

The Evolution of On-Orbit Operations of the Integrated Science Instrument Module of the NASA Webb Space Telescope

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Abstract

The most recently commissioned Flagship-class NASA Astrophysics mission, the 6.5-meter James Webb Space Telescope, is now entering its third year of routine operations. Webb provides the worldwide astrophysical research community an unprecedented view of the Universe at near- to mid-infrared wavelengths and is already beginning to expand our knowledge and revolutionize our understanding of every phase of the history of the Universe as widely anticipated by the research community. This tremendous impact would be impossible without the successful day-to-day operation of the four major Science Instruments (SIs) within Webb's Integrated Science Instrument Module (ISIM) by the Mission Operations Team (MOT) at the Space Telescope Science Institute in Baltimore, Maryland.

Collectively, ISIM provides Webb users with wavelength coverage from 0.6 to 28 μm and the ability to conduct deep photometric imaging, time-series imaging and spectroscopy, coronagraphy, aperture masking interferometry, wavefront sensing, as well as fixed-slit, multi-object, and imaging (integral field unit) spectroscopy at medium spectral resolving power. While such broad capabilities are the reason Webb is able to contribute to so many different areas of astrophysical research, the successful on-orbit operation of this complex and non-standardized collection of instrumentation has not been without challenges.

In this paper, we discuss one of the most significant operational anomalies encountered by a Webb SI since launch. We detail the anomaly investigation of a grating wheel move failure of the Mid-Infrared Instrument, including the impacts and root cause, along with the operational mitigation strategies and the revisions to the original concept of operations to successfully address the observed anomaly. While Webb MOT cannot preclude the occurrence of new ISIM anomalies in the future, we are confident that our approach to any on-orbit anomalies we encounter, as presented here, will ultimately prove successful in maintaining the wide range of capabilities and the high level of performance of Webb's SI suite over the lifespan of Webb's prime mission and beyond. The next large strategic NASA Astrophysics mission—the Roman Space Telescope—is already progressing through system assembly, integration, and testing and our flight experience with Webb directly provides Roman, as well as other future missions, with valuable insights for optimal payload operations.

Keywords: JWST, Instrumentation, Infrared, Spectroscopy, Mid-infrared, Science Operations

Acronyms/Abbreviations

Anomaly Management Board (AMB), Anomaly Response Team (ART), anomaly report (AR), Anomaly Review Board (ARB), dichroic grating wheel assembly (DGA), European Space Agency (ESA), fault management (FM), Fine Guidance Sensor (FGS), Flight Operations Team (FOT), flight software (FSW), integral field unit (IFU), Integrated Science Instrument Module (ISIM), James Webb Space Telescope (JWST), Mid-Infrared Instrument (MIRI), Mission Operations Manager (MOM), Mission Operations Team (MOT), Near-Infrared Camera (NIRCam), Near Infrared Imager and Slitless Spectrograph (NIRISS), Near-Infrared Spectrograph (NIRSpec), observing plan (OP), Operations Scripts Subsystem (OSS), Planning & Scheduling (P&S), Science Instrument (SI), Space Telescope Science Institute (STScI), telemetry monitor (TMON).

1. Introduction

The Integrated Science Instrument Module (ISIM) of the Webb Space Telescope [1] is comprised of the optical bench assemblies of the four Science Instruments (SIs) responsible for capturing science data for principal investigators with approved observing programs. By name, they are the Mid-Infrared Instrument (MIRI) [2,3], the Near-Infrared Camera (NIRCam) [4], the Near Infrared Imager and Slitless Spectrograph (NIRISS) [5], and the Near-Infrared Spectrograph (NIRSpec) [6]. The main portion of ISIM is located behind the Optical Telescope Element of Webb in

the cold portion of the Observatory (Region 1, ~40 K), while the SI electronics boxes are located in the Instrument Electronics Compartment (Region 2, ~293 K), and the ISIM Command and Data Handling system, which hosts the instrument flight software (FSW), is in the spacecraft bus on the warm side of the Observatory (Region 3, ~300 K) as shown in Fig. 1 [7].

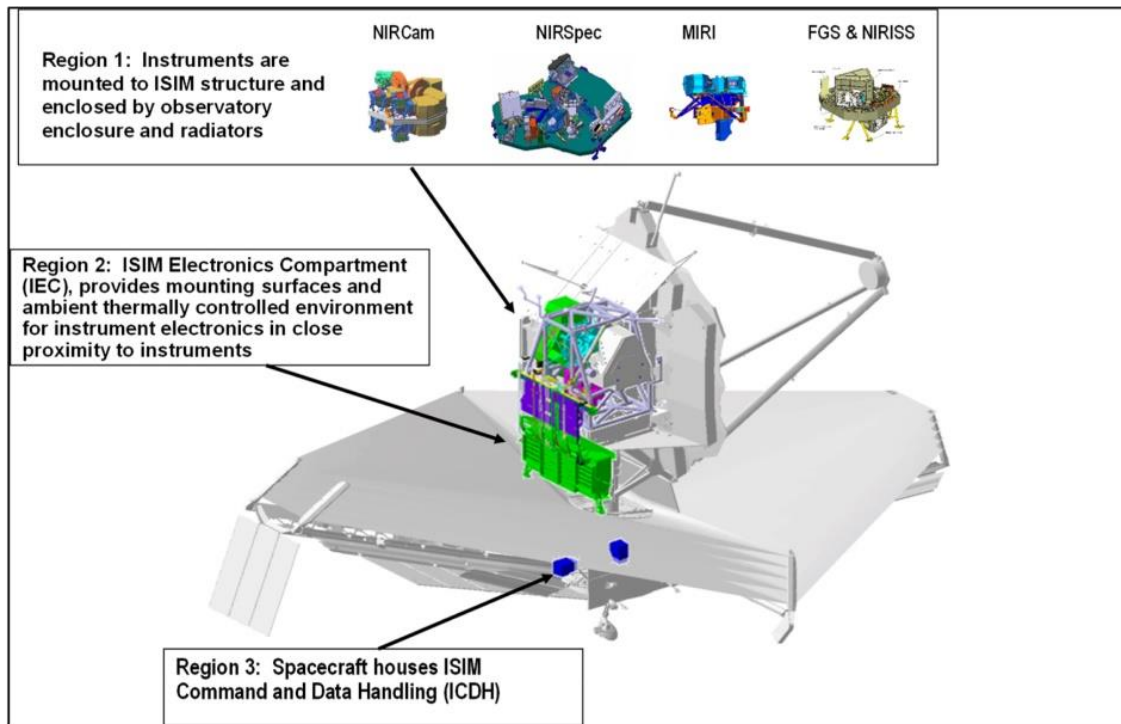


Fig. 1. Physical layout of Webb's ISIM [7].

Together, the four SIs of ISIM provide observers with an impressive range of capabilities with which to view and probe the cosmos. MIRI is Webb's "long" wavelength SI, providing sensitivity from ~5 to 28 μm , and offering broadband imaging, coronagraphic imaging (both Lyot and four quadrant phase mask), low-resolution spectroscopy (both slit and slitless), and medium-resolution integral field unit (IFU) spectroscopy observing modes to the community [8]. NIRCam is Webb's prime large field-of-view camera, providing sensitivity from ~0.6 to 5 μm , and offering imaging (29 available filters), coronagraphic imaging, wide field slitless spectroscopy, time-series imaging, and grism time series observing modes [9]. NIRISS is the sister of Webb's Fine Guidance Sensor (FGS) and offers wide field slitless spectroscopy, single object slitless spectroscopy, aperture masking interferometry, and standard imaging observing modes with wavelength sensitivity between ~0.6 and 5.0 μm [10]. In a pinch or perhaps as a last resort, NIRISS may be repurposed as a guider camera if the two FGS guiders are lost. Finally, as the name would suggest, NIRSpec is Webb's main spectrometer offering multi-object spectroscopy (using a micro-shutter assembly), IFU imaging spectroscopy, high-contrast single object fixed-slit spectroscopy, and wide aperture, high throughput bright object time series spectroscopy observing modes at low to medium spectral resolving powers between 0.6 and 5.3 μm [11].

Like all space missions that came before, Webb experienced numerous anomalies of varying magnitude since launching in December 2021 involving nearly every major Observatory subsystem. Arguably the most significant anomaly during normal operations, which commenced on 10 July 2022, for the "spacecraft portion" of Webb was a series of five related Observatory safing events involving the Attitude Control Subsystem (responsible for pointing of the spacecraft), FGS (responsible for guiding and tracking during science observations), and the Operations Script Subsystem (OSS), which autonomously executes observations, in December 2022 that has come to be known as the "December To Remember" by the Webb Mission Operations Team (MOT). The valuable lessons learned by the MOT from the "December to Remember" and some other operational anomalies the team encountered thus far are presented in [12]. Lessons learned from the anomalies encountered by Webb's communications system, which is vital to the mission as a whole, are found in [13]. On the payload side, every Webb SI and their auxiliary systems within ISIM experienced some form of anomaly, since launching the Observatory, that ultimately required investigation and

operational recovery to get back to science operations with as minimal loss of observing time as possible. The MOT successfully navigated all of these anomalies using a robust approach to anomaly management and the lessons we learned from each anomaly enabled us to continue improving the efficacy and efficiency of the Observatory for the overall benefit of the science community.

The outline of this paper is as follows. In Section 2, we present and discuss the details of the anomaly management process utilized by the Webb MOT during normal science operations. Then in Section 3, we discuss the application of our anomaly management process to one of the most significant anomalies experienced by an SI since launch: the failure of one of MIRI’s mechanisms to move to a commanded position.

2. Webb Anomaly Management During Normal Operations

In Fig. 2, we show a flow diagram that captures the anomaly management process for Webb during normal operations. Below, we describe and discuss the process in detail. Note, that the process provides flexibility in terms of the number and focus of each meeting but is strict in the sense that the path(s) forward must be formally approved and followed exactly as written.

2.1 Detection and Initial Assessment

The management of all anomalies begins with detection and reporting of anomalous behavior. During normal operations, the responsibility lies with MOT to identify anomalies by monitoring the health and safety of each Webb subsystem and by analyzing housekeeping telemetry for unexpected states and conditions that are outside of certified design and performance specification limits. This includes producing and analyzing the time history of telemetry and derived parameters to recognize changes in the behavior of the system that may lead to anomalous situations.

However, due to the fact that we are not in continuous contact with the Observatory via the Deep Space Network during normal operations (average daily contact time is 10-12 hours before 03 February 2025), the Observatory has to protect its own health and safety using on-board fault management (FM). The MOT can then detect this FM, as well as other anomalous conditions, by alarms that trip when telemetry values exceed predefined alarm limits.

When an alarm trips, a text message is automatically sent out to the MOT to alert the team of the abnormal condition. This text message is typically the first indication MOT has of an anomaly or concern of possible anomaly. The subsystem engineer identifying the situation informs the Flight Operations Team (FOT) Lead of the discovery who then informs the Webb Mission Operations Manager (MOM).

As shown in Fig. 2, the next step in our anomaly management process is an initial anomaly assessment meeting called by the MOM. One of the main goals of this meeting is conducting a health and safety assessment to determine the impacts to the Observatory and ascertaining the severity of the anomaly. Some critical ISIM telemetry have associated telemetry monitors (TMONs), which form an important component of our on-board FM system. A tripped TMON may kick off a FM response that is typically safing part or all of the Observatory, depending on the specific TMON. Whether or not we had an FM response, if any other action is required to place the Observatory in a safe configuration after the initial assessment of the anomaly, the MOT may utilize pre-coordinated activities and responses to do so with approval from the MOM.

2.2 Anomaly Management Board (AMB) and Anomaly Response Team (ART)

As shown in Fig. 2, the MOM makes the decision at the initial anomaly assessment meeting if an AMB is needed for any particular anomaly. Broadly speaking, the AMB reviews and discusses anomaly presentations. More specifically, the AMB is responsible for:

- Appointing a lead for the Anomaly Response Team (ART);
- Approving a path forward prior to the conclusion of each AMB meeting;
- Determining the severity of an anomaly;
- Chartering an Anomaly Review Board (ARB) if required and determining ARB membership;
- Writing and/or approving the ARB charter if required;
- Reviewing and commenting on the recommended containment, investigation, corrective action, and/or recovery path forward;
- Approving the closure of an ARB;
- Establishing a long-term recovery plan team if required.

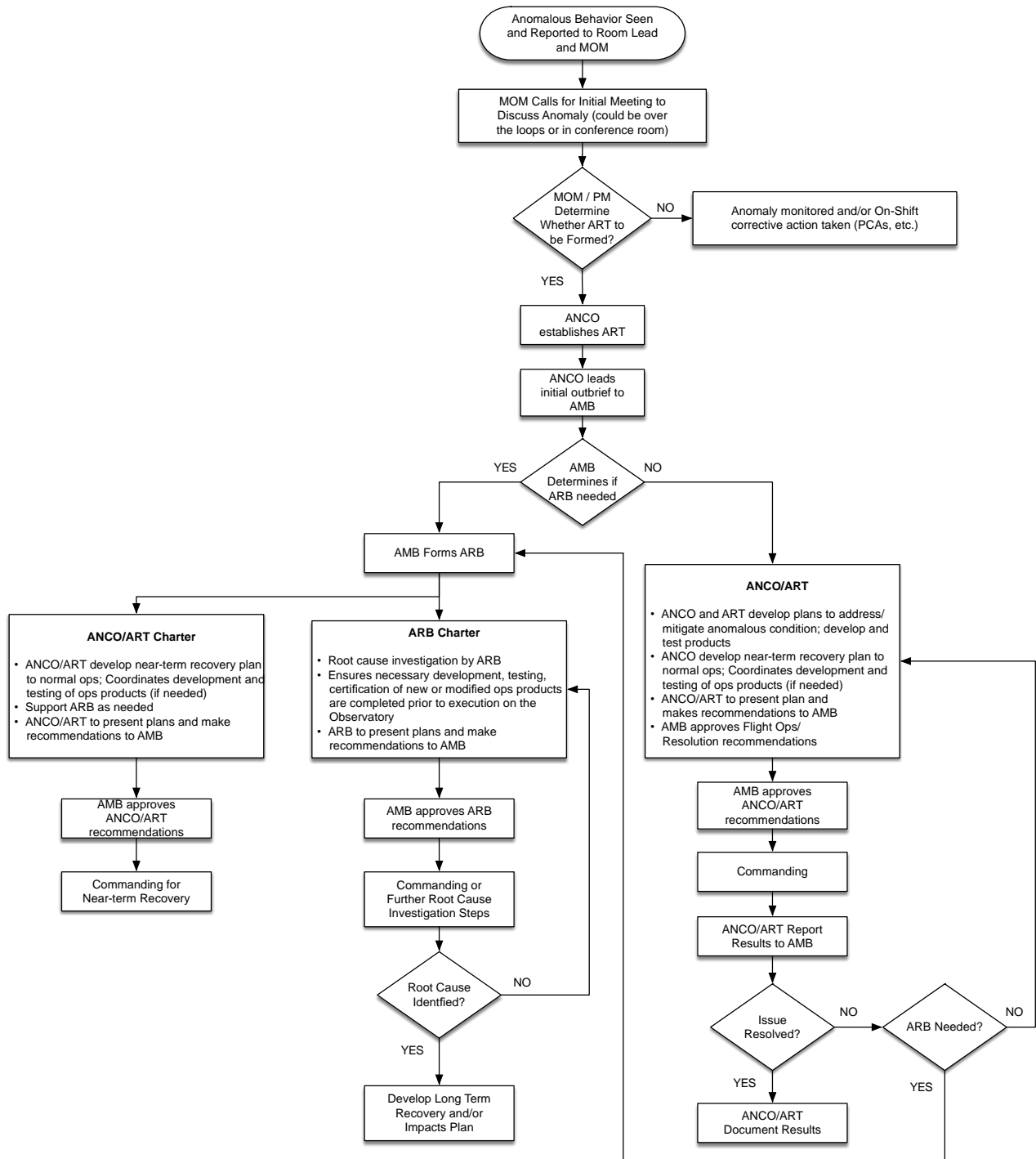


Fig. 2. Flow diagram for Webb anomaly management during normal operations.

If the MOM decides to convene an AMB, an anomaly coordinator (ANCO) gathers preliminary information and creates an anomaly report (AR) in the JWST JIRA anomaly reporting system to log pertinent information on the anomaly before the first AMB meeting. The ANCO generates an initial AMB briefing package with additional input from Observatory subsystem engineers as needed. The initial AMB briefing includes the following:

- Defining the issue under investigation;
- Providing a timeline of events;

- Providing Observatory and ground station configuration information;
- Providing details on current Observatory state of health;
- Providing details on any concurrent investigations;
- Information on containment actions taken;
- Information on current risk posture and severity of the anomaly;
- Recommendation of a path forward.

The first AMB meeting is held as soon as possible once the initial briefing package is ready to provide high-level status, to formally assemble an ART, and to approve non-emergency containment actions, and/or other possible path(s) forward. MOM/FOT Lead distributes the notification for the first AMB meeting on the anomaly to the entire Webb MOT for situational awareness.

The main focus of the first AMB meeting is to identify the need for further action(s) to ensure the immediate safety of the Observatory and who will lead the follow-on anomaly investigation. It is not intended to discuss technical considerations or possible root cause. The AMB approves the assembly of an ART to review the anomaly and Observatory status by designating an ART Lead and determining the required resources. The initial meeting culminates in an approved path forward for the ART to perform and specifying a time for the ART to bring the results back to AMB. The approved path forward must be followed exactly as written, especially actions involving Observatory commanding. Commanding sequences that fail to progress nominally require termination of the activity and returning to AMB.

2.3 Recovery and Investigating Root Cause

At the second AMB meeting, the ART Lead presents any requested containment or corrective action(s) and proposes a recovery path forward for discussion, along with the status of the anomaly investigation, including what is known about possible root cause. The outcomes of a typical second AMB meeting include:

- Review of AMB briefing package;
- Approval to expanded or modified ART as needed;
- Approval to charter an ARB as needed;
- Approval of path forward including action(s) to be completed before next meeting.

The AMB determines whether to charter the formation of an ARB to address the anomaly or if the ANCO/ART team will provide the recommended resolution (which could be iterative). The non-ARB branch of the anomaly management flow shown in Fig. 2 is typically used to handle minor issues of all types without significant overhead, especially in the case of contingencies that are well-defined and quickly understood by the ART. Note, as shown in Fig. 2, that when an AMB initially decides not to form an ARB and anomaly resolution proceeds via the ANCO/ART branch, the AMB may eventually decide to charter the formation of an ARB at any time as called for by the developing situation. This provides the anomaly management method of the Webb MOT the ability to adapt based on the outcome of approved actions and to account for new information revealed by the anomaly investigation. Additionally, the AMB may also establish a long-term recovery plan team, if required, which may be different from the ART or a possible ARB.

In rare circumstances, the AMB may charter an ARB. The intent is for the ARB to be a strategic team working longer-term issues, such as hardware failures. The membership of the ARB is determined by the AMB with the aim of possessing the expertise required to successfully complete the charter. Commonly, this includes mission management, mission systems engineering, flight operations, the pertinent engineering discipline such as the spacecraft/component/part manufacturer representative, relevant NASA engineers, mission support personnel (flight dynamics, flight software, ground system engineers, etc.), subject matter experts, and/or instrument developers. The AMB-approved charter for the ARB defines the scope of the work of an ARB, or any realization of the group/team, and typically includes preparation of a root cause and corrective action analysis report.

2.4 Closeout

There will be as many follow-on AMB meetings as required to satisfy the communication needs between those working on the anomaly and the agreed-to path forward and the AMB. Each anomaly is closed out with an AMB briefing describing the cause of the anomaly, corrective action taken, and the resulting status of the mission. For non-ARB path anomalies, root cause is not always identified. The AMB provides closure authority on the non-ARB anomaly report at AMB meetings when it is determined that no further actions are required. For ARB-path anomalies, closure will require completion of the ARB per the ARB charter, a complete recovery plan (if required), and a final

anomaly report, which may include a root cause and corrective action analysis, updated operational documentation, or risk documentation.

3. MIRI Grating Wheel Move Failure Anomaly

3.1 MIRI Medium-Resolution Spectrometer

We give a brief overview of MIRI before delving into the grating wheel anomaly. The MIRI medium-resolution spectrometer (MRS) utilizes two 1024 x 1024 arsenic-doped silicon impurity band conduction detector arrays for medium-resolution IFU spectroscopy from ~5-28 μm [14]. Two dichroic grating wheel assemblies (DGAs) are utilized together to divide the total wavelength range into four simultaneous spectral channels, referred to as Channels 1-4. Fig. 3 shows a diagram depicting the MRS light path splitting into four channels by the DGAs [14]. Additionally, the DGAs sub-divide the wavelength range of each MRS spectral channel into three sub-bands, referred to as Sub-bands A, B, and C. Operationally, obtaining a complete MIRI MRS spectrum requires three separate exposures with both DGA-A and DGA-B simultaneously at three separate positions referred to as SHORT (Sub-band A), MEDIUM (Sub-band B), and LONG (Sub-band C). See [8,14] and references therein for more details.

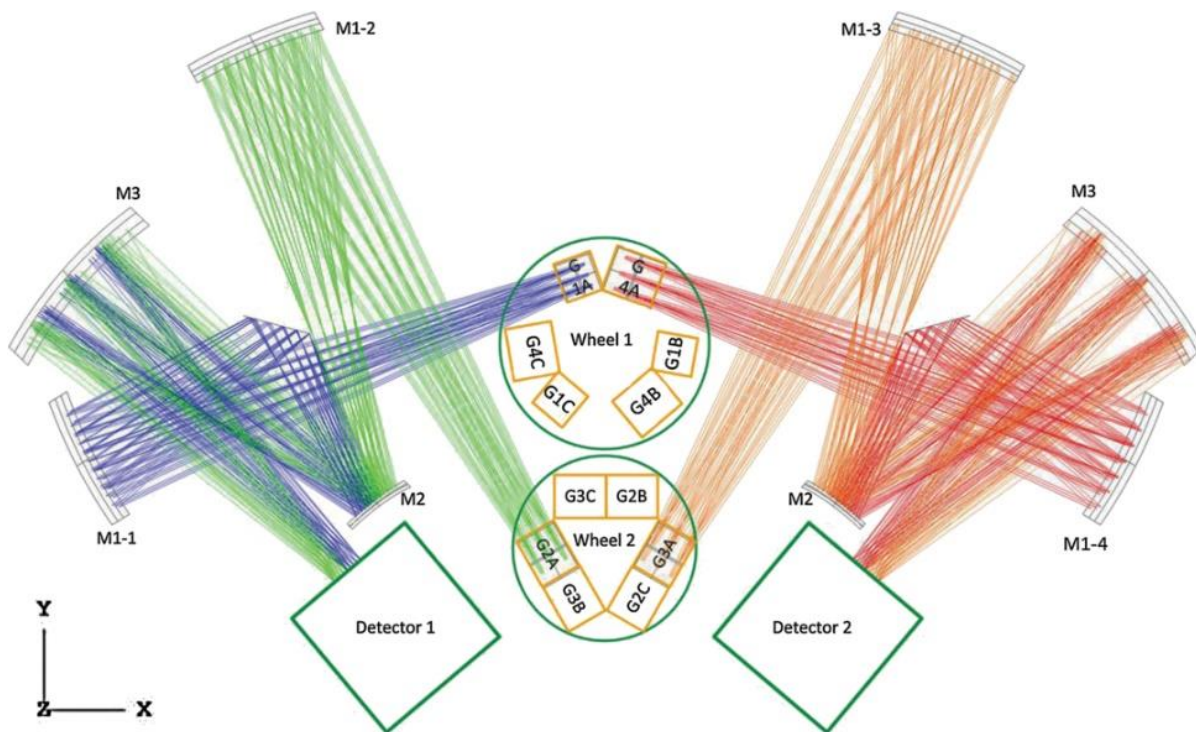


Fig. 3. MIRI MRS light path splitting into four channels by the DGAs, which rotate to 1 of 3 positions to select the spectral sub-band [14].

3.2 AR-2173 Discovery and Initial Assessment

On 24 August 2022 at 02:27:43 UTC, DGA-A of MIRI MRS failed a commanded move in the forward direction from the SHORT position to the MEDIUM position during a prime science visit using the medium-resolution spectroscopy observing mode. The Webb MOT received alarms associated with this anomaly immediately upon coming back into contact with the Observatory at 03:35:00 UTC, prompting MOT to report the discovery to the MOM and to begin investigating. As per our anomaly management process shown in Fig. 2, the MOM called an initial anomaly assessment meeting to conduct a health and safety assessment of the Observatory and to get a preliminary assessment of the severity of the anomaly.

At the initial anomaly assessment meeting, all Observatory subsystems reported green state-of-health except MIRI. Upon investigation it was clear that a significant or critical anomaly occurred because on-board FM transitioned MIRI

into safe mode and made it unavailable to OSS, which is responsible for selecting which visits from the on-board observing plan (OP) to execute [15]. Further investigation revealed that the Observatory properly continued executing the remainder of the on-board OP after the anomaly occurred, except OSS skipped any visit that intended to use MIRI due to its status of unavailable (OSS skipped 8 MIRI visits in total from the time of the anomaly until we came back into contact with the Observatory). The MOT concluded that the anomaly was localized to MIRI and no health and safety concerns existed outside of MIRI.

Webb MOT also determined that MIRI transitioned to safe mode as expected during the initial anomaly assessment meeting. As a result, there were no safety concerns for MIRI. However, the team noted their desire to recover MIRI (command it out of safe mode) as soon as possible in order to power back on the detector heaters and temperature sensors. This would alleviate thermal concerns without increasing the DGA health concern due to the failed move since MIRI recovery does not involve moving any mechanisms. After the completion of the health and safety assessment as directed by the MOM, the preliminary assessment of the anomaly severity was designated significant and required convening an AMB. Per our anomaly management process as discussed in Section 2.2, the MOM directed an ANCO to create AR-2173 to document this anomaly and compile an initial AMB briefing package.

3.3 Initial AMB Meetings for AR-2173: MIRI Recovery and DGA Health Checks

The first AMB meeting for AR-2173 was held on 24 August 2022 at 14:00 UTC and voting membership included NASA Program Management, MOM, Mission Systems Engineering, Science Instrument Lead, Project Science, Webb Mission Office, Mission Assurance, and the MIRI team. The ANCO/ART Lead presented a description of the anomaly, a timeline of events, and the Observatory state of health as per our usual anomaly management process. No substantial additional containment actions were requested since on-board FM already issued the appropriate response to put MIRI into safe mode and set it to unavailable to OSS as a result of the failed DGA-A move. The MIRI team requested to recover MIRI and to execute a detector anneal to alleviate thermal concerns from not having the detector heaters running as first noted during the initial anomaly assessment meeting. The AMB approved this request since recovery of MIRI would not involve movement of DGA-A.

Some diagnostic commanding was requested by the MIRI team including a request to conduct a position sensor read of DGA-A, which had been reporting “Unknown” since the anomaly occurred. This request was approved since reading a sensor is typically seen as benign and it would provide further clues into the possible root cause of the failed DGA-A move. The MIRI team suspected increased frictional torque as the root cause for the failed DGA-A move. In order to begin corroborating this, the team requested permission to conduct a DGA-A health check in order to measure the frictional torque experienced during each move when the DGA is moved from one position to the next in one direction and then the same in the opposite direction. The health check is a total of six moves since there are three DGA positions in total. The majority of the first AMB meeting was spent discussing any potential damage to the hardware that may result from moving DGA-A after a failed move without knowing the root cause. The group came to the consensus that moving DGA-A carried the risk of another failed move and subsequent SI safing, but there was no risk to the hardware based on the collective knowledge from MIRI telemetry and the nominal drive voltages/currents. Thus, a DGA-A health check starting with a single move from the current DGA-A position to the next in the backwards direction was approved. For reference the forward direction starting from SHORT is SHORT to MEDIUM to LONG. Since the failed DGA-A move was a move in the forward direction, starting the health check with that same move was seen as the greatest risk of another failure. Hence, the AMB approved starting the health check with a single move in the backwards direction followed by another two moves in the backwards direction and three moves in the forward direction. The health check would be terminated if the team encountered another move failure.

After AMB meeting #1 for AR-2173 and following the approved path forward, MOT successfully executed the commanding sequence to recover MIRI, perform a DGA-A position sensor read, and perform a detector anneal on 24 August 2022 at 17:50 UTC. The recovery sequence restored MIRI to a ready to observe state from safe mode but the instrument would not be used for science observations until approved by the AMB (enforced by leaving MIRI unavailable to OSS). The DGA-A position sensor read did not result in any issues and indicated that the current DGA-A position is the starting position of the move that failed (SHORT).

The AMB-approved DGA-A health check was conducted on 24 August 2022 at 21:09 UTC. All six moves (three in backwards direction then three in the forward direction) completed successfully and yielded no indications of broken position sensors or problems with the sending or receiving of telemetry that could result in the wheel position not being sensed or reported properly. The frictional torque for each move of this DGA-A health check is shown on the far right of the left panel of Fig. 4 at ~210 revolutions. Wheel revolutions is being used as a proxy for time since the total number of wheel moves (either direction) is monotonic with time. The frictional torque from previous DGA-A health checks are also shown in the left panel of Fig. 4 at ~50 and ~100 revolutions and comparison of the three DGA-A health checks suggests that the friction has been increasing with time as more and more wheel rotations have been

completed on-orbit. Note, that a DGA-A frictional torque greater than ~ 13.5 mNm would result in a failed move as may be inferred from the driving waveform used at the time of AR-2173.

After the completion of the approved path forward from AMB meeting #1 for AR-2173, the second AMB meeting was held on 25 August 2022 at 16:30 UTC. The MIRI team presented the results from execution of the approved actions from AMB meeting #1, including the DGA-A health check results shown in left panel of Fig. 4. These results indicated the problem was localized to DGA-A (possibly DGA-B as well) and therefore MIRI MRS should not be used until the issue was investigated further. It was believed that the MIRI Imager [16] could safely be used to conduct science observations in imaging, coronagraphic imaging, and low-resolution spectroscopy observing modes. Thus, AMB approval was given to set MIRI back to available to OSS but to only allow visits in the OP that do not use MRS for the time being. This condition would be enforced by the Planning & Scheduling (P&S) team for Webb through their selection of the visits to build into each new OP delivered weekly. A new OP adhering to the new constraint was built by the P&S team and uplinked on-board Webb on 26 August 2022 and MIRI was set to available immediately after.

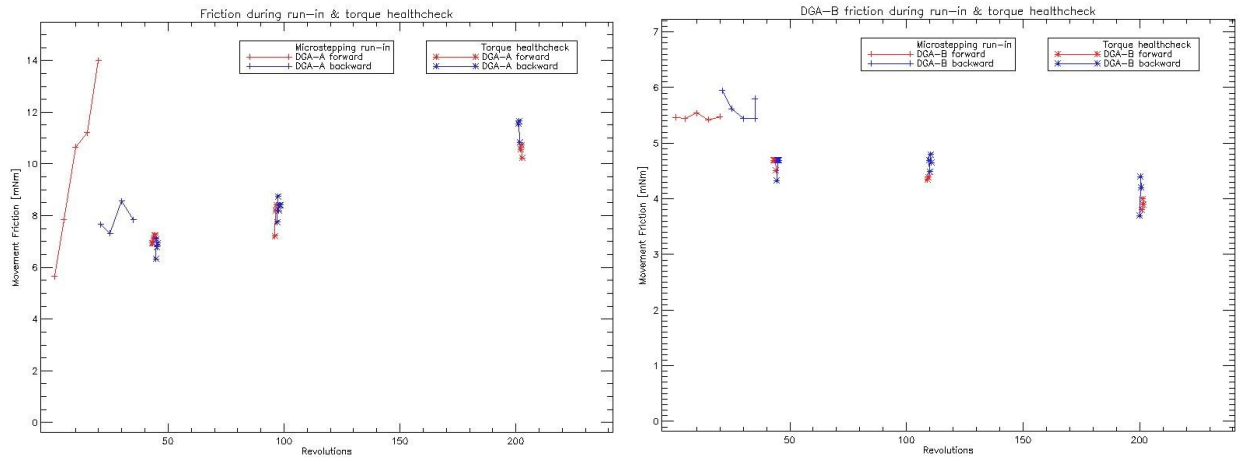


Fig. 4. DGA-A (left) and DGA-B (right) move frictional torque from real-time mechanism health check activities.

Although this anomaly only manifested in DGA-A, it was agreed upon (and formally approved) at AMB meeting #2 for AR-2173 that conducting a health check on DGA-B (real-time commanding required) would be prudent given the identical construction and operation of the two DGAs. The real-time commanding sequence for the DGA-B health check was successfully completed on 25 August 2022 at 21:20 UTC and the frictional torque for each move is shown in the right panel of Fig. 4 at ~ 200 revolutions. From these results, the team had no immediate concerns for the frictional torque levels of DGA-B.

The rest of AMB meeting #2 was devoted to the discussion of developing mitigations/solutions for the issue, assuming the failed DGA-A move was due to increased frictional torque, as a path forward. Two mitigations/solutions were identified at this AMB meeting. First, the MIRI team was given approval to build and test a new DGA-A torque mode waveform and gain table. Second, the team received approval to develop a new concept of operation for MRS.

We begin the discussion of the first identified mitigation/solution for AR-2173, the development of a new DGA-A waveform and gain table, by showing the mechanical design of the DGA in Fig. 5 and referring the reader to [17] for greater details. The DGAs are actuated by a cryo-torquer type C84 motor that is driven by one of two types of waveforms referred to as torque mode and micro-stepping mode. Torque mode was the standard mode for normal MRS operation when AR-2173 occurred. This mode uses an individually “tuned” torque mode waveform and gain table for each DGA that is designed to move the mechanism in an energy efficient manner compared to micro-stepping mode. Tuning of the torque mode waveform for DGA was performed during Observatory commissioning and accounted for the bearing frictional torque present at the time. Changes in DGA parameters at a later time after tuning may necessitate updating the torque mode waveform of the mechanism in order to account for the changes. Hence, the rationale for building and testing a new torque mode waveform and gain table for DGA-A is to account for the higher frictional torque seen in the left panel of Fig. 4.

The second path forward for mitigation/solution of AR-2173 was developing a new concept of operation for MRS. Analysis of the executed MRS visits up to the failed DGA-A move in AR-2173 revealed that DGA moves had been almost exclusively in the forward direction, despite the fact that the wheel is allowed to rotate in both directions. To understand how this situation came about, consider that when constructing an MRS observation for medium-resolution

spectroscopy the observer must specify a specific spectral configuration, either Sub-band A, B, or C corresponding to DGA position SHORT, MEDIUM, and LONG, respectively, as previously mentioned in Section 3.1. However, nearly all MRS observers will end up taking exposures in all three spectral configurations for a single target in order to cover the entire wavelength range from ~ 5 to $28 \mu\text{m}$. While there is no restriction on the order of the three spectral configurations, the order that is specified by nearly all observers is Sub-band A, B, then C because this was the default order in the JWST observation planning tool (Astronomer’s Proposal Tool) at the time of AR-2173. The natural alphabetical order of the sub-bands is likely the reason for this default order when the proposal tool was designed, although this is difficult to prove. Because MIRI FSW always takes the shortest path between two positions, the rotation of the DGAs to get exposures in all three spectral configurations for a single target ends up being in the forward direction as a result of the default order. Additionally, since the next MRS observation is also likely to take exposures in all three spectral configurations and in the same order because of the default mentioned above, the DGAs would continue rotating in the forward direction until the OP contains an MRS observation that is not a set of three exposures in Sub-band A, B, then C.

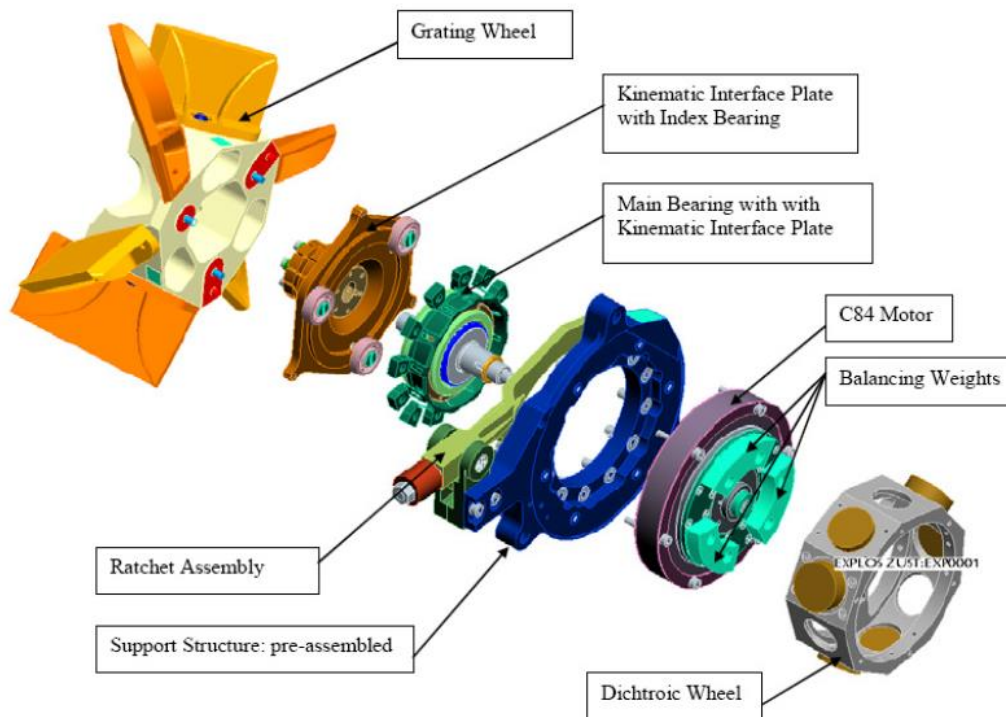


Fig. 5. Mechanical diagram of one of the MIRI DGAs showing the individual components including the main bearing and C84 motor [17].

With the analysis above in mind, two new MRS concepts of operation were proposed. The first proposal can be described as a “campaign mode” where only one MRS spectral configuration would be used per week (or other desired time period), which would minimize the total number of DGA moves compared to the original MRS concept. The second proposal called for balancing the rotation direction of the DGAs by changing the direction of rotation after a certain number of rotations (to be determined) in one direction. This second proposal was built on the observation that after many moves in one direction, frictional torque decreased when changing the direction of rotation. Hence, moving in both directions may slow down the degradation of the wheel. Note that the first proposal introduces a lot of overhead in terms of Observatory slewing, which is not quick. Hence, the second proposal was favoured, if feasible, but would initially require manual implementation by the Webb P&S team until new software tools are created.

3.4 Chartering an ARB and Probable Root Cause of AR-2173

AMB meeting #3 for AR-2173 was held on 31 August 2022 at 17:30 UTC after all approved actions from meeting #2 were completed, including the development of possible mitigations/solutions discussed in Section 3.3. The AMB, however, expressed concerns about implementing these potential mitigations/solutions without greater understanding

of the root cause of the increased frictional torque and more insight to how friction might change as we move the DGAs. Thus, the AMB decided to charter an ARB to further investigate the root cause of the failed DGA-A move before attempting to return MRS to science operations. The ARB charter, presented and approved at AMB meeting #4 on 14 September 2022, reads as follows:

- Perform detailed review of the wheel design and its failure mode and effects;
- Evaluate the flight and ground history of the device;
- Generate a root cause analysis/fishbone diagram;
- Try to determine most probable root cause;
- Formulate diagnostic tests to confirm probable root cause;
 - Identify/recommend flight and/or non-flight testing;
 - Present the evaluation of effectiveness of such tests and any risks they pose to the flight hardware;
- Determine/recommend a set of path forward options for a mechanism use profile and lifetime management strategy;
 - Risk analysis – for a set of possible paths forward;
 - Identify/recommend trending;
 - Identify/recommend “maintenance”;
 - Identify/recommend new or modified flight products;
- Review trending/maintenance/usage after a period of time to confirm findings.

A subset of the AMB participated in the ARB but, as a whole, the ARB membership included a greater level of technical expertise compared to the AMB, including representation from the MIRI instrument development team (both science and technical), ESA subject matter experts including the European Space Tribology Laboratory, the Max Planck Institute for Astronomy including Hensoldt, and NASA subject matter experts. The broadness of the ARB membership is intended to help ensure there is the requisite expertise to carry out the ARB charter successfully. Membership could be modified as needed.

As per the charter, the ARB completed a root cause analysis after conducting a thorough review of the MRS mechanisms and evaluating their history. The probable root cause for AR-2173, along with the fishbone diagram shown in Fig. 6, were presented to the AMB during meeting #5 on 19 October 2022. The accepted root cause for the failed DGA-A move in AR-2173 is a phenomenon known as “cage hang-up” of the DGA bearing assembly. This phenomenon leads to increased contact force between the stationary bearing ring and cage, resulting in elevated frictional torque of the central bearing assembly. Although we do not show details of the bearing assembly here, see [17] for an in-depth look at the mechanical design of the MIRI DGAs.

The increased force is believed to be caused by post-vibration “out of position” of the bearing balls, which can consequently pinch the cage at operational temperature and cause increased torque and periodic torque excursions. Modelling of cage hang-up shows that continued rotation of the bearing in the same direction tends to exacerbate the condition, promoting high bearing torque. Recall, that analysis of the executed MRS visits up to the occurrence of AR-2173 had rotated the DGAs almost exclusively in the forward direction and this fits with cage hang up being the probable root cause for high frictional torque in the central bearing. Modelling of cage hang-up also shows that reversing the direction of rotation could return the bearing to a lower friction torque zone. This is consistent with previous observations that reversing rotation direction decreases friction and likely contributed to the success of the DGA-A health check after AR-2173, which started with three moves in the backwards direction.

When AR-2173 occurred, the resulting failure of DGA-A to reach the commanded position was due to a change in frictional forces within DGA-A as compared to the frictional forces seen at the time the torque mode waveform and gain table to drive the cryo-torquer C84 motor was tuned. The waveform tuning did not accommodate the variability in the friction seen during on-orbit operations. Additional contributing factors to the increased frictional torque include the manufacturing tolerances of the cage material, some uncertainty over the coefficient of thermal expansion of the cage, and the impact of storage time/environment on the cage as shown in Fig. 6. Analysis suggests these are not, individually, sufficient to be drivers of the phenomenon observed.

The ARB noted from their investigation and analysis that it was considered safe to move the DGA-A without the risk of losing full MRS channel capability. Additionally, a frequency of monitoring would be established that could indicate if the model of the root cause was not complete or accurate as a plan is made to return MRS to science operation.

3.5 MRS Return to Science Operations Phase 1

Once the AMB accepted the probable root cause for AR-2173 as presented by the ARB, the ARB turned its attention to returning MRS to science operations. To do this, per the ARB charter, the ARB would need to focus on formulating

diagnostic tests to confirm probable root cause and to determine and recommend a set of path forward options for a mechanism use profile and lifetime management strategy.

At AR-2173 AMB meeting #6 on 26 October 2022, the ARB proposed a three-phase approach to return MRS to science operations. Each phase would have an AMB meeting for approval before proceeding with that phase. The three-phase approach and Phase 1 were approved by the AMB during meeting #6. In Phase 1, the ARB would gather trending data on the DGAs in positions near the current position where DGA-A failed a forward move from SHORT to MEDIUM. Additionally, a single observation program using MRS, that could not otherwise be rescheduled in the current observation cycle after 15 November 2022, would be allowed to execute.

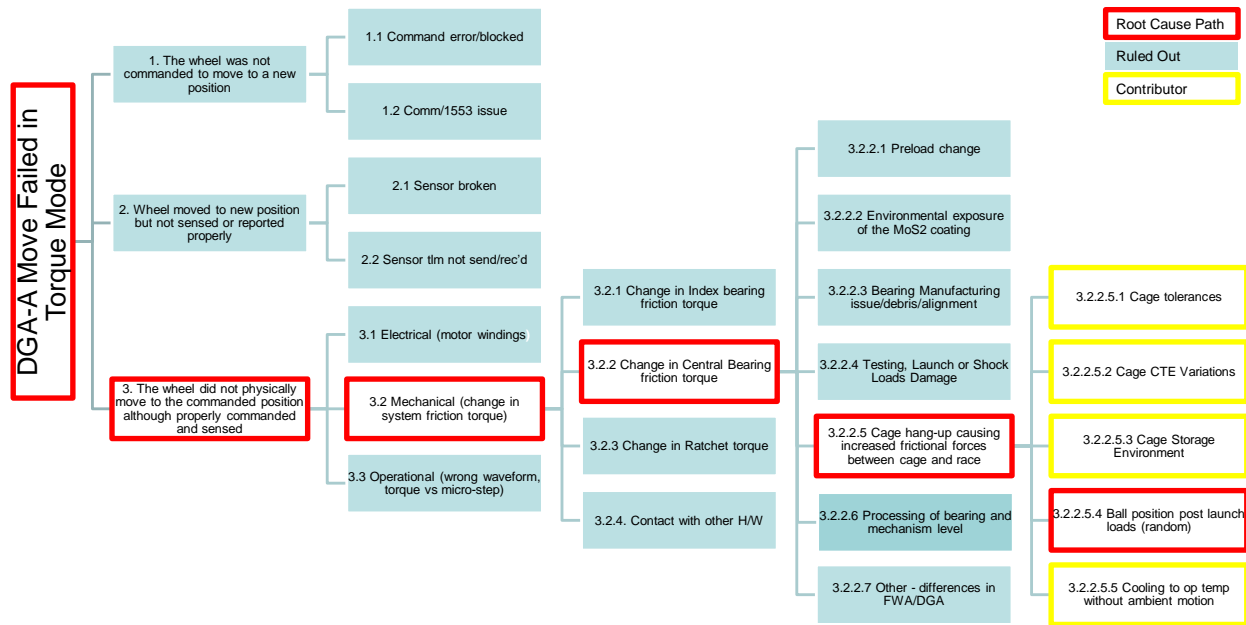


Fig. 6. AR-2173 Root Cause Tree.

Several diagnostic tests were completed during Phase 1 on 2 November 2022. First, a health check of both DGAs consisting of one backwards move followed by one forward move, using the same torque mode waveform and gain table for the DGAs as used during AR-2173, was completed successfully. The DGAs completed the moves nominally and analysis of the settling time for each move showed consistency with previous moves, which assured the ARB team that the situation was unchanged after not using MRS for two months.

Next, a DGA-A only health check consisting of three backwards revolutions (three total steps each revolution) followed by three forward revolutions using a new torque mode gain table (same waveform) was successfully completed. This new DGA-A torque mode gain table was previously developed but not yet implemented by the direction of the AMB. It is tuned to successfully change DGA-A position for up to ~18 mNm of frictional torque compared ~13.5 mNm for the previous waveform. All DGA-A moves completed nominally and the goal of this diagnostic test was to obtain a baseline for the frictional torque trending that would be conducted throughout Phase 2, including the furthest forward rotation position for the DGA-A.

Finally, another health check of both DGAs consisting of one backward revolution and one forward revolution using micro-stepping mode waveform and gain table was completed successfully. Unlike the torque mode waveform and gain table, which is tuned to each mechanism’s frictional torque at the time, the micro-stepping waveform is insensitive to changes in frictional torque because it uses ~150 mA of the full 300 mA of available motor current, but at the cost of higher thermal dissipation for each move. Nonetheless, the higher heat dissipation of the micro-stepping waveform is compatible with the thermal budget for MIRI so the ARB proposed using this waveform for normal MRS operations to make the DGAs less susceptible to changes in frictional torque due to the higher motorization margin. This proposal was approved by the AMB contingent upon the successful demonstration of a DGA move in micro-stepping mode. Thus, the goal of this diagnostic test was to gather data to verify that micro-stepping mode moves the DGAs correctly, to see if the settling profile was useful for trending, and to be able to compare torque mode and micro-

stepping modes over the same positions to compare settling times for the frictional force model to correlate the gain. All moves for both DGAs completed nominally with micro-stepping mode.

We will mention to conclude our discussion of Phase 1 that the approved science program (program ID: 1247) was successfully executed via OP on 13 November 2022 and left DGA-A in the SHORT position and -5 revolutions from the AR-2173 position.

3.6 MRS Return to Science Operations Phase 2

After the successful completion of the diagnostic tests during Phase 1 on 2 November 2022, the ARB presented Phase 2 to the AMB at meeting #7 on 7 November 2022 for approval. A model of the DGA-A central bearing assembly predicted that frictional torque peaks are related to the alignment of the bearing components. Specifically, the relative rotation angle between the components. Thus, the goal moving forward is to stay out of any range that may contain a bearing component alignment that results in a frictional torque peak. The bearing model predicted no frictional torque peaks in the range between the current DGA-A position and up to 100 revolutions in the backward direction.

The goal of Phase 2 was to move the DGAs over the newly identified low-frictional-torque operating range to verify whether a new concept of MRS operations, where forward and backward rotations would be balanced to stay within this operational range, is viable. As the DGAs are moved from the current position (-5 revolutions from the AR-2173 zero position), angle vs time data during settling would be taken via real-time commanding using torque mode, and MRS science data would be taken via OSS using micro-stepping mode. The gathering of angle vs time data during settling allows for the monitoring of the frictional torque. Data from frictional torque trending at various locations in the new operating range and any potential impacts from poor DGA optical repeatability in the MRS science data would be reviewed by the ARB before ending Phase 2 and finalizing the Phase 3 start position.

The ARB defined “Stop Criteria” for Phase 2, which are specific outcomes that would lead to the termination of the remaining Phase 2 activities and call for a return to AMB. They are:

1. A DGA move fails during friction torque trending data collection using torque mode,
2. A DGA move fails during an OP-driven MRS science observation,
3. Friction torque trending data collection shows increased friction torque, higher than expected friction torque, or noisy friction torque.

An occurrence of (2) would mean that micro-stepping mode failed and would nominally put MIRI into safe mode and OSS would continue with visits for other instruments. An occurrence of (1) or (3) might indicate that the model for the root cause is inaccurate and needs to be modified. If (1) occurred, MIRI would be marked unavailable to OSS and the team would return to AMB. The same action would be taken if (3) occurred showing a frictional torque increase per revolution at more than double the rate seen during commissioning to date as a trend over multiple datasets. A single frictional torque spike would only call for an ARB review but not termination of Phase 2.

Additionally, the ARB identified and addressed several concerns for Phase 2 as part of their risk statement. First, there was a possibility that a torque mode move during friction torque trending data collection would fail. The likelihood of this outcome was considered very low due to the new torque mode gain table discussed in Section 3.5. Second, there was a possibility that the frictional torque trend would not be in line with the expected profile of the probable root cause. The likelihood of this possibility was considered low due to the bearing model prediction. The ARB noted that the operational plan for Phase 2 was still seen as the lowest risk range in which to move DGA-A. Third, there was a possibility that frictional torque may increase beyond the capability of micro-stepping mode. The likelihood of this outcome was considered very low due to the reduced sensitivity of micro-stepping to changes in frictional torque. Additionally, micro-stepping mode can be programmed to utilize the full 300 mA of available current if needed. Fourth, there was a possibility that the required torque will increase beyond the capability of the ratchet and would impact science performance due to lack of optical repeatability. The likelihood of this outcome was considered very low because a frictional torque value for the central bearing approaching the ratchet design torque of ~35 mNm will likely result in a failed move triggering a “Stop Criteria” for Phase 2 long before the ability of the ratchet to position the wheel becomes affected. Fifth and finally, there was a possibility that the required torque to move one step may increase beyond the capability of the motor. The likelihood of this outcome was considered very low due to the fact there is significant motor torque margin available.

Phase 2 was approved by the AMB and started on 16 November 2022 until successfully completed on 26 January 2023. Fig. 7 shows the frictional torque trending results and the DGA-A rotational position from the AR-2173 zero position during Phase 2 (~400 steps to ~750 steps since 1 June 2022). Reminder that we are using DGA steps as a proxy for time since the number of steps (in any direction) is monotonic with time. The results show no violations of the Phase 2 “Stop Criteria.”

3.7 MRS Return to Science Operations Phase 3

The ARB presented the proposal for Phase 3 at AMB meeting #8 on 7 December 2022. If approved by the AMB, Phase 3 would return MIRI MRS to science operations contingent upon the successful completion of Phase 2. The formal concept of operation for MRS in Phase 3, which was already touched on in Section 3.6, is to construct MRS visits within the weekly OPs such that the operating range of the DGAs is in a window from -20 to -50 rotations from the AR-2173 zero position, with no less than 3 and no more than 20 consecutive rotations undertaken in one direction before making a change of direction. This new operational range is now written into a JWST limitation, MIRI-L-2621, which if violated, increases the risk of loss of science observing time. In Phase 3, frictional torque trending (data collection bi-weekly) and optical repeatability trending would continue with the anticipation that as ARB reviewed more trending data as time goes on and without any DGA issues, requests for approval to decrease the frequency of trending would be made to the AMB.

Averaged DGA-A derived Movement Frictional Torque (IDL tool) as a function of number of STEPs (any direction) since 1st June 2022 (averaged over each test) ---- 9th Feb 2023

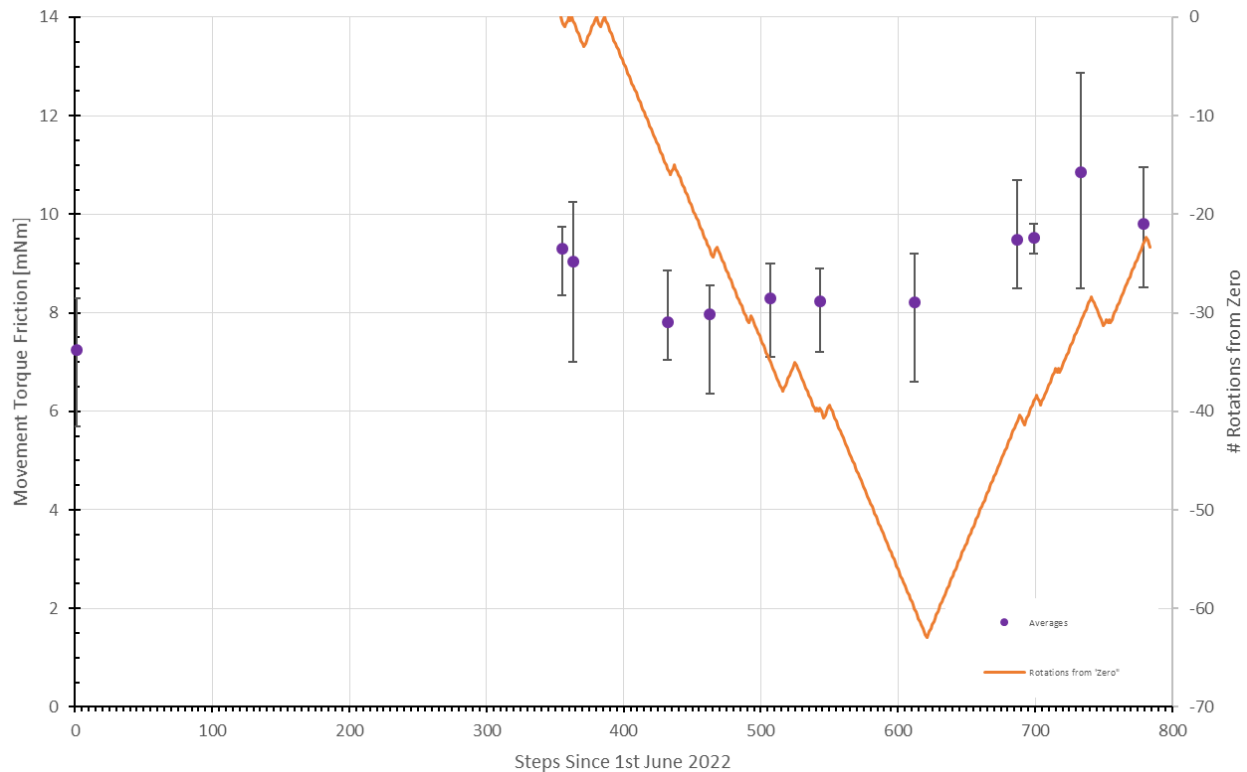


Fig. 7. Frictional torque trending and rotational position from AR-2173 zero position during Phase 2.

Phase 3 was approved by the AMB and formally began after the end of Phase 2 in January 2023. No problems were encountered in Phase 3 with each review of the incoming frictional torque trending data showing that the results match expectations and that the frictional torque remains in the acceptable and comfortable region. Correspondingly, no issues with the optical repeatability have been flagged in the MIRI MRS science data to date. While AR-2173 formally remains open as of writing, closure of the AR is only pending the submission of the final ARB report. Thus, we can report that MIRI MRS is fully back to normal science operations with its new concept of operation to balance forward and backward rotations of the DGAs to remain within a low-frictional-torque operating range.

6. Conclusions

In this paper, we presented the approach to anomaly management utilized by the Webb MOT to overcome numerous operational anomalies, and thereby, successfully maintaining Webb’s scientific productivity with no permanent loss of functionality since launch to date. The method provides flexibility to handle anomalies of varying magnitude and significance, but is also strict enough where necessary to provide a robust approach to maintaining the health and safety of the Observatory for continued mission success. As such, we believe all future space missions

similar to Webb would benefit from an examination of these methods and adapting the approach to suit their mission needs.

The MIRI DGA-A move failure documented in AR-2173 and detailed in this paper resulted in the longest lapse in scientific functionality of any SI observing mode of the Webb Observatory to date. While our anomaly management methods ultimately led to a successful new concept of operation for MIRI’s medium-resolution spectroscopy mode, enabling its return to science operations with no failures or further degradation observed since, we have several significant lessons learned that would benefit other missions. First, it was tremendously beneficial and productive from a science execution perspective to be able to continue science observations with the other SIs and even with the MIRI Imager while MRS was down. Building such compartmentalization into the design of a mission should be done whenever possible.

Second, needing real-time commanding to execute friction torque trending data collection consumed a lot of time, cumulatively, that could have otherwise have been used for science observations. In this case for MIRI, the need for real-time commanding for friction torque trending data collection was due to the lack of architecture to downlink the diagnostic file created during the wheel trending moves. Other SIs, namely NIRCam, designed their FSW to send down data for every single mechanism move that is executed on-board. MIRI FSW was eventually updated with this capability, allowing OSS to execute the friction torque trending data collection, making it much more efficient operationally. We suggest future missions consider similar functionality for their FSW since mechanism moves are among the most common actions performed on-board and it is prudent to be able to access and analyze the entire dataset from all moves when the situation calls for it, like a move failure or other discrepancy.

Finally, we believe our experience with increased frictional torque in the central bearing assembly of the MIRI DGAs due to cage hang-up provides future missions with some valuable knowledge and insight we hope may be used to avoid similar failures. For elements with similar design and environments, it would likely be difficult to predict and avoid the conditions that may result in cage hang-up of a bearing system. However, it was the initial implementation of the JWST observation planning tool for MRS observations that was responsible for the operation of the DGAs in an unforeseen and undesirable manner, namely rotating almost exclusively in the forward direction, despite the hardware and FSW being designed to rotate the mechanism in both directions. Thus, we suggest future missions to examine the impact of subtle choices in their observation planning tools to the operation of their mechanisms before similar problems are encountered and result in the loss of observing time.

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