James Webb Space Telescope Ground to Flight Interface Design

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Abstract—The James Webb Space Telescope (JWST) is a space-based infrared observatory planned for launch in 2013, which leverages the Hubble Space Telescope (HST) technical and scientific expertise. Unlike HST, JWST uses an event-driven design for 7 to 10 days of autonomous spacecraft and science operations.

In the JWST event-driven commanding design, scripts on-board the observatory construct and issue commands in real-time to the flight-software. The on-board scripts interrogate telemetry to determine whether the issued command has been completed. Event-driven commanding simplifies the software systems, especially the uplink products needed for the spacecraft and science operations, since most of the command creation occurs on-board the spacecraft.

The JWST high-level ground to flight interface consists of the uplink products and the on-board script directives used to drive science operations. The purpose of the uplink products is to tell the telescope where to look and to specify the observation and instrument parameters. The on-board script directives allow re-planning of observations from the ground in real-time without interrupting ongoing observatory operations. This paper describes the ground to flight interface design and its advantages, which include commonality, simplicity and low lifecycle costs. [1] [2]

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1. INTRODUCTION

Prior to discussing the ground to flight interface design for the James Webb Space Telescope (JWST) in Section 4, this section gives a brief description of the key features of the JWST mission, including the JWST orbit, which drives many of the requirements for the ground to flight interface. Another crucial feature of the JWST mission is the event-driven commanding concept, which is discussed in Section 2. The event-driven commanding defines the uplink products that are needed to operate the JWST observatory. Section 3 provides an overview of the relevant JWST science operations, including the generation of the products uplinked to the spacecraft from the ground. Sections 5 and 6 present a brief status and the conclusions respectively.

The JWST will be a large, space-based infrared (IR) telescope. The JWST is planned for launch no earlier than 2013. The launch vehicle will be an Ariane 5 rocket and the JWST spacecraft will carry enough propellant for a 10 year mission. The scientific and functional capabilities leverage expertise and techniques from successful space-based observatories managed by NASA, including the Hubble Space Telescope, the Spitzer Space Telescope and the Chandra X-ray Observatory. The JWST will have a wavelength range of 0.6 to 29 micro-meters (Figure 1). The JWST science goals for this wavelength range include the study of the early universe, the first luminous sources to form, the evolution of galaxies, and the birth of stars and planetary systems, as well as, the origins of life. (Gardner *et al.* 2006)

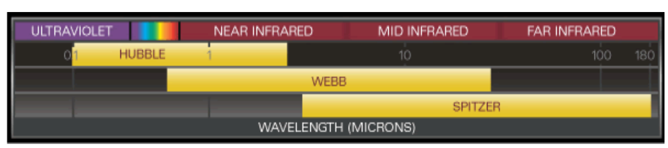

Figure 1 – Graphic showing the wavelength ranges used by the Hubble Space Telescope, Spitzer Space Telescope and James Webb Space Telescope. The JWST science goals build upon previous missions. (Credit: http://jwstsite.stsci.edu/gallery)

JWST Orbit

A space-based observatory is well suited for science investigations using the infrared region of light, since earth-based infrared observations are limited by the thermal environment. To build upon ongoing space-based infrared observatories, the JWST will orbit the second Earth-Sun Lagrange point (L2-orbit), which is 940,000 miles (1.5 x

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[1] 1-4244-1488-1/08/$25.00 ©2008 IEEE.
[2] IEEEAC paper #1222, Version 3, Updated December 15, 2007

10^6 km) from Earth. A similar orbit, called the first Earth-Sun Lagrange point (L1), was used by the Solar and Heliospheric Observatory (SOHO). Other distant orbits were considered but the L2-orbit maintains about the same Earth-to-observatory distance, which has the advantage of using the same ground antennae for the data rate.

JWST will not be located exactly at the L2 point since this is not a stable orbit and communication will be plagued by radio interference generated by the Sun. Thus a disadvantage of the L2-orbit is that thruster firings will be needed every 22 days to maintain the same orbit. The resulting momentum build-up will need to be unloaded further reducing propellant. Another disadvantage of the L2-orbit is that communication with the spacecraft is limited to a brief 4-hour contact window per day.

The advantages of the L2-orbit are a cold environment, under 50 Kelvin (-370 degrees Fahrenheit), which is necessary for successful infrared astronomy. Also, observing efficiency will be free of the pointing restrictions of Earth-orbiting observatories, since the Sun, Earth and Moon are relatively in the same line of sight, which simplifies scheduling observations. Furthermore, at the L2-orbit there will not be any Earth and Moon eclipses of the Sun, permitting continuous electrical power. (Gardner *et al.* 2006)

Figure 2 – Full-scale model of the James Webb Space Telescope on display at the International Society for 2006 Optical Engineering's (SPIE) meeting in Orlando. The 20 foot primary mirror, which consists of 18 beryllium segments, is shown at the end of the rainbow. Also, the distinct "V" groove radiator design of the sunshield is visible. (Credit: http://www.jwst.nasa.gov/model.html)

JWST Description

The JWST consists of a telescope, a science instrument package, a sunshield, and a spacecraft (Figure 2). Innovative technologies have been a hallmark of the JWST development. The telescope includes a 20 foot folding primary mirror comprised of 18 beryllium segments, which will be deployed in two steps. Beryllium mirrors were used successfully for the Spitzer and IRAS observatories. The mirror segments will be brought into optical alignment in flight using a process of periodic wavefront sensing and control. The science instrument package includes four infrared detectors and a fine guidance sensor. The science instruments are optimized for 0.6 to 29 micro-meters wavelength range. The short wavelength range is limited by the gold coated beryllium mirrors and the long wavelength range is limited by the detector technology. The sunshield provides passive cooling of the telescope and instruments. It consists of a five-layer "V" groove radiator design to reduce solar energy to tens of milli-watt. It will be folded about the telescope during launch and deployed a few days after launch, prior to the L2-orbit insertion. The spacecraft provides the pointing and observatory house-keeping capabilities. The spacecraft attitude control is based on the Chandra X-ray Observatory implementation. (Gardner *et al.* 2006)

2. EVENT-DRIVEN COMMANDING CONCEPT

Many earth-orbiting observatories, such as HST, use absolute time commanding for nominal operations. Absolute time commanding involves scheduling sequences of commands, where each sequence is assigned an absolute start time. Also, in some cases, it is appropriate to assign a relative execution time, usually for pulse commands (e.g., switching relays). A command is issued to the flight software when the spacecraft computer time is equivalent to the start time for a given command. Absolute time driven commanding requires the exact knowledge of when commands start and stop to avoid commanding conflicts or queuing commands in the flight software, which may lead to flight software errors. This approach works well for satellites with many contact opportunities and well defined external constraints (e.g., earth occultation).

In the JWST event-driven commanding design, scripts on-board the observatory construct and issue the commands in real-time to the flight-software. The on-board scripts interrogate telemetry to determine whether the issued command has been completed. Unlike, absolute time commanding, the event-driven commanding does not require detailed task or time modeling, since the on-board scripts have the knowledge of when commands have been completed. Also, the JWST on-board scripts will have the ability to respond to certain real-time errors by skipping affected observations, such as for guide star acquisition failures. In the absolute time commanding design, similar events will consume valuable telescope time, since the on-board software will wait until the affected observation time has elapsed before proceeding to the next observation. For further discussion regarding the JWST event-driven commanding concept and operations, see Balzano and Isaacs (2006).

Event-driven Advantages

The JWST architecture will use an event-driven commanding design to take advantage of modern on-board computers and software, as well as, the relatively constraint free L2-orbit, which simplifies the planning and scheduling of observatory activities. The advantages of the JWST event-driven commanding compared to absolute time commanding are summarized below (Dashevsky & Balzano, 2007).

(1) Detailed time-modeling of each command is no longer required, which simplifies the planning and scheduling software systems.

(2) More efficient use of the observatory since the on-board scripts are allowed to autonomously skip portions of the observations plan in response to real-time events.

(3) Minimal time between software response to mechanism motion and other hardware commanding since on-board scripts check telemetry to verify when tasks have completed.

(4) The on-board scripts and the observation plan are human-readable, which reduces interpretation mistakes and simplifies implementation and testing.

(5) Flexibility to change science instrument operations by updating the affected on-board scripts instead of uploading a new flight-software executable.

(6) No binary command loads uplinked to the spacecraft, which removes considerable testing and bit validation procedures.

Test-as-you-will-fly Approach

The process for the on-board script development applies a "test-as-you-will-fly" philosophy (Balzano & Isaacs, 2006). The "test-as-you-will-fly" approach involves early and frequent testing of the on-board scripts, which includes realistic flight scenarios and failure cases. All of the on-board scripts are tested using the current flight software, flight-like computer board, operating system and ground system software. A benefit of the "test-as-you-will-fly" approach is reduced flight operational incompatibilities since problems are identified well before delivery of the on-board scripts to flight operations.

3. Overview of Science Operations

There will be a variety of systems to accomplish the JWST mission, however, this paper will focus on the ones involved in the generation and distribution of the products that are used for JWST science operations.

The Space Telescope Science Institute (STScI) will be responsible for the Science and Operations Center (S&OC) for the JWST in a similar capacity as for HST operations. Also, STScI will coordinate the selection of observing programs from the astronomical community and public outreach activities. Based on HST utilization, the S&OC will support an estimated 1500 science observations (~3 hours exposure time per observation) requested by 200 to 300 investigators per year. The goal is for the JWST observatory to be doing something productive over 90% of the time, with 60% to 70% science efficiency (Bagget *et al*, 2004). The S&OC responsibilities include planning and scheduling of the science programs, the generation of the observation data, flight operations and science data release, which are discussed below (Figure 3).

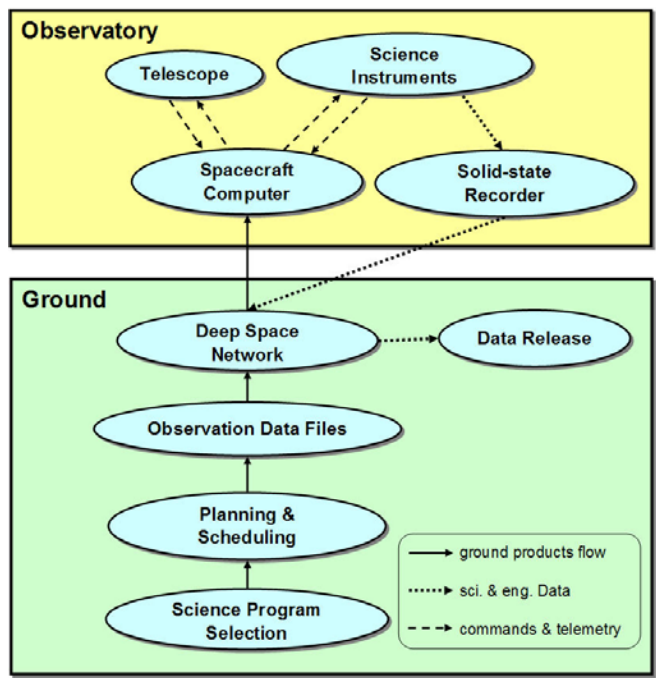

Figure 3 – High-level representation of the JWST ground systems and the observatory components.

Planning and Scheduling

Following program selection, a long-range plan will be constructed for JWST observations. Automated planning tools will be used to generate a long-range plan from a pool of approved science observations, routine calibrations and observatory maintenance activities. To reduce the complexity of the ground systems, the same planning tools will be used by JWST users for their science programs as for the calibration programs and maintenance activities. The long-range plan will assign scheduling windows for approximately a year of JWST observations, with a high probability (90%) of execution. These observations will be used to develop a short term schedule for a 22 day period, which is on the same timescale as for orbital maintenance. The development of the short term schedule will begin about one month before the chosen observations are executed, which will provide the latest information about the observation targets and guide stars. The output of the short-range plan will a time ordered list of observations for 7 to 10 days of JWST operations.

Observation Data Generation

The observation data uplinked to the spacecraft every 7 to 10 days consists of several files, including:

(1) Observation Plan, which is a time ordered list of observations (i.e., “to do list”);

(2) Visits, which are the details or parameters needed to execute each observation (i.e., “what to do”) – each observation in the Observation Plan has a corresponding Visit file;

(3) Micro-shutter array configurations for spectroscopic observations.

The Observation Plan and the Visit files are in a human readable format and processed by scripts on-board the spacecraft, which contain the “how to” logic. The on-board scripts refer to the Observation Plan to determine which Visit file to process next. The purpose of each Visit file is to dictate to the on-board scripts all the observation parameters, such as the target, guide stars, start and end time for the observation window, science instrument configuration, parallel observations, etc. Typically, a Visit file will consist of observations at the same telescope pointing (small angle maneuvers will be possible in the same Visit). Each Visit file may contain several exposures for the same target and guide stars combination. Based on the Visit parameters, the on-board scripts will generate the associated commands in real-time, which are issued to the flight software for execution. (Balzano and Zak, 2006)

In the Visit file (refer to Figure 4), observation parameters are specified in a layered fashion:

(1) Group

(2) Sequence

(3) Activity

The layered design specifies the order and execution priority of observations. Parallel observations are specified as multiple Sequences within the same Group. (Balzano and Rehm, 2002)

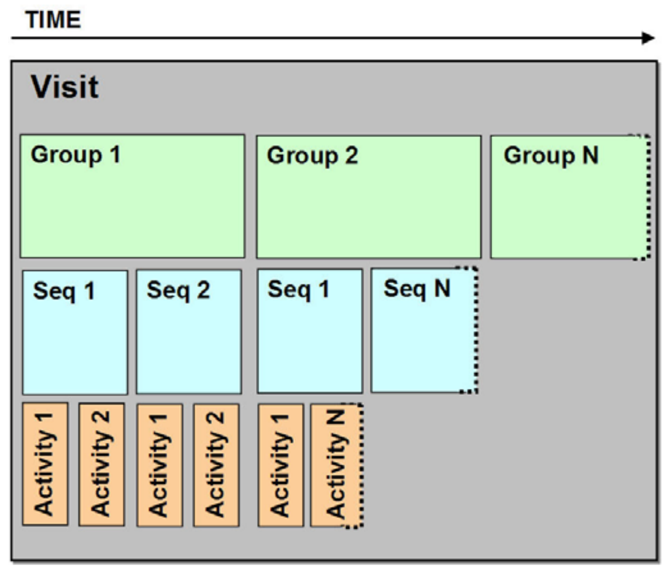

Figure 4 – A Visit file contains the details for the observation from the Observation Plan, including observation time window, guide star and target information, and science instrument configurations.

For example (refer to Figure 5), the first Group in a Visit will typically contain the parameters for a spacecraft maneuver to slew the telescope near the target. The second Group will contain the parameters for acquisition of guide stars, which are needed to maintain the same telescope pointing. The third Group may contain multiple Sequences with multiple Activities that specify the science observations. Each of these Groups may also include internal science calibration data taken in parallel with observations or telescope maneuvers.

Flight Operations

Flight operations will deliver the observation data products to NASA’s Deep Space Network (DSN) to uplink to the JWST spacecraft during the 4 hour per day spacecraft communication window. Also, flight operations will perform the telemetry capture, processing and analysis functions to monitor the observatory and notify the operations personnel in the event of an anomaly.

Data Release

Science and engineering data will be stored on a 471 Giga-bit solid-state recorder. The solid-state recorder data capacity was chosen to allow for missed contact opportunities and to have continuous science operations without data loss for up to 48 hours. The data volume is driven by 80 Mega-pixel detector arrays used for the science observations. Also, the infrared detectors require multiple readouts to remove cosmic rays (i.e., high energy particles) from the science data, which increases the data volume. The DSN will downlink up to 232 Giga-bits (compressed) science and engineering data from the solid-state recorder during the 4 hour per day communication window.

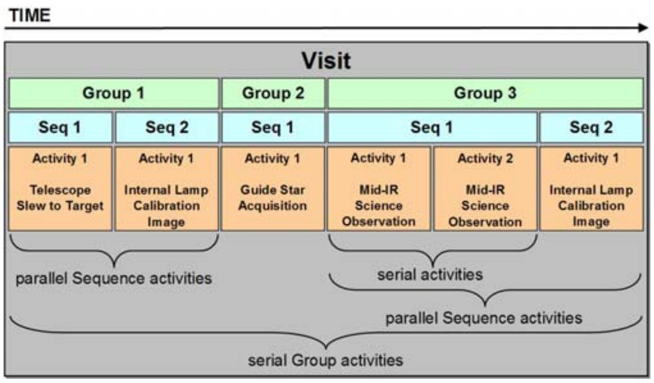

Figure 5 – Priority of observation execution in a Visit file is depends on the activity layering.

On the ground, much of the data will be cached at a ground station before transmission to STScI where it will be automatically processed within 48 hours and stored in the Multimission Archive. The Multimission Archive at STScI was originally developed for the HST in the 1990s and was extended for multiple space astronomy missions. For JWST, the daily volume of data transferred to the ground will be about 30 times the HST data volume. One of the challenges resulting of the JWST data volume will be the development of "on-the-fly" science data calibration, which will ensure that the optimum calibration data will be used to process the science observations. Typically, the request and retrieval for science data will be made using automated tools originally developed for HST data.

4. GROUND TO FLIGHT INTERFACE

The physical component of the ground to flight interface on the spacecraft will consist of two-axis gimbaled high-gain Earth-pointing Ka and S band antenna, which will permit uninterrupted science observations during data downlinks and command uplinks. The S band will be used for real-time communications and commanding of the spacecraft. The K band will be used to for the high-speed data downlink. (Gardner *et al*, 2006)

The high-level ground to flight interface will consist of two components: (a) the observation data (Observation Plan, Visit files and configuration files for spectroscopic observations; refer to Section 3 for details); and (b) the on-board script directives, which include (Figure 6):

(1) add and start a new observation plan;

(2) add Visits to the observation plan for re-planning;

(3) delete Visits from the observation plan for re-planning;

(4) stop the observation plan after a specified breakpoint;

(5) stop the observation plan either gracefully or immediately.

The high-level ground to flight interface design principles includes commonality, simplicity and low lifecycle costs. The applications of these principles are discussed below.

Commonality

Ground and flight operations will use the same high-level interface to command the spacecraft and science instruments. The on-board scripts will process the Visit files, based on the time ordered list of observations from the Observation Plan, to construct and issue commands in real-time to the flight software. Also, the on-board scripts interrogate telemetry returned by the flight software to determine the status of the issued command (see top part of Figure 6). The on-board scripts contain rules for the Observation Plan directives in response to errors. The same interface used to manage the Observation Plan is used during real-time operations from the ground. The JWST parallel processing capability of the on-board scripts permits the ground operator to manage the on-board Observation Plan without interrupting ongoing observations or spacecraft maneuvers.

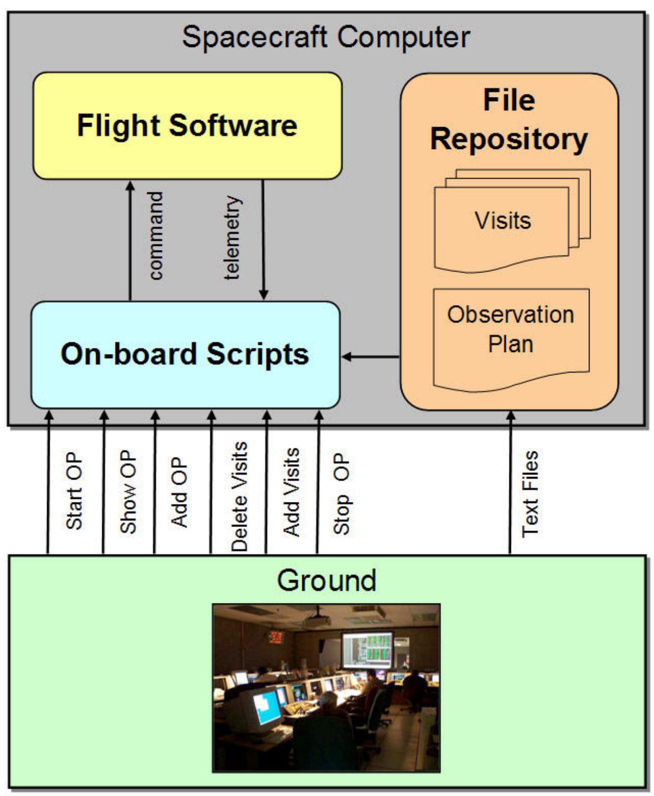

Figure 6 – The ground operator will use the same high-level interface as the on-board scripts to modify the Observation Plan (OP).

For the most part, JWST is designed to be operated autonomously by the on-board software. Real-time commanding from the ground will not be needed except during the early stages of the commissioning phase, starting the Observation Plan, regular orbital maintenance and non-nominal operations, such as for an anomalous recovery of a science instrument.

Simplicity

The high-level ground to flight interface reduces and simplifies the software systems compared to those involved in absolute time commanding, such as for HST. The Observation Plan and Visit files are in a human readable format, since all the commands are constructed on-board the spacecraft. Binary command loads will not be used for JWST. As a result, ground systems involved in the translation and verification of commands are no longer required. Also, much of the detailed time modeling of tasks and overhead for commands is significantly reduced, since the on-board scripts will construct commands as soon as the previous command finishes execution. The on-board scripts will check telemetry to determine the status of the issued command.

The scheduling software will be simplified since at the L2-orbit there are fewer constraints than in low-earth orbit. Also, typical observations will have large, uninterrupted scheduling windows. Each observation will have a start and end time, which will be used by the on-board scripts to determine whether an observation may be executed.

Low Lifecycle Costs

Prior to launch, hardware receives the lion's share of the funding. Following launch, cost will be driven by the software requirements. The commonality and simplification of many of the software systems will reduce the lifecycle costs, compared to absolute time operations, such as for HST. Also, the on-board scripts and flight software will be used on the ground during integration and testing, which reduces the need for custom systems used only on the ground. (Dashevsky and Balzano, 2007)

5. STATUS AND FUTURE CHALLENGES

Currently, a prototype of the ground to flight interface is under development and testing. Also, over 60% of the on-board script development is complete. Ongoing research includes the development of the methodology to indentify failure paths and appropriate response for the event-driven commanding. Higher fidelity simulators are very desirable for testing on-board scripts and the ground to flight interface. Preparations to test the on-board scripts with the science instrument hardware will be starting in the New Year.

6. CONCLUSION

The JWST event-driven commanding design takes advantage of advances in spacecraft computing and the L2-orbit. The L2-orbit removes many of the physical constraints that, otherwise, must be modeled by the planning and scheduling system. The JWST event-driven commanding concept is based on the on-board scripts constructing and issuing commands in real-time to the flight software. Also the on-board scripts interrogate the telemetry to determine the status of the issued commands. Event-driven commanding simplifies the uplink products, which are used to operate the spacecraft and science instruments and define the ground to flight interface.

The ground to flight interface consists of human readable files that include a time ordered list of observations (Observation Plan), observation parameters (specified in Visit files), and configuration data for the micro-shutter array needed for spectroscopic observations. The other component of the ground to flight interface is the on-board scripts directives that are used to manage the Observation Plan for re-planning purposes.

The JWST ground to flight interface design applies commonality, simplicity and lower lifecycle costs. Both ground and flight operations will use a common interface to command the spacecraft and science instruments during nominal operations. Also, the same high-level interface will be available during the JWST integration and testing phase. The ground to flight interface design simplifies and reduces the systems on the ground traditionally required for absolute time commanding, since the on-board scripts contain the "how to" knowledge. Therefore, detailed time and task modeling is no longer needed. Following JWST launch, lifecycle costs will be reduced as a result of fewer and simpler system requirements and the automation of planning and scheduling tools.

7. ACKNOWLEDGMENTS

The authors would like to thank Dean Zak (STScI) for many constructive discussions regarding the on-board script directives, Rusty Whitman (STScI) for providing useful information related to the Multimission Archive and Jeff Valenti (STScI) for estimating the JWST science program utilization.

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BIOGRAPHY

Ilana Dashevsky is developing the JWST Observatory Planning Ground System and portions of the JWST on-board commanding software. Also, she upgrades and maintains the commanding software for the day-to-day operation of the Hubble Space Telescope. Ilana has over a decade of experience and insight into many aspects of the flight and science operations for the Hubble Space Telescope.