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

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WARNING
HIGH DIFFRACTION ZONE
CORONAGRAPHICS 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

Polarization-dependent aberrations

Deformable mirrors

Masks

Synthetic  Measured

SPC pupil mask  HLC focal plane mask
CGI Wavefront Control

*Hybrid Lyot Coronagraph, $\lambda=546-604$ nm*

Contrast = $2 \times 10^{-3}$

Before flattening
No HLC DM pattern
No masks

After flattening
No HLC DM pattern
No masks

After flattening
No HLC DM pattern
HLC masks

After flattening
HLC DM pattern
HLC masks

After HOWFS
HLC DM pattern
HLC masks

$\sim 10^{-9}$

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)

Δθ_{sky} = 166°   Δθ_{sun} = 3.5°

- Solar incidence angles
- Reaction wheel speeds
- Mechanism motions
- Electronics usage
OS Time Series Computation Process

Observing scenario times & orientation
CGI power plant (mechanisms, heaters)

3x - 8x jitter MUF

Reaction wheel speeds
Dynamics model
Pointing errors
quasi-LOWFS model
Pointing jitter

Models
Sigfit + Code V)
changes

2x structural MUF

Diffraction model
(PROPER)

Photon counting
(photon_count)
Detector model
(emccd_detect)
CGI speckle images

See Alice Liu's talk on Thursday for more on STOP modeling
OS11 Low-Order Aberration Variations
(before LOWFS correction)

pm RMS ΔWFE from t = 170h

0° astig
X Coma
45° astig
Focus
Y Coma
OS11 Pointing Jitter

Reaction wheel speeds

Post-correction pointing jitter

Wheel speed (revolutions/s)

Jitter (mas RMS)

Hours

Hours
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)**

<table>
<thead>
<tr>
<th>Target + Planets</th>
<th>Reference</th>
<th>Difference</th>
<th>Actual Planets</th>
</tr>
</thead>
</table>
| +Roll            | ![Image]
| -Roll            | ![Image] |

- **Roll**: 5 x 10^-9 @ r = 3.5 λ/D
- **Roll**: 2 x 10^-9 @ r = 4.5 λ/D
Observing Scenario → Finite Element Models → Changes in aberrations, alignments, pointing → STOP model → Diffraction Model → Sensitivities → Statistics of the variations → Analytical Model → Statistics of the field → SNR

Error Budget → Analytical 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):

\[
S = \xi_{pl} \cdot F_{\text{star}} \cdot \text{throughput} \cdot \text{time}
\]

• So the astrophysical quantity of interest is:

\[
\xi_{pl} = \kappa \cdot S \quad \text{where} \quad \kappa \equiv \frac{1}{F_{\text{star}} \cdot \text{throughput} \cdot \text{time}}
\]
Flux Ratio Noise – The Error Budget Metric

• The flux ratio is given by:

• 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
Error Budget Flowdown from the Top

Planet Photometry (Objective) → Planet Flux Ratio → Required SNR → Flux Ratio Noise

3 main branches of the budget:
- Speckle Noise
- Measurement Noise
- Calibration Error

\[ C \propto |E + \Delta E|^2 = |E|^2 + |\Delta E|^2 + 2\mathcal{R}\{E^*\Delta E\} \]

Cross term: most important term

amplifying role

Initial disturbed Corona graph
Roman CGI Error Budget

**CGI TOP LEVEL ERROR BUDGET**

**Threshold IMG NF B1**

- **View Date**: 8/7/2023
- **575 nm 10% BW**

**Planet**
- **Threshold Companion**
  - **Flux Ratio**: 100 ppb
  - **Sep.**: 376 mas
  - **Host V**: 5 mag

**Target Flux Ratio**
- **[ppb]**
  - **Req.**: 100.00

**SNR**
- **Value**: 5.0

**Flux Ratio Noise**
- **[ppb]**
  - **Required**: 20.00
  - **Allocated**: 12.77
  - **CBE**: 4.17

**CBE margin rel.**: 79.2%

**Unallocated reserve**: 36.1%

**Allocation**
- **All loc.**: 4.76
- **CBE**: 2.52

**Calibration Errors**
- **[ppb]**
  - **Alloc.**: 4.76
  - **CBE**: 2.52

**Photometry Noise**
- **[ppb]**
  - **Alloc.**: 4.42
  - **CBE**: 2.05

**L4 Detection Efficiency Calibration**
- **[ppb]**
  - **Alloc.**: 3.72
  - **CBE**: 1.51

**L4 Star Photometry Calibration**
- **[ppb]**
  - **Alloc.**: 2.00
  - **CBE**: 1.41

**L4 Core Throughput Calibration**
- **[ppb]**
  - **Alloc.**: 2.20
  - **CBE**: 1.44

**L4 Stray Light**
- **[ppb]**
  - **Alloc.**: 0.86
  - **CBE**: 0.21

**L4 Detector/Elec Noise**
- **[ppb]**
  - **Alloc.**: 2.62
  - **CBE**: 1.27

**Stellar Leakage Photon Noise**
- **[ppb]**
  - **Alloc.**: 1.72
  - **CBE**: 0.57

**Planet Photon Noise**
- **[ppb]**
  - **Alloc.**: 2.39
  - **CBE**: 1.40

**L4 Diff. Imaging (RDI) Random Noise**
- **[ppb]**
  - **Alloc.**: 1.76
  - **CBE**: 0.42

**Zodi Photon Noise**
- **[ppb]**
  - **Alloc.**: 0.49
  - **CBE**: 0.21

**L4 Initial Static Raw Contrast**
- **[ppb]**
  - **Alloc.**: 25.00
  - **CBE**: 10.10

**L4 Internal Cont Stability**
- **[ppb]**
  - **Alloc.**: 13.00
  - **CBE**: 1.44

**L4 External Cont Stability**
- **[ppb]**
  - **Alloc.**: 8.00
  - **CBE**: 2.96

**Systematic Contrast Errors**
- **[ppb]**
  - **Alloc.**: 4.00
  - **CBE**: 1.81

**Differential Flux Ratio**
- **w/Post Proc [ppb]**
  - **Alloc.**: 10.99
  - **CBE**: 2.61

**Differential Contrast**
- **[ppb]**
  - **Alloc.**: 15.78
  - **CBE**: 3.75

**Conversion**
- **k_c** = 1.39

**Δxi** = (k_c / k_pp) ΔC

**L2 Post-Processing Gain**
- **(k_pp)**
  - **Value**: 2.0

**ΔC**

**Conversion to FRN**

**Conversion to FRN**

**Δxi** = (k_c / k_pp) ΔC

**ΔC**
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)

<table>
<thead>
<tr>
<th>$r$</th>
<th>Analytical Model FRN</th>
<th>Numerical Model FRN</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-4</td>
<td>0.79</td>
<td>0.79</td>
<td>0%</td>
</tr>
<tr>
<td>4-5</td>
<td>0.56</td>
<td>0.47</td>
<td>19%</td>
</tr>
<tr>
<td>5-6</td>
<td>0.38</td>
<td>0.38</td>
<td>0%</td>
</tr>
<tr>
<td>6-7</td>
<td>0.38</td>
<td>0.36</td>
<td>5%</td>
</tr>
<tr>
<td>7-8</td>
<td>0.33</td>
<td>0.40</td>
<td>-16%</td>
</tr>
<tr>
<td>8-9</td>
<td>0.33</td>
<td>0.48</td>
<td>-31%</td>
</tr>
</tbody>
</table>
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