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On-orbit JWST backgrounds from stray light and thermal emission

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ABSTRACT

Backgrounds observed by JWST will be a critical parameter for overall observatory sensitivity. JWST's background, sensitivity and other performance requirements drove the observatory's open architecture, sunshield geometry, orbit at L2 and other unique characteristics. These requirements were verified by analysis, to be measured for the first time on-orbit. Modeling JWSTs backgrounds is complex, as JWST backgrounds have multiple components including: backgrounds from in-field sources (such as Zodiacal Light) and stray light from scattering of sky sources outside the field; thermal self-emission of optical surfaces; and scattering of thermal self-emission from other Observatory surfaces. The unbaffled telescope design allows stray light paths from multiple directions. The 5-layer sunshield passively cools and shades the telescope and science instruments; however, there are thermal paths that may affect thermal performance. In-field backgrounds and stray light from sky sources can depend on the telescope's pointing and observation date. The thermal emission contributions will depend on the Observatory's sun orientation and recent history. The JWST Background Tool (JBT) uses the stray light models, in-field backgrounds, and thermal models to predict the expected backgrounds. On-orbit, several positions were measured at multiple wavelengths with NIRCam and MIRI to probe JWST's backgrounds and validate model predictions. These results may be used to update the JWST Exposure Time Calculator in preparation for the Cycle 2 proposal call. This conference proceeding will provide a summary of the modeling backgrounds and report on the measured on-orbit backgrounds.

Keywords: JWST, infrared
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1. INTRODUCTION

The successful launch and deployment of the James Webb Space Telescope, and its subsequent commissioning program, has opened a new era in astronomy. Among JWST's scientific goals is investigation of galaxy formation, study of the early universe, and analysis of exoplanet atmospheres. These science cases, as well as most others require stable, predictable and low backgrounds. A key task in the development of the JWST design was careful modelling and prediction of the stray light paths, thermal self-emission, and zodiacal/galactic in-field backgrounds. These models also informed the tools made available to astronomers for preparing their observation plans, namely the JWST Backgrounds Tool (JBT) and the Exposure Time Calculator (ETC). A key observatory commissioning activity was to evaluate the on-orbit observatory backgrounds and determine the accuracy of the JBT and ETC through a series of observations at key sky locations using the MIRI and NIRCAM instruments.

2. OVERVIEW

2.1 JWST

JWST features a 6.5-meter infrared-optimized primary mirror, with three near infrared instruments: NIRCam, NIRSpec and NIRISS, and one mid-infrared instrument MIRI. These instruments give access to the E/M spectrum from 0.6 to 28

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microns in both imaging and spectroscopy. Other modes, such as coronography are also available. JWST orbits at L2, where the tennis-court-sized 5-layer sunshield maintains a ~40K environment for the telescope and science instruments. MIRI additionally has a cryocooler to achieve its operational 6K temperatures. As the sunshield, primary mirror and other observatory structures are too large to launch fully deployed, JWST was launched in a 'folded up' configuration and was successfully deployed remotely on its journey to L2. This was followed by a 6-month period of telescope phasing, checkout and instrument commissioning. JWST was declared fully commissioned in early July 2022.

2.2 Observatory Commissioning Overview

There were several stages to JWST's commissioning process: Spacecraft Commissioning (Launch to ~L+30); Transition Period (~L+30 to ~L+40); OTE Commissioning (~L+40 to ~L+120); and SI Commissioning (~L+120 to ~L+180) (see Friedman, Hagedorn, Perrin, 2017; McElwain et al., 2018). The primary control method for commissioning planning was through 'Commissioning Activity Requests' or CARs. For more information on commissioning please see McElwain et al 2022)

Executed throughout these stages were a number of 'Observatory Level' commissioning activities, aimed at characterizing performance that affected the JWST observatory as a whole, rather than just one instrument or sub-system. These activities were designed in the same manner as SI and OTE commissioning activities in the same CAR process. Observatory commissioning plans were developed by the JWST Project Science Team at NASA GSFC. One such activity was background characterization, which utilized measurements from both MIRI and NIRCam to evaluate the predictive models of JWST performance provided by the Exposure Time Calculator (ETC) and JWST Backgrounds Tool (JBT).

2.3 Background Characterization

As with any telescope, especially one operating in the infrared, JWST is especially concerned with backgrounds. Low background levels are essential to many of JWST's key science cases, such as investigation of the first galaxies, tracing star formation through cosmic time, etc. These concerns drove careful modeling and prediction of the expected backgrounds JWST would encounter using on as-built test and alignment data. This work was especially challenging given that JWST is a cutting edge, innovative design. For more detailed information on the modeling of the JWST stray light and backgrounds, see Lightsey et al 2014. The JWST Backgrounds Tool (JBT) uses the models developed by Paul Lightsey to predict the expected background at a given wavelength, sky location and day of year. The total background is further broken down into three sub-components: Stray Light, In-field, and Thermal self-emission (figure 1). Each of these sub-components changes slightly depending on the wavelength, date of observation and/or location of target.

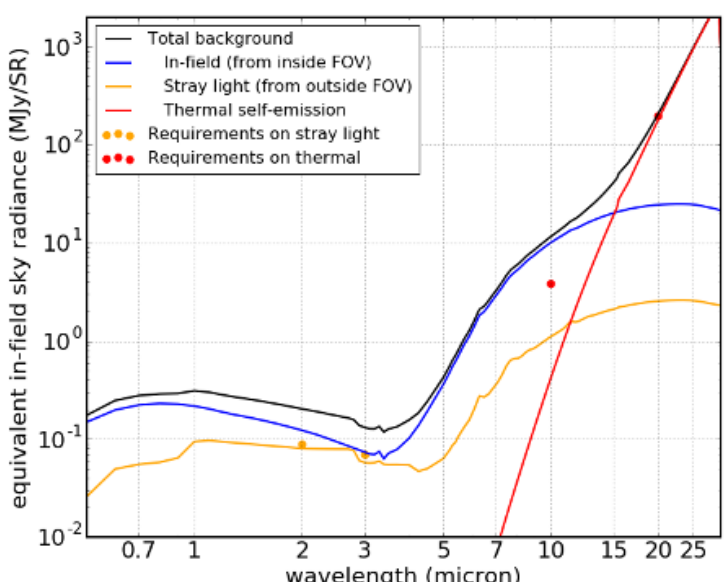

Figure 1: Background prediction from the JWST Backgrounds Tool

2.4 Stray Light Component

JWST differs from its predecessors in multiple ways (size, instrumentation, location of orbit, etc.). However, the most obvious difference is in JWST's open telescope design, Unlike Hubble, Spitzer or Herschel, JWST does not have a light baffle enclosing the telescope, and instead uses other structures to control stray light and thermal backgrounds, such as the Aft-Optics System (AOS), frill and sunshield (Lightsey et al. 2012). Two of the stray light paths of most concern were the 'rogue' and 'truant' paths. In the truant path, light passes from behind the primary to bounce off the secondary and into the Integrated Science Instrument Module (ISIM). The frill, a soft structure that runs the circumference of the primary mirror, in combination with a pupil mask at the Fine Steering Mirror controls for this stray light path. The AOS, exit pupil and internal stops control for the Rogue path, where light 'in front' of the telescope enters the ISIM directly without first being focused by the telescope optics. It should be noted that the stray light modeled by the JBT is for the observatory. Instrument-specific glints and stray light would be characterized at the instrument level. In figure 2, the frill can be seen as the black soft structure outlining the primary mirror, while the AOS is visible as the snout in the center of the primary.

Figure 2: Image of the JWST primary mirror. The frill is the black structure outlining the primary, The AOS is the black snout protruding from the center of the primary mirror Credit: NASA/Desiree Stover

2.5 In-field component

The observed backgrounds also depend on the time of year and location of the observation, which is captured in the in-field component. This component is dominated by the Galactic and zodiacal emission of a given position and Day of Year. This component does vary throughout the visibility window of each position, creating a ‘bathtub’-like effect in the total background curves. This time dependent variation arises due to the changing sun angle as JWST orbits at L2. Essentially the observatory is looking thorough changing amounts of Zodiacal light as its orbit progresses. This behavior was also modeled and is included in the ETC and JBT background calculations. To measure the time-and positional dependence of both the in-field and stray light components, eight pointed observations were made using parallel observations with NIRCAM and MIRI in multiple NIR and MIR filter bands (8 filters for NIRCam, 4 for MIRI)

2.6 Thermal Self-Emission

In the mid-Infrared, the dominant background component becomes the thermal self-emission from the Telescope, sunshield, and other observatory components. Most observatory optics are passively cooled to ~40K by being in the shadow of the sunshield, which is sized and shaped to block the thermal radiation from the Earth, moon and Sun. Regions of the core and sunshield are warmer than the 40K optics, and the thermal emission from the optics themselves is dominated by the bottom mirror segments at ~55K. As the mid-infrared instrument on JWST this thermal self-emission is of particular concern to MIRI, especially any systematic variation of this thermal background. One potential source of thermal variation could be with the pointing of the observatory. JWST observes essentially an annulus on the sky—the observatory can view the full 360 degrees about the sun line, and pitch between a solar elongation of 135 to 85 degrees (or +45 to -5 degrees pitch). The -5 pitch direction is considered the ‘hot’ attitude, as the sun illuminates the front of the sunshield, while the +45 pitch is considered the ‘cold’ attitude. The MIRI team executed background measurements at both the hot and cold attitudes to measure any pitch-dependent variation in thermal backgrounds. These tests were coordinated with the pointed observations to ensure adequate overlap for comparison of results.

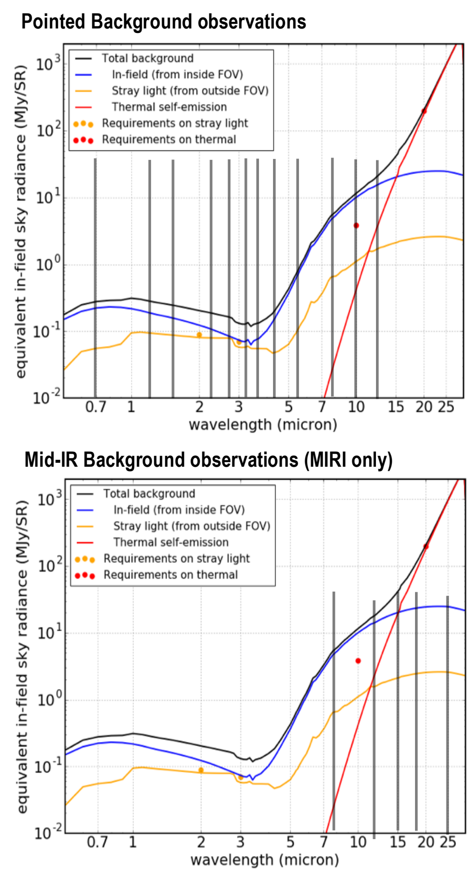

Figure 3: (Top) JBT prediction with NIRCam and MIRI filters marked for the pointed background observations; (bottom) MIRI filters marked for the Mid-IR Observations

3. BACKGROUND OBSERVATIONS

3.1 Observations summary

Two major activities were aimed at measuring JWST backgrounds for comparison to models. First, a series of 8 sky pointings were observed in 8 NIRCam and 4 MIRI filters. The second activity made observations of a hot and a cold attitude field, each in 6 MIRI filters. This activity obtained MIRI measurements over the course of several days to characterize the changes in background levels with time. The filter selection observing technique and MIRI acquisition settings were coordinated between the two tests so that comparisons would be possible, while still offering adequate coverage of the entire JWST wavelength regime (see figure 3). Both activities compared the observed backgrounds to those predicted by the JBT and ETC.

3.2 Pointed Observations

For the NIRCam/MIRI observations, eight fields were selected. These fields represent a wide variety of potential targets with a diverse set of predicted background levels of dominant contributors to those backgrounds. All eight fields were observed once during a three-day period during SI commissioning. Because of this, some of the original targets (e.g., the deep fields and Galactic Center) had to be replaced with observable pointings that had representative background predictions. Three of the fields were selected to represent low background deep fields—the Extended Groth Strip was observed, as were fields representative of the Hubble Ultra Deep field and the Hubble Deep Field South. While these observations did not go nearly as deep as science observations, they were selected to give an indication if there are any deviations in the background models which should be addressed prior to the expected observation campaigns in Cycle 1. The fourth field is the 1.2 times minimum Zodi Benchmark. This field is where the near-infrared background is 1.2 times its lowest value on the sky and was selected to be a particularly stressing case for stray light. Likewise, the Galactic Center Offset pointing is also a stressing case for stray light. The 'moderate background' pointing was selected to have backgrounds roughly halfway between the Galactic Center and deep field pointings. A measurement was made in the southern Continuous Viewing Zone, to enable monitoring of backgrounds, as the CVZ allows year-round observability. Finally, to provide a high-Mid IR backgrounds case, we also selected a field with high Zodiacal light background, but low contributions from other background sources. Table 1 summarizes the pointings.

Table 1: Pointed background Observation Targets. Note the * indicates a field where a substitute was used due to observability

ID	FIELD NAME	Background	Rationale
1	HUDF*	Low NIR background	Key field
2	Ext Groth Strip (offset)	Low NIR background	Key field
3	HDF-S*	Low NIR background	Key field
4	Benchmark-1.2 min Zodi	High NIR background	Requirement Benchmark
5	Galactic Center (Offset)	High NIR & MIR background	Stressing NIR/MIR case
6	Mid-Range Background	Moderate NIR & MIR background	Moderate background field
7	CVZ-S	High MIR background	Monitoring
8	High Zodi, Low non-Zodi	High MIR background	Stressing MIR case

All eight pointings were observed in parallel NIRCam/MIRI exposures, in four filters with the NIRCam Short Wavelength Channel (F070W, F115W, F150W, and F200W), in four filters with the NIRCam Long Wavelength Channel (F277W, F356W, F444W and F480M), and four filters with MIRI (F560W, F770W, F1000W, and F1280W).

3.3 Mid-IR Background Observations

MIRI additionally observed fields meant to investigate phenomena that might affect the mid-Infrared backgrounds MIRI would be sensitive to. Of particular interest was 1) any variation or deviation from predictions of the measured backgrounds with respect to telescope pitch, and 2) Any deviation from predictions of the time dependence of mid-IR backgrounds. These measurements were taken with MIRI-only, in the F770W, F1280W, F1500W, F1800W and F2100W filters. Objective 1 was obtained by observing fields at the hot, the cold attitudes during the thermal characterization activity (see McElwain et al, 2022). This will allow measurement of the mid-infrared background variability under the most extreme conditions. This activity also measured target fields over the course of several days, thus allowing evaluation of the time dependence of the mid-IR backgrounds. The F770W and F1280W MIRI filters are used in both these and the NIRCAM/MIRI pointed observations, allowing for comparison between the data sets.

4. RESULTS

4.1 Overall

In both the pointed observations and the MIRI-only background observations. It appears that there are no gross deviations from the predicted background levels. Please note that evaluation of commissioning data was ongoing as of the writing of these proceedings, thus these numbers may be revised in the future. Potential observers should refer to the online JWST documentation system, JDOX, for the most up-to-date information.

4.2 Pointed Observations: Benchmark & CVZ-S

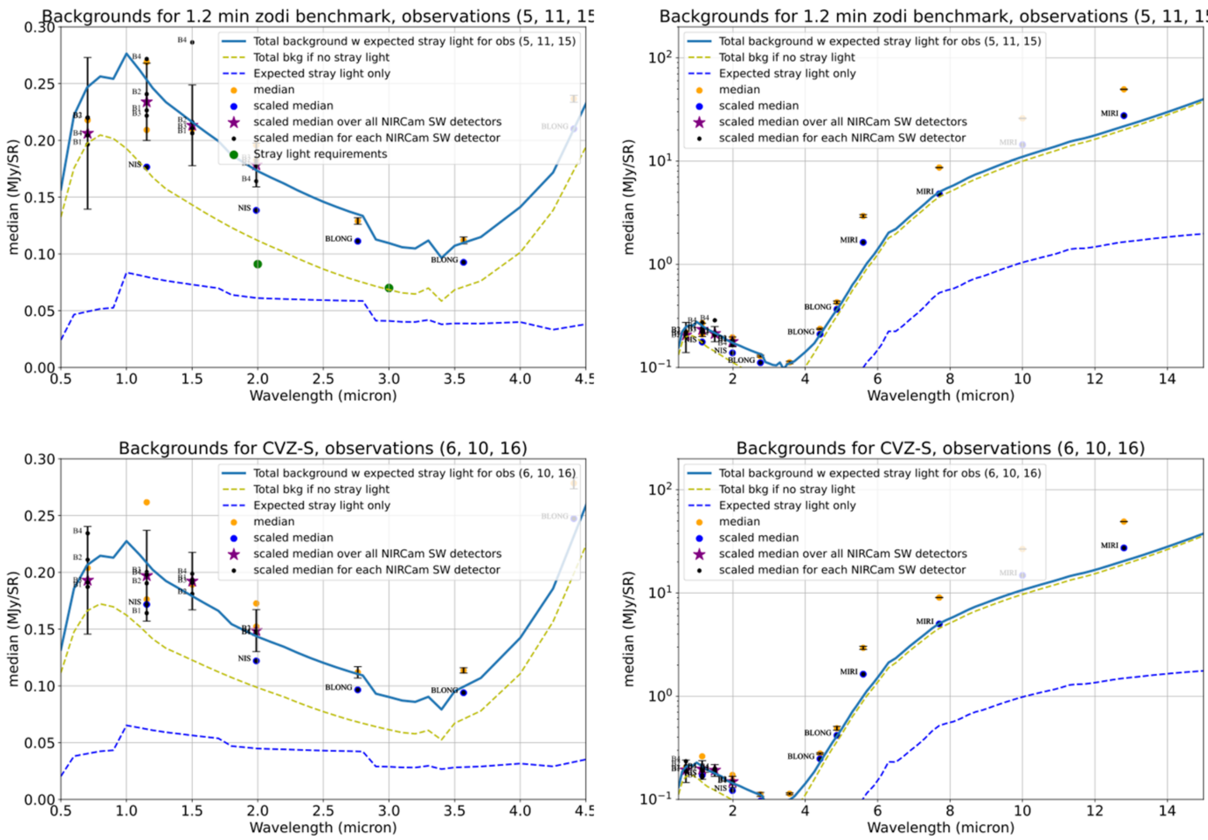

Figure 4: Background observations (Black dots) and JBT predictions (blue lines). left column: NIR results, right column: NIR and MIR results for 1.2 min zodi (top) and CVZ-S (bottom) fields

The 1.2 min Zodi Benchmark pointing agrees well with the predicted background levels in both NIRCam and MIRI, with potentially better than expected performance in the NIR. JWST background performance requirements are evaluated at this position, thus JWST has met (or exceeded) these requirements. The CVZ-S observations likewise show good agreement with the models.

4.3 Low Background Fields

The low background fields agree well with predictions, though they show markedly lower than expected backgrounds at the shortest wavelengths in the near-IR. These results conflict with findings from other IR instruments, and thus need to be resolved in future analysis.

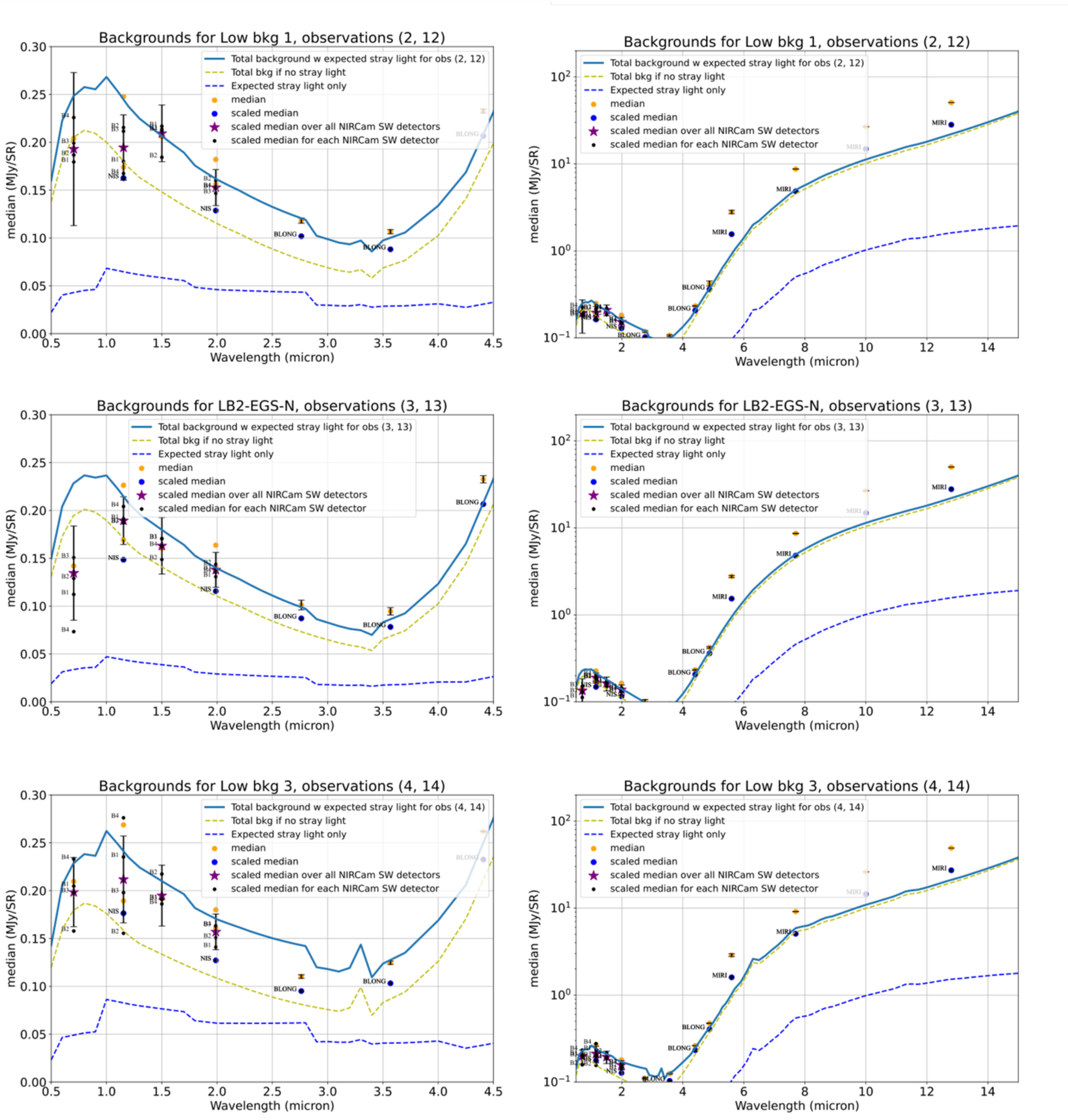

Figure 5: Background observations (Black dots) and JBT predictions (blue lines). left column: NIR results, right column: NIR and MIR results for low background 1 (top) EGS-N (middle) and Low Background 3 (bottom) fields

4.4 High background fields

The higher background fields show more deviation from the predicted values for backgrounds. For the Galactic bulge pointing, this may be due to the low spatial resolution of the galaxy model for the in-field component. JWST is resolving the bulge into individual stars, which may explain the discrepancies. The 'High Zodi' pointing is less clear why there is such a large discrepancy, so requires further investigation.

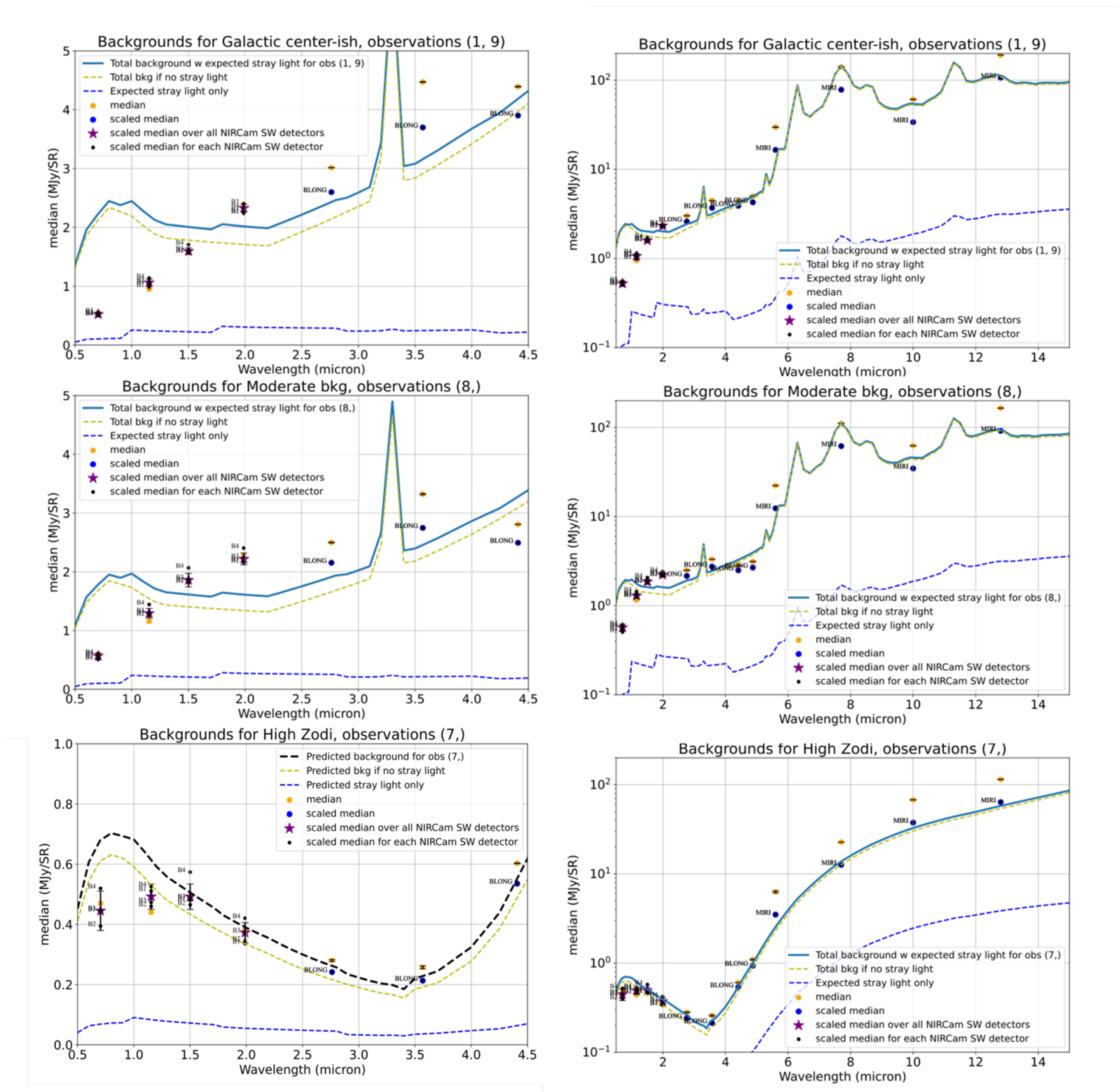

Figure 6: Background observations (Black dots) and JBT predictions (blue lines). left column: NIR results, right column: NIR and MIR results for Galactic Bulge (top) Moderate Background (middle) and High Zodi (bottom) fields

4.5 Mid-IR Observations

The MIRI-only observations also showed good agreement between the predicted and measured behavior. Measurements of thermal background changes due to pitch found that any shift was negligible. Likewise, when comparing the expected backgrounds over a span of days, analysis showed that the predictions and measurements agreed.

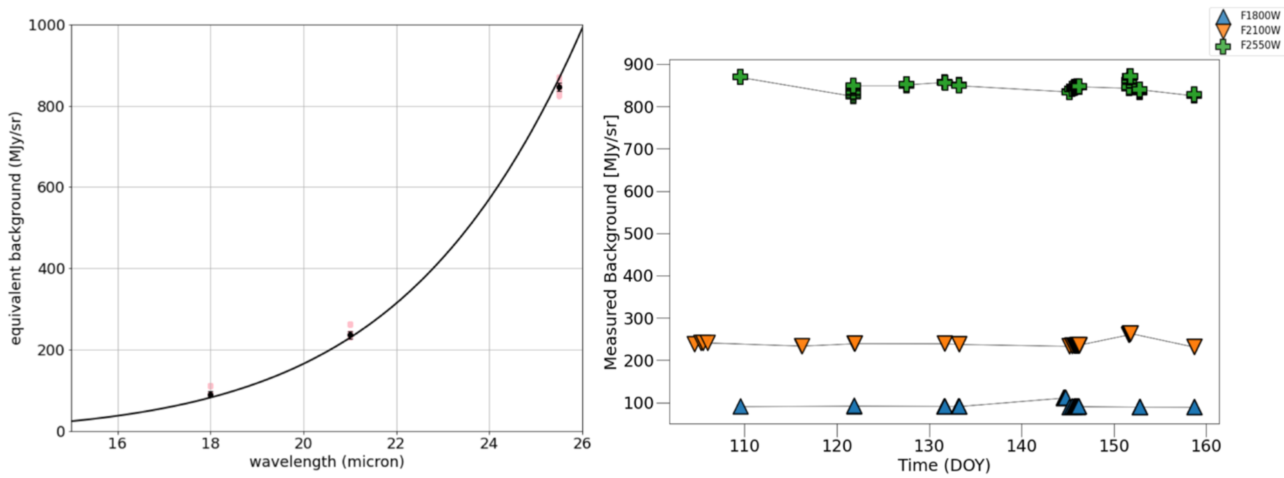

Figure 7: Left- Mid-IR measurements (dots) plotted o predicted backgrounds (black line); right- time dependent MIR backgrounds as measured by MIRI

5. CONCLUSIONS

As part of JWST commissioning, a careful examination of the near- and mid- infrared backgrounds was undertaken. This included NIRCam/MIRI observations of eight field selected as stressing cases or fields chosen to represent likely science fields, such as deep field. MIRI also conducted background measurements in the mid-infrared. Both investigations found that the background predictions were relatively accurate, although the NIR measured backgrounds appear to be lower than predicted, especially in low background fields. No variation with respect to pitch in the thermal background was observed, and the time dependence predictions were also accurate.

Analysis is still ongoing, with emphasis on understanding the deviations in the measured backgrounds from predictions at the shorter wavelengths. Additionally, the team is investigating the possibility of implementing serendipitously measuring the backgrounds in science observations. This would allow for monitoring of backgrounds throughout the lifetime of the mission.

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