



CALIFORNIA INSTITUTE OF TECHNOLOGY

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Date: February 22, 2007

Refer to: L070018-00-A

Dr. Thomas Carruthers  
LIGO Program Director  
Mathematics and Physics Sciences Directorate, Physics Division  
National Science Foundation  
4201 Wilson Boulevard  
Arlington Virginia, 22230

Dear Tom:

In response to your letter of January 12 requesting information on the status of Advanced LIGO budgeting in anticipation of the March 2007 Congressional budget hearings, the Advanced LIGO management has prepared the following summary of the current budget and schedule for the Advanced LIGO MREFC anticipating a construction start in FY08. We have reviewed the President's budget request for 2008, and in this letter make our comments in that context. We are also providing a response to the comments and recommendations in the report of the May 2006 Baseline Review panel and an explanation as to why the definition of the end of the Advanced LIGO construction era—the achievement of lock for each of the three interferometers several hours—is a reasonable one.

**Schedule:** We have made no changes in the baseline project start, project duration and project completion dates validated at the May 2006 Baseline review. We have responded to the recommendation of the May 2006 Baseline Review to manage to a schedule in which the total of 11 months of schedule contingency is shown at the end of the project. Thus we will meet the overall schedule outlined in the President's budget request. We are still looking at ways to optimize the detailed project schedule and so may present some modified dates for intermediate milestones at the June 2007 review. In any event we will maintain the current key milestones for the acceptance of the interferometers.

**Budget:** Since the May 2006 Baseline Review we have continued to refine our estimate of the cost of Advanced LIGO. We have responded to the to the advice of the Baseline review panel and have re-evaluated several cost elements in the May 2006 Baseline estimate- adjusted the scope of the computing, incorporated changes in management manpower costs, and re-evaluated the impact of commodity costs.

We find that the cost of Advanced LIGO, in 2006 dollars, is the same (to within \$1,000) as the cost presented at the May 2006 Baseline review. There remain several changes that may be still be made before the June 2007 review in a few subsystem cost estimates, but these should not change the overall cost and we are confident that the magnitude of the cost impact will be small compared to the contingency on the impacted subsystems. These changes might even result in a somewhat increased contingency for the project.

We have also recalculated the "then-year" cost of Advanced LIGO using the recently revised OMB 'Economic Assumptions for Large Facility Projects' recommended by the NSF. We find that there has been an increase in both the escalation factor for 2006 (which we used in bringing prices forward for the May 2006 Baseline review) and the anticipated escalation in out-years. Using the same approach to partitioning the escalation between the manpower and materials that was presented at the May 2006 Baseline review and using the revised NSF recommended escalation factors leads to an increase in our total escalated cost estimate (then-year dollars) to \$209.44M for the project. This increase of \$4.32M represents a 2.1% increase due to the revised NSF recommended out-year escalation factors. We attach a table that provides additional detail about this impact

including the 2006 and revised NSF recommended escalation factors and the year-by-year impact of these factors on the cost estimate.

In addition, we have noted the change in the NSF recommended escalation factor for 2005-2006 from 7.9% to 12.5%. This change impacts some elements of our Baseline cost estimate (May 2006) that were determined using the 2005-2006 escalation factor of 7.9% recommended by the NSF at the time of our Baseline review. To understand this we will need to check the timing of quotes from the 2005-2006 time frame that were used in the Baseline estimate and determine the impact on the baseline cost. The range of impact on the estimated cost of Advanced LIGO will certainly be no more than a few %. Once our analysis of this is complete we will consult with you to determine if it would be appropriate to update the Baseline cost of Advanced LIGO or to reduce contingency with the concurrent increase in risk.

To ensure that our cost estimates and schedule are as complete and correct as possible we will be performing a thorough internal review of the project in the next few months. The result of that internal review will form the basis for any changes from the current baseline that would be presented at the planned June 2007 NSF External Review of Advanced LIGO. If there are any changes we do not anticipate that they would be significant.

We are attaching to this letter documents which address the other two topics raised in your letter of January 12, 2006 - our response to the comments and recommendations in the report of the May 2006 Baseline Review panel and an explanation as to why the definition of the end of the Advanced LIGO construction era—the achievement of lock for each of the three interferometers several hours—is a reasonable one.

Please let us know if any further information is required, or if the information in this letter raises any questions.

Yours sincerely,



Jay Marx  
Executive Director, LIGO Laboratory

Cc: David Shoemaker, Advanced LIGO Project Leader  
Joseph L. Dehmer, Physics Division Director  
Mark Coles, Deputy Director—Large Facility Projects  
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Attached:

1. Table describing impact of new escalation factors on Advanced LIGO cost
2. Document providing response to comments and recommendations of the 2006 Baseline Review panel.
3. Document explaining the reasonableness of the definition of construction being complete (M070004-00-M)

### Comparison of Total Project Cost for 2006 versus 2007 Escalation Factors

2006 NSF Recommended Escalation Factors									
	2007	2008	2009	2010	2011	2012	2013	2014	2015
Yrly Travel and Labor	1.024	1.024	1.024	1.024	1.024	1.025	1.025	1.025	1.025
Yrly Equipment	1.054	1.054	1.054	1.054	1.054	1.054	1.054	1.054	1.054

2007 NSF Recommended Escalation Factors									
NSF Escalation factors	2007	2008	2009	2010	2011	2012	2013	2014	2015
Yrly Travel and Labor	1.021	1.026	1.026	1.025	1.024	1.023	1.023	1.023	1.023
Yrly Equipment	1.074	1.067	1.065	1.064	1.063	1.062	1.062	1.062	1.062

Category	Spending Profile - NSF Request (\$Millions)										
	TOTAL (\$M)	FY08	FY09	FY10	FY11	FY12	FY13	FY14	FY15		
Equipment (2006\$)	101.03	23.92	34.84	26.43	3.33	1.73	0.10	10.69			
Labor (2006\$)	65.08	5.91	9.91	11.97	8.30	14.87	10.53	3.31	0.28		
Travel (2006\$)	6.11	0.37	0.76	0.94	0.78	1.97	1.01	0.26	0.01		
<b>Grand Total 2006\$</b>	<b>172.21</b>	<b>30.19</b>	<b>45.51</b>	<b>39.33</b>	<b>12.41</b>	<b>18.58</b>	<b>11.64</b>	<b>14.26</b>	<b>0.29</b>		
<b>Total 2006 Escal. Factors</b>	<b>205.12</b>	<b>32.75</b>	<b>51.43</b>	<b>46.30</b>	<b>15.21</b>	<b>23.73</b>	<b>15.50</b>	<b>19.78</b>	<b>0.42</b>	<b>19.1%</b>	<b>overall escalation</b>
Cum. Spending 2006 Escal. Factors		32.75	84.19	130.49	145.69	169.43	184.92	204.71	205.12		
<b>Total 2007 Escal. Factors</b>	<b>209.44</b>	<b>33.98</b>	<b>53.99</b>	<b>48.54</b>	<b>14.83</b>	<b>21.98</b>	<b>13.78</b>	<b>21.98</b>	<b>0.36</b>	<b>21.6%</b>	<b>overall escalation</b>
Cum. Spending 2006 Escal. Factors		33.98	87.97	136.51	151.34	173.32	187.10	209.08	209.44		
<b>Yearly Difference Escalated 2007 Total - 2006 Total</b>	<b>4.32</b>	<b>1.23</b>	<b>2.56</b>	<b>2.24</b>	<b>-0.38</b>	<b>-1.75</b>	<b>-1.72</b>	<b>2.20</b>	<b>-0.06</b>	<b>2.1%</b>	<b>Project Increase</b>



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## Status of the LIGO Response to Recommendations from the May 2006 Advanced LIGO Baseline Review

The Baseline Review of the Advanced LIGO Project was conducted by a review panel of experts on behalf of the National Science Foundation on May 31 – June 2, 2006 at the Massachusetts Institute of Technology in Cambridge, MA. The focus of this review was on the scientific case and goals, the requested budget, the proposed schedule and milestones, the management plan, the technical readiness of the project, and an early look at the proposed operating budget along with likely education and outreach activities to be funded separately.

A set of recommendations was developed in the course of the review and presented in the Final Report of the review committee. This document gives the Advanced LIGO team's response and status as of 1 February 2007. In the Summary Recommendations, there are also a number of points without recommendations, labeled as 'Observation', included to keep the numbering of points consecutive.

### SUMMARY RECOMMENDATIONS

#### *Management, Costing and Integration*

**1. Recommendation:** *Facility modifications of existing LIGO involve many activities with stringent requirements on cleanliness. The plans appear to be well organized with a large dependence for cleanliness practices through the use of legacy personnel from LIGO. The more stringent requirements of Advanced LIGO with respect to cleanliness will require extra attention to detail.*

**Response:** We are developing our procedures and the requirements for them through the installation of prototypes at the LASTI full-scale test facility. We are also studying means to produce near laminar flow in the chambers during the installation procedure.

**Status:** In process, to be fully addressed by the end of Seismic Isolation Subsystem development.

**2. Recommendation:** *Because of commodity price increases beyond the standard escalators, the cost of the steel vacuum tubes and other components needed appear to be underestimated by as much as 1 M\$. The costs of the test masses and the coatings may also be subject to currency fluctuations and may require extra contingency.*

**Response:** We have updated our estimates in the present Project costing to correct for our earlier under-estimation.

**Status:** Addressed.

3. **Recommendation:** *Because of the complexity of the project, quality assurance, logistics and inventory control require special attention. Management should increase emphasis on safety management, including recognition of hazards in addition to lasers (e.g. mechanical and electrical).*

**Response:** Individuals to address quality assurance and inventory control for Advanced LIGO have been identified. The Laboratory has established a cross-site safety committee concerned with all safety matters.

**Status:** Procedures and manpower in place.

4. **Observation:** *The proposed model for personnel needed to carry out the installation and testing of the Advanced LIGO components using LIGO personnel augmented by contract labor is credible.*

5. **Recommendation:** *The needed project management structure is in place with a clear plan. To insure a timely execution of that plan there needs to be a project execution plan agreed to between Advanced LIGO and the National Science Foundation. This will be particularly important in the area of timely approval of large contracts and the agreement as to what constitutes completion of the project. A limited number of milestones should be part of this plan.*

**Response:** The NSF and the Advanced LIGO Project are working to establish a shared project execution plan and set of top-level milestones.

**Status:** In process, expected to be mutually approved at June 2007 review.

6. **Observation:** *The readiness of the Advanced LIGO construction project is very good. There appears to be an additional six months of schedule float giving a total of 11 months for the project, which is comfortable for a project of this complexity and duration.*

7. **Observation:** *Detailed examination of the cost analysis of several WBS items to the lowest level gave confidence in their cost estimate. The rule of thumb indicator ratios added further confidence that the cost estimate including their contingency analysis was credible. The Panel identified approximately 3 M\$ of underestimated costs with a comparable amount of overestimated costs. The Panel believes that the project can be completed successfully on schedule within the estimated total project cost.*

8. **Observation:** *The project's multi-tiered approach in their risk analysis combined with their Monte Carlo analysis led to an average contingency of 27% with individual WBS elements varying from 11 to 75%. Again, the Panel finds the analysis credible, consistent, and appropriate for a project of this complexity.*

9. **Observation:** *The foreign contributions to Advanced LIGO are essential. The prototype laser that is operating at the Albert Einstein Institute in Germany is operating at 180 watts and meets specifications in the areas that have been tested to date. The UK consortium is providing components for the state of the art suspension system that they pioneered in GEO along with a significant number of the test masses. Both projects are on budget and on schedule with a total hardware contribution in excess of 12 M\$. The LSC is also contributing R&D and technical expertise along with components that will be constructed under contract with the Advanced LIGO project.*

10. **Recommendation:** *To insure realization of the full scientific potential of Advanced LIGO, the planning for the operational budget of Advanced LIGO needs to begin soon. The Panel recommends that the projected state of the laboratory in 2015 be used as the template for determining the elements and their cost for this operations budget. The plan should outline the transition from the current operations budget to this state.*

**Response:** The LIGO Laboratory has provided its vision for the future operational budget to the NSF at its recent annual review. Further development will take place in preparation for the Laboratory Proposal for continuing operations, expected to be submitted in September 2007.

**Status:** In process, to be fully addressed with the establishment of a new cooperative agreement with Caltech.

**11. Recommendation:** *With the successful achievement of design sensitivity by LIGO and the maturity of the Advanced LIGO construction project, it is surprising that MIT and Caltech have not taken this opportunity to allocate more faculty positions to capitalize on this exciting field.*

**Response:** The recent junior appointment at Caltech has proved to be very successful in engaging students in our field, and another arriving in September 2007 will further support the field. MIT has a search open for junior faculty, and a LIGO Lab postdoc is on the short list for that position.

**Status:** Ongoing.

## ***Seismic Isolation and Suspension***

**12. Observation:** *The HEPI system for the primary seismic isolation has been operating very successfully at the Livingston Observatory for about one year and has enabled 24/7 operation of the interferometer. The cost is known as well as the installation time and effort.*

**13. Observation:** *The first full scale prototype of the internal seismic isolation system is being assembled for test at the LASTI facility at MIT. The system should be under test during the fall with a production readiness review scheduled for next July. The design builds on the 2/3 scale prototype that was successfully tested at Stanford.*

**14. Observation:** *The rest of the suspension system builds on the very successful GEO system giving confidence that the tests of the complete system will be successful.*

**15. Recommendation:** *The potential noise from charging of the test masses remains a concern. Tests to determine the magnitude of this effect should continue to receive priority. The violin mode of the fiber suspension also deserves special attention with respect to possible increased noise contributions.*

**Response:** A program of study for the nature, and means for mitigation, of electrostatic forces is now in full swing.

**Status:** In process, to be fully addressed by the end of development (planned for the second quarter of FY08) of the Core Optics subsystem.

**16. Recommendation:** *The cost to build and the manpower required to assemble and install these systems are reasonable. One concern is the limited number of expert personnel available to install and perform the initial qualification of these complex systems.*

**Response:** Several new postdocs and students are immersed in the prototype development and test of the systems, increasing the potential pool of future skilled scientists. We will continue to look for people to train.

**Status:** Ongoing.

**17. Recommendation:** *Limited testing before installation, particularly the noise performance of the inertial sensors critical to achieving the ultimate sensitivity in Advanced LIGO, may be a good investment to minimize the time required to achieve the design sensitivity.*

**Response:** We have incorporated this recommendation in our test plans.

**Status:** Addressed.

## ***Optics***

**18. Observation:** *The prototype of the laser system that is being provided by the Albert Einstein Institute in Germany has now been operating at 180 watts for two months and has achieved design specifications in several areas. This is exciting progress on this key system.*

**19. Recommendation:** *The premode cleaner following the laser has very high power densities that may be problematic. The design and testing of this element should have high priority.*

**Response:** We have given the pre mode cleaner design a high priority and will ensure that adequate and timely testing takes place.

**Status:** In process, to be fully addressed by the end of the Pre-Stabilized Laser development (planned for the third quarter of FY09).

20. **Observation:** Fused silica has been chosen as the test mass material. The metrology techniques required to measure the tight specifications are nearly there with important contributions from the international partners.

21. **Recommendation:** The coatings for the optics have the potential to be a limiting noise source in the key frequency range. A more aggressive program with more funding to lower this source is recommended.

**Response:** We continue to focus considerable manpower and other resources on this challenge and opportunity. In addition to maintaining the development with the two vendors pursuing designs, we have also brought those vendors together in a small meeting to allow all non-proprietary elements of the processes to be discussed, providing cross-pollination. We have a two-pronged strategy. The first element is to confirm that we can reliably produce the present best coatings, sufficient to meet the Advanced LIGO performance curves, in a production environment. The second element is to continue exploration of both refinements in the current approach and a search for alternative materials which might allow either a change in the coatings planned for the initial installation, or an opportunity to improve the sensitivity of Advanced LIGO in the longer term.

**Status:** In process. The initial coating process must be frozen no later than early FY09. We intend to maintain a development program in the LIGO Laboratory in this domain in the long term.

22. **Recommendation:** Parametric instabilities due to photon pressure continue to be a concern. Simulation efforts and measurements should receive priority.

**Response:** Good progress has been made in the analysis and modeling, with a reduction in the number of anticipated excited modes. Experiments have supported modeling, and more are in preparation.

**Status:** In process, to be fully addressed by the end of development of the Core Optics subsystem (planned for the second quarter of FY08).

23. **Observation:** Examination of the eight auxiliary optics systems revealed no critical issues with good progress on all systems.

24. **Recommendation:** The signal recycling cavity design has not been finalized and may involve additional suspended optics. These costs appear to not have been estimated with the same precision as the rest of the cost estimate.

**Response:** While the choice of a marginal or fully stable recycling cavity is still being studied, the costing has been re-examined for the alternative configuration and is comfortably smaller than the contingency on the impacted subsystems.

**Status:** In process. The configuration will be established by the June 2007 Review.

25. **Observation:** The thermal compensation schemes appear to be effective although the material properties of the compensation plates are still to be optimized. This scheme may provide a possible route to limit the potential effects of parametric instabilities.

26. **Observation:** The input optics design appears to be in good shape. The proposed DC modulation technique may be an effective way to limit coupling of amplitude and phase noise effects.

## **Data Systems, Data Acquisition, Controls, and Computing**

27. **Recommendation:** The proposed budget for computing systems would yield a system with 400 Tflop capability when Moore's Law is taken into account. The budget for the proposed storage capacity yields 6 Pbytes of storage. These capacities significantly exceed the documented needs. These budgets/requirements should be appropriately modified either by assigning a much larger fraction of contingency or justification of the increased capability.

**Response:** A bottom-up re-estimate, motivated by the astrophysics, has been made. It has resulted in a reduction in the budget for this subsystem, reflected in the current Project costing.

**Status:** Addressed.

28. **Recommendation:** *The data acquisition and control systems appear to be making good progress. Examination of personnel needs indicate that the addition of at least one real time programmer would be justified.*

**Response:** A position has been opened and advertised for an additional real-time programmer.

**Status:** In process.

29. **Observation:** *Sensing and Control of the Advanced LIGO interferometer consists of a number of subsystems that are well motivated upgrades of those used in LIGO, many of which have undergone prototyping at the 40 meter. The costs appear to be a reasonable extrapolation of the current systems in LIGO.*

30. **Recommendation:** *The interface of the Sensing and Control system with the rest of the interferometer control system needs careful attention. A simulation of the complete system response with hardware in the loop has the potential to significantly shorten the time needed to achieve initial lock.*

**Response:** Hardware ‘in the loop’ is being employed in the Caltech 40m, and in the integrated mechanical tests at the MIT LASTI facility.

**Status:** Addressed.

31. **Recommendation:** *The proposed seismic platform interferometer needs further design and evaluation.*

**Response:** Agreed. An LSC collaborator has taken on the task of putting the SPI on a firm basis, with simulations and the development of a conceptual design. The endeavor will be reviewed as an Advanced LIGO element.

**Status:** In process. Review planned for mid-2007; to be fully addressed by the end of Interferometer Sensing and Control development (planned for the first quarter of FY09).

32. **Recommendation:** *Enhancements to LIGO can provide opportunities for advance testing of Advanced LIGO components and would extend the scientific reach of LIGO.* **Response:** This appears to be a very rewarding approach to real-life performance testing of the seismic isolation, suspension, output mode cleaner, DC readout, and thermal compensation system for Advanced LIGO. It also provides valuable training for the Observatory staff.

**Status:** Addressed.

# DETAILED TECHNICAL RECOMMENDATIONS

## *Management and Systems Integration*

### **4.01 FMP Facility Modifications (includes old WBS 4.10 Support Equip 8.4M\$ with total contingency of \$1.4M)**

1. **Recommendation:** *Ensure field management staff at both sites is in place and up to speed prior to project start in FY08.*

**Response:** There are two elements in our plan to ensure that the Observatory staff is up to speed.

- 1) The full-scale testing of mechanical systems at the MIT LASTI facility makes use of Observatory staff members, who take sabbaticals of one or several weeks to help in the installation, characterization, and review of Advanced LIGO elements. This includes scientific and technical staff.
- 2) The enhancements to initial LIGO provide an excellent opportunity for training *in situ* of the observatory staff. The suspensions, seismic isolation, interferometer sensing and control, auxiliary optics, laser, and input optics subsystems have Advanced LIGO elements being installed, by combined teams of Observatory and LSC staff, as part of the enhancements program. It is planned to add new operators in the near future (operations funds permitting) to allow more experienced operators to become skilled at assembly, installation, and testing.

**Status:** Addressed.

2. **Recommendation:** *Implement an inventory management system.*

**Response:** We have identified an Observatory operator, who is familiar with procedures and difficulties at the observatories. He has started to research solutions, and will propose a solution to management, and then carry out the plan for an inventory management system.

**Status:** In process. Approach to be established by June Review, to be operational by the start of the Project.

### **Installation and Testing (WBS 4.13) (\$32.1M total cost including \$7.9M contingency)**

1. **Recommendation:** *Work out the installation sequence independently of the presently scheduled shutdown plan. The shutdown sequence of the current facilities may be subject to change and the Advanced LIGO project staff needs to be ready to provide management with meaningful choices planned well ahead of time.*

**Response:** The task of detailed installation and planning is included in the project management team scope. A baseline installation plan will be developed in the first funded year of the project. This baseline plan will include potential options and branch points to allow for change as the project progresses.

**Status:** In process, to be fully addressed October 2008.

### **Project Management (WBS 4.14) (\$17.2M total cost including \$2.8M contingency)**

1. **Recommendation:** *Develop a procurement plan within the next 12 months and before project construction start coordination.*

**Response:** The procurement plan preparation is well underway, and will be in place by the planned May-June Advanced LIGO Review. A draft plan has been produced by the project controls team and will undergo revisions after review in March by the Caltech LIGO Business and Procurements personnel. The final plan will be reviewed by an internal LIGO review team in the April time frame. The actual details of the list of procurements will be finalized when the MREFC funding profile is known.

**Status:** In process, to be fully addressed at the time of the May-June 2006 Advanced LIGO final baseline review.

2. **Recommendation:** *Develop specifics for strengthening quality assurance activities within the next 12 months and before construction start. This may involve adding skilled staff.*

**Response:** A senior scientist in the Lab has taken on the responsibility to organize and put into action a quality assurance program. The day to day responsibility will transition to a quality assurance professional in the production phase.

**Status:** In process. Systems to be in place and in use by the June Review, and to be fully addressed by the time of the Project start.

3. **Recommendation:** *Develop some uniformity across the four project sites for safety reporting procedures as compatible as possible with the site specific practices.*

**Response:** A Safety Committee has been established which spans the two campuses and the two Observatories, organized under the Laboratory Operations and chaired by the LIGO Laboratory Deputy Director (who has the responsibility for Lab safety).

**Status:** Addressed.

4. **Recommendation:** *Develop a stand-alone CCB procedure or include as an appendix in the PEP*

**Response:** We are editing the PEP to minimize redundancy with other Laboratory and Project documents, and will pursue this recommendation in that process.

**Status:** In process. To be fully addressed by the June Review.

## ***Overall management***

1. **Recommendation:** *Develop NSF Project Execution Plan in concert with the existing draft of the Advanced LIGO Project Execution Plan.*

**Response:** The NSF Internal Management Plan incorporates the LIGO Project Execution Plan as an integral element.

**Status:** Addressed (by the NSF).

2. **Recommendation:** *Within the context of the two PEPs, the Project Team and NSF management should agree on a manageable set of procurements to be reviewed and approved by NSF*

**Response:** The project procurement plan that is under development will provide a list of procurements with detailed procurement information. That plan will be ready by the time of the May-June Advanced LIGO review. An agreement as to the scope and method for reviewing procurements can be determined at the time of the review.

**Status:** In process, to be fully addressed the May-June Advanced LIGO final baseline review.

## ***Project Cost***

1. **Recommendation:** *Incorporate the Committee cost estimate recommendations into the baseline and continue improving the estimate with time*

**Response:** This has been completed. The Budget to be included with this letter addresses these issues.

**Status:** Addressed.

## ***Project Schedule***

1. **Recommendation:** *Generate 11 months of total schedule float by removing parallel subsystem delivery constraints and remove the specified ahead of time meshing with the LIGO operations.*

**Response:** The Project schedule has been modified to show the float in this way.

**Status:** Addressed.

2. **Recommendation:** *Within the next 12 months develop a summary level schedule with corresponding milestones.*

**Response:** Agreed.

**Status:** In process. To be fully addressed by the June Review.

## ***Project Risks***

1. **Recommendation:** *Incorporate lessons learned from the initial LIGO from the QA area into Advanced LIGO through a formal process – for example by developing a data base to track experiences.*

**Response:** As an experiment to find the best solution, we are using Problem Tracking software (GNATS, used by the Laboratory software development teams) to track hardware problems.

**Status:** In process. Systems to be in place and in operation by the June Review and to be fully addressed by the Project start.

2. **Recommendation:** *Examine relevant Import/Export control issues and if necessary get a formal assessment.*

**Response:** We have discussed the issues with Caltech Counsel, and are preparing a summary of the potential issues in Advanced LIGO for them to help establish a position.

**Status:** In process. Progress to be reported at the June Review.

3. **Recommendation:** *Continue to push the two host institutions to make appropriate investments in developing and maintaining an attractive career path for the highly skilled people needed for LIGO.*

**Response:** The recent faculty hire at Caltech is proving to be a powerful magnet for students and capable postdocs. A new faculty search at MIT include individuals from the field (in fact from the LIGO Laboratory) on the short list, and the MIT LIGO senior staff are encouraging a positive consideration of the candidate.

**Status:** Ongoing.

## ***Quality System***

1. **Recommendation:** *It is the sense of the Panel that an overarching quality system is needed including a true quality coordinator, quality policy, quality plan and quality audits. The problem is that a quality professional will tend to implement an excessive system inappropriate to a research and development effort. In the end it may be easier to train a scientist in quality procedures because they will implement an appropriate level of effort and will have credibility during implementation.*

**Response:** As mentioned above, a Lab senior scientist with experience in quality has taken on the responsibility to organize and put into action a quality assurance program. The day to day responsibility will transition to a quality assurance professional in the production phase.

**Status:** Addressed.

2. **Recommendation:** *Raising the threshold for NSF approval of purchases should be considered.*

**Response:** This would be desirable from the Laboratory and Project perspective.

**Status:** This is under consideration at NSF.

## ***Operations Planning***

**Recommendation:** *... the plan presented also assumed the consumable costs (computers, supplies, etc) of Advanced LIGO staff will be borne by LIGO Laboratory operations. This does not make sense to the Panel – a suitable budget (based on recent experience) for materials and supplies for staff should be reflected in the Advanced LIGO budget. This would appear to be about \$1M since much of the M&S connected with*

*the hardware is already in the Advanced LIGO budget. This amount was accounted for in the Cost section of this report.*

**Response:** In the current budget have now included M&S costs appropriately charged to the Project.

**Status:** Addressed.

1. **Recommendation:** *Develop with the NSF an out year operating budget, circa 2015, and then reach agreement on the intervening years' operating budget. This will validate (or not) the assumptions made within the Advanced LIGO construction budget for staff transition and technology base maintenances.*

**Response:** This recommendation, targeted at the Operations of the Laboratory, is being addressed; a draft was presented at most recent LIGO Lab review. There will be further discussion with the NSF.

**Status:** In process. To be fully addressed by the establishment of the new Cooperative Agreement.

## ***Seismic Isolation (WBS 4.02) SEI***

**Recommendation:** *A cost saving analysis of the upfront effort vs. possible down time should be performed for the unit components that can be qualified before assembly.*

**Response:** We plan to qualify all of the sensors for the Seismic System before assembly.

**Status:** Addressed.

## ***Suspension (WBS 4.03) SUS***

**Recommendation:** *An overall test plan starting in the prototyping phase should be developed. There are a number of places where early testing could benefit the program.*

**Response:** We agree this is a priority, and a robust program is in place and has been underway for several years. The test plans have been used to guide the independent testing performed at the LASTI facility on suspension prototypes. For the critical suspensions, two stages of prototype testing are foreseen, one with metal masses, and a second with optics as a payload. The first round of this testing is complete for the input mode-cleaner style suspensions, and underway for the test-mass style suspensions. Prototype testing of the output mode-cleaner suspension will be undertaken in connection with the initial LIGO enhancements program.

**Status:** Addressed.

## ***Optics Design***

**No recommendations.**

## ***Pre-stabilized laser***

1. **Recommendation:** *The Panel encourages the German team to continue their effort and suggest that they share problems of added noise in the photodiodes with researchers at NIST that face similar issues.*

**Response:** The Max-Planck group is in contact with Tom Carruthers, and establishing a contact with his colleagues at NRL who have developed high-current photodiodes. The Max Planck group is almost finished in setting up an automated experiment to test spatial response of diodes. Once that is ready we'll offer to perform that measurement on the diodes produced as NRL and will do noise measurement on those diodes as well. We will contact NIST in addition to the effort described above.

**Status:** In process. To be fully addressed by the end of Pre-Stabilized Laser development.

2. **Recommendation:** *The Panel suggests the AEI/LIGO Laboratory monthly meetings be formalized with formal meeting minutes.*

**Response:** This is now incorporated into the functioning of the Laser group.

**Status:** Addressed.

## ***Test Masses***

**Recommendation:** *Coating development (see below) is the only element that could delay the test mass delivery and consequently should be followed closely.*

**Response:** See below.

## ***Coatings***

**Recommendation:** *The thermal noise in the coatings of the core optics remains a potential limitation to the mid-band strain sensitivity of the advanced detectors. The Panel strongly recommends that LIGO maintain (and possibly increase) the current level of research toward the development of mechanically low-loss, high-finesse optical coatings whose contribution to the thermal noise budget of the advanced detectors will be negligible.*

**Response:** We have been continuing our focus on this front. In addition to maintaining the development with the two vendors pursuing designs, we have also brought those vendors together in a small meeting to allow all non-proprietary elements of the processes to be discussed, providing cross-pollination. We have a two-pronged strategy. The first element is to confirm that we can reliably produce the present best coatings, sufficient to meet the Advanced LIGO performance curves, in a production environment. The second element is to continue exploration of both refinements in the current approach and a search for alternative materials which might allow either a change in the coatings planned for the initial installation, or an opportunity to change out e.g., the end test masses with spares coated with lower-loss mirrors in a near-term upgrade.

**Status:** Addressed.

## ***Test Masses Electrostatic Charging***

**Recommendation:** *The understanding and, if necessary, elimination of the impact of electrostatic charging on Advanced LIGO performance should be prioritized.*

**Response:** A team has been established, with the Lab coating expert leading the effort. That group is pursuing both the characterization of the problem and investigating methods for mitigation. Elements in the activity are

- Observation and documentation of probable charging events in initial LIGO, and the resolution through venting. GEO-600 scientists indicate that similar phenomena are observed there
- A design for a replacement limit ('earthquake') stop has been prototyped and tested in a stand-alone initial LIGO prototype, and is planned to be fitted at the time of the enhancements to initial LIGO – and will be ready earlier if an opportunity or need arises.
- Kelvin probes have been acquired in two LSC laboratories to study the amount and migration of charge on surfaces; they are presently being shaken down. This complements work in Moscow using an alternative modulation technique for watching the time evolution of charge.
- Conductive coatings and implantation are being studied as mitigation methods, causing both a rapid equipartition of charge and allowing a path for discharge through coated fused silica suspension fibers. This is of course complicated by the competing optical and mechanical requirements on those elements.
- An ultra-violet discharge approach, pioneered for the NASA LISA mission, is being investigated; a concern here is potential damage to the coatings. In general, discussion has been opened with several scientists working on charging issues in LISA, with one group suggesting they would like to join in investigation of the phenomena.

We will continue to report on progress in this area.

**Status:** Addressed.

## ***Auxiliary Optics System (AOS)***

1. **Recommendation:** *The Panel encourages continuing the effort to improve TCS including a sensing method since it seems to be an effective way to control overall mode quality in the system. It provides a way to mitigate the parametric instability, the impact of which on the overall system is still not known.*

**Response:** We concur. A choice has been made of a Hartmann sensor from an LSC collaborator to measure the deformations, and plans are being developed to make a complete prototype test of the TCS (Thermal Compensation System) in the context of the tests on the test mass suspension at LASTI.

**Status:** Addressed.

2. **Recommendation:** *The Panel encourages the design of the compensation plates.*

**Response:** Progress has been made on this front. Our analysis shows that direct thermal compensation of the ITM will needlessly complicate the compensation-plate thermal compensation, since the arm cavity thermal distortion can be controlled by heating the ETM only. Estimates of the heat diffusion in the suspension structure coupled with measurements at LASTI show that the heat load of the ring heater on the ETM structure is unlikely to cause problems, and a prototype heater is being built to test this at LASTI.

**Status:** Addressed.

3. **Recommendation:** *The Panel encourages continuing the effort to qualify a second vendor for the parabolic mirrors.*

**Response:** A Russian vendor has been qualified as a second (and much less expensive) source. The facility is a Russian military plant with the capability of making large diameter optics suitable for LIGO. They use a computerized grinding and polishing method which enables them to fabricate an individual off-axis parabolic mirror, without having to make a large blank and "cookie cut" the individual off-axis segments as our previous vendor SORL does. They use interferometric test equipment for verifying the surface figure to 1/8 wavelength @ 633 nm as we specify. The cost per set of parabolic mirrors is approximately 1/3 the cost of previous quotes, and their quoted delivery schedule is shorter. We will maintain our option of the US supplier, and test the ability of the newly identified source to supply prototype elements.

**Status:** Addressed.

## ***Input Optics***

### *Power Control*

**Recommendation:** *Continue to improve use of TFP's due to simplicity, consider calcite, if necessary, and ensure proper safety considerations in the design and use of the beam dumps.*

**Response:** Commercially available fused silica Thin Film Polarizers (Karl Lambrecht) have been tested for performance at high power and deliver 40 dB extinction ratios, adequate for power control applications. Commercially available water-cooled beam dumps (Kentek) can safely dissipate 300W powers. We have measured the integrated backscatter for a 100 W input beam to be approximately 10 mW. Alternative custom beam dumps which absorb the laser power have been designed and tested which have < 1 mW backscatter (and this could be better; limited by AR coatings).

**Status:** Addressed.

### *Mode Cleaner*

**Recommendation:** *Perform thermal modeling, modify control loops to handle the larger mass associated with larger optics, perform 'lifetime' (mean time between failure) measurements of mode cleaner optics, and perform scattered light characterization/ calculation.*

**Response:** We have lowered the mode cleaner finesse from 2000 to 500 due to a re-evaluation of the jitter suppression requirements and the expected PSL jitter performance, thus reducing thermal loading.

Thermal loading in the MC is dominated by coating absorption. Modal modeling performed on the original high finesse (2000) mode cleaner design determined that coating absorptions above 1 ppm would lead to internal mode distortions at the few percent level for the highest expected AdL laser powers. For the newly

baselined lower finesse design and coating absorption of 0.5 ppm, a numerical propagation analysis yields mirror surface deformations at the level  $< \lambda/200$  and negligibly small mode distortions.

A long term in-vacuum exposure and damage testing experiment has been set up and we are waiting to receive mirrors from LMA Virgo to start the test.

**Status:** Addressed.

#### *Faraday Isolator Chain*

**Recommendation:** Consider improvement of thermal compensation at highest power, for a given performance of the adaptive mode expanding telescope. Consider the use of calcite polarizers for improved isolation.

**Response:** Calcite polarizers (extinction ratios of  $\sim 60$  dB) are now in the baseline design for the Faraday isolator. The best achieved isolation to date is 49 dB at 200 W loading (double pass), and the induced thermal lens focal length at the highest power is expected to be  $> 50$  m based on our experiments. As a back up, the input optics adaptive mode matching telescope is designed to compensate for thermal lensing in the components.

**Status:** Addressed.

## ***Instabilities***

**Recommendation:** The Panel strongly recommends that LIGO continue their pursuit of a better theoretical understanding and modelling of the various instabilities that will arise at the higher power operation of Advanced LIGO toward developing solutions that will mitigate or eliminate the instabilities. To the degree possible, the Panel recommends that laboratory tests be carried out which mimic the high power operation of Advanced LIGO, which will be immensely helpful in the real-world identification, understanding and mitigation of any instabilities. Care must be taken to avoid degradation of the strain sensitivity by the application of the mitigation procedure.

**Response:** An Advanced LIGO Optics Summit was held in November 2006 which brought together experts on this subject from five continents. Significant modeling and experiment had preceded that meeting, allowing a complete synthesis of information. There is still a range of estimates of the effect and many proposed means to mitigate the effects, but a consensus as described is perceived by the Lab Advanced LIGO Optics and Systems team.

There are few likely parametric instability gain parameter  $R > 1$  modes for the full design AdL ( $< 10$ , conservatively). For a typical, as built, parameter set (tolerances, TLs, mismatches, etc) it is extremely unlikely that there will be cases of  $R \gg 1$ . All predictions of huge  $R$  values (and thus rapid runaway) require extreme fine tuning of the arms and recycling cavity(ies). Slight TCS (or other) adjustment of the radius of curvature would be sufficient to avoid such  $R \gg 1$  cases.

The addition of signal recycling (in the typically detuned status of 2. above) can, at most, increase the peak gain  $R$  by a factor 2 above what  $R$  would be in the same interferometer with the signal recycling cavity removed.

Given that a typical, instantaneous interferometer configuration will not support  $R \gg 1$  growth, any instability will only likely erupt when AdLIGO is turned up to its very highest power level. Thus the parametric instability will not likely be a distraction through most commissioning (but note the Braginsky, Vyatchnain, et al. note that specific scan tuning of the recycling can allow PI cases to be studied earlier in commissioning if desired).

The issue of whether stable recycling cavities worsens or assuages the PI prognosis is still unresolved. Our current take is that the introduction of finite Gouy phases shifts around the peak gain points in the PI spectrum in a complex way. However the average number of  $R > 1$  cases as well as the likelihood of individuals being fine tuned such that  $R \gg 1$  is not changed.

On the experimental front, we are to date lacking a specific operative example of such an instability to observe and study. It has been a significant step forward that the quantum measurement group at MIT has indeed been able to study a related case in a light weight suspended mirror. The related experimental field of [micro] cavity cooling, which uses the same fundamental mechanisms, has really taken off and focused a lot of good thinking and ideas in the area.

The Australian GinGin program to actually induce a PI in a long cavity seems to be well in focus and being pursued. The presentations at the Optics Summit gave encouragement about their program yielding timely results; LIGO is supporting this effort.

The effort to use a ring damper (at the Caltech TNI, with analytical and numerical support from the community) to selectively lower some mode Qs with minimal effect on the net thermal noise is moving forward. There is also a study the adaptation of the test mass electrostatic to control PI modes via feedback, with strongly encouraging results. This approach will be studied at the LASTI installation as part of the suspension-test mass prototype characterization..

With the apparent small number of excited mechanical modes, and the progress toward experimental confirmation of the models for excitation and control, we feel that the situation is manageable and will be well understood in a timely way.

**Status:** In process, to be fully addressed by the end of development of the Core Optics subsystem (planned for the second quarter of FY08).

## ***Interferometer Sensing and Control (WBS 4.8) (ISC)***

1. **Recommendation:** *The control testing and simulation plan needs clarification. The Panel recognizes that these activities come under the domain of a different WBS (4.12.1) but recommends that future reviews provide a mechanism for review of the end to end control problem.*

**Response:** In future reviews we will pro-actively present material addressing the end-to-end control issues.  
**Status:** Addressed.

2. **Recommendation:** *The Panel recommends that the project investigate the possibility of exercising ISC hardware with simulations of the relevant actuator transfer functions (and also the converse to exercise the actuator hardware with simulation of ISC hardware).*

**Response:** This is underway at our two large scale prototyping installations, the 40m interferometer at Caltech and LASTI at MIT.

- At the Caltech 40m, a full suspended-mirror interferometer will all of the longitudinal control degrees of freedom and the planned interferometer topology is equipped with the planned acquisition and control hardware and software. Locking codes, input/output matrices, and combined optical/mechanical transfer functions can all be compared with models.
- At MIT LASTI, full scale suspension and isolation systems along with single longitudinal cavity control are being installed and commissioned. Once complete, the hierarchy of mechanical control will be studied, modeled, and optimized.

Lastly, the enhancements to initial LIGO will test the DC readout along with the active input coupling optics in a very demanding ‘prototype’ environment and will provide feedback for further ISC design.

**Status:** Addressed.

3. **Recommendation:** *The testing plan for ISC hardware components and subsystems needs clarification. The Panel applauds the team’s idea of outsourcing tests of components and subsystems to LSC members, to allow other institutions ownership in more of the LIGO hardware.*

**Response:** The testing plan for ISC is in preparation and will be reviewed as the overall design advances.  
**Status:** In process. To be addressed by the ISC PDR.

4) **Recommendation:** *The cost basis for software requirements could be improved. Staffing and thus costing estimates for computing needs are immature. For example, the control and supervisory software is*

unlikely to need simulation. The separation of programming activities into three parts, one for each interferometer, appears artificial.

**Response:** The control software includes time-critical elements and we do want to be sure that it can handle the data rates; we will use a mixture of tests on the prototype systems as described above, and simulation if needed. The artificial separation of programming between interferometers will be ‘cleaned up’, thanks. We have reviewed the cost estimate and believe it is appropriate to the system.

**Status:** In process. To be fully addressed by the end of development of the Data and Control Systems.

5) **Recommendation:** *The panel recommends an execution plan for the seismic platform interferometer (SPI), including scheduling of a CDR. The benefits from an SPI, and thus the requirements on it, need a firm basis from simulations of the system and/or from prototyping.*

**Response:** Agreed. An LSC collaborator has taken on the task of putting the SPI on a firm basis, with simulations and the development of a conceptual design. The endeavor will be reviewed as an Advanced LIGO element.

**Status:** In process. To be fully addressed by mid-2007.

24. **Recommendation:** *The signal recycling cavity design has not been finalized and may involve additional suspended optics. These costs appear to not have been estimated with the same precision as the rest of the cost estimate.*

**Response:** While the choice of a marginal or fully stable recycling cavity is still being studied, the costing has been re-examined for the alternative configuration and is comfortably smaller than the contingency on the impacted subsystems.

**Status:** In process. The configuration will be established by the June 2007 Review.

## ***Data Acquisition, Diagnostics, Network & Supervisory Control (WBS 4.9) (DAQ)***

1. **Recommendation:** *Myrinet is rapidly losing marketshare to Infiniband, and may not be a well-supported technology by the time of Advanced LIGO. Infiniband is also less expensive. Prototyping work with Infiniband should begin soon to determine if that technology satisfies the deterministic timing requirements needed for the real time network.*

**Response:** We agree that it is a good idea to investigate Infiniband for our realtime networking. It is now in our prototype/test plan to evaluate this technology over the course of the next year.

**Status:** Addressed.

2. **Recommendation:** *The IFO Mass Storage should be scoped at the required level and then costed with a realistic model.*

**Response:** Agreed. The current cost estimate is safe, having not included Moore’s law.

**Status:** In process. To be fully addressed by the end of development of the DAQ subsystem (planned for the first quarter of FY09).

3. **Recommendation:** *LIGO management should pay careful attention to resource loading the realtime programming needs, and supplement the current staff in this area with at least one additional person.*

**Response:** We have opened a job for an additional real-time programmer to complement the current staff.

**Status:** Addressed.

## ***Data and Computing Systems (WBS 4.10) (DCS)***

1. **Recommendation:** *The DCS group should complete the computing plan document (as planned), taking into account all current data on computing requirements. This document should be updated annually to track the evolution of algorithm performance and computing needs.*

**Response:** Agreed. A survey has been performed and used to help re-scope and re-cost the DSC subsystem.

**Status:** Addressed.

2. **Recommendation:** *The Advanced LIGO project should fix a firm upper limit on the uncharacterized computing requirements for the project, perhaps an additional 50 teraflops above what is documented today. Significant future changes in computing requirements should trigger a change control mechanism, with an increase in cost and scope if needed. Hiding contingency within the computing budget should be avoided.*

**Response:** Please see below.

3. **Recommendation:** *Based upon the new computing requirements (characterized and uncharacterized), and upon a firm adherence to 5 cycles of performance doubling (based upon a procurement at the beginning of 2014), a new cost estimate should be generated. Management should track that the cost of this system will rise if the project decides to complete earlier than now planned, at about 5% per month earlier for all commodity parts (computers, disks, networking). Similarly, it will fall by 5% a month if the project is delayed.*

**Response:** Please see below.

4. **Recommendation:** *Cost estimates for networking should be reduced under the assumption that 10G ethernet will cost then what 1G ethernet costs today.*

**Response:** Please see below.

5. **Recommendation:** *Capacity requirements for the Gateway Servers and Dataservers should be motivated by specific performance data. Assumptions of needing "Enterprise Class" servers should be dropped. Based upon specific performance requirements, new cost estimates should be generated.*

**Response:** These useful panel recommendations were taken into account in a re-costing of the subsystem from the bottom-up, enquiring of analysis teams the basis for the requests. A decision was taken to supply 50% of the computing power identified as needed by the search teams in the LSC, with the understanding that the community will supply the remainder; that is roughly the situation today for initial LIGO analysis. Timing of the acquisitions was re-evaluated. The reduction in the bottom line is reflected in the current Project estimates, and is comparable to those estimated by the committee.

**Status:** Addressed.



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Date: January 12, 2007

Refer to: LIGO-M070004-00-M

From: David Shoemaker, Advanced LIGO Leader; Jay Marx, LIGO Executive Director  
To: Tom Carruthers, Beverly Berger

## **Advanced LIGO: Criteria for the end of the MREFC project and transition from the Commissioning Stage to the Operations Stage**

The Advanced LIGO MREFC project is scoped to deliver three interferometers with the capability of reaching a sensitivity about an order of magnitude better than initial LIGO, following a post-project operating stage with a transition to full science capabilities. The definition of project completion for the MREFC takes account two important elements: 1. the need for acceptance criteria that will assure the project delivers working interferometers and a solid foundation for achieving the full science capabilities envisioned for Advanced LIGO in a reasonable time, and 2. distinguishing between those activities that are best performed in the disciplined environment of a formal project and those that have an intrinsic research nature and so are best carried out in the operations stage by research personnel supported from an R & RA account.

Upon project completion all three interferometers will have demonstrated stable operation and Advanced LIGO will be a working gravitational wave detector.

In the following we describe both commissioning of Advanced LIGO and the follow-on operations that will provide both data for astrophysics research and instrument research on the interferometers to understand and control effects leading to full design sensitivity after a reasonable period of time.

### **Commissioning**

During the final phase of the Advanced LIGO MREFC Project there will extensive commissioning of the subsystems, and then of the full interferometers. Each of the subsystems for each interferometer will be separately tested to meet their acceptance requirements, and then integrated with neighboring systems and tested together. Once all subsystems for an interferometer are accepted, the full interferometer will be required to function to allow the entire system to be brought to the operational condition ('first lock') for several hours.

The commissioning will be carried out by a team consisting of those who designed and installed and tested the hardware and software. Subsystem commissioning will demonstrate that the subsystems meet requirements. Full interferometer commissioning leading to "first lock" will demonstrate the compatibility of subsystems, the overall integration of the full instrument, and the critical step of stable operation of each interferometer as a working instrument. This approach to commissioning is consistent with the Commissioning Stage described in the NSF Guidelines for Planning and Managing the MREFC Account.

Each subsystem has 4-8 months of scheduled commissioning time for its own test and integration phase, and then each complete interferometer undergoes 14-15 months of commissioning to reach the level of understanding and refinement required, culminating in the locking milestone for interferometer acceptance. Once all three interferometers have met this requirement Advanced LIGO will move on to the operations phase as a working gravitational wave detector.

## **Discussion of the “End of Project” criteria**

The achievement of the locked condition for several hours is a very stringent requirement. It means that there is a working interferometer with all subsystems performing as a single, stable instrument, with laser light circulating in the arm cavities, optical alignment at the required precision, control loops operating to stabilize the system, and both strain and diagnostic signals being read out.

Thus the formal MREFC project deliverables of three interferometers which have each achieved stable lock for several hours provides a firm foundation for and assurance that the full scientific potential of the instruments will be reached after a reasonable period of operations, consisting of both science running and activities to achieve increasing sensitivity.

The locked condition for LIGO interferometers is very much like the acceptance requirement traditionally used in projects to construct particle accelerators and colliders where the formal construction ends after an accelerated beam is demonstrated at a beam current that is significantly less than needed for full science capabilities. The achievement of the full beam current, stability, and emittance in such facilities takes place gradually during following period of operations.

We note here that the report of the NSF Baseline Review of Advanced LIGO (June 2006) endorses our definition of project completion. That report states: “The Project Completion Criteria proposed in the PEP (completion of subsystem acceptance and achieving lock for two hours) are an appropriate and clearly defined set of definitions that should avoid confusion. Achieving lock represents a demonstration of integrated operation of all of the subsystems and provides the basis for the optimization of sensitivity, which will follow as part of the operation of Advanced LIGO.”

## **The operations phase**

Once the commissioning of each interferometer is complete and the interferometer is accepted, the operations phase for each interferometer will begin and Advanced LIGO will have made the important transition from a construction project to a working gravitational wave detector.

Initial operations of Advanced LIGO lasting perhaps 6 months or so will consist mainly of testing, operations staff training, and research to identify and mitigate noise and improve sensitivity and robustness of operations. The next phase of operations for all interferometers will be a series of modest science runs alternated with periods of effort aimed at improvements of sensitivity and robustness of operations until the full design sensitivity is reached and long science runs can begin.

Like other large physics experiments (accelerators, fusion machines, etc.), there is considerable ‘tuning’ to be done once the basic instrument is in place. In LIGO there are many hundreds of servo loops whose multidimensional transfer functions needs to optimized; incursions into the vacuum system will probably be needed to iteratively find optimal optics placement; and many software elements will need refinement as we learn more about the instrument as-built. The effort is iterative, in part because reducing one noise source exposes others, and in part due to interactions between the subsystems. The various tunings of Advanced LIGO present different, and happily largely separable, challenges, and can be worked on in an order which most quickly leads to interesting astrophysics.

The plan for the operations-phase of Advanced LIGO will result in as much science-quality data for astrophysics research as possible while recognizing the complexity of the instrument and time it will take to bring it to the full design sensitivity at all frequencies. Thus, the interval from the end of the construction project to the achievement of full sensitivity includes significant intervals of science data taking, data analysis and astrophysics studies.

We note that the testing, refinement, user training, and engineering studies which follow the ‘first lock’ are well suited to the operations stage. There will be research efforts with the interferometers to understand new instrumental effects, their consequences and possible mitigation, a process that does not have the linear, predictable flow of a project, but rather the character of traditional physics research. We will also want, in this phase, to engage graduate students and postdocs for their unique qualities of focus and

imagination, but recognizing that their education and the nature of their activities are not well served by a hierarchical project-style management. During the operations phase we do not anticipate significant engineering or large-scale fabrication so capital costs are minimal and the procurement machinery of the project is no longer needed.

Once the inherent sensitivity of the interferometers is reached, lengthy science runs at full sensitivity will take place. Operations will be supported from an R & RA account and managed under a Cooperative Agreement.

NATIONAL SCIENCE FOUNDATION  
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January 12, 2007

Dr. Jay Marx  
Executive Director, LIGO Laboratory  
M/C 18-34  
California Institute of Technology  
Pasadena, CA 91125

Re: Advanced LIGO baseline review schedule for 2007

Dear Jay:

The purpose of this letter is to inform you of a schedule worked out by NSF's Physics Division and the BFA Office for final baselining of the Advanced LIGO project. It is also a formal request for preliminary information about the Advanced LIGO budget.

A letter from LIGO describing the status of Advanced LIGO budgeting must be received and two NSF reviews must be scheduled before funds are released for the project:

1. NSF needs preliminary input about any anticipated changes to Advanced LIGO's budget prior to the March 2007 Congressional budget hearings. A letter to the NSF Program Director detailing any schedule or budget changes, together with a remediation plan for incorporating the changes into Advanced LIGO's baseline plans, should be written as soon as possible after the release of the President's FY 2008 Budget Request to Congress. The letter should also contain a response to issues about Advanced LIGO's baseline plan raised by the May 2006 Baseline Review panel. NSF also requests an explanation as to why the definition of the end of the construction era—the achievement of a simultaneous lock for all three interferometers—is felt to be a reasonable one.
2. An external NSF review will be held in the June 2007 time frame to consider only changes in the baseline schedule and budget as presented to the May 2006 Baseline Review panel.
3. After Congress appropriates the funds for Advanced LIGO, but before the funds are released, a small review panel or an internal NSF inquiry will be held to finalize any further changes in Advanced LIGO's budget and schedule. Please note that the date for this review cannot be predicted at this time, but we will let you know with as much lead time as possible so that you can prepare.

NSF expects to be informed as soon as possible, regardless of the above schedule, of any changes made to Advanced LIGO's schedule or budget, as well as of any technical developments and any changes in project risk.

Barring substantial Congressional changes to the budget, we anticipate and hope that these reviews will not make excessive demands on the time and resources of LIGO personnel.

Sincerely yours,



Thomas F. Carruthers  
Program Director, MPS/PHY

cc: David Shoemaker, Advanced LIGO Project Manager  
Joseph L. Dehmer, Physics Division Director  
Mark Coles, Deputy Director - Large Facility Projects