Science operations with the James Webb Space Telescope

Jane Rigby, George Sonneborn (NASA Goddard Space Flight Center),
Joe Pollizzi, Thomas Brown, John Isaacs (Space Telescope Science Institute)

ABSTRACT

The James Webb Space Telescope (JWST) will be a powerful space observatory whose four science instruments will deliver rich imaging and multiplexed spectroscopic datasets to the astronomical and planetary science communities. The ground segment for JWST, now being designed and built, will carry out JWST's science operations. The ground segment includes:

* software that the scientific community will use to propose and specify new observations;
* software that will schedule both science and calibration observations in a way that optimizes observing efficiency while managing the accumulation of momentum;
* the infrastructure to regularly measure and maintain the telescope's wavefront;
* orbit determination, ranging, and tracking;
* communication via the Deep Space Network to command the observatory and retrieve scientific data;
* onboard scripts that execute each observing program in an event-driven fashion, with occasional interruptions for targets of opportunity or time-critical observations; and
* a system that processes and calibrates the data into science-ready products, automatically recalibrates when calibrations improve, and archives the data for timely access by the principal investigator and later worldwide access by the scientific community.

This ground system builds on experience from operating the Hubble Space Telescope, while solving challenges that are unique to the James Webb Space Telescope. In this paper, we describe the elements of the JWST ground system, how it will work operationally from the perspective of the observatory itself, and how a typical user will interact with the system to turn his/her idea into scientific discovery.

Keyword list: James Webb Space Telescope, operations, telescopes, observatories, scheduling, ground system

1. INTRODUCTION

The James Webb Space Telescope[1,2] will be a passively cooled (40 K), extremely sensitive observatory with a 6.5 meter diameter primary mirror. Its four science instruments NIRCam[3], NIRSpec[4], MIRI[5], and NIRISS[6] LINKS will have spectroscopic and imaging capability over a wavelength range of 0.7-28 micron, with modes that include coronagraphy, integral field spectroscopy, and multi-object spectroscopy. The science instruments are part of the Integrated Science Instrument Module[3].

1.1 Science goals

The four primary science themes for JWST[8] are First Light and Reionization, The Assembly of Galaxies, The Birth of Stars and Protoplanetary Systems, and Planetary Systems and the Origins of Life. These four science themes set the science requirements for the mission, which will result in a highly sensitive observatory capable of pursuing a wide variety of scientific investigations, from the formation of our solar system to the formation of the first galaxies.

Subsequent whitepapers[9] have added supplemental science cases, and have updated the four science themes to reflect progress in certain rapidly-changing subfields. At the 2011 workshop, "Frontier Science Opportunities with JWST"[10], the scientific community developed additional innovative science programs for JWST.

1.2 Comparison of JWST operations to those of current space observatories

JWST's operations have many similarities to the operations of current space observatories Spitzer, Chandra, and Hubble. As is true for those observatories, the vast majority of observing time will be allocated to guest observers, with time allocated through a competitive process of peer review. A minority of observing time in the first three cycles will be reserved for the science working group and the principal investigators of the science instruments. In a typical day, the observatory will execute observations from several different science programs; the resulting data will be downlinked, reduced into science-quality products, and archived, with the principal investigator receiving notification when the data are ready for retrieval. Most data will have some proprietary period, after which the data will be publically available for download from an internet archive.

However, in several key ways, operations with JWST will be quite different than with previous observatories. First, both JWST flight operations and JWST science operations will be run by the Space Telescope Science Institute (STScI) in Baltimore, Maryland, which will be responsible for the health and safety of the observatory. By contrast, for Hubble these functions are separate: flight operations are run by the NASA Goddard Space Flight Center (GSFC) in Greenbelt, Maryland, while science operations are run by STScI.

Second, JWST will orbit the second Sun-Earth Lagrange point (L2), which is four times further from the Earth than is the Moon. As such, JWST will not suffer the Earth occultations that block most targets from view for half of each Hubble orbit. Thus, JWST has the potential for higher observing efficiency than Hubble, but has no occultations in which to "hide" slews and other non-observing functions. Also, JWST is a physically larger telescope that will be slower to slew than Hubble or Spitzer, and as such, slewtime is expected to be a significant source of overhead for the observatory.

Because JWST employs a large sunshade and is passively cooled (rather than actively cooled by evaporation of cryogen), its lifetime is limited by propellant, not cryogen. JWST will use propellant for three purposes: to fire mid-course corrections to arrive at L2; to dump angular momentum from the reaction wheels (which are torqued by net solar radiation pressure); and to keep station in orbit around L2. The propellant has been sized for ten years of operations. JWST will make station-keeping maneuvers at a nominal frequency of 21 days, and dump angular momentum as needed.

Unlike Spitzer, JWST will not be confusion limited[11,12]. As such, long integrations should build sensitivity as the square root of time, enabling extremely deep observations of deep fields. However, one expects that JWST will also make a large number of short observations, since any targets bright enough to have been previously discovered by Spitzer, Hubble, or other observatories will only require short integrations with JWST, given JWST's dramatically better sensitivity[13]. Science operations will need to seek efficiencies for both long and short observations.

JWST's mirrors and science instruments must remain in the shadow of its sunshield. As a result, like Spitzer but unlike Hubble, at any one time JWST will be able to observe an annular portion of the celestial sphere, which in JWST's case encompasses at least 35% of the sky. This "field of regard" rotates as the observatory orbits the sun, such that any point on the celestial sphere can be observed over the course of a year. Much like Spitzer, most points on the celestial sphere will be observable for two windows per year, approximately two months in duration. For a given target, the amount of mid-infrared zodiacal light varies predictably and significantly (factor of ~2) through these windows. Thus, the scheduling software must be capable of calculating these observability windows and the expected background levels, and of scheduling zodiacal-limited observations when the background is predicted to be low.

2. JWST SCIENCE OPERATIONS AS A SYSTEM

The scientific operations of JWST will be managed by a multi-component ground system. Before discussing each component of this system in detail, we consider the system as a whole – the look and feel of JWST operations, as seen by two different perspectives – by a typical scientific user, and by the space telescope itself.

2.1 A scientific user

We now consider JWST operations from the perspective of a scientist in the community. Approximately 1,450 unique principal investigators have used Hubble[14], and 750 have used Spitzer[15], each with a greater number of co-investigators. We expect that JWST will also have a large, broad user community.

The lifecycle of a JWST scientific program begins when a scientist, perhaps inspired by previous data from JWST or another space or ground-based telescope, has a great idea – for how a set of specific JWST observations can answer an unsolved problem in astrophysics or planetary science. The scientist justifies the importance of this unsolved problem and explains how the observations can solve it, by writing and submitting a proposal to the cyclical JWST Call for Proposals. During the proposal-writing process, the scientist and her team of co-investigators refer to handbooks that define the capabilities of the observatory and its instruments, as well as exposure time calculators that estimate the integration times required to achieve the proposal's science goals.

The proposal is evaluated by a panel of peer experts, and is ranked sufficiently highly to be selected. As principal investigator of this approved program, the scientist uses a SOC-provided planning tool to specify every technical detail of the observations, from the science instrument modes to be used, to the target location, dither position, filter, and detector readout mode. If necessary the scientist constrains the observations, for example by specifying an absolute time window (for time-critical observations such as exoplanet transits), by providing an ephemeris for moving targets, or by specifying that a given observation must be observed before or after another.

The observations are checked and ingested by the SOC, worked into the long-term schedule of the observatory, and eventually added to the weekly schedule that is uploaded to the observatory. Automatic notifications are sent to the scientist when observations are pending, and again when the observations have executed and the data are ready in the archive. Because the scientist completely specifies the observations in advance, she plays no part during the actual data acquisition, unlike at most ground-based observatories.

After the data are relayed to earth and processed, the scientist downloads the processed, science-ready data from the archive, and analyzes them using a combination of JWST-specific SOC-developed software tools and general open-source tools. Her team's analysis is financially supported in part by guest observer funds. The scientist and her team write a paper describing the data and results, which they submit to a peer-reviewed scientific journal. These results may inspire follow-on JWST proposals, in which case the cycle begins anew.

2.2 The observatory

We now consider JWST operations from the perspective of the observatory. Approximately weekly, JWST will receive new commands from the ground, including roughly a week's worth of scheduled scientific observations and calibration observations. The observatory will step sequentially through the list, checking that each target is observable, and skipping any that are not. If an observation fails, for example because of a failed guidestar acquisition, the observatory will continue on to the next observation if it can safely begin. In a typical week, the observatory will execute a mix of science operations, calibrations, and observatory maintenance functions such as wavefront monitoring.

During science operations, JWST's high-gain antenna will contact a ground station and send back data for roughly four hours. The observatory will make two such contacts per day.

3. THE COMPONENTS OF THE JWST GROUND SYSTEM

As shown in Figure 1, the ground system is one of the three segments of JWST, along with the observatory segment and the launch segment. The ground system is in turn divided into three elements: the Science & Operations Center (S&OC), institutional systems, and common systems.

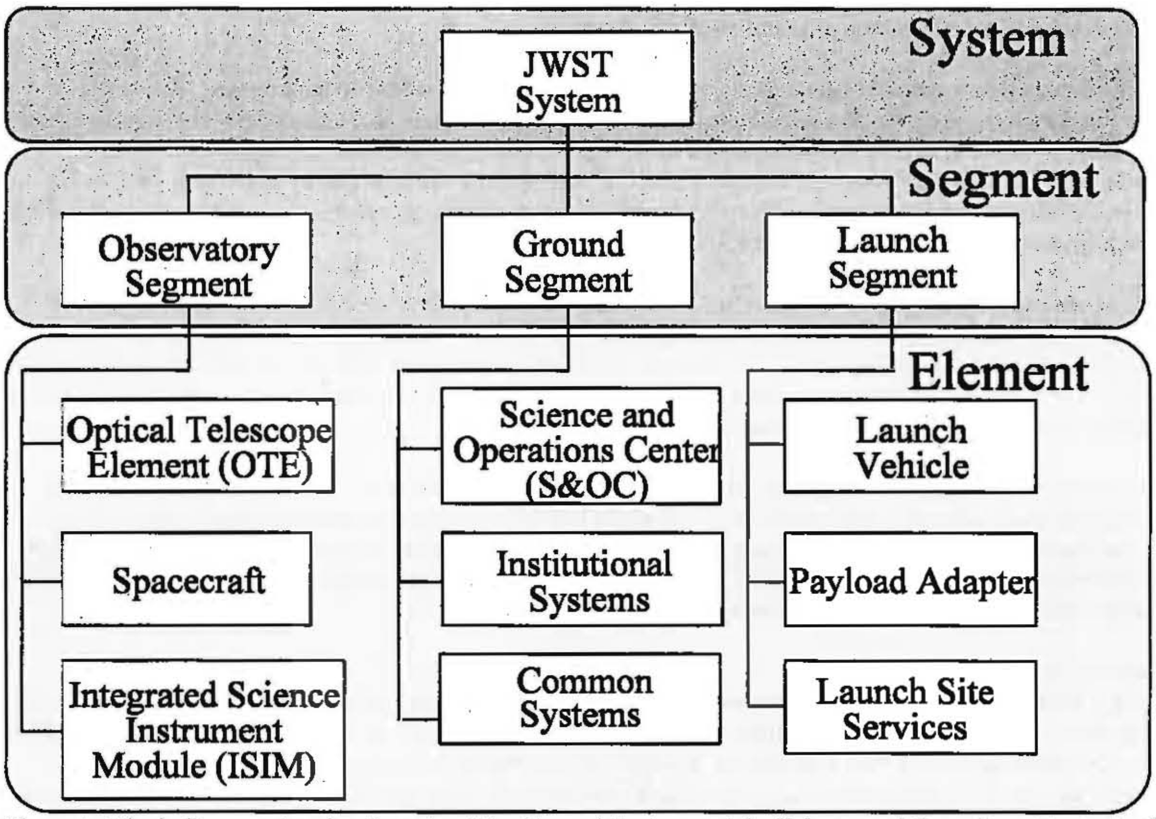

Figure 1: Block diagram showing the role of the Ground System and the Science and Operations Center in the JWST mission.

The JWST ground segment's institutional systems are made up of government resources including the Deep Space Network (DSN) which provides the communications links between the observatory and the Earth, the Goddard Space Flight Center's (GSFC) Flight Dynamics Facility (FDF) which provides orbit determination and tracking and ranging support., and the NASA Integrated Services Network (NISN) which provides the telecommunication services to transmit the data between the deep space network and the science operations center.

The JWST ground segment's common systems are common to both the integration and test phase of the mission and to the science operations phase. These include: the Common Command and Telemetry System (CCTS) which communicates with the observatory to provide real-time commanding and health and safety monitoring; the project reference database (PRD) which manages and distributes configuration--controlled mission data used in development, integration and test, and operations; and the Integrated Ground Support Systems (IGSS) which supports the developing and testing of the JWST science instruments, the integrated science instrument module, and the PRD.

The Space Telescope Science Institute (STScI) is contracted to develop and run the JWST science operations center (SOC). The SOC will be responsible for operating JWST by executing science and mission operations, enabling users to plan their investigations, and capturing calibrating, archiving, and distributing the data.

We now summarize the components of the science and operations center, and the role of each component in science operations.

3.1 Proposal planning

The goal of the proposal planning subsystem is to process scientific ideas into scheduled observations. Using tools from this subsystem, prospective users will explore observing strategies, calculate exposure times, and submit observing proposals as well as fully specified observing plans (which will either be due at proposal time, or in a later "Phase II").

The subsystem will process submitted proposals through the peer review process, and send accepted proposals to the scheduling software, which will generate long-range schedules and short-term observation plans. The subsystem will also manage grants to investigators.

The prospective user will use this system when designing his observations. From among a rich set of scientific capabilities choices (four science instruments with a variety of spectroscopic and imaging modes, grisms and filters, and a variety of readout modes), potential users will define their observations via a planning tool. To determine the integration time required for these observations, proposers will use exposure time calculators that calculate instrument sensitivity, expected background levels, and signal-to-noise ratio for a given observing setup. In addition, for NIRSPEC spectroscopy, users will use a tool to specify the configuration of the microshutter array, a procedure similar to laying out spectroscopic multi-object masks on a ground-based telescope.

The scheduling software will evaluate the entire pool of observations for a given cycle and smoothly place them into a long-range plan. Scheduling JWST observations is an optimization problem with multiple constraints. Known constraints are that most targets are only observable for a fraction of the year; the zodiacal background level changes dramatically during those observable windows; total slew times should be minimized to increase observing efficiency[16]; some observations will have absolute timing or relational ("Two to six weeks after A, do B") constraints; the telescope wavefront must be regularly monitored and maintained; and momentum must be dumped regularly. In addition, there is the possibility that the scheduling software might also optimize the schedule to limit the rate at which angular momentum builds up in the reaction wheels. Additional constraints might arise; for a tangential example, as the Chandra X-ray Observatory ages its schedule is increasingly restricted thermally to avoid overheating. The goal of scheduling is for each observation to be scheduled in a time window when it can be safely observed by JWST, when any special constraints are satisfied, and (if relevant for that observation) when the background Zodiacal light is relatively low.

The scheduling of JWST is described in more detail in [17].

3.2 Communications

The detectors on JWST's science instruments have many pixels and read out frequently – these two factors mean that JWST generates a high rate of science data. JWST's communications system is designed to send commands from Earth to the observatory, and to downlink engineering telemetry and the large volume of science data back to Earth. JWST will communicate with the ground via NASA's Deep Space Network (DSN), using the Goldstone, Canberra, and Madrid stations, in Ka band (26 GHz), at a selectable downlink rate of 7, 14, or 28 Megabits per second. Each four-hour contact can downlink 229 Gigabits of science data; two contacts per day are planned during normal science operations. JWST communications are described in more detail in [18].

3.3 Flight dynamics

The Flight Dynamics Facility (FDF) at the NASA Goddard Space Flight Center will be responsible for ranging, tracking, determining the orbit of JWST, and verifying the results of orbital maneuvers. Key maneuvers will be the mid-course corrections required to insert JWST into orbit around the second Earth-Sun Lagrange point (L2), as well as subsequent maneuvers to maintain the orbit around L2, as well as maneuvers to dump the angular momentum from solar photon pressure that accumulates in the reaction wheels.

3.4 Flight operations

The flight operations subsystem will send commands to the observatory, capture telemetry, monitor the status of and detect anomalies in the observatory and the ground system, protect the health and safety of the observatory, and send updates to the flight software.

3.5 Onboard scripts

JWST is event-driven rather than timing-driven, meaning that it will sequentially step through a list of scientific observations, skipping any that fail (for example, because of failure to acquire a guide star. This method can be contrasted with the real-time scheduling used by Hubble, under which if an observation fails, the observatory sits idle until the next observation is scheduled to begin. The motivation for event-driven operations is increased observing efficiency. Though normal operations are event-driven, it is possible to schedule observations that must occur at a specified time, or within a time window (for example, transiting exoplanets). In addition, targets of opportunity (for example, a high redshift gamma ray burst) can be added to the schedule on less than two days' notice.

JWST's event-driven operations will be provided through the use of an on-board JavaScript engine. This methodology builds on that used for Hubble instruments. Approximately weekly, a set of event-driven text file scripts will be sent from the JWST ground system to the observatory for on-board execution. Each of these visit files contains an ordered list of activities, for example a slew, a target acquisition, and a set of exposures with dithers and filter wheel moves. Onboard scripts are described in more detail in [19,20].

3.6 Wavefront sensing and control

The wavefront sensing and control subsystem monitors the optical performance of the observatory. It uses NIRCam images to detect the observatory wavefront error and, where necessary, compute the appropriate corrections to send to the mirror actuators. This system is critical to commissioning the telescope and maintaining its performance over the mission. The mirror management subsystem is developed by Ball Aerospace and Technology Corporation.

3.7 Data management

The JWST data management subsystem will reformat the data from telemetry to FITS standard, associate related observations, process the science data into calibrated, physical units, and store the data in an archive. Each instrument will have a calibration pipeline; a calibration reference database will assign appropriate calibration frames to each science dataset. Where possible, the pipelines will share common modules (for example one task with suitably adjusted parameters, can measure slopes for several different JWST instruments.) The resulting data products will be "science-ready", in that the calibrations will be reliable and the data will be in physical units, for example right ascension, declination, and flux density for images, and wavelength and flux density for spectra. It is not yet clear how much extra user processing may be required by the user for the most specialized modes, for example coronagraphy.

The Hubble archive processes data "on the fly" as users request them, which has the advantage that the user will always receive data with the latest calibrations applied, and the disadvantage that users must wait minutes to hours (days in the past, especially during peak usage) for the data to process. By contrast, the Spitzer cryogenic archive was reprocessed several times over the course of the cryogenic mission. The advantage was that data were immediately available for downloading but the disadvantage was that the data often had out-of-date calibrations, and the user had no choice but reduce from scratch, or wait weeks to months for the reprocessing wave to catch up to the desired datasets.

The plan for JWST incorporates the best aspects of these two approaches: most datasets will be immediately available for download as with Spitzer, but downloaded datasets will always have the latest calibrations as with Hubble. The method for achieving this is to have the archive automatically reprocess data when relevant calibration files are updated. In this scheme, integrated over a year, almost all data will be immediately available for download with current calibrations; a small minority of data will require reprocessing with the latest calibrations before they can be downloaded.

As with current NASA space observatories, most JWST science data will have a proprietary period, after which time they will become public. Eventually all JWST scientific data will be publically available for download. As with Spitzer, Hubble, and Chandra, the rich archival datasets from JWST should enable considerable scientific return beyond the original intent of the PI who proposed the observations. As evidence of this, in recent years 35% of new Hubble publications have used archival rather than new observations[21].

The JWST data management subsystem is described in more detail in [22].

3. SUMMARY

To summarize, the James Webb Space Telescope will have thousands of users, who will interact with the JWST ground system to plan, execute, retrieve, and help analyze their scientific data. Behind the scenes, the ground system will schedule the telescope efficiently, keep the observatory safe and healthy, and process, calibrate, and archive the data. The ground system to accomplish these tasks is being built and tested now; it builds on the success of and lessons from current NASA space observatories.

4. REFERENCES

[1] Sabelhaus, P., Campbell, D., Clampin, M., Decker, J., Greenhouse, M., Johns, A., Menzel, M., Smith, R., & Sullivan, P., "An Overview of the James Webb Space Telescope Project", Proc. SPIE 5899, 241-254
[2] Clampin, M., "Overview of the James Webb Space Telescope Observatory", Proc. SPIE 8146 (2011)
[3] Horner, S., Rieke, M., & the NIRCam Team, "The Near Infrared Camera for the James Webb Space Telescope", Proc. SPIE 5487, 628-634 (2004)
[4] Posselt, W., et al., "NIRSpec: near-infrared spectrograph for the JWST", Proc. SPIE 5487, 688-697 (2004)
[5] Wright, G. et al., "Design and development of MIRI, the mid-IR instrument for JWST", Proc. SPIE 7010, 27 (2008)
[6] Rowlands, N. et al. "The JWST fine guidance sensor", Proc. SPIE 5487, 664-675 (2004)
[7] Greenhouse, M., et al., "Status of the James Webb Space Telescope Integrated Science Instrument Module System", Proc. SPIE 8146 (2011)
[8] Gardner et al., "The James Webb Space Telescope," Space Science Reviews 123, 485–606 (2006)
[9] http://www.stsci.edu/jwst/doc-archive/white-papers/
[10] Workshop, "Frontier Science Opportunities with the James Webb Space Telescope", http://www.stsci.edu/institute/conference/jwst2011
[11] Dole, H., et al, "Confusion of Extragalactic Sources in the Mid- and Far-Infrared: Spitzer and Beyond", ApJ, 154, 93-96 (2004)
[12] Windhorst, R., Haithi, N., Cohen, S., Jansen, R., Kawata. D., Driver, S., & Gibson, B. "High resolution science with high redshift galaxies", Advances in Space Research, 41, 1965-1971 (2008)
[13] JWST Sensitivity, http://www.stsci.edu/jwst/science/sensitivity
[14] Sembach, K., private communication
[15] Approved Spitzer programs, http://irsa.ipac.caltech.edu/data/SPITZER/docs/files/spitzer/spitzer_programs.txt
[16] Gordon, K., et al. "Optimizing the Observing Efficiency of the James Webb Space Telescope", Proc. SPIE, this issue
[17] Kinzel, W. "JWST planning and scheduling operations and concepts", Proc. SPIE 7737 (2010)
[18] Johns, A., Seaton, B., Gal-Edd, J., Jones, R., Fatig, C. & Wasiak, F., "James Webb Space Telescope –L2 Communications for Science Data Processing", Pro. SPIE 7016 (2008)
[19] Balzano, V. & Zak, D., "Event-Driven James Webb Space Telescope Operations using on-board JavaScripts", Proc. SPIE 6274 (2006)
[20] Balzano, V., Zak, D., & Whitman W., "The Care and Feeding of the JWST On-board Event-driven System", Proc. SPIE 7737 (2010)
[21] Apai, D., Lagerstrom, J., Reid, I., Levay, K. Fraser, E., Nota, A., & Henneken, E., "Lessons from a High-Impact Observatory: The Hubble Space Telescope Science Productivity between 1998 and 2008", PASP, 122, 808-826 (2010)
[22] Swade, D., "Data Management Subsystem Software Architecture for JWST", Proc. SPIE 7737 (2010)