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James Webb Space Telescope (JWST) Test Assessment Team (TAT)

FINAL REPORT

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August 27, 2010

JPL
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1. Executive Summary

The TAT carefully examined the planned testing of ISIM and OTIS, including whether any change in the Level 1 science requirements, or a postulated assumption of increased mission risk, could support a rationale that the planned testing at JSC could be eliminated.

Irrespective of whether the Level 1 science requirements could be so adjusted, the TAT concluded that a significant level of thermal, optical, and electrical/mechanical testing is required at JSC to reach a reasonable level of mission risk, albeit not at the level planned by the Project.

The TAT identified a significant number of opportunities to optimize the OTIS test plan at JSC that will better manage the overall technical and programmatic risk to the mission. This would be accomplished by reducing the planned timeline and allowing for the earliest possible detection of critical problems, such as those that might require opening the test chamber and implementing a second, corrective cryogenic test cycle.

The TAT concluded that ISIM testing at GSFC can be reduced from 14 to 10 months and believes that OTIS testing at JSC can be reduced from 167 to 90 days with an acceptable reduction in prelaunch predictability of performance and without predictable loss of science capability. This reduction could shorten the critical path, avoiding significant cost growth. At the same time, additional non-critical path tests at GSFC would lay the best possible foundation for shortened ISIM testing at GSFC and OTIS testing at JSC. This will significantly increase the likelihood that OTIS testing will be achieved according to plan and at an adequate level of risk.

However, a significant—and not easily quantifiable—risk remains that problems will be found that either directly threaten mission success and/or do not allow an adequate characterization of the risk to mission success. The Program needs to establish appropriate reserves to address such problems. This will require careful planning, such as establishing a clear definition of critical items (including test priorities), predicted results, decision criteria, and contingency plans.

As the actual testing is under way, near-real-time decisions involving technical, programmatic, and scientific risk will be required. Therefore the implementation of a decision-making structure and process leveraging the experience base of the Hubble Space Telescope (HST) Servicing missions is needed. This will ensure that all relevant technical and programmatic information can be quickly assembled and communicated and that the appropriate risk acceptance authorities can be engaged in a timely manner.

Timely analysis of thermal performance is required to support decision making during thermal testing. The capability to do this is at present inadequate; substantial improvements are required.

Overall, ISIM and OTIS testing and the periphery and supporting tests appear not to have been adequately considered as an integrated whole, leading to potential gaps and/or overlaps. To properly address this, the Program should quickly establish a new I&T leadership position to focus on and fully integrate and optimize planning for the remaining tests.

Taken in their totality, the recommendations made in this report would decrease programmatic costs, decrease the risk of future cost growth, and shorten the schedule of the current plan. While the changes proposed would result in some increase in the uncertainty of in-flight performance predictions, there would be negligible difference in the probability of unacceptable in-flight performance. At the same time, the changes would improve the likelihood that the testing will be accomplished per plan.

The scale, complexity, and cryogenic nature of JWST prohibit an end-to-end system test and instead require an innovative approach to system verification, with more dependence on analysis and piece-wise testing. JWST is an important step in learning to execute I&T for complex systems. The lessons learned on JWST will lay the groundwork for future visionary missions.

2. Testing Assessment Task Overview

The JWST Mission Critical Design Review (MCDR) was held in April and May of 2010. Concerns raised at that review led to the formation of an independent, external Test Assessment Team (TAT) to review plans for the JWST Integrated Science Instrument Module (ISIM) and Optical Telescope Element/ISIM cryogenic testing.

The convening authority for the TAT was the Astrophysics Division of the NASA Science Mission Directorate (SMD). The TAT included nine members and three NASA consultants with considerable experience in system engineering, science instrument development, system verification, thermal balance modeling and testing, and cryogenic testing technology, as well as expertise in the science and observational domains relevant to the JWST science objectives. Partial biographies of the TAT members, highlighting their expertise relevant to TAT activities, appear in Section 6.

The TAT completed its assessment and delivered a preliminary report to NASA on August 20, 2010.

2.1 Chartered Review Activities

The TAT was chartered to—

1. Determine whether the plans sufficiently test the relevant observatory functions.
2. Determine whether the key optical and thermal objectives are clearly identified.
3. Determine whether the test plans themselves are properly scoped and prioritized.
4. Identify any duplicative or unnecessary tests that might exist in the plans.
5. Determine if the current plan is overly ambitious in scope or inappropriately optimistic regarding hardware performance and analysis capabilities.

The TAT was asked to consider the practical limitations of operating a cryogenic vacuum chamber from both the human and hardware perspectives, as well as the sheer complexities of performing the test while evaluating whether or not the plan as conceived is the correct plan.

NASA requested an assessment of plans with the data currently available, while recognizing that test plans of different elements are of varying maturity. NASA also sought the following findings:

6. Identify elements of the mission science requirements that place the most stringent constraints on the test program (operational, logistical, scheduling, staffing, etc.).
7. Determine if easing of specific science requirements that drive the complexity of test plans could reduce that complexity and thereby enhance the probability that the test program could be completed within the existing hardware capabilities and schedule.

8. Suggest alternative approaches to verifying the system-level thermal and optical and overall scientific performance if such approaches could generate cost reductions without increasing programmatic risk beyond acceptable levels.

Many areas of testing that bear critically on the success of JWST lie outside the TAT Charter. These include sunshield thermal performance, sunshield and telescope structural deployments, flight-system electrical functionality, and launch dynamics exposure. The TAT assumed in its deliberations that these tests have been properly scoped, will be properly executed, and that the results are acceptable prior to the execution of the tests that are the subject matter of this review—namely the instrument assembly test (ISIM) and the Optical Telescope Element/ISIM assembly test (OTIS). The TAT also assumed that the spacecraft stand-alone testing would be adequate.

The TAT notes that in the current test plan, the mating of the flight MIRI with the flight MIRI cooler equipment in the spacecraft occurs after OTIS testing and cannot be tested prior to launch.

2.2 Process and Schedule

The TAT conducted its work over a seven-week period beginning on July 16, 2010. Prior to the start date, JWST Program information was posted to a secure file exchange site so that TAT members could study the Program. Documents studied included requirements and specification documents, test plans, material from the JWST MCDR, presentations from Johnson Test Design Review, and budget and schedule overviews, among others.

The TAT also reviewed the reports of the Science Assessment Team charted by NASA HQ in June 2005 to reevaluate and prioritize the scientific capabilities of the mission (Science Assessment Team Interim Report 26 July 2005 & Science Assessment Team Final Report 23 August 2005). The TAT was pleased to see that the JWST Project implemented the recommendations of the SAT.

Teleconferences (telecons) to gather and analyze information from the JWST Program were held on July 16, 20, 22, and 29. Each telecon lasted approximately four hours, and involved TAT members and JWST Program scientists and engineers from varying disciplines. Topics covered during the telecons included overviews of JWST science goals, verification plans, OTIS test plans, ISIM test plans, and the cryo-cooler design.

A TAT meeting and tour were held at Ball Aerospace on July 27. Participants toured primary mirror actuator test facilities, primary mirror test and assembly, and the JWST Testbed Telescope. A second TAT meeting and tour at JSC immediately followed on July 28. Details of the testing at JSC were reviewed and the participants saw the cryo chamber and facility where the integrated telescope (OTIS) will be tested.

During the telecons and subsequent meetings, the TAT developed a list of detailed questions for consideration. These were informal questions and included numerous addendums and sub-questions, all of which were addressed throughout the meetings.

A weeklong meeting followed at the Northrop Grumman facility in Redondo Beach, California, from August 2–6. The JWST team presented additional information to the TAT and supplied answers to submitted questions. The TAT questioned Program members, interviewed key Program members individually, and held numerous internal discussions. Also during this week, the TAT began the writing and editing of draft inputs for this report.

Following two weeks of developing and reviewing the draft report, the final report was completed during the fourth week of August.

The NASA consultants on the TAT were precluded from directing the task or from “pushing” TAT findings in any specific direction. The TAT Chair and the non–civil servants on the TAT were completely in charge of the final recommendations. Civil servants involved with the Project did not sign the final report. While they were free to offer advice (for use or not), they did not direct answers. In any cases when consensus was not reached among the TAT participants, the responsibility for determining the “final answers” rested solely with the TAT Chair.

The JWST Program Executive was the SMD point of contact for the team. The TAT Chair and Executive Secretary maintained close communication with the SMD point of contact on schedule and assessment status.

The Executive Secretary took meeting notes, maintained lists of action items and questions at each meeting, arranged the meetings and telecons, maintained the team’s schedule, created lists of potential findings, and assembled the final report.

The TAT documentarian transcribed the meeting conversations and documented the TAT proceedings; the documentarian and a technical editor assisted the Executive Secretary and the TAT Chair with the development of this final report.

2.3 Deliverables

The deliverables from the JWST test assessment were a presentation to the SMD to review the assessment results and this final report containing specific recommendations concerning the JWST integration and test plans at Goddard Space Flight Center (GSFC) and Johnson Space Flight Center (JSC).

3. Responses to the Eight Specific Charges in the Charter

NASA tasked the TAT to examine a set of specific issues. The responses to these issues follow. They are closely related to the Findings, Assessments, and Recommendations appearing in Section 4, and are based on the telecons, the meetings at Northrop Grumman, and the extensive material and responses to questions provided by the Project.

3.1 Do the plans sufficiently test the relevant observatory functions?

Plans are in place that test observatory thermal and optical functions to the maximum extent practical.

Matrices have been presented that show the relationship between key thermal and optical verification requirements and test venues where they are verified. These high-level summaries of the test plan appear thorough. The matrices appear in Appendix A, Figures A-3 and A-4. Test facilities (especially the SES at GSFC and Chamber A at JSC) are being modified to accommodate JWST needs. There appear to be no compromises regarding customization of these facilities for JWST.

In spite of the Project's commitment to test facilities, the scale, complexity, and cryogenic nature of the observatory necessitate more dependence on analysis and piece-wise test verification than is typical for NASA payloads in this class (i.e., prior great observatories). As a result, different verification processes will be required.

3.2 Are the key optical and thermal objectives clearly identified?

The objectives of the test program for the optical system were clearly identified and presented to the TAT in a prioritized form.

In particular, the rationale for the optical testing at JSC emphasized the testing that could only be done at that level of assembly. The most important measurement objectives involve verifying key alignments at cryogenic temperatures that cannot be corrected by the active optical system, particularly the alignment of the ISIM to the AOS. The Program considered verification of adequate actuator range, verification of the global tilt of the phased primary mirror relative to the AOS, and demonstration of the operation of the Wavefront Sensing and Control (WFSC) system to be high priorities.

The objectives of the thermal test program are centered on the validation of detailed thermal models of the OTIS in the test facility and on workmanship checks of the thermal system. However, the mapping of these thermal model parameters to the ultimate scientific performance of the observatory needs to be more clearly elucidated. In particular, a prioritization of test objectives is required. Additionally, more work is needed to determine the thermal stability criteria during the test.

3.3 Are the test plans themselves properly scoped and prioritized?

The JWST test plans are not consistent with the money or time available.

The Program presented multiple examples of their efforts to improve these plans through both scope and prioritization efforts. However, further opportunities exist and should be pursued.

Efficiency can be improved by eliminating repeated tests at the ISIM and OTIS levels and by adding more concurrent optical and thermal testing. The scope of thermal testing can be limited by reducing the number and duration of thermal balance tests, particularly for tests on the critical path. The scope of the optical testing can be reduced by eliminating some lower priority tests.

The Program could achieve significant savings through improvements in test plans. More effective systems engineering and management follow-through would prevent further schedule delays and cost increases.

3.4 Do duplicative or unnecessary tests exist in the plans?

Some duplicative and unnecessary tests exist in the plans. There are opportunities in the optical test plans for improved efficiency as well as for the elimination of some repeated tests. Also, there are multiple thermal test points in the OTIS testing at JSC, but by adding some tests off the critical path, the OTIS tests can be simplified and would save significant overall schedule time while preserving the risk-reduction objectives. Further discussion of these options appears in Section 5.1.

3.5 Is the current testing plan overly ambitious?

The TAT was asked to assess if the current plan is overly ambitious in scope and optimistic regarding hardware performance and analysis capabilities.

The optical test plan is not overly ambitious in scope and can be executed largely as planned. The thermal test plan, however, is overly ambitious in scope and cannot be executed in the time allotted in the current schedule. The additional time required is significant, but some elements of the plan can be eliminated and replaced with alternate testing that is off the critical path or perhaps performed concurrently with optical testing.

Regarding hardware performance, neither the optical nor the thermal test plans are overly optimistic. The optical test plan is assessed to be realistic. The thermal test plan is assessed to be cautious and respectful of the subtle but consequential character of a cryo test of unprecedented complexity. The plan is overly optimistic with respect to the first-time performance of the thermal GSE. Unless the thermal Pathfinder testing is added as recommended in Section 4.4.2, the likelihood of completing OTIS testing without a chamber break is low.

Regarding analysis capabilities, the optical test plan is assessed to be realistic. However, the thermal plan is extraordinarily optimistic regarding the execution time of thermal simulations. The plan is not executable given the current extreme simulation turnaround times.

3.6 Which science requirements drive the test program?

The TAT was asked to assess which elements of the mission science requirements place the most stringent constraints on the test program (operational, logistical, scheduling, staffing, etc.).

JWST has a range of science requirements that place constraints on the basic performance parameters of the telescope and its instruments, which in turn place verification constraints on the test program. For JWST, the most stringent Level 1 science requirements fall into two broad categories: very sensitive imaging and low-resolution spectroscopy of extremely faint sources over the wavelength range $1\ \mu m < \lambda < 3\ \mu m$; and background-limited imaging and moderate-resolution spectroscopy of brighter sources, $3\ \mu m < \lambda < 28\ \mu m$. These categories are discussed in further detail in Section 5.2.

3.7 Can relaxation of science requirements simplify the test plan?

The Charter asks that the team assess whether some relaxation of specific science requirements that particularly drive the complexity of test plans may reduce test complexity and enhance the probability that the test program would have a reasonable chance of being completed within hardware capabilities and allotted schedule.

Relaxation of the science requirements would not necessarily lead to a straightforward simplification of the test plans. However, there are test-related requirements that could be relaxed to simplify the test program, as discussed in Section 5.3.

3.8 Are there alternative approaches to verifying system performance?

The TAT was asked to identify alternative approaches to verifying system-level thermal, optical, and scientific performance if such approaches are likely to result in cost savings or cost avoidance while at the same time not increasing the programmatic risk beyond acceptable levels.

Alternative approaches to verifying system-level thermal, optical, and scientific performance that reduce cost and schedule without increasing risk beyond an acceptable level have been identified and are discussed in Section 4.4.

It is not possible to completely eliminate OTIS testing at JSC. The TAT considered whether any change in the Level 1 science requirements or an assumption of increased mission risk could support such a decision. Even if the Level 1 science requirements could be so adjusted, the TAT concluded that a significant level of thermal, optical and electrical/mechanical testing is required at JSC to reach a reasonable level of mission risk.

The TAT did find that the ISIM and OTIS testing can be shortened—reducing the overall Program critical path—by adding other tests that are not on the critical path. This should significantly increase the likelihood that the JSC testing will be achieved according to plan without increasing the programmatic risk beyond acceptable levels.

4. Findings, Assessments, and Recommendations

This section contains the TAT's Findings, Assessments, and Recommendations. In the context of this section—

- Findings are meant to be statements of fact, i.e., objective statements without opinion and without prejudice.
- Assessments are subjective and represent opinions of the team members about what the Findings could imply as adverse consequences to the program, and are intended to lay the basis and rationale for the Recommendations.
- Recommendations are subjective and represent opinions of the team members as to how the Project might deal with the consequences of the Findings.

The credibility of the Assessments and Recommendations rests on the experience and knowledge of the team members.

4.1 Science and Testing Priorities

4.1.1 Prioritization of Verification Tasks

4.1.1.1 Finding

The JWST I&T is a large program designed to verify JWST performance in a traditional, requirements-based way.

4.1.1.2 Assessment

The JWST I&T program is a requirements-based verification approach that has evolved into a number of large, complicated tests. Many of the requirements are necessarily verified by analysis, using high-fidelity models supported by complex tests.

In reality, the complexity and scale of the JWST flight system will require significant compromises to the formal verification of requirements as practiced in traditional NASA programs. The verification program must be tailored because of the technical and programmatic limitations of a program such as JWST.

In terms of ensuring an operating scientifically productive facility, some requirements are particularly important while others have less impact. The requirements could be prioritized based on risk to overall mission success and on difficulty of implementation. The prioritized list could be used to design and implement the test program. Verifications that have low risk of failure or low consequences due to a failure could be considered optional.

A fundamental set of verification tasks exists that would ensure that the system operates at a minimally acceptable level. These "irreducible verification tasks" should be carried out early in ISIM and OTIS testing so that if testing were halted earlier than planned (due to facility problems or cost and schedule constraints), those verifications would have already been completed.

4.1.1.3 Recommendations

Tailor the verification program based on technical and programmatic limitations in the following manner:

1. Identify and prioritize key system requirements.
2. Use the prioritized list to design and implement the test program.
3. Identify irreducible testing verification tasks and give these tasks higher priority during ISIM and OTIS testing.

4.1.2 OTIS Testing at JSC

4.1.2.1 Finding

The activities proposed by the Project for JSC cryo-vac testing range from looking for major faults that would essentially prevent the observatory from functioning on-orbit to detailed validation of analytical models that can be used in combination with test data to predict on-orbit performance.

4.1.2.2 Assessment

The distinction between functional testing and performance testing is important in the context of resource-constrained testing. The OTIS test program has not been structured to appreciate the distinction between those high-priority tests that greatly reduce the risk that the observatory will not function ("proof of life") from those that endeavor to predict levels of performance.

While OTIS performance tests clearly increase confidence in the on-orbit performance of the observatory, these tests should only follow satisfactory conclusion of the functional tests. Given the possibility of cost growth and schedule erosion, performance testing should not be permitted to continue beyond the time allocated in the schedule.

OTIS testing is planned for 167 days. All OTIS testing can and should be concluded in 90 days, and certainly in no more than 120 days. The goals driving the overall test planning should be to take the OTIS testing off the critical path and to find critical problems early. Given the likelihood of cost growth and schedule erosion attendant to the OTIS testing activities, continued testing past the planned end-date would be justified only if the risk to achieving Level 1 science requirements was unacceptable.

If a critical problem is detected (optical, thermal, mechanical, electrical, etc.), a warm-up would be needed to carry out a repair and a second cool-down would be required to verify the repair and continue with the rest of the planned testing. If the test program is designed to detect such problems early enough in the test cycle, it should be possible to fit the additional warm-up and cool-down time into the existing schedule. Therefore, critical functionality tests should occur as early as possible in the test sequence, followed by any remaining functionality tests and then by performance testing.

4.1.2.3 Recommendations

4. Plan to conclude all OTIS testing in 90 days with the intent that continued work at JSC past the planned end-date is justified only if there is substantial risk to achieving Level 1 science requirements.
5. Establish the clear priority of functional tests in the chamber over performance testing.
6. Complete critical functionality tests early in the testing sequence.

4.1.3 MIRI Testing at JSC

4.1.3.1 Finding

One of the objectives of the OTIS testing at JSC is to verify that MIRI and its cooler will operate on-orbit.

4.1.3.2 Assessment

The thermal requirements for ISIM are strongly driven by the requirement to cool MIRI to a temperature substantially below the other instrument requirements. MIRI requires operation of an associated cryo-cooler. In order for the cryo-cooler to work properly it must first be cooled to a critical temperature called the pinch point. Once the pinch point is reached, the cryo-cooler begins operation and cools MIRI to its required operating temperature of 7 K.

During OTIS testing, there could be a temperature range (perhaps due to an unexpected heat leak in the test setup) wherein ISIM or the MIRI cryo-cooler could be operating too warm to confidently predict that the MIRI pinch-point temperature would be reached on-orbit, yet low enough to demonstrate proper operation of NIRCam, NIRSpec, TFI, and the FGS. This situation is discussed in more detail in Section 5.3 under “MIRI Verification During OTIS Testing.”

Should the temperature in the OTIS test stabilize in this range, the Project will be faced with a decision of whether to

- continue testing with the objective of understanding the cause of the problem;
- declare the test a success without having verified that MIRI and its cooler will operate on orbit; or
- interrupt the test, break vacuum, fix the problem, and then repeat the test.

Given the high cost of repeating the test, or even the expense of spending time to understand the problem, the Project should develop criteria that can be used to guide the decision-making process during the test. The criteria should explicitly acknowledge that under certain circumstances, and in the interest of avoiding cost growth and schedule erosion, the Project is prepared to forego the test objective of verifying that MIRI will operate on-orbit.

These criteria could lead to a decision to launch JWST, having verified NIRCam, NIRSpec, and TFI on-orbit performance, but without having verified that MIRI will operate in orbit. If taken, this decision will be painful; therefore the criteria need to be developed and thoroughly vetted among the principal stakeholders well before the start of the test.

Failure to verify that the MIRI pinch point will be reached on-orbit in the test chamber does not necessarily mean that the pinch-point temperature will not be reached on orbit. Therefore, proving this in the chamber should not be a priority objective of the OTIS testing, especially if it requires prolonging the chamber test or a second pump down and cryo cycle.

4.1.3.3 Recommendation

7. Modify the JSC thermal test criteria as follows:
    a. Set the upper limit of the acceptable ISIM test temperature range to that below which NIRCam, NIRSpec, and FGS (and TFI) would be expected to perform adequately.
    b. Explicitly acknowledge the increased likelihood that the MIRI cryo-cooler will not function properly toward the upper end of this range.

c. Establish the principle that verification of MIRI performance will not be the sole justification for a second OTIS test cycle or for prolonging the first cycle, i.e., the test plan will be driven primarily by NIRCam, FGS, and NIRSpec.

4.1.4 NIR Detector Operating Margins

4.1.4.1 Finding

The detector operating temperature for the NIR detectors is specified at ~37 K, with a maximum allowable temperature of 45 K.

4.1.4.2 Assessment

In order to meet the Level 1 science requirements, the detector operating temperature for NIRCam is specified at ~37 K with a maximum allowable of 45 K. This difference is only 8 K and implies that the actual test temperatures in flight and in the test chamber must fall within this rather narrow range. However, based on measured laboratory data, the short-wave NIRCam works acceptably all the way to 80 K, while the long-wave channel meets specification at 47 K and can function with some degradation up to 55 K. In Section 5.3, Figure 5.3 shows the expected NIRCam performance as a function of temperature. The difference between the specified operating temperature and the temperature where the instrument performance begins to degrade at a rapid rate is defined as "headroom." The headroom for the short-wave NIRCam detectors is greater than 40 K; it is 18 K for the long-wave channel.

The same 5 μm–cutoff NIR detectors are common among NIRCam, NIRSpec, and TFI; however because of the lower backgrounds, the allowable temperature for NIRSpec and TFI will be lower. Measurements of the current NIRSpec detectors from 35 to 40 K suggest that the dark current might increase rapidly after 45 K. Whether any headroom exists for the NIRSpec and TFI detectors, and at what magnitude, is unknown because performance data at extended temperature ranges for the flight detectors for these instruments do not exist. Knowing the available headroom is crucial given the uncertainties in the thermal modeling and the extrapolations thereof to on-orbit performance. Dark-current data on the NIRSpec and TFI flight detectors is needed in the 45–60 K range to establish the available headroom and to understand how instrument performance degrades at these warmer temperatures.

The available headroom should be used for decision making during ISIM and OTIS testing. This would allow the Project to establish wider temperature acceptability limits in the OTIS tests, and even wider limits corresponding to some predetermined relaxation of the L1–derived science requirements.

The Program should not allow itself to become trapped into trying to verify an on-orbit temperature performance of the NIRSpec and TFI detectors (at, e.g., ~37 K) if acceptable functionality can be demonstrated at a higher temperature. NIRSpec detectors with lower average dark current—and therefore more headroom—would allow NIRSpec to function in the contingency of on-orbit temperatures that are warmer than anticipated. Such detectors could also make a decisive difference in the OTIS test program if the ISIM temperatures are several degrees warmer than anticipated and no straightforward fix can be found. For these reasons, it would be worthwhile to try to obtain NIRSpec detectors that support additional headroom.

In 2006, early test detectors provided an existence proof of devices with better dark-current characteristics, but they were judged not acceptable for flight because of a large population of unacceptable pixels. Today, higher in-flight temperature limits might be preferable to a smaller population of unacceptable pixels. Providing NIRSpec with detectors that matched the best of the early devices would significantly increase the potential headroom.

There is an incongruity between the Project's driving concern about achieving low on-orbit temperatures (< 45 K) while rejecting detectors that would have enabled adequate on-orbit operation in the contingency that the telescope stabilizes at a higher temperature. Similarly, there is an absence of recovery plans should the temperature in the OTIS test chamber not get that low.

The detector rejection, based on strict engineering evaluation, should have been tempered by a science system evaluation of the alternative. Instead, the rejection seems to have been driven by the fact that the temperature required for proper operation of MIRI would necessarily mean that NIRCam and NIRSpec would be within their specified temperature ranges.

A more graceful mission fallback wherein the system failed to meet MIRI temperatures in flight while allowing degraded operation of the others would seem to be preferable, but this was ruled out by the detector selection criteria.

4.1.4.3 Recommendations

8. Acquire dark-current data for the flight NIRSpec, and possibly all the NIR detectors, at temperatures up to at least 60 K.
9. Make a concerted effort to obtain new NIRSpec flight detectors with improved dark-current performance.

4.2 Organization and Decision Making

4.2.1 Dedicated I&T Lead

4.2.1.1 Finding

There is no single dedicated project test lead focused on the overall global optimization of the test program and on the approach required for systems of the physical size and nature of the JWST spacecraft.

4.2.1.2 Assessment

A single dedicated project test lead who understands the whole test program, supported by discipline experts, could optimize the test program from this point forward. A traditional "Test as you Fly" (TAYF) verification program is not possible because of the physical size of JWST and the infeasibility of replicating the gravity and thermal environment of JWST in operation. A different approach is required for the system-level test program that combines direct verifications of function and performance and validation of models used to predict on-orbit performance. A dedicated project test lead could carefully design and implement an approach using a clear guiding strategy that is comprehensive, coherent, and minimally redundant across the entire program, including ISIM, Pathfinders, and the OTIS tests.

OTIS system-level testing is costly and complex. Because of this, the scope must be restricted to verify only those requirements and models that cannot be verified at lower levels. The plans do not show sufficient focus on OTIS testing as part of an integrated and optimized whole or on setting testing priorities. There were some gaps and overlaps in the test plans. A clear strategy and set of priorities could allow the Project to identify additional gaps and overlaps.

Strong focused leadership will be necessary to fully optimize the test program.

4.2.1.3 Recommendations

10. Establish an overall I&T Lead with responsibility for defining and documenting a clear I&T approach.
11. Adopt an overall I&T plan that takes maximum advantage of efficiencies across all phases of the test program with the goal of minimizing the risk of cost and schedule growth during OTIS testing at JSC.

4.2.2 Decision Making During OTIS Testing

4.2.2.1 Finding

The Project believes there is a 10–50% probability that a fault, workmanship error, or test anomaly will necessitate the breaking of the JSC vacuum to bring OTIS back to room temperature and may subsequently require a repeat cyro cycle at JSC.

4.2.2.2 Assessment

The range of uncertainty and the number of different postulated potential reasons for breaking chamber will require rapid decision making to drive efficient execution and replanning in response to emerging issues.

As described elsewhere in this report, the OTIS testing at JSC should be structured with an early set of tests that supports the quickest possible determination that either the observatory is likely to function and perform to at least a minimally acceptable level, or that the chamber must be opened to correct some problem. If achieving the conditions and the data quality needed to fully meet the test objective proves difficult, or if the testing produces ambiguous results that do not lead to a clear assessment of risk, a decision process is needed that supports rapid risk determination and decision making. The intent would be to minimize test time when the results do not make a material difference in the likely decisions.

The decision process requires pre-established criteria, contingency planning, and rapid turnaround and communication of technical assessments and analyses. The criteria should cover test success, test interruption and resumption, and test abort. The contingency planning should address extending, repeating, or adding test sequences and conditions. The emerging results should drive the evolving timeline, including terminating or extending either subset events or the overall test. All of this should be available for review and discussion at the test readiness reviews.

To facilitate real-time, test-related decision making, all necessary parties to decisions should be assembled (in person or electronically), briefed, and trained on their roles and responsibilities well before the start of the actual OTIS tests. Participation by the decision makers and risk acceptors will be necessary to endorse the execution of contingency plans and also to approve plans to deal with unanticipated events. The Project should exploit the considerable processes and experience developed and successfully applied for the Hubble Servicing missions, including rapid access to the SMD Associate Administrator and Center Directors (or their delegates).

4.2.2.3 Recommendations

12. Develop decision criteria and contingency plans.

13. Employ a command-and-decision structure during JWST testing similar to the one used during the Hubble Servicing missions.

4.2.3 I&T Reorganization

4.2.3.1 Finding

The JWST Project intends to have personnel in the GSFC JWST organization take over the OTIS test and integration responsibilities from NGAS.

4.2.3.2 Assessment

The rationale for doing this was unclear in terms of expected benefits and likely impact on the planned work. The Project held that it would be more efficient and cost effective for the Project to manage the I&T work since the majority of hardware integration work and OTE pre-tests work was to be performed at GSFC.

In effect, this move will relieve NGAS of a large degree of responsibility under the contract. It is not clear that the effect of this change has been fully evaluated in terms of contract scope changes, seamless transfer of responsibility, contract value cost offsets, in-flight award fee, or potential loss of contractor motivation and continuity of work. Also, it is not clear that GSFC has the ability to adequately staff their new proposed responsibility, especially in light of the likely staffing demands that NASA's revised Joint Polar Satellite System (JPSS) Program will require.

4.2.3.3 Recommendations

14. Carefully reassess the full implications of the proposed reorganization.
15. Get GSFC management commitment that the necessary staff can and will be committed to the new responsibility.

4.3 Optical Testing Priorities and Efficiencies

4.3.1 Prioritization of Optical Tests

4.3.1.1 Finding

OTIS optical testing at JSC is planned for 42 days.

4.3.1.2 Assessment

Much of the 42 days of optical testing is driven by a focus on functional and requirements verification to predict on-orbit performance. A delineation of testing priorities based upon functional and key performance verification was not clear.

OTIS optical testing should contain the minimum amount of testing needed to validate acceptable performance. There was little discussion on clear criteria that would accomplish this. Such criteria could guide the team on how to maximize the return on limited test time and how to avoid overextending lower priority tests to the detriment of higher priority tests. The criteria should acknowledge the priority of optical tests and can be structured to support rapid decision making during testing. They should also delineate the triage tests, i.e., tests the Project would forego as needed to maintain the timeline and in the need to capture higher priority tests.

The key optical tests at JSC are the alignment of the AOS to the ISIM package through the use of the downward-looking "half-pass" tests and the pupil alignment tests.

The planned pupil alignment verification should give unambiguous results, and the pupil image through NIRCam should easily distinguish between direct rogue path and indirect scatter in the chamber. Therefore, the rogue-path tests, which may give ambiguous results, should be eliminated, which may also eliminate the need for arrays of sources at the top of the chamber.

The Center of Curvature test of the primary mirror is valuable. The test should include coarsely phasing the mirror, recognizing that the test goal is to verify that the mirror segments are within the actuator capture range rather than phasing to a submicron level. Another test goal should be to verify that all actuators can deploy and work at both the coarse and fine levels.

Photogrammetry (PG) provides the best measure of mechanical placement of the primary mirror outer edges with respect to the secondary mirror and the AOS.

The pass-and-a-half tests send light through the entire optical system and are intended to give a cross check to the pupil-alignment and photogrammetry measurements, but the tests are likely to produce anomalies. Time spent investigating anomalies relative to conflicting photogrammetry and pupil-alignment tests is not worthwhile and should be avoided. The pass-and-a-half testing should be eliminated, or clear criteria must be set, including limiting the time allowed for this testing. For example, alignment measurements should only focus on identifying extreme cases in which a mirror is outside the active adjustment range.

Other tests that could drive the OTIS testing at JSC timeline are the cryogenic frill test and the WFSC demonstrations–calibrations. While such tests are “nice to have,” they will not drive conclusions on minimum observatory acceptability. Prior to MCDR, the plan was to conduct the frill test while warm. Since then it was eliminated. It would be a better use of resources and should be reconsidered.

4.3.1.3 Recommendations

16. Establish the following priorities during optical testing at JSC:
    a. Mechanism tests where appropriate (e.g., PMSA deployments)
    b. Photogrammetric optical alignment
    c. AOS-to-ISIM alignment
    d. Verification of integrated FSM/FGS functionality
    e. Center of Curvature test of the primary mirror
17. Establish go/no-go criteria; put cross checks and extrapolations to on-orbit performance on the triage list.
18. Eliminate cryo frill and rogue-path tests and reduce the scope of the pass-and-a-half testing.

4.3.2 ISIM Instrument and Optical Testing

4.3.2.1 Finding

The ISIM test timeline showed approximately two months of dedicated instrument and optical testing. This includes optical alignment and WFSC tests/demonstrations plus a two-week test period designated as Comprehensive Performance Testing (CPT). The Project stated that CPT would be repeated during OTIS testing at JSC.

4.3.2.2 Assessment

Comprehensive performance testing of the science instruments prior to delivery to ISIM is a Project requirement. The Project stated that CPT would be repeated during OTIS testing, which could mean that the Project may be anticipating delivery of instruments before the completion of the science instrument (SI) comprehensive testing. Instrument performance testing after integration with ISIM will be problematic and should be avoided.

ISIM testing should concentrate on integrated instrument package issues such as the alignment of each instrument at cryogenic temperatures to the telescope. Assuming that the science instruments will have undergone extensive performance testing at lower levels, comprehensive performance testing at the ISIM and OTIS level is unnecessary and inappropriate.

Instrument performance testing, WFSC demonstrations, or day-in-the-life testing are not consistent with the key test objectives for ISIM and OTIS given schedule and cost constraints.

Elimination or reduction of instrument performance testing would save substantial time during ISIM and OTIS testing. Additional time could be saved by overlapping CPT testing with thermal or other optical tests.

WFSC demonstrations should be limited to functional aspects (such as checking for sign errors when measuring influence functions), since this testing is highly unlikely to lead to any change in hardware prior to launch.

4.3.2.3 Recommendations

19. Eliminate or significantly reduce the science instrument CPT at the ISIM and OTIS levels and concentrate on efficient functional testing at these points.
20. Significantly reduce WFSC testing and demonstrations, concentrating on functional testing and first-order influence functions (e.g., polarity checks).
21. Eliminate WFS testing at the ISIM level that can be accomplished at the OTIS level.
22. Increase concurrent CPT, WFSC, and thermal testing during ISIM testing.

4.4 Alternative Thermal Testing Plans

4.4.1 Thermal Balance Testing at JSC

4.4.1.1 Finding

The timeline for OTIS testing at JSC includes two thermal balance tests, which account for about 60–70 days of testing.

4.4.1.2 Assessment

Combining the two planned thermal balance point tests at JSC into a single test would reduce the JSC timeline by 40 days or $40M at the putative cost of $1M per day.

A single thermal test might not produce enough data to correlate the thermal model. However, this can be offset by repeating the core thermal test using the updated core design and lessons learned from the first test. The second core test could be done off the critical path and would provide the model validation data that the second thermal balance point would have provided.

Another essential condition for reducing the number of thermal balance tests is the enhanced Pathfinder test discussed in Section 4.4.2. Pathfinder thermal test data, in addition to data from the second core test and other planned tests, will provide the data needed for thermal design validation.

4.4.1.3 Recommendations

23. Add a core test of the current design.
24. Combine the two thermal balance points in the current plan into a single test for workmanship verification and cross-checking of the analytical model.

4.4.2 Enhanced Pathfinder Testing

4.4.2.1 Finding

The baseline Pathfinder tests are designed to verify the optical GSE but not the thermal GSE. An additional objective for the Pathfinder test is to practice test procedures for both the GSE and the JSC chamber.

4.4.2.2 Assessment

The Pathfinder test can be enhanced to include temperature measurements and a new thermal model accounting for the partial OTE.

The enhanced Pathfinder test would provide an opportunity to validate the thermal GSE design substantially before the start of OTIS testing and is also essential for doing only a single thermal balance test at JSC.

4.4.2.3 Recommendations

25. Add thermal testing to the Pathfinder test.
26. Develop a thermal model for the enhanced Pathfinder test configuration.

4.4.3 ISIM Cryo Testing

4.4.3.1 Finding

The ISIM test is presently baselined for two cryo cycles. The first cycle spans 17 weeks; the second cycle, after sine vibration and acoustic testing of the ISIM, spans approximately 13 weeks.

4.4.3.2 Assessment

The ISIM I&T is on the critical path and approximately 16 weeks, a considerable saving, could be achieved by running ISIM for only one cryo cycle. A single cycle would fulfill all the required optical and thermal test objectives.

The first planned cryo cycle would have established an earlier compatibility between ISIM and OSIM before vibration and acoustic testing. Instead, this can be done by running a test offline with the ISIM structure, OSIM, and the NIRCam ETU, which has a partial focal plane and optics that mimic the flight design.

The first cycle would also have measured the SI displacements at cryogenic temperatures. The loss of this data could be mitigated during a planned cryo-proof test of the ISIM structure. During this test, mass surrogates for the SIs would be mounted to the structure with models of the kinematic mounts. If targets were provided, the cryogenic shift of the surrogate instruments could be measured by photogrammetry. An assessment of the ETU kinematic mounts versus the flight mounts would also be needed. Recent tests on the ISIM structure show that it is more stable than required for both cool-down and repeatability. Measuring the displacements with surrogate SIs instead of flight SIs would provide valuable data on SI shifts.

With regard to the first planned test, it is not necessary to check optical alignment before vibration testing. Structures change their alignment and o settle into a permanent position during initial vibration testing at protoflight levels. Further settling during lower level vibration, such as during launch, is negligible. And therefore, a single optical measurement after vibration is all that is required for optical alignment purposes, that is to say, the first planned cryo cycle and optical alignment can be eliminated.

4.4.3.3 Recommendations

27. Run a new cryo test, off the critical path, with OSIM and the NIRCam ETU.
28. Measure surrogate SI displacements during and after the cool-down phase of the ISIM structure proof-load test.
29. Eliminate the ISIM cryo test before sine vibration and acoustic testing.

4.4.4 Chamber Checkout at JSC

4.4.4.1 Finding

The JSC chamber modification includes several completely new or significantly modified systems, including vacuum, liquid nitrogen, helium refrigeration, and data acquisition and control. Initial chamber operations are conducted with OTIS GSE installed.

4.4.4.2 Assessment

A major facility modification of this type may result in facility-specific issues that must be addressed and corrected. Facility issues may be difficult to isolate when the facility has not been functionally exercised and characterized alone. Initial chamber operations are intended primarily to validate that the chamber modifications perform as intended. The presence of OTIS GSE during this period could introduce problems not related to the chamber modifications, per se.

The JSC crew has little or no experience in operating a facility for clean, cryogenic, optical test. The crew needs experience and familiarity with the new facility systems. Failure to identify facility-specific problems and provide adequate crew training prior to JWST–specific operations could result in lengthy unplanned downtimes that would jeopardize the OTIS test schedule.

4.4.4.3 Recommendation

30. Postpone installation of the OTIS GSE until after the chamber commissioning is complete.

4.5 Thermal Test Efficiencies

4.5.1 Thermal Simulation Turnaround Time

4.5.1.1 Finding

The current turnaround times of thermal simulations range from days to weeks.

4.5.1.2 Assessment

These turnaround times do not support the rapid assessments and decision making needed for the planning and execution of the thermal tests. Ambiguous or unexpected thermal test results could stall OTIS testing and lead to rapid cost growth. Faster thermal simulation turnaround times are needed to support quick diagnoses of thermal problems. This is necessary given the putative $1M per day cost of chamber dwell time.

Turnaround times could be shortened by making changes to computer hardware, models, software packages, and/or procedures.

4.5.1.3 Recommendation

31. Take measures to shorten the turnaround times for thermal simulations to a few hours.

4.5.2 Thermal Test Assessment Criteria

4.5.2.1 Finding

The thermal stabilization criterion is 20 mK per hour over a specified period of time.

4.5.2.2 Assessment

The OTIS test creates an environment that is close to actual on-orbit conditions but has significant and appropriate deviations.

The existing stabilization criteria are driven by the desire for high-fidelity, quantitative validation of the thermal model. However, a tiered set of stabilization criteria would substantially reduce the test time by tying them to functional performance criteria rather than solely to model validation criteria. The criteria should be used to decide when to stop testing or proceed to the next test phase, and should be structured in the following order of priority:

- detection of problems that threaten Level 1 requirements,
- detection of major workmanship problems,
- reaching temperatures that show satisfactory on-orbit performance will be achieved, and
- reaching sufficiently stable temperatures that enable model validation suitable for high-fidelity on-orbit performance prediction.

Tiered criteria would lead to shorter test times, since the success criteria for test phases can be chosen ahead of time and can include consideration of cost and schedule constraints.

4.5.2.3 Recommendation

32. Develop the tiered set of criteria that permit progressive assessments of hardware integrity based on information gained from the OTIS test as it evolves, and use them to—
    a. plan the OTIS testing,
    b. facilitate decision making before and during testing, and
    c. reduce the test time.

4.5.3 Parallel Optical and Thermal Testing at JSC

4.5.3.1 Finding

The timeline for OTIS testing at JSC includes both optical and thermal balance tests, encompassing 167 days in the chamber. For the most part, optical and thermal balance tests occur in distinct parts of the timeline.

4.5.3.2 Assessment

The rationale for performing the thermal balance test in a separate segment of the timeline was to avoid disturbances caused by the optical GSE. In particular, the thermal loads from the Center of Curvature Optical Assembly (COCOA) and photogrammetric cameras were considered unacceptable disturbances. However the simulation, showing the negative impact on thermal testing, was simplistic and unrealistic. For example, 100 hours of open shutter time for COCOA was assumed in the simulation, when in fact measurement runs can be accomplished in a tiny fraction of the time.

A more realistic assessment would include the following:

- Realistic COCOA test times.
- Thermal mitigations to COCOA and photogrammetric equipment or operations.
- Operating the photogrammetry cameras continuously during optical test—the thermal team should analyze the level of thermal uncertainty induced by the cameras.

Even a limited amount of concurrent optical and thermal testing could yield significant schedule reduction.

4.5.3.3 Recommendations

33. Replan the OTIS testing to eliminate 25 days of testing by conducting optical testing concurrently with thermal testing.
34. Perform the optical test at the 2.5 K elevated temperature level (T8) during the warm-up and do not stabilize.

4.5.4 Use of Radiator Margin

4.5.4.1 Finding

The ISIM radiators have 50% margin. The IEC harness radiator has ~50% margin.

4.5.4.2 Assessment

The JWST radiators have heat-load margin based on worst case thermal analysis.

Radiator margin is a system margin that compensates for the uncertainty in knowledge of the actual in-flight thermal performance. The margin also offsets anomalous conditions that are encountered during thermal testing.

As thermal balance testing progresses towards increasingly stable temperatures, the respective error term in the prediction of on orbit temperatures approaches zero. The uncertainty resulting from a system that has not yet reached steady-state temperatures can be estimated as the test progresses. Some of the available radiator margin can compensate for this uncertainty to shorten the test duration.

4.5.4.3 Recommendation

35. Apply radiator margin to reduce stabilization times.

5. Detailed Discussion of Three Charter Responses

5.1 Duplicative and Unnecessary Tests

This section provides elaboration of the information provided in Section 3.4.

Some duplicative and unnecessary tests exist in the plans.

All optical and thermal tests indicated in the plans serve the purpose of identifying and reducing risks. None of them is necessary for meeting the science requirements except in the sense that an unidentified problem could compromise the science. There are no measurements to be made that are intended to set final parameters of the hardware. Thus, the question must be answered in the context of what is meant by adequate risk reduction.

Some tests measure quantities that could be helpful in the early commissioning of the observatory in orbit. Such tests are not essential in the sense that they could be done in orbit, instead of spending time doing them on the ground. However, testing on the ground can be valued at $1M per day, while on-orbit operations can be valued at $5M per day based on the projected cost of mission operations over the limited lifetime of the JWST. Thus, a day saved in on-orbit calibration returns yields another day of higher value science data return.

Thermal Tests

At present, there are multiple thermal test points in the OTIS testing at JSC, but by adding some tests off the critical path, the OTIS tests can be simplified and would save significant overall schedule time while preserving the risk-reduction objectives. These suggestions are discussed in the findings.

The essential thermal issue is whether or not the detectors in the science instruments can reach the desired working temperature. If the detectors have cooled successfully, there is not much risk that the telescope optics or structure temperatures will be at too high a temperature for successful execution of the science program.

The observatory design allows the detectors to be sufficiently cold. Tests act as verification that the as-built system matches the design to an adequate degree and checks the integrity of the thermal system after the OTIS is subjected to sine vibration and acoustic tests. OTIS testing is necessary for this reason.

Optical Tests

At present, there are opportunities with the optical tests for improved efficiency, as well as for reduction of some repeat tests as described in Section 4.3.

The essential optical issues are whether or not the science instruments will receive the collected starlight with adequately small wavefront errors, and if there is proper pupil alignment (to avoid light leaks into the instruments). If properly implemented, the observatory design provides the desired performance. The optical tests act as verification that the as-built system matches the design to an adequate degree.

During lower level testing, the optics will have been cryo-tested individually and science instruments will have been cryo-tested. The package of science instruments will have been tested at the ISIM level. Higher level testing of the OTIS at JSC would primarily verify that—

- No gross error has occurred in the assembly of the primary mirror system.

- The telescope alignment is correct.
- The optical system has the required precision and range to align on-orbit.

Findings and recommendations related to this Section can be found in Sections 4.3 and 4.4.

5.2 Science requirements that drive the test program

This section elaborates on the information provided in Section 3.6.

The TAT was asked to assess which elements of the mission science requirements place the most stringent constraints on the test program (operational, logistical, scheduling, staffing, etc.).

JWST has a range of science requirements that place constraints on the basic performance parameters of the telescope and its instruments, which in turn place verification constraints on the test program. For JWST, the most stringent Level 1 science requirements fall into two broad categories: very sensitive imaging and low-resolution spectroscopy of extremely faint sources over the wavelength range $1\ \mu m < \lambda < 3\ \mu m$, and background-limited imaging and moderate-resolution spectroscopy of brighter sources, $3\ \mu m < \lambda < 28\ \mu m$.

In general, for any telescope operating in the background-limited regime—the typical case for JWST—the crucial observational parameter is the integration time needed to reach a given signal-to-noise ratio. This is given by the following equation:

$$t \propto \left(\frac{Signal}{Noise} \right)^2 \times \frac{D^2}{A} \times \frac{B_\lambda}{\eta_\lambda}$$

where—

- *D* is the image quality, or delivered encircled energy diameter of the telescope for a point source;
- *A* is the collecting area of the telescope;
- η_λ is the wavelength dependent throughput of the observatory, directly proportional to the detector quantum efficiency and dependent on the quality of the optical alignment; and
- B_λ is the total wavelength-dependent background flux per unit solid angle. In the thermal infrared, B_λ includes the backgrounds of the instrument and the telescope, as well as the sky background. At L2, the sky background is dominated by the zodiacal light; by cryogenic cooling of its mid-IR detectors, JWST is designed to be limited by the zodiacal background for wavelengths $\lambda < 10\ \mu m$.

The key assumption for background-limited observations is that the detector read noise and dark current are suppressed both by low-noise electronics and cryogenic cooling to be significantly below B_λ at any given wavelength λ (see Figure 5-1). The first category of science requirements is largely set by the science goal of detecting "first-light galaxies" at $\lambda = 2\ \mu m$, which requires the detection and characterization of extremely faint sources (flux densities $\sim 1.0 \times 10^{-34} Wm^{-2}Hz^{-1}$ or ~10 nJy). The science instruments for this Program are NIRCam, NIRSpec, and TFI. The key observatory parameters that directly affect reaching such faint sensitivities are the temperature of the shortwave detectors and instruments, (to minimize the effects of detector dark current and intrinsic instrument background), the near-infrared image quality of the telescope (to minimize the time to reach a given signal-to-noise ratio in the background limited regime), optical alignment (to use the available collecting area of JWST while minimizing stray light and scattering from near-by bright astrophysical sources), and, to some extent, the stability of the telescope since many of these sources will require long (10~100 hours) on-source integrations.

Both for ISIM and OTIS, testing the optical alignment and cryogenic image quality of the OTE and demonstrating that NIRCam, NIRSpec, and TFI can achieve the requisite temperatures place the most stringent requirement on these elements of the test program with respect to key science programs.

Figure 5-1 shows the zodiacal background expected at L2 compared to the background requirements for the telescope and instruments. To meet the science goals, this effectively means JWST is designed to ensure that broadband observations will be limited by the zodiacal background at wavelengths $\lambda < 10$ μm. (Figure 5-1 was taken from Figure 30, Space Science Reviews (2006), 123: 480–606.)

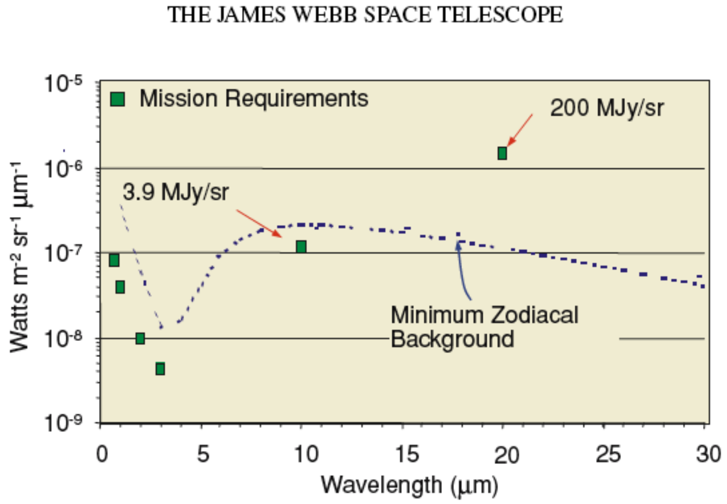


Figure 5-1: Zodiacal background expected at L2 compared to the background requirements for the telescope and instruments.

The second category of science requirements focuses on imaging and spectroscopy in wavelengths beyond 3 μm. This includes understanding, primarily through spectroscopic measurements with NIRSpec, TFI, and MIRI, the physical and chemical properties of young stellar objects, circumstellar debris disks, extra-solar giant planets, and Solar System objects. Important observations of the properties of galaxies during the epoch of galaxy assembly, in the redshift interval $1 < z < 3$, are also carried out in this regime, as is the ruling out of an older generation of stars to confirm the nature of the sources as first-generation objects.

Figure 5-2 is an example of a key science observation driving the requirements beyond 3 μm taken from the JWST science requirements documents (Figure 6-2, p. 6-5). This shows the potential ability of JWST to characterize extra-solar planets relying on spectroscopy across the 2–5-μm range, with the lowest mass planets ($M_J = 2$) being detected only in the 4–5-μm band with NIRCam.

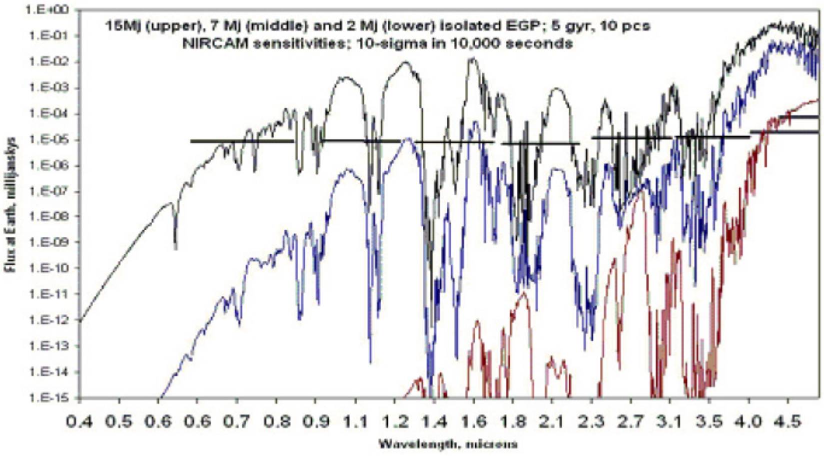


Figure 5-2: An example of a key science observation driving the requirements beyond 3 μm.

For ISIM and OTIS testing, the second category of science requirements does not place stringent requirements on the telescope image quality. However, it does place stringent requirements on the detector and instrument temperatures, the alignment of the instruments to the telescope (particularly the alignment of the instrument pupils with respect to the telescope aperture so the instruments see only the low-emissivity telescope mirrors and not high-emissivity structures), and the on-orbit temperature of the OTE for observations at wavelengths $\lambda > 10$ μm.

5.3 Relaxation of test-related requirements

This section elaborates on the information provided in Section 3.7.

The Charter asks that the team assess whether some relaxation of specific science requirements that particularly drive the complexity of test plans may reduce test complexity and enhance the probability that the test program would have a reasonable chance of being completed within hardware capabilities and allotted schedule.

Relaxation of the science requirements would not necessarily lead to a straightforward simplification of the test plans. However, there are other key requirements that could be relaxed to simplify the test program. For example, the image quality that is verified on the ground during OTIS testing could be relaxed without affecting the on-orbit image quality. Also, the requirement that OTIS testing verify the correct operation of MIRI's cryo-cooler could be eliminated if needed, as discussed below.

A simplification of the test plan cannot always be represented as a change in a Level 1 science requirement. For example, the current thermal requirements for the NIRCam science detectors can be exceeded somewhat before the detector dark currents reach a level where science capability is significantly reduced. This suggests that the range of acceptable operational temperatures for NIRCam could be increased. However, such an increase cannot be described by relaxing a Level 1 science requirement such as the flux-detection requirement. Relaxing the flux-detection requirement by a factor of 2 translates into a very small operating temperature change because of the strong non-linear dependence of the dark current on the operating temperature of the detectors. Directly relaxing the requirement on the range of operating temperatures captures the desired change more clearly.

MIRI Verification during OTIS Testing

For JWST to succeed as a Flagship-class facility, the NIRCam, NIRSpec, and TFI instruments must be capable of reliable measurements of faint galaxies and quasars that represent “first light.” Reaching those faint limits requires diffraction-limited imaging at 2 µm, as discussed in Section 5.2. However, image quality does not have to be verified to that level during OTIS testing since it will have been established during lower-level tests. Verification of image quality during OTIS testing could be relaxed to a 3 µm–diffraction limit. This would provide useful margin for the test program but would not compromise the telescope’s on-orbit image quality.

The other important issue relating science requirements to testing involves MIRI, which provides the only IR capabilities above 5 µm. These are for the most part aimed at the study of young stars and the formation of planets, the evolution of starbursts, and accreting massive black holes over the history of the universe. MIRI requires operation of an associated cryo-cooler. In order for the cryo-cooler to work properly it must first be cooled to a critical temperature called the pinch point. Once the pinch point is reached, the cryo-cooler begins operation and cools MIRI to its required operating temperature of 7 K.

In contrast, the NIR detectors used in the other instruments have warmer operating temperatures of about 37 K. Based on current laboratory data they could be run high as ~45 K before substantially impacting the science potential of these instruments. Figures 5-3 (a) and (b) show the case for the NIRCam detectors, which could run as warm as 80 K at short wavelengths. The most stringent temperature requirement of this group is set by NIRSpec dark-current performance. Measurements of the current NIRSpec detectors from 35 to 40 K suggest that the dark current might increase rapidly after 45 K. The precise upper limit on the NIRSpec detectors needs to be confirmed with further laboratory tests.

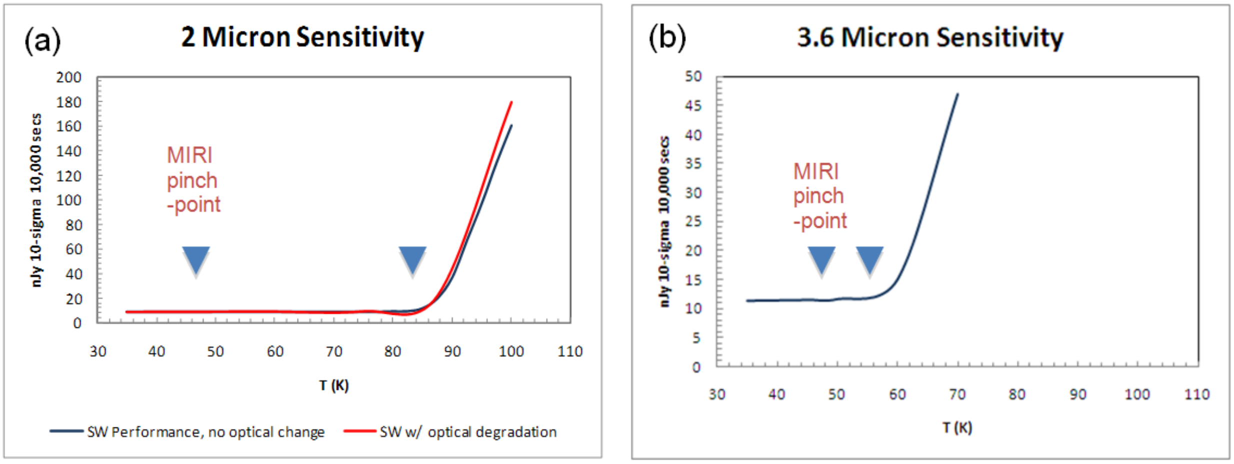


Figure 5-3: (a) Variation of observing sensitivity with temperature for NIRCam at 2 µm of the short-wavelength channel. The two dominant effects are the rapid increase in dark current above 80 K (black curve), and the degradation in encircled energy due to NIRCam’s approximate 1nm/°K increase in wavefront error (combined effect, red curve). (b) Variation of sensitivity with temperature for the NIRCam long-wavelength channel at 3.56 µm. The shape of this curve, and the rapid degradation in sensitivity beyond 55 K due to increasing dark current, is indicative of how NIRCam’s sensitivity would vary at any wavelength. In all cases the sensitivities are expressed in nJy representing a 10-sigma detection in 10,000 seconds. (Courtesy M. Rieke.)

During OTIS testing, there could be a temperature range (perhaps due to an unexpected heat leak in the test setup) wherein ISIM or the MIRI cryo-cooler could be operating too warm to confidently predict that the MIRI pinch-point temperature would be reached on-orbit, yet low enough to demonstrate proper operation of NIRCam, NIRSpec, TFI, and the FGS. (Figure 5-3 shows the size of that temperature range for the case of the NIRCam detectors.) OTIS testing could potentially be simplified by eliminating the requirement to verify MIRI cryo-cooler performance.

Such a test situation could lead to a decision to launch JWST having verified NIRCam, NIRSpec, and TFI on-orbit performance, but without having verified that MIRI will operate in orbit. (This does not necessarily mean that MIRI would not function on-orbit, just that correct operation is unverified.) The possible loss of MIRI science would be substantial, but the JWST mission would still be left with a large fraction of its core science program intact. The NIRCam, NIRSpec, and TFI can carry out a vigorous observing program that would justify flying JWST.

Findings, assessments, and recommendations related to this topic appear in Sections 4.1.3 and 4.1.4.

6. Biographies

JOHN CASANI (CHAIR)

John Casani is currently Special Assistant to the Director at the Jet Propulsion Laboratory. He has been a leader in the development and management of spacecraft systems. The majority of his career has been in systems engineering and project management. He was Project Manager for three major space missions at JPL: Voyager, Galileo, and Cassini. He held senior project positions in many of the early space programs, including Explorer, Pioneer, Ranger, and Mariner. He is the recipient of the National Academy of Engineering Founders Award and the National Aerospace Museum Lifetime Achievement Award. He is an Honorary Fellow of the AIAA and a member of the International Astronautics Academy.

Casani has received several NASA awards, including the Distinguished Service Medal, the Exceptional Achievement Medal, and the Medal for Outstanding Leadership. He received the AIAA Space System Award and the von Kármán Lectureship, the National Space Club Astronauts Engineer Award, and the AAS Space Flight Award. He has a BSEE and an Honorary Doctor of Science degree from the University of Pennsylvania and an honorary degree in Aerospace Engineering from the University of Rome.

ALAN DRESSLER

Alan Dressler is an astronomer at the Observatories of the Carnegie Institution in Pasadena, California. Dressler's principal area of research is the formation and evolution of galaxies. He makes observations with large ground-based telescopes such as Magellan, and space-based telescopes such as the Hubble and Spitzer. Dressler studies the effects of galaxy birth and environment on the development of galaxy type, structure, and star formation; it involves observing galaxies so distant that they are seen in their youth, billions of years ago. Dressler is a member of the NIRCam team—the principal camera for JWST—and is the PI of *IMACS*, a reimaging optical spectrograph, the most used instrument on the Magellan–Baade 6.5-m telescope.

From 1993–1995, Dressler led the "HST & Beyond Committee" for the Associated Universities for Research in Astronomy, whose principal recommendation was for the building of what is now the James Webb Space Telescope (JWST). In response to the report, NASA created an Origins Theme within the Office of Space Science. Dressler later chaired the Program's advisory committee and promoted the development of JWST, also serving on the JWST *Science Assessment Team* review in 2005.

Dressler chaired the panel on *Ground-Based OIR Astronomy* in the 2000 Decadal Survey of Astronomy and Astrophysics (AANM), and the *Electromagnetic Observations from Spac*e panel for the Astro2010 Survey. He was elected to the National Academy of Sciences in 1996 and awarded the NASA Public Service Medal in 1999. Dressler is an author on over 250 scientific papers and the author of many popular articles, as well as the Knopf book *Voyage to the Great Attractor: Exploring Intergalactic Space* (1994).

MILT HEFLIN

Milt Heflin is the Johnson Space Center Associate Director (Technical). During his 44-year NASA career he has served as Recovery Engineer for eight Apollo splashdowns; Flight

Controller in Mission Control for the Space Shuttle Approach and Landing Tests and for the first nine Space Shuttle missions; and Flight Director for 20 Space Shuttle missions, including seven of these as the Lead Flight Director—one of which was the First Servicing Mission to the Hubble Space Telescope in 1993. He has held several management roles including Chief of the Flight Director Office and Deputy Director of the Mission Operations Directorate. He is a recipient of the Presidential Rank Award of Meritorious Senior Executive, two NASA Exceptional Service Medals, the NASA Outstanding Leadership Medal, and a co-recipient of the 1993 "*Collier Trophy.*" He is also a member of the Oklahoma Aviation and Space Hall of Fame and the Aviation Week & Space Technology Laureates Hall of Fame.

WILLIAM IRACE

William Irace is the Project Manager of the Widefield Infrared Survey Explorer (WISE) mission. Irace has had important roles on several successful space cryogenic astronomy missions since he joined JPL in 1971. He led the systems engineering team of the InfraRed Astronomical Satellite (IRAS) instrument and was Payload Manager and then Deputy Project Manager of the Spitzer Space Telescope Project. Irace also has had key roles in the design and construction of the first ground based W.M. Keck Observatory, leading the systems engineering effort and coordinating assembly and commissioning of the telescope. In 2003, Irace was awarded NASA's Outstanding Leadership Medal for his leadership on the Spitzer Space Telescope Project development. Irace earned BS and MS degrees in aeronautical engineering from Purdue University.

JEFF KEGLEY

Jeff Kegley is the Manager of NASA's X-ray & Cryogenic Facility, a dual-capability environmental simulation facility used to perform ground calibration of X-ray telescope optical systems, and cryogenic, optical wavefront measurements of large, direct-incidence optics. His 21 years of space environmental test experience includes 12 years of cryogenic testing spanning over 70 optical, functional, structural deformation, and technology demonstration tests and includes extensive development of Helium gas–conductivity methods to augment heat transfer from test articles. Kegley's facility design and development experience includes the Shuttle Main Engine Technology Test Bed, the Advanced Turbopump Development Facility for Shuttle Main Engine, the X-ray Calibration Facility for Chandra Observatory flight optics and instrument calibration, and subsequent modifications to the X-ray Calibration Facility to provide 20-K test capability in support of James Webb Space Telescope structures and primary mirror segments. He earned a BS in Mechanical Engineering from Tennessee Technological University in 1987 and an MS in Mechanical Engineering with emphasis in the Fluid and Thermal Sciences from Auburn University in 1991.

MATT MOUNTAIN

Matt Mountain is the Director of the Space Telescope Science Institute and a Professor of Physics and Astronomy at the Johns Hopkins University. He has been a leader in the development and construction of infrared astronomical instrumentation and facilities. He was project scientist for the cryogenic infrared spectrograph, CGS4 on the United Kingdom Infrared Telescope (UKIRT), then headed its early active and adaptive optics program. He went on to become Project Scientist then Director for the Gemini Observatory, heading the team that designed, built and commissioned the two infrared optimized Gemini 8-m Telescopes and their instrumentation on Mauna Kea, Hawaii, and Cerro Pachón in Chile. Mountain is the Telescope Scientist for the James Webb Space Telescope. He is a Fellow of the American Astronomical

Society, the Royal Astronomical Society, and the American Association for the Advancement of Science; he is also a member of the International Society for Optical Engineering.

JERRY NELSON

Jerry Nelson is Professor of Astronomy and Astrophysics at the University of California, Santa Cruz. He has a long history of astronomical research and work on the design and construction of large ground-based telescopes and related science instruments. He is responsible for the basic design and development of the idea of building segmented primary mirrors for telescopes. He is the Project Scientist of the Keck Observatory, which has been in successful science operation for 17 years. He is the Project Scientist for the proposed Thirty Meter Telescope (TMT), a ground-based telescope with 492 mirror segments (approximately the same size as the JWST segments). He is a member of the National Academy of Sciences and has recently been awarded the Kavli Prize in Astrophysics.

JACOBUS (JIM) OSCHMANN

Jim Oschmann is Vice President and General Manager of the Antenna & Video Technologies strategic business unit for Ball Aerospace & Technologies Corp. Oschmann is in charge of acquisition and execution of programs that apply antenna, radio frequency, and video technologies for our nation's tactical defense needs.

Oschmann has held several key leadership positions at Ball Aerospace. Most recently, he served as the director of Program Execution for the Advanced Technologies & Products business area. Prior to joining Ball Aerospace in July of 2004, Oschmann served in technical and managerial positions across industry and the science community, including leadership positions at the Gemini Observatory and the National Solar Observatory. Earlier in his career, he worked in the aerospace industry at Sensis Corporation, Hughes Aircraft, and TRW.

Oschmann holds a BS in Optics from the University of Rochester and MS degrees in Optical Sciences and Business Administration from the University of Arizona. He is the chairman of the Society of Photographic Instrumentation Engineers conference on Optical, Infrared and Millimeter Space Telescopes and has previously chaired the Astronomy Symposium and two ground-based telescope conferences. He serves on various National Science Foundation review and advisory boards for ground-based astronomy. Oschmann also holds two patents on bar-code technology and has over 20 publications.

MICHAEL RYSCHKEWITSCH

Michael Ryschkewitsch serves as the NASA Chief Engineer. After 10 years of undergraduate, graduate, and postdoctoral experimental low-temperature physics research, he joined NASA Goddard Space Flight Center to work as cryogenics engineer on the Cosmic Background Explorer Project. On COBE he had multiple assignments, including lead engineer on the liquid Helium Dewar used to cool two of the three instruments and leader of the cryogenic mechanisms tiger team. He has extensive experience in instrument- and spacecraft-level development and verification in both project and engineering management roles, including optical and cryogenic systems such as the HST First Servicing Mission and COSTAR instrument, the Compton Gamma Ray Observatory, the Broad Band X-Ray Telescope, and Astro–E. He also participated extensively in the early planning and reviews of the JWST Project.

ALLAN SHERMAN

Allan Sherman is presently an aerospace engineering consultant and leader of the JWST Engineering Review Board. After beginning his career in industry he joined Goddard Space

Flight Center in 1966. At Goddard, Sherman was a leader for cryogenic missions and created the Cryogenics Branch. The most notable of these missions was the Cosmic Background Explorer to which he was a major contributor. His career then followed the path of systems engineering and management. As Division Chief, Deputy Director of Engineering and Director of Engineering, his work included supporting virtually all of Goddard's flight programs and technology. This included managing in-house programs such as XTE, SMEX, Shuttle-attached payloads, TRMM, CIRS, and technically review of out-of-house programs. His awards include NASA's Distinguished Service Medal, Outstanding Leadership Medal, and Exceptional Engineering Achievement Medal.

In 1997, Sherman joined Lockheed Martin corporate headquarters as Director of Advanced Development programs. In this position, he reviewed new commercial satellite programs, chaired anomaly and failure boards, was mission success manager for the EOS Terra system, reviewed technology investment programs and served on or led boards to review and make recommendations for programs with technical or programmatic issues. Sherman joined Ball Aerospace in 2003 and managed the East Coast office, supporting both JWST and internal Ball work. He became a private consultant two years later. Sherman received his BS and MS degrees in Mechanical Engineering from Cornell University and his PhD in Aerospace Engineering from the University of Maryland. He has chaired the external review board for the Aerospace Engineering Department at the University of Maryland for the last 16 years.

GEORG SIEBES

Georg Siebes is the Deputy Division Manager of the Mechanical Systems Division at the Jet Propulsion Laboratory. He has been at JPL for 26 years, starting as a thermal engineer and later on leading thermal system designs as Principal Engineer. Siebes has worked all stages of a project lifecycle, including projects such as UARS MLS, NSCAT, QuikScat, SeaWinds, WFPC-II, SIR-C, TOPEX, Deep Impact, CloudSat, and Aquarius. In addition to project and line management, Siebes is the author of JPL's Standard for System Thermal Testing, a member of JPL's System Engineering Advancement Management Oversight Group, the co-lead of JPL's Integrated Model Centric Engineering initiative, a U.S. delegate to ISO 10303 (STEP) TC184/SC4, a member of NASA's PDML Steering Committee, a member of the PDES Inc. Technical Advisory Board, and the customer chair emeritus of JPL's CIO advisory board. Siebes obtained his Diplom-Ingenieur degree (MS) in Mechanical Engineering in 1983 from the Rheinisch-Westfälische Technische Hochschule in Aachen, Germany, with a specialization in Thermodynamics and Heat Transfer. He is a member of AIAA and INCOSE.

ERICK YOUNG

Erick Young is the Director of SOFIA Science Mission Operations. Prior to assuming that position in 2009, he was an Astronomer at the University of Arizona specializing in infrared instrumentation and star formation. Young has a BS in Physics from the University of California, Davis, and a PhD in Astronomy from the State University of New York at Stony Brook. Beginning with the IRAS mission in 1979, he has been on the science teams and participated in the development of many space infrared astronomy missions, including Spacelab-II Infrared Telescope, Hubble Space Telescope NICMOS Instrument, Infrared Space Observatory Short Wavelength Spectrometer instrument, and Hubble Space Telescope Wide Field Camera-3 instrument. For the Spitzer Space Telescope, Young served as Deputy PI on the MIPS instrument as well as a member of the Facility Scientist Team. On JWST, he was the lead on the development of the focal plane arrays for the NIRCam instrument. Young was chair of the

NASA Infrared, Submillimeter, and Radio Detector Working Group. He is the recipient of the George Van Biesbroeck Prize as well as five NASA Group Achievement Awards.

ERIN ELLIOTT (EXECUTIVE SECRETARY)

Erin Elliott is currently a Senior Astronomical Optical Scientist at the Space Telescope Science Institute, where she is working on Wavefront Sensing and Control (WFSC) and maintenance for JWST. Until December 2009, she was a Senior Optical Engineer at Ball Aerospace working on WFSC algorithms and hardware for the NIRCam instrument. She was awarded a JWST Significant Achievement Award for her work on the WFSC hardware. Elliott completed her PhD at the University of Arizona's Optical Sciences Center in 2002. She was awarded a Michelson Interferometry Fellowship to support her dissertation work on the optical design of multiple-aperture imaging systems. Elliott also holds BS degrees from the University of Minnesota in physics and astronomy.

Appendix A: Figures

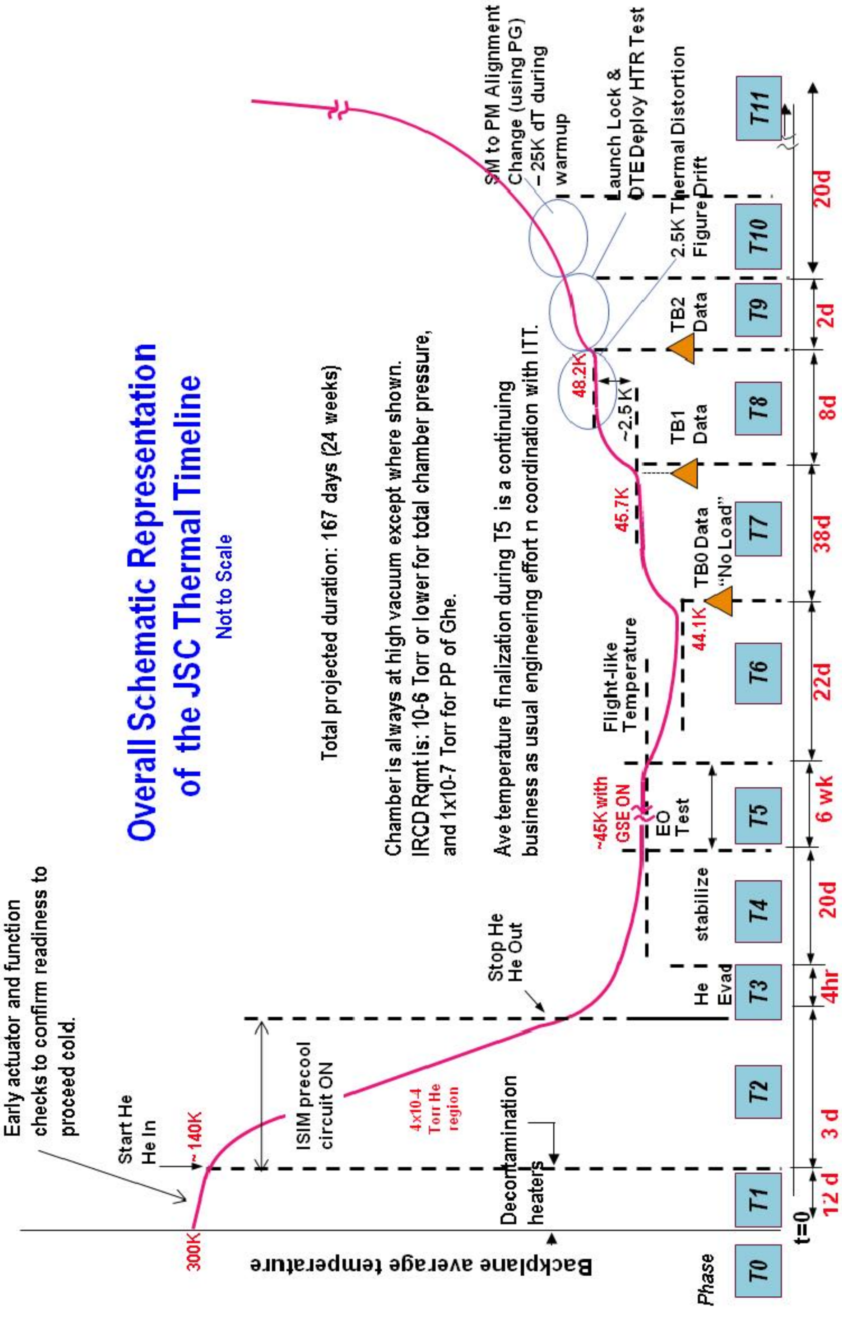


Figure A-1: Schematic representation of the JSC thermal timeline. The axes are not to scale.

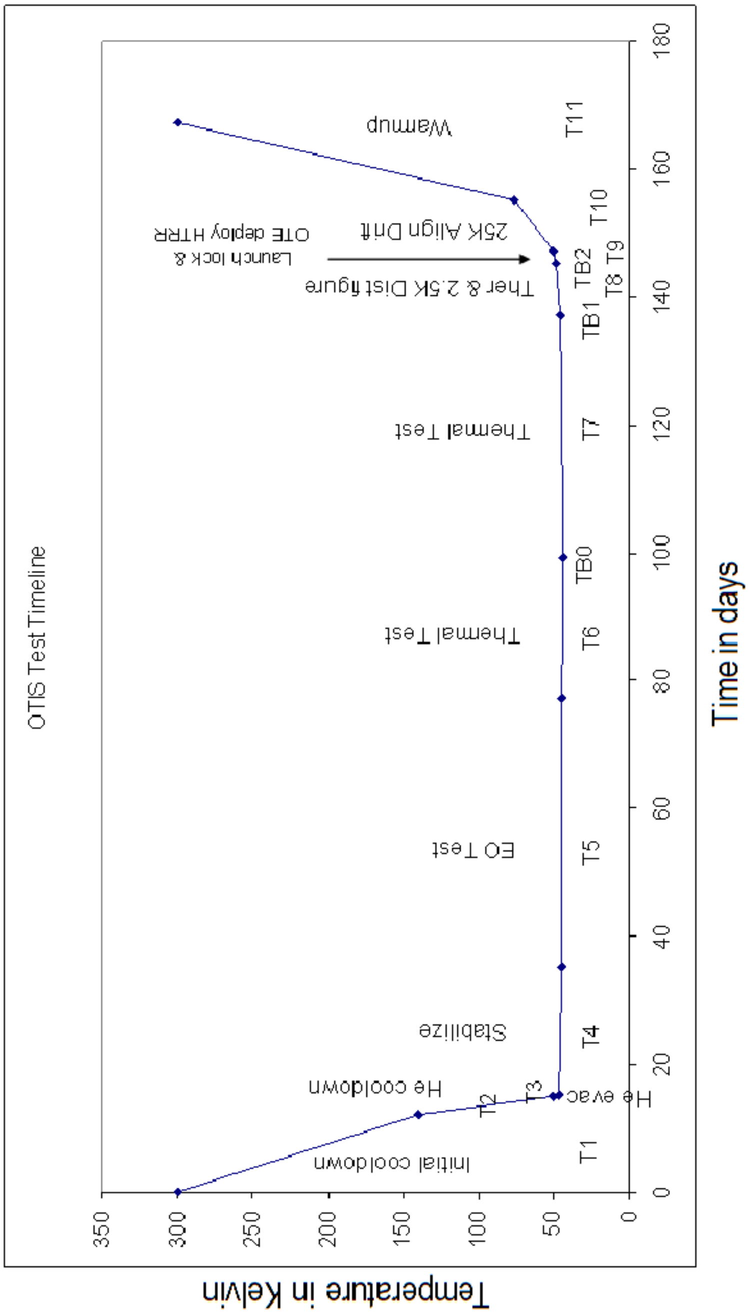
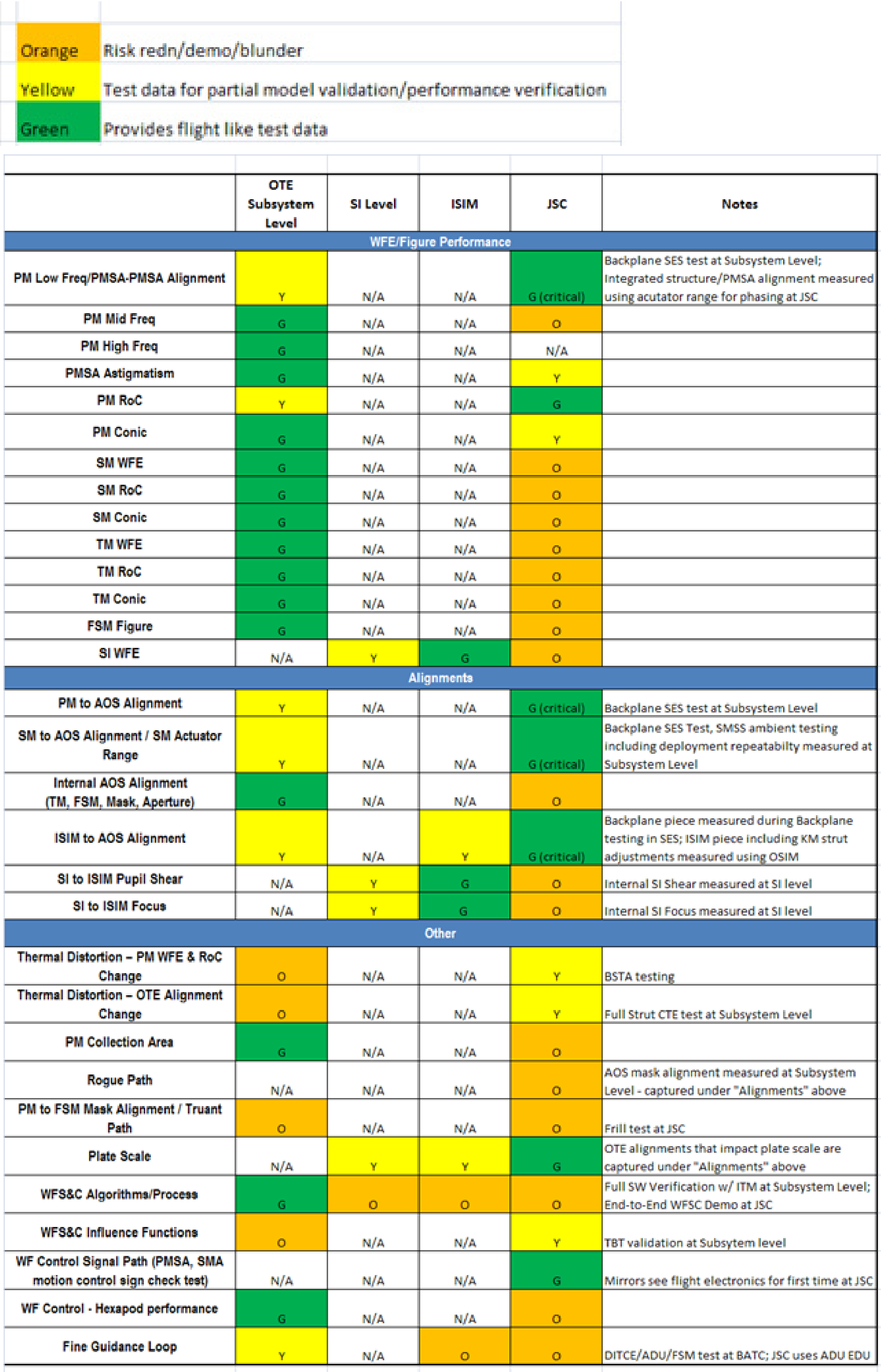


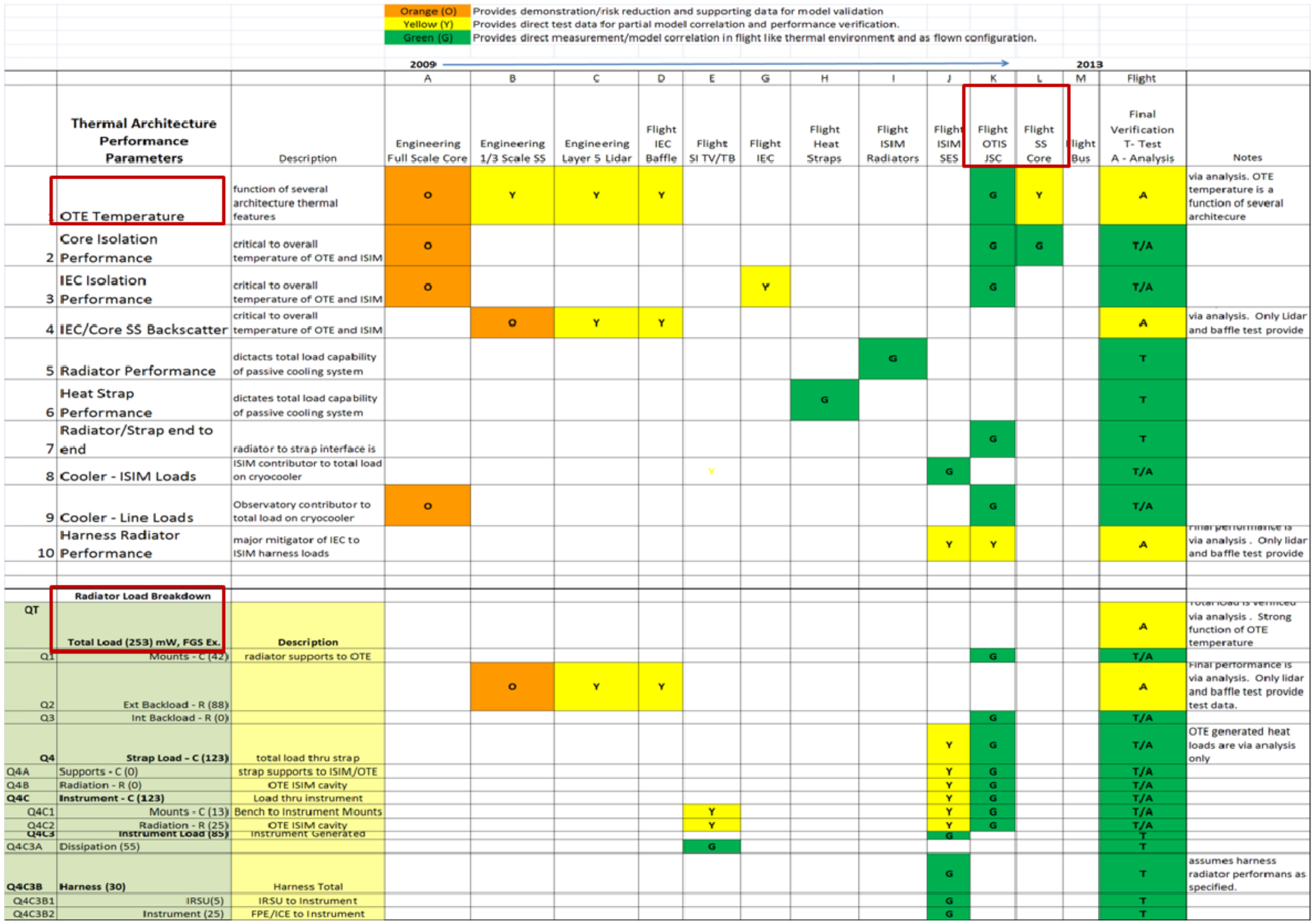
Figure A-2: Plot of the JSC thermal timeline. Axes are to scale.



Orange	Risk redn/demo/blunder
Yellow	Test data for partial model validation/performance verification
Green	Provides flight like test data

	OTE Subsystem Level	SI Level	ISIM	JSC	Notes
WFE/Figure Performance					
PM Low Freq/PMSA-PMSA Alignment	Y	N/A	N/A	G (critical)	Backplane SES test at Subsystem Level; Integrated structure/PMSA alignment measured using acutator range for phasing at JSC
PM Mid Freq	G	N/A	N/A	O	
PM High Freq	G	N/A	N/A	N/A	
PMSA Astigmatism	G	N/A	N/A	Y	
PM RoC	Y	N/A	N/A	G	
PM Conic	G	N/A	N/A	Y	
SM WFE	G	N/A	N/A	O	
SM RoC	G	N/A	N/A	O	
SM Conic	G	N/A	N/A	O	
TM WFE	G	N/A	N/A	O	
TM RoC	G	N/A	N/A	O	
TM Conic	G	N/A	N/A	O	
FSM Figure	G	N/A	N/A	O	
SI WFE	N/A	Y	G	O	
Alignments					
PM to AOS Alignment	Y	N/A	N/A	G (critical)	Backplane SES test at Subsystem Level
SM to AOS Alignment / SM Actuator Range	Y	N/A	N/A	G (critical)	Backplane SES Test, SMSS ambient testing including deployment repeatabilty measured at Subsystem Level
Internal AOS Alignment (TM, FSM, Mask, Aperture)	G	N/A	N/A	O	
ISIM to AOS Alignment	Y	N/A	Y	G (critical)	Backplane piece measured during Backplane testing in SES; ISIM piece including KM strut adjustments measured using OSIM
SI to ISIM Pupil Shear	N/A	Y	G	O	Internal SI Shear measured at SI level
SI to ISIM Focus	N/A	Y	G	O	Internal SI Focus measured at SI level
Other					
Thermal Distortion – PM WFE & RoC Change	O	N/A	N/A	Y	BSTA testing
Thermal Distortion – OTE Alignment Change	O	N/A	N/A	Y	Full Strut CTE test at Subsystem Level
PM Collection Area	G	N/A	N/A	O	
Rogue Path	N/A	N/A	N/A	O	AOS mask alignment measured at Subsystem Level - captured under "Alignments" above
PM to FSM Mask Alignment / Truant Path	O	N/A	N/A	O	Frill test at JSC
Plate Scale	N/A	Y	Y	G	OTE alignments that impact plate scale are captured under "Alignments" above
WFS&C Algorithms/Process	G	O	O	O	Full SW Verification w/ ITM at Subsystem Level; End-to-End WFSC Demo at JSC
WFS&C Influence Functions	O	N/A	N/A	Y	TBT validation at Subsytem level
WF Control Signal Path (PMSA, SMA motion control sign check test)	N/A	N/A	N/A	G	Mirrors see flight electronics for first time at JSC
WF Control - Hexapod performance	G	N/A	N/A	O	
Fine Guidance Loop	Y	N/A	O	O	DITCE/ADU/FSM test at BATC; JSC uses ADU EDU

Figure A-3: Overview of JWST optical performance verification plan.



🟧 Orange (O) Provides demonstration/risk reduction and supporting data for model validation

🟨 Yellow (Y) Provides direct test data for partial model correlation and performance verification.

🟩 Green (G) Provides direct measurement/model correlation in flight like thermal environment and as flown configuration.

2009 → 2013

			A	B	C	D	E	G	H	I	J	K	L	M	Flight	
	Thermal Architecture Performance Parameters	Description	Engineering Full Scale Core	Engineering 1/3 Scale SS	Engineering Layer 5 Lidar	Flight IEC Baffle	Flight SI TV/TB	Flight IEC	Flight Heat Straps	Flight ISIM Radiators	Flight ISIM SES	Flight OTIS JSC	Flight SS Core	Flight Bus	Final Verification T- Test A - Analysis	Notes
1	OTE Temperature	function of several architecture thermal features	O	Y	Y	Y						G	Y		A	via analysis. OTE temperature is a function of several architecure
2	Core Isolation Performance	critical to overall temperature of OTE and ISIM	O									G	G		T/A	
3	IEC Isolation Performance	critical to overall temperature of OTE and ISIM	O					Y				G			T/A	
4	IEC/Core SS Backscatter	critical to overall temperature of OTE and ISIM		O	Y	Y									A	via analysis. Only Lidar and baffle test provide
5	Radiator Performance	dictacts total load capability of passive cooling system								G					T	
6	Heat Strap Performance	dictates total load capability of passive cooling system							G						T	
7	Radiator/Strap end to end	radiator to strap interface is										G			T	
8	Cooler - ISIM Loads	ISIM contributor to total load on cryocooler					Y				G				T/A	
9	Cooler - Line Loads	Observatory contributor to total load on cryocooler	O									G			T/A	
10	Harness Radiator Performance	major mitigator of IEC to ISIM harness loads									Y	Y			A	Final performance is via analysis . Only lidar and baffle test provide
	Radiator Load Breakdown															
QT	Total Load (253) mW, FGS Ex.	Description													A	Total load is verified via analysis . Strong function of OTE temperature
Q1	Mounts - C (42)	radiator supports to OTE										G			T/A	
Q2	Ext Backload - R (88)			O	Y	Y									A	Final performance is via analysis. Only lidar and baffle test provide test data.
Q3	Int Backload - R (0)											G			T/A	
Q4	Strap Load - C (123)	total load thru strap									Y	G			T/A	OTE generated heat loads are via analysis only
Q4A	Supports - C (0)	strap supports to ISIM/OTE									Y	G			T/A	
Q4B	Radiation - R (0)	OTE ISIM cavity									Y	G			T/A	
Q4C	Instrument - C (123)	Load thru instrument									Y	G			T/A	
Q4C1	Mounts - C (13)	Bench to Instrument Mounts					Y				Y	G			T/A	
Q4C2	Radiation - R (25)	OTE ISIM cavity					Y				Y	G			T/A	
Q4C3	Instrument Load (85)	Instrument Generated									G				T	
Q4C3A	Dissipation (55)						G								T	
Q4C3B	Harness (30)	Harness Total									G				T	assumes harness radiator performans as specified.
Q4C3B1	IRSU(5)	IRSU to Instrument									G				T	
Q4C3B2	Instrument (25)	FPE/ICE to Instrument									G				T	

Figure A-4: JWST Observatory passive cryogenic performance verification overview.

Appendix B: Acronyms

AIAA	American Institute of Aeronautics and Astronautics
AOS	Aft Optical System
AoS	Acquisition of Signal
ATK	Alliant Techsystems Incorporated
Be	Beryllium
CDR	Critical Design Review
CIO	Center Information Officer
CoC	Center of Curvature
COCI	Center of Curvature Interferometric Test
COCOA	Center of Curvature Optical Assembly
CPT	Comprehensive Performance Testing
CSA	Canadian Space Agency
DOF, DoF	Degree(s) of Freedom
DOORS	Dynamic Object Oriented Requirements System
DTA	Deployable Tower Assembly
EGP	Extrasolar Giant Planet
EDT	Estimated Development Time
EDU	Engineering Development Unit
EO Test	Electro-Optical Test
ESA	European Space Agency
ETU	Engineering Test Unit
FACA	Federal Advisory Committee Act
FFRDC	Federally Funded Research and Development Center
FGS	Fine Guidance Sensor
FSM	Fine Steering Mirror
FSM	Fine Steering Mirror
FTE	Full Time Employee
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center
He	Helium
HST	Hubble Space Telescope
I&T	Integration and Test
IEC	ISIM Electronics Compartment
IEC	Instrument Electronics Compartment
IEEE	Institute of Electrical and Electronics Engineers
IRAS	Infrared Astronomical Satellite
IRCD	Interface Requirements Control Document
ISIM	Integrated Science Instrument Module
ISO	International Standards Organization
ITT	ITT Corporation
Jy	Jansky

JPL	Jet Propulsion Laboratory (Pasadena, California)
JPSS	Joint Polar Satellite System
JRIS	JWST Requirements Information System
JSC	Johnson Space Center
JWST	James Webb Space Telescope
K	Kelvin
LIDAR	Light Detection and Ranging
LV, L/V	Launch Vehicle
MCDR	Mission Critical Design Review
MIRI	Mid-Infrared Instrument
MLS	Microwave Limb Sounder
mK	milliKelvin
mW	milliwatt
NASA	National Aeronautics and Space Administration
NGAS	Northrop Grumman Aerospace Corporation
NICMOS	Near-Infrared Camera and Multi-Object Spectrometer (HST)
NIR	Near- Infrared
NIRCam	Near-Infrared Camera
NIRSpec	Near-Infrared Spectrograph
nm	nanometers
NSCAT	NASA Scatterometer
OSIM	OTE Simulator
OTE	Optical Telescope Element
OTIS	OTE / ISIM assembly
PDES	Produce Data Exchange using Standards
PG	Photogrammetry
PIL	Pupil Imaging Lens
PIT	Product Integrity Team
PM	Primary Mirror
PMBA	Primary Mirror Backplane Assembly
PMBSS	Primary Mirror Backplane Support Structure
PMSA	Primary Mirror Segment Assembly
PP	Pinch Point
RMS	Remote Manipulator System (Space Shuttle)
RoC	Radius of Curvature
SE	System Engineer
SES	Space Environment Simulation/ Simulator
SI	Science instrument
SIR-C	Spaceborne Imaging Radar - Camera
SMA	Secondary Mirror Assembly
SMD	Science Mission Directorate
SMSS	Secondary Mirror Support Structure
SOFIA	Stratospheric Observatory for Infrared Astronomy
SS, SSH	Sunshield
SSDIF	Spacecraft Systems Development and Integration Facility (Goddard)
STEP	Standard for the Exchange of Product model data (ISO 10303)
SVP	System Verification Plan

TAT	Test Assessment Team
TAYF	Test as you Fly
TDR	Test Discrepancy Report
TFI	Tunable Filter Imager
TIM	Technical Interchange Meeting
TM	Tertiary Mirror
TMS	Thermal Management Subsystem
TMT	Thirty Meter Telescope
UARS	Upper Atmosphere Research Satellite
UKIRT	United Kingdom Infrared Telescope
µm	Micrometers (microns)
V&V	Verification and Validation
WFE	Wavefront Error
WFPC2 WFPC-II	Wide Field Planetary Camera 2 (HST)
WFS	Wavefront Sensing
WFSC	Wavefront Sensing and Control
WISE	Widefield Infrared Survey Explorer
XRCF	X-ray Calibration Facility