INDEPENDENT COST ESTIMATE OF THE LARGE SYNOPTIC SURVEY TELESCOPE CAMERA PROJECT

UPDATE FOR CRITICAL DECISION–3, APPROVE START OF CONSTRUCTION

LSST Camera
APPROVED

Effective Date
29 Oct 2015

U.S. DEPARTMENT OF ENERGY

OFFICE OF

PROJECT MANAGEMENT OVERSIGHT AND ASSESSMENTS

August 2015

Independent Cost Estimate of the Large Synoptic Survey Telescope Camera Project, Update for Critical Decision–3

AUGUST 2015

Executive Summary

In March 2015, the U.S. Department of Energy (DOE) Office of Project Management Oversight and Assessments (PMOA) developed an independent cost estimate (ICE) for the Large Synoptic Survey Telescope (LSST) Camera project in support of Critical Decision (CD)–2, Approve Performance Baseline.

The LSST Camera project, with a DOE baseline cost of $168 million, is now preparing for CD-3, Approve Start of Construction. The Consolidated Appropriations Act, 2012[1], (Public Law 112-74) requires an ICE for a project having a total cost of more than $100 million prior to the approval of CD-3. Based on the limited time that has elapsed between the approval of CD-2 and the request for approval of CD-3, PMOA determined that an update of the March 2015 estimate was appropriate to identify any changes that may have altered the baseline project costs and examine whether the project cost estimate supports starting construction of the camera.

The ICE team evaluated: (1) the project schedule health, including whether the schedule is logical and well planned, and whether it follows U.S. Government Accountability Office (GAO) guidelines,[2] (2) the cost and schedule risk and how the project is managing it, and (3) the funding profile.

The ICE team determined the following in regard to the project costs and schedule:

- *Schedule health*. The health metrics indicate that the schedule is well planned and logical, and features a high degree of schedule margin. While a few of the metrics fall outside the GAO guideline thresholds, this is not

[1] Consolidated Appropriations Act, 2012, Public Law 112-74, Section 310, December 23, 2011.

[2] GAO, *GAO Schedule Assessment Guide: Best Practices for project schedules*, GAO-12-120G, May 2012.

unusual for a project of this type and size, and pose no risk to successful project execution.

- *Cost and schedule risk analysis.* The project risk management process and risk register demonstrate that the project is properly managing risk. The cost and schedule risks are well within the contingency budget and schedule margin.

- *Funding profile analysis.* The planned project funding profile is sufficient to keep the project well-funded through completion. FY16 cumulative funding exceeds cumulative budget demands by $19.4M. However, if DOE budgetary constraints are implemented and funding is frozen at the FY15 level, excess cumulative funding then drops to $13.6M. This is still more than adequate, but the project team may want to address this as a potential risk in the risk register.

Based upon its review, the ICE team concluded that the project's cost, scope, and schedule did not significantly change since the March 2015 CD-2 cost estimate review. The ICE team considers the project's cost and schedule to be reasonable and achievable, and supports approval of CD-3 at the current Total Project Cost (TPC) of $168 million and CD-4, Project Completion, date of March 2022.

The ICE team recommends the project team take the following actions to enhance overall cost and schedule performance:

- Continue to identify and quantify risks, comparing them with contingency funding.

- Identify and measure quantifiable backup data for longer-duration tasks to ensure project status and earned value are accurately measured and presented.

- Review longer-duration tasks to identify whether they can be broken down into more measurable and manageable short-term tasks.

- Review the schedule float to ensure the distribution across tasks is balanced for the remaining work. In addition, the impact of the float on the critical path analysis should also be reviewed.

- Review the coding in Primavera P6 that identifies activities on the primary critical path to ensure that activities are correctly assigned to the critical path.

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Section 1
Introduction

1.1 PURPOSE

This independent cost estimate (ICE) updates the March 2015 ICE performed for Critical Decision (CD)–2, Approve Performance Baseline, for the Large Synoptic Survey Telescope (LSST) Camera project.[3] It assesses whether the LSST Camera project is ready for CD-3, Approve Start of Construction.

1.2 PROJECT DESCRIPTION

The Large Synoptic Survey Telescope (LSST) will be a large-aperture, wide-field, optical imaging facility designed to address some of the most pressing questions about the structure and evolution of the universe and the objects in it.[4] The LSST is a joint project funded by the National Science Foundation (NSF) and Department of Energy. The observatory, including the site, the telescope, and data management will be funded by NSF: the LSST Camera will be funded by DOE SC/HEP. There is one Project Director for both the LSST Camera and the NSF construction effort. The LSST Camera project will design, fabricate, and lab-test an integrated camera system prior to delivery for installation onto the LSST situated on the El Penon peak of Cerra Pachon in Chile. The Camera, as an integrated functional system, will be assembled and completed at the SLAC National Accelerator Laboratory (SLAC) by CD-4, *Approve Project Completion*. The shipment of the Camera to Chile and final installation on the telescope are outside of the project scope. For details on the LSST Camera project, see the March 2015 ICE.[5]

The LSST Camera project—with a DOE baseline cost of $168 million—is now preparing for CD-3, Approve Start of Construction. The Consolidated Appropriations Act, 2012,[6] (Public Law 112-74) requires an ICE for a project having a total cost of more than $100 million prior to the approval of CD-3. Based on the limited time that has elapsed between the approval of CD-2 and the request for approval of CD-3, PMOA determined that an update of the March 2015 estimate

[3] *Independent Cost Estimate of Department of Energy Office of Science, Large Synoptic Survey Telescope (LSST) Camera Project, SLAC National Accelerator Laboratory, Menlo Park, California*, March 2015.

[4] Large Synoptic Survey Telescope (LSST) Camera Conceptual Design Report.

[5] See Note 3.

[6] See Note 1.

was appropriate to identify any changes that may have altered the baselined project costs and examine whether the project cost estimate supports starting construction of the camera.

The ICE team evaluated (1) the project schedule health, including whether the schedule is logical and well planned, and whether it follows U.S. Government Accountability Office (GAO) guidelines,[7] (2) the cost and schedule risk and how the project is managing it, and (3) the funding profile.

[7] See Note 2.

Section 2
Review Approach and Updates

2.1 APPROACH

The ICE report for CD-2 of the LSST Camera project was published in March 2015. Discussions with the project team revealed no significant cost changes since that time. Thus, the ICE team determined that an update to the March 2015 ICE was appropriate. The update focused on:

- Identifying significant project changes since the previous report.
- Comprehensively evaluating the schedule.
- Validating whether the funding profile supports the project schedule.

For the previous ICE approach and scope, see the March 2015 ICE.[8]

2.2 GROUND RULES AND ASSUMPTIONS

In reviewing the LSST Camera project, the ICE team utilized the following assumptions:

- The ICE team's cost and schedule risk assessment used post-mitigation risks from the risk register and related metrics for the Monte Carlo simulation model.
- All other ground rules and assumptions remains unchanged from the previous ICE and can be found in project document LCA-10894-C.

2.3 UPDATES

2.3.1 Shutter Minimum Exposure Time

The project team updated the shutter minimum exposure time KPPs since the last ICE (Table 2-1) but before CD-2 approval. A 15-second exposure was required for the normal cadence of the survey and will be used every observing night. However, as the project closed in on CD-2, the LSST scientists asked the project team to increase shutter speed for greater camera flexibility. A 2-second exposure time will enable the camera to capture brighter objects and study transients (near-

[8] See Note 3.

Earth objects, asteroids, comets, etc.). Thus, the project team updated its threshold "shutter minimum exposure time" from 15 to 2 seconds.

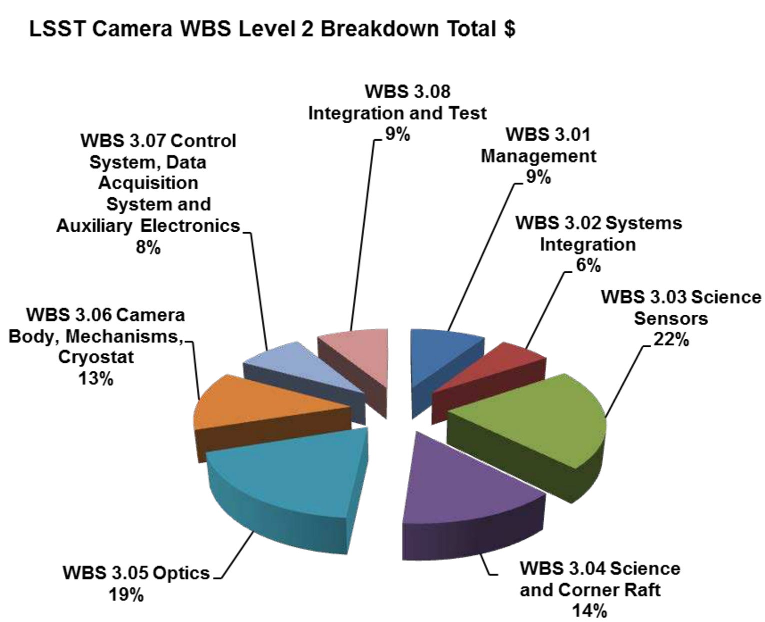
Table A-1. LSST Camera KPPs

Performance Measure	Threshold	Objectives
Field of view coverage	9.3 square degrees	9.6 square degrees
Pixel size	0.2 arcsec	0.2 arcsec
Number of pixels	2.6 Gigapixels	3.2 Gigapixels
Array readout time	3 seconds	2 seconds
Sensitivity range	320–1050 nm	320–1050 nm
Shutter minimum exposure time	2 seconds (updated)	1 second
Readout electron noise (single exposure)	13 electrons	9 electrons

2.3.2 Cost Breakdown

At work breakdown structure (WBS) level 2, the LSST camera cost percentages have changed slightly (Figure 2-1). WBS 3.02 (Systems Integration) went from 7 to 6 percent; WBS 3.05 (Optics) went from 20 to 19 percent; WBS 3.06 (Camera Body, Mechanisms, Cryostat) went from 12 to 13 percent. Small adjustments like these are expected as design and R&D activities progress as these have since March 2015.

Figure 2-1. WBS Cost Changes



The project has also made a few changes (activity work plan adjustments) through the formal performance measurement baseline change request (BCR) process.

Since CD-2 approval, the project processed 11 BCRs through June 2015, adding $611,607 to the performance measurement baseline.

Section 3
ICE Team Findings

3.1 SCHEDULE

The project WBS consists of six level 1 milestones, 28 level 2 milestones, 265 level 3 milestones, and 1,281 level 4, 5, and 6 milestones, for a total of 1,580 milestones. Document LCA-10884 contains the project's milestone dictionary. The schedule is organized by WBS and includes project activities, CD approval dates, major procurement purchase order dates, and milestones.

3.1.1 Analysis and Results

The ICE team reviewed the project schedule to validate the overall project duration and ensure the project's funding profile supports the proposed schedule. We independently checked the schedule risk analysis to validate the project's associated schedule margin. Tables 3-1 and 3-2 show specific DOE level 1 and 2 milestones, respectively.

Table A-1. WBS Level 1 Milestones

Milestone	Date
CD-0, Approve Mission Need	6/20/11 (actual)
CD-1, Approve Alternative Selection and Cost Range	4/11/12 (actual)
CD-3a, Approve Start of Long-Lead Procurements	6/5/2014 (actual)
CD-2, Approve Performance Baseline	1/15/15 (actual)
CD-3, Approve Start of Construction	1/2016
CD-4, Approve Project Completion	3/2022

Table A-2. WBS Level 2 Milestones

Milestone	Date
Conceptual Design Complete (Ready for CD-1)	11/30/11 (actual)
Prototype Science Sensors Received	1/3/12 (actual)
Vertical Slice Test—Phase 1	5/16/13 (actual)
Sensor Final Design Complete (Ready for CD-3a)	3/31/14 (actual)
First Article Sensor Contract (Ready for Award)	4/24/14 (actual)
Performance Baseline Established (Ready for CD-2)	10/16/14 (actual)
Camera Design Complete (Ready for CD-3)	8/2015

Table A-2. WBS Level 2 Milestones

Milestone	Date
First Sensor Tested	1/2016
First RTM Ready for Integration	5/2017
Cryostat Assembly Ready for Integration	9/2017
L3 Assembly Ready for Integration	7/2018
Sensor Production Complete	3/2019
Commissioning Camera Ready to Ship for Testing	5/2019
Early Hardware and Software Ready for Summit	7/2019
L1/L2 Assembly Ready for Integration	8/2019
1st Filter Coated and Ready for Integration	8/2019
Loaded Cryostat Ready for Integration	10/2019
Camera Fully Integrated & Ready for Verification Testing	5/2020
Camera Pre-Ship/Operations Readiness Review Complete	11/2020
KPPs achieved (Ready for CD-4)	2021

3.1.2Health Analysis and Assessment

The ICE team used the LSST Camera forecast project schedule, developed with Primavera P6, to evaluate the schedule. Tables 3-3 and 3-4 show the results of the ICE team qualitative schedule evaluation using the Primavera tool. The text that follows describes these results.

Table A-1. Primavera Schedule Task Health Metrics

		1		2	3	4			5	6	7	8	9				10
Assessment criteria		Missing Pred	Missing Succ	Negative Lags	Have Lags	Relationship Types			Hard Constraints	High Float	Negative Float	High Duration	Invalid Dates				No Assigned Resources
Goal		Less than 5%	Less than 5%	0 tasks	Less than 5%	FS 90% or greater	SS, FF Less then 10 %	SF 0 Task	5% or less	Less than 5%	Less than 5%	Less than 5%	Invalid Actual Start 0 tasks	Invalid Actual Finish 0 tasks	Invalid Forecast Start 0 tasks	Invalid Forecast Finish 0 tasks	0 tasks
# Links for incompleted Tasks	Incompleted Tasks	0	0	0	270	3675	633	0	0	2911	0	906	0	0	0	0	379
4308	2919	0.0%	0.0%	0.0%	9.25%	85.3%	7.3%	0.0%	0.0%	99.73%	0.0%	31.04%	0.00%	0.00%	0.00%	0.00%	13.0%

Table A-2. Primavera Schedule Milestone Health Metrics

	1		2	3	4	5			
Assessment criteria	Missing Pred	Missing Succ	Hard Constraints	High Float	Negative Float	Invalid Dates			
Goal	1 Milestone	1 Milestone	Only Contractual Milestones	For Information	0 Milestone	Invalid Actual Start 0 Milestone	Invalid Actual Finish 0 Milestone	Invalid Forecast Start 0 Milestone	Invalid Forecast Finish 0 Milestone
	0	2	0	952	0	0	0	0	0

(Appendix B, Table B-1, shows the completion status of the WBS level 3 design activities.)

The ICE team found parameters that fell outside Defense Contract Management Agency (DCMA) "14 Point Schedule Metrics" guidelines.[9]

- *Tasks with lags (9.25 vs. 5 percent)*. On a large-scale aircraft production program, having more than 5 percent of tasks with lags could result in significant issues with inventory control, production flow, and balance and high unit cost. On development projects such as the LSST project, lags offer more flexibility, so a higher percentage of tasks with lags is not unusual. The percentage of tasks with lags—9.25 percent—is above the guideline threshold. This is to be expected for a technical development project where for example successors may begin prior to the completion of a predecessor. This poses no threat to execution of the schedule.

- *Finish-to-start relationships (85.3 vs. 90 percent)*. Similar rationale applies to the number of finish-to-start relationships. On large-scale production programs, many of the tasks are expected to be repetitive, and having finish-to-start relationships of less than 90 percent can negatively impact performance. This is not the case with LSST Camera project, at an estimated 85 percent, which is reasonable and healthy. Given its current cost performance and schedule performance indexes, the number of relationships is sufficient to drive successful execution.

- *High float (99.7 vs. 5 percent)*. This threshold is established to prevent float added to an entire project's completion date or to high-level elements in the WBS. Float needs to be distributed at the task level, where a high degree of float actually represents schedule margin. Under GAO best practices, adequate float ensures success.

  Typically, Office of Science projects exhibit a high degree of float and schedule margin. The LSST Camera project is well planned and has accounted for risk with the proper amount of float on the correct tasks. The high degree of float on the remaining effort is a positive indication of schedule margin and flexibility. It is well distributed among critical tasks and gives the project the ability to strive for an early finish while leaving margin to deal with issues and ensure timely completion.

  The project is about to enter the construction, integration, and verification phases of development and production. Significant schedule risk remains to be retired on critical components. The high level of float in the schedule offers the project the ability to make adjustments and work-arounds to the plan to execute the project and keep the schedule on track.

- *Tasks with durations of more than 2 months (31 vs. 5 percent)*. The purpose of this threshold is to maximize the sample rate of tasks and task completions monthly. Having too many tasks that span more than 2

[9] DCMA, *Earned Value Management System (EVMS) Program Analysis Pamphlet (PAP)*, DCMA-EA PAM 200.1, October 2012.

months may indicate that tasks need to be broken down into finer, more discrete tasks. In this way, they can be measured and managed more effectively. The primary concern is that issues may be hidden in longer-duration critical tasks, making them not immediately apparent.

The number of LSST tasks of long duration (more than 44 days) is greater than the guideline. This is attributable to the high float and a number of tasks that reasonably exceed 2 months. The earned value technique the LSST project controls team has defined for earning value on task completions is 0/100, so variances may not appear until the scheduled completion of the task. While this is not an issue in terms of execution, the CAMs for these tasks should use quantifiable backup data (QBD) for long tasks that summarize their incremental completion so they can be more accurately measured while being executed.

- *Milestones with no successor (2 vs 1)*. Ideally, a project has only one milestone with no successor which is project completion. However, having two milestones with no successors is not an issue for the LSST Camera project because it has two completion (early and late finish) milestones:

  CAMM6050 APPROVED: CD-4, Project Completion - 13 Jan 2020

  CAMM1060 COMP: CD-4, Approve Project Completion - 29 Sep 2020

3.2 Risk and Uncertainty Analysis

The ICE team reviewed the reasonableness of the project team's cost and schedule risk analyses, relying on the completeness of the project teams risk identification as presented in the CD-3 risk register. We used these reviews to ensure the reasonableness of the LSST Camera project contingency allowances, that is, their appropriateness for determining management reserve and DOE budget contingency, as well as for contractor schedule reserve and DOE schedule contingency, as described in the subsections that follow.

3.2.1 Cost Contingency

The project team updated cost contingency using the data developed at the grassroots level by control account for CD-2, on the basis of the changes in the risks and risk levels as of July 2015. The CAMs calculated $24 million in cost contingency at CD-2. In June 2015, $19 million contingency budget remain, 21 percent of the remaining budget. The use of approximately $5M in contingency funds during this period was planned to mitigate risks prior to CD-3. Table 3-5 summarizes the contingency budgets and Estimates to Complete. Based on an assessment and analysis of the risks and impacts at post-mitigation (described in the next subsection), the contingency budgets remaining are reasonable to complete the effort required to mitigate cost and schedule risk.

Table A-1. LLST Camera Project Contingency Analysis ($000)

WBS (L2)	BAC	Actuals (thru Jun15)	Budget to Go	Contingency (BOE)	Contingency (BOE) %
3.01 Management	12,520	5,246	7,274	716	10%
3.02 Systems Integration	8,614	3,645	4,969	535	11%
3.03 Science Sensors	29,649	9,558	20,090	5,207	26%
3.04 Science & Corner Raft Systems	18,732	6,100	12,632	3,474	27%
3.05 Optics	25,145	7,274	17,871	3,916	22%
3.06 Camera Body, Mechanisms, Cryostat	17,587	5,727	11,860	2,843	24%
3.07 Control System, Data Acq Sys, Aux Elec	11,094	3,140	7,954	1,281	16%
3.08 Integration and Test	11,900	1,040	10,861	1,685	16%
Sub Total	135,240	41,730	93,511	19,656	21%
Contingency (TPC)	32,760		35%		
Total	168,000				

3.2.2 Risk Impact on Cost and Schedule

Following the contingency reasonableness review, the ICE team used the Palisade @Risk7 simulation tool to assess the impact of risks on the project cost and schedule. @Risk7 is a commercial off-the-shelf, add-on module to Microsoft Excel used to analyze risk impact via Monte Carlo simulations, on the basis of probability of impact and cost impact ranges from discrete risks recorded in a risk registry.

The method used to develop the simulations for risk impact on cost and schedule for CD-3 was very similar to that for CD-2. The ICE team reviewed the CD-3 (July 2015) risk register and selected all risks—52 of them—that had a "greater than insignificant" impact on the schedule and cost at the post-mitigation point.

Table 3-6 compares the LSST Camera project classification of risks at CD-2 and CD-3. The process appears well developed and executed. As expected, the risk management team continues to identify, quantify, mitigate, and retire risks as the project team executes. Although the total number of identified risks (moderate and high) has increased to 22, risks greater than insignificant have decreased from 54 to 52.

Table A-1. CAM Risk Registry—Total Risk Exposure

Category	CD-2		CD-3		Change	
	Current assessment	Post-mitigation exposure	Current assessment	Post-mitigation exposure	Current assessment	Post-mitigation exposure
Insignificant	136	241	172	265	36	24

Table A-1. CAM Risk Registry—Total Risk Exposure

Category	CD-2		CD-3		Change	
	Current assessment	Post-mitigation exposure	Current assessment	Post-mitigation exposure	Current assessment	Post-mitigation exposure
Minor	131	47	123	48	–8	1
Moderate	25	7	18	4	–7	–3
High	3	0	4	0	1	0
Critical	0	0	0	0	0	0
Total	295	295	317	317	22	22

The ICE team used the residual likelihood and impact levels, minimum/maximum cost impact, and minimum/maximum schedule impact from the CD-3 risk register as inputs for the model, running the Monte Carlo simulations to assess cost and schedule impact after the risks were retired. As noted in the assumptions, the accuracy of the simulations largely depend on the identification and classification of all LSST project risks.

(Appendix C contains the figures and tables that detail the results of our assessment of the impact of risks on the project cost and schedule.)

3.2.3 Summary

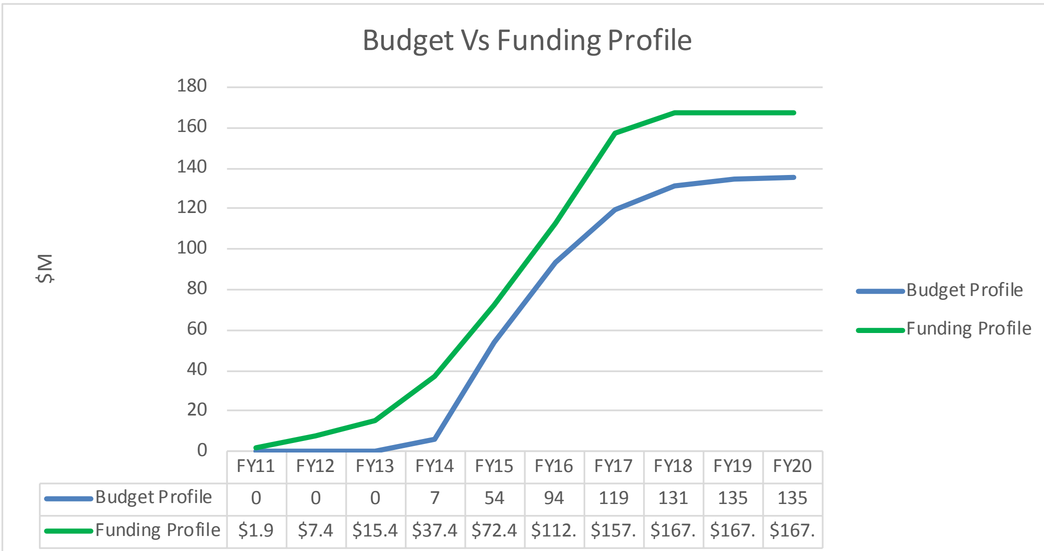
Overall, the results of the risk analysis for impact on cost and schedule indicate that the LSST project remains on track to complete within budget and schedule:

- Based on a 90 percent confidence interval, the mean impact of the risks post-mitigation on project costs is $9.7 million and the maximum cost overrun is $16.14 million, well within the remaining contingency budget of $19 million.
- Based on a 90 percent confidence interval, the mean impact on schedule duration post-mitigation is 10.8 months and the maximum schedule slippage is 17.71 months, well within the 23 months of schedule margin.
- The contingency budget plan is reasonable to cover the remaining project risk, minimizing overall impact and realizing opportunities.

3.3 Funding Profile Compared with Budget Assessment

- Figure 3-1 shows the annual funding profile compared with the budget at completion and most recent estimate at completion (EAC). As shown, the funding plan supports the project budget baseline and EAC. From the convergence of the curves near first quarter 2016, funding must be provided in a timely manner. If budgetary constraints are implemented, and funding is frozen at FY 15 level, then the excess cumulative funding drops to $13.6M. This is still more than adequate but the LSST project team may want to address this risk in the risk register.

Figure 3-1. Budget vs. Funding Profile



3.4 GAO Best Practices

The ICE team compared the LSST Camera Primavera P6 project schedule with GAO schedule best practices.[10] According to GAO best practices, "the critical path is theoretically the sequence of activities that represents the longest path from the project's start and finish dates." However, as schedules become more complex, float values may not represent the true critical path of the program. Also, when activities that represent level-of-effort work are entered into the schedule, it can affect what the longest path represents.

The ICE team initially analyzed the LSST Forecast schedule for a critical path using the longest path. However, because the program contains FY activities (those that represent a year's worth of effort) in the schedule, a filter for the longest path cannot be used for a critical path analysis. Instead, the ICE team assessed a critical path to the "COMP: PSR/ORR - Camera Pre-Ship/Operations Readiness Review Complete" activity (CAMM2290). To reduce any noncritical drivers affecting the analysis, we removed every finish constraint that could affect the critical path to the CAMM2290 activity. We assessed only the main critical path, although there could be different critical paths for different deliveries.

[10] See Note 2.

In our critical path analysis, we found that the LSST Camera project had identified the program critical path. It uses the Critical Path (CP1) field with a "CP4" code to identify the path through the network. In addition, we found that it is using another field, LSST Camera Critical Paths, to identify critical paths specific to the camera on the program. The coding in the fields appears to properly identify the critical path through the program.

However, the Critical Path (CP1) field has additional coding that identifies activities on the critical path that are slightly off of the deliverable critical path based on its float. The ICE team recommends cleaning up this field for the main critical path and identifying any off-critical-path activities as such.

Appendix D contains our detailed analysis of the project team's application of GAO best practices for project schedules.

Section 4

Conclusions and Recommendations

4.1 Conclusions

The LSST Camera project schedule is well laid out, healthy (according to GAO and Defense Contract Management Agency guidelines), and executable to a successful conclusion. The ICE team concludes the following from each element of our analysis:

- *Schedule health.* The health metrics indicate that the schedule is logical and well planned, and features a high degree of margin. While a few of the metrics fall outside the guideline thresholds, they are not unusual for a project of this type and size, and pose limited risk to successful project execution. “One-off” development projects typically have long-duration tasks for capabilities that may not be completely defined. However, the LSST project team should continue, as much as possible, to break down longer tasks into more manageable, measurable, shorter-term, discrete tasks. In addition, as noted in Section 3.1, the LSST project team should consider the level of float and the impact on the critical path, as well as clean up the P6 coding (CP1) field that identifies activities on and off the critical path.

- *Cost and schedule risk analysis.* First, the project risk management process and risk register demonstrate that the project is managing the risk. The risks as described at post-mitigation in terms of cost and schedule impact are reasonable and realistic. A reasonable contingency plan and budget are in place, maximizing the probability that the forecast conditions at post-mitigation will actually occur. The mean impact on cost due to risk is expected to be $9.7 million, well within the contingency budget and LSST Camera project target cost. The mean impact on the schedule is 10.8 months, well within the 23-month schedule margin. On the basis of a 90 percent confidence interval, the mean impact on cost due to risk is expected to be $9.7 million, well within the contingency budget and LSST Camera project target cost. The mean impact on the schedule is 10.8 months, well within the 23-month schedule margin.

- *Funding profile analysis.* The LSST Camera project funding profile is sufficient to keep the project well-funded through completion. Key risks are associated with funding. Also, the funding profile and project budget differential (Figure 3-1) approaches the minimum in 2016, a critical year in the project for procurement and fabrication of critical systems. Project funding must remain above the project budget demand in this time frame.

The funding at completion compared with the budget at completion demonstrates a high degree of margin. In short, the funding profile supports the project plan through completion.

4.2 RECOMMENDATIONS

Based upon its review, the ICE team concluded that the project's cost, scope, and schedule did not significantly change since the March 2015 CD-2 cost estimate review. The LSST project schedule is well developed and executable. The risk management process is also well defined, and risks are continuously identified, classified, and mitigated. Contingency funding and overall project funding is adequate to ensure successful completion of the project. The ICE team supports approval of CD-3, Approve Start of Construction, at the CD-2 approved Total Project Cost (TPC) of $168 million and CD-4, Project Completion, date of March 2022.

Additionally, the ICE team recommends the project team take the following actions to enhance overall cost and schedule performance:

- Continue to identify and quantify risks, comparing them with contingency funding.
- Identify and measure quantifiable backup data for longer-duration tasks to ensure project status and earned value are accurately measured and presented.
- Review longer-duration tasks to identify whether they can be broken down into more measurable and manageable short-term tasks.
- Review the schedule float regarding its impact on the critical path analysis as well as coding in Primavera P6 that identifies activities on the primary critical path.

Appendix A
Report Authors

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Mr. Huizenga has over 32 years of experience in program and project management responsible for successful completion of capital projects around the world. His distinguished career began with 20 years as a U.S. Air Force Officer in the Civil Engineering career field. In this capacity he designed, managed and constructed numerous facilities throughout the United States, England, Egypt, Japan and Thailand. After retiring from the Air Force, Brian went to work for the Missile Defense Agency (MDA) as the Director of Engineering and Environmental Management. This job tested his skills to complete critical Missile Defense facilities in support of a fast-paced program to deploy the Nation's first Missile Defense Shield, managing the design and construction of key assets worldwide. While at MDA, Brian was granted membership in the DoD Defense Acquisition Corps, earned Level III Certification in two career fields: 1) Systems Planning, Research, Development and Engineering, 2) Test and Evaluation Engineering. Mr. Huizenga has been with the Department of Energy for 6 years at his current position in PMOA supporting the Office of Science capital asset program. Mr. Huizenga has a BS degree in Mechanical Engineering, an MBA and is a Certified Cost Professional.

BASEM NESHEIWAT, KM SYSTEMS GROUP, MBA, MSEE, BSEE

Mr. Nesheiwat is a multi-disciplined program management professional with over 30 years of experience in diverse areas. He is a Master Scheduler with expertise in developing, implementing, managing, and assessing large complex systems including Missile Defense Systems, Electronic Warfare Systems, Global Positioning System (GPS), Command, Control, Communication and Information systems, terrestrial and satellite-based telephony systems, air traffic control systems, transportation management systems and Seabed Mining systems

His expertise includes program planning and integration including the development of program WBS, IMP/IMS, critical path analysis, risk assessments, and customer submittals. He has also led teams in cam training and performed multiple successful integrated baseline reviews (IBR). He has tracked program risks and opportunities, recommended cost containment initiatives, and led the system engineering team for program reviews (SRR,PDR,CDR).

DAVE SCOTT, VICE PRESIDENT, KM SYSTEMS GROUP

Mr. Scott has more than 25 years of experience with both government and commercial customers in the implementation of systems and processes to improve management processes. He also has over 10 years of project and earned value management systems (EVMS) experience in the public sector. He has supported many federal clients including the Department of Energy (DOE). Department of Defense (DOD), Federal Aviation Administration (FAA), National Oceanic and Atmospheric Administration (NOAA), Smithsonian Astrophysical Observatory (SAO) and MIT Lincoln Laboratory.

He has extensive experience working with clients to evaluate their current project and earned value management capabilities and systems. He also has experience designing ANSI/EIA 748 compliant EVMS systems and processes leveraging his broad knowledge of most major commercially developed project and earned value management tools. He is a regular presenter at conferences and training workshops.

Mr. Scott supports the Government Accountability Office (GAO) expert sessions and has contributed to GAO guides regarding project scheduling, cost management, and Agile best practices. He also supports several project management associations including the College of Performance Management, Project Management Institute EVM Community of Practice, and the National Defense Industrial Association (NDIA) Integrated Program Management Division (IPMD).

Appendix B

WBS Level 3 Design Completion

Table B-1 shows the completion status of the WBS level 3 design activities on the basis of an analysis of the LSST Camera schedule using development and design filters. The ICE team could not validate all of the statuses from the actual schedule.

Table B-1. Completion Status of WBS Level 3 Design Activities

WBS no.	Title	Percent complete	Comments
3.01.01	Project Management	N/A	Management
3.01.02	Project Support	N/A	Management
3.01.03	Performance Safety & Assurance	N/A	Management
3.02.01	Systems Engineering	N/A	Management
3.02.02	System Integration & Analysis	90	Completed FDR in June 2015, small support for some subsystems left
3.03.01	Science Sensors	N/A	Management
3.03.02	Science Sensors Devices	100	Completed FDR May 2013; prototypes tested and shown to fully meet specification; CD-3a approval
3.03.03	Science Sensors Test Stands	100	Completed FDR May 2013
3.04.01	Science Raft System	95	Completed FDR in May 2015
3.04.02	Corner Raft System	80	Completed PDR September 2014; electronics and mechanical prototype completed FDR in December 2015
3.05.01	Optics System Management	N/A	Management
3.05.02	Filter Assembly	100	Completed FDR in June 2015
3.05.03	L1-L2 Assembly	80	Completed vendor PDR in January 2015; design-build contract awarded June 2014; vendor FDR planned August 2015
3.05.04	L3 Assembly	70	Completed PDR July 2014; final design-build RFP awarded June 2015
3.06.01	Camera Body	60	Completed PDR May 2014
3.06.02	Shutter	65	Completed PDR May 2014; early prototype and testing completed; engineering validation test unit underway
3.06.03	Filter Exchange System	90	Completed FDR April 2015; delta FDR planned in summer 2015
3.06.04	Cryostat	80	Completed FDR in June 2015; refrigeration FDR planned for autumn 2015
3.06.05	Utility Trunk	60	Completed PDR August 2014

Table B-1. Completion Status of WBS Level 3 Design Activities

WBS no.	Title	Percent complete	Comments
3.07.01	Camera Control System	80	Completed FDR June 2015; full working prototype demonstrated successfully and used for filter exchange system, refrigeration, science raft, and shutter prototype systems
3.07.02	Data Acquisition System	80	Completed FDR June 2015; DAQ prototypes have been fabricated and successfully used for sensor testing; DAQ prototypes have validated their requirements.
3.08.01	I&T Integration & Management	N/A	Management
3.08.02	Verification Test Systems	60	Completed PDR October 2014
3.08.03	Cryostat I&T	60	Completed PDR October 2014
3.08.04	Camera I&T	60	Completed PDR October 2014
3.08.06	Commissioning Camera	95	Completed PDR October 2014

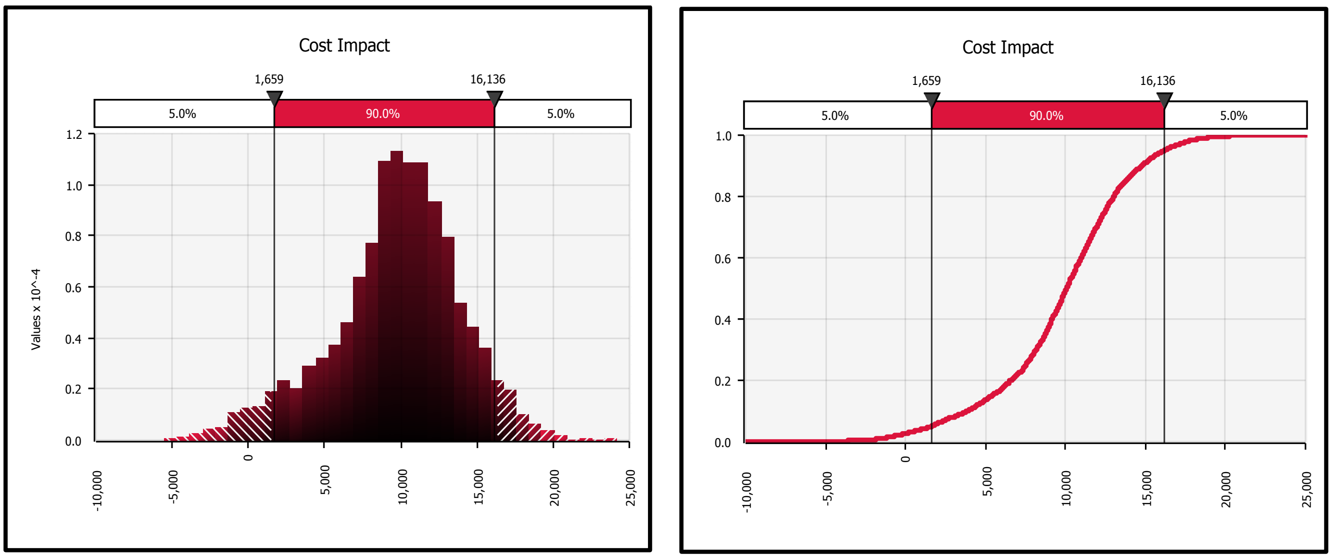
Note: N/A = not applicable; FDR = final design review; PDR = preliminary design review; RFP = request for proposals; DAQ = data acquisition system; I&T = integration and test.

Appendix C
Risk Analysis

In this appendix, the ICE team includes figures and tables that detail the results of our assessment of the impact of risks on the project cost and schedule.

Figure C-1 shows the Monte Carlo simulation results using a PERT distribution for cost and schedule impact and sensitivity to discrete risks at post-mitigation.

Figure C-1. Risk Model Cost Impact Analysis Results ($000)



The first graph is the distribution of impact against the frequency of its occurrence in the Monte Carlo simulation runs. The x-axis represents the value of impact in dollars, and the y-axis represents the frequency of occurrence in the simulation runs. Hence, the residual risk post-mitigation is 90 percent likely to impact the cost of the project by a minimum of $1.66 million to a maximum of $16.14 million.[11] The S-curve graph depicts this same distribution as a function of confidence level, where the y-axis represents the level of confidence.

Figure C-2 features a "tornado chart" that shows the sensitivity of project cost to the discrete risks. On the basis of a 90 percent confidence interval, the mean impact on cost under this distribution is $9.7 million and the maximum cost overrun

[11] The CD-2 report used 80 and 99 percent confidence levels. The ICE team used 90 percent (the mean), which we believe is a more useful number. The CD-2 maximum total cost overrun at 99 percent was $7.32 million.

is $16.14 million, well within the remaining contingency budget and the LSST Camera project total budget.

Figure C-2. Risk Model Cost Sensitivity Analysis ($000)

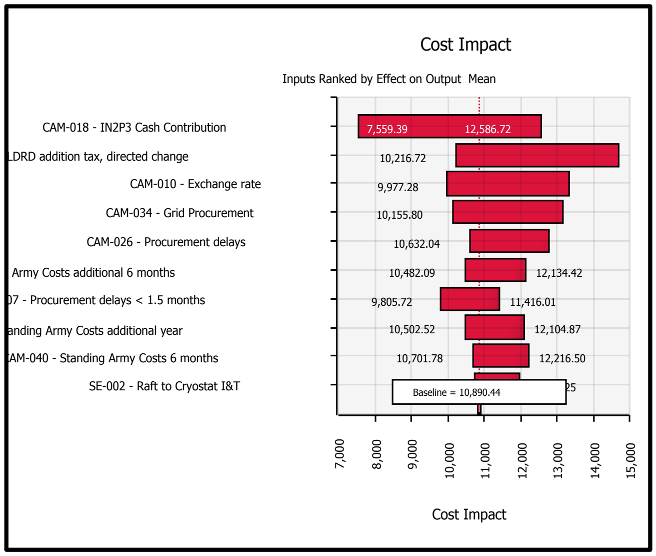


Table C-1 shows each of the top six risks and its cost sensitivity impact (beyond that, the impact converges to the mean impact).

Table C-1. Risks and Cost Sensitivity ($ million)

Number	Title	Cost sensitivity	
		Minimum	Maximum
CAM-033	Sensor Cost	$2.49	$10.9
CAM-043	LDRD Addition Tax, Directed Change	$9.1	$13.5
CAM-018	IN2P3 Cash Contribution	$7.0	$11.3
CAM-010	Exchange Rate	$8.7	$12.1
CAM-034	Grid Procurement	$9.0	$11.8
CAM-026	Procurement delays	$9.4	$11.8

Figure C-3 shows the schedule duration impacts of the 53 post-mitigation risks. The first graph is the distribution of impact against the frequency of its occurrence in the Monte Carlo simulation runs. The x-axis represents the schedule duration impact in months and the y-axis represents the frequency of occurrence in the simulation runs. Hence, the residual risk post-mitigation is 90 percent likely to impact the duration of the project schedule from 4.7 to 17.7 months.[12] The S-curve graph shows this same distribution as a function of confidence level, where the y-axis represents the level of confidence.

[12] The CD-2 maximum schedule slip at 99 percent was 12.8 months.

Figure C-3. Risk Model Schedule Duration Impact Analysis Results (Months)

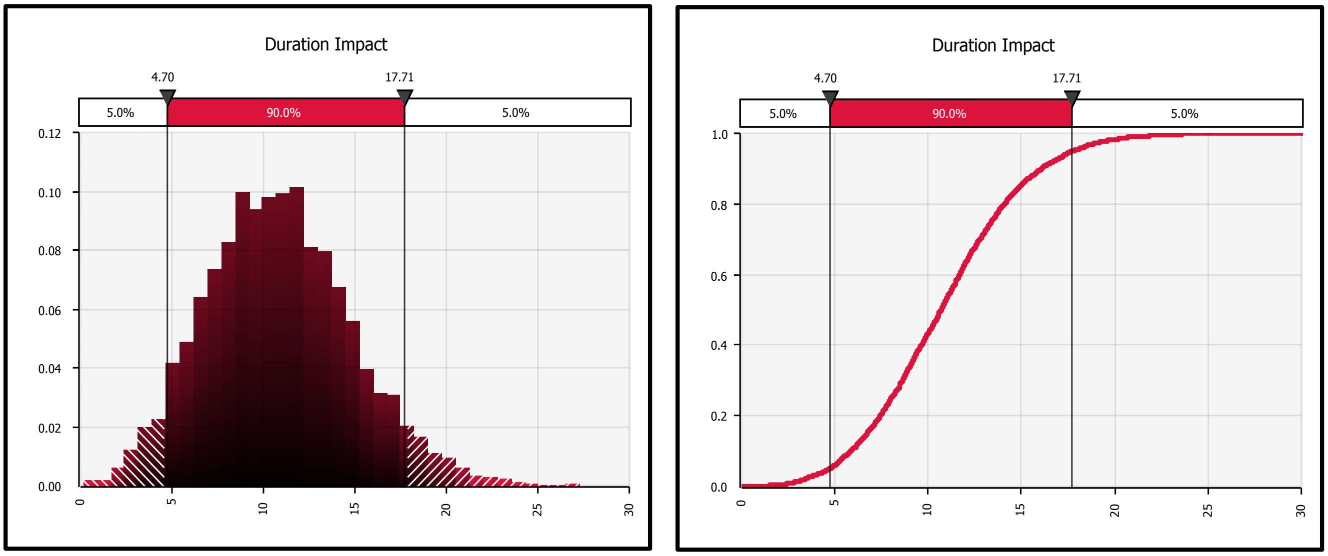


Figure C-4 includes a tornado chart representing the sensitivity of impact on project schedule duration of the discrete risks. Based on a 90 percent confidence interval, the mean impact on duration is 10.8 months and the maximum schedule slippage is 17.71 months, well within the project schedule margin of 23 months.

Figure C-4. Risk Model Schedule Duration Impact Sensitivity Analysis (Months)

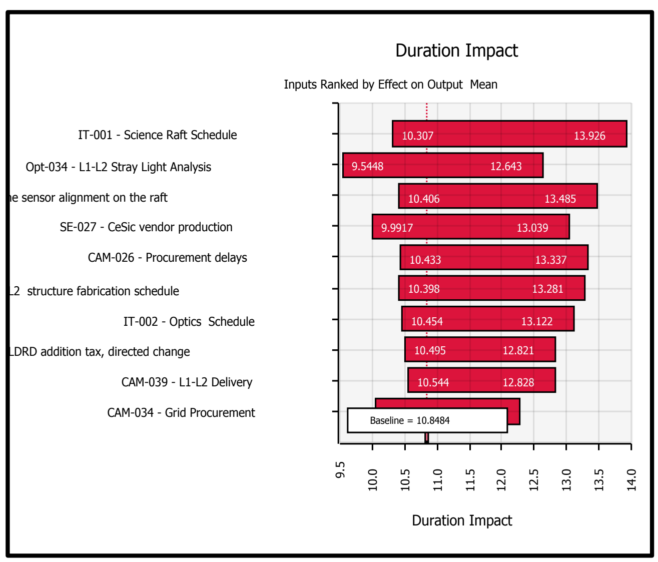


Table C-2 shows each of the top 10 risks and their respective schedule duration sensitivity impact (beyond that the impacts reduce to convergence at the mean impact of 10.8 months).

Table C-2. Top Risk Schedule Impact Sensitivities

Number	Title	Schedule sensitivity (months)	
		Minimum	Maximum
IT-001	Science Raft Schedule	10.3	13.9
OPT-034	LDRD Addition Tax, Directed Change	9.5	12.6
SRFT-003	In2p3 Cash Contribution	10.4	13.5
SE-027	Exchange Rate	10	13
CAM-026	Procurement delays	10.4	13.3
OPT-022	L1-L2 Structure Fabrication Schedule	10.4	13.3
IT-002	Optics Schedule	10.5	13.1
CAM-043	LDRD Addition Tax, Directed Change	10.5	12.8
CAM-039	L1-L2 Delivery	10.5	12.8
CAM-034	Grid Procurement	10	12.3

Our schedule sensitivity analysis shows a consistent minimum and maximum impact among the top 10 risks. The Science Raft Schedule and its associated funding and the Optics Structure procurement and fabrication are key schedule drivers, ultimately impacting the integration of the camera system. These top 10 risks are the primary drivers of the 10.8-month mean schedule delay.

Appendix D
GAO Best Practices

Table D-1 compares the LSST project team schedule with GAO best practices.[13] This analysis was based on a detailed review of the LSST Primavera P6 Project Schedule.

Table D-1. Traceability of LSST Schedule to GAO Best Practices

GAO Best Practice	Best Practice Guidelines	ICE Team Assessment
1. Capturing All Activities	The schedule should reflect all activities as defined in the project's WBS and show the work necessary to accomplish a project's objectives.	The schedule captures all activities, and they are traceable to the WBS. By comparing the WBS index with the P6 schedule, the ICE team concluded the LSST Camera schedule includes all level 1, 2, and 3 WBS elements. (Appendix B shows the completion status of all WBS level 3 activities on the basis of the schedule analysis.)
2. Sequencing All Activities	The schedule should be planned so that critical project dates can be met. To do this, activities need to be logically sequenced. Date constraints and lags should be minimized and justified to help ensure that the interdependence of activities that collectively lead to the completion of events or milestones can be established and used to guide work and measure progress.	As shown in the Schedule Health Assessment, the goals stated in this best practice have been achieved. The schedule is sequenced in a logical manner, with zero missing predecessors, successors and tasks with negative lags. 85.3% of the task relationships are Finish-To-Start, only 7.3% have Start-To-Start or Finish-To-Finish relationships, zero tasks have Start-To-Finish Relationships and zero tasks have hard constraints. Finally, there are no tasks with invalid Actual Start, Forecast Start, Actual Finish and Forecast Finish Dates. This is a strong indication that not only is the sequencing valid, but that the schedule is statused and monitored properly and the schedule baseline is controlled.
3. Assigning Resources to All Activities	When the schedule is developed, the project team should assign resources to all activities. The schedule should reflect the resources (labor, materials, and overhead) needed to do the work, whether they will be available when needed, and any funding or time constraints.	The LSST Camera schedule shows labor hours for most, but not all, of the WBS elements. About 13 percent of the total schedule—379 tasks—does not have resources assigned (ideally, no tasks in a project schedule have no resources assigned). Large-scale development projects, however, often have more level-of-effort (LOE) support, especially for engineering development, quality, safety, procurement, and other activities estimated at a functional level. Although many of the tasks they perform

[13] See Note 2.

Table D-1. Traceability of LSST Schedule to GAO Best Practices

GAO Best Practice	Best Practice Guidelines	ICE Team Assessment
		are represented and tracked in the schedule, the resources for performing the tasks are pulled from the LOE line item. Given the grass-roots estimates the control account managers (CAMs) perform, this low level of tasks poses little risk of performance degradation or impact on the overall schedule.
4. Establishing the Duration of All Activities	In general, estimated detail activity durations should be shorter than 2 working months, or approximately 44 working days, for near-term effort.	All tasks in the schedule have durations assigned with actual and forecast starts and finishes. They also are sequenced in a logical and reasonable manner, with a high level of finish-to-start. According to the LSST Camera schedule, there are 906 remaining activities, or 31 percent, which have a duration of more than 44 days.
5. Verifying That The Schedule Can Be Traced Horizontally And Vertically.	The detailed schedule should be horizontally traceable, meaning that it should link products and outcomes associated with other sequenced activities. These links are commonly referred to as “hand-offs” and serve to verify that activities are arranged in the right order for achieving aggregated products or outcomes. The integrated master schedule (IMS) should also be vertically traceable—that is, varying levels of activities and supporting sub-activities can be traced. Such mapping or alignment of levels enables different groups to work to the same master schedule.	As described in the sequencing best practice, the LSST schedule is well horizontally aligned logically, and the “hand-offs” in the schedule are arranged in the proper order. The minimal number of tasks with lags Finish-To-Finish, Start-To-Start, Start-To-Finish and hard constraints, supports the assessment that the schedule is well structured horizontally. The schedule is also tied to the LSST WBS, creating strong and consistent vertical traceability. This enables the entire LSST program to manage and work to the same IMS.
6. Confirming That The Critical Path Is Valid	The schedule should identify the program critical path— the path of longest duration through the sequence of activities. Establishing a valid critical path is necessary for examining the effects of any activity’s slipping along this path. The program critical path determines the program’s earliest completion date and focuses the team’s energy and management’s attention on the activities that will lead to the project’s success.	According to GAO best practices, “the critical path is theoretically the sequence of activities that represents the longest path from the project’s start and finish dates.” However, as schedules become more complex, float values may not represent the true critical path of the program. Additionally, when activities that represent level of effort work are entered into the schedule, it can affect what the longest path represents. The LSST Forecast schedule was initially analyzed for a critical path using the longest path. However, because the program contains FY activities (activities that represent a year worth of effort) in the schedule, a filter for the longest path cannot be used for a critical path analysis. Instead, a critical path was assessed to

Table D-1. Traceability of LSST Schedule to GAO Best Practices

GAO Best Practice	Best Practice Guidelines	ICE Team Assessment
		the "COMP: PSR/ORR - Camera Pre-Ship/Operations Readiness Review Complete" activity (CAMM2290). In order to reduce any non-critical drivers affecting the analysis, every finish constraint that could affect the critical path to the CAMM2290 activity was removed. Only the main critical path was assessed in this review even though there could be different critical paths for different deliveries. The result of the critical path analysis found that the LSST program had identified the program critical path. The program uses the Critical Path (CP1) field with a "CP4" code to identify the path through the network. In addition, the analysis also found that the program is using another field, LSST Camera Critical Paths, to identify critical paths specific to the camera on the program. The coding in the fields appears to properly identify the critical path through the program. However, there is additional coding in the Critical Path (CP1) field that identifies activities on the critical path which are slightly off of the deliverable critical path based on its float. It is recommended that this field be cleaned up for the main critical path and any off critical path activities be identified as such.
7. Ensuring Reasonable Total Float	The Office of Science typically requires each project to have enough float to ensure it can successfully complete. Total float is tied to the overall confidence level of a schedule, assuming schedule risk has been analyzed. The more optimistic a schedule may be, the lower the available float is, and the more pessimistic the project is about meeting the completion date, the higher the available float.	The LSST Camera project has a high (99.7 percent) degree of float. Although this could be considered high for a production program, it is not unusual—and is actually a positive attribute—for a development project involving high-risk technology. Office of Science capital asset projects often involve high levels of schedule float. The results indicate that the schedule is healthy, well linked, logical, and realistic, with a good margin and valid actual and forecast start and completion dates for all tasks and milestones.
8. Conducting a Schedule Risk Analysis	A schedule risk analysis uses a good (CPM) schedule and data about project schedule risks and opportunities as well as statistical simulation to predict the level of confidence in meeting a program's completion date, determine the time contingency needed for a level of confidence, and	As shown in the Schedule Analysis in Appendix C, the ICE team performed a detailed schedule risk analysis. In summary, the analysis performed with Monte-Carlo simulation runs using the PERT method with each of the discrete risks at post mitigation provides a 90% confidence interval, the mean impact on duration is 10.8 months, the maximum schedule slippage

Table D-1. Traceability of LSST Schedule to GAO Best Practices

GAO Best Practice	Best Practice Guidelines	ICE Team Assessment
	identify high-priority risks and opportunities. As a result, the baseline schedule should include a buffer or reserve of extra time.	is 17.71 months, which is well within the project schedule margin of 23 months. Analysis of the contingency plans and budget to mitigate the risks provides a high level of confidence that the risks will be reduced to the post-mitigation probability and impact levels on schedule.
9. Updating The Schedule Using Actual Progress and Logic	Progress updates and logic provide a realistic forecast of start and completion dates for program activities. Maintaining the integrity of the schedule logic at regular intervals is necessary to reflect the true status of the program. To ensure that the schedule is properly updated, people responsible for the updating should be trained in critical path method scheduling.	On LSST, all of the CAMS have been trained to properly update the schedule and evaluate the cost incurred to establish Earned Value at the control account level. The schedule is updated weekly to reflect progress, determine the true status of the schedule, and identify issues in a timely manner to facilitate resolution with minimum impact to schedule performance. The current LSST CPI and SPI levels are a strong indicator that the process is robust and that the schedule progress reporting is accurate.
10. Maintaining a Baseline Schedule	A baseline schedule is the basis for managing the project scope, the time period for accomplishing it, and the required resources. The baseline schedule is designated the target schedule, subject to a configuration management control process, against which project performance can be measured, monitored, and reported. The schedule should be continually monitored so as to reveal when forecasted completion dates differ from planned dates and whether schedule variances will affect downstream work. A corresponding baseline document explains the overall approach to the project, defines custom fields in the schedule file, details ground rules and assumptions used in developing the schedule, and justifies constraints, lags, long activity durations, and any other unique features of the schedule.	As described throughout this report, the LSST program has instituted a disciplined process for managing and controlling the baseline schedule. The baseline dates, resources, durations and task relationships are all subject to the program Baseline Change Request (BCR) process and approval cycle. Only after a BCR has been thoroughly reviewed and approved using this process can a change to the baseline schedule be incorporated. The baseline document describes the changes and any potential impacts on cost, schedule, risk or technical performance. Since CD-2, eleven BCR's have been incorporated using this process, and are reflected in the current baseline analyzed for this report.

Appendix E
Abbreviations

CAM	control account manager
CD	Critical Decision
DAQ	data acquisition system
DOE	U.S. Department of Energy
FDR	final design review
GAO	U.S. Government Accountability Office
I&T	integration and test
ICE	independent cost review
KPP	key performance parameter
LOE	level of effort
LSST	Large Synoptic Survey Telescope
PDR	preliminary design review
PMOA	Office of Project Management Oversight and Assessments
QBD	quantifiable backup data
RFP	request for proposals
WBS	work breakdown structure