Jet Propulsion Laboratory
California Institute of Technology

Tellus1 scientific, LLC

Modeling and Error Budgets: The Roman Space Telescope Coronagraph Instrument (CGI)

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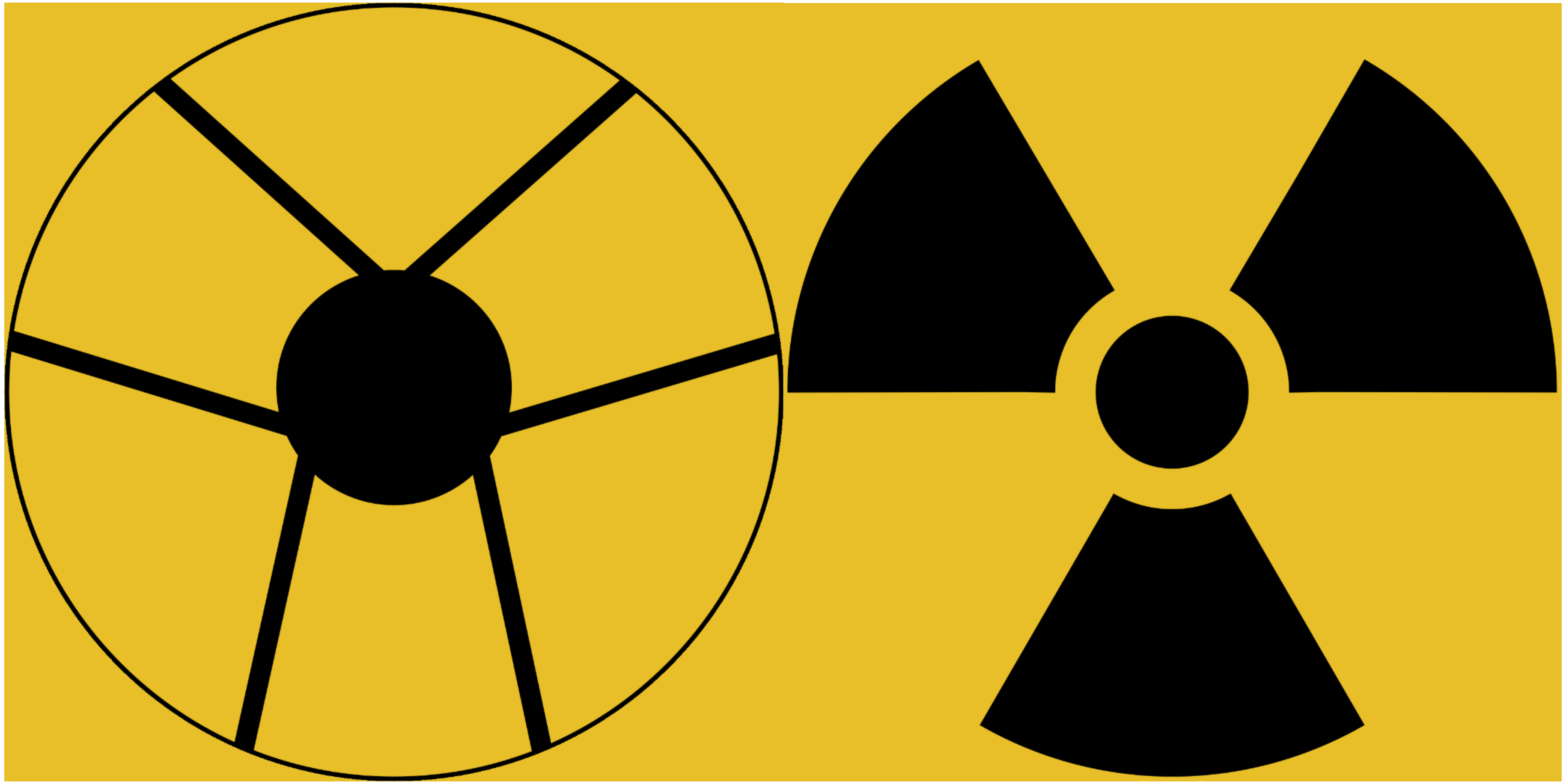
CL#23-4622

WARNING

HIGH DIFFRACTION ZONE

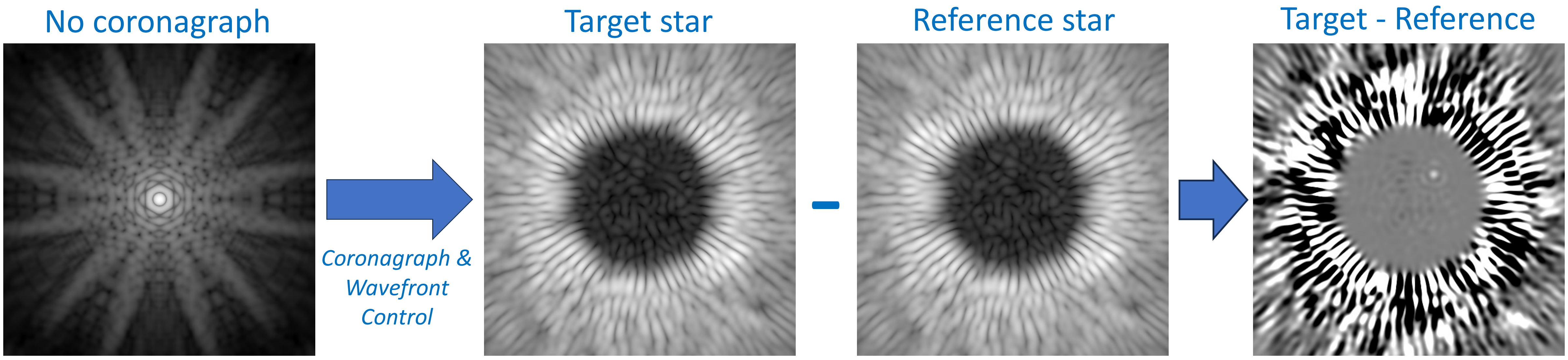


CORONAGRAPHS REQUIRED AT ALL TIMES

Fundamental Coronagraph Characteristics

- Starlight suppression
  - How dark is the field around the star (the dark hole)?
- Throughput
  - How much exoplanet light ends up on the detector?
- Stability
  - How sensitive is the coronagraph to time-dependent variables (e.g., low-order aberrations, pointing errors)?

Modeling: How dark, how stable?



How dark a dark hole?

Diffraction modeling:

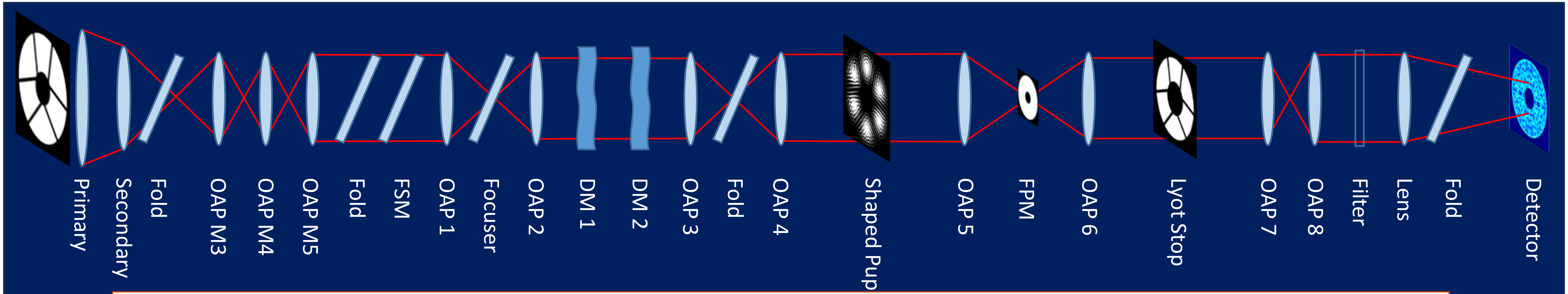
- *System aberrations (e.g. defocus)*
- *Optical surface errors (polishing, coating)*
- *Mask errors & misalignments*
- *Polarization-dependent errors*
- *High & low order wavefront control*

How stable is the system over time?

Structural/thermal/optical (STOP) modeling:

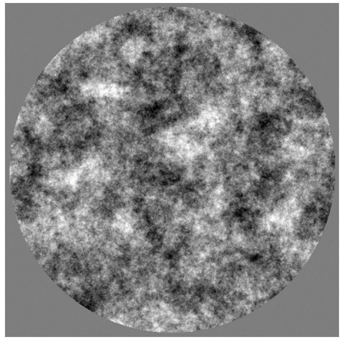
- *Solar incidence changes*
- *Heat dissipation (mechanism motions, electronics)*
- *Heater control loops*
- *Reaction wheel speed changes*
- *Low order wavefront control (pointing)*

Roman+CGI Unfolded Layout

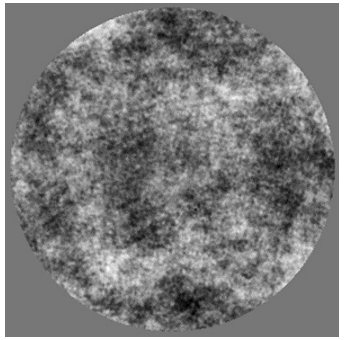


Broadband image = multiple monochromatic images x 4 polarization components

Optic polishing errors

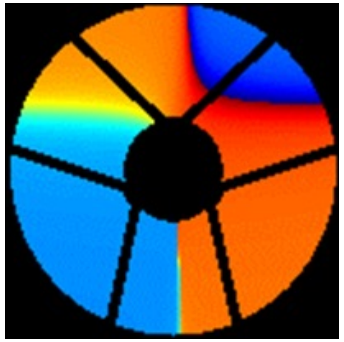


Synthetic



Measured

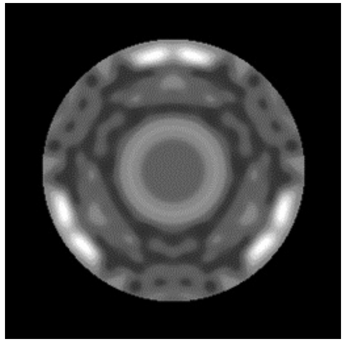
Polarization-dependent aberrations



Deformable mirrors

Masks

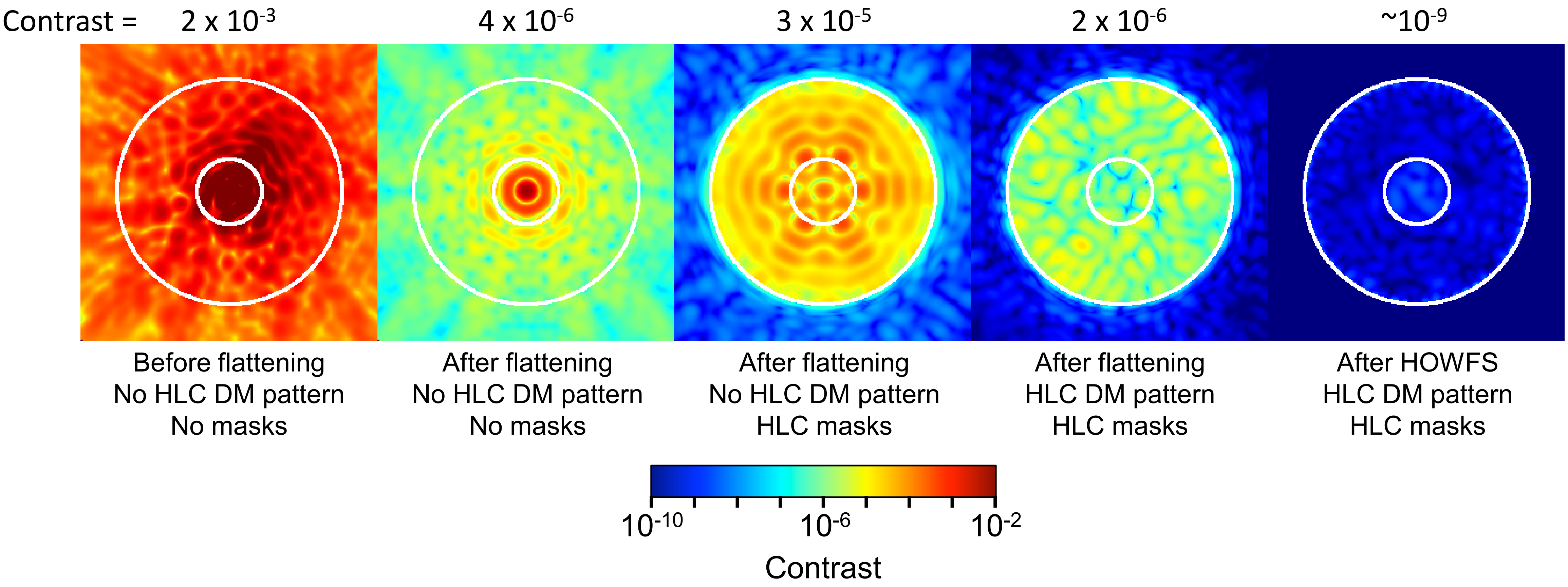
SPC pupil mask



HLC focal plane mask

CGI Wavefront Control

Hybrid Lyot Coronagraph, λ=546-604 nm



The same wavefront control algorithms are used in the models, testbeds, and on-orbit

Observing Scenario 11 Timeline

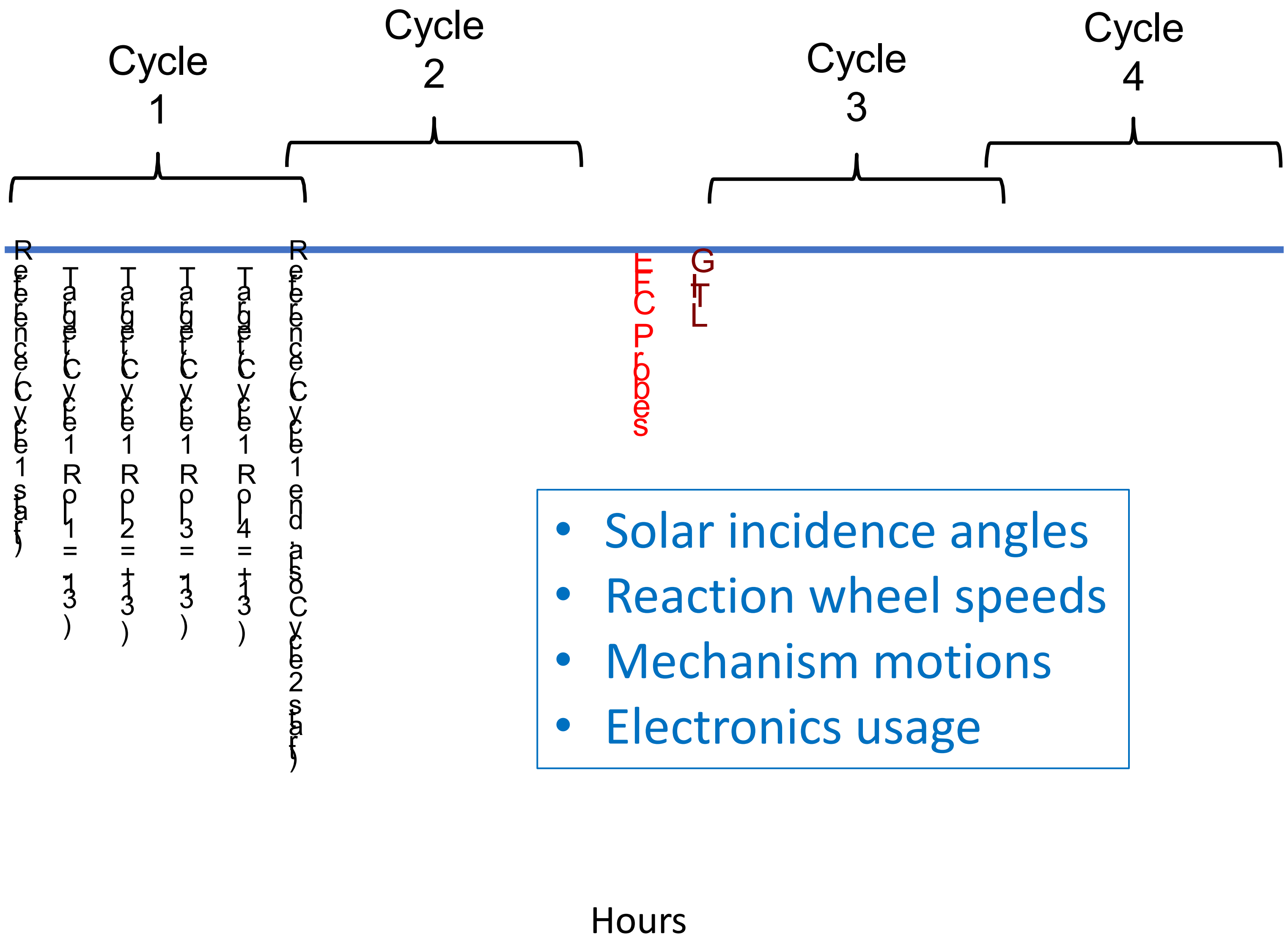
Target star:

47 UMa (G1V, V=5.0)

Reference star:

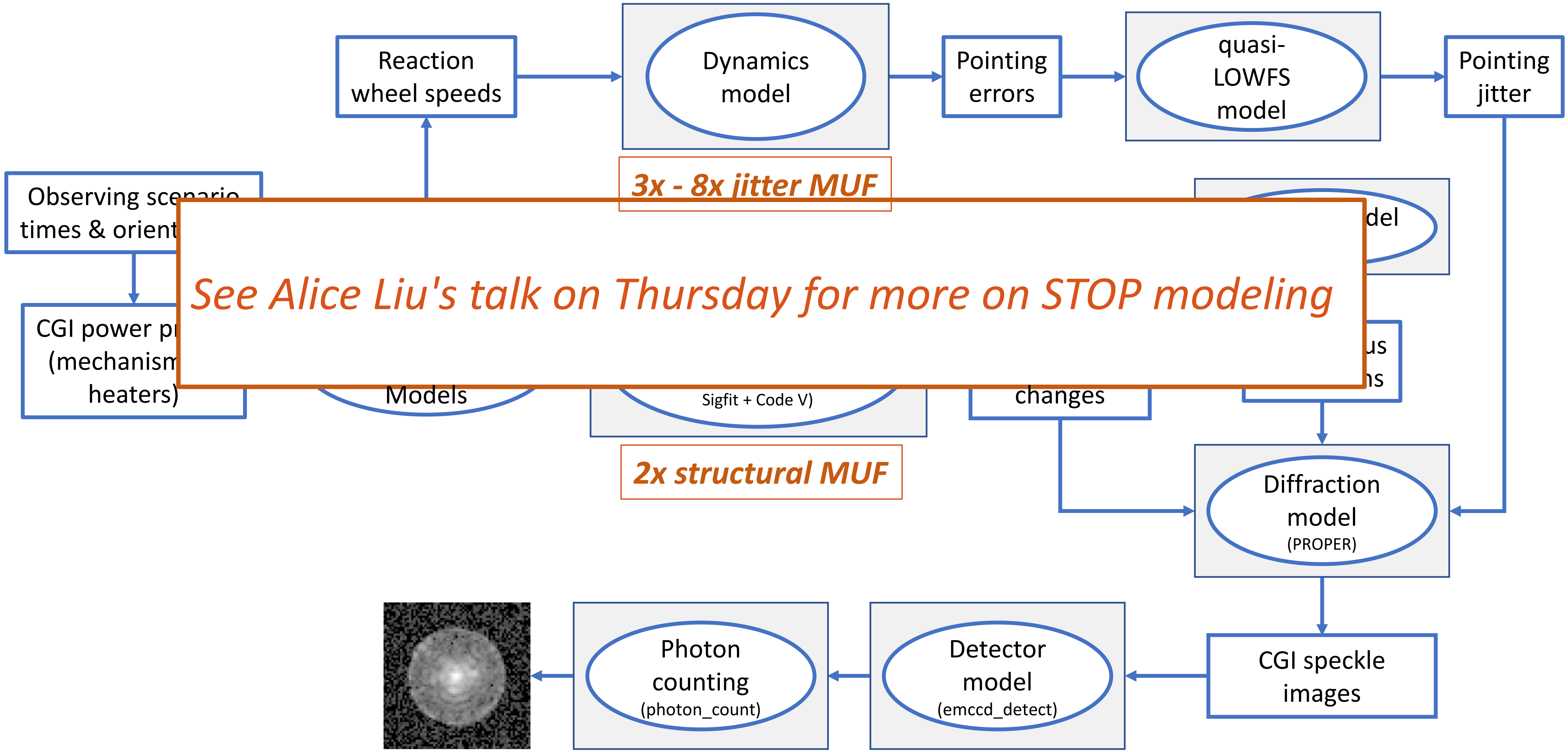
ζ Pup (O4I, V=2.3)

$\Delta\theta_{sky}$ = 166° $\Delta\theta_{sun}$ = 3.5°

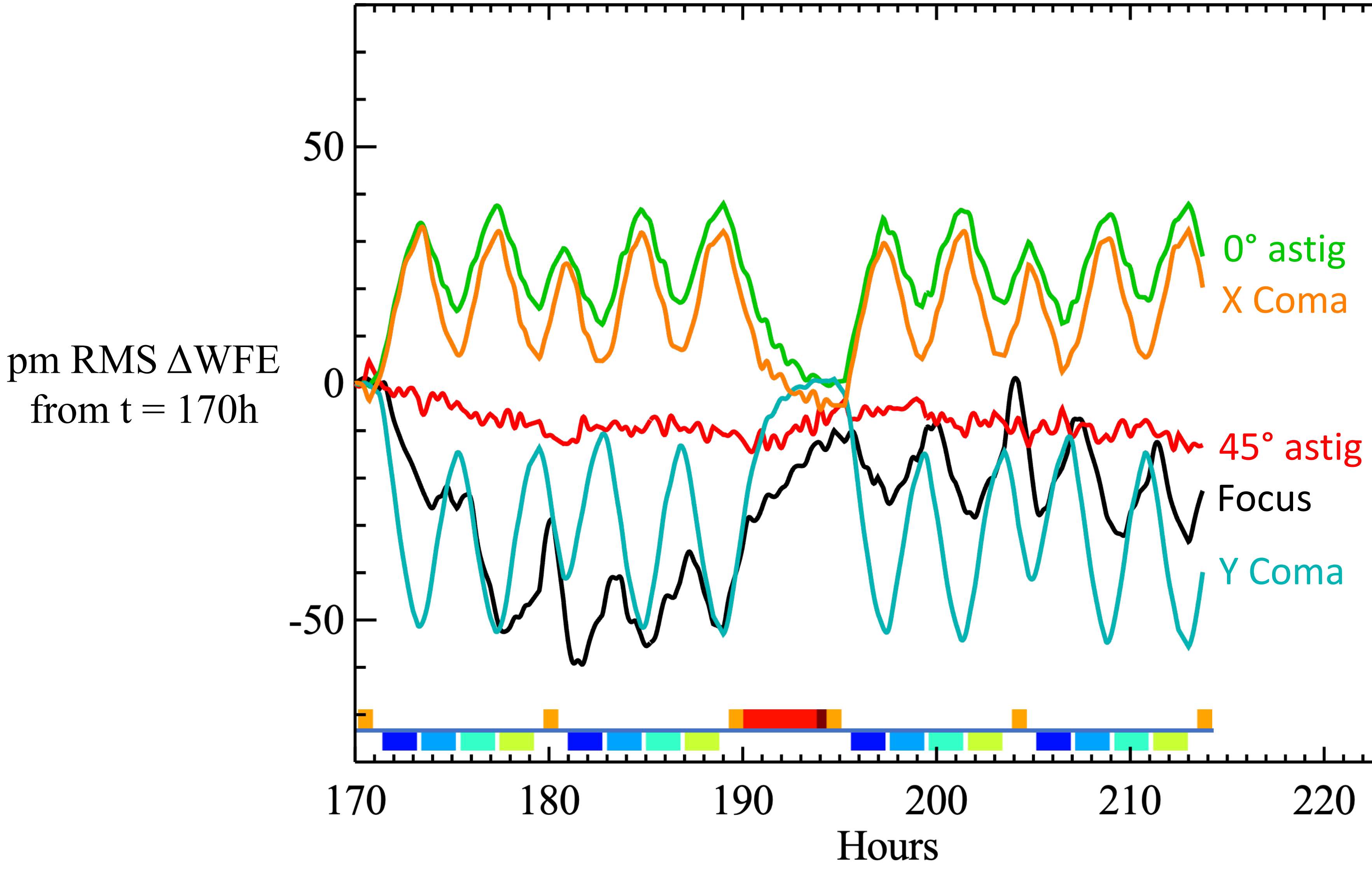


- Solar incidence angles
- Reaction wheel speeds
- Mechanism motions
- Electronics usage

OS Time Series Computation Process

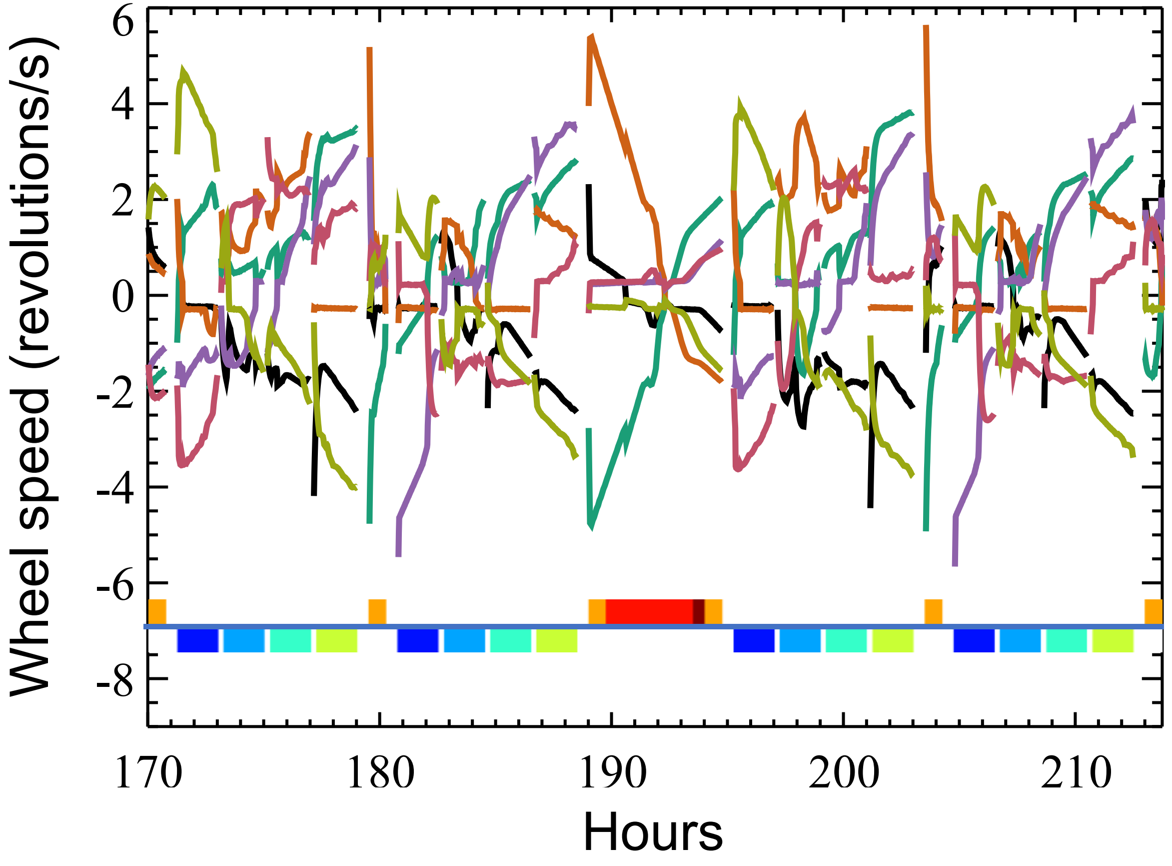


OS11 Low-Order Aberration Variations
(before LOWFS correction)

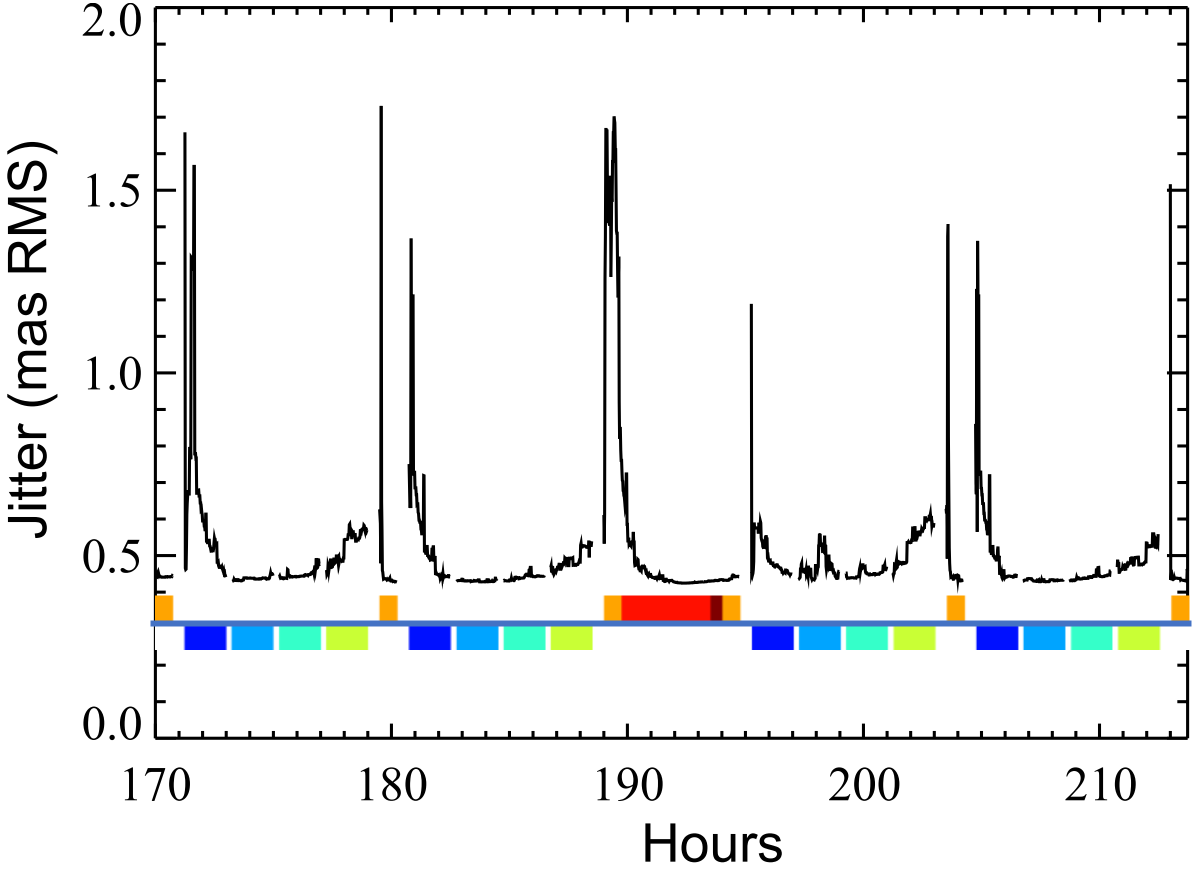


OS11 Pointing Jitter

Reaction wheel speeds

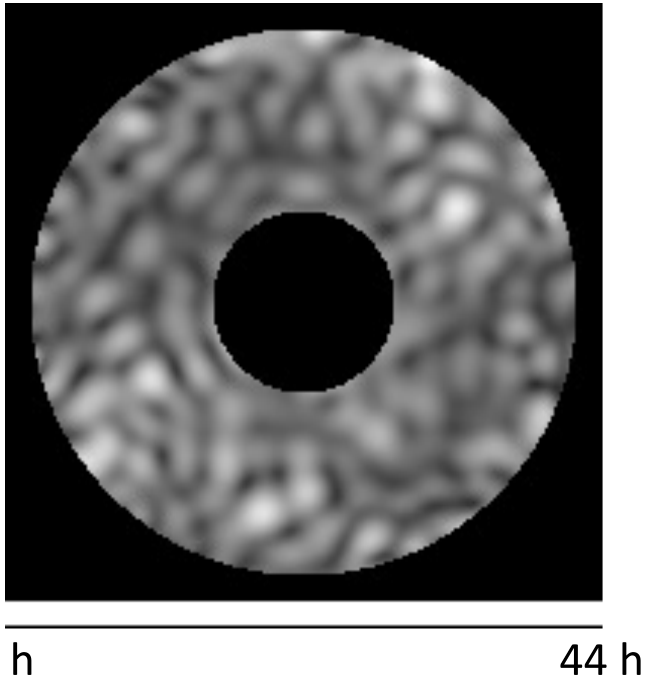


Post-correction pointing jitter



OS 11 Time Series with Jitter

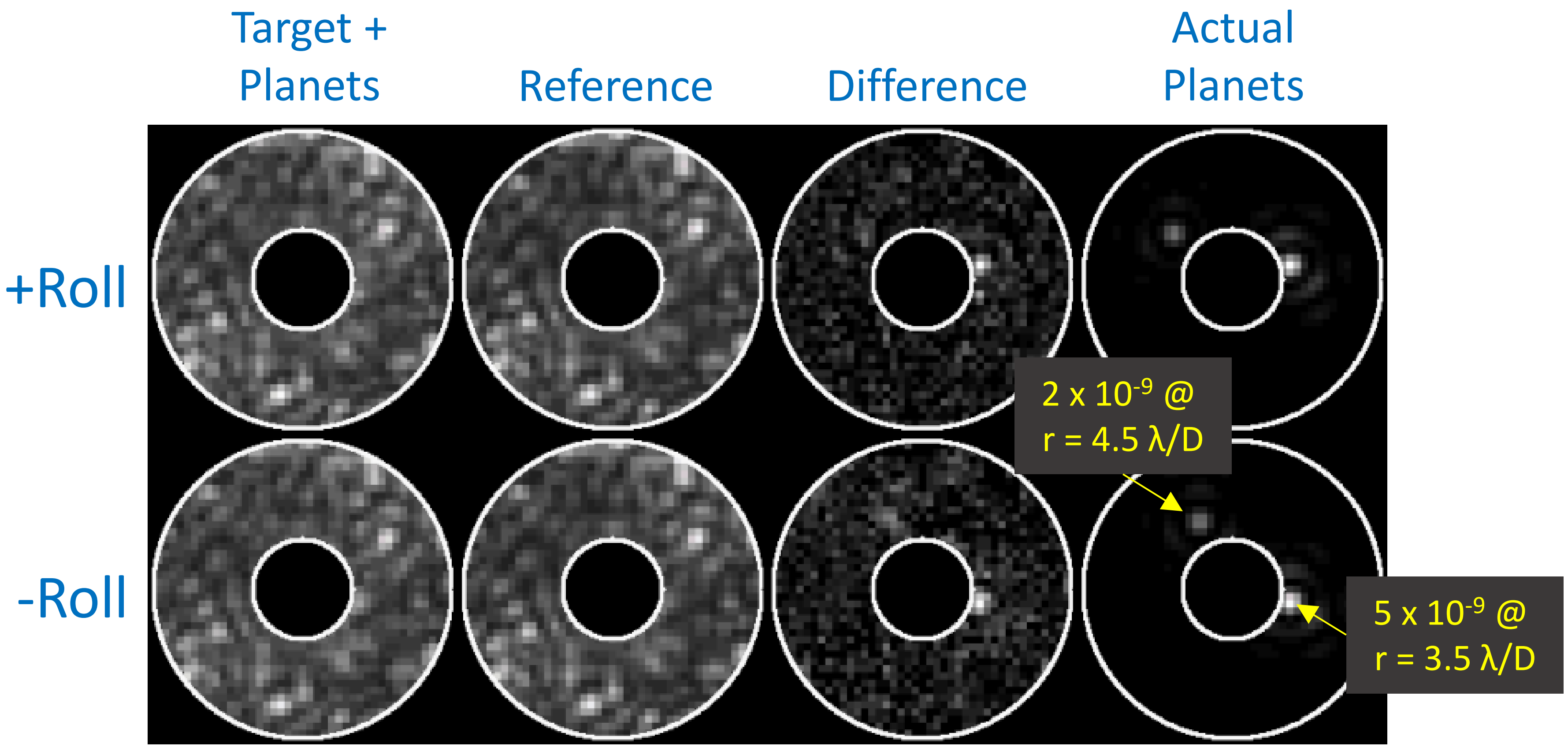
HLC (λ=546-604 nm), with jitter & LOWFS corrections

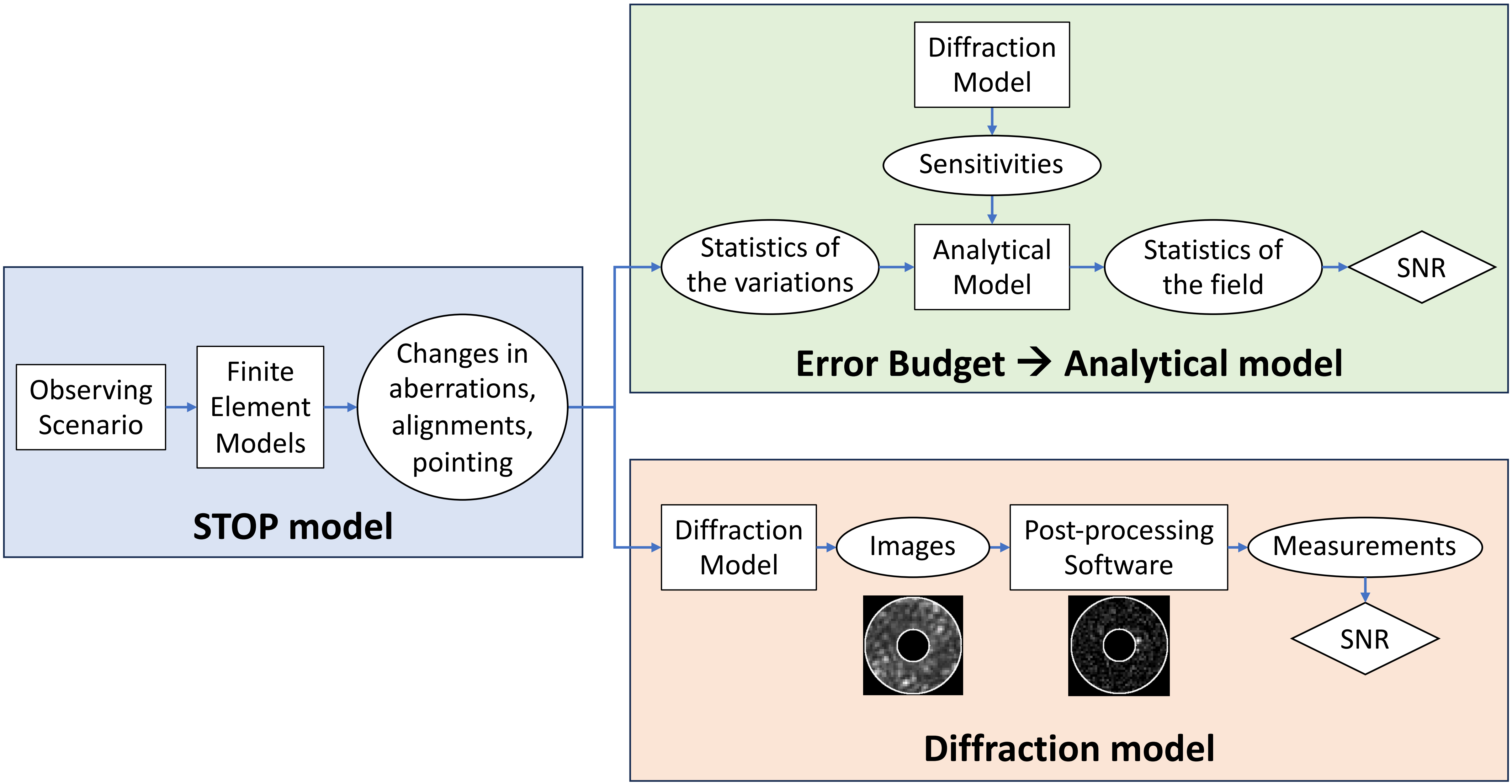


Time series data (HLC, SPC-Spec, SPC-WFOV) available at
roman.ipac.caltech.edu

OS11 Simple Post-Processing Simulations

HLC (λ=546-604 nm)




Diffraction Model
Sensitivities
Statistics of the variations
Analytical Model
Statistics of the field
SNR
Error Budget → Analytical model
Observing Scenario
Finite Element Models
Changes in aberrations, alignments, pointing
STOP model
Diffraction Model
Images
Post-processing Software
Measurements
SNR
Diffraction model

Error Budget Fundamental Properties

Before making an error budget, you must decide on:

- The Observing Scenario
- The Error Metric
  - A single value that can summarize how good the performance is
  - Defined in the context of the observing scenario

Flux Ratio

- Flux Ratio is a property of the planet
- The **signal** (*S*) is proportional to the Flux Ratio:
  - It is in counts (electrons):

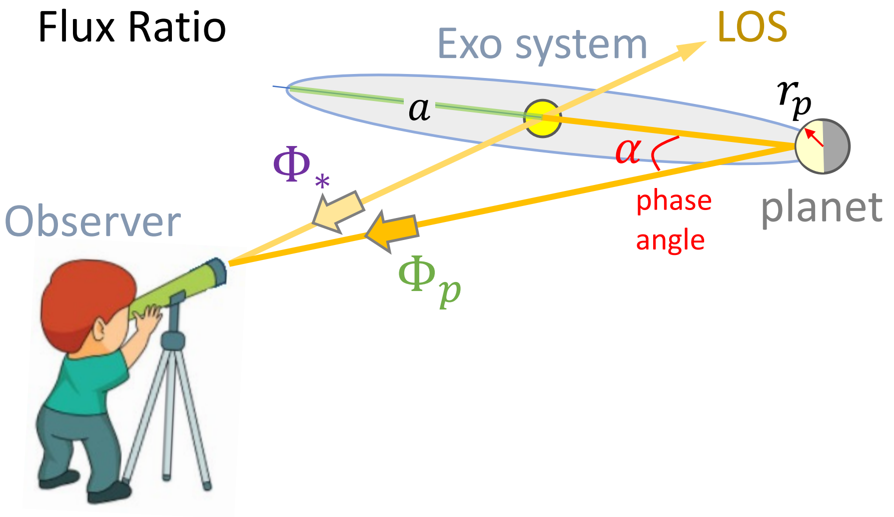
$$S = \xi_{pl} \cdot F_{star} \cdot throughput \cdot time$$

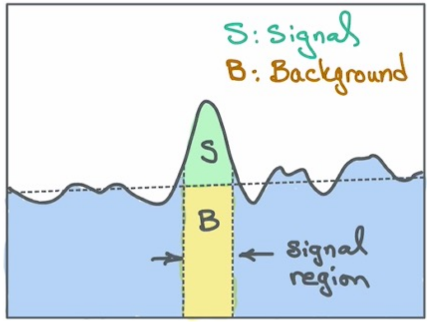
- So the astrophysical quantity of interest is:

$$\xi_{pl} = \kappa \cdot S \qquad \text{where} \qquad \kappa \equiv \frac{1}{F_{star} \cdot throughput \cdot time}$$

Flux Ratio:

$$\xi_{pl} \equiv \frac{\Phi_p}{\Phi_*}$$ Planet Flux Ratio





Flux Ratio Noise – The Error Budget Metric

- The flux ratio is given by:

$$\xi_{pl} = \kappa \cdot S$$

- ξ_{pl}: the scientifically interesting quantity
- κ: a conversion factor that depends on the instrument and observing scenario
- S: the signal we observe

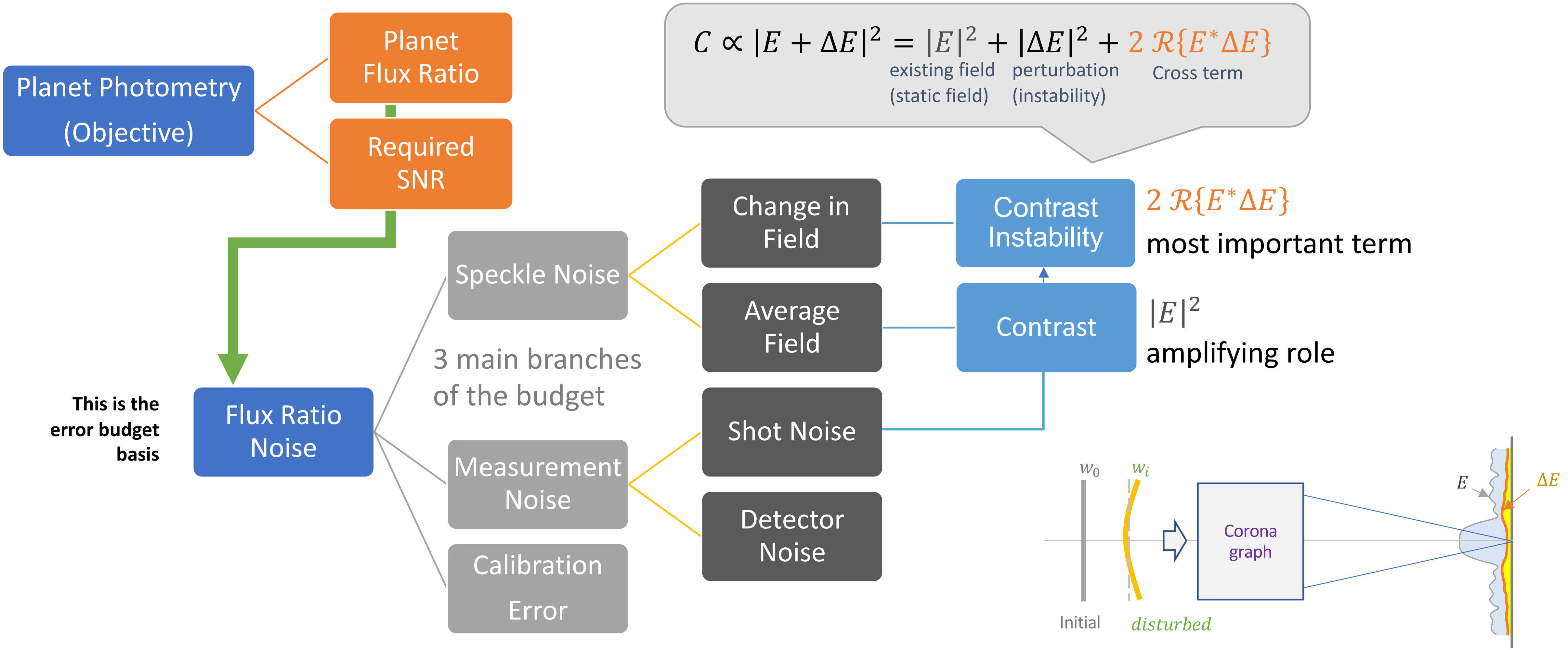
- The Error Budget is based on measuring this with the smallest error
  - So we define **flux ratio noise (FRN)** as the error budget metric.

- FRN can be obtained by taking the differential of the above and using root sum square (⨁) instead of (+) and (-)
  - True when the errors are independent

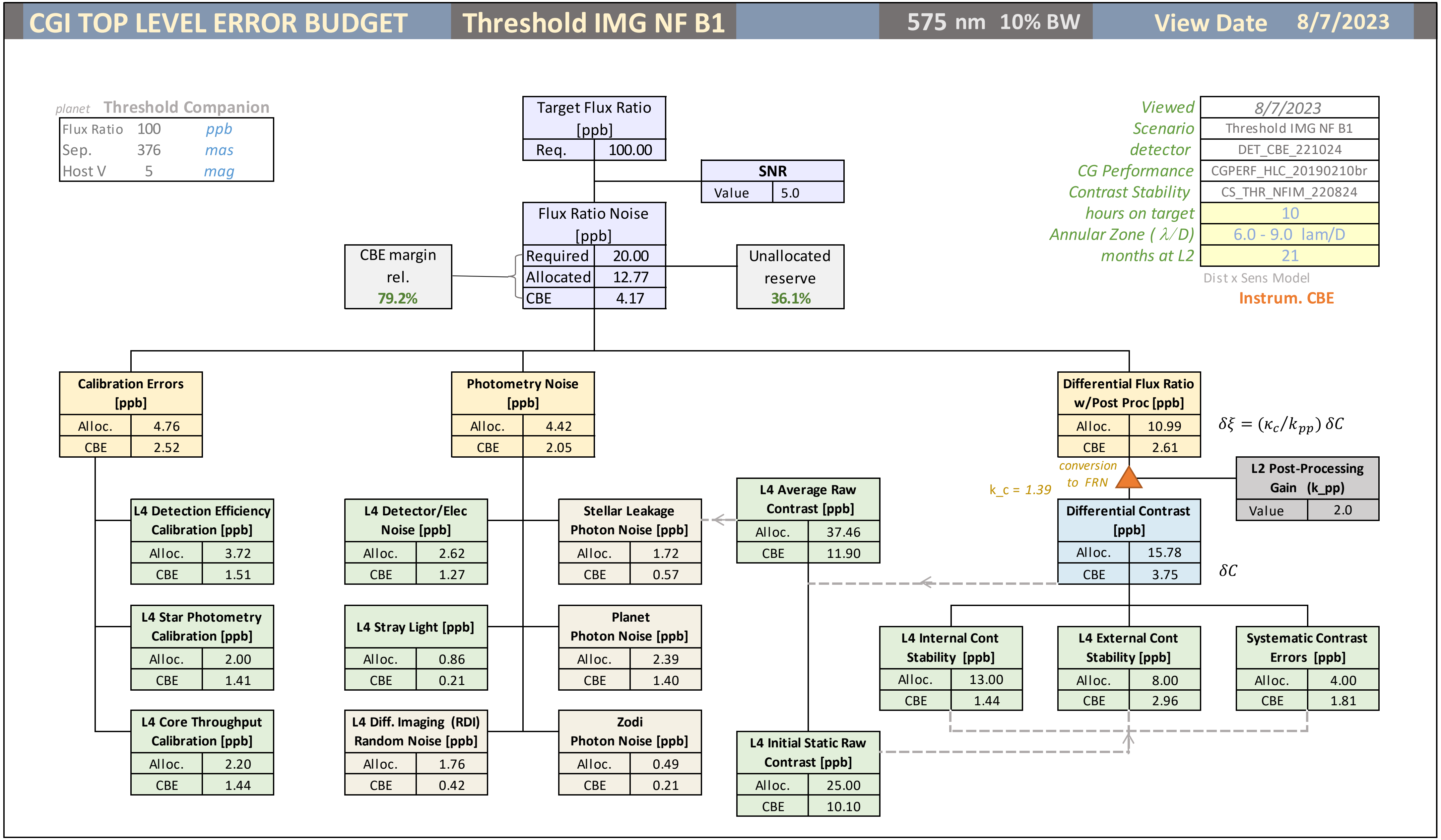
$$\delta\xi = \kappa \cdot \delta S \oplus \delta\kappa \cdot S$$

- $\delta\xi$: flux ratio noise **(FRN)**
- κ: Calibration Factor
- δS: Signal Extraction Errors
- $\delta\kappa$: Calibration Errors
- S: signal counts, e^-

Error Budget Flowdown from the Top



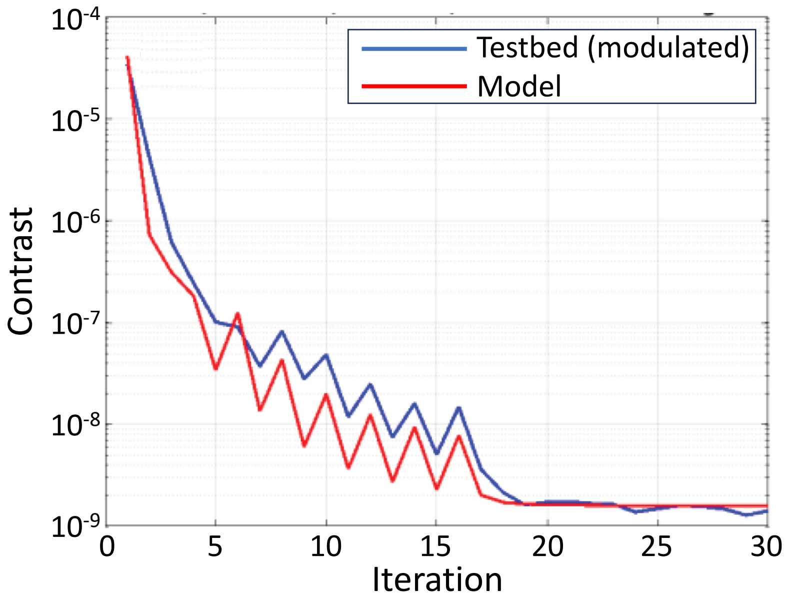
Roman CGI Error Budget



Model Validation & Verification

- **Numerical models vs JPL Testbed**
  - Aberration sensitivity
  - Dark hole contrast
  - EFC convergence rate
  - Initial DM patterns

See Zhou et al., SPIE Proc., 11443 (2020)
Also, see Alice Liu's talk on Thursday for STOP validation



- **Error budget vs Numerical models**
  - Comparison using OS6 results
  - Numerical model measurements
  - Analytical model statistics

See Nemati et al., JATIS (submitted) (2023)

r λ/D	Analytical Model FRN	Numerical Model FRN	Error
3-4	0.79	0.79	0%
4-5	0.56	0.47	19%
5-6	0.38	0.38	0%
6-7	0.38	0.36	5%
7-8	0.33	0.40	-16%
8-9	0.33	0.48	-31%

Summary

- We've been modeling CGI for 10 years to levels never previously attained
  - Using resources only available for flight projects
  - Models have been validated against testbed experiments
  - The algorithms, tools, and experience are directly applicable to HWO
- Because the coronagraph will not be tested with the actual telescope, modeling is critical for on-orbit performance predictions
  - This will be the case for any large space telescope coronagraph
- Review of CGI modeling by Krist et al. submitted to JATIS
- Nemati et al. paper on CGI error budget submitted to JATIS
- Modeling talks & posters at upcoming SPIE