Phase and Pupil Amplitude Recovery for JWST Space-Optics Control


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Introduction

- The James Webb Space Telescope (JWST) is the successor to the HST (launch in 2014)
- JWST will operate in a manner similar to HST: enabling a range of science investigations proposed by astronomers worldwide
- General Observer community will drive science investigations
JWST is an Astrophysics Mission

The development of technical requirements for JWST is driven by:

- **First-light and re-ionization**: Identify the first bright objects in the early Universe and follow ionization history

- **Galaxy formation and Evolution**: Shed light on how galaxies and dark matter evolved to present

- **Star formation in our galaxy**: Study the birth and early development of stars

- **Planetary systems**: Observe the physical and chemical properties of solar systems
Optical Systems Engineering

- Verification of Requirements:

- Optical Performance Requirements Group 6 (OPRG6): summary of requirements and Performance Characterization Flows (PCFs)

- General goals of PCFs: Verify requirements formally assigned to the group by ISIM (40 requirements: 2 ISIM, 22 NIRCam, 16 IOS, ALL 40 are related to NIRCam)

Integrated Science Instrument Module = ISIM
Goals of Performance Requirements

• Verify the requirements assigned to ISIM

• Include the “ISIM Testing with OSIM” section of the Wavefront Sensing and Control Test Plan (Ball Aerospace)

• Provide a thorough demonstration/verification of the ISIM wavefront sensing capabilities testable by OSIM

• Coarse-Phasing, Fine-Phasing, MIMF: To emphasize high-level WFS performance metrics over low-level requirements
Integrated Science Instrument Module (ISIM)
ISIM (Component Form)
Integrated Science Instrument Module (ISIM)
NIRCam ETU Cryo Verification

- NIRCam: the primary JWST science camera, also used for WFSC
- Verification of WFSC Functions:
  - phase retrieval performance,
  - coarse phasing performance,
  - ghost images,
  - diamond turning artifacts
- April 2010, testing completed at Lockheed Martin facility
Example Phase Retrieval Data

-8\(\lambda\)  -4\(\lambda\)  +4\(\lambda\)  +8\(\lambda\)  +12\(\lambda\)

pupil data:
Ghost Irradiance

Older NIRCam Pathfinder

NIRCam ETU

ghost irradiance

relative ghost irradiance = 1/8
Phase Retrieval Approach

- **Non-Linear Optimization (NLO):**

- Incorporating variable sampling and pupil-amplitude reconstruction:
  - B. Dean, “Gradient Calculations for the NLO Approach to Phase Retrieval,” Code 551; Doc # 20100405BHDVer1a, April 5, 2010

- **Iterative Transform:**

\[
\hat{E} = \left[ \frac{1}{N} \sum_{n}^{\text{pixels}} w_n(x) \left| I_n(x) - I'_n(x) \right|^2 \right]^{1/2}
\]

\[
\sum_{x}^{\text{pixels}} w_n(x) \left| I_n(x) \right|^2
\]
Example Phase Retrieval Results

Across the FOV:

Complex Field Retrieval (Phase)
4.5.11 ETU4 JWST

Complex Field Retrieval (Phase)
4.5.12 ETU5 JWST

Complex Field Retrieval (Phase)
4.5.10 ETU3 JWST

Complex Field Retrieval (Phase)
4.5.9 ETU2 JWST

Complex Field Retrieval (Phase)
4.5.8 ETU1 JWST

Across the FOV:
Pupil Amplitude Estimation

Start:

Initial Estimate:
JWST-like Amplitude Retrieval

Complex Field Retrieval (Amplitude)
4.5.8 ETU1 JWST

Amplitude [arb]
Circular Amplitude Retrieval

Complex Field Retrieval (Amplitude)
4.5.3 ETU1 F/20
• Tip, tilt, and defocus are optimized to minimize the error metric
• In this approach, starting values only need to be approximate
Algorithms Tested Using Simple Testbeds

Results are correlated with PDI and alternative implementations of algorithms
Example Testbed Data

defocus: 
-20 mm -15 mm -10 mm -05 mm +05 mm +10 mm +15 mm +20 mm

Run 1: 
Run 2: 
Run 3: 
Run 4: 
Run 5:
Initial Plate Scale Estimation using the MTF

- λ = 633 nm
- λ = 642 nm
- λ = 660 nm
- λ = 780 nm
- λ = 1065 nm

Example cutoff radius
Determining Q Values (initially: grid search)

Retrieval with 36 Zernikes
4.5.9 ETU1 JWST Set 1

Final Error Metric Value (NRMSE Intensity)

Qavg=2.198
Stddev=0.003

-8 λ
-4 λ
+4 λ
+8 λ
Theory: Data Parameters Estimated from the MTF

- Solve for these parameters directly from the data

- Diameter of the MTF defines the optical passband:
  \[2 \times \nu_b\]

- Define:
  \[
  \begin{align*}
  \nu_b & \equiv \text{cut-off frequency (band-limit)} \\
  \nu_\Delta & \equiv \text{data sampling frequency} \\
  p & \equiv \text{plate scale (radians)} \\
  Q & \equiv \text{image sampling parameter}
  \end{align*}
  \]

\[
Q \equiv \frac{\nu_\Delta}{\nu_b} = \frac{\lambda f_\#}{\Delta x} = \frac{\lambda}{p \cdot D}
\]
Pupil Amplitude Estimation vs. $\lambda$

$\lambda = 633$ nm  $\lambda = 642$ nm  $\lambda = 660$ nm  $\lambda = 780$ nm
Pupil Amplitude Estimation vs. # of Images

2-images:

4-images:

6-images:

8-images:
Least Square Error vs. Starting Pupil Amplitude

\[
\hat{E} = \left[ \frac{1}{N} \sum_{n=1}^{N} \sum_{x} \text{pixels} w_n(x) \left| I_n(x) - I'_n(x) \right|^2 \right]^{1/2}
\]

![Graph showing least square error vs. wavelength for Astigmatism and Coma.](image)
Pupil Amplitude Estimation vs Rotation (clocking)
Typical Phase Retrieval Results

-20 mm  -15 mm  -10 mm  -5 mm  +5 mm  +10 mm  +15 mm  +20 mm

Data 1  Data 2  Data 3  Data 4  Data 5  Data 6  Data 7  Data 8

Model 1  Model 2  Model 3  Model 4  Model 5  Model 6  Model 7  Model 8

MTF data 1  MTF data 2  MTF data 3  MTF data 4  MTF data 5  MTF data 6  MTF data 7  MTF data 8

MTF Model 1  MTF Model 2  MTF Model 3  MTF Model 4  MTF Model 5  MTF Model 6  MTF Model 7  MTF Model 8
Summary

- A robust suite of algorithms have been developed for JWST sensing and control.
- NIRCam ETU instrument tests indicate that WFS will meet NIRCam specific OPRG-6 requirements.
- We consider pupil amplitude estimation to be a “standard” component of the analysis.
- Ground testing of JWST instruments indicate that accurate estimation of phase and pupil amplitude are expected, even with subsystem deployment anomalies.