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## JWST TECHNICAL MEMORANDUM

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### Table Of Contents

Abstract.....	2
1 Routine Maintenance Wavefront Sensing and Control overview.....	3
1.1 The WFS&C Calibration Program.....	3
1.2 The WFS&C Visits.....	4
1.3 Nominal WFS&C Operations.....	5
2 On sky performance insights and findings.....	6
3 Correction criteria.....	10
4 Improvements and efficiencies.....	12
4.1 Change In Scheduling Assumption.....	12
4.2 Reducing Cadence Of The WFS&C Observations.....	13
4.3 Addressing Persistence Issues By Switching From NRCA3 To NRCA1.....	13
4.4 Dithering Removal.....	14
4.5 Summary Of Time Gain.....	15
5 Future improvements.....	15
6 Conclusions.....	16
7 References.....	16
8 Appendix: statistics about observing times.....	18

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# *JWST Wavefront Sensing & Control Operations and Efficiencies*

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21 January 2026

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## **ABSTRACT**

The James Webb Space Telescope (JWST), like other telescopes with a segmented primary mirror, requires regular verification of the alignment and phasing of its Optical Telescope Element (OTE) to ensure that the scientific observations are obtained with the best image quality possible. JWST's routine Wavefront Sensing and Control (WFS&C) program allows the measurement and maintenance of the wavefront (WF) via special observations for sensing the wavefront error (WFE) and executing mirror corrections, as needed, to keep these errors as low as possible below the pre-launch requirement of 150 nm rms at NIRCam and 122 nm for the OTE alone.

As every other calibration program, the routine maintenance WFS&C visits use precious observing time that could otherwise be spent on collecting photons from distant stars and galaxies. As such, it is a driver for the WF team to find ways to reduce the time spent on the calibration visits without increasing the risk of performing science observations with a degraded WFE. This paper describes these efforts, which decreased the total telescope time used for the program from about 180-200 hours in Cycles 1 and 2 to less than 130 hours in Cycle 3 and an expected total lower than 100 hours in Cycle 4.

We start in section 1 with a general presentation of the routine maintenance WFS&C visits. In section 2, we describe what we have learned about on-sky performance from July 2022 to July 2025 and in section 3 we define our correction criteria based on those findings. In section 4, we then discuss the improvements to the WFS&C calibration program implemented in Cycles 2 to 4, which halved the time used for the WFS&C visits. We briefly present in section 5 additional improvements explored by the WF team before summarizing our work in section 6.

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## 1 Routine Maintenance Wavefront Sensing and Control overview

The JWST routine maintenance calibration program for WFS&C is an observatory science calibration program with a mission level requirement levied on its existence. The JWST Mission Level 1 requirement states:

*“The JWST System shall perform image-based wavefront sensing and control to meet all image quality requirements.” (JWST-RQMT-000634).*

In support of this high-level requirement, STScI and Ball Aerospace (now BAE Systems) developed end-to-end tools and processes to support the acquisition, calibration and analysis of the JWST WFS&C observations.

In this section we describe the nominal WFS&C visit and operations. For a detailed description of the WFS&C employed for telescope commissioning, see Acton et al. (2022). The telescope's required, predicted, and ground-measured optical performance is described by Lightsey et al (2014), while Feinberg et al. (2024) provide post-launch details about the requirements' origins, breakdown, and ground and space verification.

### 1.1 The WFS&C calibration program

Routine maintenance WFS&C observations have been performed since the end of the OTE commissioning in the Spring of 2022. The OTE-26 commissioning program “Routine WFS&C/CC Jitter Maintenance” (see Section 6.1 of McElwain et al. 2023) initiated routine sensing. A series of calibration programs like OTE-26 have then been carried out in each science operations cycle. Each routine maintenance WFS&C visit has used a specific template in the Astronomer's Proposal Tool <sup>1</sup>(APT): “WFS&C NIRCcam Fine Phasing” (see Figure 1). Table 1 (see Appendix in section 8) lists the WFS&C calibration programs used in commissioning and science operations through Cycle 3 with statistics on the number of observations performed and the time spent executing these.

Another part of the OTE calibration program has been the “NIRCcam PIL Images for Monitoring the Primary Mirror”, the so-called selfies of the primary mirror, which have enabled the WF team to track micro-meteoroid impacts on the reflective surfaces of the telescope.

In this memorandum, we focus on the WFS&C measurements program only and our goal is to describe how the findings from this routine maintenance program has allowed us to optimize the visits execution and reduce the amount of time they used every cycle.

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<sup>1</sup> The APT can be found here: <https://www.stsci.edu/scientific-community/software/astronomers-proposal-tool-apt>

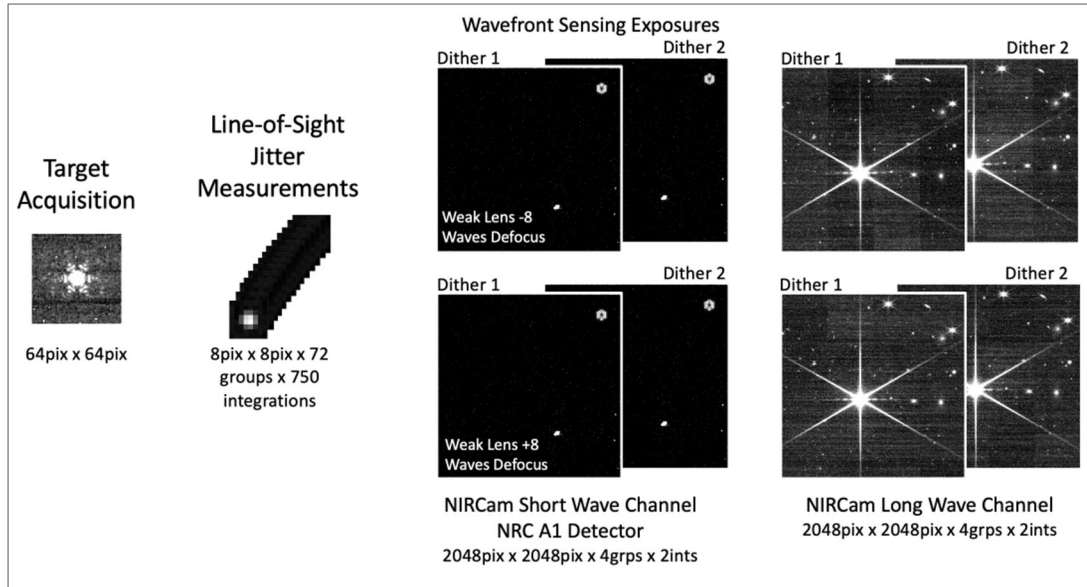


Figure 1: an overview of the data collected during a routine maintenance WFS&C visit.

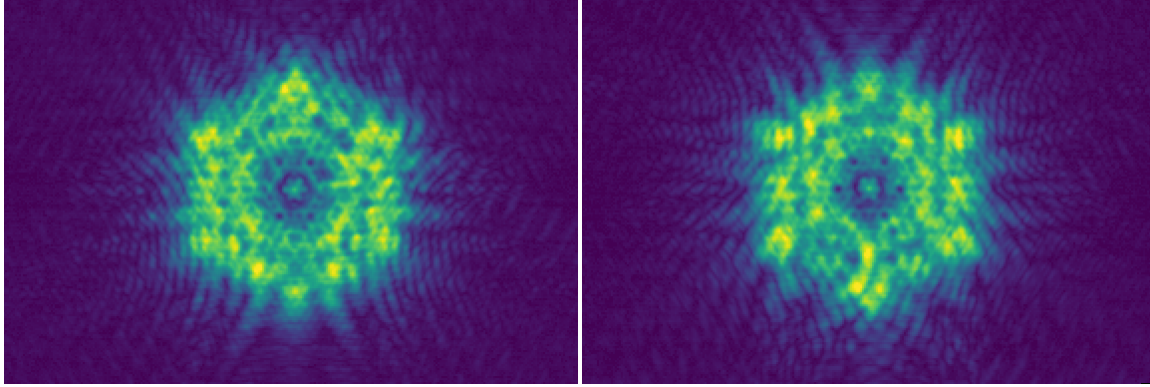
## 1.2 The WFS&C visits

A visit that used the “WFS&C NIRCam Fine Phasing” template at the beginning of science operations was described as follows:

- The visit starts with a Target Acquisition (TA) in a 64 x 64 subarray, with target placement determined by the aperture paired to the subarray.
- Next, a series of 8 x 8 subarray line-of-sight (LOS) images are taken, with target placement also determined by the aperture paired to the subarray. The LOS pointing jitter measurements are acquired of the star and provide a cube with a small 8 x 8 field observed across many groups and integrations. The purpose of this exposure is to monitor the observatory jitter (see Hartig & Lallo 2022).
- Lastly, the Fine Phasing (FP) activities are executed. Two images are obtained with NIRCam, each the combination of two exposures executed with a 5-pixel dither pattern. The first image uses the weak lens +8 (WLP8) and the second uses the weak lens -8 (WLM8) element in the pupil wheel (see Figure 2). At short wavelengths, the filter wheel is set to F212N and at long wavelength the filter wheel was set to F405N until November 27<sup>th</sup>, 2022, after which it was set to F356W. All weak lens (WL) images are observed using the RAPID detector readout pattern with 4 groups and 2 integrations, for an observing time of about 96 seconds per exposure.

The targets used for the WFS&C visits are about 400 isolated stars, uniformly distributed across the sky, with K band magnitude of  $7.0 \pm 0.1$ . An example of the data acquired in a WFS&C visit is presented in Figure 1 and a close-up on FP images obtained near the end of Cycle 3 is shown in Figure 2.

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**Figure 2: WL images (Level 3) with the WLM8 (left) and the WLP8 pupil (right). The WL images above are from one of the last visits in Cycle 3, on June 24<sup>th</sup>, 2025, when the WFE was about 67 nm. A non-linear scale was used to highlight the finer details which serve to estimate the WFE.**

### 1.3 Nominal WFS&C operations

The short wavelengths WL images are the critical data used to monitor the WF on standard sensing measurements. The pair of WL images (WLM8 and WLP8) provides the phase diversity required to derive an optical path difference (OPD) or phase map via automatic analysis in the WFS&C Analysis Software (WAS), from which the WFE of the OTE is computed. The OPD is then decomposed into a Segment Update Request (SUR) containing the required mirror "poses" (usually in piston, tip and tilt) to reach the best achievable WFE at the time of the measurement (see West et al. 2022 for a detailed discussion of the influence function matrix for JWST mirror alignment). The OPD and the WL images then become publicly available in the Mikulski Archive for Space Telescopes (MAST) and via the STPSF<sup>2</sup> python package.

If the WF team judges it necessary to correct the primary mirror, based on specific criteria (see section 3), the SUR is then used to generate a Wavefront Control (WFC) file where the poses are converted into segment actuator changes. This safely moves the primary mirror segments and the secondary mirror during a WFS&C visit. In a visit that executes a correction, two images (WLM8 and WLP8) are obtained right before the mirror moves ("sensing" images) and two images are obtained right after the mirror moves ("control" images), on the same target, to verify the correction was applied as expected.

The broad baseline mission allocation for regular WFS&C visits is defined in the JWST Mission Operations Concept Document (MO-419, see also MO-1084):

*"The OTE will be adjusted only when necessary, but should not require adjustment more frequently than once every 14 days (MR-115). Thus, wavefront maintenance visits may be scheduled as frequently as every 2 days."*

In terms of overall time allocation, the WFS&C visits are included in the following:

<sup>2</sup> More information about STPSF can be found here: <https://stpsf.readthedocs.io/en/latest/>

*“15% of the time will be devoted to overhead for visit activities (such as slew, guide star acquisition, SI configuration, offset maneuvers) and Observatory overhead activities (such as station-keeping, momentum dumps, wavefront sensing and control).” (MO-416).*

With the pre-launch assumptions about the frequency of visits aligned with MO-419, a total of about 180 visits were expected per year, including about 25 with a mirror correction. Given pre-launch assumptions about the typical duration of a WFS&C visit, it was estimated that the routine WFS&C maintenance program would require a grand total of about 210 hours or about 2.4% of telescope time per year.

The goal of this memorandum is to explain the changes made to either the WFS&C visit template or the WFS&C operations to reduce the total telescope time used for the routine maintenance WFS&C calibration program and otherwise positively affect the scientific return of the JWST mission.

## 2 On sky performance insights and findings

A previous OTE Science Performance Memo (Lajoie et al. 2023) detailed the Cycle 1 experience with routine maintenance WFS&C visits. In this section, we summarize the main takeaways on the evolution of the measured WFE in Cycles 1 through 3, which ran from July 2022 to July 2025, and highlight a specific finding on the persistence of the NIRCcam detector.

Figure 3, Figure 4, and Figure 5 show the measured WFE and the “floor” WFE (i.e. the predicted WFE value we would achieve if we were to perform a mirror correction) for Cycles 1, 2, and 3. Each figure also shows the slopes of a linear fit to each series of WFE measurements, where a series comprises all the WFS&C visits starting right after a corrective move (indicated by a vertical line) and ending right before an increase larger than 5 nm (a WFE jump) or the next corrective move, whichever happened first. Figure 6 then combines all the slopes in one figure to reveal how the WFE trending has evolved since the end of commissioning. Below are the main insights:

- **Time between corrective moves:** The frequency of corrective moves of the primary mirror has decreased from every 10-30 days in early Cycle 1 to 20-70 days in the end of Cycle 1 and early in Cycle 2. In the second half of Cycle 2 and into Cycle 3 there was a period without a correction that lasted more than 180 days. Consequently, the number of corrections made in each cycle decreased from 13 in Cycle 1 to 11 in Cycle 2 and five in Cycle 3.
- **Nature of changing WFE:** Early in Cycle 1, all corrections were made following large sudden jumps in WFE that brought its value above 80 nm. Since late 2022, such jumps have occasionally been seen but the dominant evolution of WFE has been slow and steady instead. The rate of increase of the WFE has been declining with time and seems to have reached a plateau. The slope has decreased from 0.2-0.4 nm/day early in Cycle 1 to 0.1-0.2 nm/day into Cycles 2 and 3. An asymptotic fit to the rates (see Figure 6)

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indicates a plateau at about 0.1 nm/day, though several series have been even flatter (e.g. 0.044 nm/day from March 31<sup>st</sup> 2024 to October 3<sup>rd</sup> 2024).

- **Phase Wrap Event:** In February 2024, we measured the largest WFE since the end of commissioning and the first at a level above the 131 nm requirement since July 2022. This event included a “phase wrapped” piston error on C5, meaning that the wavefront from that segment was advanced or delayed by over an integer wavelength. We acquired an additional pair of WL images with the F187N filter on the subsequent WFS&C visit to resolve any possible  $2\pi$  phase ambiguity at 2.12 microns, correct the mirror misalignment, and restore excellent image quality. This event was documented in an OTE Science Performance Memo (Perrin et al. 2024).
- **Correctable and uncorrectable micro-meteoroid (uM) hits:** uM hits on the primary mirror caused an increase of the “floor” WFE. Compared with corrections to only the mirror segments' piston, tip, and tilt (PTT), corrections to a segment's radius of curvature (RoC) can effectively remove some of the uM-induced error, with the most effective removals achievable for hits closest to the segment's center. Two corrections included the RoC mode and removed the *cumulative correctable* contribution of uM hits in March 2023 (0.8 nm) and October 2024 (1.0 nm) and consequently lowered the “floor” WFE. However, the overall increase in the “floor” WFE from about 59 nm early in Cycle 1 to 62.5 nm at the end of Cycle 3 was due to the *cumulative uncorrectable* contribution of uM hits, even with the addition of the RoC mode. Most of the *uncorrectable* contribution since the end of commissioning (about 2 nm) was caused by a hit on segment B2 in January 2025 while the increase of about 1 nm seen in September 2023 was due to the correction of a detector effect. The B2 uM hit was the second most significant after the well-known segment C3 event during commissioning, but with a much smaller effect on the WFE. The floor WFE indeed only increased by about 4 nm, about half of which was immediately corrected with the inclusion of the RoC mode for the third time since the end of commissioning (see the red dots increase in late January 2025 in Figure 5). The residual uncorrectable WFE increase for the B2 hit (about 2 nm) was about eight times smaller than for the C3 hit, when the floor WFE increased from about 44 nm to about 60 nm after correcting all available degrees of freedom including RoC, clocking, and radial translation. A future OTE Science Performance Memo (Telfer et al.) will describe in detail our investigation of uM hits and the use of additional modes to further mitigate the related WFE increase.

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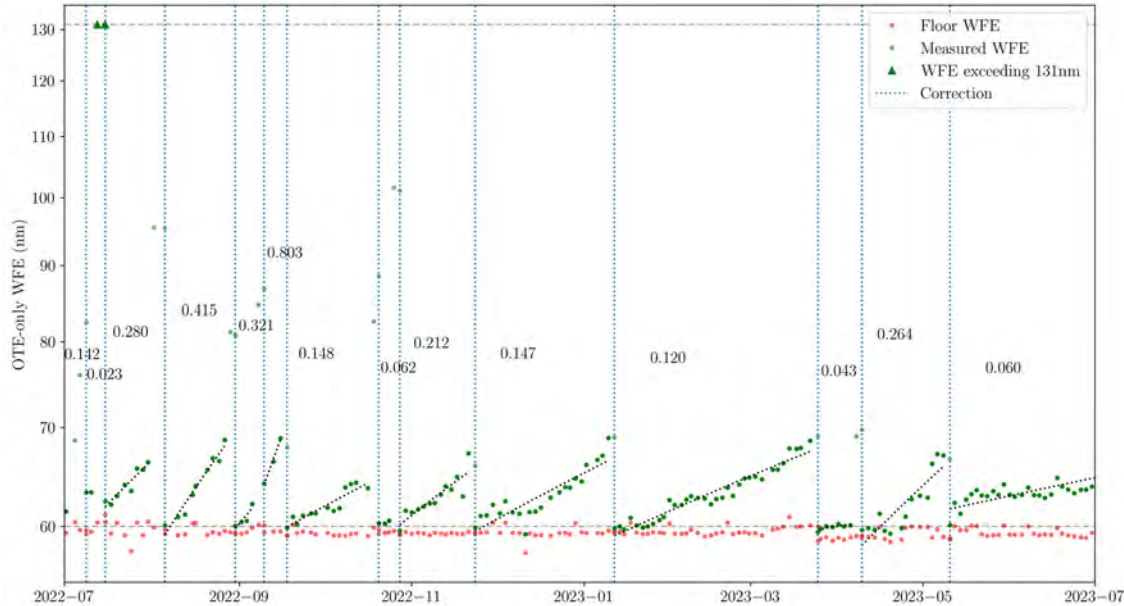


Figure 3: measured WFE (green dots) and best achievable WFE with PTT mirror moves only (red dots) over the course of Cycle 1 (all visits from July 1<sup>st</sup>, 2022 to July 1<sup>st</sup>, 2023 are shown). Measured WFE above the 131 nm requirement are shown as green triangles at 131 nm. The vertical dotted lines show when corrective mirror moves were performed. The horizontal dashed lines show the 60 and 131 nm WFE levels. The number above each series is the slope (in nm/day) of the linear fit to the “valid” points in the series (see text for details). The y-axis uses a logarithmic scale to better show variations near the floor.



Figure 4: same as Figure 3 but for Cycle 2 (all visits from July 1<sup>st</sup>, 2023 to July 1<sup>st</sup>, 2024 are shown).

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Figure 5: same as Figure 3 but for Cycle 3 (all visits from July 1<sup>st</sup>, 2024 to July 1<sup>st</sup>, 2025 are shown).

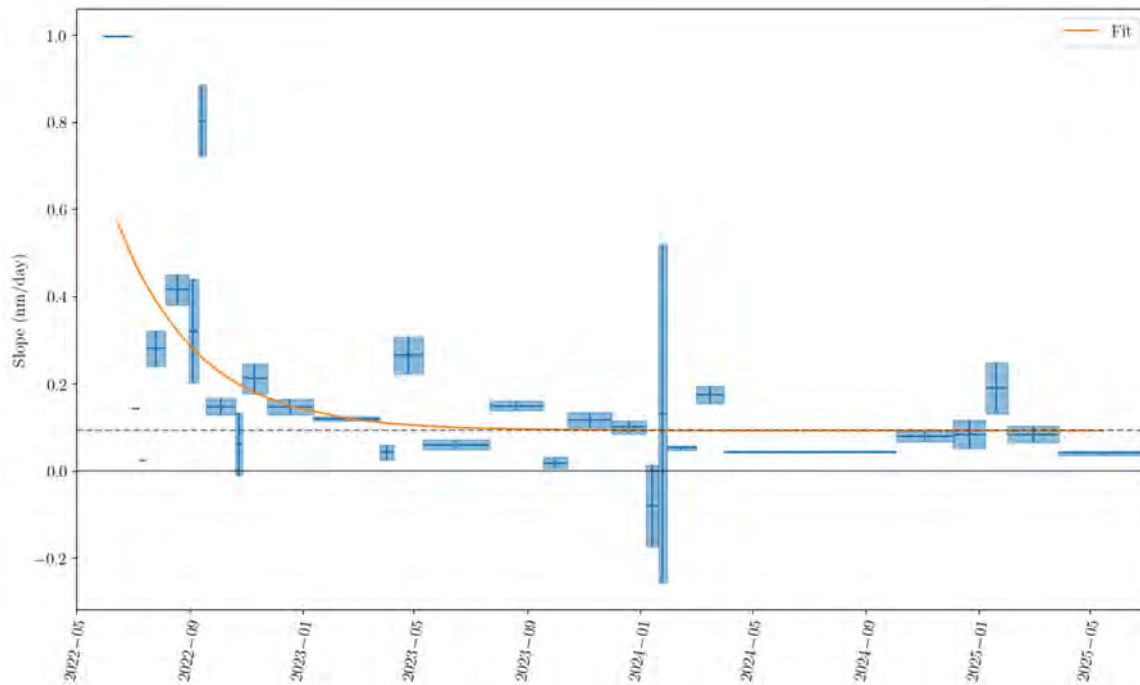
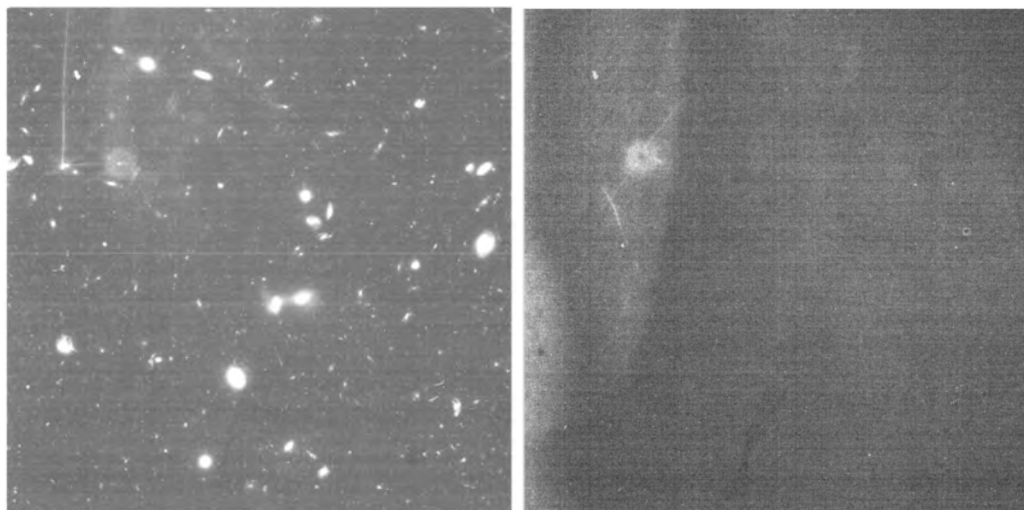


Figure 6: average WFE drift (nm/day) for each series of routine maintenance WFS&C visits in between corrections, starting on June 14, 2022. The height of the box is the uncertainty on the slope while the width is the duration of the series. The orange line shows the best fit to the blue boxes with an  $A + B / \exp(t/\tau)$  function where the asymptotic value  $A$  is about 0.09 nm/day (dashed line) and  $\tau$  is about 90 days.

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Also, through experience gained in Cycles 1 through 3 operations it was found that the persistence on the NIRCcam A3 detector, where the WF target was observed since the end of commissioning, was significantly worse than any other NIRCcam detector<sup>3</sup>. Figure 7 shows an example of the persistence on a science visit obtained shortly after a routine maintenance WFS&C visit and the residual of the WFS&C target on top of the expected persistence effect. Clearly, the bright targets used for WFS&C visits, despite being significantly defocused, were causing imprints in science observations obtained with NIRCcam shortly after the WL observations.



**Figure 7:** (Left) an example of a science observation showing the persistence image of the routine maintenance WFS&C visit target (diffuse hexagon shape in the top left quadrant). (Right) the mean residual NIRCcam A3 Cycle 1 dark image constructed by averaging darks after performing dark subtraction with the CRDS reference file. The large-scale pattern that covers the leftmost third of the detector is expected from “normal” persistence while the residual image from the WFS&C target appears significantly brighter.

This experience gained in the first three years of operations showed that JWST had entered its current, stable state by early 2023. The general decrease in the frequency and amplitude of large WFE jumps resulted in a reduced number of corrective mirror moves performed each cycle. This increased stability of the OTE has informed the WF team's determination of appropriate correction criteria (see section 3), and, together with our understanding of the persistence concern, guided changes to WFS&C operations that we describe in section 4.

### 3 Correction criteria

Here we describe the correction criteria that have been developed by the WF Team to collect the best science observations without exceeding (1) the pre-launch correction cadence requirement (i.e., once every two weeks) and (2) the pre-launch WFE requirement (i.e., 131 nm).

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<sup>3</sup> See the JWST User Information Page: <https://jwst-docs.stsci.edu/jwst-near-infrared-camera/nircam-performance/nircam-persistence#gsc.tab=0>

The WFE evolution described in the previous section confirms that the WFE was much better than the pre-flight requirement, which incorporated significant margins. Even at the beginning of Cycle 1 (July to November 2022), when the occurrence of sudden jumps was frequent, corrections were performed on a roughly 2-week cadence, matching the pre-launch expectation, even though the WFE did exceed pre-launch requirement only once (see Figure 3). Correction moves were indeed performed when the WFE reached values in the 80 to 100 nm range instead.

As the OTE stability improved, the occurrence of sudden WFE jumps decreased and the threshold at which corrections were performed was adjusted to about 70 nm early in 2023. Our assumption was that if the “floor” WFE was near 60 nm, an increase of about 10 nm was enough to warrant a correction. As the “floor” WFE increased because of *uncorrectable* WFE (e.g. uM hits, see section 2), this *primary criterion* was later converted to an excess (measured WFE minus “floor” WFE) of about 8 nm.

The WF team has reached a better understanding of the frequency, amplitude, and impact of sudden WFE jumps. We also recognize that while the root mean square (RMS) WFE was the best single metric to represent optical performance of the OTE, additional considerations would be appropriate to (1) limit science observations taken with highly unbalanced WFE, such as when a few misaligned segments were dominating the overall WFE, and (2) account for cases where the WFE would be acceptable by the RMS metric but would have an unusual effect on image quality. In addition, some of the increase in WFE due to uM hits could be corrected using the radius of curvature (RoC) actuators, which over the lifetime of the mission would significantly reduce the total WFE. For these reasons the WF team defined *additional criteria*:

- No more than two PMSA should have corrective moves (piston, tip, or tilt) larger than 50 nano-unit<sup>4</sup>. This was like the exit criterion of the Fine Phasing step in commissioning (i.e., no PMSA should need any correction move greater than 50 nano-unit) and was thus maintained for consistency.
- The loss of encircled energy (EE) should not exceed 0.75% in the NIRCcam F212N filter, relative to that measured right after the last mirror correction. In this context, the EE is calculated within a 2.5-pixel radius aperture and based on the simulated PSF using the latest phase map and the STPSF package. This allowed the WF team to track a relevant scientific metric that characterized the quality of the PSF delivered by the telescope.
- Correction moves should include the RoC mode if the addition of that mode would further improve the WFE by about 1 nm. This was to compensate for the slow accumulation of uM hits uncorrectable by the PTT modes alone.

When some or all the criteria were met, the WFE was said to be in “correction territory” and the WF team looked at the global context before planning a correction. This included:

- the trend of the WFE in the previous days or weeks: was it drifting slowly above an 8 nm excess or was there a sudden jump that made it significantly larger?

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<sup>4</sup> The term “nano-unit” in this document refers to both the nanometers and nanoradians units used in the WF analysis.

- the schedule of science observations: were there time-critical or linked visits that would be impacted if mirror corrections were added to the schedule?

In the case of a slow drift, delaying a correction by a few days would not adversely impact the planned science visits, especially if requesting a schedule intercept would be disruptive for time-critical observations. In the case of a large sudden jump, a correction was usually warranted sooner rather than later to avoid any impact on future science observations.

We note here that by the end of Cycle 3, outside of the February 2024 phase wrap event (described in section 2), no science observation was ever repeated for image quality reasons because of a WFE reaching values as high as 90 nm (see van der Marel 2025). Keeping the primary criterion for a correction as an excess of 8 nm above the “floor” WFE (about 60 nm for most of Cycles 1 to 3) allowed the WF team to keep some margins and thus avoid any impact on science observations by letting the WFE drift for too long.

## **4 Improvements and efficiencies**

In this section we present the operational improvements and efficiencies implemented during Cycles 1 to 3 by the WF team and based on the flight behavior of the OTE described in Section 2.

### **4.1 Change in scheduling assumption**

In the planning and scheduling of Cycle 1, every WFS&C visit was assumed to be a default “sensing-and-control” visit i.e., with a mirror correction of 170 moves. This conservative approach, even under the pre-flight assumption of a correction every 14 days, led to discrepancies between the as-planned and as-executed schedules, since in effect, most WFS&C visits were “sensing only” and used significantly less telescope time than the assumed “sensing-and-control” visit (0.57 hour instead of 1.54 hour, excluding slewing duration). These discrepancies in turn led to a decrease in the observatory efficiency and instances of observatory idling when awaiting time critical visits (e.g. exoplanet transit observations).

Given the on-sky performance of the OTE in Cycle 1 (i.e., fewer mirror corrections than the requirement), starting in Cycle 2, the WFS&C program was planned under the opposite assumption that every visit is a “sensing only” visit i.e., without a mirror correction. Therefore, the as-planned schedule has become much closer to the as-executed schedule, which has directly resulted in time savings, by reducing instances of observatory idling, thus increasing on-sky efficiency. Measuring the actual saving due to this change is however impossible because many other timing uncertainties besides WFS&C visits play a role e.g., failed visits upstream or the actual duration of acquisition.

Consequently, though, when a mirror move is required, the Planning and Scheduling (P&S) team must ensure downstream time-critical science visits are not affected and, if necessary, generate an intercept Observing Plan with additional padding to reflect the longer duration for the WFS&C visit.

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## 4.2 Reducing cadence of the WFS&C observations

Given the increased stability of the telescope observed during Cycles 1 and 2 (see section 2), the WF team determined that the routine maintenance WFS&C visit cadence could be decreased from one every two days to one every four days.

The typical evolution of the WFE has been that of a gradual increase, accompanied at times by small jumps of less than a few nm, and even more rarely by jumps that were large enough for the WFE to exceed values of about 90 nm, a level at which some types of science might be affected. Under these circumstances, the WF team determined that the WFE of the OTE could be effectively maintained at levels that would have no measurable impact on the JWST science results even at a decreased cadence of one visit every four days. Therefore, starting December 4th, 2024, following a mirror correction, the time between routine WFS&C visits was officially changed from two to four days. This change was expected to return about 80 hours of telescope time to science observations per year i.e., half the time spent on “sensing-only” visits.

The WF team has investigated generalizing the issue of optimal WFS&C cadence for different OTE behaviors. On the one hand, a fast cadence consumes excessive observing time characterizing the mirror state when it is not undergoing significant changes. On the other hand, a slower cadence delays the detection and correction of mirror misalignments and may instead result in additional observing time spent repeating sensitive science observations affected by periods of higher WFE. The optimal sensing cadence, considering these factors, the duration of WFS&C visits, and observed events from the first cycles of science operations, was modeled and quantified in an OTE Science Performance Memo (van der Marel 2025). It was found to be about  $6\pm 1$  days – only slightly longer than the 4-day cadence implemented in December 2024 – and would only lead to little additional gain (less than 10 hours per year). The slightly conservative approach of a 4-day cadence allowed the WF team to continue evaluating the impact of WFE drifts and jumps while already returning a significant amount of time to science observations.

## 4.3 Addressing persistence issues by switching from NRCA3 to NRCA1

Persistence on the NIRCam A3 detector meant that some science observations obtained with NIRCam shortly after a WFS&C visit were suffering from the persistent image of the bright, though defocused, stars the WF team was using as targets. To minimize that impact, the WF team decided to define a new field point (FP) in the NIRCam A1 detector – NRCA1-FP6 – to replace the NIRCam A3 FP in use since commissioning.

Below are the aspects that were considered and that led to this decision.

- The new FP should be on a detector with low persistence like A1, B1, or A4, as indicated by in-flight measurements<sup>5</sup>.

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<sup>5</sup> See the JWST User Information Page: <https://jwst-docs.stsci.edu/jwst-near-infrared-camera/nircam-performance/nircam-persistence#gsc.tab=0>

- The new FP should also be far enough from the detector’s edges to allow the phase retrieval to be executed on a 512-pixel by 512-pixel window, revealing finer details (e.g. small  $\mu\text{M}$  hits) in the OPD.
- The new FP should also be in a region with a low number of bad pixels and with a minimum of instrumental defect. NRCA3-FP1 was for instance near the border between amplifiers, which led to artificial features in the OPD until the effect was fixed in October 2023.
- The new FP should finally be close to the “center” of the focal plane. NRCA3-FP1 was located not far from that center. Optimizing the WFE at that location was ideal as it should not introduce biases at the edges of the focal plane, in the other instruments.

During pre-launch development on the ground, calibrated phase maps at several FPs in NIRCcam were obtained to enable subtraction of instrumental WFE from measurements in flight. However, none of these locations used in the multi-instrument multi-focus (MIMF; Acton et al. 2022) activity in commissioning met the desired criteria for a new sensing FP in flight. The decision was thus made to create a new FP at the pixel coordinates (1828.5, 1813.5) on the A1 detector.

To fully enable this new FP, a target phase map then had to be measured in flight at the chosen location. The WF team used a differential approach and designed a visit where a WF target was observed at NRCA3-FP1 and NRCA1-FP6 in an uninterrupted sequence, to minimize the potential for changes in the OTE phase map. The difference between the two OPDs thus gave the difference between the known target phase map at NRCA3-FP1 and that needed at NRCA1-FP6. This visit (4556:007) was executed during Cycle 2 and since December 4<sup>th</sup>, 2024, at the same time the operations switched to a four-day cadence, the WFS&C visits have been using the new FP.

#### 4.4 Dithering removal

The operational concept for routine maintenance WFS&C visits relied on the use of level 3 images (dither combined images, see section 1) to reach a high enough signal-to-noise ratio (SNR) for the input data to the WAS analysis. In addition, the use of dithering allowed the WF team to mitigate bad pixels and to use individual exposure images (Level 2) in case of an issue with either exposure. However, since the end of commissioning, the WF team performed the WAS analysis on Level 2 images only once, in July 2023, when Level 3 data processing was delayed.

The WF team then investigated whether the systematic use of Level 2 images would have any significant effect on the WFE measurements. A comparison was performed on a handful of visits using the Level 3 images or either of the Level 2 images. This set of visits included one mirror correction. For all visits, PTT moves were derived and compared. It was found that the Level 3 and Level 2 cases differed by an average of 0.28 nano-units RMS, with an average peak-to-valley difference of 1 nano-units. The two Level 2 analyses differed by an average of 0.32 nano-units RMS and a peak-to-valley difference of 1.4 nano-units. These differences were deemed inconsequential as PTT mirror moves were typically executed only when larger than 50 nano-units (see section 3).

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This change has been approved and implemented in the Cycle 4 routine maintenance WFS&C program starting in July 2025. It will return about ten hours of on-sky time per year to the science observations.

#### 4.5 Summary of time gain

Table 1 and Table 2 (see Appendix in section 8) provide statistics on the number of WFS&C observations performed, and the time used for these in Cycle 1 to 3. Here we summarize the reduction in the on-sky calibration time that resulted from the operational improvements detailed previously in this section.

- In Cycle 1, the grand total on-sky execution time for WFS&C was about 180 hours which corresponds to 2.1% of the total available time, very close to pre-launch expectations.
- In Cycle 2, almost 200 hours were spent on WFS&C visits which corresponds to 2.2% of the total available time, almost matching the pre-launch expectation.
- In Cycle 3, the reduction in the “sensing” cadence led to an immediate reduction in the number of visits and the total time spent on WFS&C visits amounted to 127 hours, which corresponds to 1.4% of the total available time.
- In Cycle 4, with the implementation of all the improvements described in this report, the total time used for WFS&C observations should amount to about 1.0% of the total telescope time available in a cycle (the exact fraction will depend on the number of mirror corrections performed), a reduction by more than half relative to Cycles 1 and 2.

#### 5 Future improvements

Further possible improvements or efficiencies are under consideration for future cycles, with some examples being:

- The LOS jitter has been much lower than the observatory requirements of 7 milli-arcseconds, consistently around 1 milli-arcsecond, so the value of continued jitter monitoring as a regular part of each WFS&C visit could be assessed and weighed against the benefits of the more precise wavefront target centering it offers.
- A time-based wavefront control criteria could be considered, such that we do not remain for long periods of time in a regime that is better than our criteria but worse than the achievable “floor”.
- The WF team has also considered supplementing routine WFS&C by using other types of science or engineering data to sense OTE state changes between WFS visits. Other suitable data could be:
  - Fine Guide Sensor (FGS) data from Track images, acquired at the beginning of all guided visits, which provide a set of consistent, high-cadence coarse monitoring of PSF variations.
  - NIRCcam focus-diverse *parallel* imaging observations using weak lenses, which would allow phase retrieval determinations, though the same target selection criteria

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- as the WFS&C routine program (e.g., magnitude, location on the NIRCam detector) could not be applied and would depend on the prime observation.
- NIRCam *in-focus* science observations, which offer a rich and potentially sensitive dataset, though of widely varying quality and suitability (i.e. star-rich vs star-poor fields), for long-term trending of significant WFE changes.

## 6 Conclusions

As JWST completed Cycle 3 in June 2025, the routine maintenance WFS&C program had successfully characterized the OTE's stability during science operations, maintaining the WFE at levels much lower than required pre-launch. The WF team, in collaboration with the wider JWST mission, has worked to minimize the impact of the calibration program on science observations through the operational improvements outlined in this paper and implemented by the time Cycle 4 started in July 2025:

- **Planned WFS&C visit duration:** the assumption that every WFS&C visit included a mirror correction was removed to improve scheduling efficiency and better accommodate time-critical science observations.
- **NIRCam target position:** the WFS&C targets have been repositioned on a different NIRCam detector to reduce persistence issues.
- **WFS&C cadence:** the time between consecutive WFS&C visits has been increased from 2 to 4 days.
- **Dithering pattern:** the WL observations have been redefined to use only one exposure per image instead of two.

These combined improvements have led to a significant reduction of the time spent on the routine maintenance WFS&C visits, **from more than 2.1% of the total telescope time available in Cycles 1 and 2 to about 1.0% in Cycle 4** and have helped minimize the impact from these visits on the scientific observations of JWST (e.g., detector persistence, schedule gaps). Additional improvements are considered by the WF team to further reduce the WFS&C program's cost in observing time and remain under investigation at this time.

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## 8 Appendix: statistics about observing times

**Table 1: List of programs used for routine maintenance WFS&C in each cycle, along with the total number observations executed for these programs, the number of mirror corrections executed, and the total time spent executing these observations. All visits up to July 1<sup>st</sup>, 2025 are included.**

Cycle	Program ID	Number of visits (incl. failed or other visits)	Number of visits with a correction	Time spent per sensing / sensing and control visit (hours)	Grand total (incl. failed or other visits) (hours)
Commissioning	1163	92	31	1.24 / 2.53	122.8 (5.4)
1	2586	53 (6)	4	1.04 / 1.64	55.6 (4.2)
	2724	36 (1)	3	0.94 / 1.57	35.4 (0.7)
	2725	57 (1)	2	0.98 / 1.83	57.3 (0.7)
	2726	27 (0)	5	0.97 / 1.96	31.2 (-)
	4431	7 (1)	1	0.86 / 1.98	7.5 (1.2)
2	4500	23 (0)	1	1.05 / 2.24	25.3 (-)
	4501	44 (1)	3	0.90 / 1.59	41.3 (0.3)
	4502	16 (1)	0	0.97 / -	15.9 (1.4)
	4503	12 (0)	1	0.97 / 2.42	13.1 (-)
	4504	26 (3)	0	1.00 / -	25.0 (2.0)
	4505	23 (1)	0	1.06 / -	23.3 (0.0)
	4506	5 (1)	0	1.07 / -	4.9 (0.6)
	4507	16 (1)	2	1.07 / 1.74	18.0 (0.6)
	4508	6 (0)	0	1.02 / -	6.1 (-)
	4509	16 (0)	1	1.01 / 1.90	17.1 (-)
	4556	4 (0)	2	0.72 / 3.08	7.3 (-)
3	6689	24 (2)	0	0.91 / -	21.9 (1.8)
	6690	24 (2)	2	0.98 / 1.60	23.3 (0.4)
	6691	8 (0)	2	1.09 / 1.48	9.5 (-)
	6692	3 (0)	0	0.88 / -	2.6 (-)
	6693	17 (1)	0	0.90 / -	15.5 (1.1)
	6694	9 (0)	0	0.86 / -	7.7 (-)
	6695	11 (1)	0	1.09 / -	11.6 (0.7)
	6696	17 (2)	1	0.97 / 1.63	16.8 (1.8)
	6697	7 (0)	0	0.81 / -	5.7 (-)
	6698	12 (1)	0	0.81 / -	9.6 (0.6)

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**Table 2: Total number of observations and corrections per cycle. All visits up to July 1<sup>st</sup>, 2025 are included**

Cycle and dates	Number of visits (incl. failed or other visits)	Number of visits with a correction	Time spent per sensing / sensing and control visit (hours)	Grand total (incl. failed or other visits) (hours)
Commissioning (until July 1 <sup>st</sup> , 2022)	93	32	1.24 / 2.55	125.3 (5.4)
1 (July 1 <sup>st</sup> 2022 to July 1 <sup>st</sup> , 2023)	177 (9)	13	0.98 / 1.71 0.56 / 1.31 (excl. slew)	181.7 (6.9)
2 (July 1 <sup>st</sup> 2023 to July 1 <sup>st</sup> , 2024)	190 (8)	11	0.99 / 2.09 0.56 / 1.52 (excl. slew)	197.0 (4.9)
3 (July 1 <sup>st</sup> 2024 to July 1 <sup>st</sup> , 2025)	135 (9)	5	0.93 / 1.56 0.56 / 1.30 (excl. slew)	127.0 (6.3)

*Notes: In both Table 1 and Table 2 we also indicate the number of visits within the WFS&C program that failed or otherwise did not count as routine maintenance visits, as well as the time sent on those. Out of the 17 such visits over the course of Cycles 1 and 2, 13 were due to guiding failure resulting in about 9 hours of visits lost. The four other visits were marked as “UNSUCCESSFUL” in the guiding data and the corresponding OSS event messages indicated that the NIRCcam target acquisition was the last step in the visit, which was a sign of a failed target acquisition.*

*The boundary between cycles (on July 1<sup>st</sup> of each year) did not always imply that programs from one cycle could only be used in that cycle. For instance, observations from PID 2726 and 4431, two Cycle 1 programs, were executed after July 1<sup>st</sup> 2023, during Cycle 2. Section 4.5 properly sums the visits executed in each given cycle.*