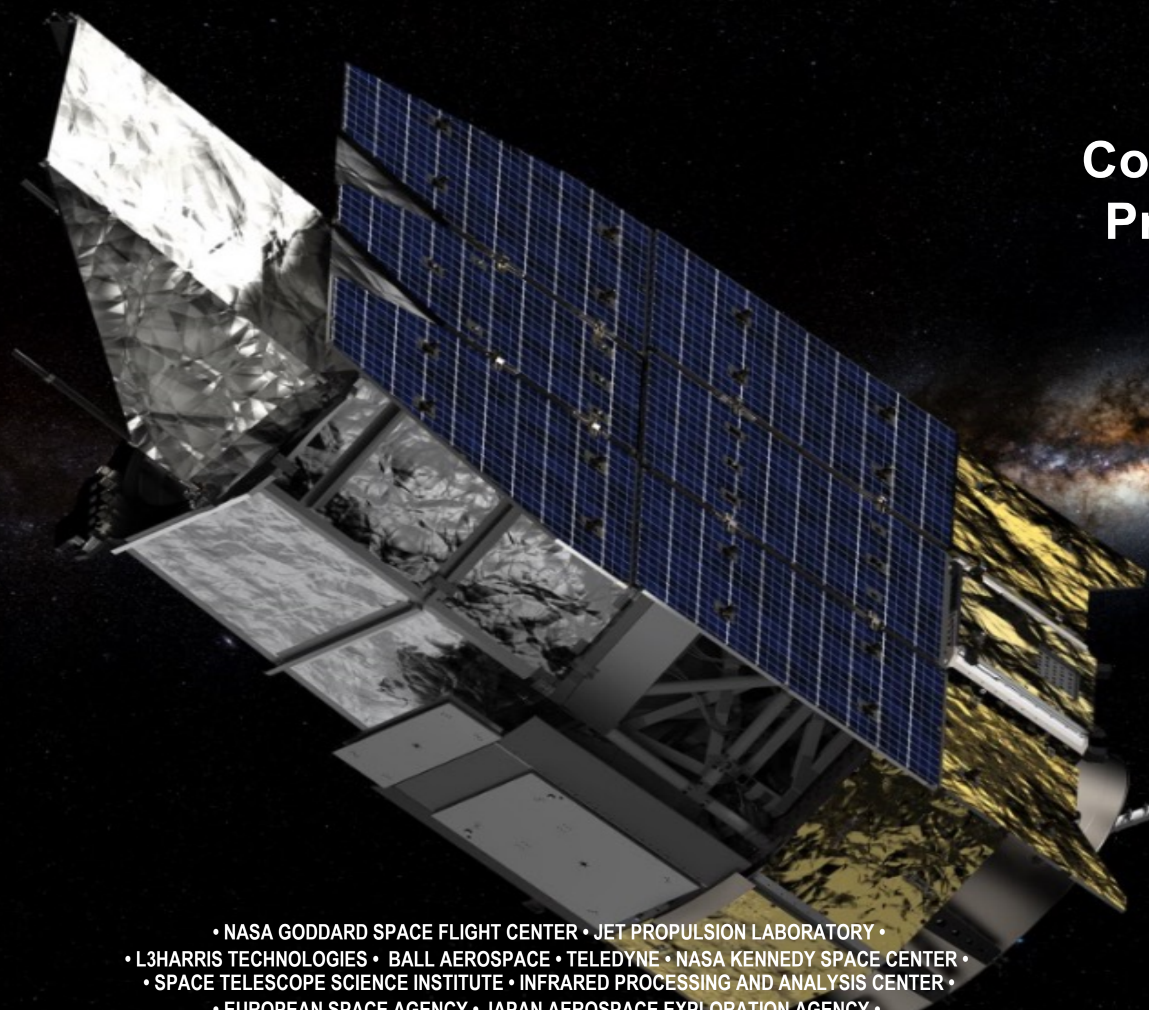


Jet Propulsion Laboratory
California Institute of Technology

# Coronagraph Top-Level Performance Predictions Update based on TVAC Results and Error Budget


Brian Kern

Jet Propulsion Laboratory

California Institute of Technology

Pasadena, CA 91109


August 26 – 27, 2024

• NASA GODDARD SPACE FLIGHT CENTER • JET PROPULSION LABORATORY •
• L3HARRIS TECHNOLOGIES • BALL AEROSPACE • TELEDYNE • NASA KENNEDY SPACE CENTER •
• SPACE TELESCOPE SCIENCE INSTITUTE • INFRARED PROCESSING AND ANALYSIS CENTER •
• EUROPEAN SPACE AGENCY • JAPAN AEROSPACE EXPLORATION AGENCY •
• CENTRE NATIONAL d'ÉTUDES SPATIALES • MAX PLANCK INSTITUTE FOR ASTRONOMY •

# Outline



- CGI performance requirements
- differential imaging
- "external" disturbances from observatory
- FRN budget
- context beyond CGI requirements

FRN budget was created and is maintained by Bijan Nemati

# top-level instrument performance requirement



- Top-level performance requirement describes a relative photometric measurement of a hypothetical planet
  - star brightness: V=5
  - planet flux ratio: $10^{-7}$
  - bandpass:10% @ 575 nm (λ/D ~ 50 mas)
  - distance from star to planet: 6 – 9 λ/D
  - integration time: 10 hrs
  - stellar angular diameter: 0.8 mas
  - signal-to-noise ratio (SNR): 5

only discussing Hybrid Lyot Coronagraph (HLC) direct imaging performance here

- Flux ratio $10^{-7}$ and SNR=5 imply a Flux Ratio Noise (FRN) of $2\times10^{-8}$

| CGIRD ID | Name | Primary Text | Verification Approach |
|---|---|---|---|
| CGIRD-505 | REQ: L3 CGI - Imaging with Narrow FoV Flux Ratio Noise | CGI shall be able to measure the flux ratio of a point source to the occulted star within 10 hours of integration time in CGI Filter Band 1 with a flux ratio noise as shown in Table 12. | Verification via the CGI flux ratio noise (FRN) budget using inputs from a combination of L4 test results and L4 analysis results. |

**Table 12:**

| Angular separation (lambda/D) | 6-9 |
|---|---|
| Point source Flux Ratio | $1\times10^{-7}$ |
| Flux Ratio Noise | $2\times10^{-8}$ |
| Stellar Radius (mas) | 0.4 |
| Stellar V mag | 5 |

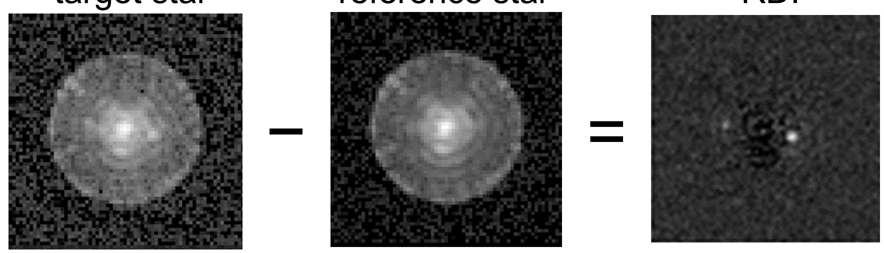
- Instrument "top level" is Level 3
  - L3 is instrument,
    L1-L2 is mission / observatory

# RDI context for flux ratio measurement

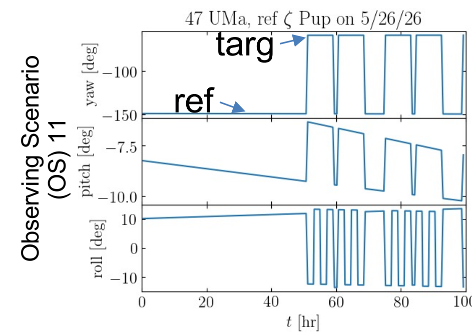
Jet Propulsion Laboratory
California Institute of Technology

ROMAN CORONAGRAPH

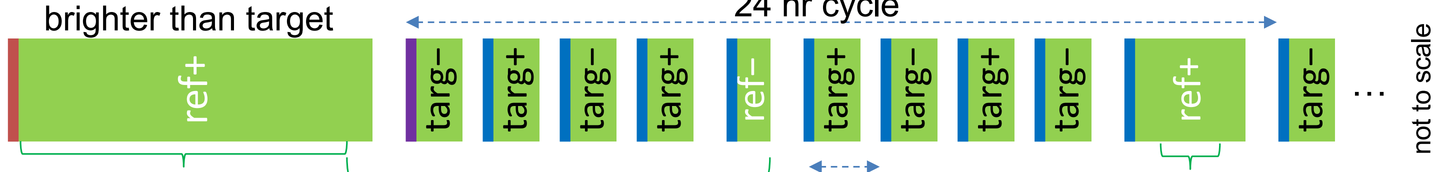
- All CGI quantification of flux ratio performance is in the context of a differential measurement, of a target star (with planet whose flux ratio we are measuring) and a reference star
- Reference Differential Imaging (RDI) is enabled by the observing scenario (OS), and that observing scenario then the foundation for STOP and dynamics analysis




John Krist models




reference star is ~ 16x brighter than target




HOWFSC on reference star

HOWFSC update

10 hr integration time from L3 requirement

longer observations are accounted for (and modeled) but not part of requirements

all performance context is differential

# OTA + TCA to CGI interface specification



- CGI is not responsible for the stability of the OTA + Tertiary Collimator Assembly (TCA) optics, and Instrument Carrier (IC) mechanical stability
  - "inputs" to CGI
- Interface specifications ("will" statements) are provided through the CGI Requirements Document (CGIRD)

WFE drift at max levels dominate the CGI contrast stability

| CGIRD | Name | Primary Text | REQ Value | CBE Val | Margin |
|---|---|---|---|---|---|
| 687 | 9.4.8 **OTA Wavefront Error Drift, Z5-Z11** | The RSS of Z5-Z11 WFE change at the OTA-CGI exit pupil between any two points in time during a 10 hr CGI observation will not exceed 250 pm, except during slew and settling. | 250 pm | 52 pm | 79% |
| 688 | 9.4.9 **OTA Wavefront Error Drift, Z4-Z11** | After averaging over 100 s frames, a weighted sum (defined in Table 55) of changes in WFE Rejection Filtered (WRF, defined in Figure 23) Z4-Z11 WFE at the CGI entrance pupil between any two points in time during a 10 hr CGI observation will not exceed 150 pm, except during slew and settling. | 150 pm | 3.1 pm | 98% |
| 696 | 9.4.13.1 **LoS Jitter at OTA-CGI Interface** | The root mean square (RMS) Line of Sight (LoS) jitter at the OTA-CGI exit pupil, after applying the Jitter Rejection Filter (JRF, defined in Figure 24 below), during accepted CGI frames will be less than 0.57 milliarcsec on sky per axis. | 0.57 mas | 0.57 mas (>=94.3 % of the time) | OK |

but telescope stability margins are high

note: OS10 results shown (CDR 2021)

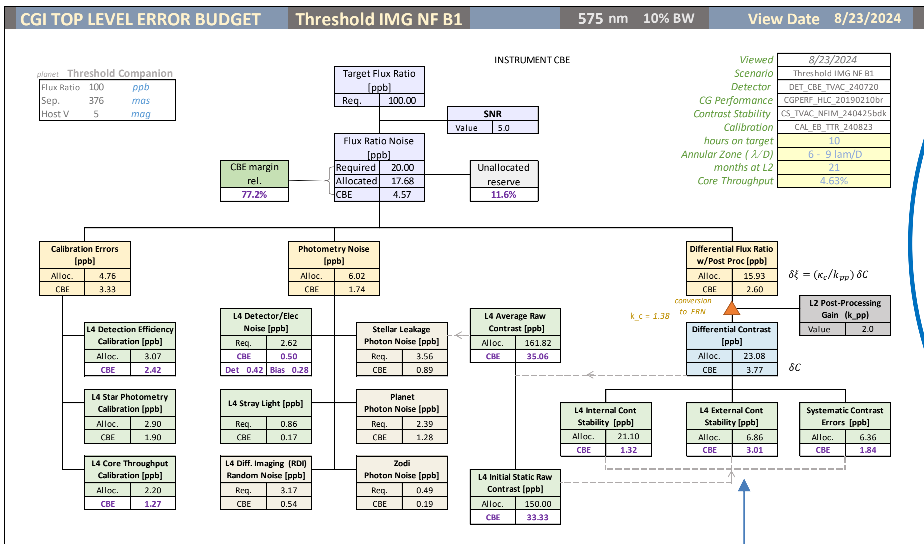
- Other optical stability specifications are also in CGIRD: pupil shear, boresight stability, WFE jitter
- Context is that CGI must meet its L3 performance in the presence of the worst specified stability

observatory is more stable than its specification

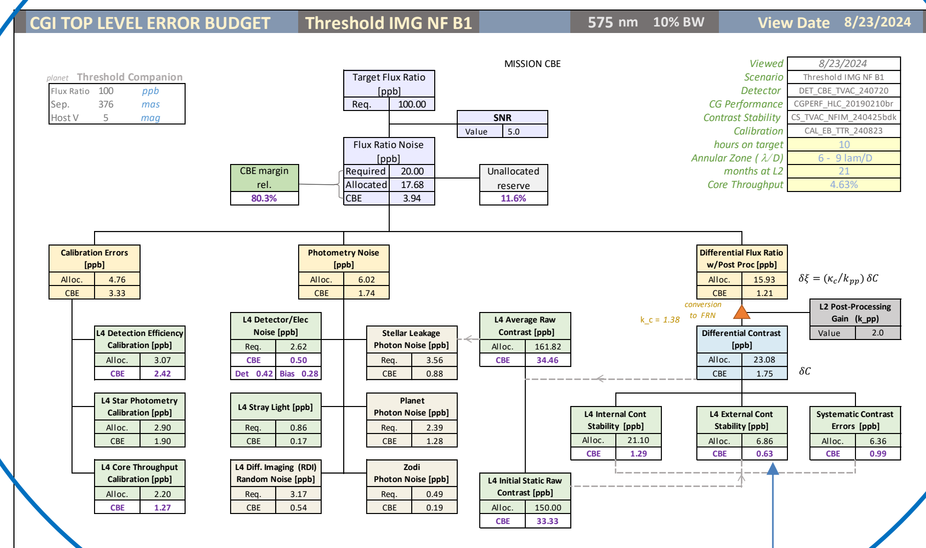
# CBEs and verification

Current Best Estimate = CBE

instrument CBE with “worst case” observatory stability




mission CBE: observatory stability at model expectations (with Model Uncertainty Factors)




appropriate conservatism given maturity of models

“letter of the law” stability inputs

“mission CBE” includes modeled (not worst-case) stability of the observatory outside CGI

# structure of the FRN budget graphic



- Flowdown of L3 FRN requirement divides into 3 branches

1. calibration

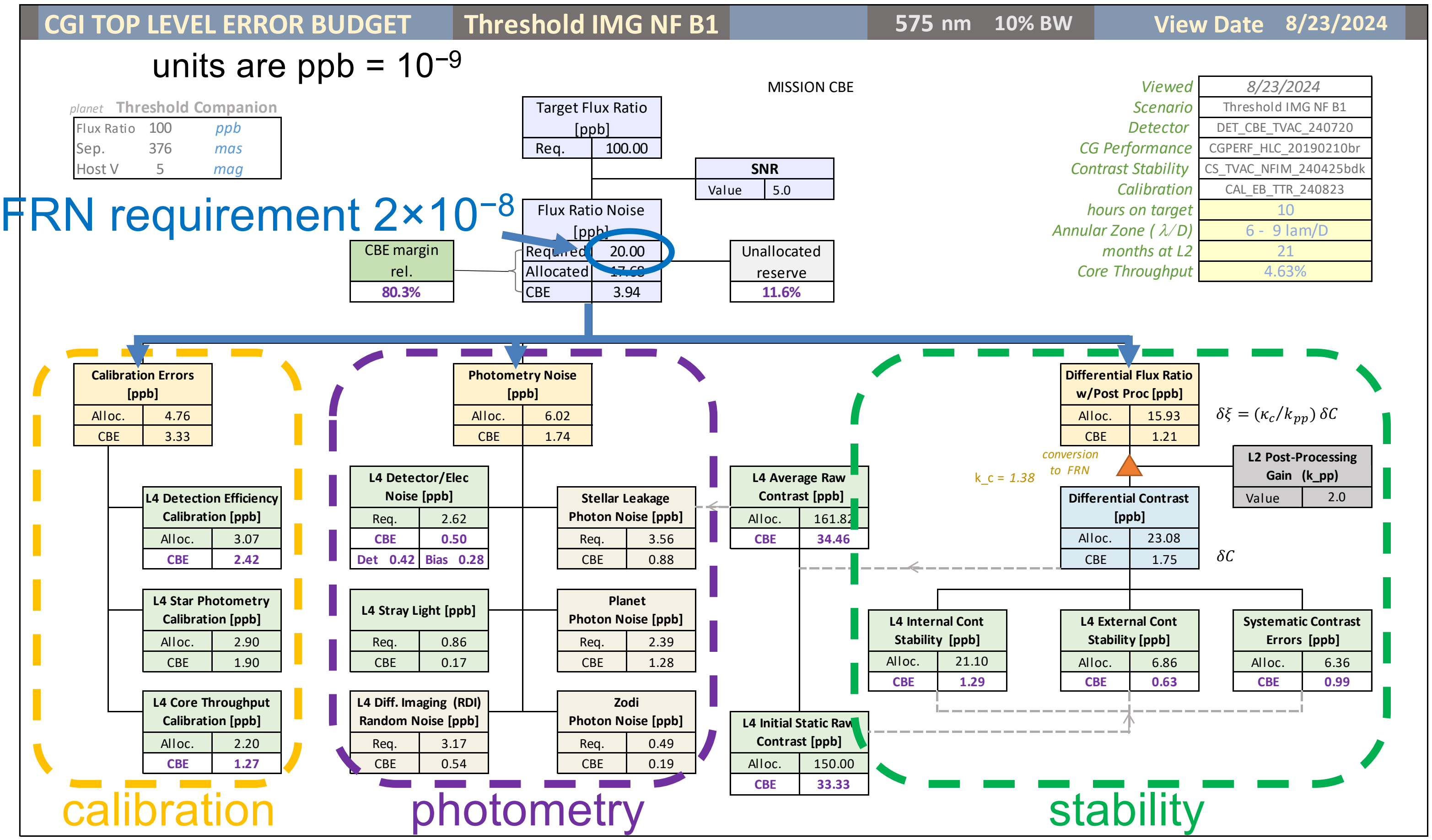
   errors in scale factors that convert planet photons into flux ratio (normalization)

2. photometry

   shot noise from star + planet + zodi, detector noise

3. stability

   over- or under-subtraction of starlight in differential image (temporal change in speckle brightness)



# updates from testing

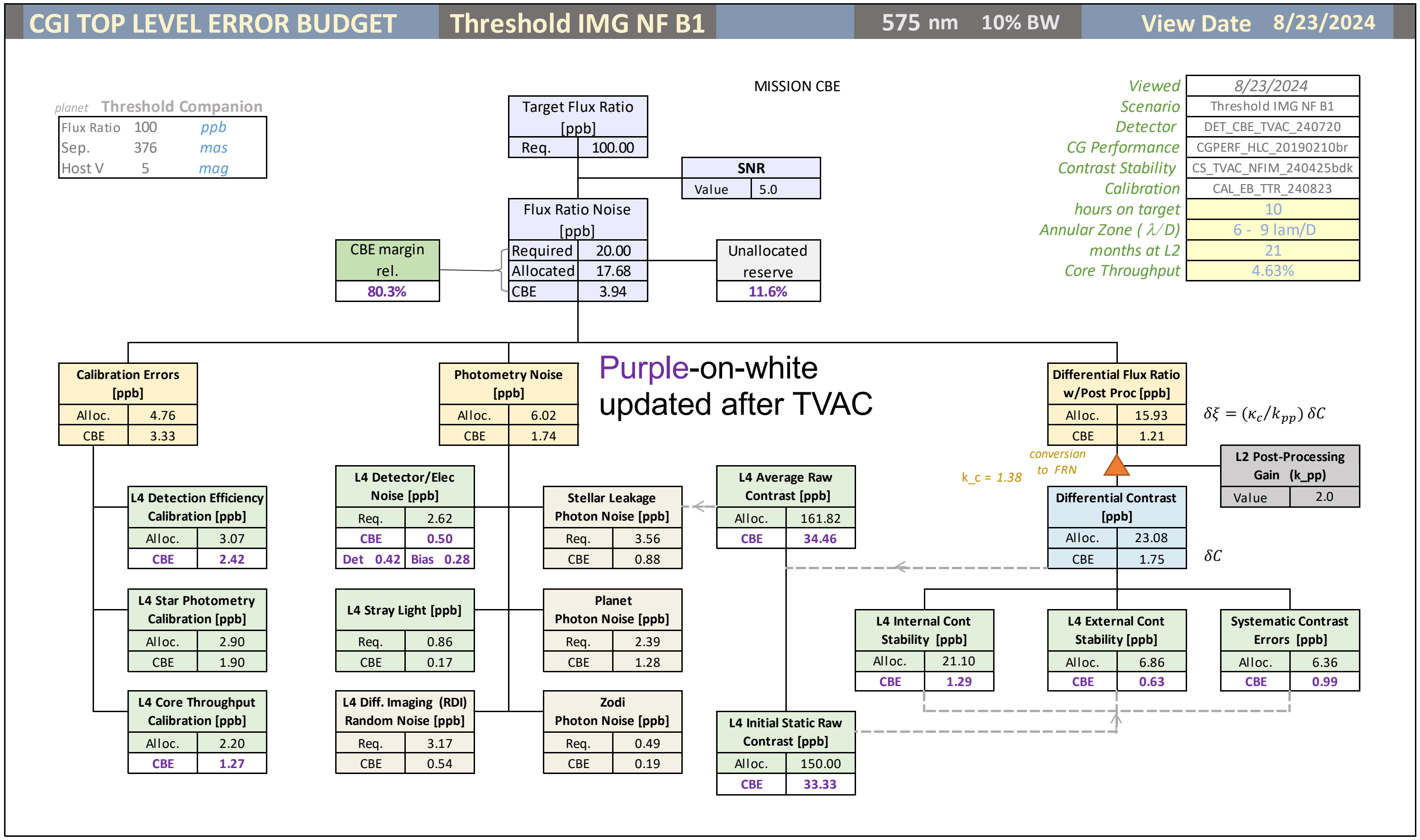
Jet Propulsion Laboratory
California Institute of Technology

ROMAN CORONAGRAPH

TVAC results incorporated:

- calibration
  - flat fields
  - core throughput
- photometry
  - dark current
  - CIC
  - read noise
  - EM gain (7000×)
  - total raw contrast
- stability
  - initial raw contrast
    - coherent
    - incoherent
  - DM temperature stability

No “surprises”



# CBE in requirements context



- CGI reports CBEs to show compliance with requirements
  - conservatism is relevant to confidence that estimates meet requirements
  - some quantities are expressed as “not to exceed,” or 3-sigma confidence intervals
  - quantities produced by modeling are “assumed worse” by Model Uncertainty Factor (MUF)
    - MUF values (factors) are based on institutional experience with previous mission life cycles
    - MUFs range from 2-8 depending on model fidelity
    - some stability terms have multiple “compounded” MUFs
      - MUFs on observatory disturbances (CGI inputs) × MUFs on CGI sensitivities to inputs
- CBEs reported here can be interpreted as “upper limits”
  - not an “unbiased” estimate of in-flight performance
- CBEs reported here are answers only to the requirements-based observing context
  - 10 hr observation of $10^{-7}$ flux ratio planet
    - lower flux ratio planets produce smaller errors for many terms, e.g., calibrations (fractional errors)
  - “nominal” case investigated here is a ~ median case for expected observatory disturbances
    - individual “best case” observations may perform significantly better
  - in practice, CGI intends to explore far longer observations (hundreds of hours for spectroscopy)
  - in flight, CGI will be able to tailor observing scenario with feedback from actual disturbances measured during previous in-flight observations

significant engineering-based conservatism in mission CBE

# largest contributors to FRN



Largest contributors to FRN mission CBE (arbitrarily grouped):

1. calibration errors

   small fraction of $10^{-7}$ (bright) planet

   unrelated to detection confidence

2. planet shot noise

   large due to bright planet

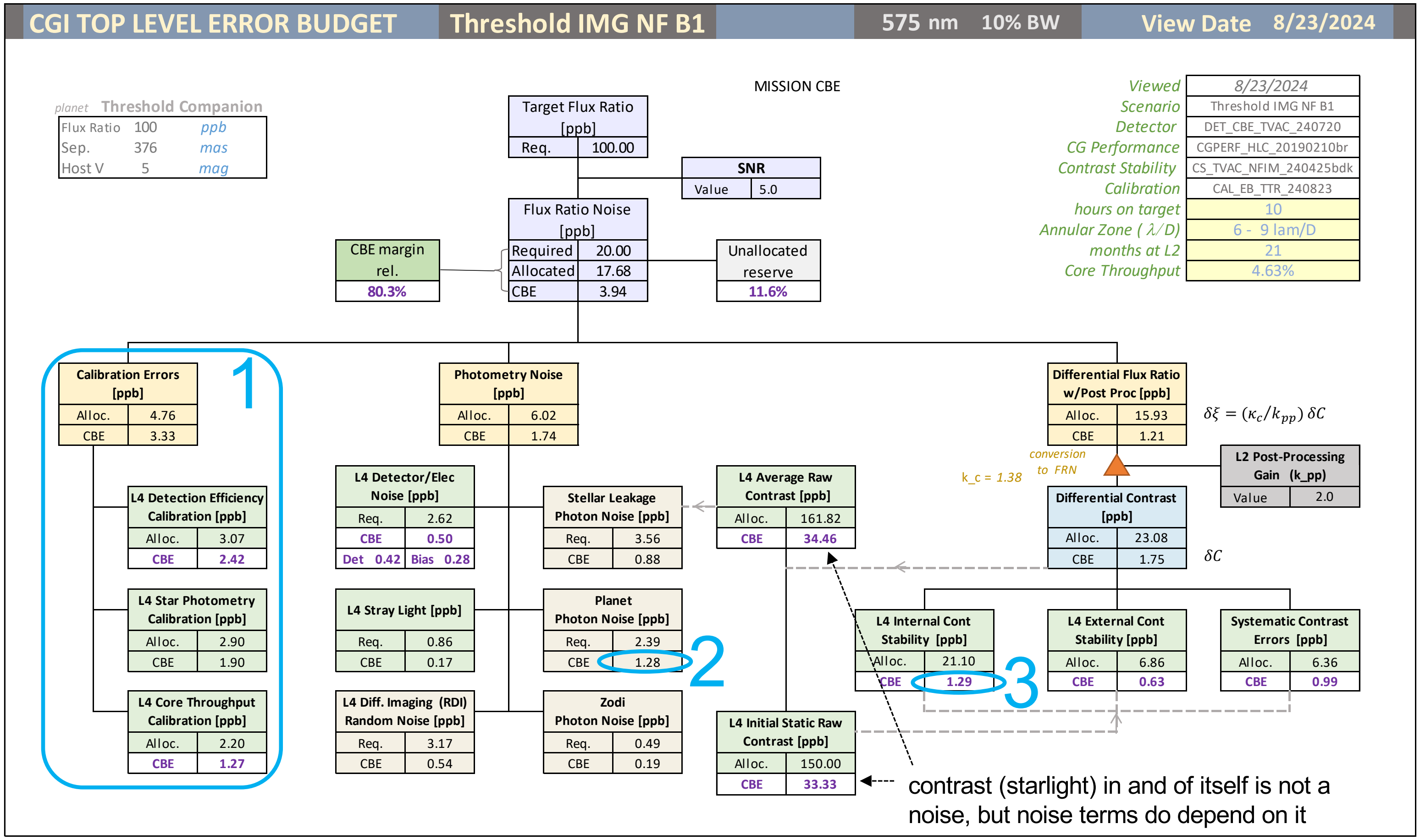
3. internal contrast stability

   dominated by LOWFSC side-effects

   – pointing repeatability between target and reference star

   – LOCam bias pattern stability

   – worst-case DM actuator quantization during Z5-Z11 control



# extrapolation to challenging targets



- what would it take to image ~ 3e-9 flux ratio planet with SNR=5?
  - better contrast
    - TVAC measurements ~ 1e-8 coherent, 2e-8 incoherent
    - reducing coherent contrast by ~ 2× would sufficiently reduce impact of disturbances on contrast stability
    - might require ~ hundreds of hours of HOWFSC?
      - hard to predict
  - longer integration times
    - ~ 100 hr integration times significantly reduce photometry noise
    - multiple 10-hr target-reference cycles will improve some stability terms
      - terms that are uncorrelated on multiple observing cycles will average down
      - can consider combining observations using different reference stars for greater decorrelation of errors
  - tailor LOWFSC operation for best trade between reduction of disturbances and reduction of “side effects”
- what would it take to image ~ 1e-9 flux ratio planet with SNR=5?
  - likely need to rely on significantly better post-processing
    - tailor observations to “calibrate” types of errors, train postprocessing to reject specific disturbances
  - develop HOWFSC techniques to ensure significantly different dark hole E-field morphologies with similarly “good” contrast
    - further decorrelate errors across multiple observations

# work to go



- Evaluate FRN for spectroscopy, Wide FoV (shaped pupil coronagraphs)
- Evaluate expected performance
  - instead of “not-to-exceed” performance
- Evaluate options to achieve sufficient performance on challenging targets
  - flux ratio $\lesssim$ few × $10^{-9}$