James Webb Space Telescope – Applying Lessons Learned to I&T

Alan Johns*[a], Bonita Seaton[a], Jonathan Gal-Edd[a], Ronald Jones[b],
Curtis Fatig[c,] Francis Wasiak[d]
[a]Goddard Space Flight Center/NASA, 8800 Greenbelt Road, Greenbelt, Maryland 20771;
[b]ASRC/GSFC, 8800 Greenbelt Road, Greenbelt, Maryland 20771;
[c]SAIC/GSFC, 8800 Greenbelt Road, Greenbelt, Maryland 20771;
[d]General Dynamics Corporation/GSFC, 8800 Greenbelt Road, Greenbelt, Maryland 20771

ABSTRACT

The James Webb Space Telescope (JWST) is part of a new generation of spacecraft acquiring large data volumes from remote regions in space. To support a mission such as the JWST, it is imperative that lessons learned from the development of previous missions such as the Hubble Space Telescope and the Earth Observing System mission set be applied throughout the development and operational lifecycles. One example of a key lesson that should be applied is that core components, such as the command and telemetry system and the project database, should be developed early, used throughout development and testing, and evolved into the operational system. The purpose of applying lessons learned is to reap benefits in programmatic or technical parameters such as risk reduction, end product quality, cost efficiency, and schedule optimization. In the cited example, the early development and use of the operational command and telemetry system as well as the establishment of the intended operational database will allow these components to be used by the developers of various spacecraft components such that development, testing, and operations will all use the same core components. This will reduce risk through the elimination of transitions between development and operational components and improve end product quality by extending the verification of those components through continual use. This paper will discuss key lessons learned that have been or are being applied to the JWST Ground Segment integration and test program.

Keywords: JWST, Integration, Testing

1. INTRODUCTION

The James Webb Space Telescope (JWST), as shown in Figure 1, is a large, cryo-cooled, infrared-optimized telescope to be placed in orbit at the second Lagrange point (L2) (see figure 2). It is designed to enable fundamental breakthroughs in our understanding of the formation and evolution of galaxies, stars, and planetary systems[1] with a five-year mission and ten-year design goal. The JWST is scheduled to launch in 2013 from Kourou, French Guiana aboard an Ariane 5 launch vehicle. The JWST is designated to succeed the Hubble Space Telescope (HST) and Spitzer as part of the National Aeronautics and Space Administration (NASA) Great Observatories program. It will be controlled out of the JWST Science and Operations Center (S&OC), located at the Space Telescope Science Institute in Baltimore, Maryland.

Figure 1 – Members of JWST team,
shown with the full-scale mockup.

*alan.t.johns@nasa.gov; phone 1 301 286-9295; fax 1 301 286-7021

During the development phase, the importance of operations in the mission lifecycle is sometimes not given sufficient priority in the decision making process. This can lead to higher operations costs and complexity in the long term when a more "operations friendly" design and implementation might have been achieved. The JWST project will extend over 20 years from initiation of requirements definition and development to end-of-life. With a mission goal of 10 years of operations contributing significantly to this lifetime, operations efficiency and costs are a significant consideration. As such, the JWST Project has made a conscious decision to involve operations personnel from the beginning of development. JWST system engineers gathered in 1998 to look at various options, technologies, and industry trends to determine how to implement this objective.

Figure 2 - Lagrange Points.

1.1 The Starting Point

The JWST Ground Segment and Operations (GS&O) team actively reviewed past and current practices and issues from various NASA programs. This included large and small programs at the Goddard Space Flight Center as well as other NASA centers. This is an ongoing process that started with studies on the implementation of best practices and lessons learned. The JWST team had paid particular attention to the missions shown in Figures 3 through 6, such as HST, Spitzer, and the Earth Observation System (EOS), as well as the European Space Agency (ESA) Herschel-Plank mission which is also a L2 mission. As part of those lessons, to remove any ambiguity in interpreting requirements or defining joint integration and test (I&T) and operations items, interface control document (ICD) development began very early in the mission life cycle.
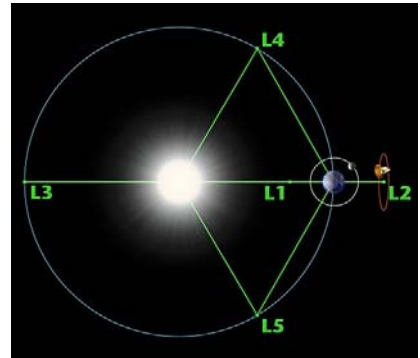

Figure 4 - Herschel

Figure 3 - Spitzer

Figure 5 – EOS Satellite

Figure 6 - HST

1.2 Where We Are Today

The JWST project is currently in the hardware and software development phase, see Figure 7. The I&T of the various

Figure 7 – JWST I&T

elements is at the unit and component level. During the requirements definition and design phases, the JWST Project developed ICDs for the spacecraft, science instrument, and ground system elements. The JWST Project has also developed and deployed Science Instrument Test System (SITS) development and test units which contain both the Common Command and Telemetry System (CCTS) and the project database which contains command and telemetry definitions as well as all configured data utilized to control spacecraft components. The JWST Project supplied each science instrument and flight software developer and test group with the SITS units which provide the tools necessary to construct project database inputs, send commands, receive telemetry, provide loads, exercise dumps, format the science data, and control ground support equipment (GSE). Currently thirty-two such systems have been deployed at locations worldwide, all using the formats, protocols, and databases that will ultimately be used in the operational S&OC Flight Operations Subsystem (FOS).

1.3 Where We Are Going

The JWST launch readiness date is June 2013. By that date, the JWST Ground Segment will have been developed and tested, and operations personnel training will be completed. Ground Segment testing will include the full range of test levels from development-level testing to system testing, acceptance testing, mission operations testing and simulations through end-to-end testing. The Ground Segment will also participate in project-level I&T activities. These activities not only require the use of the CCTS and the project database, but the other systems that perform mission planning, flight and science operations, and data archive systems (see Figure 8).
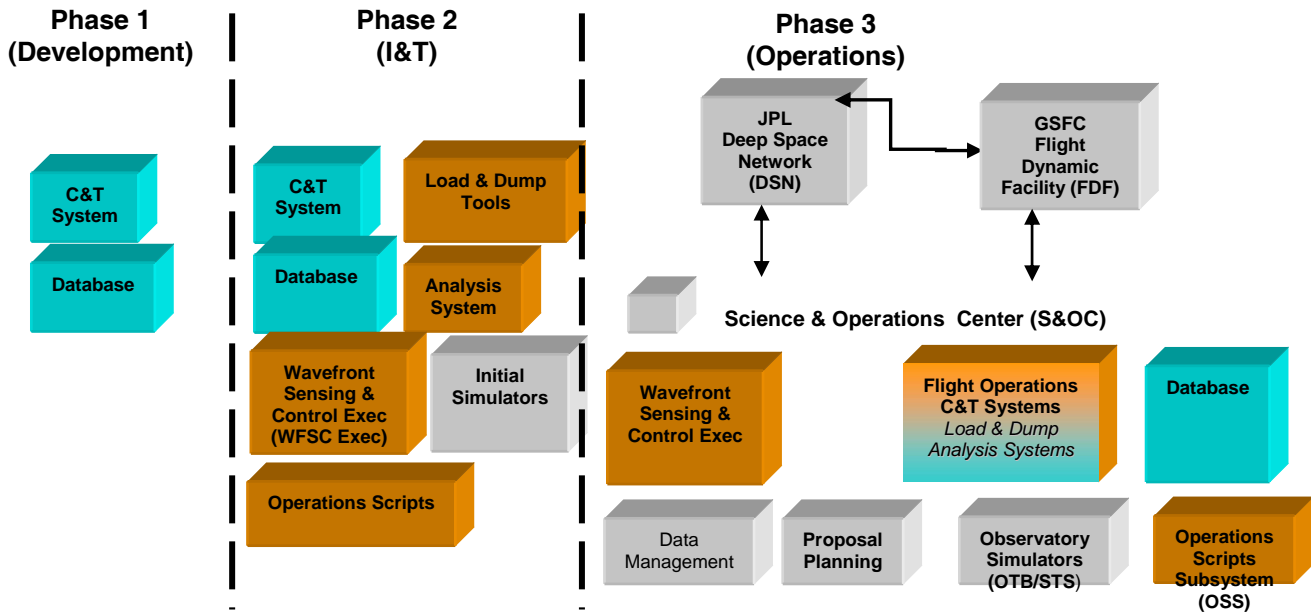

Figure 8 – Ground Segment Development Phases

2. LESSONS TO BE LEARNED

As all programs begin, a key factor that drives the requirement and interface definitions is the experience of the project personnel; we all come with our own experiences, biases, and lessons learned from our past. While this experience base is invaluable, it is also limited by the experiences of the personnel involved. As such, it is important to ensure that the pool of applicable lessons learned has adequate breadth and depth. The JWST Project recognizes the importance of considering and applying lessons learned and has culled lessons learned from various sources, including the NASA and GSFC lessons learned databases and has made them easily accessible from the Project's internal website. To achieve the technical and programmatic benefits of applying lessons learned, JWST GS&O personnel have brought their personal

work experiences to bear, have reviewed and continue to review the JWST and GSFC Lessons Learned, and have met with other missions to gain additional insight.

The culmination of this review and analysis of lessons learned has led to the adaptation of numerous lessons learned in the JWST Ground Segment I&T program and planning. Key among these lessons are (1) adopt standards and protocols, (2) develop core system components early, (3) decouple the project database from operations applications, (4) employ sufficient science data during testing, and (5) archive the data collected during I&T. Each of these lessons, their implementation, plans, and benefits are discussed in the following sections.

3. JWST KEY I&T DECISIONS

With the selection of prime contactor in 2000, the JWST Project began making major key decisions for I&T that would be carried forward to the eventual operational system. These key decisions are shown below as they relate to each of the lessons learned:

1. Adopt standards and protocols: Use Consultative Committee for Space Data Systems (CCSDS) standards and institutional capabilities; use the formats and protocols that will be utilized during the mission to develop the interfaces between the command and telemetry system and the spacecraft simulator.

2. Develop core system components early: Use the same command and telemetry system and project database during all phases of development, I&T and operations.

3. Decouple the project database from operations applications, such as the command and telemetry system.

4. Exercise science data during I&T: Process the science data during development and I&T the same way it will be done in operations.

5. Archive the data collected during I&T: Archive system level I&T data at the control center for post-launch access.

3.1 Adopt Standard Formats and Protocols

The decision to adopt standards for JWST data functions allowed common formats and protocols to be documented and implemented early in the mission lifecycle. The formats and protocols are defined in JWST high-level ICDs and requirement documentation that assures the formats and protocols are flowed down to lower-level interfaces and maintained across systems. These formats and protocols were decided early in the development process, resulting in little to no impact to the various systems under development.

Adoption of these standards reduced the risk to the operational system by allowing for the formats and protocols to be tested during the development and I&T phases of the JWST mission. Furthermore, development and test time between the I&T facilities, the S&OC, the communications network, and the spacecraft will be reduced since the CCSDS standards that were chosen are familiar to the entities involved. The use of the CCSDS standards also enabled reuse of some existing flight software code. Selecting the standards early in the process allowed for the early definition of interfaces, which then allows for early testing of interfaces. The significant CCSDS standards adopted by JWST are:

CCSDS 201.0-B-3 CCSDS Telecommand Channel Service

CCSDS 202.0-B-3 CCSDS Telecommand Data Routing Service

CCSDS 202.1-B-2 CCSDS Telecommand Command Operation Procedures

CCSDS 203.0-B-2 CCSDS Telecommand Data Management Service

CCSDS 301.0-B-3 CCSDS Time Code Formats

CCSDS 727.0-B-1 CCSDS File Delivery Protocol (CFDP)

CCSDS 701.0-B-3 CCSDS Advanced Orbiting Systems, Networks and Data Links

CCSDS 101.0-B-6 CCSDS Telemetry Channel Coding

Examples of the how the above standards will be being utilized in the I&T and operations environments are listed below:

1. Real-Time Data Downlink: CCSDS virtual channel packets with Reed-Solomon encoding, which provides guaranteed data delivery.

2. Stored Data Downlink: CFDP Type 2, which provides guaranteed data delivery.

3. Command Uplink: CCSDS Communications Operations Procedurel-1 (COP-1) and CFDP, which provides guaranteed data delivery.

4. Project database: Coded in XML and transfer by CCSDS XTCE.

In addition to using these standards, the JWST Project adopted a protocol defining the detailed bit and byte relationships for JWST data. These relationships are defined in the JWST Project configuration controlled documentation. Including this level of detail in the JWST documentation removes any ambiguity during the development of the flight software and ground system elements thereby avoiding potential rework.

3.2 Develop Core System Components Early

The JWST Ground Segment is primarily based on HST and EOS heritage and the lessons learned from these large-scale missions—with a significant departure that embodies the lesson of develop core system components early. Like most missions, the EOS Terra Project utilized different C&T systems for its I&T and operations phases. The original EOS Terra C&T system was replaced by Raytheon's Eclipse commercial-off-the-shelf (COTS) system approximately one year prior to launch due to technical problems. Had a common C&T system been used from development through the I&T effort, the problems with the original system could have been discovered earlier and possibly mitigated.

Learning from this experience, the JWST Project is using the Raytheon Eclipse system for instrument and subsystem software and hardware development, I&T activities and for mission operations. Also leveraging off the EOS experience base with the Eclipse product, the JWST Project has had the following enhancements made to Eclipse: a fast turnaround (in minutes) capability for database updates, storage of engineering data in a generic decommutated format and Web-based functionality for generic user interfaces.

The core C&T system and database are currently being used in the spacecraft and instrument laboratories during the development phase. These systems can be considered "mini-Mission Operations Centers," providing all the capabilities needed to command, monitor, and process data. Utilizing the same systems during development, I&T, and operations eliminates "throw out" knowledge of systems that could have been used in various phases and, perhaps more importantly, allows for input and buy-in from all teams early in the mission life cycle. The JWST Project is using the "Test-As-You-Fly, Fly-As-You Test" and "Test Early And Often" concepts to reduce flight operations development and testing as well as reducing risk. These concepts are enabled by using the same core system components throughout the lifecycle. Moreover, the JWST integration approach for the common C&T system is to incrementally deliver software builds based upon the user's development schedules. This approach incorporates lessons learned and corrections into subsequent builds, provides design flexibility to accommodate changes and enhancements, and provides early integration of key capabilities.

In addition to the early definition and development of the C&T system, the project database was defined before the selection of the prime contractor. The project database contains all configured data utilized to control the Observatory and its components. This includes command and telemetry definitions, command procedures, display pages, flight software loads, and other operational products. Early development and deployment of the project database has allowed a common understanding of database formats and rules to be facilitated among all users. The JWST Project developed tools to manage the database at a central location as well as a toolkit that has been deployed on standard desktop computers to all science instrument, flight software, and spacecraft hardware vendors.

3.3 Decouple the Project Database from Operations Applications

The project database is independent of any other development, I&T and operations systems (such as C&T, planning and scheduling, trending, simulators and automation). The JWST project database is developed in the Extensible Markup Language (XML) and is stored in a non-proprietary format in American Standard Code for Information Interchange (ASCII). The JWST project database ICD defines the XML tags, definitions and relationships between tags. This allows for any ground system element to ingest the database and convert the data to their own internal format. The JWST XML database also can be converted to the CCSDS XTCE standard, providing compliance with the international standard. This use of the XML has saved the JWST Project time in testing the new database, avoided costs associated with other COTS products, and provided ease of use throughout the lifecycle due XML's self-describing features.

3.4 Exercise Science Data During I&T

The JWST Project has defined the ground system processing of the science data for each of the four JWST instruments prior to start of flight software and hardware development. Each instrument development team has been provided a common tool that converts the science data from the spacewire-based format in which the data is originally collected to the format in which the data is stored onboard on the solid state recorder (SSR). Once the data is in the SSR format, it is transformed to the Flexible Image Transport System (FITS) format (along with any necessary engineering data). These various formats are identical to what will be used on orbit, by the DSN and the Flight Operations Team (FOT). This allows the science instrument teams to have the same calibration tools for I&T and mission operations.

3.5 Archive the Data Collected During I&T

Throughout system and observatory level I&T testing, all data deemed significant will be collected and archived at the S&OC. This will allow for the quick comparison of test data with on-orbit data for troubleshooting and calibration activities. Users often underestimate the size of the data to be saved, and in general will want to save more than is needed, and when asked, will resist deleting anything. When engineering the system for storing the archived data, expandability, XML tagging of the data, and generic input formats will allow for any expansion that will need to occur. The key drivers for the development of the I&T data archive are:

- Quick access to historical data,

- Support of anomaly investigation and trending and calibration,

- Correlation to operational data,

- Online access to data and

- Collection of input from developer sites through launch site testing.

The archive of I&T data is enabled by the use of the common C&T system and the project database, which allows the same tools, and archive system to be used for development and operations.

4. I&T APPROACHES RESULTING FROM LESSONS LEARNED

Based on lessons learned, the JWST Project team will use the following approaches for integration and test of the Ground Segment:

- Define the flight interfaces, project database structure, science data processing, load/dump formats, and generic engineering formats early in the development process.

- Test early and often.

- Test as you fly, fly as you test.

- Integrate on incremental software builds, adding new capabilities with each build.

- Verify that the S&OC is compliant with all ICDs. Perform integration and interface connectivity testing for each of the external elements. Ensure the resolution of all S&OC discrepancies and incorporate lessons learned for future integrations.

- Roll lessons learned during I&T into the development of operational products and operations concepts.

- Segregate the Ground Segment with ICDs between each element, allowing vendors to supply different components and keeping the total system open and adaptable.

- Utilize a central, application independent, XML-based, CCSDS XTCE compliant project database to minimize cost.

- Utilize open engineering and science data formats, defined in ICDs, to allow dissimilar systems used during I&T to have access to data without design impacts.

- Utilize CCSDS CFDP to reduce the amount of processing needed at end user site.

- Utilize web-based technologies for user displays to provide more flexibility, quicker development, and reduce long-term costs.

- Evolve the common C&T and project database systems from development through I&T to operations to ensure mission success.

- Utilize a modular approach to system development to allow technology upgrades to occur naturally.

5. SUMMARY

JWST Ground Segment development and I&T activities have employed numerous lessons learned to reduce risk, improve quality and optimize development schedules. Key among these lessons are (1) adoption of standards and protocols, (2) early development of core system components, (3) decoupling of the project database from operations applications, (4) exercise of science data during I&T, and (5) archive of the I&T data at the operations center.

REFERENCES

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