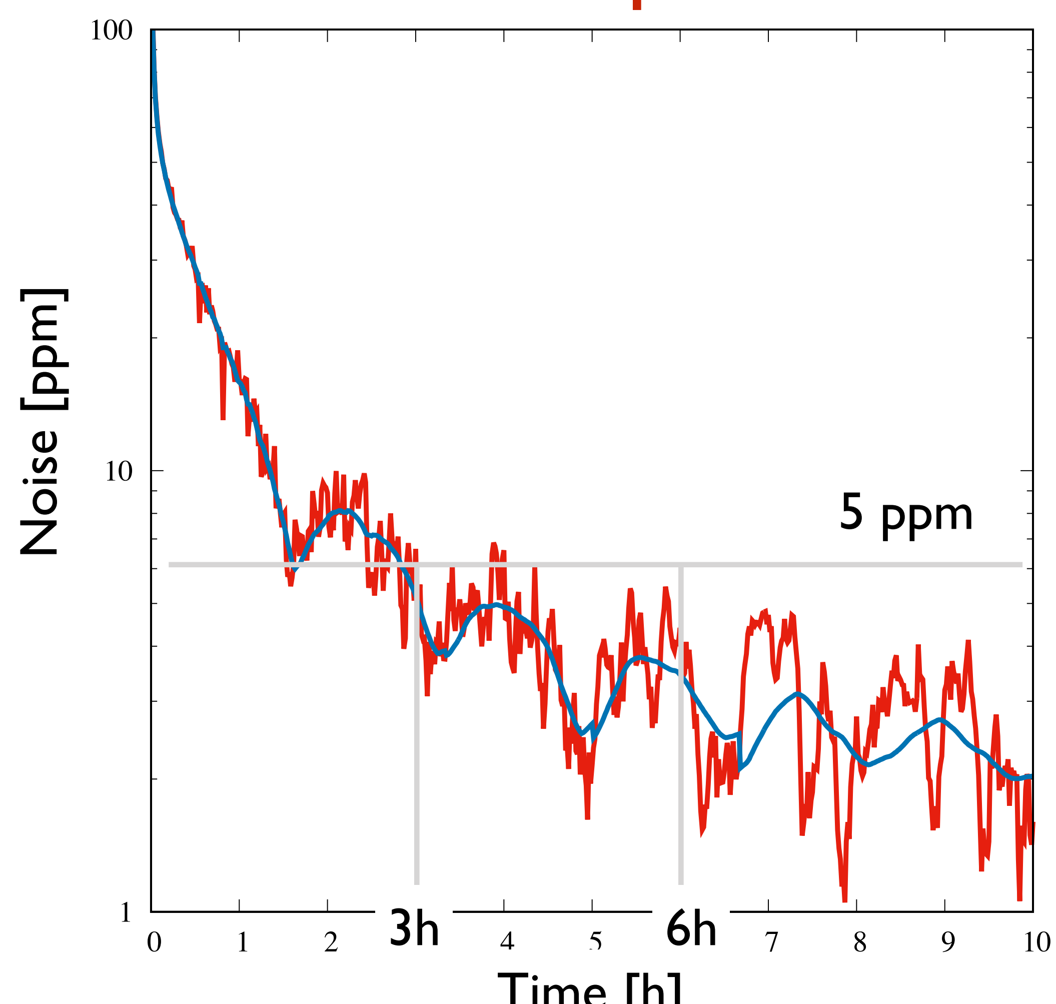
+

Pointing jitter



+

Residual FF assuming a Gaussian distribution with **σ** = 0.1%



48 h simulation with a jitter time series rms of 4”.

Instrumental Noises

Read-out noise: CCD + Analog chain random noise.

If the exposure time is lower than 12 seconds, the read-out frequency is 230 kHz. Otherwise, 100 kHz.

$$t_{exp}\begin{cases} \leq 12\,s \;\rightarrow\; \mathrm{RON} = 18\, e^{-}/px \\ > 12\,s \;\rightarrow\; \mathrm{RON} = 12\, e^{-}/px \end{cases}$$

CCD gain variability with T

Measurements on the flight CCD show that, for a temperature stability better than 10 mK, the noise contribution due to gain fluctuations with temperature is ~10 ppm.

Quantum efficiency variability with T

From measurements, the QE variability with T is ~1 ppm/mK. The temperature stability is better than 10 mK. Therefore, the noise contribution is ~10 ppm.

CCD gain and QE variability with T are anti-correlated

$$N_{gain,QE} = \max\left(N_{gain}, N_{QE}\right) \simeq 10\ \mathrm{ppm}$$

Analog electronics stability:

CCD gain change due to bias voltages, the analog electronics ADC gain variations in the PSDU input voltages and the analog electronics ADC gain variations due to variations in temperature.

$$N_{AES} < 10\ ppm$$

Instrumental Noises

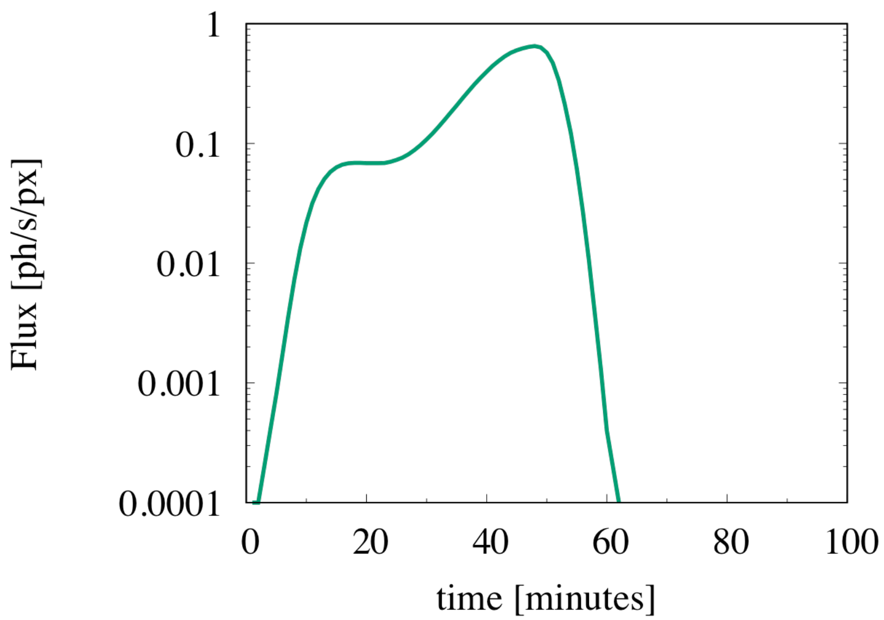
Dark current variation with T: negligible

Timing error: lower than 2 ppm

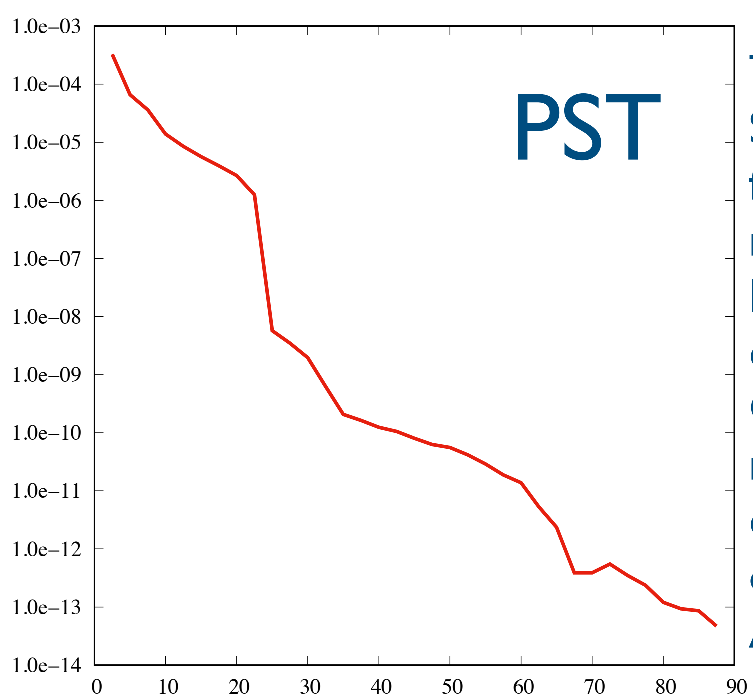
Quantisation noise: negligible

Earth Straylight

Orbit dependence

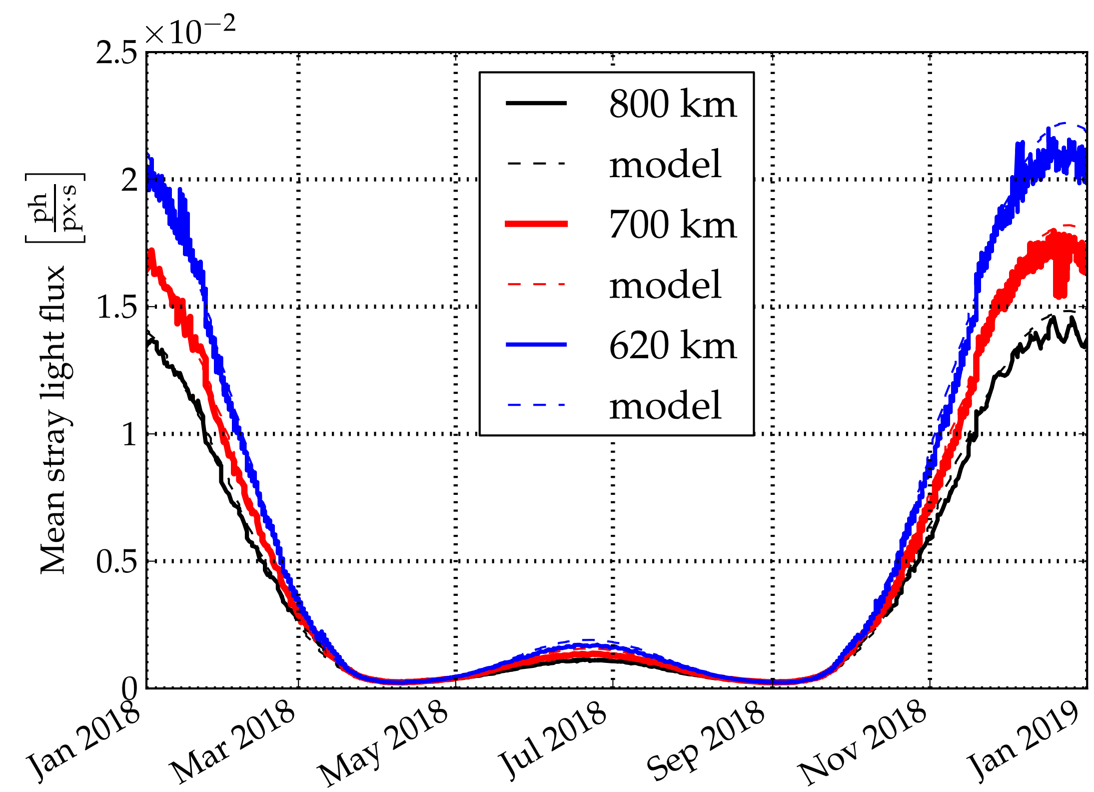


Pointing direction: RA= 8 h 6 min 6 seg and DEC= -31.5º;
date: 4/2/2018, 08:46 h; orbit altitude 700 km



The PST (Point Source Transmission function) cannot be measured in the lab. It will be "measured" during In-Orbit Commissioning and monitored with dedicated M&C observations (see R. Alonso's talk).

Seasonal dependence



Assumption: SL contamination in the images can be eliminated with an efficiency better than 99%.

Noise Budget SL contamination <u>allocation</u>:

- 5 ppm for V=9
- 70 ppm for V=12

See D. Ehrenreich's talk for sky coverage

Noise Budget

Methodology

For the total noise estimation, we assume that all noises are independent, although this may not strictly apply to all the cases. Independent noises are added in quadrature. Let's N_i be one of the noises mentioned in Sec. 1.3 . The total noise expected after uninterrupted integration time t is:

$$\boxed{N = \sqrt{\sum N_i^2}}$$

Noises are added in quadrature

To calculate the Noise Budget we generated an excel sheet where the individual sources of noise mentioned in Sec. 2 are considered (RD01). White noises average with time as:

$$N_{white} = \frac{N_{white}^{exp}}{\sqrt{number\ of\ exposures}}$$

where N_{white}^{exp} is the noise per exposure. The white noises per exposure considered here, N_{white}^{exp}, are the previously defined N_{shot}, N_{sky}, N_{RON}, N_{ACRN}, N_{dark} and N_Q. CR_{noise} already includes in its definition the time average.

Systematic noises do not average with time (worst case assumption); their noise values are independent of the exposure time. These are: N_{SL}, $N_{ff+jitter}$, N_{dark}^{sys}, $N_{gain+QE\ var}$, N_{AES}, and N_{TE}.

Finally, to calculate the total error budget, all noises are added in quadrature.

Note that contamination by background stars and stellar noise are not included in the NB.

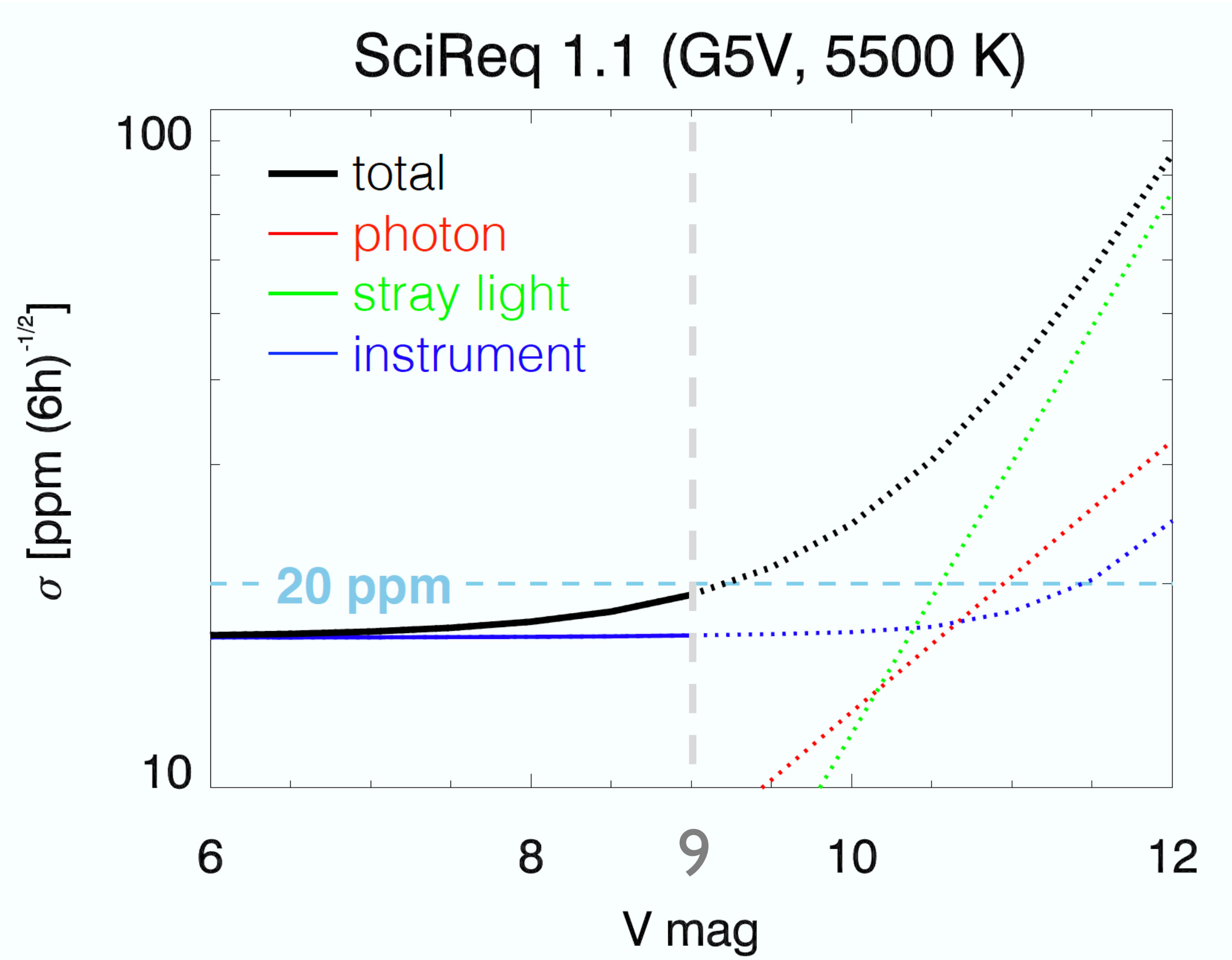
Noise Budget calculation

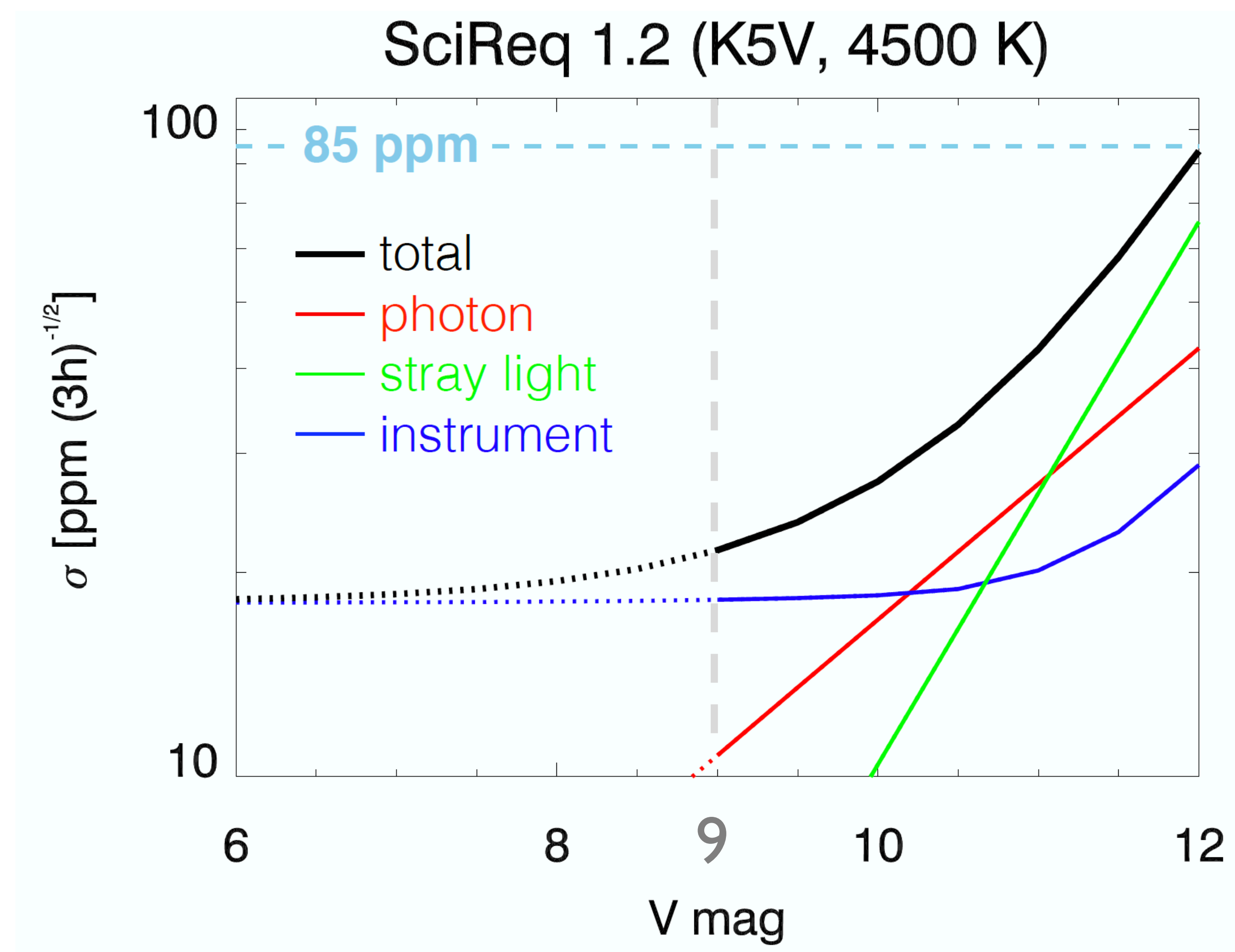
Input parameters

Parameter	Value
Radius PSF	12 px
Photometric aperture (radius)	30 px
Read Out Noise (CCD+FEE)	18 e-/px or 12e-/px
Quantisation	16 bits
Pixel Size	13 µm
Angular scale	1 arcsec/px
Pixel Full Well Cap.	132 000 e-
Image Size	200×200 px
Operating Temperature	233 K
Detector Temperature Stability	0.01 K
Dark Current	0.08 e-/px/s
Flat Field Knowledge	0.1%
Earth Stray Light	~0.3 e-/px/s [7]
Zodiacal Light	4.02 e-/px/s
Detector Gain Variability	10 ppm
Detector QE variation with temp.	10 ppm
Timing error	2 ppm
Analog electronics stability	10 ppm
CR parameter *C*	132 ppm

Case Number	**A**	**B**	**C**
Mv star	6 (ST = G8)	9 (ST = G8)	12 (ST = K5)
Exposure time [s]	1	10	60
Integration time [h]	6	6	3
Global throughput (CCD+Optics)	49%	49%	45%
Shot noise [ppm]	2.0 [299]	**8.1** [377]	**42.8** [574]
Background (inc. dark) [ppm]	0.2 [24]	0.6 [28]	7.1 [96]
Cosmic rays [ppm]	7.0	7.0	9.8
Earth stray light [ppm]	0.3	5.0	**69.1**
Jitter + Flat Field + Breathing [ppm]	5	5	5
Read out noise (CCD) [ppm]	0.6 [86]	2.9 [136]	15.7 [211]
Dark current variation noise [ppm]	0	0	0.3
CCD Gain variability + QE change [ppm]	**10**	**10**	10
Analog electronics stability [ppm]	**10**	**10**	10
Timing error [ppm]	2	2	2
Quantization noise [ppm]	0 [1.1]	0 [1.8]	0.2 [3]
Error time average [ppm]	**17.0**	**19.5**	**85.0**

Noise Budget





CHEOPS

Very bright stars

esa

Read-out mode: Ultrabright

Exposure time < 1 s

Exposure repetition period: t_{exp} + 1 s

The duty cycle is inefficient

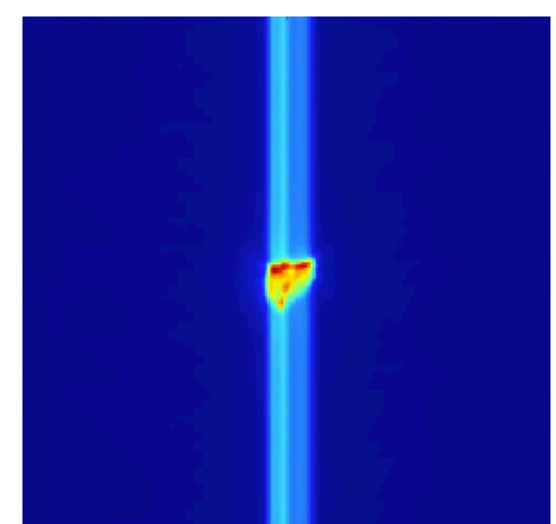
Noise Budget for 6h integration time

V	T_{exp} = 1s	T_{exp} = 0.5 s	T_{exp} = 0.1 s
6	16.8 ppm	17.1 ppm	19.0 ppm
5	16.7ppm	16.8 ppm	17.4 ppm
4	16.7 ppm	16.7 ppm	16.9 ppm
3	16.65 ppm	16.65 ppm	16.75 ppm
2	16.65 ppm	16.65 ppm	16.7 ppm
1	16.65 ppm	16.65 ppm	16.7 ppm

Saturation

Star T_{eff} = 5500 K

Note that the transfer time from the image section to the storage section is 25 milliseconds. Therefore, the shorter the exposure time, the lower S/N between the star and the smearing trails.



Ageing

Dark current and bad pixels

Will be monitored during the mission (see R. Alonso's talk)

Dark current @ Beginning of Life: negligible
Dark current @ End of life: could be two orders of magnitude larger. This can lead to a significant increase in the noise budget, specially for faint stars.

Bad Pixels: hot, warm and random telegraphic pixels.
Bad pixels could affect more than 10% of the CCD pixels. Bad pixels that cannot be detected are particularly dangerous. Undetectable bad pixels could increase the noise budget in 20%. Detectable bad pixels can be corrected and the quality of the lightcurve will then depend on the correction method.

Ageing

Charge Transfer Inefficiency (CTI)

Will be monitored during the mission (see R. Alonso's talk)

CTI will induce trails in stars. Trails of background stars will rotate in and out the aperture with the satellite's orbital period.

Uncorrected CTI effect could lead to a sensitive increase of the noise budget. Preliminary proposed correction method limits this increase by a factor 4.

The change in the CTI will be monitored during the mission and correction methods will be studied to reduce its impact.

Conclusions

- The performance science requirements (SciReq. 1.1 and 1.2) are met.
  1. Estimated noise budget for bright stars < 20 ppm
  2. Estimate noise budget for fainter stars < 85 ppm

- The instrumental noise dominates for bright stars, while the photon noise (*and the straylight contamination*)* dominates (*could dominate*) for fainter stars.

- Exposures shorter than 1 second are possible (down to 1 millisecond). Although the duty cycle of this read-out mode is inefficient, it should be used for very bright stars in order to avoid saturation in the PSF.

- Not surprisingly, the instrument performance (specially the CCD) is expected to degrade with time. Monitoring and characterisation observations are planned to follow the evolution closely and to implement SW mitigation strategies when possible.

* The straylight contamination of an image depends on the pointing


рахмат
danke
謝謝
ngiyabonga
spas
teşekkür ederim
Баярлалаа
mersi
kia ora
barka
welalin
tack
mahalo
tapadh leat
спасибо
faafetai lava
vinaka
спасибі
blagodaram
dank je
misaotra
matondo
paldies
grazzi
kiitos
dankie
nanni
nandri
mauruuru
thank you
gracias
хвала
dhanyavad
asante
manana
bedankt
köszönöm
obrigada
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shukriya
mercê
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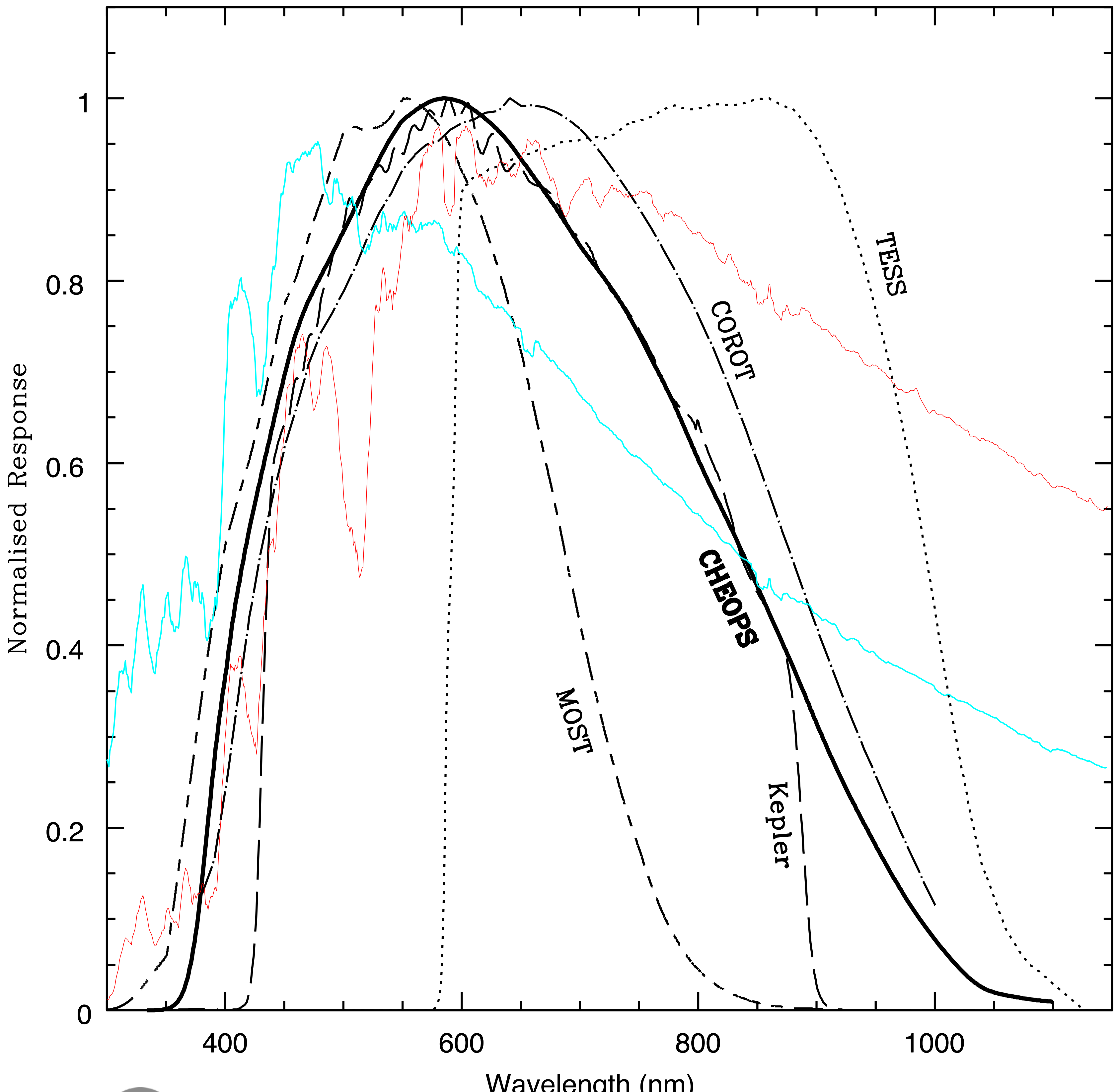
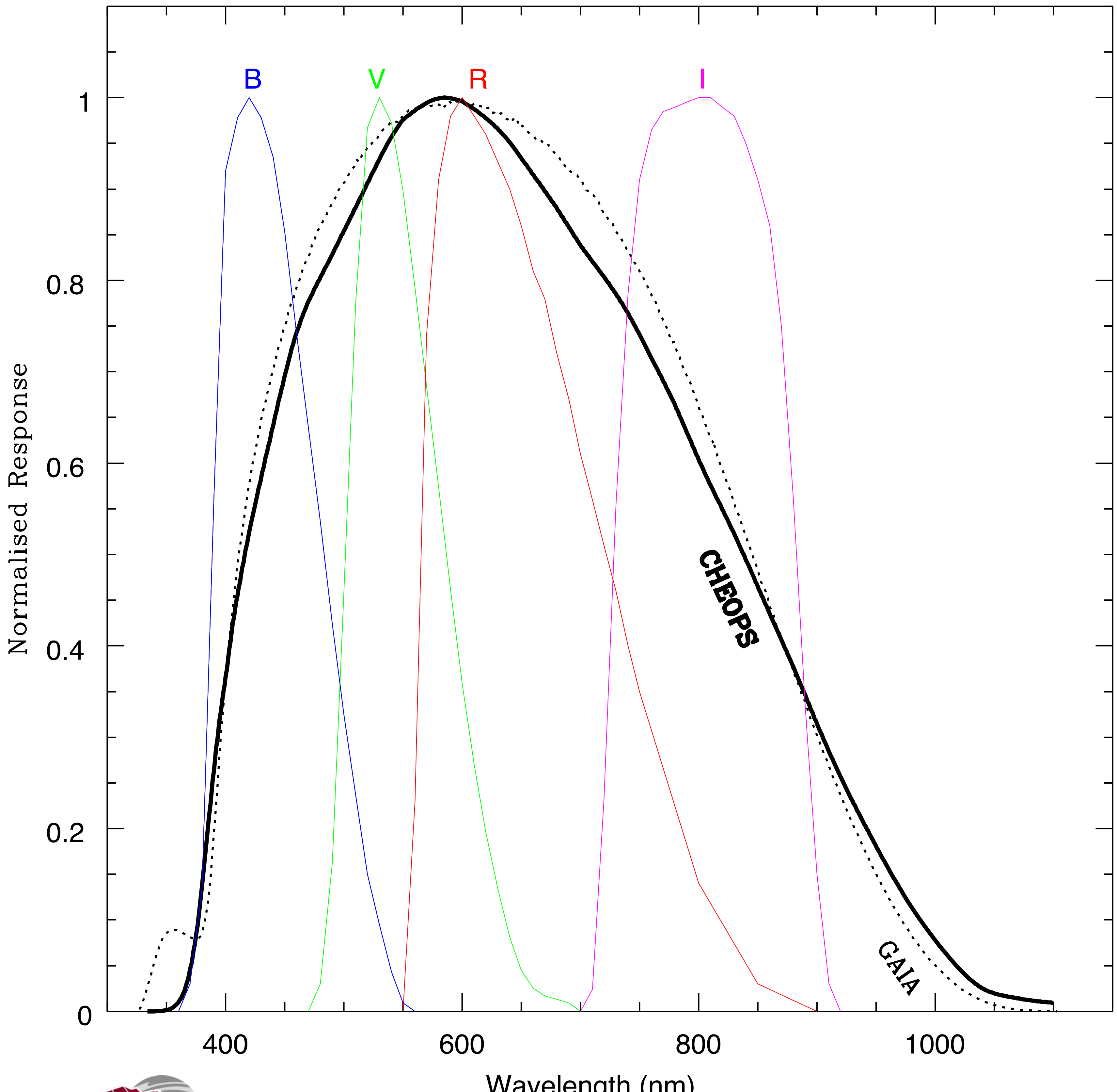
kam sah hamnida
rahmat
তোমাকে ধন্যবাদ
감사합니다
xièxie
merci

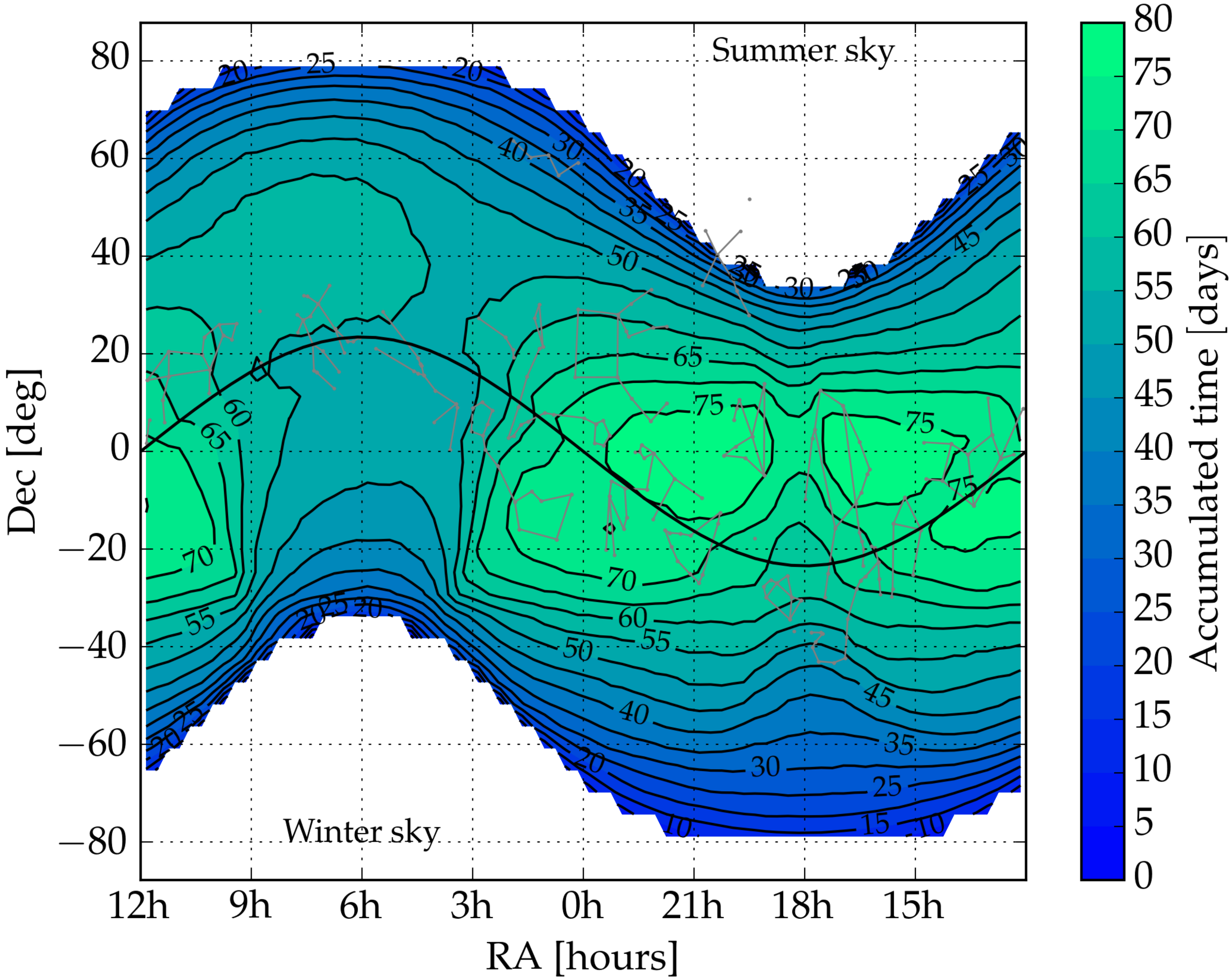
Backup slides



Backup slides



Backup slides



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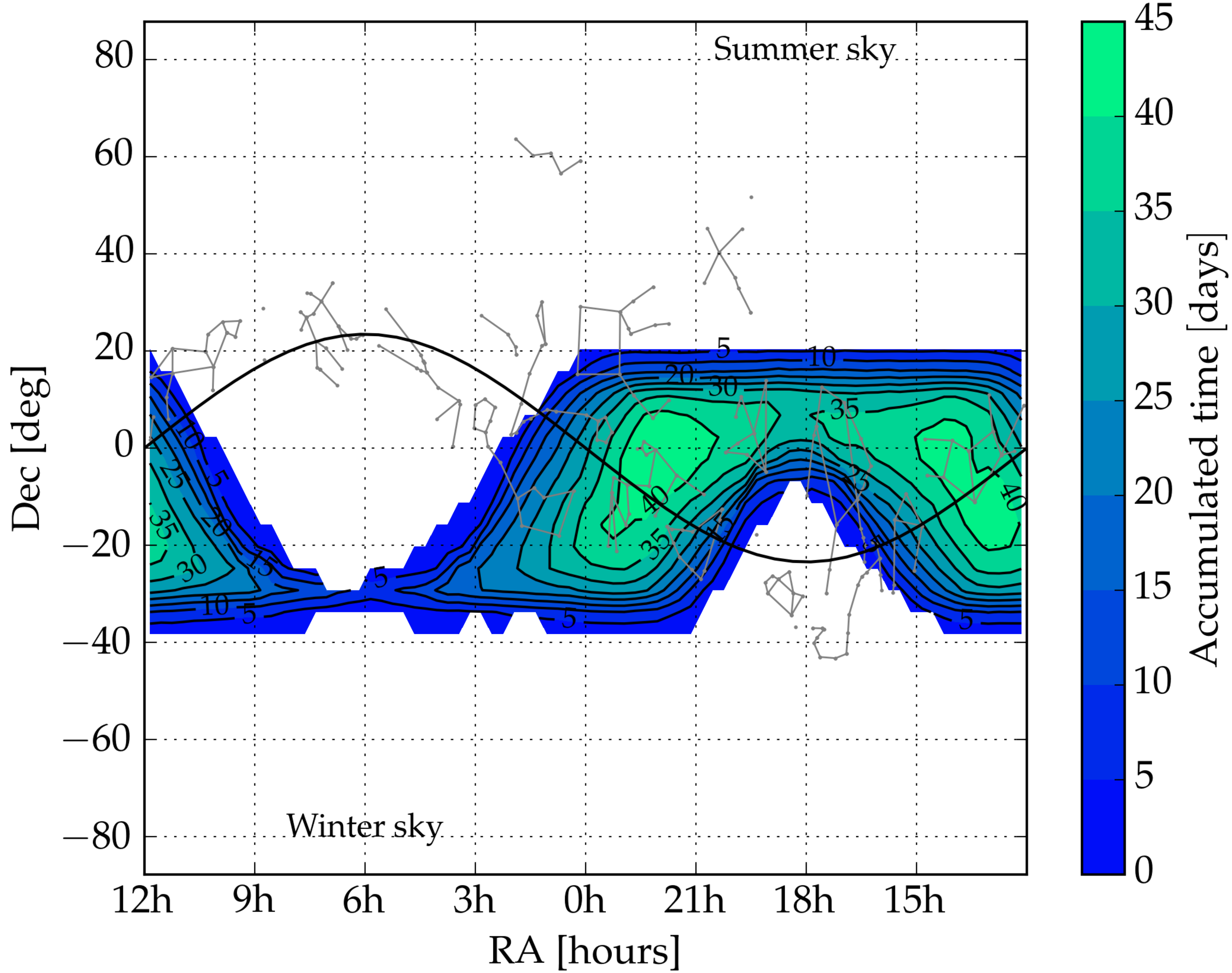
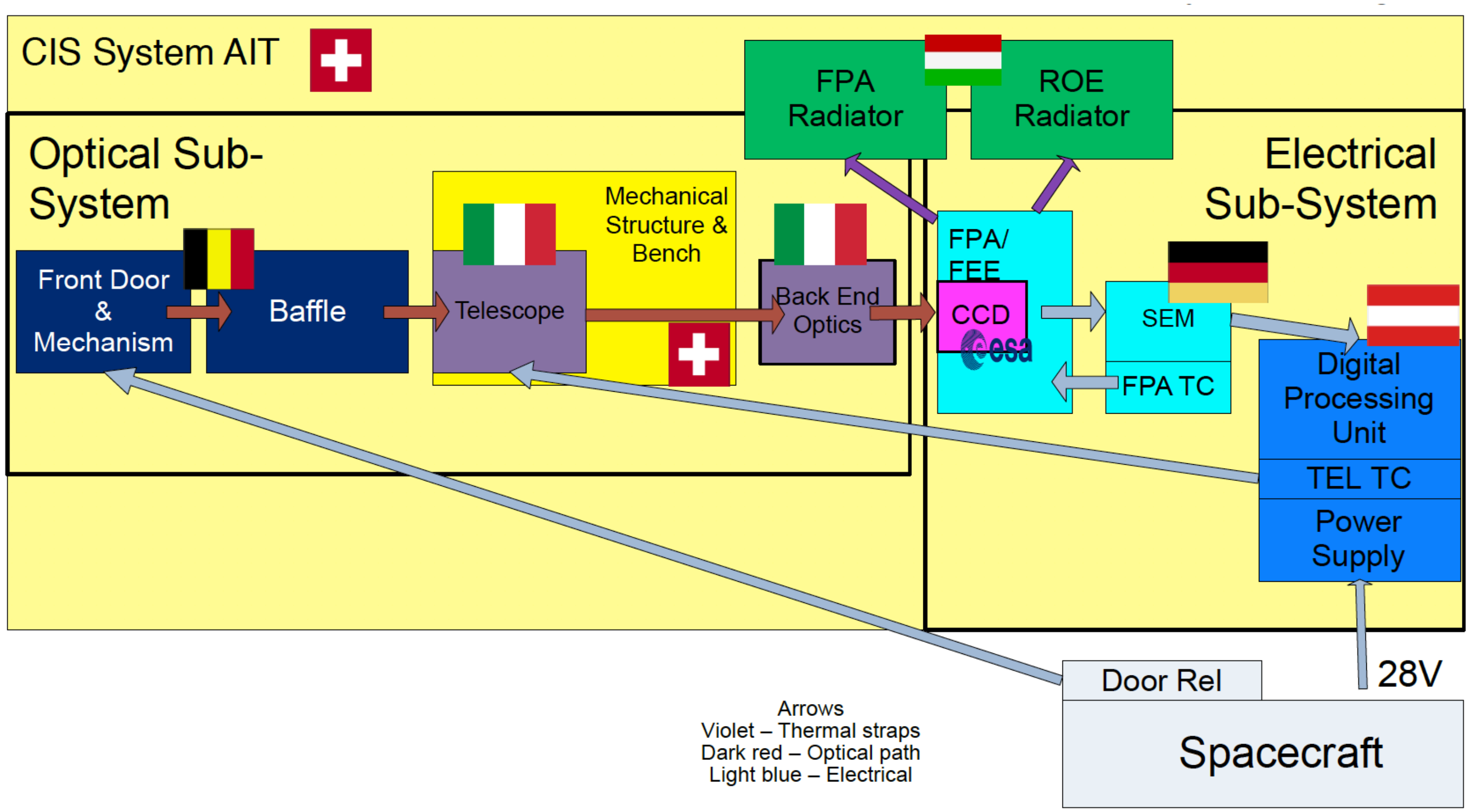
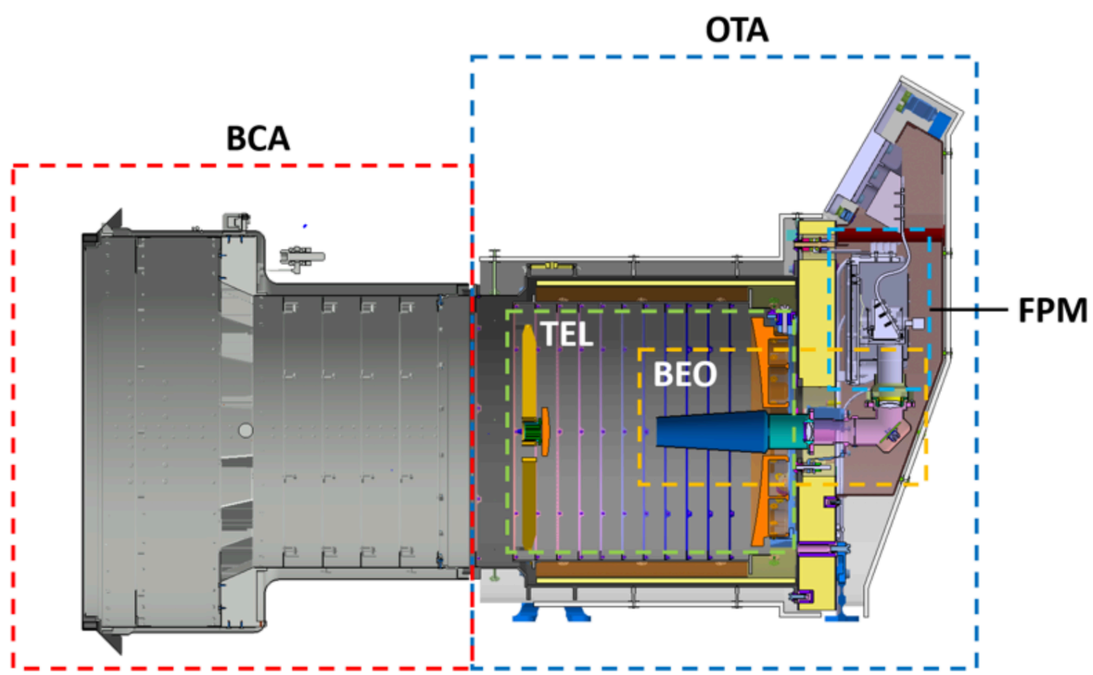
Backup slides



Payload Description

Subsystem	*Acronym*	*Organization*
Instrument Prime	CIS	UBE
Outer baffle and door	BCA	CSL
Telescope Structure and Optical Bench	OTA	UBE
Telescope optical design and optical components	TEL	INAF
FPA and FEE Radiators	RAD	ADM
Focal plane, thermal control, and proximity electronics	FPM	DLR
Sensor electronics module	SEM	DLR
Backend electronics	BEE	IWF
DCDC Power converter	DCDC	IWF (RSA)
Detector	CCD	ESA
Payload Computer	DPU	IWF
Science Calibration	CAL	UGE

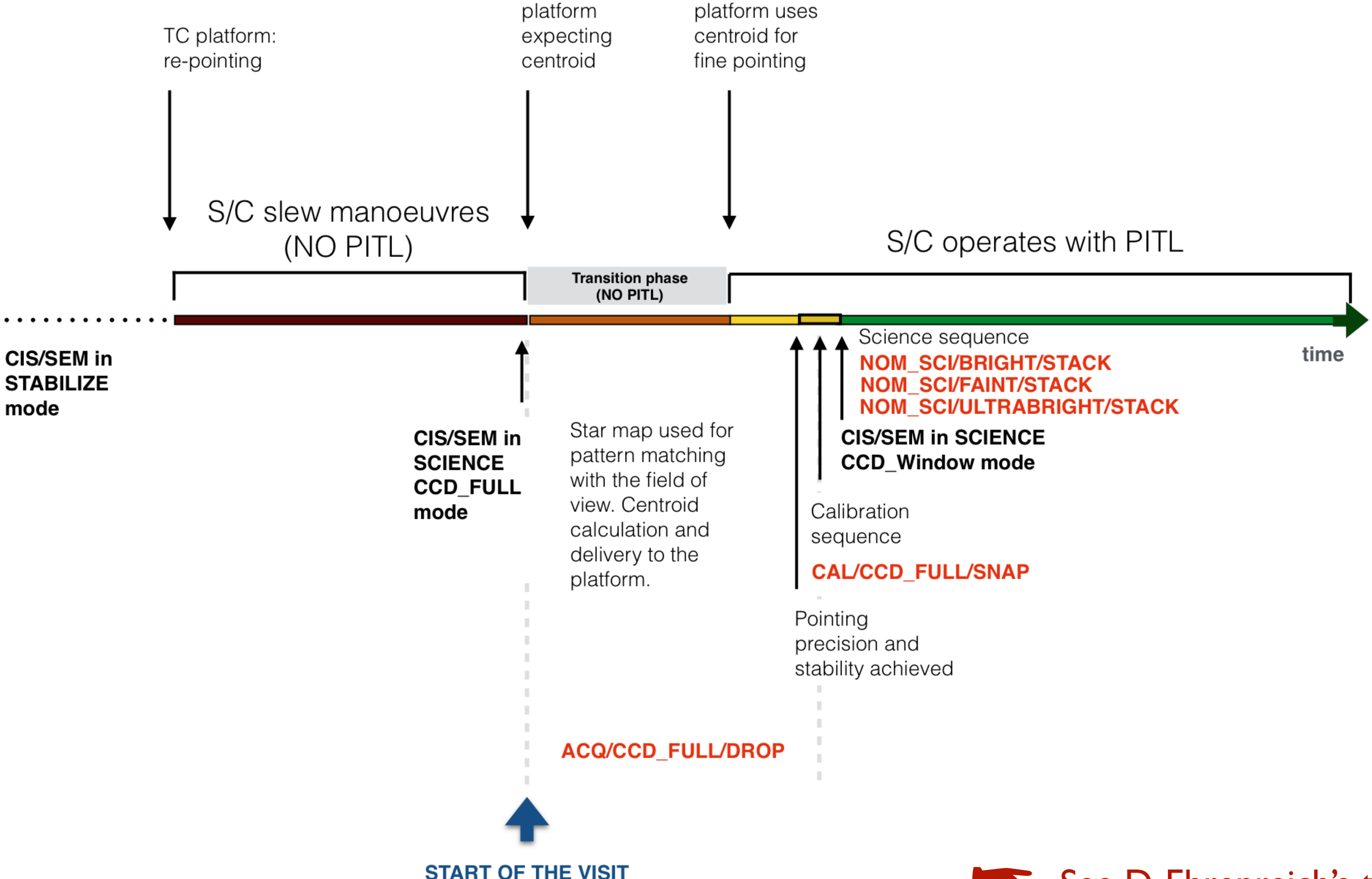




Observation activities

Observation activities		
1	NOM_SCI	Nominal Science. Acquisition of images for a scientific study. This activity is the core of a nominal visit. A typical example is the observation of a star from either the core science programme (GTO) or guest observers programme (GO).
2	ACQ	Acquisition. Here acquisition refers to target acquisition in the detector. Once the CIS receives the star map of the targeted region of the sky and starts the pattern recognition by comparing it with the field of view, the instrument acquisition consists in putting the target star at the desired location on the detector
3	CAL	Calibration. Sequence of images acquired at the beginning and (possibly) at the end of each nominal visit for calibration purposes. Required by, and used as input to, the on-ground science data processing pipeline.
4	M&C	Monitoring and characterisation. Visits dedicated to on-going characterisation of the instrument and monitoring of the instrument performance ☛ See R. Alonso's talk

CHEOPS Visit



See D. Ehrenreich's talk