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What is it like to operate the James Webb Space Telescope?

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Abstract

As these words are being written in late June 2022, a team of scientists and engineers are conducting the final steps of commissioning the James Webb Space Telescope (JWST). From the launch on Christmas day 2021, the Space Telescope Science Institute (STScI) in Baltimore, Maryland has been the focus of activity to deploy, align and activate the telescope and its science instruments. Despite the daunting complexity of the observatory, each of the critical stages of commissioning were conducted more flawlessly than the team could possibly have imagined. The current day to day activity involves testing and characterizing each operating mode of the science instruments and processing actual observational data for the first time. By the time of the conference, you will have seen wonders of the universe revealed using JWST's ground breaking capabilities.

At STScI decades of preparations have been invested in getting ready to operate JWST. STScI engaged with NASA, the European Space Agency and the Canadian Space Agency from the very first formative stages of the mission, to define what science a large infrared space-based observatory could do, and to study how to implement such a mission. STScI worked with the international engineering and science teams through what proved to be a long design, development and testing process to get the observatory ready for launch. As a primary responsibility, on contract to NASA, STScI developed and built the JWST Science and Operations Center. STScI now conducts the science program for the mission, engaging thousands of astronomers from around the world, and performs flight operations of the telescope.

By the time of this conference, commissioning of the observatory will have been completed and the science program will be entering its eighth month. Early observations are demonstrating that as planned, the capabilities of this observatory are spectacular but how does the reality of operating JWST compare to the mission operations concept? This paper will discuss how operating an open architecture, cryogenic, 6.5 meter, segmented, deployable, infrared telescope at L2 compares with what was expected and prepared for.

Keywords: JWST, space telescope, operations, astronomy

Acronyms/Abbreviations

CCSDS – Consultative Committee for Space Data Systems
DSN – Deep Space Network
ERO – Early Release Observations
FGS – Fine Guidance Sensor
HST – Hubble Space Telescope
JWST – James Webb Space Telescope
L2 – second Sun Earth Lagrange point
MAST – Mikulski Archive at Space Telescope
MAZ – Micrometeoroid Avoidance Zone
MCC – Mid-Course Correction
MIRI – Mid-InfraRed Instrument

NIRCam – Near InfraRed Camera
NIRISS – Near InfraRed Imager and Slitless Spectrograph
NIRSpec – Near InfraRed Spectrograph
OSS – Operations Scripts Subsystem
OTE – Optical Telescope Element
RLP – Rotating Libration Point
SSR – Solid State Recorder
STScI – Space Telescope Science Institute
TAC – Time Allocation Committee
WFE – WaveFront Error

1. Introduction

1.1 Science themes

JWST is designed to explore four science themes:

- First Light in the Universe
- Assembly of Galaxies
- Physics of Star Formation
- Formation of Planetary Systems and the Conditions for Life

The science that will be performed by the observatory is not limited to these areas of research but the capabilities required for these four themes have provided a sound basis for design of a telescope and science instruments that enable a wide range of science investigations.

To carry out its scientific mission JWST observes in the wavelength range 0.6 μm to 28 μm . It has a 25 m² primary mirror that is diffraction limited at 2 μm and is passively cooled by a large sunshield to ~ 40 K. The observatory is outfitted with four scientific instruments, three that operate in the 0.6 μm to 5 μm wavelength range; NIRCam – a camera providing wide-field medium and narrow-band imaging, NIRSpec – a wide-field multi-object spectrograph, NIRISS – an imager and slitless spectrograph that is packaged with a fine guidance sensor (FGS); and one instrument that operates in the 5 μm to 28 μm wavelength range, MIRI – a mid-infrared imager and integral field spectrograph.

The primary mirror is segmented, comprised of eighteen 1.2 m hexagonal sections. This architecture enabled the mirror to be much lower in mass than a monolithic mirror and allowed it to be folded to fit into the shroud of the Ariane 5 launch vehicle. Each mirror segment is mounted on seven actuators that control its position and shape to precisely align it with the other segments. When aligned, the eighteen segments function like a single 6.5 m diameter mirror.

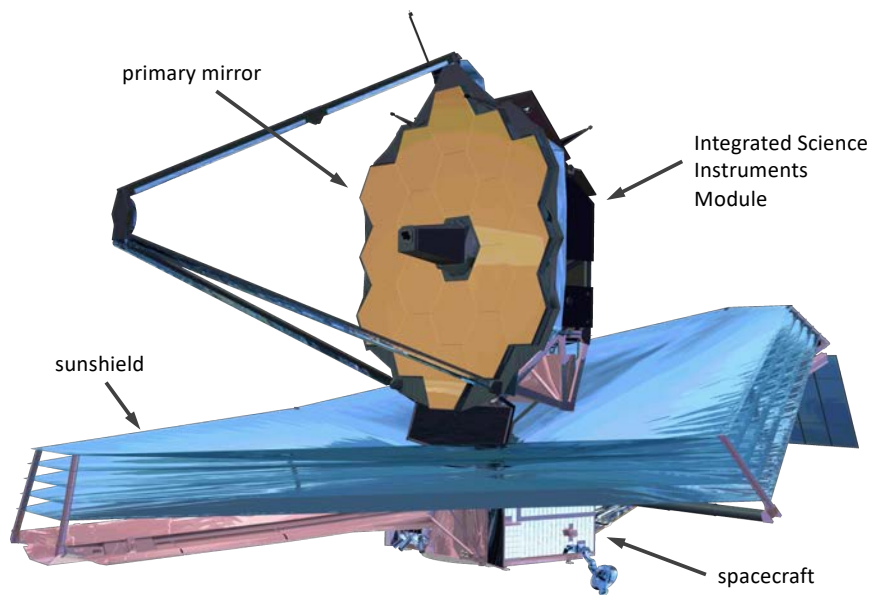


Figure 1 - JWST Observatory

1.2 Observing with JWST

JWST was developed for use by the international astronomy community. In consideration of the complexity of the science instruments and the observatory, STScI astronomers acquired in-depth knowledge of how to use JWST during development and testing of the observatory, so that they could make this expertise available to the astronomy community. On-line assistance is provided to proposers (a help desk) as is a large repository of documentation. A concerted outreach program has been conducted including Webinars on how to observe with JWST and process the science data.

The JWST operations data flow, illustrated in Figure 2, begins with and ends with the astronomers. Throughout the flow proposals cycle through a number of stages, preparation and submission, program selection, visit planning and scheduling, operation plan upload to the observatory, execution, science data download, data processing, archive and distribution.

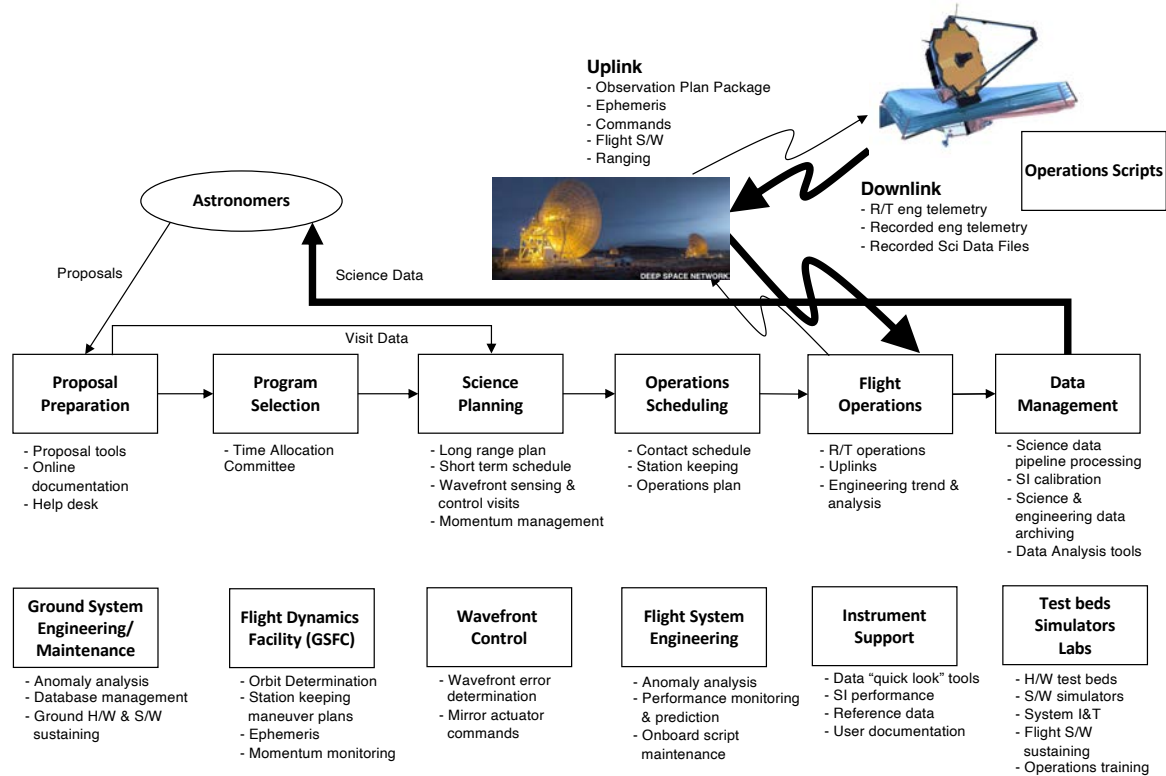


Figure 2 - JWST Ground Systems and Operations Data Flow

Observing cycles are initiated once a year when STScI issues a call soliciting science proposals from the international astronomy community. STScI provides a suite of software tools to enable astronomers to craft proposals for observations using the 17-science instrument observing modes. Through a double-blind peer review process, one year of observations are selected from the set of submissions. These are the proposals that constitute the “best” science, observations that will extend the boundaries of current knowledge and that can only be performed with JWST. The peer review is called the Time Allocation Committee (TAC) because the key resource that is being awarded to astronomers is observing time. The actual observing program is selected by the STScI Director based on the TAC recommendations. In the first two years of operations a portion of the available observing time is also granted to “guaranteed time” observers, members of the instrument development teams and the science working group. The annually awarded set of observing time is referred to as an observing cycle. Cycle 1 observations have been performed since the end of commissioning. Cycle 2 observations will commence in July 2023. Amazing images, spectra and science results have begun to flow.

1.3 Operations goals

The operational goal of the JWST mission is to execute a science program employing approaches that maximize the scientific productivity of the mission. Considering that the mission lifetime is finite, this includes optimizing the turn-around time from the initial receipt of data to science results and to subsequent observations.

In the time since the abstract to this paper was written, the science instruments were characterized and an Early Release Observation Program (ERO) was executed. The ERO programs showcase many of the observing capabilities of the observatory. The ERO data products were released on July 12, 2022 and proved to be immensely popular; more than 500 TB of data products were downloaded within a few days. At the same time as the ERO release, the science

data archive was opened to astronomers resulting in more than 40 TB a day of science data being downloaded. Data were staged on Amazon Web Services to accommodate the peak in activity.

The operations focus has been to transition the observatory into scientifically productive steady state “normal operations”. The performance of the telescope and of the science instruments are significantly better than requirements. Operations have been relatively smooth but not entirely as planned. As anticipated that there would be some differences between the operations concept and the actual behavior of the observatory.

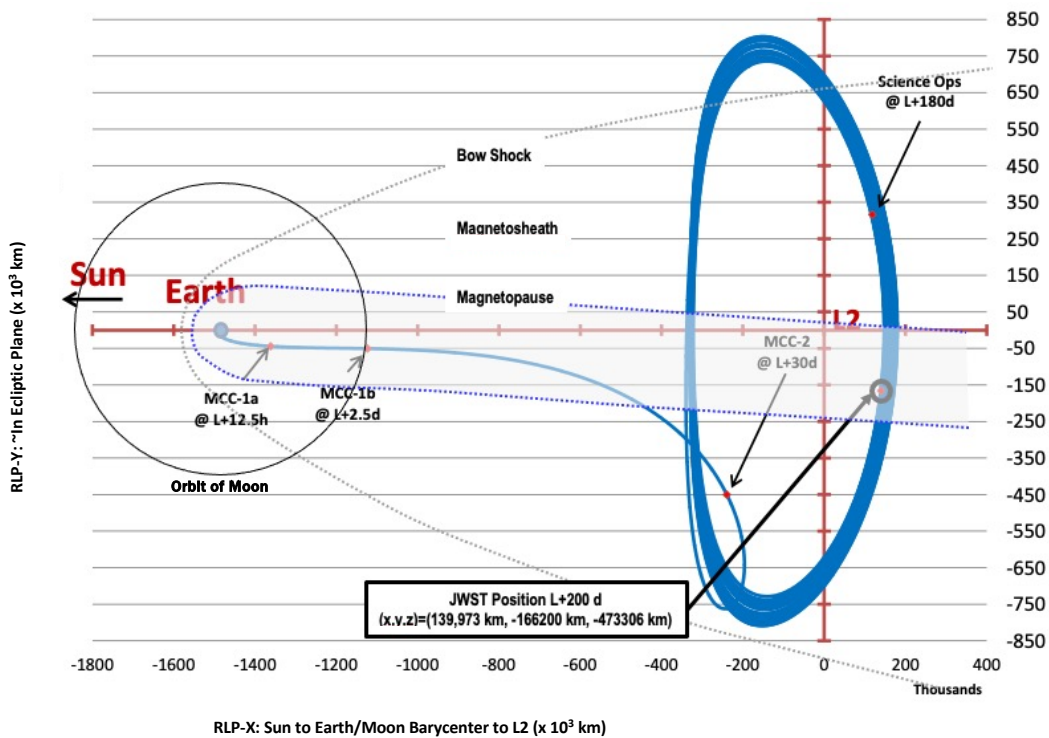
2. Mission Operations Concept

What is the mission operations concept and how do actual operations compare?

2.1 Orbit

The orbit is a key facet of the design and operations of the observatory. Ideally it provides a thermally stable environment at a distance that facilitates communication with the Earth. The JWST orbit is a Sun-Earth second Lagrange point halo orbit, that as shown in Figure 3, keeps the observatory “close” to Earth.

From the perspective of the observatory this orbit places all of the brightest sources of light, the Sun, the Earth and the Moon, in one region of the sky. By constraining the semi-major axis to less than 832,000 km, the optics and the science instrument module can be kept in darkness, shaded from these significant sources of illumination by a relatively flat sunshield. Similarly, bounding the semi-minor axis to less than 520,000 km above or below the ecliptic retains sufficient communication contact time with ground stations in the southern and northern hemispheres respectively. This orbit achieves the requirement of being thermally stable and affording good communications with the Earth.



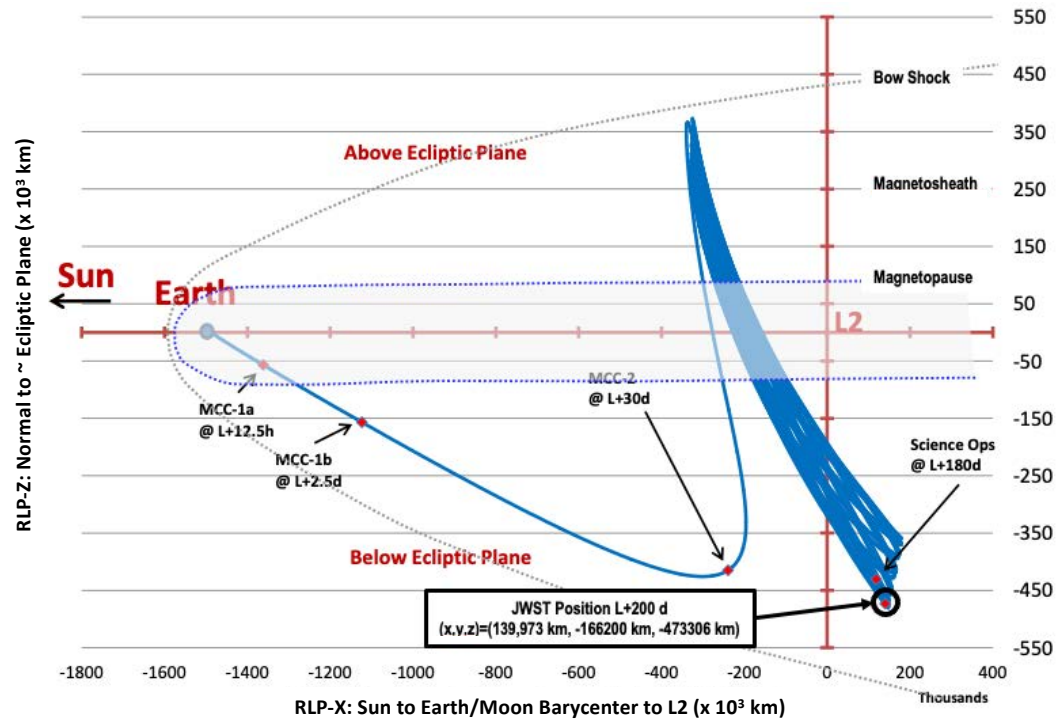


Figure 3 - JWST L2 Halo Orbit

2.2 Passive and Active Cooling

Low temperatures are necessary to operate infrared detectors and to prevent heat emitted by the telescope from swamping the faint infrared light from the astronomical sources the telescope is to observe. The multiple layers of the sunshield block light and radiate heat out the side from between the layers. This allows the portions of the observatory behind the sunshield to passively cool and to achieve a stable operating temperature.

The near-infrared instruments have detectors formulated with Mercury-Cadmium-Telluride with a 5 μm cutoff, that have an optimal operating temperature of 37 K. The mid-infrared detectors are made with Arsenic-doped Silicon. For them to function requires additional cooling to ~ 6 K. This is accomplished by a cryo-cooler, one of the technologies developed for the mission. An active cooler has the benefit that it is not lifetime limited by an expendable cryogen but the downside is that unless its pump is perfectly balanced it could create vibrations that would shake the optics and blur observations. To mitigate this the active vibrating portion of the cooler is located far from the detectors on the warm side of the sunshield, resulting in ten-meter-long lines being required to feed coolant to the cooling head at the detectors.

2.3 Field of Regard

The size and shape of the sunshield, the optical architecture and the orbit allow the observatory to point at targets within a donut shaped region sky while preventing the mirror and instrument module becoming illuminated (Figure 4 - Field of Regard). As the observatory orbits the sun, the field of regard sweeps over the celestial sphere making all points in the sky visible twice a year. Areas at the northern and southern ecliptic poles are continuously viewable. At any time of the year 39.7% of the celestial sphere can be observed.

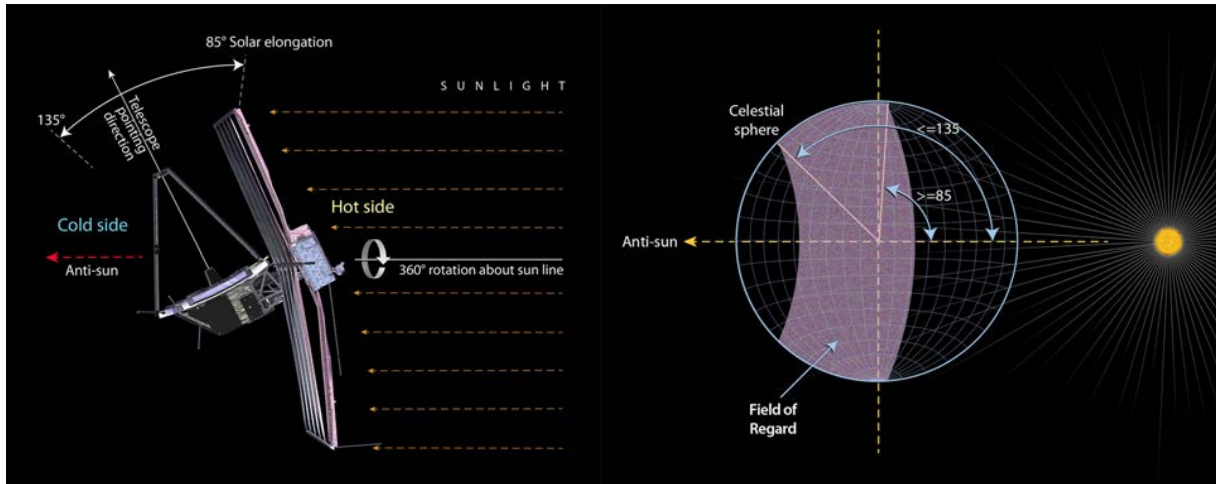


Figure 4 - Field of Regard

2.4 Communications

Being at L2, communication with the observatory requires large ground stations. JWST utilizes the Deep Space Network (DSN). Ground stations located at Goldstone in the United States, Madrid in Spain and Canberra in Australia provide good contact availability over the course of each day (up to continuous contact). The distribution of contacts between northern and southern hemispheres provides ranging and tracking data suitable for orbit determination.

The operations concept for communication with the observatory was to have a minimum of one four-hour DSN contact every 12 hours. In reality, the contact cadence and durations are somewhat less regular and have been normalized to a total of 12 hours per day. This change helps to contend with CCSDS File Data Protocol latency and other communication realities. More intensive planning and interaction with DSN has been required than anticipated but this has established a very good working relationship.

Data volume is an important consideration in science scheduling. Depending on the science instrument used and whether other science instrument observations are conducted at the same time (parallel observations) the data volume generated can exceed the volume that can be downloaded in a single contact. Missed contacts present an additional challenge. These are handled by managing the observing schedule to keep the stored data volume below a level that will allow the extra stored data resulting from a missed contact to be downloaded over the subsequent three contacts. If the solid-state recorder (SSR) becomes filled the observatory stops executing the science program, a circumstance to be avoided. The merit of the missed contact operations strategy has been demonstrated; several missed contacts have occurred. Only in one instance, because a high data volume observation had just completed prior to the missed contact, did the SSR become full causing the observatory to sit idle for a few hours.

Challenges arise not just from JWST operations alone. DSN is a shared NASA resource that is allocated in accordance with pre-established priorities. Being that JWST is a research mission, other missions that use the same wavebands such as the recent Artemis moon mission, can have a higher priority. During the Artemis flights when the moon is in a region of the sky close to JWST there is less antenna time available. The first launch opportunities for Artemis 1 in August 2022 presented planning problems for JWST because less than the required contact time was available for a period of weeks. To avoid filling the SSR and stopping science, observing schedules were prepared that were populated by low data volume observations. This strategy can provide some relief but it risks congesting the remainder of the observing cycle with time periods of high data volume science that could exceed the downlink capacity and the on-board storage volume. The silver lining to the Artemis 1 launch delays was that when the mission did launch its operations were conducted at a time when JWST and the moon were in different sectors of the sky thus reducing competition for DSN antenna time.

2.5 Planning and Scheduling

In the course of conducting science operations the observatory executes a series of visits, the basic unit of science operations. Each visit requires slewing the telescope with the reaction wheels to point at the target, identifying and locking onto a guide star using the FGS (guide star acquisition), and operating the science instrument to obtain the science data. Guide star information is stored in a catalog that has accurate positions and magnitudes of approximately

a billion stars. When observing a target requires acquisition of a different guide star, this is a separate visit. The data associated with each visit is packaged together in a self-contained file. Proposals from astronomers typically consist of many visits.

2.5.1 Long Range Plan

After the set of observing proposals that will constitute an observing cycle has been selected, the constituent visits of the proposals are assembled into a long-range plan on the order of a year in duration. In the long range plan the visits are assigned to a general timeframe. Developing a time efficient plan that satisfies constraints of target visibility, timing interdependencies, data volume and other factors requires a couple of months of effort by the planning and scheduling team.

For science Cycle 1, 266 observing programs were competitively selected from 1173 proposals submitted. These observing programs will be executed as 1886 visits. Combined with 778 visits for guaranteed time observations and 21 visits from an early release science program results in there being 2685 planned visits in Cycle 1.

2.5.2 Short Term Schedule

On an on-going basis, schedules of three weeks of operations activities are built from the visits in the long-range plan combined with communication contacts, momentum unloads, station keeping operations, mirror operations, other engineering activities, calibration visits, and parallel science visits (visits that can be performed at the same time as other visits). Every week an observation plan of seven days of operations is uploaded to the observatory. The upcoming week's schedule can be viewed on the STScI website at <https://www.stsci.edu/jwst/science-execution/observing-schedules>.

On-board operations are directed by the Operations Scripts Subsystem (OSS). OSS loads and reads the visit files in accordance with the observation plan, and issues commands to the observatory and to the science instruments. Safe operation is facilitated by the on-board fault management system that monitors telemetry to look for problems and places the observatory in a safe state if required.

During normal operations, when a new observation plan is uploaded, it is appended to the end of the observation plan already executing on board. Observatory operations are normally autonomous and can continue without interruption during communication contacts and during changes to the observation plan. Observation plan execution follows an event driven paradigm (Figure 5) wherein rather than beginning at a fixed start time, visits are executed during a plan window defined by an earliest start time and latest end time. This strategy is designed to make operations more efficient by allowing visits to slide forward in time and execute earlier should a prior visit fail (such as due to a guide star acquisition problem or an instrument fault).

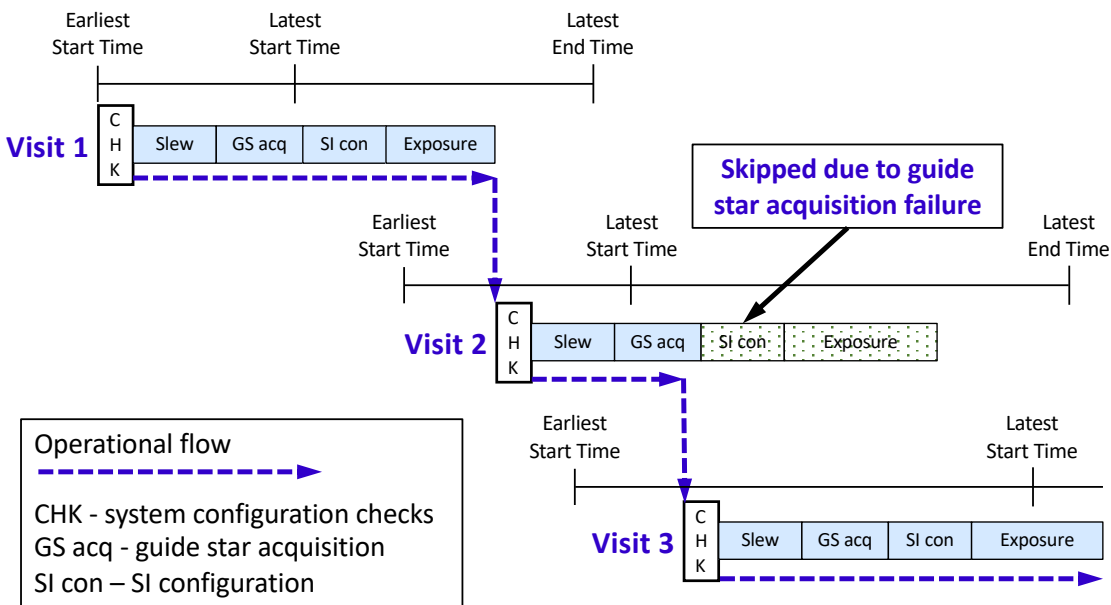


Figure 5 - Event Driven Operations

Complicating the scheduling, some science visits have highly constrained timing windows such as observations of exoplanet transits and of moving targets. There can also be interdependencies between visits such as timing gaps or a need for specific telescope orientations that may only be achievable at particular times of the year. As discussed in section 2.12 some operations are performed in real-time during contacts, such as station keeping and flight software loads. Many of these require interruption of the observation plan.

The goal in building the schedule is to maximize the amount of time the observatory spends observing science targets. The requirement is for the observatory to perform science observations 70% of the time. Early indications are that the actual efficiency is higher than the requirement.

2.6 Pointing and Target Acquisition

As mentioned in section 2.5, visits begin by slewing the observatory to bring the guide star into the field of view of the FGS. The slews are structured so that they also bring the astronomical target into the field of view of the desired science instrument, see Figure 6. A 90 degree slew from one pointing to another including acquisition of the guide star requires on the order of 60 minutes. Observations of targets can have durations ranging from a few seconds to tens of thousands of seconds. Once in the FGS field of view, pattern matching between the guider image and the guide star catalog checks that the correct guide star has been selected. Through a series of additional steps, the guide star is isolated within a small sub-array on the guider (that can be read out quickly) and the computed centroid location is used by the attitude control system to bring the pointing of the observatory within 0.1" of the commanded position. If necessary tighter pointing accuracy can be achieved through additional operational steps with the science instruments.

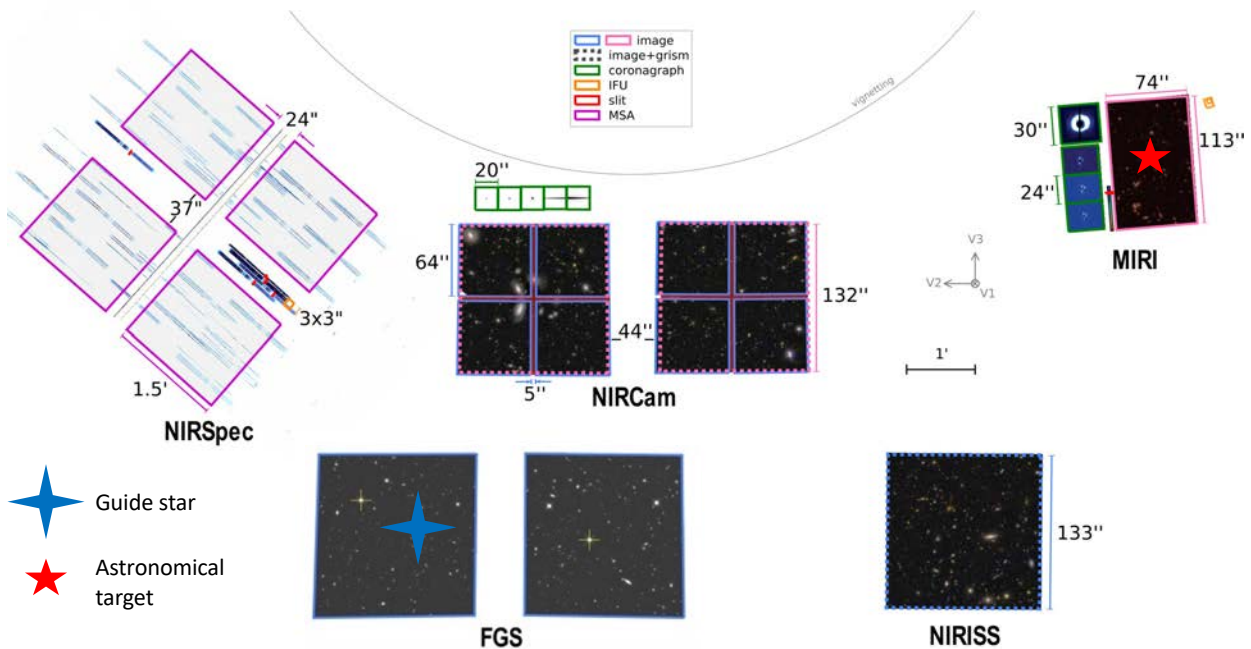


Figure 6 – Science Instruments Fields of View

The combined capability of the FGS and the guide star catalog should nominally provide a 95% probability of acquiring a guide star. In early observations performance was marginally lower than this. Failures to acquire guide stars resulted from a combination of factors, the improved resolution of JWST revealed that some of the guide stars in the catalog were actually extended sources (galaxies), a small fraction of guide star positions in the catalog were in error and some others were duplicates. Moreover, JWST is observing in the infrared whereas the catalog is predominantly based on shorter wavelength observations. A significant contributor to guiding problems is that the guide star is occasionally placed on a hot pixel in the guider detectors. Many of the initial problems have been resolved by updates to the guide star catalog and adjustments to the on-board guide star selection methodology. Updated hot

pixel maps are uploaded to the observatory every six weeks. The guiding success rate has risen to better than 96% in recent months.

Moving targets are conceptually similar to fixed targets except that since the observatory must track the moving target, the guide star will move in the FGS field of view. A single moving target observation can have several different guide stars, that transit into and out of the guider field of view during the observation. Per the operations concept moving target speeds of up to 0.030 "/s need to be supported to enable observations of objects in our solar system. During commissioning, observations of asteroids moving at more than double this rate were demonstrated (asteroid 464798). This accomplishment was eclipsed early in normal operations by successful observation of the Didymos - Dimorphos asteroid system during the Double Asteroid Redirection Test (DART) mission. The DART impact observation required tracking at a rate of 0.110 "/s, more than three times the design speed. Succeeding necessitated careful planning and on sky testing prior to execution but the observation did work, yielding images in nine out of twelve visits.

2.7 Momentum Management

The sunshield is subject to radiation pressure that applies a force and a torque to the observatory. To hold to a fixed attitude, the torque must be counteracted by changing the spin rate of the reaction wheels. When the wheels have spun up to a high rotation rate momentum is unloaded by firing thrusters.

The angular momentum of the reaction wheels is actively managed to keep within operational limits. As part of generating the weekly observation plan, the planning and scheduling system predicts the weekly momentum profile, and inserts commanded momentum unloads into the schedule as needed. Momentum unloads are executed autonomously under direction of the on-board script subsystem. The timing of momentum unloads is largely a consequence of the characteristics of the science program, the schedule of the targets observed, the pointing direction and the observatory attitude during those visits and their duration. At any time, target visibility within the field of regard determines the suite of targets that are available to be scheduled.

Orbit determination places an upper bound on how many momentum unloads can be performed during each 21-day station keeping cycle because each momentum unload disturbs the orbit. In practice this limit (8 in 21 days) has not been a factor. Since transitioning to normal operations in July 2022 only four momentum unloads have been performed, an average of one every seven weeks, far fewer than expected. One might conclude that science scheduling has generally not been constrained by momentum considerations.

2.8 Station Keeping

Because L2 is a saddle point in the Sun-Earth gravitational potential the orbit is not stable. Periodic station keeping maneuvers are required to maintain the orbit by firing on-board thrusters. Because of the safety-critical nature of these commands, station keeping maneuvers are carried out during ground contacts using stored command sequences. The minimum cadence is dictated by how long is required to achieve a sufficiently accurate measurement of the ephemeris by ranging with DSN. Pre-launch analysis established that station keeping should be performed every 21 days. Not allowing the time required for each burn to get too long reduces the fuel usage over the mission lifetime. Conceptually, executing station keeping maneuvers as soon as the ephemeris is determined minimizes the fuel use.

In practice the average time between station keeping maneuvers has been much longer than 21 days. Operating at the planned cadence proved not to be not beneficial because the required burns would have been so short that the thrusters would not even exit their transient thrust phase, resulting in a less predictable orbit correction. In November 2022 the planned frequency was changed to 42 days.

2.9 Wavefront Sensing and Control

Wavefront sensing visits, involve imaging a reference star and processing the image to determine the wavefront error, a measure of optical quality. These visits are performed once every two days to monitor the error and determine when to make corrections to the mirror shape by moving the actuators on the back of the mirror segments. The pre-launch plan was to perform corrections every 14 days. In practice through the first six months of regular science operations, only eight corrections have been required, an average of one every 24 days. As of the time of writing the last interval between corrections was 49 days. Also notable, the drift in the wavefront error has been less than modelled. Most corrections have been made when the error rises above a threshold of 80 nm rms whereas prior to launch the expectation was to correct when the error rose above 100 nm rms.

One of the drivers for the frequency of the mirror corrections is a phenomenon of tilt events. These are small relatively fast (~10 s) inclinations of a single mirror segment. Each tilt event has a measurable but usually modest effect on the overall optical quality but they can be of significance for some high precision observations. These events

are not entirely unexpected as some mirror segment tilts did occur during thermal vacuum testing. Over the time since launch, the frequency and the magnitude of the tilt events has been decreasing consistent with the expectation that they are a mechanical stress release phenomenon. To take advantage of the superior stability, the Wave Front Sensing and Control Team recently reduced the wavefront error correction threshold to 70 nm rms.

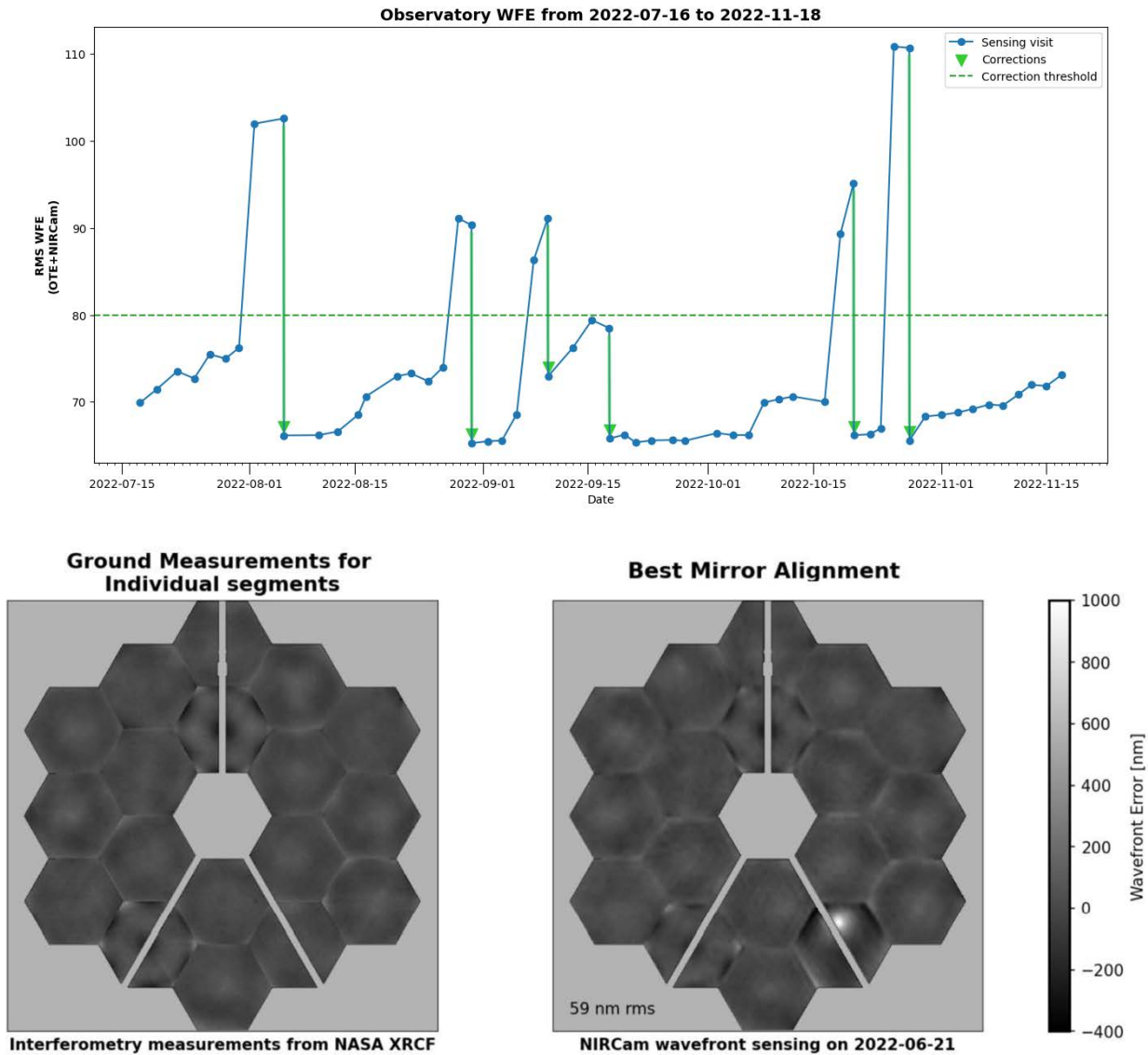


Figure 7 - Wavefront Error

2.10 Micrometeoroids

The primary mirror is experiencing about one measurable hit by a micrometeoroid each month (a measurable wavefront error increase). Given that the observatory has a large primary mirror exposed to space, it was expected that there would be impacts. The majority of the observed impacts match well to the pre-launch model. Degradation of the mirror surface due to impacts is incorporated into the lifetime budget for the wavefront error. One micrometeoroid impact that occurred in May 2022 caused a level of damage that is well outside what was expected.

Analysis of the May event has led to implementation of a Micrometeoroid Avoidance Zone. (MAZ). Visits will be scheduled to avoid pointing within 75 degrees of the ram direction of the orbit around the sun unless absolutely necessary to observe a science target. Pointing in the ram direction increases the average velocity of micrometeoroids by a factor of two, (from ~30 km/s to ~60 km/s) increasing the kinetic energy by a factor of four. Avoiding the ram

direction will reduce the frequency of high energy impacts. The goal is to spend less than 15% of the time pointing in the MAZ beginning in the second cycle of the science program. In addition, visits will be scheduled to avoid pointing in the direction of major meteor showers (the Geminids and the Quadrantids). Meteor showers should only affect two to four days of the schedule per year.

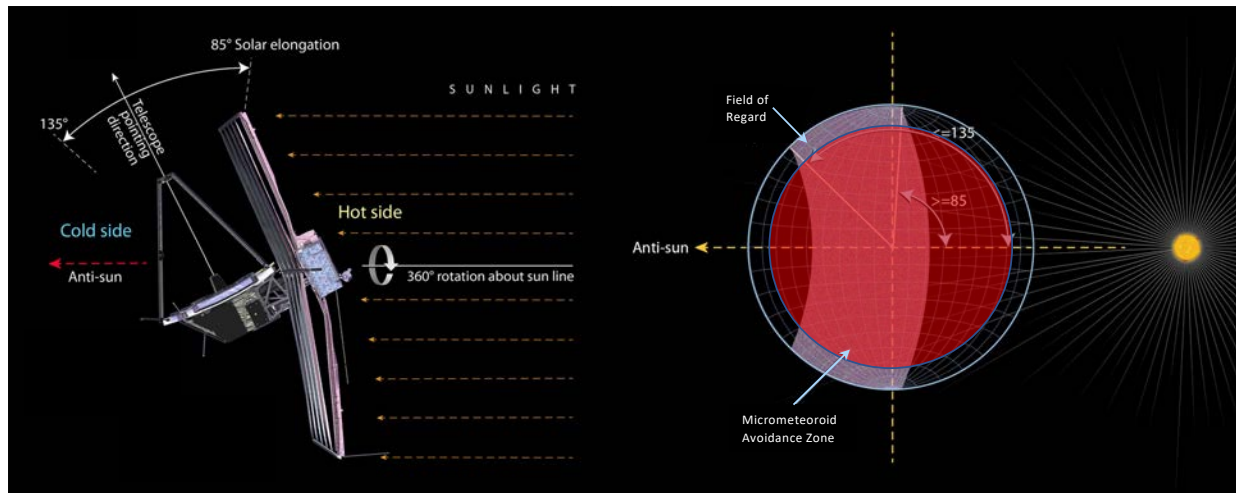


Figure 8 - Micrometeoroid Avoidance Zone

The astronomer's proposal tools have been augmented to advise observers when their proposed visits result in pointing in the MAZ and to require justification for doing so. Similarly, the planning and scheduling tools used by the science operations team have been modified to incorporate a constraint that avoids scheduling visits in the MAZ whenever possible.

2.11 Calibration and Data Management

Since the original data release in July 2022 archive operations have been relatively uneventful. JWST data is served through the Mikulski Archive at Space Telescope (MAST) which is a repository of data from many space telescopes including the Hubble Space Telescope (HST). By contrast, the data pipeline that feeds data to the archive has been experiencing very heavy data processing loads that have slowed science data calibration. Science data are reprocessed whenever new calibration reference files are obtained. In the steady state data accessed through MAST are required to have been processed with the current calibration 95% of the time. Initially science data processing used calibration files developed from ground tests and early commissioning observations. When new flight calibration data became available the entire archive of JWST data began to be reprocessed. The combination of the frequency of the availability of new calibration reference files, the data volume in the archive and how broadly each reference file applied to existing data, outstripped the pipeline's capacity to reprocess the archived data. Judicious management of the updates and prioritization of the data sets to which they were applied have ultimately allowed reprocessing to begin to converge on the requirement.

2.12 Real-Time Operations

The frequency of real-time engineering activities (such as science instrument reconfigurations, observatory recovery operations, and software patches) has been decreasing since the observatory was in continuous contact during commissioning (Figure 9). Conversely, the time periods when operations are executed under direction of the OSS without real-time intervention are becoming longer. While regular staffing in the flight control room is down to the time periods around and during contacts (Figure 10), the frequency of real-time engineering activities beyond communication contacts has not yet consistently reached the anticipated target of one set of activities per week.

Some of the real-time activities result from fault management system responses. Since launch, the fault management system has suspended science operations on ten occasions, putting the observatory into one of the multiple levels of safe states. The majority of these resulted from nuances of the control system behavior and system level interactions. There have also been instances when individual science instruments transitioned into a safe state due to unexpected telemetry. In all cases investigation of the underlying causes was quickly undertaken, and appropriate steps

were executed to bring the observatory safely back into operation. At the time of writing a science instrument investigation is ongoing. It pertains to high torque experienced when rotating the MIRI Medium Resolution Spectroscopy grating wheel. Operational procedure changes have allowed MIRI to be operated while additional diagnostic telemetry is being obtained. Actual impacts to the science program from operational anomalies have been few, because in the normal course of planning, observations that do not execute as originally scheduled are rescheduled at future times. Only observations of transient phenomena such as a particular supernova are usually not able to be replanned.

Other real-time engineering activities are necessarily conducted for more routine functions, hot pixel map updates, periodically clearing stuck bits, and deploying software updates. The mission is in that post launch phase during which we are learning the actual on-orbit behavior of the flight systems and optimizing the operations processes.



Figure 9 – Commissioning Operations Rehearsal

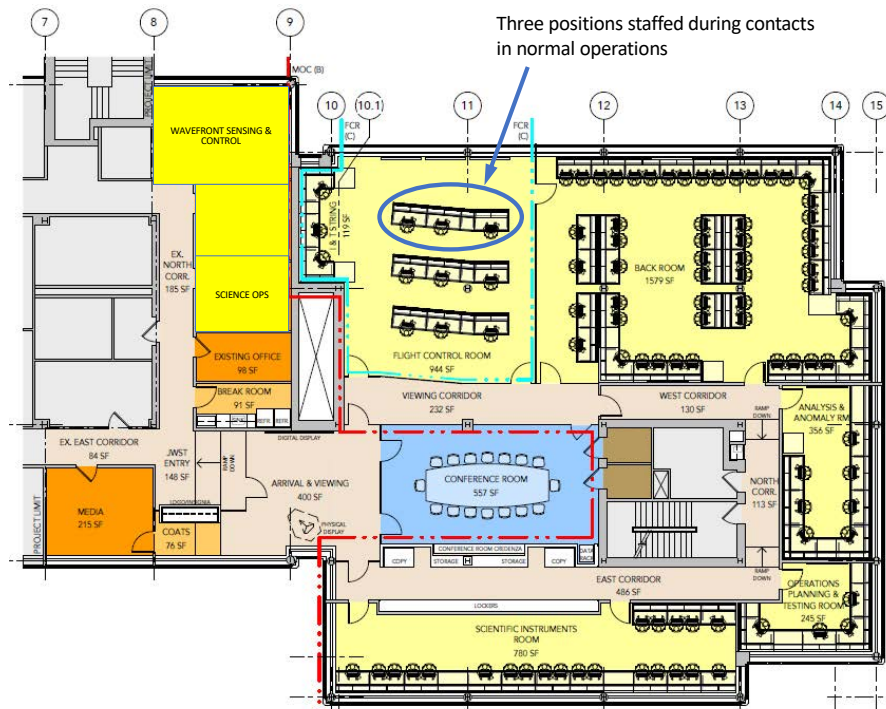


Figure 10 – Normal Operations Staffing During Contacts

3.0 Operations Cadence

The Mission Operations Concept for JWST envisioned on-going operations falling into a regular cadence that is illustrated in Table 1. For the most part that has been achieved and the frequency of some activities is beneficially lower than predicted but some operational activities are still transitioning to a steady state.

Table 1 - Operations Cadence

Activity	Planned Frequency	Frequency if different
Communications contacts	twice daily	>= twice daily
Recorded data playback	each contact	
Clock correlation	each contact	
Ranging	each contact	
Wavefront sensing	every 2 days	
Wavefront correction	every 14 days as needed	~ every 24 days
Observation Plan uploads	weekly	~ twice a week
Momentum unloads	as needed (< 8 in 21 days)	~ every 7 weeks
Ephemeris updates	weekly	
Station keeping	every 21 days	every 42 days
Contact schedule updates	weekly	
FGS hot pixel map updates	as needed	~ every 6 weeks

Short-term schedule and operations plan management has so far been a more frequent and labor-intensive activity than expected. STScI conducts science operations for the HST mission with the same team that operates JWST. HST operations are not event driven but are scheduled for and execute at predetermined absolute times. For JWST event driven operations have been successful in avoiding having the observatory sit idle when a visit fails to execute, whereas if a visit fails to execute on HST, the observatory waits without observing until the start of the next visit. While the event driven approach results in gains in observing efficiency, so far the paradigm has been found to require more active management of the short-term schedule and more frequent updates to the loaded operations plan. Advancing to the next visit in the observation plan when a visit fails also causes the accumulated momentum to differ from that predicted and results in differences from the expected data volume. It can also cause potential gaps downstream in the short-term schedule that require new visits to be scheduled. To date on average two observation plans per week have been uploaded, this is twice the expected frequency. As the science operations team gains experience with JWST they are examining strategies to optimize the workload. For now, while the cadence of the uploads has been slowly decreasing, managing the schedule for event driven operations seems likely to remain a more resource intensive activity than for a fixed time schedule.

4.0 Characteristics of the Science Program

One of the JWST science advisory committees noted that the combined effect of the annual observing cycle and the time required to analyze science data from observations would result in many Cycle 1 programs not being followed up until Cycle 3 or later. With a nominal operating life of only five observing cycles, they suggested that opportunity to fully investigate observed phenomena with JWST would be limited. The committee recommended that STScI should from the very beginning of the science program be prepared to operate JWST as efficiently as the HST was operating even though HST was decades into operations. While sounding like a daunting challenge STScI was already on a course to achieve most aspects of this. Delays in the launch provided opportunity to develop additional data analysis tools that help to quickly turn data into science. Extensive rehearsals, not so much of commissioning but of normal operations were crucial to achieving a smooth transition into regular on-going observations. A concerted effort was also already conceived of, to provide the astronomy community with tutorials on how to observe with JWST and how to process JWST data. This too has been beneficial in getting results flowing from what is undoubtedly the most complex space-based observatory ever flown.

Fundamentally operations of the observatory are driven by the interests of the observers and the nature of the science questions that they pursue. The operations concept for JWST was initially guided by an expectation that the observatory would often be used to perform long deep exposures. Some of the observations do, but the observatory is

so much more sensitive than prior observatories that ground breaking science can be achieved even with short exposure times. Evidence that there would be many short exposures emerged years before launch through design reference mission studies in which astronomers were invited to prepare proposals for science they would like to conduct with JWST. These studies used early versions of the actual proposal preparation tool. Two iterations of the design reference mission, each of which generated more than a year of candidate observing programs, served as vital tools for exercising the science software and for guiding operations and design decisions. The actual Cycle 1 science program reflects what astronomers showed us in these exercises, that JWST would produce cutting edge results from the very beginning of the mission.

5.0 Conclusions

The JWST Mission is early in its operations phase, still in the time period when the actual on-orbit behaviors of the flight systems are being revealed. The observatory is performing exceptionally well, in a manner that is very similar to how its operation was envisioned but with enough differences to give the operations, engineering and science teams interesting and engaging challenges.

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