Relative Throughput of the Near-IR Science Instruments of the James Webb Space Telescope as Measured in the Ground Testing of the Integrated Science Instrument Module

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Purpose of Test

- The primary purpose of this test was to trend the relative throughput of the JWST near-IR science instruments (NIRCam, NIRSpec, NIRISS, and FGS) as a way to monitor for any potential changes from gross problems such as contamination or degradation of an optic.
- These results also give the first relative throughput of the instruments in their flight-like configurations and can be used to verify and update model predictions.
- They can also be used for trending with the on-orbit throughputs that will be measured during commissioning.
- Data was obtained during Cryo-Vacuum testing of the Integrated Science Instrument Module (ISIM) at the Goddard Space Flight Center (GSFC) as part of 2 test procedures, the Initial Optical Baseline (IOB) December 29, 2015 and the Final Performance (FP) January 25, 2016 (which bracket most of the SI testing in this Cryo-Vacuum test). The results will also be compared to a similar test from a previous Cryo-Vacuum test (data from September 14, 2014) to bracket ISIM-level testing.

Data Collection (IOB & FP)

Point Source Observations

Source	NRCA3	NRCB4	NRCALONG	NRCBLONG	NIRISS	NRS1	FGS1	FGS2
LD106	1800	1800			1800	1800	1800	1800
LD155	2200	2200			2200	2200	2200	2200
LED21	30000	30000			30000	30000	30000	30000
Tungsten/F277W			400 @ T=1200	400 @ T=1200	400 @ T=1200			
LED35			4500 2600	4500 2600	4500 2600	4500 2600	4500 2600	4500 2600
Tungsten/F480M			4000 @ T=1200	4000 @ T=1200	4000 @ T=1200			

Flux setting and temperature for each source is shown. NIRISS exposures were 1.1 to 1.9% clipped and NIRSpec exposures were 0.3 to 0.5% clipped by having to move the Pupil Select Mechanism to reach the fiber to those instruments, all others were 0.2% clipped or less.

The same source and flux setting was used for each Science Instrument for a direct comparison at 1.06, 1.55, 2.1, and 3.5 μm for all Science Instruments, and at 2.77 and 4.8 μm for NIRCam LW and NIRISS. The source was shuttered but not turned off between exposures for the different instruments.

Spectral Observations

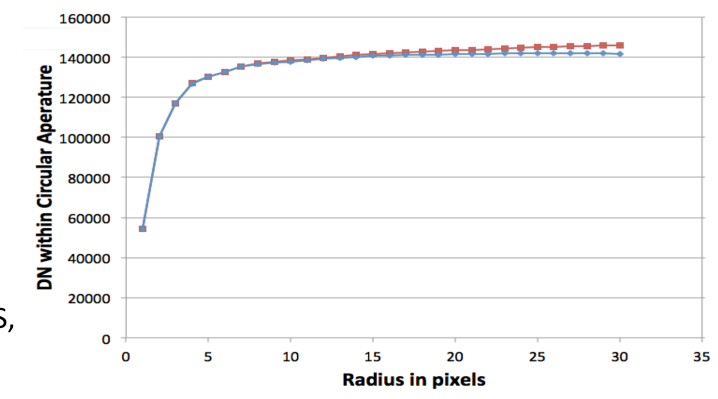
Science Instrument GRISM/GRATING	F277W	F322W2	F444W	F150W	F200W	F150LP	F170LP	F290LP
NIRCam Mod A GRISMR	900 @ T=1200	900 @ T=1200	900 @ T=1200					
NIRCam Mod B GRISMR	900 @ T=1200	900 @ T=1200	900 @ T=1200					
NIRISS GR150C				900 @ T=1200	900 @ T=1200			
NIRSpec GR140M						900 @ T=1200		
NIRSpec GR235M							900 @ T=1200	
NIRSpec GR395M								900 @ T=1200

A flux setting of 900 and temperature setting of 1200 was used for the tungsten source. NIRISS exposures were ~1.1% clipped and NIRSpec exposures were ~0.6% clipped.

The source and source flux setting was the same for all instruments spectral exposures. The source was shuttered but not turned off between exposures for the different instruments.

Data Reduction – point source data

1. Calibrated data (a slope fit the non-destructive read "up the ramp") was used for this analysis. Note, while these reductions subtract a dark image and divide by a flat field no linearity correction is applied.
2. The calibrated image is read in as is the data quality image. Pixels flagged as hot pixels in the data quality image are replaced by the average of the neighboring pixels in the image. Visual inspection, and planned pointing location selection, showed that no hot pixels were inside the core of the PSF (where interpolation would not be accurate).
3. A background exposure treated in the same way is subtracted where applicable (FGS exposures, NIRSpec exposures using the Long Pass filters, the LED35 and F480M exposures all SIs).
4. A column average of ~200 columns was taken on either side of the point source (several hundred pixels away) and then averaged and subtracted column by column in the data image to remove row by row differences in the bias.
5. Photometry was done using a Growth Curve (counts within concentric circular apertures centered on the Gaussian peak of the PSF. Background was measured from radius 22 – 30 pixels (typically) but was smaller for NIRSpec because of the small size of the Imaging window (7-10 pixels).



6. A total number of DN was then selected within a radius of 15 pixels (NIRCam SW), 10 pixels (NIRCam LW, NIRISS, and FGS), and 5 pixels (NIRSpec).
7. DN changed to e-/sec - multiply by the gain and divide by exposure time. The gains used were derived using data from the NIRCam, NIRISS, and FGS linearity tests. NIRSpec gain was derived from detector testing done at GFSC. Note: the uncertainty in the gain is the largest error in the ratio of the throughput of one SI to another.
8. Apply Aperture correction – Aperture corrections were derived using model images which take into account the source spectrum and all of the optical elements of the science instrument. These noiseless, zero background model images were treated in the same as the data images. The flux within the same aperture as was used with the data was compared to the total and a correction was derived. Typically the corrections were ~5% for the bluer bands and ~10-15% for the redder bands.
9. Apply correction for clipping due to off nominal pupil – Corrections done using Code V* models.
10. Apply correction for quantum yield effect for LD106 and LD155 data – Correction using the wavelength cut off gives ~25% for all detectors at 1.06 microns and ~8.5% at 1.55 microns except for NIRCam SW (where the 2.5 μm cutoff leads to no correction).
11. Apply correction for different band pass – Although the source is the same, the light passes through different filters (or in the case of FGS no filter) for different Science Instruments. - The integral of the source spectrum across a flat topped normalized to 1.0 filter curve.

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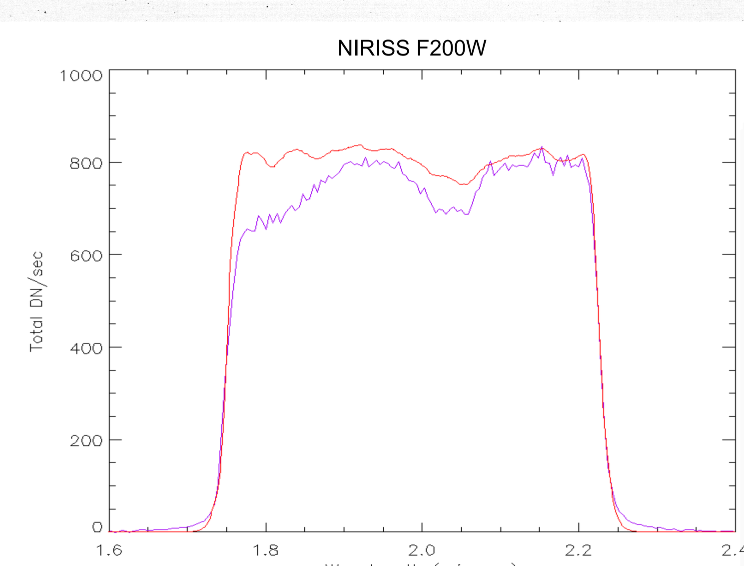
Data Reduction – spectral data

1. NIRSpec data was reduced to DN/sec/micron by Stephan Birkmann of the NIRSpec team.
2. NIRCam and NIRISS data were reduced using the calibrated data and treated the same way as the point source data.
3. One dimensional spectra were extracted from the spectral images using a wide slit to make sure we got virtually all of the flux from the source. Background was measured in slits of the same size above and below the spectra, averaged and subtracted.

4. Wavelength Calibration for NIRCam and NIRISS – The filter curve long and short wave cutoff give the wavelength scale in combination with the dispersions measured by the NIRCam and NIRISS teams.
5. The spectra were divided by the exposure time and the dispersion and multiplied by the gain to put the units into e-/sec/μm.



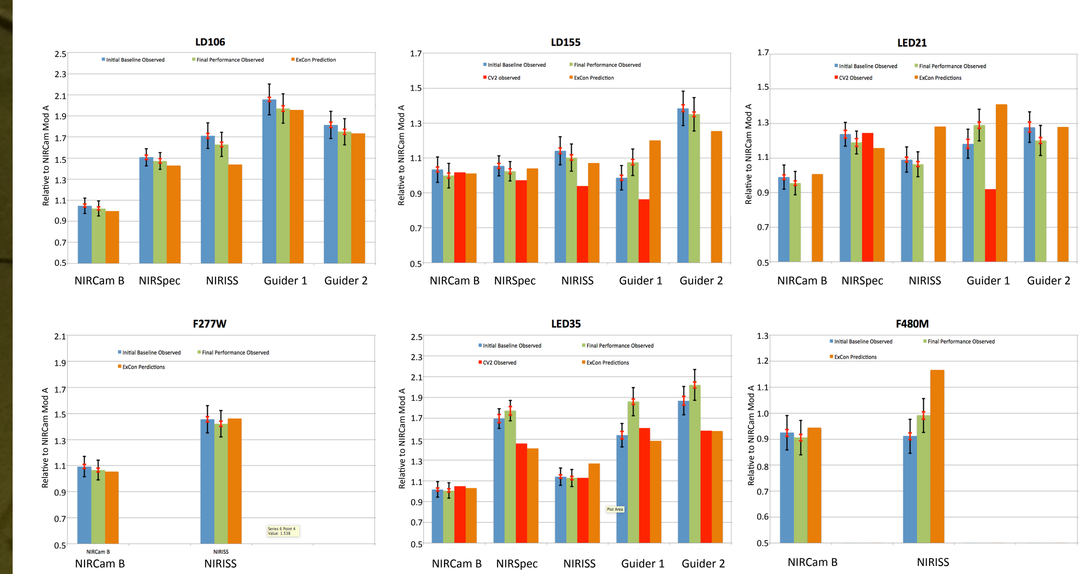
Conclusions

1. **Bottom Line: Relative NIR SI throughputs look good** – This test was conceived as a check to make sure that none of the Near-IR Science Instruments has a gross problem (e.g. contamination, degradation of an optic). All comparisons show relative throughput reasonably close to expectations (with the largest uncertainty for the LED35 3.5μm comparison – the shape of the LED spectrum appears to change with flux in a way that explains the larger uncertainty for the LED35 data).

2. **Predictions of throughput (using an optical component model) are in reasonable agreement with what we observe** – This shows that the measured component curves are a fairly good representation of the actual response of each element with wavelength.

3. **The Sensitivity Requirement for the ISIM** – There is a requirement that the Science Instruments for James Webb Space Telescope (JWST) reach certain sensitivity performance levels. These requirements are verified by a combination of instrument testing and analysis of the component efficiencies. The results of the throughput cross calibration test show that the component efficiency curves as measured in the past are close to what is in the delivered science instruments. The results of this test serves as a cross check that the ISIM module meets the sensitivity requirements.

Results – Throughput relative to NIRCam Mod A



- Blue = Initial Optical Baseline (Dec 29, 2015), Green = Final Performance (Jan 25, 2016), Red = data from Sept 14, 2014 (note the detectors were changed after these data were collected), Orange = Model Predictions.
- Blue vs. Green is a measure of stability across the recent Cryo-Vac test.
- Green vs. Orange is a measure of the accuracy of the instrument component efficiencies.

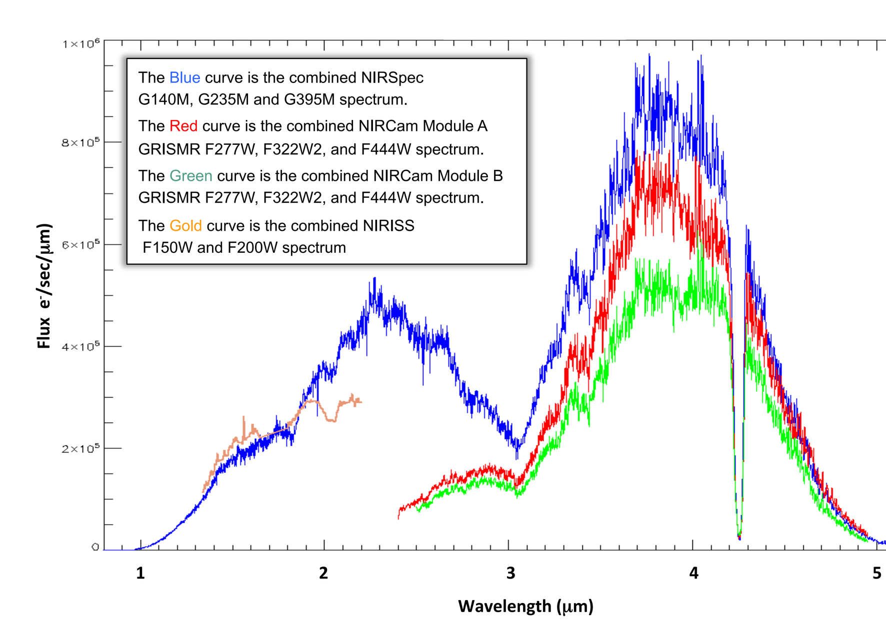
Comparison of relative Throughput to expected from the SI components relative Throughput

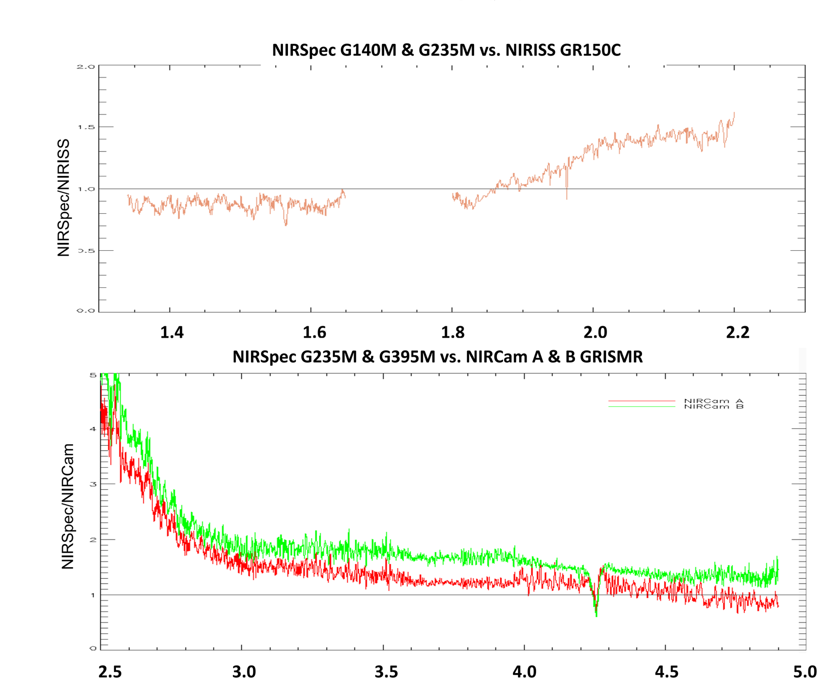
Source	NRCA3	NRCB4	NRCALONG	NRCBLONG	NIRISS	NRS1	FGS1	FGS2
LD106	1.000 1.000	1.049 1.024			1.189 1.132	1.055 1.031	1.051 1.007	1.047 1.010
LD155	1.000 1.000	1.022 0.987			1.065 1.029	1.014 0.984	0.821 0.896	1.104 1.076
LED21	1.000 1.000	0.982 0.948			0.851 0.830	1.069 1.028	0.838 0.914	1.000 0.939
Tungsten/F277W			1.000 1.000	1.038 1.012	0.997 0.974			
LED35			1.000 1.000	0.986 0.977	0.901 0.890	1.202 1.256	1.035 1.253	1.184 1.280
Tungsten/F480M			1.000 1.000	0.980 0.961	0.782 0.851			

Each number represents the ratio $\frac{\text{measured (SI/NIRCam A)}}{\text{Model (SI/NIRCam A)}}$

The numbers in blue are from the Initial Optical Baseline
The numbers in green are from the Final Performance

Results – Spectral Comparison





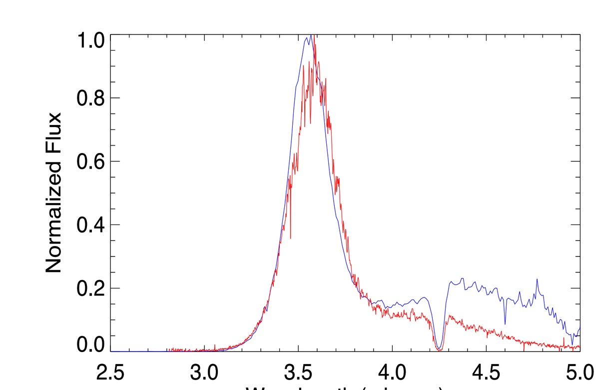
The NIRSpec Spectra divided by the NIRISS Spectra (top) and by the NIRCam module A (**red curve**) and module B (**green curve**) Spectra (bottom) for the FP data. Higher numbers are lower throughput relative to NIRSpec. Note how NIRCam B has lower throughput than NIRCam A.

Sources of Errors & Uncertainty

- The knowledge of detector gains are most likely the largest source of error in the ratio of the throughput of one SI to another. We estimates the error in the gain to be about 2% for NIRSpec and 5% for all other SI detectors. However this cancels when comparing results form the Initial Optical Baseline to the Final Performance (unless the gain has changed between them).
- Photon noise - The Shot noise associated with the measurements of the detected number of DN within the selected aperture is a source of random error in each SI throughput and thus in the ratio.
- Determining the background to subtract has an inherent uncertainty We estimate this from the growth curve for the point source data (as described above) and from the background extractions for the spectral data (as described above).
- A linearity correction may be needed – Although an effort was made in collecting the data to avoid going into the most non-linear regime this was not always the case, especially for the Initial Optical Baseline LED35 data.
- Source Stability – Data taken for one SI at the start and end of each sequence shows that with the exception of the Initial Optical Baseline LED35 data the difference was always less than 4% and usually less than 2% (the Initial Baseline LED35 difference was 7.5%).
- The effect of the pupil offset – The Code V* model computed corrections for the percent clipped amounted to less than 2% in all cases. Any error is therefore the error in computing the correction – a fraction of a small percentage.
- The model images may not match the actual PSF – This would produce an error in the derived aperture corrections – (Probably a small error).
- The input spectra may not be known well enough – Producing an error in the correction for source clipping by the filters. This is especially be a problem for LED35 (see the next panel)
- The quantum yield correction for lower wavelengths may be different from what we used. – 1.25 for 1.06 μm and 1.085 for 1.55 μm.

LED35 Spectrum

The point source exposures of the LED35 source have the largest differences with the predicted ratio to NIRCam module A. This is especially true for NIRSpec (using a long pass filter) and Guider 1 and 2 (no filter) and especially in the Final Performance. Spectra of the LED35 source taken with the NIRSpec prism on August 7, 2014 and the G395M grating on December 29, 2015 show that there is a long red tail that is outside the filter bandpass for NIRCam and NIRISS. The power in this tail may be a function of the flux setting.



The blue curve is the prism spectra spectra of the LED35 source taken August 7, 2014
The red curve is the G395M spectra of the LED35 source taken December 29, 2015.

Dec 29, 2015 Spectra flux was	130,000
August 7, 2014 Spectra flux was	80,000
Initial Optical Baseline flux was	4,500
Final Performance flux was	2,600

The difference in the red tail may be an indication that the tail is more pronounced with a lower flux setting in keeping with the larger than expected ratio of observed Guider and NIRSpec to NIRCam A throughput during the Final Performance relative to the Initial Optical Baseline.