Forty years of mid-infrared (mid-IR, 5-30 µm) imaging in space with observatories such as the Infrared Astronomical Satellite (IRAS), the Infrared Space Observatory (ISO), the Spitzer Space Telescope, Akari, and the Wide-Field Infrared Survey Explorer (WISE) have unveiled a new view of the universe with a wealth of scientific reward. Mid-IR imaging not only enables us to see deep into the dust structures as well as the centre of our own Galaxy and Local Group, but also samples important dust continuum features such as Polycyclic Aromatic Hydrocarbons (PAH; 7.7 and 11.3 µm) and silicates (10 and 18 µm) that reveal the dominant energetic processes in galaxies across cosmic time (Tielens 2008). Moreover, deep wide-area surveys have shown that mid-IR photometric bands from Spitzer’s IRAC and MIPS instruments have proved to be powerful diagnostic tools for galaxy evolution in studying star formation processes (Elbaz et al. 2007; Noeske et al. 2007; Madau & Dickinson 2014), active galactic nuclei (Richards et al. 2006; Daddi et al. 2007; Donley et al. 2012), and even the very high redshift universe (Stark et al. 2009; Smit et al. 2015). The latest space-based IR observatory is the James Webb Space Telescope (JWST), which has begun a golden age of IR astrophysics and it is the Mid-Infrared Instrument’s (MIRI) imager that is providing imaging between 5 and 28 µm with unparalleled resolution and sensitivity that will open new vistas for discovery in all areas of astronomy.

After launch, JWST was commissioned in preparation for science operations in a phase of the mission that ran for 6 months up to the end of June 2022. An overview of the science perfor-
mance of JWST at the end of commissioning has been presented in Rigby et al. (2023) and specifically for MIRI in Wright et al. (2023). After the launch and deployment of the observatory, the commissioning and preliminary calibration phase of the instruments took place in the latter half of the commissioning period. This is especially true for MIRI, which being the coldest instrument in the observatory, and the only instrument that is actively cooled, took the longest to cool down to its operating temperature. Therefore, most of MIRI commissioning observations were obtained in a relatively short time frame between late May and the end of June 2022. In order to conduct the MIRI imager commissioning efficiently, a detailed set of tests was outlined and prepared well in advance of launch, including algorithms for analysing the data. This work was referred to as Commissioning Analysis Projects (CAPs), and for the MIRI imager, contained analysis and characterisation of: basic functionality, the point spread function (PSF), plate scale and geometric distortion, glints and scattered light, flat fields, sky background, operations, image artefacts, performance checks, and initial photometric calibration. The results of the MIRI imager CAPs project are presented here.

The MIRI imager, as well as the other MIRI modes and JWST instruments, was put through extensive ground testing both at Goddard Space Flight Center and Houston Space Flight Center, where the latter involved a full end-to-end test with the flight optical telescope assembly. However, although these demonstrated functionality and basic performance, the tests were limited for the MIRI imager because the test sources and backgrounds were optimised for the near-infrared instrument and not mid-IR (5 to 28 μm). Consequently, many aspects of the MIRI imager performance were not well characterised prior to launch, including the imager background, the flats and bright target limits as well as detector performance related to imaging. Therefore, the in-flight commissioning tests were important for demonstrating performance and preparing the initial calibrations to ready the instrument modes for science observations.

We note that the aim of the in-flight commissioning tests was not to fully calibrate the MIRI imager, but to measure and check the in-flight performance compared with the instrument design specifications and the team’s ground test measurements. The results presented here show the performance as understood from commissioning at the start of JWST operations, and to the best of our knowledge from the first year of operations. The MIRI imager calibration and performance analysis will continue throughout the JWST mission, and the reader should refer to JWST documentation to get the most up to date information on the MIRI imager.

This paper is organised as follows. We begin with an overview of the MIRI imager and summarising the key results of the imager commissioning program (Section 2 and 3). Next we discuss in detail the results of the MIRI imager commissioning including the point spread functions (PSFs) (Section 4), flux calibration (Section 5), backgrounds (Section 6), distortion (Section 7) and flat fields (Section 8). After which we describe some of the imaging artefacts that may be seen during and after data processing (Section 9), and then discuss how the results of commissioning feed into the best observing practices for MIRI imaging (Section 10). Section 11 briefly summarises experience with the MIRI imager during its first year of science operations.

The near-infrared instruments were prioritised in ground testing because they are the primary instruments for mirror alignment and phasing.

### Table 1. Basic parameters of the MIRI imager

<table>
<thead>
<tr>
<th>Imaging Filters</th>
<th>λ0 [μm]</th>
<th>R = λ/Δλ</th>
<th>FWHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>F560W</td>
<td>5.6</td>
<td>4.7</td>
<td>0.277</td>
</tr>
<tr>
<td>F770W</td>
<td>7.7</td>
<td>3.5</td>
<td>0.269</td>
</tr>
<tr>
<td>F1000W</td>
<td>10.0</td>
<td>5.0</td>
<td>0.328</td>
</tr>
<tr>
<td>F1130W</td>
<td>11.3</td>
<td>16.1</td>
<td>0.375</td>
</tr>
<tr>
<td>F1280W</td>
<td>12.8</td>
<td>5.3</td>
<td>0.420</td>
</tr>
<tr>
<td>F1500W</td>
<td>15.0</td>
<td>5.0</td>
<td>0.488</td>
</tr>
<tr>
<td>F1800W</td>
<td>18.0</td>
<td>6.0</td>
<td>0.591</td>
</tr>
<tr>
<td>F2100W</td>
<td>21.0</td>
<td>4.2</td>
<td>0.674</td>
</tr>
<tr>
<td>F2550W</td>
<td>25.5</td>
<td>6.4</td>
<td>0.803</td>
</tr>
</tbody>
</table>

**Notes.** Top: MIRI imaging filters, central wavelengths, resolving powers and full width half maxima. Bottom: MIRI imaging subarrays, pixel and usable sizes, frame times.

---

2. **Imager overview**

The MIRI imager (Bouchez et al. 2015) consists of an all reflecting design with 9 primary filters (see Figure 1). The imager shares its detector focal plane system with MIRI’s Low Resolution Spectrometer (LRS) and Coronagraphs, giving it a rectangular unobstructed field of view of 74 × 113 arcsec2, which is roughly a quarter of the size of the Near InfraRed Camera (NIRCam) imager field on JWST, with a plate scale of 0.11 arcsec pixel−1. The imager full detector array is the entire 1024 × 1024 pixel square array shown in Figure 2 that encompasses the imager field of view, the coronagraphs and LRS mask. The imager field of view covers 2/3 of the full array. The Lyot mask region is also included in imager science data products because the Lyot coronagraph has no additional optics. The full imager array can be read out in FASTR1 or SLOWR1 mode with readout times per frame of 2.775 and 23.890 seconds respectively, where the slower readout mode can be used to reduce data volume (see Morrison et al. 2023). To prevent detector saturation on bright targets or backgrounds, MIRI imaging can also be obtained in subarray mode, which reads smaller sections of the detector at a faster rate by manipulating the detector clocking patterns (Ressler et al. 2015). The subarrays, only available when using the FASTR1 readout pattern, are: BRIGHTSKY (512 × 512 pixel2, group time 0.865 s), SUB256 (256 × 256 pixel2, group time 0.300 s), SUB128 (136 × 128 pixel2, group time 0.119 s) and SUB64 (72 × 64 pixel2, group time 0.085 s). The basic parameters for the MIRI imager are provided in Table 1. The MIRI imaging filter bandpasses, in units of photon-to-electron conversion efficiency, are shown in Figure 1.

In Figure 2 we show examples of MIRI imaging from the commissioning program (Program Identification – hereafter PID 1024 ; Observations 5 and 9) that were used for the calibration of the geometric distortion of the instrument (see Section 7). The images show a field in the Large Magellanic Cloud (LMC) taken both at 5.6 (top) and 15.0 μm (bottom). In the single pointed image, we clearly see the imager’s rectangular field of view, and also the three 4-quadrant phase mask (4QPM) coronagraphs to the left of the image, the Lyot coronagraphic mask region to the
Fig. 1. MIRI imaging filter bandpasses.

top left, as well as the LRS slit that all share the same detector as the imager. The Lyot mask region is particularly important to MIRI imaging because the light arriving in the Lyot quadrant passes through the same optical elements as for the MIRI imager, with the exception of the Lyot stop. Thus, this small area can be used, calibrated and analysed as for the main imager region. The 4QPM coronagraphs include additional optical elements that require a calibration different from that of the imager. For these reasons, mosaic images obtained from the official JWST pipeline (the level 3 12d FITS files) include both the imager and the Lyot regions, but have the 4QPM coronagraph regions masked (Figure 2, right column).

Also in Figure 2, we can see a small rectangular protrusion into the imager field of view on the left hand edge (labelled in bottom-left panel). This is known as the ‘knife edge,’ and was used to perform a knife edge optical test, whereby a point source could be moved across the edge of the detector and the signal measured as a function of position. This enables the PSF at the entrance focal plane (where the knife edge and coronagraphs are mounted in the focal plane structure) to be measured by fitting the signal distribution as a function of source position and comparing it to the optical model.

We also identify regions of bad pixels in Figure 2 which appear as small dark patches in the single point images. Figure 3's mosaicked images on the right show that these bad pixel areas are well mitigated with the 4-point dither pattern strategy of this observation. JWST data products have a number of different flag identifiers for bad pixels including hot, open, dead and low quantum efficiency depending on the characteristics of the loss of performance (FWHM) and encircled energies were measured to be within the exception of the glow-stick feature mentioned in the previous section, which is thought to have no impact on MIRI imaging. Although bright glow-stick features at longer wavelength could cause row artefacts as discussed in Section 9.2.

Descriptions and references on the MIRI design, build and ground testing are in Wright et al. (2015) and specifically for the imager in Bouchet et al. (2015). More information on the MIRI imager can be found in the JWST documentation at the following link: JWST Documentation - MIRI Imaging, which will include the most up-to-date information for observers during the mission.

3. Key imager commissioning results

The primary aim of JWST/MIRI commissioning was to verify that the instrument’s on-orbit functionality and performance were consistent with the scientific capabilities estimated from ground testing. With over 3500 exposures taken in imaging mode, the commissioning analysis showed that MIRI imaging was equal to or better than expectations from pre-flight testing and, wherever possible, we mapped all the results to our requirements. The commissioning tests confirmed the correct functionality of the instrument mode including filters, slits, offsets and dither patterns as well as testing the templates of the Astronomer Proposal Tool (APT). No operational constraints or limitations on the instrument were necessary.

In terms of image quality, the full width half maximum (FWHM) and encircled energies were measured to be within a few percent of expectations for all filters and field positions. Tests for stray light and optical ghosts showed no issues, with the exception of the glow-stick feature mentioned in the previous section, which is thought to have no impact on MIRI imaging.

The team produced and tested calibration files including darks and flats and verified that the data pipeline successfully processed the data to scientific quality. With this the relative photometric response of imaging was shown to be determined better than 5% at 80% encircled energy including the response between different subarrays and filters. The low impact of persistent images and other artefacts was demonstrated as well as the recovery from the effects of cosmic rays including the effective mitigation of image artefacts using the process of annealing - raising the temperature of the detectors to release trapped charge.

Lastly, MIRI’s sensitivity was measured to be two orders of magnitude better than Spitzer at 5.6 µm and 1 order of magnitude better than Spitzer at 5.6 μm.
4. Point spread functions

To verify the optical quality of the MIRI imager, and quantify detector artefacts, a commissioning program (PID 1028) was dedicated to the characterisation of the imager PSF. The objectives were three-fold: (1) measure the in-flight PSF properties with a high dynamic range for all MIRI bands; (2) evaluate and check the variations of the PSF properties across the field of view of the imager; and (3) reconstruct a 'super-resolved' PSF at a spatial resolution higher than the diffraction limit at 5.6 µm. The latter objective was, because the PSF is undersampled at this wavelength, to check the optical quality at 5.6 µm and perform a fine characterisation of the cross artefact. The cross artefact was known pre-launch and referred to as 'the cruciform', arising from the diffraction of infrared photons in the detector substrate (Gáspár et al. 2021). In the following, we briefly describe the data analysis, and a general assessment of the optical quality made during commissioning. A separate paper discusses the PSF in detail.

In summary, the commissioning observations were nearly all executed according to plan, and of sufficient quality to kick-start the on-orbit calibration program, which would be used as a baseline for the JWST ETC and Cycle 2 proposal preparations. Calibrations will keep improving in time, as more data is acquired and the subtleties of the instrument behaviour are studied in depth.
modelling done for photometry and precise astrometric calibration (Libralato et al. 2024).

4.1. Data acquisition and reduction

All PID 1028 exposures were obtained in FASTR1 readout mode on 2022 May 24. Observations 1 to 5 were dedicated to the fine sampling of the PSF at F560W in 5 positions in the field of view. We observed the MIRI standard star 2MASS J17430448+6655015 (A5V type) with the 16-points microscanning dither pattern, which is a non-standard dither pattern built to sample the surface of a pixel to enable the best PSF reconstruction possible. The shifts between each dither position need to be random fractions of a pixel to mitigate the effects of intra-pixel gain variations, and the pointing accuracy was typically 2 mas. In Appendix B, we show the dither patterns and a comparison between the requested positions and the observed positions (Figure 8.1). The total exposure time per position was about 40 min (10 groups × 5 integrations per exposure, making a total of 80 exposures per position). This was designed to permit construction of a very high signal-to-noise ratio PSF and a dynamic range sufficient to evaluate the intensity in the wings of the PSF out to a large radius. The F560W data were processed up to stage-2 cal FITS products, and high-resolution PSFs were reconstructed from the cal.fits files using the deconvolution method described in Guillard et al. (2010). For all other filters, the target star was placed in the centre of the field of view (Observation 6), and all the data were reprocessed up to stage 3 (i2d.fits) with the version 1.8.3.dev17-gf4081ef2 of the JSWT pipeline, and version 1019.pmap of the CRDS context.

4.2. PSF cosmatics and metrics

Figures 3 and 4 show the PSF cosmatics and metrics, and comparison with WebbPSF simulations, and show that the MIRI imaging performance is diffraction-limited at wavelengths longer than 10 µm (from F1000W and onward). The excess (respectively 14% and 3%) with respect to the diffraction limit at respectively 5.6 (F560W) and 7.7 µm (F770W) is due to the broadening of the PSF induced by the diffraction and scattering in the detector substrate (see section 4.3). The under-sampling of the PSF at 5.6 µm makes it necessary to use a deconvolution technique, combined with fine-raster dithering, to reconstruct super-resolved PSFs, and we follow the methodology described in Guillard et al. (2010) to do so with commissioning data, lab data from ground-based test campaigns, and optical models (Zemax and WebbPSF simulations). Figure 5 shows a 'historical' gallery of F560W PSFs, which compares those different datasets and highlights the remarkable agreement between optical models and super-resolved PSFs reconstructed from the lab and flight data. The deconvolution of the sub-pixel, 4 × 4-points dither data (microscanning pattern) performed during commissioning led to a gain in spatial resolution of a factor of ≈ 3 (Figure 5, 3rd column, bottom row). This allowed us to check the optical performance at 5.6 µm and perform a fine comparison between data and models.

In Figure 9, we show PSF radial profiles for the F560W and F2550W filters in the centre of the field of view of the MIRI imager, and we compare the data with WebbPSF simulations. The top panel displays the super-resolved F560W, which shows in particular that the cruciform artefact dominates the flux profile at radii longer than the secondary Airy ring (see Sect. 4.3 for details). The cumulative radial flux profiles (Encircled Energy, EE, normalised at a radius of 5 arcsec or 45 pixels) are
Table 2. MIRI imager PSF metrics

<table>
<thead>
<tr>
<th>Filter</th>
<th>Data (EE normalized to 5 arcsec)</th>
<th>WebbPSF (EE normalized to 5 arcsec)</th>
<th>Data / WebbPSF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FWHM [arcsec]</td>
<td>EE within 1st dark Airy ring</td>
<td>FWHM [arcsec]</td>
</tr>
<tr>
<td>F560W</td>
<td>0.207</td>
<td>55 – 63%</td>
<td>0.182</td>
</tr>
<tr>
<td>F770W</td>
<td>0.269</td>
<td>62%</td>
<td>0.260</td>
</tr>
<tr>
<td>F1000W</td>
<td>0.328</td>
<td>71%</td>
<td>0.321</td>
</tr>
<tr>
<td>F1130W</td>
<td>0.375</td>
<td>73%</td>
<td>0.368</td>
</tr>
<tr>
<td>F1280W</td>
<td>0.420</td>
<td>65%</td>
<td>0.412</td>
</tr>
<tr>
<td>F1500W</td>
<td>0.488</td>
<td>77%</td>
<td>0.483</td>
</tr>
<tr>
<td>F1800W</td>
<td>0.591</td>
<td>74%</td>
<td>0.580</td>
</tr>
<tr>
<td>F2100W</td>
<td>0.674</td>
<td>72%</td>
<td>0.665</td>
</tr>
<tr>
<td>F2550W</td>
<td>0.803</td>
<td>68%</td>
<td>0.812</td>
</tr>
</tbody>
</table>

Notes. MIRI imager PSF metrics, measured on commissioning data (2nd and 3rd columns), and WebbPSF models (4th and 5th columns). The last two columns tabulate FWHM and EEs (Encircled energies) ratios between data and models. FWHM are average values in x and y directions from fitting a bi-dimensional Airy function to the images.

5. Flux calibration

The imager flux calibration is provided as the reference file used by the pipeline in the PHOTOM step, that converts from units of DN s$^{-1}$ to physical units of MJy sr$^{-1}$. DN stands for Data Number and is the raw signal unit of the MIRI detectors. During commissioning, the flux calibration was based on two spectro-photometric calibrators (and one additional calibrator in sub-array mode only) observed in two different epochs separated by about 12 days (PID 1027; see Table 3). We also used the CALSPEC stellar models that, in combination with the ground-based photon-conversion-efficiency, provided a theoretical measurement to compare to the in-flight aperture photometry (readers are referred to Gordon et al. (2022) for additional details). The data of these spectro-photometric calibrators were processed with the 1.5.3a0 version of the JWST pipeline, version 11.16.6 of CRDS and context jwst_0865.pmap. Some steps utilized dedicated commissioning reference files that at the time were not in CRDS. The calibration factors were derived as follows:

1. Process data down to the dither-combined images (that is the pipeline stage 3 data products 12d FITS files). For this data reduction, the PHOTOM step was skipped, to preserve units of DN s$^{-1}$.
2. Using source masking, generate and subtract a background model.
3. Identify the spectrophotometric calibrator.
4. Multiply by the average pixel area in steradian.

3 The position of the cross-artefact shifts from the PSF centre and bends slightly when one moves around in the FoV. This is thought to be caused by the non-normal incidence of the beam on the pixel grating lattices, which will be modelled in a future paper.
5. Perform aperture photometry at different radius to produce the curve of growth, determine the 60%, 70% and 80% of the encircled energy.
6. Subtract the local sky estimated as the median value of the pixels with an annulus centred on the calibrator.
7. Because the JWST calibration pipeline assumes infinite aperture, perform the aperture correction using WebbPSF (we assume infinite aperture).
8. Define calibration factors as the ratio of the CALSPEC model-based photometric measurement per filter, and the measured aperture-corrected photometry.
9. Repeat process for each filter, and average results from different epochs.

The MIRI imager photometric stability was evaluated with a single repeat of the BD+60-1753 and J1743045 measurements in FULL array FASTR1 mode (as defined in Commissioning Activity Request MIRI-011). Data were taken at a minimum of 9 and maximum of 12 days apart. As shown is Figure 8 all photometric measurements (80% encircled energy) are consistent within 5%, well in line with the requirements.

6. Backgrounds

The sensitivity of MIRI imaging is background limited at all bands. Hence, a proper background correction is needed for improving science performance of the imager. The background emission is dominated by astronomical origins (zodiacal light and Milky Way interstellar medium) at $\lambda \lesssim 12.5\mu m$ and by the observatory stray light and thermal self-emission at longer wavelengths (refer to Rigby et al. [2023b] for a detailed analysis of JWST background emission spectrum). Here, we present the MIRI imager thermal background measurements that were performed during the commissioning period. We also provide recommendations for observations planning and data reduction to mitigate the effects of the background, particularly at longer wavelengths. Finally, we describe our monitoring program and show how the background varies over time and as a function of telescope attitude in the two reddest MIRI imager filters.

6.1. Observations and methodology

The commissioning program that was dedicated to assessing the MIRI thermal background level and variation is PID 1052. The program observed ‘blank’ fields that were selected to not have any obvious sources in the WISE 3 bands combined images, in two different telescope attitude configurations, ‘Hot’ and ‘Cold’, to capture the extreme cases in terms of the amount of solar energy input onto the illuminated side of the sunshield. The Hot attitude is when the angle between the Sun-observatory line (sunline) and the telescope pointing direction is 90° ± 5°, when the largest area of the sunshield is exposed to sunlight. The Cold attitude is when the angle is 130° ± 5°, when the telescope pointing is most away from the Sun. The goal was to assess the variation of the thermal background as seen by MIRI long-wavelength bands in these two bounding conditions.

The observations used MIRI filter bands F770W, F1280W, F1500W, F1800W, F2100W, and F2550W. These filters, covering all but the shortest wavelength band of MIRI, probe the regimes where different observatory components (tower, sunshield, Optical Telescope Element) are expected to dominate. For example, the sunshield emission, that represents one of the main contributors to the thermal background seen by MIRI, be-

Fig. 5. Stamps of the F560W PSF core (4′′×4′′ boxes), showing the Zemax simulations (1st column), the ground-based PSF tests done at CEA with the imager ETM in 2008-2009 (2nd column), the flight PSF commissioning data (3rd column), and the WebbPSF simulations computed during commissioning (last column). On the top right image, an approximate representation (exponential profile) of the cruciform was added on top of the WebbPSF model. All PSF images are shown on a log-scale, with same relative stretch, at the center of the imager field of view. The top row shows native resolution data with 0.11 arcsec pixel$^{-1}$ scale. The bottom row shows super-resolved PSFs. The Zemax and WebbPSF high-resolution simulations, as well as the reconstructed image of the super-resolved flight and ground-based PSFs, are shown with an oversampling factor of 4. The base of the cruciform (cross aligned in horizontal X and vertical Y directions) is visible both on ground-based and flight images.
Fig. 6. PSF radial profiles at 5.6 and 25.5 µm: comparison between in-flight PSFs and simulated WebbPSFs. The left panels show radial profiles, normalised to the flux of the central pixel. The blue, green and orange curves show respectively: the flight data (see Figure 3 for images), the WebbPSFs without the cruciform artefact, and the WebbPSFs with the cruciform artefact (see text for details). For the F560W filter, the profile at large radii (outside the secondary Airy ring at \( r > 6 \) pixels) is dominated by the cruciform. At 25.5 µm, there is no cruciform. The right panels show encircled energy (cumulative radial flux) profiles, normalised at a radius of 5 arcsecs (≈ 45 MIRIM pixels). The red dashed lines highlight the position of the radius containing 65% of the total encircled energy within 5 arcsecs.
Table 3. Spectrophotometric calibrators

<table>
<thead>
<tr>
<th>Calibrator</th>
<th>RA [h:m:s]</th>
<th>DEC [°:′″]</th>
<th>Spectral Type</th>
<th>Filters</th>
<th>Subarray/Readout</th>
<th>Execution Date</th>
</tr>
</thead>
</table>

Notes. Spectrophotometric calibrators from commissioning program 'MIRI Imager Photometric Zero Points and Stability', PID 1027. All dates are UTC, and celestial coordinates are ICRS.

Table 4. MIRI imager background measurements during commissioning

<table>
<thead>
<tr>
<th>Filter</th>
<th>Average background [MJy/sr]</th>
<th>Variation between Cold and Hot attitudes (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F770W</td>
<td>6.7</td>
<td>73</td>
</tr>
<tr>
<td>F1280W</td>
<td>36.0</td>
<td>0.9</td>
</tr>
<tr>
<td>F1500W</td>
<td>60.8</td>
<td>0.3</td>
</tr>
<tr>
<td>F1800W</td>
<td>91.3</td>
<td>0.5</td>
</tr>
<tr>
<td>F2100W</td>
<td>238.7</td>
<td>0.7</td>
</tr>
<tr>
<td>F2550W</td>
<td>853.3</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Fig. 7. Image of β Doradus from the commissioning program PID 1023, where the blue rectangles highlight the cross-shaped artefact, referred to as the cruciform. This artefact is easily identified in the flight images for wavelengths shorter than 12 µm.

6.2. Background analysis results

Hot and Cold attitudes and temporal variation. The thermal infrared backgrounds in the F1280W, F1500W, F1800W, F2100W, and F2550W filters are shown in Table 4. At long wavelengths (>12 µm), where the thermal emission dominates, the background measurements in the two Hot and Cold bounding conditions are consistent within 1%. This is in agreement with pre-launch predictions of the ETC.

A more significant background variation is observed in the F770W filter (~ 7%, Table 4) during commissioning, with no correlation with the telescope orientation. This variation is also larger than that expected by the mirror temperature variation during the thermal stability test (moving from Hot to Cold attitude) by ~ 0.2 K. In fact, this large variation in F770W is likely due to an astronomical origin. The F770W filter traces the emission from Polycyclic Aromatic Hydrocarbon (PAH) dust grains, which emit strongly at 7.7 µm (Tielens 2008). The WISE 12 µm images (which trace two strong PAH bands at 7.7 and 11.3 µm) indicate that the pointing of the hot attitude observations was very close to a region with enhanced PAH emission. Therefore, the origin of the F770W background difference between the two attitudes is astrophysical. None of the other observed MIRI filters trace strong PAH bands to show the same effect, the only other filter that directly traces a PAH band is F1130W, which was not included in the Hot-Cold attitude test.

Background spatial structure variation. Figure 9 shows the F2100W background image, where individual sources are subtracted using multiple dithers of the same pointing. A spatial structure that varies up to ~ 10% across the field is observed.
This structure is persistent among all MIRI filters. To better understand the origin of this structure, we construct a master background by identifying bright sources (mostly point sources in these observations) through subtracting consecutive dithered images in each filter\(^5\) and replacing their value with interpolated sky value from other dithers. By normalizing the master backgrounds to their median value, and subtracting the Cold and Hot normalized backgrounds from each other in each filter, the residual image has a smooth structure with a symmetrical distribution centered at 0 and standard deviations of < 1%.

As the dominant observed spatial structure is constant with time and consistent among all MIRI filters, it is suspected to be due to imperfect flat field correction. Current flat field images (CRDS 11.16.15) reduce the variation to < 5% across the field. Background spatial variation needs to be revisited in the future with better flat field corrections as the flat field is currently the dominant source of variation. In Section [10.2] we discuss strategies to correct this spatial structure.

7. Distortion

Distortion across the imager field of view must be well characterised in order to support accurate astrometry and the photometric correction of non-uniformity in the on-sky projected area of detector pixels. The MIRI imager distortion map is shown in Figure [10] where image displacements of up to 1 arcsecond are seen at the corners of the field relative to the centre. The observed ‘pin-cushion’ like pattern is primarily a result of MIRI’s off-axis all-reflective optical design, where the symmetry axis marked in the figure results from a symmetry plane in the optics which bisects the detector along a line parallel and close to the central column of the detector. A smaller additional component arises from the observatory optics, with a displacement amplitude which varies with distance from the telescope optical axis.

The distortion is geometrically well behaved, allowing us to represent the vector displacement at any point in the field using two sets of fourth order polynomial transforms, \(\mathbf{X}_{\text{out}} = \mathbf{Y}_{\text{in}}^A \mathbf{X}_{\text{in}}^A\) and \(\mathbf{Y}_{\text{out}} = \mathbf{Y}_{\text{in}}^B \mathbf{X}_{\text{in}}^B\). \(\mathbf{X}\) and \(\mathbf{Y}\) are vectors of the form \(\mathbf{X} = [X, Y, 1]^T\), \(\mathbf{Y} = [V_2, V_3, 1]^T\), where \(0 \leq i \leq 5\) and \(x\) is the focal plane coordinate. \(A\) and \(B\) are 5x5 upper-diagonal matrices, where terms up to \(x^4\) have been found to be sufficient to achieve a positional accuracy better than 5 milliarcseconds rms when mapping between pixel (row, column) and sky (V2, V3) focal plane coordinates. In general, the \(A\) and \(B\) matrices are derived using a Singular Value Decomposition (SVD) method to find the optimum set of transforms which fit conjugate pairs of coordinates which have been measured accurately in the ‘sky’ and ‘detector’ focal planes. For ground testing these coordinates were obtained from the Zemax optical model, with Figure [10] showing the displacement of the projected regular grid of points compared to a purely affine transform, comprising offset, scaling and rotation only.

During commissioning and as one of its first on-sky observations (PID 1024), the MIRI imager was used to map a region of the JWST Astrometric Calibration Field in the Large Magellanic Cloud. This field contains >200,000 isolated stars with \(K\)-band magnitudes ranging from \(8 < K < 24\)\(^5\) and positional accuracy of \(\sim 1\) mas (see Sahlmann 2017 and JWST-Data-\textcopyright2021-GAIA-EDR3-Calibration) and more recently, benefits from GAIA EDR3 astrometry (Gaia Collaboration et al. 2021). We used the positions, proper motions, extrapolated \(K\)-band fluxes, and expected observatory position angle to model and optimise our observations using the MIRI simulator, MIRISim (Klaassen et al. 2021, see Figure [13]).
Figure 11 then shows an example of the distortion vector field measured using two observations with the F770W filter, where the polynomial transform from detector to Gaia coordinates was calculated using the SVD method described above. The agreement of the flight and optical model (Figure 10) is seen to be excellent.

Approximately 2500 of the Gaia catalogued stars were identified with accurate centroids in MIRI’s shortest wavelength filters, sufficient to provide a 1 sigma error well below the 5 mas target, as shown in Figure 11. At longer wavelengths the combination of increasing background limited shot noise and the Rayleigh-jeans spectral shape of the targets causes this number to fall to just 20 or so identifications for the F2100W filter. This lack of long wavelength identifications is mitigated by the all-reflective optical design of the imager, such that the high order (i.e. non-affine) elements of the distortion transforms in all bands is well described by a single set of transforms. Individual filters only differ by adding a boresight offset, as a result of the small variations (of the order of 1") in the wedge angle of the refractive elements.

The simulated and on-orbit measured observations are shown in Figure 13, where the agreement in dynamic range and source count reflects the close match between MIRI’s on-orbit performance and the predictions of pre-flight models. This good correlation helped in the automated identification and cross-matching of stars in the images with their catalogue counterparts.

Non-parallelism between the faces of refractive elements in the imager optical train (the band-pass filters) cause the distortion map to be shifted on the detector, by tens up to approximately a hundred milli-arcseconds. The JWST pipeline is therefore provided with an offset vector to account for the shift and support the accurate co-alignment of images taken in multiple wavebands.

This impact of finite wedge angles in refractive elements is more severe for the operation of the 4QPM coronagraphs, where a bright target must be positioned behind the coronagraphic null with an accuracy of 5 mas, after both the boresight offset due to the phase mask itself and that of the filter being used for target acquisition (TA) have been taken into account. In practice, the problem was solved on a case by case basis, with the effective pointing position measured for each TA filter, acquisition strategy and phase mask combination in turn. A detailed description of this process may be found in Boccaletti et al. (2022).

The on-sky projected area of a pixel across the entire detector is shown in Figure 12, where it is calculated by evaluating the flight-measured on-sky position of all pixel corners and then calculating the geometric area of each quadrilateral. The area varies between 0.970 to 1.017 times the baseline value of 0.0121 arcsec².

8. Flat fields

Pre-flight pixel flats were made from data taken with the MIRI Telescope Simulator during Flight Model testing at the Rutherford Appleton Laboratory and observations with the imager internal calibration source during instrument Cryo-Vacuum testing at NASA Goddard Space Flight Center. These tests did not include the telescope optical elements. From these data a considerable effort was made to create high quality pixel flats, where features of the test set up and instrument meant that the data sets were not optimised for the task. Therefore, it was important in commissioning to verify that firstly the flats were applicable to flight data and to measure for the first time the low spatial frequency ‘sky’ flat field, which is dominated by the telescope and observatory environment and thus could not be measured on the ground.

The flat field commissioning activities for the imager were conducted in two programs which also overlap in their goals: one for the external flat fields (PID 1040) and another for the pixel flat (PID 1051). The input data for the commissioning flat analysis came from three sources: (1) an internal calibration lamp source, a highly stable source to be used throughout the mission but with non-uniform illumination for the imager, (2) a low stellar density sky background, ideal for deriving the low frequency ‘sky’ flat field, which is dominated by the telescope and observatory environment and thus could not be measured on the ground. From ground testing we know that the MIRI imager pixel flats are wavelength-dependent and therefore a flat correction for
The initial flat fields created in commissioning were constructed using sigma-clipping of many observations aligned in array coordinates, using extended emission that fills the imager’s field of view, and filtering out sources that are in different array positions in different observations. Observations taken from commissioning program PID 1040 of a large region in the Large Magellanic Cloud composed mostly of point sources were used initially for constructing the flat fields for all imaging filters. After commissioning, the flat fields for F1000W, F1280W, F1500W, F1800W, and F2100W were updated by including additional observations. These additional observations, taken in the first two months of science operations, were visually determined to be mostly composed of point sources. These flat fields are shown in Figure 14.

The flat fields were constructed by properly combining multiple dithered on-sky observations and made independently between filters and using only full frame observations. The Lyot region is included in the full frame flat fields as the observations are valid for regular imaging filters except for the regions eclipsed by the Lyot spot and support bar. The eight pixels at the four edges of the detector were masked in the flat fields due to undesirable detector effects. Subarray flat fields are created on-the-fly in the pipeline by cutting out the appropriate region from the full frame flat fields.

9. Image artefacts

MIRI’s Si:As blocked impurity band (BIB) detectors are state of the art for mid-infrared imaging. Nevertheless operating detectors at temperatures around 5 Kelvin is still challenging. In this section we describe some of the known non-ideal behaviours seen in MIRI’s focal plane arrays as well of some of the corrections and mitigation available at the time or writing. We note that there is no effect or artefact that is known to significantly reduce MIRI’s imaging performance.

9.1. Persistence

Persistent images are a common artefact of cooled infrared detectors - a memory effect where a residual of a previous image is seen in the subsequent exposure. Previous infrared space observatories such as Spitzer and WISE, which used similar detector technology to MIRI (Si:AS IBC detectors), recorded persistent structure in imaging (Hora et al. 2004; Wright et al. 2010). In these missions, the persistence structures were removed using a process known as annealing, where the detectors are temporarily heated by around 15 degrees to help release any trapped charge. In this section we describe some of the known non-ideal behaviours seen in MIRI’s focal plane arrays as well of some of the corrections and mitigation available at the time or writing. We note that there is no effect or artefact that is known to significantly reduce MIRI’s imaging performance.

The principal commissioning activity to investigate persistence in MIRI detectors was designed to imprint an image of the full frame flat fields.

Perspective as discussed in this paper is also commonly referred to as latents/latency but we, and the JWST documentation in general, avoid the word “latency” because it is also associated with properties that cannot be attributed to the persistence effect we describe.
a bright target on the imager detector and analyse its decay (if any) for up to 40 minutes. Data from the commissioning activity can be found in PID 1039 where the target chosen for the imager test was the Seyfert galaxy NGC 6552: a compact, bright, mid-infrared source in the Northern continuous viewing zone for JWST. The Seyfert galaxy was observed for nearly 10 minutes in the same position on the detector. The bright nucleus saturated the pixels at the galaxy centre in less than 3 groups (< 10 seconds). With only 3 groups or less the pipeline could not fit a slope to the data and therefore no flux value is assigned to the nucleus pixels and is masked in the image (black pixels). The top row of Figure 15 shows the primary result of the test where on the left is the galaxy image, or ‘soak’ image. The soak image is the one that contains the source of the persistence for instance a bright target. The central and image to the right are subsequent images taken at the same detector position that the bright galaxy was observed, but a different sky position. These follow up images in Figure 15 demonstrates that persistence from the galaxy nucleus is seen but at a very low level. The level of persistence seen 15 minutes after the galaxy was observed is <0.01% of the flux of the target and appears to dissipate entirely by the next observation 30 minutes after the soak image ended. This provides us with initial evidence that persistence artefacts are likely to have a low impact on MIRI data, where such levels of persistence are easily averaged out in the process of mosaicking dithered imaging, which is the recommended imaging technique.

Next, as part of the anneal verification and testing program (PID 1023), we observed the bright \( K_{mag} = 2 \) star \( \beta \) Doradus in four MIRI imager filters (F560W, F770W, F1000W and F1280W). The tests were designed to provide an extreme test of detector saturation in order to test that the anneal recovery process works to remove any residual detector artefacts including persistence. \( \beta \) Dor is an order of magnitude brighter than the Seyfert galaxy NGC 6552 at mid-infrared wavelengths where the core of the stars PSF saturated the detector in less than 1 frame (<2.7 s) and was imaged for 250 seconds. Before the anneal pro-

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7 A paper detailing the results of the imaging and MRS spectroscopic data for NGC 6552 has been published by Álvarez-Márquez et al. (2023b).
Fig. 15. Examples of persistence in flux/rate images (pipeline level 2a). Top row shows results from the persistence test in PID 1039. Each row, left to right, shows the same position on the detector. Left: image of the Seyfert galaxy (NGC 6552, β Dor, or NGC 6543) that saturates the detector at its core. Centre: the next exposure taken 15 minutes after the first image - a faint persistence residual from the galaxy nucleus can just be seen in the image. Right: showing the same position 30 minutes after the first image was observed - the persistence residual is very faint. The images for β Dor are from PID 1023. The bottom row shows persistence from the extended structure of the bright planetary nebula NGC 6543. Note the scale for the soak images on the left is log while that for the other images is linear and all units are DN s$^{-1}$.
cess was done we took several images to confirm any persistence artefacts from the bright star. The middle row of Figure 15 shows the final image of β Dor test at 12.8 μm as well as the subsequent 5.6 μm images taken of an off-source background close to the star approximately 18 and 30 minutes after the soak image. In the image, observed 18 minutes after the soak image, it is still possible to make out a persistent imprint of the 12.8 μm PSF of β Dor. However, as for the Seyfert galaxy test, the contrast of the persistence image left by the star compared to the background is very low, only a few tenths of a DN s⁻¹ above the nominal background. Likewise, the background imaged 30 minutes after the last observation of β Dor shows very little persistence from the extreme hard saturated observations. We re-iterate here that these images show persistence from a single pointing and the average image of the stack of dithered images in the pipeline mosaicking step will further reduce the impact on the final image product. Choosing large dither patterns will also help reduce the impact of persistence for compact sources to avoid imaging a bright object on area already affected by persistence. The β Dor test confirmed the low impact of persistence for extremely bright targets as well as for longer wavelength data up to 12.8 μm. In addition this test provided evidence that is was not necessary to have to anneal after bright observation to remove persistence artefacts as used in previous missions with similar detectors for instance WISE.

Lastly, in the bottom row of Figure 15 we show an example of persistence from an extended object, the Cat’s Eye nebula NGC 6543. The mid-infrared bright nebula was observed for 10 minutes in the same detector position. This example shows that the planetary nebula is the brightest at its core and most of its extended structure is not saturated or only partially saturated in the soak image. However, the persistence image, taken approximately 15 minutes after, traces the extended structure of the target. This confirms what was seen in ground tests: that persistence is dependent on the soak time as well as the flux from the source. An image does not have to be saturated to cause persistence. It also demonstrates that persistence from extended objects can be more easily seen in imaging because the spatially extended low contrast artefacts can clearly be distinguished from the background unlike point source persistence.

In Figure 16 we show observations of β Dor F1000W image from the test - the 3rd positional offset of the star. The image is a cut out of the part of the detector image where the previous two offset positions of the bright star were made using the F560W and F770W filters (See Figure 25 for reference). In this image we can see a persistence artefact from the bright star at these two positions and persistence from the slew between them - again at low contrast compared to the background. Also in Figure 16 in the right panel we show which of the pixels in the first position image at F560W reached saturation - defined here as more than 61500 counts. The observation was made with 1 integration with 90 groups and the plot is colour coded by the group number in which the pixel saturated. For example, a pixel that reached 61500 counts in less than 10 groups is marked in red. If the pixel reached 61500 counts in groups 10 to 20 of the integration it is marked in blue and so forth. Figure 16 then clearly shows that the central core of the star saturated first followed by pixels further out from the centre. Figure 16 also demonstrates that the persistence signature left by the bright star, seen in the left panel of Figure 16 corresponds well to the pixels of the detector that reached saturation before the end of the ramp, as marked in the right panel of Figure 16. We note here that this is not just to the areas of highest flux. From ground testing we expect short integration, high flux, saturating imaging to produce relatively strong persistence that decays quickly whereas bright unsaturated imaging, with long soak times, to have relatively weaker persistence but longer decay times. In summary, the persistence artefacts from bright sources seen in MIRI during the commissioning period are very low contrast and dissipate within approximately 30 minutes of the observation of origin. This means that strong persistence between different scientific programs that would affect data quality for science appears unlikely given the long observatory overheads, especially slew times. Although, persistence within a science program may be seen on timescales of 15 minutes or less. However, there are many factors that contribute to whether or not a persistence artefact is made or seen. Notably the depth of the subsequent image is important as seen in the next section, where deep imaging can reveal very low contrast persistence that would otherwise not be seen. We note that the pipeline has persistence tools for the near-IR detectors but these are not applicable to MIRI data at the time of writing. Lastly, we know that increasing the number of integrations can mitigate persistence or, more specifically, reducing the counts per pixel per integration. Using this strategy must be balanced with keeping enough groups per integration for calibration, typically more than 10 when possible.

9.1.1. Slew persistence

As shown in Figure 15 and 16 persistence artefacts can also be seen when a bright target slewed across the imager field of view. This has the potential to be the most common persistence artefact in imaging due to the short lead time (< 5 minutes) between the slew and the start of observations. It is also worth noting that slew persistence can be seen in a different filter than the one used in the previous observation. Because the movement of the MIRI filter wheel is the last activity before a MIRI imaging observation, an object saturating the detector in the filter used for the previous image, and thus during the subsequent slew, may well appear fainter and non-saturating when the next filter is chosen and the object imaged.

A prominent example of slew persistence appeared throughout the whole seven hour data set of the Early Release Observation (ERO) program targeting the lensed cluster SMACS0723. Figure 17 shows the first exposure of the data set where an elongated ‘check mark’ shaped persistence streak can be seen in the image (PID 2736). The origin of this slew persistence appears to be a K = 4 star (HD 92209) imaged with the F2300C filter as the last observation in a commissioning test (PID 1045, Observation 75) taken approximately 4 hours before the observations of SMACS0723. The check mark shape comes from the initial slew followed by a guide star correction to put the star in the centre of the imager field of view. Note we still see this slew persistence at the end of the SMACS0723 observations, some 11 hours after the star of origin was observed. This confirms that long-lived persistence can exist in MIRI imaging which is also consistent with ground detector tests made at NASA’s Jet Propulsion Laboratory that saw persistence lasting at least 10 hours. However, these long-lived persistence are at a very low contrast, where the difference between the persistence artefact and the background is less than 0.5 DN s⁻¹. Why the slew persistence in this case was particularly long-lived is not known at the time of writing.

Another possible source of persistence in imaging is from the movement of the filter wheel at the start of an observation. The filter wheel is moved for an observation after the target is positioned in the field of view of the imager. As the filter wheel turns, a target may leave a persistence signature when passing through a filter in which it is very bright. In particular the F-
Fig. 16. Left: image of β Dor at 10 µm at the position where the bright star was observed in the previous two observations at 5.6 and 7.7 µm. The persistence images of the star in the two positions can be seen in low contrast as well as that of the slew between positions. Right: identification of the pixels that are marked as 'hard' saturated in the first position observation at 5.6 µm. We can see the persistence image matches well the image structure of the hard saturated pixels from the image.

Fig. 17. Left: level 2a flux image from the ERO program of the lensed cluster observations of SMACS0723 (PID 2736). Slew persistence that resembles a check mark can be seen in the image taken 5 hours after the bright star that was the origin of the slew persistence. Right: image taken 12 hours later in program PID 1124. The slew persistence can just be made out in this image.

9.1.2. Persistence from the background

As discussed in Section 6, the thermal background of JWST at MIRI’s longest wavelengths has a high flux (Glasse et al. 2015) and this can also be a source of persistence. In particular, if an observation at short wavelength follows directly after an observation at long wavelength a persistence from the higher background image may be seen at short wavelength. During the commissioning of MIRI we tested the impact of persistence from high background observations in program PID 1039. Figure 18 shows the results where we plot the background flux at 5.6 µm from the short wavelength integrations taken before and after a 300 second observation at 25.5 µm. The plot shows that the background flux clearly increased in the 5.6 µm images taken after the observation at 25.5 µm and then decreases back towards the nominal background level measured before the long wavelength observation. In fact, we see that the background does not quite recover to the nominal 5.6 µm observation level even 30 minutes after the long wavelength observation. Looking back at Figure 15, in the centre row of the figure we can see the change in background at 5.6 µm 18 minutes and 30 minutes after the first image due to the persistence from the background of the 12.8 µm observation of β Dor taken before. It is important to note that this flux change in the background is small - around 0.5 DN/s over 30 minutes, but nonetheless this can be significant for imaging and therefore dithered and mosaicked imaging may require background matching in the pipeline. This change in the background is unlikely to affect most science programs. However, as a general rule, we recommend observers to transition from short

Lens filter which has a wide wavelength throughput, can leave an imprint on the detector. An example can be seen in Section 10.4 Figure 26. In the 5.6 µm image there is an imprint behind the star that resembles the JWST mirrors and this is in fact the persistence image of the F-Lens filter passing across the imager.

The MIRI F-Lens was used during ground testing to form a pupil image from which optical alignment can be verified. This test was repeated in flight to determine whether the pupil alignment had changed and to check for vignetting. The in-flight measurement showed MIRI remained aligned and met requirements reference in Kubalak et al. (2016).
9.1.3. Persistence from cosmic rays

The sample up-the-ramp method, where the flux is derived by measuring the slope of the ramp created by successive non-destructive reads of the detector (Morrison et al. 2023), is used by all JWST instruments. When a cosmic ray hits a pixel, adding unwanted signal to the data, the slope of the two ramps either side of the hit can be measured separately and the flux derived. Using this technique cosmic rays are very effectively removed in MIRI data with the JWST pipeline’s jump algorithm in the processing of data from level 1b to level 2a. However, in commissioning the team noticed that some cosmic ray artefacts were not removed. An example of such an artefact can be seen in Figure 20 which we refer to as cosmic ray ’showers’ [9]. After further analysis we discovered that showers were the residuals of high energy cosmic ray hits where the energy arriving in the detector is spread over more than one pixel as well as secondary hits. The residual signal from these powerful cosmic rays can then leave persistence artefacts which we see as a shower in the flux image. Showers in MIRI detectors have a variety of different forms from spherical to very elongated and can spread out over hundreds of pixels. The residual showers will have the largest impact on short wavelength data with low backgrounds, for example, deep imaging programs, where the background is dominated by cosmic showers and cannot be easily averaged out in the dithered mosaicked image. Figure 19 shows examples of the persistence from cosmic rays as the signal from the cosmic ray is seen to decay after the jump, where the amplitude of the effect increases with the cosmic ray power. The cosmic ray example in Figure 20 also pulls up the values of the entire row of pixels that it hits and this row pull-up can also leave a persistence signature.

9.2. Row and column artefacts

Si:As BIB detectors are prone to rows and columns artefacts that come from the target that are in high contrast to the background. Such artefacts were also seen in the Spitzer/IRAC detectors, especially channels 3 and 4, as well as in the MIPS silicon IBC arrays, described as a “jailbar” effect. The effect in MIRI’s detectors was extensively studied during several ground test campaigns with flight spare focal plane arrays and flight clone electronics at NASA’s Jet Propulsion Laboratory. The results of those tests are presented in Dicken et al. (2022). The key result from
those tests is that, although the row and column artefacts are seen in the flux images, they actually result from a change to the signal measured in the ramp in level 1 data. The signal change results in a distortion or bend in the flux ramp that is related to how quickly the bright contrasting source saturates the pixels in the affected rows and columns. We also found that the row and column effects are often seen together but have different properties and therefore have different origins or mechanisms that produce them. One key difference is that the column artefact is seen only in the columns that contain the bright source but the row artefact can be seen in the rows above (in the read direction) the bright pixels causing the artifact. Finally, because these effects are seen in a number of different array types, covering two different multiplexers and detector types (Si:As, In:Sb) with MIRI and Spitzer, this confirms that the artefacts originate in the multiplexer rather than in the detector layers.

Figure 21 shows a commissioning F1000W image of a bright spectral calibration, the planetary nebula SMP-LMC-58. The bright central core of the nebula causes row and column structure in the image which is seen as a column with lower flux than the background above and below the nebula while rows with higher flux than the nominal background either side of the nebula. The image is shown in detector coordinates so the row and column artefacts follows the XY directions of the pixel grid in the detector plane, whereas the PSF can be differentiated because it is an angle of a few degrees. This image is the mosaicked combined image of a 4-point dither observation, showing that dithering does not mitigate row and column artefacts. The artefact is tied to the source and not the detector, so the process of dithering, moving the object to different positions in the detector cannot mitigate the row and column artefacts. And hence is reinforced in the stacking and averaging of the mosaicked image process.

Commissioning analysis shows that we see row and column artefacts at all wavelengths of the MIRI imager - a result we were not able to verify in pre-launch ground testing due to the low backgrounds of the test environments. Additionally, in flight, the column artefact appears to manifest differently above and below the source of origin whereas in pre-flight testing the artefact was identical above and below the source of origin. This can be seen in Figure 21 where the column artefact above the nebula is more enhanced in the flux image than below. This is currently not well understood. We also see less incidence of row artefacts than we were expecting from ground testing. This is likely because the row artefacts are seen at lower contrast than the column artefact effect where they can be spread over many rows in the read direction up the detector beyond the source of origin.

At the time of writing there is no pipeline correction for row and column artefacts. The MIRI team have trialled several column and row filtering tools, similar to those available for Spitzer data, with good initial results. For any future development of a pipeline correction for row and column artefacts see the MIRI JWST documentation pages.

9.3. Stripes at low background

When showing low background imaging at high contrast, such as the 5.6 µm imaging in Figure 15 and 20, stripping in the background can be seen in the level 2 processed images. This stripping is an artefact left over from the reset anomaly correction which is part of the dark correction in the pipeline (see Morison et al. 2023). The dark correction works well to remove the reset structure but in commissioning it became clear that the dark and reset anomaly change in time. Therefore, a dark correction data product made from data at a different epoch than the data...
being processed may not completely subtract the anomaly as it should. This issue is mitigated as the background increases with wavelength for imaging because the dark subtraction becomes less dominant as photon noise increases with higher background emission. The reset anomaly is also more dominant in the first 25 groups of data, therefore longer ramps tend to see reduced striping at low backgrounds. At the time of writing, corrections for this issue are still being worked on and the reader should refer to JWST documentation for future updates.

10. Recommended best practices

10.1. Dithering

Dithering in MIRI imaging is a recommended technique that provides a variety of benefits. It improves the PSF sampling, which for MIRI is mostly relevant at wavelengths shorter than 7 μm, where the PSF is slightly undersampled. Dithering also facilitates the subtraction of the background for point source imaging where much the image is ‘source’ free, as well as mitigating the impact of bad pixels (see Figure 2), and minimising detector effects. A minimum of four dither positions or more is recommended to allow redundancy when creating the mosaic to mitigate against the effects of bad pixels, detector artefacts and cosmic ray residuals.

As shown on Section 10.2.2.4 cosmic ray showers are prevalent in MIRI data and can have a significant impact on mosaicked imaging. When a high energy cosmic ray causes a residual the size of tens of pixels (known as a cosmic ray shower in MIRI) it can appear as an artefact in the mosaic when the dither pattern step size is smaller than the cosmic ray shower residual. To mitigate this in MIRI imaging, the MIRI team now recommends dither patterns with long steps in between positions, which will facilitate their removal during the dithered image combination step as this reduces the chance of overlap of artefacts between dither positions. In particular, the Cycling pattern with size ‘LARGE’ has been very effective at alleviating the residuals from showers as well as removing sources from the background through image stacking.

10.2. Background subtraction strategies

All MIRI observations require background subtraction, particularly at longer wavelengths where the telescope thermal emission is significant. As discussed in Section 10.1, spatial variation can be seen across the background field in observations of all MIRI filters, which hinders accurate data analysis of faint sources and structures. These features are often the residual of imperfect flat field correction and/or dark or reset anomaly corrections (Morrison et al. 2023) and can be removed in the background subtraction step. However, as more calibration data is taken in cycles 1 and 2, we expect these features to be mostly removed prior to the background correction step. We note that as the dominant spatial structure seen in MIRI data is due to flat field (a multiplicative effect), correcting it via background subtraction results in incorrect fluxes. However, this effect was measured to be < 5% across the field of view and is often dominated by other flux measurement uncertainties.

Observations of extended sources that fill most of the MIRI imager field of view (such as nearby galaxies) will benefit from dedicated background observations, while various dithers of fields with point-like sources (such as extra-galactic fields) can be used as background images themselves. Here, we discuss two strategies to construct and subtract a background image from individual dithers: 1) using the background subtraction step in level 2 of the JWST pipeline, 2) manually outside of the pipeline performed on level 2 products. We explain the two methods and their differences below.

JWST pipeline Background observations (either dedicated backgrounds or science images of sparse fields) can be input into the JWST pipeline in background subtraction step as part of the calwebb_image2 stage (2) process. If more than one background observation is given to the pipeline, they will be combined into a sigma-clipped mean before being subtracted from each of the science data images. An example notebook on how to set up the background subtraction step is provided on GitHub here: Background Subtraction Demo. Background-subtracted cal files will then be fed to the stage 3 of the pipeline to make the final combined image.

We demonstrate the result of this step using F2100W observations of two commissioning programs PID 1024 and 1028 (see Figure 22). PID 1024 used four dithers. Two dithers in each pair are very close to each other (< 0.2″) but the two pairs have a gap of ~ 5″. Using these four point dithered images as the background shows an improvement over the combined image without background subtraction is significant. However, because of the closeness of the dithers in each pair, the sources are not completely removed in the clipped mean background. Hence, we see residual, negative, images in the pipeline image result. Pipeline background subtraction works best if all the dithers are sufficiently large (more than a few FWHM of the PSF). If there are individual cal files not sufficiently far from each other, we recommend to not use them as ‘background images’.

Manual background construction Users can also construct a master background using either multiple dedicated background observations or multiple dithers of point-source-like science observations. The general methodology is to identify and remove sources from individual dithers and then, combine the source-free images to produce a single master background. Below, we explain one example for this general methodology that has been successful with MIRI data.

Instead of using sigma-clipped mean to combine the background images, as is done in the pipeline, we use difference imaging for each two dithers to identify sources in the first image, and replace the image values of the source with those from the second image (which should be only background and without source emission). This can be done for each pair with sufficiently large dithers (a few times the MIRI filter’s FWHM). Then, the median of the source-subtracted single dithers will be the master background.

The background level might change from one observation to the other, particularly in longer-wavelength observations if individual dither are taken far from each other in time as the telescope thermal emission changes. To have a zero-level background subtracted image, we also re-normalise the master background-subtracted individual dithers to have a zero median over the field.

This method also works well only if the dithers are well separated from each other (multiples of MIRI FWHMs). Examples are shown in the right panel of Figure 22. MIRI imaging standard 4-dither pattern is ideal for this method. Smaller dither patterns that are designed for parallel modes (such as NIRCam as primary) or for the MIRI MRS as the primary mode, can result in non-uniform master backgrounds and over-subtraction of flux in background-subtracted images.
Both these strategies only work well if the background observations (or science observations of point-like sources) have large dithers. Therefore, we strongly recommend observers to always take MIRI images with multiple and large dithers.

10.3. Long integrations - deep observation performance

The imager team investigated two issues to de-risk long integration deep imaging observing strategies. Firstly, Spitzer IRAC suffered from temporal signal drifts on detectors with the same technology as MIRI which could reduce the signal to noise of deep imaging programs. Signal drifts had been seen in MIRI detector ground testing, which we generally attributed to persistence, therefore we wanted to verify that no new drift component was seen in flight that may come from the telescope or spacecraft background. Also, MIRI imaging programs will have the maximum length of an integration limited from the brightness of a source or high background. For deep imaging program of, for example, high-z’ targets at low background there is no notional limit to the length of an integration. However, there is no destructive reset in an integration as the detectors sample up the long ramps and the data might thus be affected by additional noise. For example, a residual noise component could be added by cosmic rays hits whose signal is only removed by a destructive reset and this could reduce the overall signal-to-noise ratio for long integration. Therefore, in MIRI commissioning, we also investigated if there is any penalty for taking very long integrations (>100 groups) that could be used in deep imaging programs.

This commissioning activity was based on six exposures in program PID 1027 using MIRI’s shortest wavelength and lowest background filter, F560W. Each exposure was 3000 seconds in length but used different integrations lengths of:

- 90 groups = 250 seconds (FASTR1) (Repeated twice)
- 180 groups = 500 seconds (FASTR1)
- 360 groups = 1000 seconds (FASTR1)
- 540 groups = 1500 seconds (FASTR1)
- 42 groups = 1000 seconds (SLOWR1)

For each of the six exposures we used a multiple of integrations so that the total number of groups matched between each exposure - two integrations for the 540 groups data and 12 integrations for the 90 group data sets. In the test we chose not to use dithers to limit the free parameters that could affect the test.

From pre-flight predictions we expected a hit rate of 55 per second for a MIRI array. The prediction is then that about 7% of the MIRI pixels will be affected by cosmic ray hits in 100 seconds, and about 70% in 1000 seconds. In flight we see the cosmic ray rate vary significantly, the cause of which is not well understood at the time of writing.
Results of the drift investigation, showing the mean flux per integration for a 500×900 pixels box centred on the imager field of view - from PID 1027 observation 2. All data is for the F560W filter and no dither or mechanism move was made during the 600s observation.

The target was a nominally empty background region that was chosen simply because it was close to a photometric calibration star also used in program 1027. Overall, this experiment provides 6 deep exposures (both in imaging and MRS) that only differ by the number of integration’s used and to the authors knowledge is the only set of deep MIRI imaging data of its kind - taking the same image of the sky but with different detector setups.

Figure 23 shows the results for the flight drift test – plotting the 24 consecutive integrations with 90 groups - a total observation time of 100 minutes. The plot shows the mean flux within a 500×500 pixels box at the center of the imager for each integration. We do not see any evidence for a drift in the signal between integrations, where the difference in flux across the integrations is approximately 0.02 DN/s. We do see a first integration effect due to reset switch charge decay (RSCD - discussed in Morrison et al. (2023)), where the first integration of the two exposures (each with 12 integrations) is lower in value than the subsequent integrations but overall there is no tendency higher or lower signal over the 100 minute duration of the test. However, MIRI imager users might see drifts in their data which could be due to persistence. For example, when the instrument moves from long wavelength to short wavelength filters persistence may be seen in the short wavelength data as a decaying signal in the background (see Section 9.1.2).

Next we can look at the maximum integration question using the whole data set of six exposures to investigate if there is any reduction in signal to noise or other cosmetic issue for data sets with long integrations (>100 groups).

As for the drift test above, Figure 24 shows a plot of the mean flux measured per integration, where the mean flux was measured within a 500×900 pixels box centred on the imager field of view. Again, we expect the first integration of every exposure to be out of family with the subsequent exposures (Morrison et al. 2023) but it is clear there is an offset in the mean flux value between the data sets than can only be attributed to the difference in the number of integrations and readout mode used in the exposures - albeit small < 0.2 MJy sr\(^{-1}\) and well within the flux calibration error. The biggest difference is between the SLOWR1 and FASTR1 data sets which is not surprising as the readout mode is very different in SLOWR1 - where groups are averaged on board the spacecraft. For the FASTR1 data there is no trend in the flux offset with integration length although the longest integration data (540 groups) has the highest offset compared to the other exposures. These small difference are likely due to a combination of persistence residuals, RSCD and detector settling effects. It is notable that the two 90 groups exposures show near identical flux results. This repeatability is an important strength of the MIRI1 instrument and its detectors where an observation tag is repeated exactly delivers the same result to a high level of accuracy.

In Table 5 we show the results from data processed to the pipeline stage 2 (CRDS version = 11.16.22) where the resulting six images are the sum of all integrations for each exposure. Here we are looking to see if the noise, as measured by the standard deviation within the box, is higher for any of the data sets. The standard deviation varies only by 0.03 MJy sr\(^{-1}\) between the data sets with highest noise found for the longest ramps and the lowest noise found for the SLOWR1 and 180 group data.

Figure 25 shows the resulting primary image of each of the six exposures which is the combination of all integrations with the total depth of 3000s per image. Here, by eye, we can confirm the results above that there is a flux offset between the data sets most notably for the 540 group and SLOWR1 data.

From Figure 25 we note that the two sets of 90 group data appear identical as expected. The 540 group data with the longest integrations does appear noisier or more granular as indicated in the statistics above. Because there is only one integration this could be due to the residual persistence from cosmic rays that is not removed by the destructive reset between integrations that takes place in the other exposures. Striping is also seen in the data which is associated with the reset anomaly (Morrison et al. 2023), which is associated with the dark correction. The amplitude or contrast of the striping is normally very low (<0.1 DN/s) and can vary depending on the processing of the different data sets but does not have a measurable impact on the signal or noise measured. Finally, the SLOWR1 data appears cosmetically worse than the other data this could be because the pre-averaging can make it harder to remove cosmic rays artefacts from the data. Also, some structure in the image could be because SLOWR1 flats from flight data have not been made yet, so the FASTR1 flat was used for this test.

Overall, the drift and maximum integration length commissioning tests show there is no important advantage or disadvantage from either short or long integrations from a signal-to-noise ratio point of view when considering integrations of 250 to 1500 seconds. From these data alone it is hard to recommend a “best” observing method for deep imaging programs. Good imaging is obtained for all data sets using at least 90 groups per integration.

Table 5. Long integration test results

<table>
<thead>
<tr>
<th>Read Pattern</th>
<th>Ngroups</th>
<th>Nints</th>
<th>Flux/stddev</th>
</tr>
</thead>
<tbody>
<tr>
<td>FASTR1</td>
<td>180</td>
<td>6</td>
<td>2.81 ± 0.12</td>
</tr>
<tr>
<td>FASTR1</td>
<td>360</td>
<td>3</td>
<td>2.78 ± 0.12</td>
</tr>
<tr>
<td>FASTR1</td>
<td>540</td>
<td>2</td>
<td>2.92 ± 0.15</td>
</tr>
<tr>
<td>FASTR1</td>
<td>90</td>
<td>12</td>
<td>2.82 ± 0.13</td>
</tr>
<tr>
<td>FASTR1</td>
<td>90</td>
<td>12</td>
<td>2.82 ± 0.13</td>
</tr>
<tr>
<td>SLOWR1</td>
<td>42</td>
<td>3</td>
<td>2.63 ± 0.12</td>
</tr>
</tbody>
</table>

Notes. Detector parameters and flux results for the long integration test discussed in Section 10.3.
10.4. Short integrations - bright target performance

Pre-flight we had very limited MIRI imager data with bright targets using the flight system because ground test sources and backgrounds were optimised for the near-infrared instruments which are used for, for example, phasing the mirrors. Therefore, commissioning gave us the first opportunity to test how the instrument would perform in science cases that require observations at the instruments bright limits.

As discussed in Section 9.1 as part of the anneal verification and testing program (PID 1023), we observed the bright $K_{\text{mag}} = 2$ star $\beta$ Doradus in four MIRI imager filters (F560W, F770W, F1000W and F1280W). The principle aim of the test was to analyse how the detectors recovered from the bright observation with and without the annealing function as well as verifying the anneal function worked. The test used four filters to investigate the extent of the cruciform artefact for this bright target and test the expectation that it would only be present at wavelengths less than 10 $\mu$m as discussed in Section 9.3.1 (also see Gaspar et al. 2021). The observations were made in one single integration of 90 groups which equals 250 seconds where the central core of the star saturates the detector in less than one group time (<2.7 s). Therefore this data represents an extreme saturated data set for the MIRI imager.

Figure 24 shows four rate images from the bright target test where the observations were made with offsets to allow the star to be imaged in different parts of the detectors, therefore any persistent signatures in the following exposures would not overlap. As discussed above in Section 9.1 the images clearly show persistence at the locations the star was observed. However what is also apparent from Figure 24 is that, although the star clearly saturates the detector in each of the images, there is no significant artefacts in the areas of the detector that were not illuminated by the saturating star as a consequence of the very bright star observation. In particular, the F560W image shows many galaxies in the background that are clear and well detected, although the number of background targets detected drops in the longer wavelength images due to the higher backgrounds. This result shows that the imager appears to function nominally in very high contrast imaging which will be important for science cases observing faint targets in the same field of view as a bright target. As also demonstrated in pre-flight ground testing, there is no penalty in terms of science performance for saturating on a source in the imager field of view that is not the principle science target. Therefore, the best strategy for imaging a faint source which contains bright targets in the same field of view may be to saturate the bright source(s) if the target of interest is of lower flux and not too close that the halo of the bright target overlaps with the science target. This would enable the observer to use longer ramps to observe the target of interest which are easier to calibrate as well as being more efficient.

11. Normal operations post-commissioning

Use of MIRI in the 1.5 years after commissioning has confirmed the promise of the instrument and its performance as verified in the commissioning tests. The overall imaging performance (and the other central instrument features) have generally returned data fully as expected and hoped. The sensitivity of the imager has proven to be moderately better than baseline in the pre-launch exposure time calculator (ETC), as a result of careful reductions performed with a super-background strategy (Álvarez-Márquez et al. 2023a; Lyu et al. 2023). This gain provides a bonus for the science programs and also margin against degradation.

One minor issue that still exists at the time of writing with regard to imager performance, as discussed in Section 9.1.3, is the energetic particle hits on the detectors that produce extended artefacts made up of a small showers of particles freed within the detector material. This behaviour emphasises the importance of taking data in a way that provides a high level of redundancy in observations of any position within the region of interest, so these artefacts can be removed in processing without significant loss of signal to noise.

In addition, On August 2023 the JWST team announced that the MIRI Imager exhibits a reduced count rate in the long-wavelength filters. At the time of writing, the root cause of the issue is still under investigation, but the MIRI science operations are unchanged. To compensate for this issue, the JWST pipeline and flux calibration reference file has been updated to include this time-dependent throughput correction. The signal to noise is no penalty in terms of science performance for saturating on a source in the imager field of view that is not the principle science target. Therefore, the best strategy for imaging a faint source which contains bright targets in the same field of view may be to saturate the bright source(s) if the target of interest is of lower flux and not too close that the halo of the bright target overlaps with the science target. This would enable the observer to use longer ramps to observe the target of interest which are easier to calibrate as well as being more efficient.

If in doubt of the best strategy contact the JWST help desk to get advice for your specific program.
Fig. 25. Showing the stage 2 cal data for the six exposures obtained as part of the maximum integration and drift tests. The total depth of data in each image equals 3000 seconds. Flux units are MJy sr$^{-1}$ and the colour scale is identical for all six images.

Fig. 26. Showing four images of the $K_{\text{mag}} = 2$ star $\beta$ Doradus taken as part of Program 1023 (observations 32–35) in four filters at 5.6, 7.7, 10 and 12.8 $\mu$m. The star was moved across the detector using offsets in the APT in order not to overlap the images. The bright star quickly (in less than 1 group $= 2.7$ s) saturates the detector at its centre (seen in black in these images). The images are presented in calibrated flux units (MJy sr$^{-1}$), processed to level 2b in the pipeline. At 5.6 $\mu$m an ‘imprint’ of the JWST mirrors can be seen behind the source which is a persistence from slewing across the Flens as discussed in Section 9.1.1.
change is about 20% for the most strongly affected band (25.5 μm, F2550W) and this rate of change appears to be decreasing over the current mission lifetime. For more information refer to Gorden et al. in prep. and JWST MIRI documentation.

The glowstick behaviour in the 4QPM coronagraphs described in [Wright et al. (2023)] is now mitigated with a suitable strategy to put the source on the centre of the coronagraph. In addition, reference files are available to remove the glowsticks themselves virtually perfectly, leaving at worst a small increase in noise at their positions. The resulting performance is illustrated well by [Boccaletti et al. (2023)], who show strong detections of all four planets around HR 8799, including planet e at 0.4″ from star. At 11.4 μm, λ/D for the telescope is 0.4″, so the coronagraph is working well down to radii of ≤ λ/D, demonstrating the small inner working angle made possible by the 4QPM coronagraph design. An unanticipated result is how well PSF subtraction works for high contrast imaging [Gispar et al. (2023)]. This is a result of the telescope figure being much more stable than had been anticipated. It is a valuable alternative to observing with the Lyot 23 μm coronagraph, since it can reveal areas close to the star that are behind the focal plane mask for the coronagraph.

12. Summary

In summary, the pre-launch predictions for the MIRI imager, as verified during commissioning, are further confirmed and being exploited for a very broad range of mid-infrared science. The indications are that the excellent instrument performance will continue to serve the astronomical community for many years.

From the MIRI commissioning program we were able to show that the MIRI imager meets and exceeds all the requirements that were set for the instrument mode pre-launch. Since the start of the JWST science program in July 2022 the MIRI imager has met expectations and produced ground breaking data sets on topics across many disciplines of astrophysics. Highlights of the first imaging programs can be seen on the NASA and ESA websites from the early release data (ERS) and early release observations (ERO). Although this paper has outlined many of the challenges in producing high quality imaging products with MIRI these issues often refer to extreme cases of observation e.g., very high or very low background, bright targets or high contrast data sets. Figure 27 shows an RGB commissioning image of a region near the galactic centre. The image is noteworthy because no special processing was used in its production - it is simply the result of the default level 3 pipeline and calibration processing. Producing such high quality science product with minimal processing so early on in the missions stands to show the high quality of the observatory and instrument.

13. Conclusions

We have presented the in flight performance and calibration of the MIRI imager onboard JWST. This work presents the results of the MIRI imager commissioning program and the performance of the instrument mode as best understood within the first year of science operations.

As discussed in Section 3 the key results show that MIRI’s sensitivity was measured to be two orders of magnitude better than Spitzer at 5.6 μm and 1 order of magnitude better at 25.5 μm and the relative photometric response of imaging was shown to be better than 5% at 80% encircled energy including the response between different subarrays and filters. We also demonstrated the performance and stability of the JWST background for MIRI showing the background level variation is within expectations at less than 5% for hot and cold attitude temporal variation. The ability to correct distortion and flat field the imaging data was also demonstrated.

Finally we have catalogued all image artefacts known at the time of writing and presented guides to the current best practices for imaging with JWST MIRI. The reader is again encouraged to refer to the JWST documentation for the most up to date performance and guidance for the imager instrument mode in the future: JWST Documentation - MIRI Imaging.

Further information on MIRI commissioning and performance can be found in [Rigby et al. (2023a,b)] and Wright et al. (2023) and more specifically in [Argyriou et al. (2023a)] for the Medium-Resolution Spectrometer, [Morrison et al. (2023)] for the Detector Effects and Data Reduction Algorithms, Boccaletti et al. (2022) for the coronagraphs performance, Libralato et al. (2024) for the point spread function and [Argyriou et al. (2023b)] for a discussion on the brighter-fatter effect for MIRI detectors.

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Appendix A: PSF radial profiles and comparison with WebbPSF models in the corners of the image

Similarly to Figure 6, in this appendix we show F560W PSF radial profiles for the other four positions in the corners of the imager field of view where standard stars were observed, from top left (position 2) to bottom right (position 5). We compare the super-resolved PSF flight data with WebbPSF simulations, with and without the addition of the cross- artefact. The radial profiles in the corners show a similar behaviour than the centre of the field of view, with the cross- artefact dominating the flux profile at radii longer than the secondary Airy ring (see Sect. 4.3 for details). The cumulative radial flux profiles (Encircled Energy, EE, normalised at a radius of 5 arcsec or 45 pixels) are shown to the right of the radial profiles for each position. The F560W flight data is more centrally concentrated than the WebbPSF simulations including the cross- artefact. This is due to the approximate representation (exponential profile) of the cruciform spatial distribution added on top of WebbPSF simulations at the time of commissioning. We note very small variations of the central parts of the profiles across the different positions over the FoV (<1%), and overall agreement between WebbPSF profiles and flight data. However, WebbPSF models in the top left (position 2) and top right (position 3) produce PSF cores that are more asymmetric than flight data, because there are extrapolated from other positions in the FoV. Those two corners were indeed not covered by wavefront measurements during ground-based test campaigns.

Appendix B: Microscanning dithers: pointing accuracy and estimated PSF positions on the detector.

A 4 x 4 points sub-pixel microscanning dither pattern was used to sample the PSF at 5.6 μm, and reconstruct the super-resolved PSF shown in Fig. 3. We checked the accuracy of the dither positions by comparing the requested positions on the sky to the relative shifts estimated by a 2D FFT cross-correlation between individual images. The result is shown in the left panel of Fig. B.1 for two positions in the imager FoV (obs2: top left, and obs4: bottom right), as examples. The typical shift between the requested and estimated positions is less than 10 mas, which is compatible with the absolute pointing accuracy of the JWST. This is confirmed by an inspection of the Fine guidance System (FGS) data, shown on the right panel for both observations.
Fig. A.1. Same as Figure 6 for the four positions in the corners of the imager field of view. We compare the radial profiles of the flight F560W high-resolution PSFs (reconstructed from the microscanning data taken during commissioning) to WebbPSFs (with and without the cross-artefact, the cruciform).
Fig. B.1. Dither patterns used for super-resolution reconstruction of the PSF at 5.6 µm. We used a 4 × 4 pattern with sub-pixel shifts to sample the area of a pixel of the detector. We show the sub-pixel shifts (in mas, relative to the first pointing position) for Obs2 (top row) and Obs4 (bottom row). The left panel compares the nominal positions requested (blue crosses) with the actual shifts estimated from a two-pass Fourier transform cross-correlation. The right panel compares the positions from the Fine Guiding Sensor data (blue jitter ball), the estimate from the WCS astrometric solution (black points), the file header coordinates (green points), and the commanded (resp. nominal) positions (orange, resp. red, points).