Large Synoptic Survey Telescope

Final Design Review

December 2-6, 2013

Panel Report

December 30, 2013

With LSST Project Response

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Version 2

Recommendations are in blue italics.

Project Response is in red and paragraphs begin with "Project Response"

Contents

Executive Summary

The National Science Foundation convened a Panel of 15 members to conduct the Final Design Review for the Large Synoptic Survey Telescope (LSST) project. The review took place in Tucson, AZ on December 2-6, 2013. The charge to the panel is included as Appendix A.

The Panel regards the project team as very strong, with well-developed plans, schedules and cost estimates. We have no hesitation in our assessment that the project will be ready for start of construction on July 1, 2014.

We note that part of the construction, which was paid for by private donations, is already well advanced. This includes the primary mirror, which is nearly completed, and thus does not represent a cost or schedule risk to the project. The project has followed a strategy of issuing fixed price phased design/build contracts, thus accelerating the contracting process and creating an early reduction of cost risk once the contract is signed.

The most significant risk at the moment is that construction start may be delayed by late NSF funding approval. This would have the dual effect of:

- increasing costs of those contracts for which fixed price bids have been received but which will expire if not accepted within a few months, and
- delaying the end of construction and hence increasing the cost of maintaining the project team in place for a longer period than currently planned

FDR Charge – High Level Response

1. Will the LSST Project be ready to start building by July 1, 2014?

Yes; the main remaining item to complete is an agreement with the agencies on a final budget and approval to start.

2. Is the work scope for construction and commissioning complete?

Yes, subject to a potential need to reduce the technical scope depending on funding level, though such a scope reduction could be completed in time for a July 1, 2014 start.

3. Are the construction budget and schedule credible?

The schedule was delayed by one year by the FY13 Continuing Resolution. The project was able to mitigate much of the financial impact of this schedule slippage through a significant effort in re-planning and in the use of a commissioning camera to stand in for the actual camera. The currently estimated cost of $488M is reasonable and justifiable.

4. Are there appropriate means for managing risk throughout construction?

Yes. The project has already reduced risk in some areas through the early issue of fixed price design/build contracts, at least two of which are already in place.

5. Is the Project Management Plan credible and does the team have the skills and experience needed to build and commission LSST?

The team is excellent and this Panel, like previous Panels, is very impressed with the ability of project staff, including their proficiency in using project planning and tracking tools. They were able to quickly develop technical and financial analyses of various scenarios and proposed options.

6. What planning remains to be done? What must be done before construction can start?

Significant construction of non-federally funded items (e.g. the mirrors) is nearing completion. Any remaining planning will primarily be around potential de-scoping, depending on the amount of NSF / MREFC funding that is made available for the construction phase.

7. Is there a strong plan to promote science education and public outreach during construction and commissioning, continuing credibly into operations?

The plans for this outreach are well advanced, and are more extensive than for any other ground-based astronomical facility. It is commendable that EPO is integrated intimately with the rest of the project.

Q1: What are the causes of the estimated cost growth from $466M to $488M and what is their validity?

There were two reasons for the cost increase.

1. The FY 2013 Continuing Resolution led to a twelve month delay in the start of fabrication for the Camera, which is on the critical path. The NSF-funded cost of the resulting schedule delay was reduced to $7M (1.5%) through extensive re-planning of the construction schedule including the addition of a (relatively) small commissioning camera to allow commissioning to start before the actual camera is delivered.
2. Extensive revision of the costing (Basis of Estimate) resulted in the remainder of the increase. This included increases to staffing and changes to the way in which labour rates are calculated. This increase was $15M (3.2%). Note that this revision of the Basis of Estimate is expected to lower the risk of contingency usage in some areas.

Q2: Assess the options for re-scoping to bring the estimated cost back to $466M.

Although the Project had previously developed a list of technical de-scoping options, many of the items proposed on the list are no longer options. Instead, during the review the project team developed a list of several options that, taken together, could bring the cost to $466M.

The Panel considers these to be valid options, and to be a good demonstration of the Project's ability to develop technical options, but ***recommends*** *that the Project be given more time to consider these – and perhaps additional – options. These should then be ranked such that the chosen options could be added back later if funding (such as unused contingency) becomes available, and such that the reduction in scientific usefulness of the LSST is minimized. The project has impressive analytical skills and they can complete such an analysis well before July 1, 2014*

Additional Comments re: Cost

- The panel is concerned that the average contingency level of 20% may be insufficient. The project may need to generate additional re-scope options in case additional risk reduction is necessary.
- ***Recommendation****: Increasing the budget to $488M would allow additional risk reduction, but the project should also develop re-scope options*

Project Response: LSST will capture the scope options outlined for the committee during the FDR in an updated Technical Scope Option document (LPM-72).

- We note that schedule for the Camera, which is in on the critical path, has slipped one year as a direct result of the 2013 Continuing Resolution. However, the Project has made substantial changes to the plan such that the cost to NSF of this delay has been reduced from $20M to only $7M. We do not regard this delay as an event that could reasonably have been anticipated as a possible risk, and therefore:
- *We* ***recommend*** *that, if a budget of $488M is not possible, then the budget should be increased by $7M, to $473M.*
- LSST can be completed with a high degree of likelihood for $488M, subject to a start in FY14 including a first year funding of at least $15M. If not, the existing fixed price bids will become invalid and the total project cost would almost certainly increase, both because of increased quotes and because of the schedule extension and resultant increased salary costs.

WBS 1 - Project Management

The LSST Project has a management structure with a single Director and Project Manager. This evolution of the Project is a very positive change, making the DOE and NSF efforts into a single, unitary Project. The Joint Oversight Group of NSF and DOE seems to be functioning so as to integrate the efforts of the funding agencies that support LSST.

A Deputy Director has still not been put in place and this should be done expeditiously. Also the Telescope and Site Scientist position needs to be filled. It is quite desirable to have the top level of management in place prior to the start of construction.

> Project Response: The Telescope and Site Project Scientist position is now (as of 6 January 2014) an open requisition with the search committee formed. The Deputy Director position is being developed and the position is to be opened in February. Both positions are budgeted and planned to be filled in FY2014, in time for, or soon after 1 July 2014.

The Project Management team is largely in place. It is strong and very experienced. Indeed, the use of management tools is fully in place and they were used very effectively by the team during the "drill down" exercise that was conducted at the FDR review. A strong Systems Engineering (SE) team is now in place. Such a team is essential for the successful integration of the subsystems into a unified scientific instrument.

Because of the Federal budget Continuing Resolutions the LSST Camera Project has been unable to fund a full procurement of planned items that come early and that have a large cost. The LSST MREFC Project plans were redeveloped to minimize this impact. The two phase (A and B) design/build strategy for procurements that the Project has adopted has an added benefit of a work around for this problem and should allow the Project to make a quick start once approved for construction. The proposed cost profile is, in fact, quite front-end loaded, so these early procurements are critical to the schedule success of LSST.

The LSST Project is large, complex and expensive. The level 2 subsystems are themselves of a scale of many prior astronomy projects. Therefore, successful integration will require strong communication between level 2 subsystems in LSST. The interface milestones and Interface Control Documents (ICD) between WBS level 2 subsystems will make the hand-offs smoother between L2 subsystems for which the needs are specified at a defined time by the milestone and with deliverables specified by the interface agreements. The defined organizational and personnel interfaces between DOE and NSF responsibilities will be very useful because the camera, which is a DOE deliverable, is treated as a subsystem in the overall Project.

The plans for Operations and Project Commissioning now overlap so that training for Operations and a smooth handoff of responsibilities occurs over an extended period of time (2020, 2021, and 2022). This plan should ensure continuity and a well-trained team to continue Operations of the LSST.

The present activity granularity in the EVMS for the MREFC Project is approximately 3000 items (or ~$160K/activity average). This seems too large for accurate tracking. The project plans to perform a "rolling wave planning" for periods of about six months (which start about six months or later from the current time). This detailed planning should result in at least 6000 activities (~$80K/activity). It will, among other things, build in payment milestones for major contracts as they are negotiated and breakup multi-year LOE to smaller chunks to enable capturing labor rate changes. *However, the overall Memorandum of Understanding (MoU) and annual Statement of Work (SoW) should be in place with* *each LSST institution in order to obtain accurate tracking of actual costs and agreements on labor rates and overheads.*

> Project Response: The LSST Project sub-awards with all institutional partners in the construction effort will indeed include yearly Statements of Work for the forthcoming year. These contracts will set forth the deliverables and effort for the year, and will capture the overheads negotiated at the onset of Construction which will remain in force for the construction period as set forth in the government cost principles.

A series of reviews at WBS level 2 should be put in the schedule for large procurements, delivery inspections, installation and commissioning. Safety should be an integral aspect of these reviews and System Engineering could well chair the meeting and recommend to the PM for approval or otherwise. A findings document should be produced (with outside consultants at the review if possible) and the PM should respond to it with follow up.

> Project Response: The Project approach to large procurements includes a formal review of the element design and or the requirements definition prior to release of the formal procurement package. These reviews are expected to follow the review meeting process (LSE-159) which includes the conditions identified in the recommendation. These reviews will be elevated to a Level 2 milestone, or coded appropriately in the IPS so project wide emphasis is placed on the activity for PMO and SE visibility well ahead of formal review planning and execution.

In order to give PM the tools needed for the Project, *the WBS should have fields at the lowest level for which the item is either labor or equipment. The Institution and funding agency (NSF or DOE) should be unique for that WBS item. An EVMS activity should not cross FY boundaries because annual escalation rates will vary and cost estimates should reflect that variation.* The MoU and annual Statement of Work (SoW) with each institution can then be established without confusion and with enhanced accuracy since all responsibilities of a given institute can be identified at the lowest WBS level and then rolled up as needed. The SoW for a given FY could then be easily derived from the WBS as the key Project document.

> Project Response: The Project agrees with this recommendation and acknowledges that some planning packages need to be adjusted to separate labor and non-labor resource assignments into regrouped activities. Some activities currently span fiscal years and others may adjust across the yearly boundary as activity in the program progresses. As part of the rolling wave scheduling, these activities will be separated at fiscal year boundaries to support the yearly contracted efforts and the natural accounting boundary that occurs within each fiscal year. Each activity in the LSST PMCS includes an assignment code for a unique institutional assignment and a separate funding code that allows filters to be set for each type of funding and each institution.

This will allow institutional specific indirect costs, fringe benefits and labor rates to be captured. *Indirect costs should be fixed when the Institutional MoU is signed at the start of construction.* The WBS then will more accurately reflect the Project salary, wages and fringe benefits. Each WBS item at the lowest level would be institutionally unique and therefore have a unique responsible institution that reports on that item to actual cost of work performed (ACWP). Escalation rates are difficult to extrapolate over a Project of this length. *The project may wish to assign some contingency on the escalation rates in the far out years.* Historically, escalation rates have varied by a factor of three over a time interval comparable to the life of the Project.

> Project Response: The Project agrees with these comments. Indirect rates will be established with sub awardees at the onset of construction. Also, the contingency is determined on each cost element after the escalation is applied, so some level of escalation uncertainty is included in the contingency estimate. We agree that escalation varies over the timeframe of LSST so the Project Manager will consider this long term uncertainty in the "watch list" used for contingency assessment.

A few representative high risk and high cost WBS items were drilled down during the review. The basis of estimate (BOE) was well documented and of appropriate fidelity. The PM team has excellent facility with the necessary tools, Primavera and Cobra, to do the tracking and reporting for the Project. However, about 60% of the base cost is based on vendor estimates or historical data. Vendor quotes would carry reduced contingency and should be obtained as soon as is feasible (this is in accord with the Project plan). Bid risk and contractor implementation risk can be retired early in the project because of the front loaded funding profile and the phased procurements (A and B) put in place by the PM team. Scope restoration can be accomplished early on if the cost experience for the early procurements is good. Major procurements are planned for 2015 and 2016 so that the contingency usage will be much clearer after that period.

Putting EVMS in place early is important and aids the management of LSST in tracking and reporting. It is expected that EVMS reporting will be done by financially responsible parties at each LSST institute. AURA as the "host institute" can act as a "buffer" for labor costs for the PMO, since labor can be used on an as needed basis for limited times. This development should reduce the uncertainty in PMO costs.

The critical path is the delivery of the CCD sensors for the camera system. *The project should explore with the DOE/SLAC whether the two CCD vendors be carried into the production procurement contract in order to gain schedule, or reduce risk of schedule slip on the critical path.* Having rafts with two kinds of CCD is not scientifically optimal but it may be necessary for reasons of schedule slippage with a sole source vendor.

> Project Response: The CCD delivery risk is understood within the Project and mitigation of that risk is a continuous priority. The camera team is currently assessing the proposals received in response to the sensor RFP issued in November. A decision whether to proceed with two vendors will be made based on the viability of the submitted proposals.

The newly planned Commissioning Camera (ComCam) allows for early commissioning efforts, many of which are possible before the full camera arrives. The work with ComCam will enhance the commissioning effort and may uncover unforeseen issues in time to mitigate them. This is a very useful development and will provide early operations experience and the opportunity to fix problems that arise. Technical and schedule risk will certainly decrease and a reduced commissioning schedule may also result.

Recommendations

- *The project should increase the granularity and specificity of the WBS to make it a more useful PM tool.*

  Project Response: The Project acknowledges that the integrated project schedule requires higher fidelity in the activities. Many of the current activities are planning packages that were suitable for budget and schedule development but will be further refined within the rolling wave schedule development process. In some cases this increase in fidelity may also increase the resolution of the WBS but the immediate focus will be in activity planning within each WBS area.

- *The Project Manager should ensure that the SE team can conduct and "own" early reviews along with the safety management so as to identify integration problems as early as possible.*

  Project Response: The Project agrees with the recommendation and will work with the SE and Safety teams to focus on these elements of the project. LSE-159 is the Reviews Definitions Guidelines Procedures document that identifies the requirement for safety to be an element of every review. The PMCS includes a selectable code to identify the activities and milestones that are important to the Integration and commissioning activity. As the SE efforts toward requirements definition, flow down, and verification are substantially completed, the focus on these elements of the reviews will be increased. The SE team is already empowered to call and hold reviews as necessary.

- *Identification of scope contingency, both positive and negative, should be performed as soon as possible. Scientific priorities should be clearly stated by the LSST collaboration in identifying and prioritizing the scope contingencies.*

  Project Response: LSST will capture the de-scope options outlined for the committee during the FDR in an updated Technical Scope Option document (LPM-72.) The Project acknowledges the need to update the document to capture a prioritized list of de-scope options as we near the start of construction. The document will also include an enhanced assessment of science impact as well as key dates from the project plan to understand when the de-scope opportunity decision(s) will be necessary.

WBS 2 – Data Management

DM Project Management

The overall Panel assessment of the LSST Data Management (DM) effort was extremely positive. The DM team is clearly well-managed and composed of a group of motivated and knowledgeable individuals. The breadth and quality of the presentations during the DM breakout session left the Panel with the clear impression of a focused and well-coordinated team and very successfully addressed all of the specific items in the charge to the review Panel. The Panel is confident that, despite some minor concerns noted in the following discussion, the DM team is ready to proceed to construction.

In assessing the readiness of the DM design, the Panel reviewed the various data challenges the team has conducted, the extensive use of simulations in characterizing and testing the prototype system performance, as well as the evident preparation for the FDR itself including the successful response of the DM team to comments and recommendations from previous reviews. The Constructive Cost Model (COCOMO) based system for estimating the software effort, calibrated to the actual team over several releases of the software stack, was particularly impressive. The number of successful external reviews the DM team has conducted in response to previous review panel suggestions is in itself impressive and indicative of the quality of the DM project management.

During the breakout sessions, the top five risks with an exposure greater than $1M were reviewed and risk item DM-018 [the risk that the computing power required for Data Release Production exceeds the estimates by a large factor] was examined in detail. The Panel found no issues and considered this item to be well estimated. In general, the Panel felt the PMCS estimate was well structured with no obvious deficiencies. Just over 50% of the DM effort is in labor, similar to other large projects of this nature.

Looking in detail, the Processing Control and Site Infrastructure work package comprises a large fraction (practically 1/3) of total DM costs at $56M. This item is sensibly broken down into four separate elements of which the Site Infrastructure element is the largest at $42M. This element is in turn split into separate work packages for each site plus one package for a development system and one for networking. Within the Site Infrastructure work element, the largest component is 02C.07.04.01, corresponding to the Archive Center Infrastructure, at a cost of $15M. The Panel examined the hardware estimation spreadsheet for this item and found it to be very comprehensive and sensible. The manpower estimation was computed using several models including gathering estimates from experts as well as the team-calibrated, COCOMO-based estimates mentioned previously. Technology project estimation, particularly software, is notoriously difficult; however, the Panel felt the DM team has done an excellent job in constraining its estimates. The DM project currently carries a contingency of order 30% for hardware and personnel. The Panel felt this level was appropriate given the stage of the project.

In the following, comments and recommendations related to specific aspects of the DM work package are presented.

Software

The ultimate scientific deliverable of the LSST survey will be an archive containing the complete source catalog as well as the accumulated calibrated images and associated metadata. Similar to its predecessor the Sloan Digital Sky Survey (SDSS), realizing the full scientific return on the investment in the LSST will require a protracted community analysis period that extends beyond the 10 year survey period itself. To enable such a protracted analysis phase, however, will require a well-supported and persistent science archive. Although establishing and populating a science archive is clearly part of the DM work package, the Panel was concerned that no long-term data preservation plan exists. While, strictly speaking, this is not part of the construction project, such a plan is clearly necessary for the ultimate success of the LSST and may have direct implications for the DM effort during this phase.

Similarly, the Panel noted that the Level 3 software concept, both in terms of the software interfaces and allocated DAC resources, is clearly of crucial importance in enabling the wider scientific community to achieve the LSST's ultimate science goals. The Level 3 development is specifically designed to support external community access to the archived science data and provides a number of different access methods depending on anticipated data volume usage and science case. The panel was gratified to see this concept deeply embedded in the design despite the obvious pressures to streamline the development and focus on the Level 1 and Level 2 products and pipelines.

For many of the core elements of the DM work package, the Panel found that the DM group was well integrated into the international development community and making good use of existing solutions. This connection to the larger community, for example, was evident in the database development effort where the team has taken steps to address various issues such as scalability. The implementation of the shared scan capability is especially impressive. However, in terms of the infrastructure software, such as for file transfer and workload management systems, the Panel felt that the approach taken is relatively low-level (e.g. HTCONDOR, GRIDFTP, etc.) and could benefit from the experience of the High Energy Nuclear Particle (HENP) community.

Recommendations

Recommendation: *The Panel recommends that the DM team seek partners in the HENP community in order and to evaluate existing, higher level tools for various infrastructure tasks such as file transfer and job management.*

> Project Response: The Project agrees and we will increase our level of interaction with the HENP community prior to making final technology down-selections in the area of distributed file systems, job management, and workflow.

Recommendation: *Given its ultimate importance in terms of achieving LSST's scientific success, the Panel strongly recommends that the project both protect the Level 3 development against de-scope pressures and explore options for strengthening it.*

Project Response: The Project agrees, and we will identify other de-scope opportunities as required so that the Level 3 capability can be protected. Expanding the capability will be considered if the level of project funding permits it.

Recommendation: *The Panel notes that the LSST Project has no long-term data preservation plan beyond the planned 10-year mission. The project is recommended to develop such a plan and specifically to assess the potential impact of such a plan on the software development effort during the construction phase.*

Project Response: The Project agrees, and as part of the detailed Operations to be developed in FY16, we will create a post-operations data preservation plan.

The Panel was impressed that the LSST project has achieved a 60% level of prototyping for their software stack at this stage. This achievement is even more impressive given that a fraction of that prototype software is actually in use in the field by the Subaru Telescope Hyper Suprime-Cam instrument. The Panel would have liked to know what fraction of the 60% prototype software was actually in use by Hyper Suprime-Cam and what percentage of the DM requirements are covered by this 60%. Although not strictly necessary at this stage in the design process, a system verification matrix will ultimately be necessary and will address this question.

In terms of the defined data challenges, the Panel felt that such challenges were an excellent vehicle for exposing problems in the end-to-end system. There also are plans to extend these challenges to the operational phase of LSST. The Panel noted that Data Challenge 3a exposed communication problems between the teams, with teams being unsure about what tasks were being covered by which team and when. Although such communication issues are completely understandable at this stage in the project, the Panel felt *that LSST should plan for a series of full dress rehearsals up to two years before launch with a focus on the entire system.* These dress rehearsals should specifically be designed to exercise the communication between personnel and their respective functional roles rather than the software stack itself. Systems Operations Validation Testing will more typically cover the latter functionality.

Project Response: The DM team will be a full participant in the Early Integration, Full Integration, and Science Verification phases of the Project, each of which will include "dress rehearsals" of all DM capabilities and operations. The latter two phases will be a "full scale" in terms of data handled and processed as well.

Finally, the Panel felt that the DM group has a very mature approach to ranking requirements and exhibits a clear plan for implementing and testing the necessary minimum requirements for each stage in the commissioning process.

DM Infrastructure

The Panel noted that, while the infrastructure architecture design and computing, storage, and networking capacity estimation is in an advanced state of preparation, some key technology choices (e.g. whether to use commodity clusters and/or GPUs) remain preliminary. These choices must be coherent with the overall software development and can greatly improve code performance as well as impact overall development cost. These improvements could potentially lead to significant cost savings for the LSST project. Although these decisions are still outstanding, the Panel felt that the planning was in a good state and that the DM group is paying an appropriate level of attention to the issue. The Panel agreed that the current DM approach to avoid locking in a decision too early seems correct at the present time.

Recommendation: *The DM group should define or clarify the decision milestones in the project plan for key technology adoption.*

> Project Response: As defined by the LDM-240 DM Roadmap and its implementation in the IPS, there are some explicit and some implied decision milestones for each technology area. The Project agrees that we should, and will translate all implied milestones into explicit ones prior to the start of construction.

Commissioning Plan

From the discussion of the early operations and commissioning plan, it is clear that much of the Level 2 and Level 3 interfaces need to be in place at that time. It was not clear to the Panel, however, to what these "operational" components of the system will be exercised and tested during commissioning.

Recommendation: *In the verification and validation plan, the Panel recommends that the testing of the level 2 and level 3 interfaces be clarified. In particular, the testing of critical science functionality should be highlighted in terms of required capability and ordering in the commissioning timeline.*

> Project Response: As defined by the LDM-240 DM Roadmap and its implementation in the IPS, there are Level 2 and Level 3 capabilities planned to be fully capable and tested at each of the Early Integration, Full Integration, and Science Verification Phases of commissioning. The Project agrees that this should be clear, and these capabilities will be further elaborated in detail as we define the 6-month rolling wave plans for each of these commissioning phases.

The Panel noted that a portion of the commissioning budget has been allocated to supporting external, expert users from the community as part of the science verification process. Supporting such external personnel often incurs substantial overhead and runs the risk of producing little useful feedback in the absence of well defined and enforced procedures for capturing that feedback. Although it does not consider this point a serious risk, *the Panel would have liked to know how reliant the commissioning* *effort is on such outside expertise and how it guarantees that the necessary inputs are collected and fed back into the commissioning effort.*

> Project Response: The LSST Construction effort is planned and budgeted to include all the resources necessary to complete the full scope of the effort, including the final stages of integration, testing, and science verification. The Project anticipates that this commissioning effort may best involve specific expertise from targeted individuals and that this focused effort will be for short periods. Recognizing this situation, the budget includes the equivalent of an FTE of labor as well as travel costs that can be used for such targeted effort to several individuals or as a single dedicated staff member. In either scenario, the effort is embedded in the commission effort and is planned for direct involvement so feed back to the project is optimized.

Operations Plan

Although review of the operations plan was not formally part of the charge of the FDR Panel, a draft version of the operations plan was made available. A few observations on the draft are noted here.

First, the Panel felt that the level of support for continuing software development during the operational phase seemed somewhat low. The necessary level was, however, difficult to assess since the functionality to be developed and the timeline for any such additional development are unclear. Nonetheless, the Panel felt that the ratio of science staff to developers proposed in the draft plan was potentially high and should be considered relative to some nominal development plan for enhancements to be rolled out during operations.

Finally, support is currently earmarked in the draft operations plan to allow temporary hires of external staff for developing enhancements to the operational system. The draft plan associates these new hires with scientists, postdocs, and students, not necessarily software engineers. While scientists are clearly crucial for algorithmic research and prototyping, they do not as a rule generate production quality code. Consequently, additional development resources will need to be added to support integration of any scientist-driven enhancements into the operational system. Again, *the Panel felt that the ratio of developers to scientists should be revisited once the level of post-construction development is clear.*

> Project Response: The Project understands this recommendation and will review the staffing for operations during the next period of operations planning. The Project will provide an updated Operations plan in 2016 to support detailed review prior to the development of an operations proposal.

WBS 3 - Camera

Summary

The camera subsystem is a separate contract that is funded by the Department of Energy (DOE). The LSST project manager (Victor Krabbendam) works very closely with the camera project manager. Although the LSST Project Manager does not have budgetary authority for the Camera, the LSST Project

Director as well as the Camera Project Manager have this authority. Camera sensors are on the critical path #1 with 7 months of float

Telescope is the #2 critical path with 11 months of float. From PDR the number of risks being tracked by the camera team has increased from 115 to 154. The camera team feels that this is a result of looking more closely at the camera design, fabrication and assembly processes. There are 12 of these risks that are related to interfaces and each of them is being tracked in a burn down plan.

Observatory Interfaces

There are 30 distinct physical interfaces between the Camera and the rest of the observatory. There are 12 Interface Control Documents (ICDs) that describe all of the interfaces in detail. The cryostat compressor is in the basement of the observatory and is owned by the camera. The data acquisition box is off of the telescope and owned by the camera. The telescope is responsible for the cabling between the camera and the data acquisition box and for the plumbing between the camera and the compressor in the basement. Something like an 8 inch diameter clump of cooling lines and fiber and copper go across from the telescope to the camera. The telescope team is responsible for cabling onto the camera and into the rotator.

Focal Plane

The camera team has a parallel path using potentially two vendors to provide the 189 CCDs in the focal plane. One vendor has provided CCDs that meet all of the requirements. This retires significant risk. The Silicon Carbide structures that are the frame for the focal plane are made of a composite silicon carbide material that reduces the brittleness of the structure and reduces the risk for fractures while maintaining high specific stiffness. Both SLAC and Brookhaven National Laboratory have been working with this material for several years and have gained experience with this material. Neither organization has extensive experience with SiC in general but the material they have chosen is fairly new and resistant to traditional problems that have hampered SiC designs.

Optics

The optical part of the camera is being managed by Lawrence Livermore National Laboratory and consists of three lenses and a set of filters. All of the optical substrates are fused silica. There is one spare filter substrate and no spare lens substrates. Manufacturing the L1 boule is within industrial capability and there is no perceived risk in the delivery of the substrate material.

Thermal Control

The thermal design for cooling the focal plane is very intricate. There is a copper cold plate within the Dewar that each focal plane is connected to via a copper braid. The copper braid is connected to the SiC CCD support structure with an indium gasket between the copper and SiC and this is how the CCDs are cooled. The thermal load from the focal plane is ultimately removed from the Camera using the refrigeration system. Extensive prototyping of the thermal control system has been used to mitigate risk. Latent heat from the camera is also removed using the observatory glycol cooling lines.

Commissioning Camera

There is a commissioning camera that is made up of 9 CCD sensors integrated into one raft in a 3x3 array and contained within a test Dewar. The commissioning camera will have its own optics that are much smaller (~37 cm diameter) than the optics for the ultimate camera. The commissioning camera is designed to allow early testing of the telescope as well as many of the interfaces such as the data lines, copper lines, command and control etc.

Comments

The team responsible for the design and construction of the LSST Camera is very strong, well organized, and capable of delivering a camera that satisfies the requirements set out for it. Each of the team member organizations (SLAC, BNL, other) have extensive experience in building instruments on the scale of the LSST Camera. The design team at SLAC is very experienced in using the design and modeling tools that are necessary to address all of the requirements of the Camera and provide a design that will meet all of the requirements. The systems engineering team has done an excellent job negotiating requirements with the LSST project and flowing these requirements down to the subsystem and component level within the Camera. The Camera program manager clearly has a very good working relationship with the LSST program manager and project office as well as the other technical managers on the LSST project team.

The design of the camera is well advanced and ready to start construction. The high risk items in the camera have been or will soon be prototyped to reduce the risk in the final fabrication. These include a full scale fully operational filter exchange mechanism, prototype CCD arrays and associated electronics, prototype SiC CCD support structures, full scale cooling line prototypes and optical filter coating samples. The camera thermal control system has been modeled and includes all thermal loading and the multiple levels of cooling. For example, the thermal load from the Dewar window L3 is significant and is managed and included in the detailed focal plane thermal model. The review team asked for a deep dive into the thermal control in order to ascertain the maturity of this design. All of the major components have been designed and the Camera team easily answered any questions about the component level designs such as the indium gaskets between the copper thermal leads and the SIC CCD support structure. On the whole the design is mature and ready for construction.

The interfaces between the camera and the Telescope and the Data Management subsystems have been carefully considered, the requirements for each are defined, with adequate solutions for each interface item designed, and are well documented in a series of reports. There are 30 distinct physical interfaces between the Camera and the rest of the observatory. The Camera team has identified each of these physical interfaces and each is described in detail in a series of 12 Interface Control Documents (ICDs). As an example of how carefully the interfaces have been considered, there are 12 risks related to interfaces that are being tracked by the camera team and are also being watched by the Telescope team.

The design of the camera optics was presented in detail. The lens prescriptions are not difficult to fabricate and while the lenses themselves are large (L1 is 1.6 meters) the sizes are within what has been fabricated on other programs. For example the AirBorne Laser turret window is 1.6 meters in diameter.

The third lens, L3, is also the window for the Dewar. This complicates the design effort for L3 due to bending from the pressure differential between the Dewar and the outside air pressure. The optics team has modeled this extensively. LLNL has experience with meter class optics. There is one spare filter substrate but no spare lens substrates. Corning will build a furnace to make the L1 boule when the order is placed. There is no perceived risk in the delivery of the substrate material. All of the relevant issues have been considered, and the designs seem mature and ready for the start of construction.

The commissioning camera was introduced in the plans to mitigate the delay in the delivery of the ultimate LSST camera caused by the slow start in camera funding. By enabling the start of the testing of the telescope as well as software testing the commissioning camera offsets much of the schedule delay and reduces the budget increase caused by the delay of the ultimate LSST camera (the cost increase was thus reduced from about $20 M to $7.5 M). This seems like an excellent solution to this delay at a rather modest cost.

There appears to be sufficient budget and schedule contingency to anticipate on time and on budget delivery of the camera.

The procurement of the large number of CCDs, with very strict quality requirements, represents potentially the highest risk to the timely completion of the camera. The camera team is aware of this and they are focused on the delivery schedule and have developed contingency plans in the event of delayed delivery. As part of the risk reduction for CCD delivery the team has initiated a parallel path CCD development effort with two vendors. One of the vendors recently delivered a CCD array that meets all of the LSST camera requirements. The review team agrees that mixing CCDs on the focal plane from the different vendors, with different quantum efficiencies, dark currents, etc., is not an attractive option.

Recommendations

- *The fabrication of the large number of CCDs required is a potential risk to the camera completion schedule. We recommend that the camera team keep a close eye on the progress of the CCD fabrication process.*

  Project Response: The CCD delivery risk is understood across the project and specifically within the Camera Team and Project Management team. A senior member of the team has been assigned to the Sensor development effort and team members at Brookhaven National Lab, Harvard University and SLAC are dedicated to all aspects of technical testing, integration, delivery and contract management in general.

  In addition, there are three mitigation strategies that would allow for late integration of the modular science array. These mitigation strategies would add 24 months of schedule margin.

- *The Commissioning Camera mitigates both the schedule slip and the cost increase caused by the one year delay of the LSST camera due to its delayed funding start. If de-scoping becomes a necessity in the camera project the Commissioning Camera should be protected.*

Project Response: The Commissioning Camera mitigates the impact of the full camera delivery schedule, supports early efforts in telescope commissioning during the early integration period and reduces some risks for camera integration and testing efforts. The Commissioning Camera will continue to be a valuable tool to the program and is not currently viewed as a candidate for de-scoping.

WBS 4 – Telescope and Site

General

WBS 4 includes development of the LSST summit facilities and infrastructure on Cerro Pachón, the telescope structure and control system, mirror coating systems, and base facility in La Serena. Its major physical interfaces are to the LSST Camera mounted at prime focus and the Data Management System. The scope of work for WBS 4 is well defined within the overall project work break down structure (WBS). It includes all relevant activities, including the management and system engineering ones, which lead to the procurement, from final design to final testing, of the telescope, the dome, the technical building, the site infrastructure and all associated facilities, including coating plant, calibration screen and wavefront sensing. Commissioning activities of the telescope with the camera are a separate WBS activity.

Telescope System Management

The WBS 4.1 associated with the Telescope System Management covers the administration of the Telescope and Site team, basically consisting of the Tucson and the Summit offices. The key members of the team, some of whom bring a wealth of experience from previous telescopes, have been identified and will be further complemented by Chilean and increased Tucson based staff. The level of staffing is not overly generous, but it appears adequate once the Telescope & Site Scientist and Chilean office recruitments are completed. It is also expected that some team members will relocate to Chile once the construction phase demands it. The overhead cost for the transition to Chile will be borne by the Project Office and are not part of this component of the construction budget.

In terms of costing estimates, the experience acquired by the team in their work on other telescopes, including those on the summit has been applied. The administrative costs consist of labor and material for the Office team and the Summit team, but only of material and not labor for the Safety and compliance personnel, which will be provided by the Project Office. The working interfaces and the lines of reporting are well defined.

The project team has clearly understood and split the various phases of the construction, starting with the design/build procurement, manufacturing, transport, erection and commissioning of the telescope. They have successfully managed to break down each of the major phases into a very detailed and rigorous list of activities for which it has been possible to assign deliverables, durations, capital and personnel cost, with associated contingencies computed according to the overall methodology adopted across the project. The documentation readiness appears to be very good and in line with clearly defined interfaces between various work scope elements. This may have benefitted by the period between PDR and FDR, which has been used to continue with the development of detail design and associated documentation.

Partially due to a well structured and detailed WBS, the costing exercise by the project at this stage provides a reasonable level of comfort based on the level of maturity, the accuracy and the level of the contingency in the Telescope and Site area. In addition to the general FDR sessions, there was a detailed drill down in the Telescope and Site area to look into the details of the cost elements and their risks and contingencies. The team was always able to provide substantiated answers to the queries of the panel, and no specific criticisms can be made at this stage. The application of appropriate risk-derived contingency percentages based on the "basis of estimate" (Vendor Estimate, Vendor Quote, Catalog, Engineers Estimate etc) provides a rational means of determining bottom-up contingency.

In summary, the estimates seem correct, and the contingency, assigned in a bottom-up approach, is at a level, which – despite not being generous – is probably acceptable, and at least higher than in other telescope projects.

There is some concern that the assumptions related to the inflators (typically 2.5 or 3.5%) may be too low, as they are dependent on world-wide demand for commodity items (steel etc) and, within Chile, because the Chilean economy in this region has some additional volatility based on the mining industry. Even though the panel would have liked to see a higher value, there are no immediate tangible reasons for using other estimates. These assumptions are increasingly valid the longer the project stays on track with the projected schedule and budget (EVM) noting that, in the past, estimates on significantly longer time frames have been proven wrong in other projects in Chile. The fact that several significant contracts are due to be let in the very near future means these inflation factors (even if wrong) will have less of an impact on these major procurements in any case. Favorable quotes are in hand for the telescope mount, which could effectively generate some contingency level at this stage. The panel notes also that the capital costs are generally based on vendor estimates, but this is a) similar to other projects at this stage and b) the ratio between vendor quotes and vendor estimates will improve in the very near future, with a number of major procurements planned in the next 12 months. The predictions for the major cost elements like the dome, site summit and coating plant seem sound. In the case of the dome, which is similar to several existing designs, a number of vendor estimates have been averaged, after discarding at least one (low) outlier, which provides some validity to the estimate. For the site summit facilities the estimates are based on consecutive iterations with the architectural firm involved in the site development, although it should be noted that this is still a QS estimate via an A&E firm, not a construction firm. Also for the coating plant, sufficient details seem to have been used for the cost evaluation, by at least one vendor.

Finally, the project has identified a few elements of de-scoping in the Telescope and Site area, of which the most important is associated with the coating plant. The panel believes that the de-scoping exercise deserves further effort, with a focus on doing so in a manner that allows the item to be easily "re-scoped" or included in the future, either as contingency allows it or future operating funds are available. For example, one proposal for the mirror coating plant is to leave out some of the magnetrons for now, but ensure that the chamber is still capable of having them installed easily at some point in the future.

The panel noted that a transfer of the spare parts cost to operations could also generate additional construction contingency, although this is a complex and risky path that may not make the most sense from a Whole-of-Life perspective.

Recommendation

The project should continue to explore systematically any further de-scoping options with the goal of increasing the level of contingency in the Telescope and Site area.

> Project Response: LSST will capture the scope options outlined for the committee during the FDR in an updated Technical Scope Option document (LPM-72).

System Engineering

The project System Engineering interaction and integration with the Telescope and Site group is well defined. It is important that the team has a lead System Engineer who has a broad overview of the requirements flow-down and also of the ICD structure, and who is also part of the SE board.

The mix between Engineers and Scientists is an asset. The project-level documents and procedures regulating the various system engineering methodologies are securely embedded in the project and well integrated in the Telescope and Site group. The documentation produced by the group is under configuration control, and the change process is understood and applied. In terms of interfaces, the telescope systems have mainly internal interfaces, which therefore are largely administered and controlled within the team. This simplifies the understanding of the dependency of the various deliverables WBS activities, and it is a clear element of risk reduction.

A complete review of technical requirements of the various subsystems was not part of the scope of the panel. Requirements were sometimes discussed, in order to understand the subsystems and their associated complexity. It is noted that some specifications are very ambitious, like the 0.1 °C temperature uniformity in the primary mirror, or the 4 sec. slewing, settling and checking time. These requirements will demand considerable effort for them to be fulfilled, and it is recommended that analysis and technical budgets continue to be refined in order to track (as is being done) their implication on the overall performance of the telescope and their impact on cost and schedule risk.

Recommendation

The project should review the most critical technical requirements and document their implication on performance and cost and schedule risk.

> Project Response: The Project will continue to track technical requirements and performance specifications of subsystems and document their compliance status as captured in formal contractual obligations with Contractors. This process will be maintained at the Telescope management level through routine review of the risk register elements as well as within the individual design build contracts as part of the required design maturation, risk mitigation, and interface completion activities.

Telescope System Schedule

The overall schedule of the T&S activities is clearly aggressive for a telescope of this size, but it has to be noted that early procurement of long lead items is well underway. In particular the M1M3 optics fabrication and polishing is well advanced and the M2 blank has already been procured. Similarly, the mechanism for positioning the M2 and the camera are already under procurement. These factors are important contributions in supporting the schedule assumptions. In addition to these procurements we note that the excavation at the mountain summit has been completed and the risk associated with the soil/ rock load capacity and stiffness, possibly affecting pier design, has been eliminated. Offers have been received for the telescope structure and mechanisms, and procurements are under way for the summit facility. The technical risks associated with the design of the telescope, and possibly impacting the schedule, are rather low at this stage and the T&S team is in the process of mitigating those risks further by testing prototypes and using proven designs for some key elements of their deliverables. Site mobilization has started (or is about to start), which indicates a good level of readiness for the activities in Chile.

The critical path has been identified and there is some float in the duration of the major tasks.

Possible non-technical risks at this stage that can affect the schedule may be associated with the ability of the team to execute a large number of contracts at the beginning of the construction project. Here one needs to consider both the readiness of the organization in terms of obtaining approval and signing the contracts, for which the procedures are reported to be fully in place, and also the rapid recruitment of personnel who are able to successfully implement the various contracts, which implies they have different specialties than developing designs.

Overall, considering the risks mentioned above, the fundamentals for achieving the rather aggressive schedule announced by the project office (compared with other 8m class telescope projects) appear to be in place, thanks to a combination of measures like long lead item procurement, an early start on key tenders, well advanced, in-depth designs, and the extensive use of existing designs and technologies are all factors that, *per se,* are not a warranty, but contribute to an increased confidence level and risk reduction.

Procurement

The Telescope and Site group has done a considerable amount of work in preparing, planning, and costing the procurement phase of the LSST in their area of responsibility. We note once again that long lead items are already under procurement, and some of those items like the M1M3 are well underway, which diminishes the level of risk associated with the potential cost of these items.

A fundamental step in the procurement process has been the development of the design of the various subsystems and the definition of the interfaces. In all areas the process is well advanced, thanks to the effort invested to date and to the re-use of technical solutions similar to those employed in other telescopes. The project has adopted a low risk approach in most areas, and adapted the design in such a way to make possible the use of proven concepts. A typical example of this process is minor tuning of telescope (and dome) specifications (after approval to relax a science requirement) in order to be able to use the design of the wind-screen already in use at Gemini.

It has to be noted that LSST does not intend to procure based on design blueprints (i.e. “build to print”), but rather based on functional specifications (i.e. “build to performance”). For this reason, the policy adopted so far has been to share the design information widely with potential contractors, which maximizes their understanding of the work, who will probably then later bid on design/build contracts. This has the advantage of allowing the vendors to become familiar with and understand the “reference” design. This yields a time advantage, because vendors can start thinking about optimization in anticipation of fulfilling the requirements of the tender, and it also helps to reduce the perception of the risk by the bidders. It also allows a process for them to consider and propose alternatives that may be cheaper. This policy seems to have paid off, at least in the case of the telescope mount.

In general the level of design has allowed/is allowing the timely preparation of Statements of Work, Specifications and Interface Control Documents. The panel has not reviewed (apart from cursory review in a few cases) these documents, which are reported to be in good shape. The mix between frozen and semi-frozen ICDs seems appropriate to bind bidders adequately, but still leaves a margin for possible optimization. The group has a limited number of external interfaces and most of the other interfaces are dealt with in different contracts but within the same LSST group. The presence of a dedicated SE engineer in the Telescope & Site area and integrated with the overall SE is an asset. The execution of a specific Design Review prior to any major procurement (in addition to those during the contract execution) is a risk reduction measure well supported by the panel.

However, no matter how well the procurements are managed, the initiation and the execution of multiple parallel contracts will require a good mix of personnel experienced in contract management and in technical matters to keep these procurements under control. The project certainly benefits from having a number of highly experienced senior personnel, *but it is nevertheless recommended that names be assigned to the various contracts (that are not yet identified) for absolute clarity and to ensure that staffing is not going to be a bottleneck, and that during execution of the design/build contract proper procedures are in place to avoid change escalation.*

Project Response: See Below

For specific procurements, the project has decided to perform a split between Contractor’s work and certain work services bought or managed separately by the project (e.g. dome cladding). Due to the import of equipment done by AURA exempt from import duties in Chile there may be a mix of phases between the work share of overseas Contractors and the project’s own work. This represents an added complexity and demands a very clear description of the sharing of responsibilities in the tendering and contractual documents. Also, there is some risk associated with the need for extremely clear demarcation between the work packages – for example, if the building leaks it must be clear whether it is the LSST’s own staff doing the cladding or the building contractor’s responsibility.

Recommendations

The project should perform a staffing review of the personnel responsible for the various contracts and of the associated technical teams, to ensure that all contracts are monitored by personnel with an appropriate mix of contract management and engineering, and that sufficient control is maintained by the project during the work of the Contractors.

> Project Response: The Project understands the need to provided adequate managerial and technical support to multiple parallel contract efforts. We will review the staffing plan to make sure it is consistent with the necessary level of management and technical oversight for the current and upcoming work defined in the Contractor's efforts. We will assign specific individual responsibilities to these contracts as part of the authorization of work packages.

The project must ensure that where there is a potential or desired sharing of the work in the deliverables between Contractors and Project the implications are clearly understood and properly noted in the tendering process, and later in the contractual documents. Possibly use procedures already used by AURA.

> Project Response: The Project agrees and understands the importance of clarity in definition of scope and ownership of responsibility between Contractors and the Project. We will continue to work with the AURA Contract's Officer to clearly identify and document roles and responsibilities for each contracted effort in the tendering process and contractual language to all parties involved.

T & S Conclusion

1. The project is definitely ready for construction, and is significantly more ready than similar projects at this stage. The project will be able to start building by July 1, 2014.
2. The work scope for construction and commissioning is very complete at this stage. There is still more detailing which may be developed for the commissioning phase, but there is ample time for this.
3. The Construction budget and schedule are credible. The derivation of the contingency is based on a well developed bottom-up estimate results in a contingency level that appears to be justified, despite not being overly generous. *We note that the contingency associated with Tel & Site may be increased by minor de-scoping options. We recommended that the project pursue the study of these as an added reserve.*

   > Project Response: The Telescope and Site will review the de-scope options outlined in an updated Technical Scope Option document (LPM-72) and identify suitable areas of added contingency where appropriate.

4. Although project risks exists, LSST has done an excellent job of bringing the technical risks to a low level thanks to early procurement, use of proven technologies, and detailed design activities. The methods of managing risks are appropriate in the T & S area.

5. The Project Management Plan is credible. The Telescope and Site team is largely in place and the interaction between team members, lines of reporting, SE, and configuration control procedures are in place. We would like to praise the enthusiasm and the cohesion of the team, including the collaboration between engineers and scientists. The team as a whole has been very responsive to the panel queries.
6. Little planning remains to be done in the Telescope and Site area at this time, and we are confident that nothing prevents the project from starting.
7. The major single risk associated with the Telescope & Site activities of the project is the schedule. However, the fundamentals for achieving the proposed schedule are in place and a reasonable buffer exists.

WBS 5 - Education and Public Outreach

Education and Public Outreach (EPO) has been part of LSST since inception and represents 3% of the effort. EPO is well integrated into the FDR systems engineering model, which will facilitate the interactions between Data Management (DM) and EPO. Staff preparation and materials for FDR are excellent. Working with an advisory board since 2005, staff has designed an ambitious EPO program that makes LSST data available to a diverse set of non-scientist audiences including amateur scientists, citizen scientists, informal science educators, high school teachers and their students and the general public. It is important to draw the lines from the big understandings of LSST science to questions that engage the interest of these audiences and to develop scaffolding that draw audiences to deeper learning opportunities. The EPO staff recognizes the potential for large-scale use of LSST data and plans to aggressively seek partners to disseminate program opportunities and develop new programs and resources. In addition to core EPO activities, the EPO Center (EPOC) includes the public information office (public affairs) of the observatory, and has responsibilities for internship programs for the consortium.

EPO faces unusual challenges designing a platform for the EPOC that will meet needs and interests of their audiences in 2022. The audiences are large and difficult to predict: what people want to do online continues to evolve rapidly. The user interfaces that people expect are constantly increasing in sophistication, and technology changes rapidly. Therefore, flexibility in the design of the EPOC is essential. While the design is partitioned into a relatively static Data Center and a more mutable portal, the project retains the option to host some or all of the activities in the Cloud.

EPO is both a consumer and re-distributer of data produced by DM. EPO adds value to the data for its users — metadata, subsets, visualizations — and, through Citizen Science projects, produces Level 3 data products that may be tied back into the DM system. Sufficient differences between DM and EPO data make it essential that the two datasets be separate. Separation also assures security and high performance for DM users, and a clear allocation of resources.

An EPO staff of 9.5 FTE is small compared with the wide range of functions included in its responsibilities. From public affairs to undergraduate internships and reaching diverse audiences, from Web and data management to supporting scientists and educators, it may be a challenge to provide the level of service needed to sustain high quality programs. EPO will need a "broker" to support programming for each audience. Staff needs to determine whether a broker can support more than one audience and whether brokers are volunteers, on staff or part of a subcontract.

Recommendations

Recommendation: *Staff needs to assess the personnel support needed for the EPOC functions as the program prepares for operations. EPO needs to be prepared to re-scope work either by eliminating or subcontracting functions.*

> Project Response: EPO shares the concern that this ambitious EPO program as planned may be understaffed in operations. The time between now and submission of the operations proposal will be used to further evaluate this situation and build partnerships, with external funding, that could alleviate it. Also, as technology costs are better understood, in particular the relative cost of cloud versus fixed-hardware compute facilities, funds could be adjusted within the existing budget to support the planned activities in a more cost-effective manner.

Recommendation: *In preparation for the operations proposal in 2017, EPO should carefully review staff in light of the knowledge and skills needed to provide sufficient IT support for the Portal and infrastructure to support EPOC directed programs as well as external partners who may require support to access and use the EPOC data.*

> Project Response: EPO acknowledges the specific concern regarding IT support and will use the time between now and operations to evaluate and address the situation. Experiences of the Zooniverse team will be particularly beneficial to this evaluation, as they provide more and more open sources modules and APIs to the community and face similar support issues years ahead of LSST EPO.

Recommendation: *Staff needs a proactive plan for how the EPOC will support LSST engineers, scientists and other staff who want to be engaged in EPO. For example, provide support for individuals who want to mentor students and teachers, and educators, both formal and informal, who want to create content based on LSST data.*

> Project Response: Plans for support of those wanting to be engaged with EPO through content creation and mentoring activities will be developed during construction. An active EPO Users Group will be formed and from that group solutions generated. For example, content creators at science centers could hold "hack day" events at professional meetings to create content modules, we could work with the WWT Ambassadors project to help educators build LSST-related tours, and LSST datasets could be integrated into exemplary existing programs such as the Professional Development Program of the NSF Center for Adaptive Optics at UCSC. Building a strong user community for LSST EPO is essential to our success.

In light of the nature of the ultimate LSST project deliverable—fully-reduced data—and the resulting unique role of LSST EPO, it may be a challenge to design appropriate assessment during construction and then during operations ten years from now.

Recommendation: *During construction EPO should focus on usability testing and effectiveness of product design and development. Products include the website with LSST@HOME, workshop models, citizen science projects, classroom research projects and informal science education "modules." To plan for operations, EPO should remain flexible and focus on usability testing and effectiveness of product design and development for products developed for use by external content developers and leave learning evaluation to occur during operations. For LSST EPO developed experiences (e.g. citizen science and classroom modules), learning evaluation also needs to occur during construction in order to validate the efficacy of the programming.*

> Project Response: The recommended plans for evaluation will be implemented during the EPO construction phase, evaluation that examines both usability of the products developed and evaluation (as the budget allows) for learning outcomes that result from use of those products. Usability testing is incorporated into the development cycle of all deliverables and the program will be responsive to the results of that testing. The distinction between construction and operations for appropriate evaluation is appreciated, as is the clarification of appropriate evaluation for externally and internally developed products during operations itself.

EPO is committed to reaching diverse audiences and will need an aggressive effort to seek partners who are already involved with people typically underrepresented/underserved in STEM and other "inattentive" audiences. If we continue to do EPO as we always have, we will continue to attract the usual audiences.

Recommendation: *In the same way EPO has developed strong relationships with Informal Science Education organizations and programs, staff needs to build stronger relationships with appropriate organizations and programs engaged with diverse audiences to better leverage EPOC efforts. (This was also recommended at PDR.) This should include incorporating appropriate representation from these organizations/programs on the LSST EPO Advisory Committee*.

> Project Response: LSST EPO agrees with this statement. Increasing diversity on the Outreach Advisory Board will take place in 2014; candidates are being considered and vetted at this time. Our continued involvement with the AURA Workforce and Diversity Committee will connect LSST and EPO in particular to appropriate organizations and programs. Product testing and learning evaluation during construction will involve a diverse audience and specifically consider barriers known to decrease participation or retention of underrepresented groups.

WBS 6 – System Engineering and Commissioning

System Engineering

The current staffing for System Engineering equals the staffing planned for construction and the levels are robust. The total System Engineering staffing across all WBS elements is 18 individuals prior to the commissioning effort. Their efforts include simulation as well as traditional System Engineering tasks (requirements, interfaces, verification, etc.) There are 6 System Engineering staff supported directly under systems engineering, and the others are supported under the various subsystem WBS elements. The staff is experienced and expert in System Engineering especially as it applies to large telescope projects like the LSST.

Strong support for a system engineering approach is clearly evident in the project. The LSST project's approach of dedicated System Engineering staff embedded in each project team is excellent and should ensure lower implementation risk. This dispersed and large System Engineering team meets weekly to coordinate their activities. The project's approach to, and focus on, systems engineering is exemplary.

The simulation approach is extremely comprehensive, detailed and well-developed. The simulation effort covers both the hardware and the data processing algorithms. The plan to incorporate, and test, the observatory scheduler software directly into the OpSim simulation is novel and should help to reduce commissioning time/risk. The simulation activities are well integrated into the construction plan/schedule. Timely updates to the simulation/model based on subsystem-level and system-level testing will enable tracking of as-built expected performance.

Implementing requirements flow-down/tracking, interface requirements definition/tracking and verification tracking with the SysML tool is an excellent approach that complements the traditional error budget definition. This approach is elegant and provides clear visibility and traceability. Flow down of all requirements to the subsystem level has been completed and placed under configuration control.

The definition/design, implementation and status of System Engineering procedures are excellent and clearly ready for the construction phase. The only caveat is that software standards, archiving & version control practices are not common across all of the LSST groups. However, all of the groups employ similar standards and practices. A cost - benefit study is underway to determine what changes, if any, should be applied to the LSST groups that deliver production software.

The project team has responded well to all of the PDR report recommendations related to System Engineering. Specifically:

1) A Safety hire has been made and a QA hire programmed and these individuals report directly to the project manager.

2) A review of project risks was conducted, with external reviewer participation, in order to plan risk mitigation.
3) The risk management team has increased the frequency of their meetings and there is evidence of active risk register management.
4) A more formalized approach to conducting design reviews has been implemented by System Engineering (LSE-159). In particular, formal review of the Telescope & Site's procurement bid packages will be (and in some cases have recently been) conducted before issuing design & build contracts. Likewise, formal review of the DM designs will be conducted.
5) The seismic design criteria have been revised (three levels: no impact, repairable and survivable) and flowed down to the subsystems.
6) The environmental survival conditions (specifically temperature and wind) have been revisited and found to be appropriate.

Performance metrics have been established and performance estimating tools have been created (models, simulations and analyses) and validated to the extent currently possible. Performance margins have been established for the baseline design. The estimated performance margins are reasonable (neither too large nor too small). The project is ready to track performance margin as the project unfolds and to address trade-off considerations as they arise.

System Engineering has oversight/review and approval authority for all procurement and shipment readiness reviews (including product data package and compliance). This policy is well motivated and will result in fewer subsequent problems in contract execution and integration and test, respectively.

Interface definition has been established to a level appropriate to proceed with construction phase efforts, including issuing near term RFQs for the T&S contracts. The exception is the ICD between DM and the Auxiliary Instrumentation (LSE-140) which is only at a preliminary (phase 1) level, as a result of the calibration system only having recently achieved final design. The project anticipates having this ICD completed to a level sufficient to proceed with construction (phase 2) quite soon (this fall). Currently the risks associated with the interfaces amounts to a total of only 4% of the project cost.

Although System Engineering tasks in the MREFC construction phase are primarily LOE, the System Engineering effort has been detailed in the PMCS schedule with many milestones. This tasking includes ICD refinement and revision as the project proceeds through phase 3 and final completion. Near term tasks for the System Engineering group include implementing a database for as-built performance, and verification activity mapping.

The cost book estimates for Systems Engineering are commensurate with System Engineering plans.

The level of commissioning planning is appropriate for the FDR. However early documentation of the detailed procedures to be followed during commissioning (integrated testing) is encouraged.

There are two charge items that are specifically related to System Engineering:

2.b. Does the systems engineering process clearly and accurately define the LSST system and subsystem requirements, and identify who has the technical responsibility for each requirement? Is there a process for verifying compliance?

The System Engineering group has developed an elegant and comprehensive requirements flow-down process, which has clear visibility and traceability. This process also facilitates maintenance and support for trade studies. The System Engineering group has implemented this process fully to derive subsystem requirements from the top-level science requirements. Responsibilities for achieving the requirements (subsystem-level ownership) are clearly defined.

An interface and requirements verification process has been developed (LSE-160). This process has been implemented to define the verification plans and compliance matrices for both the Observatory System Specifications (OSS; LSE-171) and LSST System Requirements (LSR).

6.b Are the systems engineering, quality assurance, configuration management, financial controls and construction safety plans fully developed and implementation ready? If not, what steps must be taken to ensure they are ready in time?

All systems engineering plans are fully developed and ready for implementation. All of these plans are consistent with the Systems Engineering Management Plan (SEMP; LSE-17).

The System Engineering group should consider how best to archive and version control source files for electronics design (schematics, board/routing layouts, etc.). System Engineering has defined an approach using a PDMWorks vault for mechanical CAD files. Similarly an approach for archiving and version control coordination (and possibly check-in/out facility) is needed for the source files for electronics design files.

> Project Response: We agree this is an important component of configuration management. We will establish and maintain a database for electronics with version control appropriate for designs (source files) as well as for tracking hardware through the entire life cycle of the project.

The System Engineering group should also consider how to handle serial number tracking of modification history, particularly for electronics. This capability is likely to be needed for the commissioning phase, but an approach which is suitable in the operations phase, for example spares inventory, as well should be chosen.

> Project Response: The Telescope and Site group will develop and provide maintenance and inventory software for the observatory facility. This

system will access the Engineering Facility Database to facilitate asset lifecycle management for the designed life of the LSST. This software will support scheduled maintenance and spares inventory management from initial integration of major subsystems to commissioning and into the operations phase.

Recommendations

- *The project should complete the cost-benefit analysis of adopting uniform software standards, archiving & version control practices across all of the LSST groups as soon as possible, so that if a change in practices must occur it is early in the construction phase.*

  Project Response: A study of all software efforts within the Project is under way to create a comprehensive overview of the LSST Software Enterprise, report on the compliance to the existing standards and guidelines, and provide recommendations to Project Management on where those might be changed and where the development approaches might change to achieve the broadest possible standardization of LSST software. With these results, Project Management will work with the individual teams and Project Systems Engineering to address potential baseline changes to our approach going forward in architecture, design, development tools, and potentially staffing levels.

- *The project should ensure that phase 2 level development of the ICD between DM and the Auxiliary Instrumentation (LSE-140) is completed before construction activities related to this interface are initiated.*

  Project Response: Work is ongoing on the ICD between DM and the Auxiliary Instrumentation. The document is expected to reach phase 2 status and be placed under formal change control prior to 1 July 2014, the planned construction start.

- *The project should adopt early development and iteration on the procedures for each of the verification tests to be performed during commissioning. These procedures, once vetted, should be used to train the commissioning staff so that commissioning progress is less dependent upon critical expertise.*

  Project Response: The Project agrees with this comment and has planned accordingly. A comprehensive review of the detailed Commissioning Plan will be held approximately 2 years prior to the initiation of the commissioning phase. At this time the Commissioning Plan will include detailed procedures, sequences and success criteria required for each planned verification test. Furthermore, critical commissioning activities will be modeled using the Project's suite of simulation tools in order to train personnel and develop required supporting analysis tools.

Commissioning

The Panel reviewed the current Integration and Test, and Commissioning plans with project staff. The level of detail of the plans is appropriate for FDR. The Panel recognizes that commissioning will not begin until 2019, and plans are likely to evolve as the team's understanding of the system matures. The Panel finds that the length of time allocated is appropriate for this system, as is the level of resources allocated to this phase. The team and their work were very impressive. Experience from commissioning other telescopes had been well captured. Plans for commissioning were excellent, very thoroughly thought out and documented. Risks were well captured and schedule and cost were well based.

The panel noted the following points and made related recommendations.

Recommendations

ComCam: The inclusion of the commissioning camera (ComCam) was an excellent change introduced since PDR to mitigate for the 1-year delay in the fabrication start of the ultimate camera. By enabling the start of the testing of the Telescope as well as to begin the software development ComCam offset most of the schedule delay and reduced the budget increase caused by the fabrication delay of the ultimate camera at a rather modest cost. It also enhances the commissioning effort and may uncover unforeseen issues in time to mitigate them, and will provide early operations experience. Technical and schedule risk will certainly decrease and a reduced commissioning schedule may also result.

Recommendation: *The Commissioning Camera mitigates both the schedule slip and the cost increase caused by the 1-year delay in fabrication of the LSST camera, and considerably enhances and reduces risk on the commissioning effort. If de-scoping becomes a necessity within the camera project the Commissioning Camera should be protected.*

> Project Response: The Commissioning Camera mitigates the impact of the full camera delivery schedule, supports early efforts in telescope commissioning during the early integration period and reduces risk for camera integration and testing efforts. The Commissioning Camera will continue to be a valuable tool to the program and is not currently viewed as a candidate for de-scoping.

It will be important to verify the performance of ComCam itself to ensure that any unexpected properties intrinsic to the ComCam do not get the team investigating issues that appear to be in the rest of the system being tested when they are actually intrinsic to ComCam.

Recommendation: *The Project should develop a detailed commissioning and verification plan for the Commissioning Camera.*

Project Response: The integration of the Commissioning camera will be completed more than a year before it will be deployed on the LSST telescope. This will allow time to test and commission the camera in the lab and on an existing telescope prior to its use on the LSST. Many of the procedures needed for acceptance testing and commissioning of the full LSST Camera will apply to this instrument as well. As the overall project Commissioning Plan is further developed we will identify those activities that apply to the Commissioning Camera as part of its own commissioning effort.

Planning: Planning for commissioning is presently detailed only to a planning package level. Plans for relocations and travels exist and key personnel to relocate have been identified. The mobilization of the site personnel is starting and seems properly staffed and planned. The team understands the interdependencies of the various tasks and the critical path is identified. Available resources and primary schedule constraints are clearly defined. Detailed task planning for commissioning will be completed closer to the commencement of commissioning. Key steps, activities, and tests have been identified and specifications of each commissioning test are already written. *We suggest capturing outcomes of "thought experiments" and "use studies" in the procedures to be written. For example, step through a day in the life of someone working as each of: e.g. a telescope operator, a data processor, on telescope maintenance, on building maintenance, on mirror cleaning / coating, on science etc. What, at the system level, is needed to do their jobs, i.e. to: drive the telescope to a new point (telescope, data catalog, drive systems, coordination to camera, commands, etc.)?*

Project Response: As part of the Model Based Systems Engineering effort adopted by the Project we have captured a significant number (~300) of use cases, activity and sequence diagrams and associated narratives in SysML and other documentations detailing various technical aspects of operations. Project Systems Engineering is coordinating the efforts for further developing and detailing all the use cases, activities and sequences necessary to map out LSST operations. This material will be the basis for the Technical Operations Concept document.

The SE team should strive for early development and iteration on the procedures for each of the commissioning tasks and verification tests to be performed. These procedures, once vetted, should be used to train the commissioning staff so that commissioning progress becomes less dependent upon critical expertise being physically present.

Project Response: The Verification Matrices for the system as well as for the subsystems will be fully developed for the Commissioning Plan review (see above.) By the review the schedule of corresponding verification events will also be available. Project Systems Engineering will work with the technical teams on the details of the integration and test procedures well ahead of the time they will be carried out. These procedures will be evaluated through the regular review process.

A series of reviews at WBS level 2 should be put in the schedule for installation and commissioning

Recommendation: *A formal review of the Commissioning Plan should be incorporated into the schedule, and a level 2 milestone should be associated with that review.*

Project Response: The Project agrees with the recommendation. A review of the Commissioning Plan will be scheduled before the Operations Plan review, and marked with a level 2 milestone in the PMCS.

Recommendation: *Detailed task planning for commissioning, including procedures, should be completed ahead of the expected Operations Plan review, due the dependence of Early Operations on Commissioning.*

Project Response: The detailed plans, procedures, and schedule for integration, verification and science verification will be developed and documented for the Commissioning Plan. The commissioning plan is scheduled for completion two years ahead of the early integration period and will be subject to a comprehensive review at that time. Sufficient development and appropriate review of commissioning will be completed ahead of the Operations Plan review to fully support the important elements of scope and transition between commissioning and operations.

Changeover from Commissioning to Operations: The definition of completion of commissioning of WBS4 Telescope & Site, and WBS3 Camera, are easier to define than that for WBS2 Data Management.

Recommendation*: Appropriate boundaries between commissioning and operations should continue to be clearly delineated, and be kept under review.*

Project Response: The Project fully agrees with the Committee's recommendation. The definition of operation readiness is a key element of both the Commissioning Plan and Operations Plan. As such, it will be presented and evaluated at both reviews.

Interfaces: The schedule did not permit the same Panel members to attend both the Camera and Telescope & Site (TS) sessions, however all interfaces appeared to be well thought out and documented at the ICD level and no problems with the interfaces between 3 (Camera) and 4 (Telescope and Site) were identified in either the Camera or TS or Commissioning sessions.

Recommendation*: The interfaces should be kept under reviews during the formal review of the commissioning plan suggested above.*

Project Response: The Interface Control Documents and Interface Support Documents are under formal change control and they are continuously monitored by Project Systems Engineering. Evaluation of compliance with the interface requirements is an inherent component of every technical review, up to the in-site Acceptance Reviews of the subsystems.

Overall Conclusion: Based on experience with other projects of similar complexity, adequate resources and time have been allocated in the LSST plan for commissioning. The key steps for commissioning have been identified, and the addition of the Commissioning Camera will greatly reduce risks. Detailed planning for commissioning should proceed. The Commissioning plans are at a suitable level to proceed to the construction phase.

Environment, Safety and Health (ESH)

The project has established an effective and comprehensive ESH program that is integrated and managed within the overall project structure of LSST. Senior Project Management and other key LSST personnel exhibit strong commitment to ESH through individual actions and setting of priorities. While the position of LSST Safety Manager formally reports to the LSST Project Manager, it is widely recognized (and in fact encouraged as necessary) that the Safety Manager can interact and engage with any and all levels in the organization (including the Project Director) to ensure ESH issues are resolved in an appropriate and timely manner. The various subsystems engineers lead and demonstrate ownership of the process for analyzing hazards and ultimately, as needed, for determining risks. It is evident that there is a great deal of collaboration and integration of ESH efforts between the NSF and DOE-funded portions of the project.

The ESH personnel supporting the project are well qualified and have substantial and relevant experience. In particular, the current Safety Manager has demonstrated experience providing professional level ESH support of large telescope projects, including recent experience with installations of this type in Chile. The Safety Manager's local working knowledge of Chilean safety regulations and requirements, along with his familiarization with the Chilean culture and local safety providers will be of great service to the LSST project. In addition, an external LSST Safety Council was created for the purpose of ongoing oversight and consultation to the project. This Council has met already (August 2013) and will continue regular meetings. The recommendations noted during the Council's August 2013 meeting are in the process of being fully addressed. Chief among these is the recommendation to convert the current Safety Manager to full-time status – a recommendation that is being acted upon and will benefit the project greatly.

The conditions and the surrounding environment at the telescope site, in combination with the ESH regulatory framework and requirements in effect in Chile, present unique challenges. AURA-O is the responsible entity for ESH from a legal standpoint, while the LSST project provides for the implementation of safety procedures and policies. In recognition of this arrangement, LSST will develop detailed plans addressing all aspects of ESH pertaining to construction in Chile. Further, disaster planning has been initiated for the site and medical and fire response capability is already in place at Cerro Pachon.

Recommendations

The unique ESH concerns and considerations arising from work at a remote and relatively undeveloped telescope site require special attention. Emergency management and disaster planning while in place are critically important at this location.

Recommendation: *Continue to learn from and build on safety lessons from other observatory projects in areas such as site evacuation, emergency management planning for disasters, and transportation and food safety.*

> Project Response: The Project agrees that there continues to be lessons to learn from current observatory projects, operating observatories, and even other remote scientific efforts. LSST continues to exploit its ties with other AURA centers and other observatory construction and operation efforts on AURA property in Chile to capitalize on their experiences. LSST has participated in recent Earthquake conferences that specifically addressed earthquake preparation, warnings, and response experience in Chile and other astronomical observatories. LSST will take a more active role in seeking out such experience and in collaboration with AURA management in Chile, will plan visits to ALMA and ESO when scheduling allows but targeted for this spring 2014.

The implementation of site-specific ESH plans for the construction in Chile associated with the project will need to account for cultural differences present in Chile and ensure optimal safety resolution given the varying ESH regulatory requirements. Moreover, overlapping construction activities and the push for early commissioning could result in additional complexity in successfully managing ESH issues.

Recommendation: *Ensure ESH staff involvement in activity-level planning during all project phases, in particular to mitigate risk during periods of high construction activity and early commissioning. Draw on the experience of safety personnel stationed in Chile who have experience in addressing ESH issues at telescope sites.*

> Project Response: We agree with this recommendation and are happy to now have a full time Safety Manager who brings both broad industrial mining experience but also over a decade of specific telescope experience, including activities at observatories in Chile. He is now fully engaged and, along with the Camera Safety Manager, is actively working with sub-system groups during the design phase and will continue to work with engineers and managers through all phases of the project. As outlined in the previous comment, LSST values direct experience and lessons learned and will

continue to bring that experience to the project. In addition, LPM-18 details expectations for all personnel working on the site and requires safety procedures and plans to be completed and understood before daily-shift work begins. The Project will adopt the Chilean standard ODI (Obligacion de Informar) or obligation to inform the workers by pre-shift meetings of the known hazards and activities planned for that shift. The Project will employ Chilean safety personnel experienced in Chilean construction to guide and oversee safety compliance throughout the duration of the construction project. In addition to the above, the LSST Safety Manager will work closely with AURA-O management to ensure Project safety compliance per Chilean law.

The work for the LSST project is conducted at many institutions and this creates the potential for uneven and potentially unsatisfactory ESH program implementation (though the project does have a governing safety policy).

Recommendation: *Deepen relationships with collaborating institutions in the area of ESH, and focus on establishing assurance mechanisms for the project to ensure that all work is being carried out safely and in an environmentally responsible manner.*

Project Response: The Project fully agrees with this recommendation. With the full engagement of safety professionals, the Camera team and the Telescope and Site team are complying with the requirements of LPM-18 and have a solid culture of valuing safety. Now that the LSST Safety Manager is full time, he is charged to further develop the safety relationship with our other partners and contractors as well as to execute a plan to validate safety and environmental compliance at all collaborating institutions.

Additional external validation of ESH program and hazard review activities, such as the hazard analysis review efforts of the various subsystems, is not routinely performed. Further confirmation of the outcome of the hazard analysis process is critical as this is a lead-in to determine if a particular issue, after mitigation measures have been considered, will elevate to the project risk registry list for follow-up.

Recommendation*:* *Maximize the effectiveness of the external LSST Safety Council by involving this group further in the review of ESH program and hazard review activities. The collective expertise of the Council would be particularly well suited to offer independent review and feedback of site-specific safety plans for work at off-site locations as well as technical input into the hazard analysis process.*

Project Response: The Project agrees. The Project will utilize the expertise of the Safety Council to review and suggest improvements to all safety documentation and activities. The next meeting is planned for this Spring 2014.

Operations

The Panel reviewed the current Operations Plan with project staff. The level of detail of the plan is appropriate for FDR. There was not enough time for the team examining Commissioning to study the Data Management aspects, but they understand that no significant concerns about this were noted by those looking at Data Management plans. The plan for Commissioning and Operations and Project now overlap with an 'Early Operations' phase so that training and a smooth handoff of responsibilities occurs (2020, 2021, 2022). This is a good step to de-risk the transition to operations. The Panel expects that the project will develop a more detailed operations plan and associated budget before a 2016 request for funding for the operations era, which is currently forecast to begin in 2022 assuming construction start in 2014. The Panel found both the current plan and its costing to be reasonable at this stage.

The Project continues to explore international partnerships that would bring additional operations resources (1/3 of total) in exchange for access to the data products and expects a positive outcome from these.

Recommendations

Recommendation*: To ensure that the maximum scientific capability of LSST is realized, the project is encouraged to continue to seek additional non-federal funding, and to continue to strive to minimize operational costs.*

> Project Response: The Project is in the process of negotiating with numerous potential international partners for contributions to operations costs. At present, Memoranda of Agreement have been signed with five separate institutions, and we expect this number to expand considerably over the coming year. The Project will provide an updated Operations plan in 2016 for detailed review prior to the development of an operations proposal.

Detailed Concerns That Should Be Addressed

For WBS element 6 (Commissioning): This should include first-look issues related to survey operations, as well as installation and test, and the interface, especially between 3 and 4. Note that DOE's methodology does not count installation and commissioning as part of the formal project, whereas NSF includes this in the MREFC-supported scope. It therefore appears quite differently to the two agencies.

> Project Response: The Project understands this concern and also understands that the DOE and NSF approach the funding of on-summit commissioning differently. The LSST Commissioning Plans are first developed around the technical effort required to complete system integration and testing and the technical and scientific effort necessary to complete the science verification. This scope includes the testing of interfaces and scientific first looks indicated in the concern raised. The full commissioning effort has also been budgeted with both labor and non-labor resources. The final step the project is currently working on is to turn the high level budget contributions presented at FDR from both agencies,

and for DOE, both phases of the project, to detailed resource assignment levels. This final step will ensure all work is budgeted and clearly scoped within each budget line.

Appendix A – Charge to Panel

Charge to Large Synoptic Survey Telescope Final Design Review

December 2-6, 2013, Tucson, Arizona

Introduction

The National Science Foundation (NSF) will conduct a Final Design Review (FDR) of the Large Synoptic Survey Telescope (LSST) in concert with its Federal partner, the Department of Energy (DOE). The purpose of FDR is to ensure that the Project plans will be fully ready for construction of the NSF-supported scope, and that there is a high degree of confidence that the proposed scope can be delivered within the defined project baseline. This is also the final assessment that the design is fully capable of meeting or exceeding the proposed science requirements. NSF policy for projects funded under the Major Research Equipment and Facility Construction (MREFC) funding line requires that the baseline budget defined and approved at FDR must be sufficient to cover the needs of the project, if executed on the associated schedule and not delayed by factors external to the project which could not have been anticipated. With this condition, any unanticipated project needs would have to be dealt with through project scope reductions. The review will take place in Tucson, Arizona on December 2-6, 2013.

The DOE deliverable part of the LSST Project is defined by work breakdown structure (WBS) element 3, the camera, and is subject to DOE technical, cost and schedule reviews, and their Critical Decision approval procedures. Nevertheless, it is important that the LSST Project be a unified, single project with clear lines of authority and responsibility, with the camera completely embedded in the project management, planning, and engineering processes. The FDR panel should consider how well this has been accomplished and advise as to any improvements, corrections, and especially deficiencies, they might identify in the project integration. The FDR is not expected to review WBS3 to the same level as other elements, because this will be the subject of a formal DOE review at the appropriate time, but the panel should consider how well WBS3 is integrated into the project master schedule.

The FDR Panel will examine the projected readiness of the project to undertake construction, assessing project management and the technical status through this stage of development, planning for conducting the remaining work, including work during the intervening time between this review and the anticipated construction start (July 2014, pending the approval of the National Science Board and the availability of funds). Please bear in mind that the LSST will be built in Chile and this has implications for cost (including exchange rate fluctuations), schedule, civil construction, supply chains, and environmental, safety and health (ES&H) issues. Detailed operations plans are not expected to be ready at FDR, but should be mature enough to inform design decisions, and planning for an operations proposal should be evident. We expect to conduct a full operations review of a proposal for the LSST prime mission between one and two years before construction is completed and commissioning starts. The Panel is also asked to review changes made by the LSST project in response to directions and recommendations given to the project following the Preliminary Design Review (September 2011) and two subsequent specialized reviews held in May 2012 (one on cost estimates and one on project management that emphasized the interfaces between the DOE and NSF scopes). Detailed documentation and past reports required for this review will be made available to the FDR panel members as soon as possible.

Although there are detailed and specific questions in this charge, the panel is asked to be active and willing to draw attention to any issue they should happen to notice that they consider to be a possible risk to the project, even if it does not appear in this charge.

The FDR Panel should prepare a close-out briefing for the Project at the end of the review meeting, iterate a written report over the following two weeks, and present final findings and recommendations in writing to NSF by December 31, 2013.

Charge to the FDR Panel

The FDR Panel will review the major elements of the LSST Project as required by NSF's Large Facilities Manual and elaborated in attachments (1) and (2). The panel should answer the following overarching questions, as noted under primary numbering and in bold-face. The ancillary supporting questions can be used for elaboration and clarification but do not need to be formally answered. Wherever possible, any identified shortcomings should be accompanied by recommendations that the panel believes will correct the problem.

1. Will the LSST Project be ready to start building by July 1, 2014?

a. Will the LSST, as outlined by its Project Execution Plan (PEP), be ready to start construction of the scope defined in the NSF proposal, and thus to receive MREFC funds, starting in the fourth quarter of Federal fiscal year 2014 (July 1, 2014)?

2. Is the work scope for construction and commissioning complete?

a. Is the project scope definition sufficiently mature to begin construction? Please examine at least two major, high-cost, work packages and advise as to their completeness. Are there any areas where the documentation is not mature enough to support the planned start date?
b. Does the systems engineering process clearly and accurately define the LSST system and subsystem requirements, and identify who has the technical responsibility for each requirement? Is there a process for verifying compliance?
c. Are there reasonable interface documents? Are they appropriately defined? Are there significant risks unaccounted for within any interfaces that need further definition? What fraction of the interface documents is under change control?
d. Are the commissioning and subsequent transition to operations clearly and sufficiently described, costed, and scheduled? Do you see any risks not included in the preliminary planning for operations that should be considered in projecting future operating costs?

3. Are the construction budget and schedule credible?

a Has the project credibly defined the LSST risk-adjusted total project cost, through construction and commissioning? Was cost-risk identification suitably based on previous projects in Chile? Is the proposed LSST total project budget complete, reasonable and appropriately described?
b Does the WBS capture all of the scope? Is there a sound basis of estimate for all WBS items? Is there a sound basis for all escalation factors used?
c Are these numbers substantially based on external cost estimates? What is the distribution across different categories of external estimate? Are there any items where the elapsed time between the estimate and the expenditure is cause for concern?
d Is the proposed project schedule valid, and does the proposed schedule contingency provide the project with sufficient schedule float to manage schedule risks? How was the total float determined? In particular, is the camera sub-project properly integrated into the overall project timeline? How is the cost of the schedule contingency calculated?
e Are the methods for determining budget and schedule contingency credible? Is the budget contingency an algorithmic, bottom-up estimate? Are there noteworthy exceptions to the algorithmic contingency estimation, and if so, are they appropriately used and documented? Do they follow Project Management "best practices"?
f Does the schedule have reasonable durations for the various activities? Are there

appropriate milestones at every level, and enough milestones for proper tracking? Do these milestones appear achievable?
g Does the schedule allow for periodic construction progress, engineering design, and safety program reviews?
h Are the critical and near-critical path activities identified and evaluated? Are there suitable critical paths at each WBS level where necessary?
i Should it be necessary, are there possible scope reductions and what is their impact on meeting the science requirements? When would they need to be activated?

4. Are there appropriate means for managing risk throughout construction?

a Is the risk analysis being updated to the design and conditions at construction start? Does it reflect accepted standards for identifying realizable risks, estimating probability of occurrence and consequences? Is the risk assessment properly linked to contingency estimates and project control?
b Does the project execution plan describe an effective risk management plan, useful throughout construction, with appropriate mechanisms for identification, surveillance, and mitigation? Is it accompanied by a reasonable configuration control mechanism for handling contingency as risks arise and are retired?
c Is the change control mechanism already in use? If so, has it successfully adhered to its written processes and has it been effective?
d Is there a risk-adjusted contingency mechanism in use appropriately? Is there a proper method for estimating the interplay between budget and schedule contingencies?
e Can you identify any outstanding or inadequately managed risks and uncertainties?

5. Is the Project Management Plan credible and does the team have the skills and experience needed to build and commission LSST?

a. Is the Project suitably organized across WBS elements to place authority, accountability, and responsibility appropriately?
b. Is the distribution of authority, accountability, and responsibility, across the participating entities suitable and well defined, especially with respect to the AURA, Inc. LSST Project Office, DOE's responsible laboratory (SLAC), and the LSST Corporation?
c. Which key staff still need to be recruited? To what extent do these open positions present a risk to starting the project? What proportion of the required staff is in place?
d. Is the Project Management Control System (PMCS) fully ready, appropriately scaled, and integrated with the Earned Value Management financial status reporting system (EVMS)? Does the project team know how to use it? Is the EVMS tool ANSI-748 compliant? (*This is not currently required but may be so in future.)*
e. Do the staffing estimates, recruitment and retention strategies, labor rates and travel costs for construction, all appear reasonable and consistent with recent experience, given that the LSST will be built in Chile?
f. Is there an adequate plan for monitoring to ensure continued environmental compliance, regulatory management, and attention to health and safety?

6. What planning remains to be done? What *must* be done before construction can start?

a Has the project appropriately planned the activities from FDR to project construction start? Are there recommendations for further planning or risk reduction activities that should be accomplished before NSF makes MREFC construction funding available?
b Are the systems engineering, quality assurance, configuration management, financial controls and construction safety plans fully developed and implementation ready? If not, what steps must be taken to ensure they are ready in time?
c Are all of the critical technology elements mature, that is, prototyped, tested and construction ready? Will they be, and will any remaining anomalies be resolved?
d Are there any outstanding or unresolved MOUs, MOAs, partnership or other agreements,

that need to be completed prior to NSF's obligation of construction funding?

7. **Is there a strong plan to promote science education and public outreach during construction and commissioning, continuing credibly into operations?**

   a Consider the proposed educational outreach and broader societal impact activities and advise on the merits of the plan.
   b Review the preparatory work during construction leading up to those plans.
   c Is the planned capital investment in the outreach and education activities from MREFC funds appropriate, well-conceived, adequate to enable the plans, and investment ready?

Panel Report

FDR is required for MREFC appropriations, and the FDR panel report is a critical part of the NSF program's request for approval of authority to spend MREFC funds. The report should respond to each section of the charge and we request a short closeout presentation to the Project Team at the end of the review, including, if possible, a draft of the report for fact checking. Project comments on the draft report should be returned to the LSST Program Manager by December 18 for distribution to the FDR Panel.

The final FDR report from the panel should be submitted to NSF by December 31, 2013.

Attachment 1

Final Design Review Criteria as refined from the NSF Large Facilities Manual

1. Final construction-ready design: delivery of designs, specifications and work scopes that can be placed for bid to industry. Requires:
    a. Key functional (science, system and sub-system) requirements and performance characteristics, including internal interfaces and interconnections
    b. System architecture and equipment configuration
    c. Operational concept
    d. Reliability criteria, analysis, and mitigation

2. Tools and technologies needed to construct the project
    a. Technical maturity of critical components (including mirror controls, high-speed slew system, data pipeline, and sensors and filters as appropriate)
    b. Development and production schedule (resource loaded schedule) for any pieces needing to be prepared during the pre-construction phase

3. Project execution plan including
    a. Project organization and governance, including
        i. Organizational structure (tied to WBS-roles, responsibilities, reporting)
        ii. Governance, including advisory structure
        iii. Completion of recruitment of key staff and any procurement and account managers needed to accomplish the project
        iv. Managing sub-awardees
    b. Acquisition plans, sub-awards and subcontracting strategy, including
        i. Competition strategy
        ii. Types of contracts to be awarded
        iii. Contractor(s) responsible for developing and implementing the system, where feasible
        iv. (Note that some contracts have been started on a "design with option to build" basis. Comments on this are welcome but given that they are already in place this is less important than plans for future contracting.)
    c. Internal and institutional oversight plans, advisory committees, and plans for building and maintaining effective relationships with the research community (noting that the LSST Project will create a science-ready database of enormous utility but does not in the Project itself include support for scientific research with that database)
    d. Education and outreach plans
    e. Environmental compliance (at the telescope site in Chile and at any other locations)
    f. Plans for commissioning; definition of acceptance, definition of operational readiness (note that we expect to review a revised commissioning plan closer to time)
    g. Preliminary plans ("plans for a plan") for operations
    h. Configuration control plans
    i. Working with a unified project across NSF/DOE, and including international partners
    j. Finalization of commitments with partners

4. Fully implemented Project Management Control System, including
    a. Baseline version of resource-loaded schedule
    b. Mechanisms to generate reports using EVMS on a monthly basis that can be used as a management tool
    c. Well defined path dependencies, schedule float, and critical path

5. Updated budget and contingency, including risk analysis, presented in a detailed WBS format with WBS dictionary defining scope of all entries
    a. Refined bottom-up cost and risk estimates and contingency estimates

   b. Refined description of the basis of estimate for budget components
      i. Majority of the cost estimates should now be derived from external information
      ii. Basis of estimates integrated in WBS dictionary and cost book
   c. Refined project risk analysis, and a description of the analysis methodology (note that risks should also include cost escalation and volatility in any escalators used)
   d. Refined contingency and contingency management (budget, schedule, scope)
      i. Understanding that scope contingency is hard for this project

6. Plans for QA and ES&H, both reporting and mitigation

7. Updated operating estimates

Attachment 2

Project Execution Plan requirements per NSF Large Facilities Manual: Appendix 3 of http://www.nsf.gov/pubs/2013/nsf13038/nsf13038new.pdf

PROJECT MANAGEMENT COMPONENTS OF A CONSTRUCTION-READY PROJECT EXECUTION PLAN

Essential components of a construction-ready Project Execution Plan, common to most plans for construction of large facilities, are listed below, as an example of the extensive nature of the pre-construction planning that should be conducted prior to expending MREFC funds to execute the project. Additions or alterations to this list are likely, due to the unique nature of each specific project. While many of the listed topics cannot be substantively addressed at the earliest stage of project planning, it is important that project advocates are aware, at the outset, of the full scope of pre-construction planning activities that should be undertaken and the consequent pre-resources required. As the project matures through Conceptual Design, Preliminary and Final Design, these topics become correspondingly well defined.

- Description of the research objectives motivating the facility proposal
- Comprehensive statement of the science requirements to be fulfilled by the proposed facility (to the extent possible identifying minimum essential as well as desirable quantitative requirements), which provide a basis for determining the scope of the associated infrastructure requirements;
- Description of the infrastructure necessary to obtain the research objectives
- Work breakdown structure (WBS)
- Work breakdown structure dictionary defining scope of WBS elements
- Project budget, by WBS element
- Description of the basis of estimate for budget components
- Project risk analysis and description analysis methodology
- Contingency budget and description of method for calculating contingency
- Project schedule (and eventually a resource-loaded schedule)
- Organizational structure
- Plans and commitments for interagency and international partnerships
- Acquisition plans, sub-awards and subcontracting strategy
- Project technical and financial status reporting, function of the PMCS, and description of financial and business controls
- Project governance
- Configuration control plans
- Contingency management
- Internal and institutional oversight plans, advisory committees, and plans for building and maintaining effective relationships with the broader research community that will eventually utilize the facility to conduct research
- Quality control and quality assurance plans
- Environmental plans, permitting and assessment
- Safety and health issues
- Systems engineering requirements
- Systems integration, testing, acceptance, commissioning and operational readiness criteria
- Plans for transitioning to operational status
- Estimates of operational cost for the facility

Attachment 3

Additional charge questions provided to the Panel members at the beginning of the meeting

Q1 What are the causes of the estimated cost growth from $466M to $488M and what is their validity?

Q2 Assess the options for re-scoping to bring the estimated cost back to $466M.

Appendix B - Final Agenda

	PLENARY in CANYON III*																	
	REVIEW COMMITTEE WORK ROOM: PRIMROSE																	
	PROJECT WORK ROOM: ACACIA*																	
		Breakout Rooms						Breakout Rooms						Breakout Rooms				
		Canyon III*	Aster I	Aster II	Verbana*	Lantana	Indigo*	Canyon III*	Aster I	Aster II*	Verbana*	Lantana	Indigo*	Canyon III*	Canyon I	Lantana	Indigo*	
	Monday 2 Dec 2013	Tuesday 3 Dec 2013						Wednesday 4 Dec 2013						Thursday 5 Dec 2013				Friday 6 Dec 2013
8:00		Continental Breakfast 8:00 am - 8:30 am																
8:15		Executive Session 8:15-8:30																Executive Session 8:15-10:00
8:30		Overview Project Materials (Key docs, Costs Books website)						T&S Breakout 2a	Open	Open	DM Breakout 2a	SE/PM Risk Management and Safety Intro	Camera Breakout 2a	Open	Open	DM Follow-up	PM Q&A and Follow-up	
9:15		System Requirements and Technical Margin Ivezic																
10:00		Break 10:00-10:15																
10:15		Systems Engineering Overview Angeli						T&S Breakout 2b	EPO Breakout 2a	Open	DM Breakout 2b	SE/PM Change Control and Contingency	Open	Ops/Comm Breakout	Open	Open	Open	Debrief 10:15-Noon
11:00	Committtee Work Room becomes available for entire week.	Commissioning Overview Claver																
		Questions and Discussions																
Noon		Lunch 12:00 - 1:00 Terrace Patio																Box Lunch
1:00	Executive Session	T&S Breakout 1a	Open	EPO Breakout 1a	DM Breakout 1a	Open	Camera Breakout 1a	T&S Breakout 3a	Camera Follow-up	EPO Breakout 3a	DM Breakout 3a	SE/PM PMCS and EVMS	Open	Open	Open	Cost Drill Down	Open	
1:30	Welcome and Logistics																	
	Project Introduction Kahn																	
2:45	Break 2:45-3:00																	
3:00	Project Summary and Status Krabbendam	T&S Breakout 1b	Open	EPO Breakout 1b	DM Breakout 1b	Open	Camera Breakout 1b	T&S Breakout 3b	Open	Open	DM Breakout 3b	Safety Management	SE Breakout 1b	Open	Open	Cost Drill Down	Open	
4:00	Technical Updates																	
4:45	Executive Session 4:45 - 5:45											TPC Changes & Descope	Executive Session 4:45 - 5:45					
6:00		Reception and Dinner - provided 6:00 - 8:00 Tuesday 3 December Murphey Patio																

Each row = 15 minutes; for example 8:00 represents 8:00-8:15

* Hardwire Internet & Polycom

Appendix C - Review Panel Biographies

LSST Final Design Review, December 2-6 2013, Tucson

Review panel members

Charles Baltay (Yale)
Marge Bardeen (FNAL)
Dennis Coyne (CalTech/LIGO)
Edna DeVore (SETI)
Jim Emerson (QMUL)
Dan Green (FNAL)
Rick Kendrick (Lockheed-Martin)
Alexei Klimentov (BNL/CERN)
William O'Mullane (ESA)
Jack Salazar (LBNL)
Antony Schinckel (ATNF/ASKAP)
Richard Simon (NRAO/ALMA)
Stefano Stanghellini (ESO/ALMA)
Michael Wise (LOFAR)
Andy Woodsworth (consultant)

Agency Observers

Scott Horner, NSF LFO
Tim Kashmer, NSF BFA/DACS
Pat Knezek, NSF MPS/AST
Phil Puxley, NSF MPS/AST
Dennis Schatz, NSF EHR/ISE
Nigel Sharp, NSF MPS/AST
Jim Ulvestad, NSF MPS/AST

Hannibal Joma, DOE/SSO
Helmut Marsiske, DOE/SC
Kathy Turner, DOE/SC

Panel members’ short biographical sketches

Charles Baltay received his PhD in Physics from Yale University. He served as Assistant Professor, Associate Professor and then Professor, in the Physics Department of Columbia University, and was Director of the Nevis Laboratories of Columbia University. He then moved to Yale University as the Eugene Higgins Professor of Physics and Astronomy, where he has served as chair of the Physics Department. He initiated and carried out experiments in Particle Physics at Brookhaven National Laboratory, FermiLab, and at the Stanford Linear Accelerator Center. He served as Co-spokesman of the SLD project at the SLAC Linear Collider. He initiated and is presently carrying out the LaSilla/QUEST southern Hemisphere Variability Survey. Dr Baltay is active on the Science Definition Team of the proposed WFIRST space mission.

Marjorie G. Bardeen is manager of the Fermilab Education Office. Under her leadership numerous programs make a wealth of Lab resources available to elementary and secondary teachers and students. She is currently serving as co-Chair of the International Particle Physics Outreach Group, a network of scientists, informal science educators and communication specialists working across the globe in informal science education and outreach for particle physics. She has served on the Board of Trustees, College of DuPage and was its Chairman, 1990-92, and she has served on the Board of Education of Glenbard Township High School District #87, 1979-85, and was its President, 1980-85. Ms Bardeen is a Fellow of the American Association for the Advancement of Science, 2009 and the recipient of the 1990 Max Bieberman Distinguished Alumni Award from University High School in Urbana, Illinois. She received the 1984 “Those Who Excel” Award of the Illinois State Board of Education and was named the 1989 Outstanding Woman Leader in Education by the Suburban YWCA. Ms. Bardeen holds a B.A. in Mathematics, 1963, University of Minnesota and an Educational Certificate (Mathematics,) 1984, Elmhurst College, Elmhurst, IL.

Dennis Coyne is the chief engineer for the Laser Interferometer Gravitational-wave Observatory (LIGO) and the systems engineer for the Advanced LIGO construction project, an NSF sponsored program being carried out by Caltech, where he has been since July 1995. He is responsible for all engineering aspects of all elements of the detector (science instrument) including systems engineering, optics, opto-mechanics, servo-controls, electronics and software. Previously he directed the installation of the initial LIGO detector systems in both the Hanford, WA and the Livingston, LA observatories. Prior to LIGO, he was a principal scientist and assistant division manager at Kaman Sciences Corporation (1980-1995) where, among other efforts, he served as a Payload Development Engineer/Manager (1994 – 1995) for the HABE (High Altitude Balloon Experiment) Program (USAF Phillips Laboratory) and chief engineer (1986-1990) for the Wavefront Control Experiment (WCE) Program (USAF/SDIO). Prior to Kaman, he worked at Bell Laboratories

(1977-1980) on electronic packaging and product design. He is an ASME fellow and received his MS degree in Mechanical Engineering from the University of California at Berkeley.

Edna DeVore is the acting CEO and the Director of Education and Public Outreach (EPO) at the SETI Institute. She is a science and astronomy educator. Her work with NASA includes NASA's Kepler Mission, Astrobiology Institute research program, NASA's Stratospheric Observatory for Infrared Astronomy (with USRA), and Co-I for NASA & NSF Research Experience for Undergraduates in Astrobiology. She was Co-PI for the NSF funded "Voyages Through Time: An Integrated High School Science Curriculum" on the theme of evolution, published in 2003. DeVore served on the Board of Directors for the Astronomical Society of the Pacific for 6 years. Formerly, she was a member of the Astronomy Education Board of the AAS, the Education Board for the Foundation for Microbiology, and several advisory boards for NASA and NSF EPO projects. Previously, she taught astronomy and directed planetarium programming for grades K-14. Honors include Women in Aerospace's Public Awareness Award 2005, NASA ARC Contract Employee Award 1995, US DOE Christa McAullife Teaching Fellow 1987, Outstanding Student Researcher, School of Education, San Jose State University in 1989 and the California State University Student Research Competition, 2nd Place for Education statewide, ASTC Honor Roll of Teachers in 1987, Fellow of the International Planetarium Society. Professional activities include AAS, AAPT, NSTA, planetarium and amateur astronomy organizations. She has published more than 30 papers on science, and astronomy education. She's presented over 200 invited talks, teacher workshops, teacher short courses at science education conferences. BA: Raymond College at University of the Pacific, 1964; California teaching credential San Jose State University 1977; MA in Instructional Technology/Education from SJSU 1988; MS in Astronomy at University of Arizona 1992.

Jim Emerson received his M.A. in Natural Sciences (Physics) from the University of Cambridge in 1971 and his Ph.D. in infrared astronomy from University College London (UCL). His PhD and post doc work involved far-infrared surveys using a 40-cm telescope carried on high altitude balloons. He joined the faculty at Queen Mary University of London (QMUL) in 1979 and was a member of the science team for the Infrared Astronomical Satellite (IRAS) survey of most of the sky at 12, 25, 60 & 100 microns in 1983. He oversaw development of the UK's IRAS post mission analysis facility and served on various UK panels overseeing Computation and the UK InfraRed Telescope, UKIRT. In 1997 he became chairman of the UK's Wide Field Astronomy Panel and in 1999 formed the VISTA Consortium of 18 UK Universities and was awarded funds to build the 4-m 1.65-degree diameter field wide field survey telescope, the Visible and Infrared Survey Telescope for Astronomy (VISTA) in Chile. (VISTA was originally to be located on the peak that will now host the LSST's calibration telescope, but VISTA became an ESO telescope as part of the UK's contribution on joining ESO.) He arranged for the pipeline reduction of VISTA's data at the Cambridge Astronomical Survey Unit and the VISTA Science Archive in Edinburgh, and that both were prototyped by processing data from the UKIRT Infrared Deep Sky Surveys (UKIDSS) with its Wide

Field Camera WFCAM. He was part of the consortium that obtained EC funding to install a dark fiber link between Cerro Paranal and Antofagasta to route the large VISTA data volumes back to Europe quickly.

Dan Green is an emeritus Scientist III at Fermilab. He has done most of his research at hadron colliders; CERN ISR (Pisa, Stony Brook), D0(FNAL), SDC(Texas SSC) and CMS(CERN). He was the Project Manager for the US contributions to the CMS detector. That 167 M$ Project was completed on time and on budget. He is also the author of six books on physics. In 2014 he will lecture at UIC as an adjunct Professor. He has participated in several prior LSST reviews.

Rick Kendrick is a Fellow at the Lockheed Martin Advanced Technology Center in Palo Alto, California where he has worked for 22 years developing complex imaging systems. Mr. Kendrick has worked on the JWST NIRCAM project, on Gravity Probe B, and on the Airborne Laser, as well as with multiple space-based optical and infrared imaging payloads. His career also includes a three-year period building the Keck Interferometer on Mauna Kea, Hawaii. His current assignment is Principal Investigator on a NASA award to operate the UKIRT facility in Hawaii.

Alexei Klimentov has more than 20 years experience in computing for high energy physics and astro-particle physics. He was online computing coordinator for the L3 (LEP) experiment, and computing and software co-coordinator for AMS. He is currently Head of the Application Software Group at Brookhaven National Laboratory, and ATLAS Distributed Computing (ADC) Coordinator. ATLAS Distributed Computing delivers production quality tools for ATLAS computing activities such as databases, data placement, data processing and analysis. The system has been capable of sustaining the needed activities in the first years of LHC data-taking, with large contingency. Dr. Klimentov has led Research & Development and Task Forces in several new computing areas, leading the ADC effort for a coherent system design for 2015 and beyond. He is the lead PI for the DoE ASCR-funded project "Next Generation Workload Management System for Big Data", and a member of the Australian Governance Board on Cloud and Grid Computing.

William O'Mullane has degrees in Computer Science as well as a PhD in Physics. He has worked on space science projects since 1996 when he assisted with the production of the Hipparcos CDROMS for the European Space Agency. During this period he was also involved with the Planck and Integral science ground segments as well as contemplating the Gaia data processing problem. From 2000-2005 he worked on developing the US National Virtual Observatory (NVO) and on the Sloan Digital Sky Survey (SDSS) at the Johns Hopkins University in Baltimore, USA. In August 2005 he rejoined the European Space Agency as Gaia Science Operations Development Manager to lead the European Space Astronomy Centre development effort for Gaia and work with the Data Processing and Analysis Consortium to produce the Gaia catalogue. He is an editor of the Astronomy and Computing journal.

Jack Salazar is the Deputy Director for the Environment, Health, and Safety Division at Lawrence Berkeley National Laboratory (LBNL). In this role he is currently responsible for managing and leading more than 100 professional and technical staff in such areas as industrial hygiene and safety, construction safety, occupational medicine, environmental and radiation protection, and waste management. Jack is a Certified Industrial Hygienist (CIH) with more than 27 years of experience in implementation and management of environment, health and safety technical programs in national laboratory and academic institutions. Prior to his current role, Jack worked as a technical expert and project lead for various initiatives, including serving as the Safety Officer for the Joint Bio Energy Institute (JBEI). Earlier professional experience includes technical EH&S management assignments at UC Berkeley. Jack has a bachelor's degree in Environmental Sciences from UC Berkeley.

Antony E.T. Schinckel is the Director of the Australian Square Kilometre Array Pathfinder, a $188 million radio-astronomy interferometer being built in Western Australia. His primary interests are in large astronomy instrumentation and telescope design, project management and execution. Antony started his career at the 4-metre Anglo Australian Observatory before moving to CSIRO's 64m radiotelescope at Parkes working on its refurbishment in the early 1980's. After a stint as a guest-stipendiat at the Max Planck Institut for Radioastronomie in Bonn, he joined Caltech, where he was the Technical Director of the Caltech Submillimetre Observatory on Mauna Kea, Hawaii for 8 years. In 1996 he returned to Australia to the University of NSW to work on autonomous telescopes and observatories for the South Pole, Antarctica, working on instruments ranging from infrared telescopes to autonomous remote power facilities. In 1998 he returned to Hawaii as Director of Operations for the SAO's Submillimetre Array (SMA), where he headed the construction, commissioning, and operations activities. In 2007 he returned to Australia, where he has been working on establishing the new radio-quiet Murchison Radio-astronomy Observatory site in Western Australia. He is currently Director of the ASKAP project and is taking an increasing role in SKA activities. He has participated in a number of telescope, project and instrument reviews within the US for the NSF, as well as for other international communities, including ALMA, JCMT-SCUBA2, LSST, and others.

Richard Simon received his PhD from Caltech in 1982 and began his astronomical career at the Naval Research Laboratory, where he concentrated on interferometry and imaging, both radio and optical. In 1991 he became the head of the Radio, Infrared and Optical Sensors Branch at NRL. In 1993 Dr. Simon left NRL to accept an appointment as the Assistant Director for Computing at the

National Radio Astronomy Observatory. Beginning in 1998, Dr. Simon served as the Project Controller for the ALMA Design and Development Project at NRAO. With the formal start of the ALMA Construction project in 2002 he served as the Project Controller for the ALMA Project. He led the international team that created and implemented the Project Management Control System for the Joint ALMA Observatory, which is the key system for managing and reporting the budget, schedule and cost/schedule performance of the ALMA project. Dr. Simon lived and worked for the JAO in Chile from 2005 until his return to work for the North American ALMA Science Center at the NRAO in mid-2012. Dr. Simon thus has broad experience and expertise in cost estimation and project controls appropriate for an international astronomical observatory, and is very familiar with Chile. In 2010, after 12 years of managing the PMCS group for ALMA, Dr. Simon moved to the System Integration Science Team for ALMA, following a personal desire to gain more hands-on experience with the ALMA systems.

Stefano Stanghellini is a senior mechanical and systems engineer involved in telescope design and construction for more than 20 years. He received his Nuclear Engineering degree from Bologna University (Italy) and after employment in the nuclear and aerospace industries he joined the European Southern Observatory (ESO) in 1990. Since then he has contributed in various forms to the design, procurement and installation of ESO telescopes, starting with the VLT. He was in charge of various VLT subsystems, including the optomechanics of the primary and secondary mirror. After acting as systems engineer during the conceptual design of the VISTA survey telescope, he become responsible for the overall definition and procurement of the ALMA 12m antennas. Having recently completed the delivery and commissioning of the European share of the ALMA antennas he has taken over the responsibility for the Dome and the Telescope Structure of the ESO ELT. He has in the past served and advised on various committees, including some of those for the Gemini and ATST projects.

Michael Wise is a senior staff astronomer at ASTRON, the Netherlands Institute for Radio Astronomy, and Project Scientist for the International LOFAR Telescope. His research interests include clusters of galaxies, AGN feedback, and the formation and evolution of large-scale structure. He has worked extensively at a variety of wavelengths including X-ray, optical, infra-red, and radio. In addition to scientific research, he has over 20 years of experience supporting the construction and operation of large-scale astronomical facilities. He has served as a member of the Chandra HETG instrument team, staff scientist with the Chandra X-ray Science Center, contributed to the design of the CIAO scientific analysis software system, and now leads the development and commissioning effort for the LOFAR telescope. Along with basic astronomy research, his interests include a variety of topics in data-intensive astronomy including high performance computing, streaming processing, large-scale data storage and management, high performance formats and data access layers, and active computational archival data centers.

Andrew Woodsworth (Chair) received a PhD in physics (radio astronomy) from Queen's University. He has extensive experience as a senior manager with the National Research Council of Canada, including five years as Director General of the Institute of Information Technology and an extended period as Interim Vice-President, Life Sciences and Information Technology. He has a strong background in research management and in leading new initiatives. His major achievements included acting as NRC lead of Ca*net (first national internet in Canada), startup of the Canadian Astronomy Data Centre, project management of Canadian technical participation in the Gemini telescope project, and starting new research laboratories as the nuclei for developing technology clusters in several Canadian cities in Atlantic Canada and Québec. He served as Chairman of the Board of Compute Canada, an association of Canadian research universities operating high-performance computational and data storage systems. Dr. Woodsworth has also participated in several annual external reviews of the ALMA project and chaired the 2012 review, and he was deputy chair of the PDR for the LSST project.