LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

LIGO-M050303-00-P	*Advanced LIGO*	25 May 2006

Advanced LIGO
Project Execution Plan

Authors: Advanced LIGO Team

Edited by D. Coyne, P. Lindquist, J. Marx, D. Shoemaker, C. Wilkinson

This is an internal working note
of the LIGO Laboratory.

California Institute of Technology
LIGO Project – MS 18-34
1200 E. California Blvd.
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project – NW17-161
175 Albany St
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
P.O. Box 1970
Mail Stop S9-02
Richland WA 99352
Phone 509-372-8106
Fax 509-372-8137

LIGO Livingston Observatory
P.O. Box 940
Livingston, LA 70754
Phone 225-686-3100
Fax 225-686-7189

http://www.ligo.caltech.edu/

Advanced LIGO Project Execution Plan (PEP)

Table of Contents

1 Overview 5
1.1 Instrument sensitivity and astrophysical goals 6
1.2 Technical Description 7
1.3 Project Flow 8
2 LIGO Laboratory Organization 9
2.1 LIGO 9
2.2 Institutional responsibilities 10
2.3 LIGO Directorate 10
2.4 LIGO External Oversight Committee 11
2.5 LIGO Laboratory Advisory Mechanisms 11
2.6 LIGO Laboratory Internal Organization 12
2.7 The LIGO Scientific Collaboration 13
3 Advanced LIGO Project Organization 15
3.1 Advanced LIGO in the context of the LIGO Laboratory and the NSF 15
3.2 Advanced LIGO Project internal organization 15
3.3 Advanced LIGO advisory mechanisms 16
3.3.1 LIGO Program Advisory Committee 16
3.3.2 Advanced LIGO Change Control Board 16
3.3.3 Advanced LIGO Technical Review Board 16
3.3.4 Advanced LIGO Quality Assurance/Quality Control 17
3.3.5 Advanced LIGO Safety 17
3.3.6 Advanced LIGO Risk Management 17
3.4 LIGO Support Services – Business and Administration 17
3.5 Domestic and International Partners 17
4 Project Work Breakdown Structure 23
4.1 Facility Modification and Preparation 23
4.2 Seismic Isolation 24
4.3 Suspensions 25
4.4 Pre-Stabilized Laser 26
4.5 Input Optics 27

4.6 Core Optics 27
4.7 Auxiliary Optics 28
4.8 Interferometer Sensing and Control 29
4.9 Data Acquisition Systems 29
4.10 Data and Computing Systems 30
4.11 Installation and Testing 30
4.12 Project Management 31
4.12.1 Project Management and Controls 31
4.12.2 System Engineering and Integration 32
5 Baseline Project Definition 33
5.1 Project Cost Estimate 33
5.1.1 Basis of Estimate 33
5.1.2 Contingency Estimates 33
5.1.3 Total Project Cost in Base Year Dollars 34
5.1.4 Cost and Funding Profiles 37
5.2 Project Schedule 38
5.2.1 Schedule Estimates 38
5.2.2 Project milestones 39
5.2.3 Schedule 40
5.3 Staffing profile 43
6 Project Controls 43
6 Project Controls 44
6.1 Risk Assessment and Management 44
6.1.1 Risk Management Responsibilities 44
6.1.2 Risk Management Process 45
6.2 Earned Value Tracking 45
6.3 Configuration Management and Change Control 46
6.3.1 Document Control 47
6.3.2 Configuration Control 47
6.4 Contingency Management and Change Control 47
6.5 Quality Assurance and Quality Control 48
6.5.1 Responsibilities 48
6.5.2 Reliability, Maintainability, Availability 48

6.5.3 Quality Control ... 49
6.6 Business and Financial Controls ... 49
6.6.1 Cost Control ... 50
6.6.2 Subcontract Management ... 52
6.6.3 Procurement and Subcontracts ... 54
7 Environment, Safety, and Health Protection ... 55
7.1 Responsibilities ... 55
7.2 Environmental Protection ... 55
7.3 Safety and Health Protection ... 55
7.4 Employee Training ... 56
7.5 Documentation ... 56
7.6 Governmental Code Requirements ... 56
8 System Testing and Acceptance ... 57
9 Transition to Operations ... 58
10 Reporting and Reviews ... 59
10.1 Annual Report ... 59
10.2 Quarterly Progress Reports ... 59
10.3 Technical Reports ... 59
10.4 Other Reporting ... 60
11 Meetings and Reviews ... 61
11.1 Internal LIGO Meetings ... 61
11.2 The Program Advisory Committee ... 61
11.3 The External Oversight Committee ... 61
11.4 NSF Reviews ... 61
11.5 Workshops ... 61
12 GLOSSARY ... 62

1 Overview

Advanced LIGO is an upgrade to each of the three initial Laser Interferometer Gravitational-wave Observatory (LIGO) detectors. LIGO was conceived as an infrastructure to support a series of improving instruments, and Advanced LIGO will re-use the civil construction, vacuum equipment, and environmental monitoring system while replacing the detector components at the Hanford, Washington and Livingston, Louisiana Observatory sites. The Advanced LIGO design is the product of the LIGO Laboratory R&D program, and the focused effort of the LIGO Scientific Collaboration, informed by the experience from initial LIGO. Advanced LIGO will increase the sensitivity over initial LIGO by more than a factor of 10, and thus the volume searched and potential rate of signals by a factor of more than 1000. The available bandwidth is larger, and the frequency response tunable, to address a range of astrophysical sources of gravitational waves. It is anticipated from current astrophysical knowledge that there will be frequent observations of gravitational waves, allowing a broad exploration of heretofore inaccessible astrophysics, cosmology, and relativity. Advanced LIGO will observe in coordination with other gravitational-wave detectors.

The Advanced LIGO Project starts with a buildup phase in which components are fabricated and assembled; once a sufficient stock of elements is ready, the initial LIGO detector in one Observatory Site is decommissioned and installation commences. The second site follows shortly thereafter. The complete Advanced LIGO detector consists of three interferometers: one 4km instrument at the Livingston site, and two 4km instruments at the Hanford site. The instruments are taken through integration and test, with the prime Project objective met when each interferometer is capable of being brought reliably to an operational state ('locking') for multi-hour periods.

The United States National Science Foundation funds the project through the Major Research Equipment and Facilities Construction (MREFC) budget account. The Caltech-MIT LIGO Laboratory, with Caltech as the responsible fiduciary institution, will carry out the Project. Other members of the LIGO Scientific Collaboration (LSC), with NSF or other funding, will participate in all phases of the effort. Several International Partners are contributing significant equipment, manpower, and expertise: The UK contribution is the test mass suspension and some test mass optics, funded via PPARC, and the German contribution is the pre-stabilized laser, funded via the Max Planck Society. Operations of the LIGO Laboratory during and after the Advanced LIGO Project will be funded through the NSF Research and Related Activities (R&RA) budget account; these activities include observation with initial LIGO, research in further improvements in detectors, commissioning of Advanced LIGO, and the operation of, and observation with, Advanced LIGO.

1.1 Instrument sensitivity and astrophysical goals

The Advanced LIGO interferometer design allows tuning and optimization of the sensitivity both to best search for specific astrophysical gravitational-wave signatures and to accommodate instrumental limitations. To define the goal sensitivity of Advanced LIGO, a single measure is given: a strain sensitivity of 10^{-22} RMS, integrated over a 100 Hz bandwidth centered at the minimum noise region of the strain spectral density, a factor of 10 more sensitive than initial LIGO. This measure allows some margin with respect to our present best estimates of the possible sensitivity. Because new developments in astrophysics, through gravitational-wave detections and/or theory, may indicate a consensus for a change in focus and thus optimization of the detector, a request may be made to the NSF for a change in the definition of the goal sensitivity at a later time.

The specific starting configuration (narrow-band vs. broad-band) of the three interferometers of Advanced LIGO is best determined closer to the time of implementation. The changes to the optical system are relatively small, involving fixing the transmission of one in-vacuum suspended optic; multiple substrates are planned for this signal-recycling mirror. It is likely that we will have further information from either discoveries by the first generation of gravitational-wave detectors, and/or from a better understanding of the astrophysics, which will help in making a choice.

Advanced LIGO is designed to be a flexible platform, to evolve as technologies become available and as astrophysical insights mature. Narrowband or broadband operation is one specific variation which is in the Advanced LIGO baseline. Other modifications, such as using squeezed light to improve the sensitivity without increasing the optical power, are currently being pursued by the community, and can be considered as modifications or upgrades of Advanced LIGO as appropriate.

To obtain the maximum scientific return, LIGO is also planned to be operated as an element of an international network of gravitational wave detectors involving other long baseline interferometric detectors and acoustic detectors. Long baseline interferometric detectors are expected to be operated by the Virgo Collaboration at Pisa, Italy and by the GEO600 Collaboration at Hannover, Germany. Memoranda of Understanding to cover coordination of the observations during and after the Advanced LIGO Project are currently in discussion and will be established. Plans are also underway to establish long baseline interferometric detectors in Japan and Australia, and we will strive to coordinate with these efforts as well. Simultaneous observations in several systems improve the confidence of a detection. A global network of detectors will also be able to provide full information from the gravitational waves, in particular, the polarization and the source position on the sky.

1.2 Technical Description

The Advanced LIGO project scope is the fabrication and installation of three interferometer systems, each with 4 km long arms. Two of the interferometers are built within the LIGO Hanford Observatory infrastructure and the third is built within the LIGO Livingston Observatory infrastructure. The key elements in the technology are as follows:

Optical configuration: A power- and signal-recycled Fabry-Perot Michelson interferometer is used. The power recycling acts to impedance-match the input light to the optical losses in the interferometer. The signal recycling allows a state of resonance for the gravitational wave frequencies of interest to be selected, and to manage the power circulating in the interferometer. The Fabry-Perot cavities increase the interaction time of the light with the gravitational wave.

Light source and handling: A 180 watt Nd:YAG laser source is stabilized in frequency and intensity; the optics, modulators, and isolators have been developed to handle the resulting power densities. A high input light power is used to allow precise interrogation of the interferometer fringe, as limited by the quantum noise (radiation pressure and photon shot noise). The input light is filtered by transmission through a mechanically isolated in-vacuum triangular cavity and mode-matched to the arm cavities with a reflective telescope. An output mode cleaner cleans the output beam, which is detected with in-vacuum photodetectors.

Optics: The test masses are made of fused silica, 40kg in mass, 32cm diameter; the significant mass reduces the motion due to the photon pressure. Dielectric coatings have been developed which are low in optical absorption (to reduce thermal focusing) and low in mechanical loss (to reduce the thermal noise contribution). A thermal compensation system further reduces the focusing and allows operation at a range of laser powers.

Mechanical suspension and isolation: The main optics are suspended via a quadruple pendulum to provide mechanical filtering and multiple points of position and angle actuation. The final suspension stage employs fused silica fibers, to reduce the thermal noise. A combination of high-gain servos, and passive isolation approaches, reduces both the in-band motion of the optics and the motion at the lower control frequencies.

Signal and Data handling: Analog signals are conditioned and converted close to the sensors. The control systems for the interferometer are realized using digital real-time servos. All data can be centrally monitored and all systems centrally controlled; excitation and signal injections can be performed for diagnostics and calibrations. Data collection and archiving of the strain signals, along with auxiliary control information and environmental data, is performed. Computing clusters sized for the anticipated analysis tasks are part of the project.

Infrastructure: The Advanced LIGO interferometers will be housed in the vacuum equipment and use the beam tubes currently in use for initial LIGO. The vacuum chamber currently at 2km from the vertex at Hanford, used for the half-length interferometer in initial LIGO, will be moved to the 4km point to permit two 4km arm-length instruments. Clean rooms and materials handling and storage will be adapted to Advanced LIGO needs. Otherwise, the infrastructure at the sites will remain unchanged.

While all of the initial LIGO interferometer components, and control and data systems, are planned to be replaced, where possible, reuse of components (e.g., optical tables, optical components) will be made.

1.3 Project Flow

The research and development program preceding the Project provides final designs. There are two principal considerations which drive the Project flow: a desire to minimize the down-time of the observatories, and limits on the highly-skilled manpower needed to assemble, install, and test the equipment.

As soon as Project funds (assumed FY2008) are available, the Advanced LIGO Project will start to fabricate the subsystem elements and stockpile them at the Observatories. Where practical, subsystems are tested stand-alone.

Once a critical mass of subsystems is ready for installation, one initial LIGO site (Livingston) is taken off-line, and the interferometer components are removed. The new components are installed.

After the first phase of installation in the first interferometer is complete and successful, involving the primary mechanical elements, and the skilled manpower and equipment are ready, the second site (Hanford) is taken off-line, components removed, and installation commences.

The Livingston site will be the first to be complete in installation. Integration and test follow, bringing the instrument to the point where all subsystems are functional and the complete instrument can be brought into the operational ‘locked’ mode (length control servo controls functioning, usable strain signal output) for multi-hour intervals. The instrument will be accepted.

Each of the two Hanford interferometers will also be integrated and tested, and when all subsystems are functional and each instrument can be ‘locked’ for multi-hour intervals, the instruments will be accepted, and the primary objective for the Advanced LIGO Project will be fulfilled.

Just-in-time purchase and implementation of the data analysis computational resources will be undertaken, probably shortly after the acceptance of the interferometers.

After acceptance of the interferometers, commissioning of the instruments will proceed under the LIGO Laboratory Operations NSF Research and Related Activities (R&RA) funded effort.

2 LIGO Laboratory Organization

The Advanced LIGO (ADL) Project is managed and staffed as part of the LIGO Laboratory. The mission of the LIGO Laboratory is to support the LIGO Scientific Collaboration (LSC) by observing gravitational wave sources and opening new field of GW Astronomy; operating the LIGO facilities to support the national and international scientific community; developing advanced detectors and techniques that push the limits of interferometer performance for GW science; supporting scientific education and public outreach related to gravitational wave astronomy; and successfully carrying out Advanced LIGO.

2.1 LIGO

The organization chart for LIGO, comprising the LIGO Laboratory and the LSC, appears in Figure 1 below.

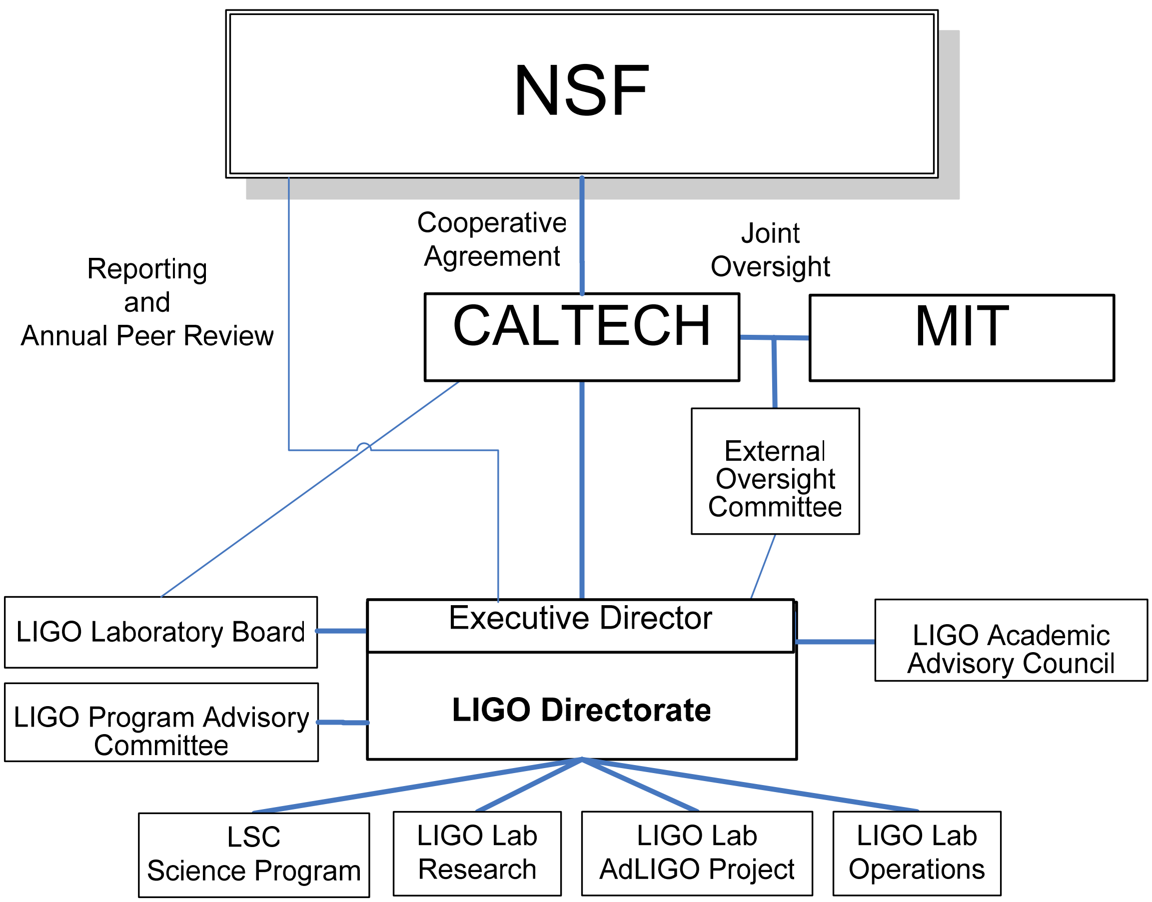


Figure 1: Overall Organization of the LIGO Laboratory and the LIGO Scientific Collaboration in relation to the NSF and the host institutions.

2.2 Institutional responsibilities

The LIGO Laboratory is operated by Caltech and MIT under a cooperative agreement between NSF and Caltech with MIT as a subcontractor.

Caltech is accountable to NSF for the performance of the LIGO Laboratory, as described in the LIGO Annual Work Plan. Caltech and MIT are responsible for staffing the Laboratory, providing institutional support and ensuring adequate oversight of the execution and performance of the program. Caltech's Office of Sponsored Research is responsible for matters between Caltech and NSF that pertain to the administration of the terms and conditions of the Cooperative Agreement and will accomplish this through formal communications with the NSF Division of Grants and Agreements. Legal review and matters related to real property and property management will be the responsibility of the Caltech Legal Counsel reporting to the President and the Caltech Vice President for Business and Finance, respectively.

LIGO activities at Caltech are part of the Division of Physics, Mathematics and Astronomy (PMA) through which academic appointments and educational matters are administered. The Division also provides administrative and logistical support to LIGO and oversight of the Caltech effort on LIGO.

The MIT roles and responsibilities are defined through a Memorandum of Understanding and subcontract with Caltech. The MIT subcontract is subject to NSF review. The MIT administration shares responsibility with the Caltech administration for overall oversight of the execution and performance of the LIGO program through representatives on the LIGO Oversight Committee. The MIT administration is also responsible for oversight, staffing and support of the MIT LIGO Group and for insuring that it successfully meets its institutional commitments. It is the policy of the LIGO Laboratory to have a fully integrated MIT participation with institutional boundaries minimized.

At MIT, academic appointments and educational aspects of LIGO are administered through the Department of Physics; research activities are supported through the MIT Kavli Institute of Astrophysics and Space Research. The Department of Physics and the MIT Kavli Institute of Astrophysics and Space Research provide oversight of the MIT effort on LIGO and they report to the President of MIT through the Dean of Science.

2.3 LIGO Directorate

The LIGO Directorate consists of the LIGO Executive Director, the LIGO Laboratory Deputy Director and the Spokesperson for the LIGO Scientific Collaboration (LSC).

The LIGO Executive Director has overall responsibility for LIGO. The Director’s primary responsibility is to ensure the development and implementation of the LIGO program in a timely and cost effective manner with the goal of detecting gravitational waves and carrying out a program of gravitational wave astronomy. The Deputy Director is primarily responsible for executing the LIGO Laboratory program and for organizing and directing the Laboratory team composed of Caltech and MIT staff. The Executive Director is the principal point for communication and interaction with NSF, through its LIGO Program Manager. The Executive Director is also responsible for maintaining interactions and collaboration with the scientific community (both national and international). The Executive Director and the Deputy Director are fully informed in regards to all major issues and are mutually involved in the decision making as appropriate.

The LIGO Scientific Collaboration (LSC) Spokesperson is a key member of LIGO Directorate. As a member of the LIGO Directorate the LSC Spokesperson is responsible to assure effective integration of the LSC with LIGO Laboratory so that the efforts of the LSC in data analysis and other aspects of the LIGO scientific program can be planned and carried out in a manner that maximizes the contribution to the scientific goals of LIGO. The LSC Spokesperson is involved in the decision making as appropriate and shares many of the responsibilities with the Executive Director and Deputy Director.

2.4 LIGO External Oversight Committee

The presidents of Caltech and MIT have established a LIGO Oversight Committee, chaired by a member appointed by the Caltech President and composed of three members from each of Caltech and MIT and four members from other key “stake holder” LIGO Scientific Collaboration (LSC) institutions as well as two nonvoting technical representatives elected by the LSC. The Oversight Committee reports to the presidents through the Chair of Physics, Mathematics and Astronomy at Caltech and the Dean of Science at MIT. It regularly provides review of LIGO program status and progress as required. The Oversight Committee functions under a formal written charge.

The primary responsibilities of the External Oversight Committee are to assure that management of the LIGO is consistent with Caltech and MIT policies and procedures, to monitor the scientific, financial and schedule status of all significant LIGO activities, and to provide recommendations to ensure that the program has adequate institutional support. The Oversight Committee also provides oversight for the LSC activities within LIGO and reports to and advises other major “stakeholders” in the LIGO effort. The LIGO Executive Director reports progress on a periodic basis to the LIGO Oversight Committee.

2.5 LIGO Laboratory Advisory Mechanisms

The LIGO Laboratory Directorate receives advice on a periodic basis from three groups:

- The LIGO Program Advisory Committee (PAC),
- The LIGO Laboratory Board (LLB), and
- The LIGO Academic Advisory Council (LAAC).

The LIGO Program Advisory Committee (PAC) is the principal source of advice to LIGO on scientific policy, technical choices, support of the scientific community and organizational matters. It provides peer review of scientific and technical proposals for the scientific use of LIGO. The Directorate provides these reviews, and an analysis of the priority and impact of these proposals on LIGO, to the NSF for use in making decisions on disposition of proposals.

The LIGO PAC will be specifically charged to advise the Advanced LIGO Project Leader on Advanced LIGO issues, and the membership of the PAC will be chosen to ensure that expertise is available in the PAC for this role. A member will be designated as the Subcommittee Chair for Advanced LIGO.

The Committee meets several times per year and will be asked for advice through a written charge provided by the LIGO Executive Director. The Committee members are appointed by the LIGO Executive Director in consultation with the Deputy Director, the LSC Spokesperson, the Advanced LIGO Leader, and the PAC Chair.

The LIGO Laboratory Board is advisory to the LIGO Laboratory Directorate. The LIGO Directorate consults with and is advised by the LIGO Laboratory Board concerning significant decisions affecting the LIGO Laboratory as well as significant issues pertaining to the institutional interests of Caltech and MIT. The membership of the Board consists of two members appointed by Caltech, two members appointed by MIT, the LSC Spokesperson and one other member designated by the LSC Spokesperson, and confirmed by the LSC Executive Committee (described in the LSC Charter and Bylaws[1]).

The LIGO Academic Advisory Council advises the LIGO Executive Director and Directorate on issues related to education of students and postdocs who are participating in LIGO and the quality of the education they receive through their participation in LIGO. The LIGO Academic Advisory Council membership consists three faculty members who are involved in LIGO, one from Caltech, from MIT and another LSC institution. Members are chosen by the LIGO Executive Director with advice from the LSC Spokesperson, the LIGO Laboratory Deputy Director and the leader of the MIT LIGO group and serve for a 2-year term.

2.6 LIGO Laboratory Internal Organization

The LIGO Laboratory is organized around a mixture of site-based groups at Caltech, the two LIGO observatories and at MIT, and several Laboratory-wide groups. The Advanced LIGO Project is a well defined functional group within the LIGO Laboratory. There is significant overlap in the group memberships. Each group reports to the Directorate and is led by a Group Leader and, as needed, a Deputy Group Leader with these positions serving as line management for the respective group. Each group is represented on the Laboratory Executive Committee.

Staff assignment to a functional group represents the principal assignment for each staff member. A matrix approach is then used to assign personnel from the functional groups to staff the various activities of LIGO Laboratory including the Advanced LIGO Project.

To allow key LIGO Scientific Collaboration members to assume positions of responsibility in LIGO Operations and especially for Advanced LIGO, Visiting Associate in LIGO positions have been created at Caltech.

[1]LSC Charter: LIGO M980279; LSC Bylaws: LIGO M050172

At Caltech, there are site-based groups which address Optical and Mechanical Design, Control and Data systems, and the Caltech Science group which spans instrument and astrophysics interests. Members participate in the Laboratory-wide Groups via the matrix approach.

The MIT Group is a separate functional group, participating actively in all aspects of the LIGO Laboratory program as a broad science group. Members participate in the Laboratory-wide Groups via the matrix approach.

The Hanford Observatory and the Livingston Observatory are also organized as separate functional groups within the LIGO Laboratory. The staff at each Observatory is structured to support operations, maintenance and the scientific program. During some periods of Advanced LIGO installation at the observatories, normal operations will be interrupted and a significant number of site personnel will be available to support the Advanced LIGO Project.

2.7 The LIGO Scientific Collaboration

LIGO is a national facility operated for the cognizant scientific community, organized as the LIGO Scientific Collaboration (LSC), now comprising approximately 500 members (including LIGO Laboratory scientists) from 40 institutions from the United States and eight foreign countries. The LSC has its own internal governance and the LSC Charter and Bylaws codify the responsibilities and privileges of LSC membership.

The LSC and the LIGO Laboratory are integrated into a single organizational entity effectively bringing the LSC under the umbrella of the LIGO in order to strengthen overall planning and execution of data analysis and other LSC responsibilities for the LIGO science program without changing the internal structure of the LSC. This integrated structure is also essential to assure that LSC involvement in the Advanced LIGO Project can take place in the context of LIGO Laboratory project planning and controls.

LSC activity Memoranda of Understanding (MOUs) are established between each member institution in the LIGO Scientific Collaboration (LSC) and the Laboratory. Attachments to the LSC MOUs define requirements and the work to be accomplished for the following year. At the end of each year, each group reports accomplishments relative to the plan. The LSC reports to the NSF through the LIGO Directorate and is reviewed annually by the NSF external panel as a part of the LIGO Laboratory review.

In general, individual LSC groups propose and receive their research funding directly from the NSF or their national funding agency. Under this arrangement, it is important that the groups be able to add value to the Advanced LIGO Project by participating as volunteers in all phases of the Advanced LIGO Project from design to testing.

However, specific groups will carry the specific responsibility for a delivery (some combination of design, fabrication, installation, integration, and test) of Advanced LIGO subsystems or parts thereof, and this will be undertaken either via contributions (when non-NSF funding is available) or via subcontract from the LIGO Laboratory (covered by the NSF Advanced LIGO grant to Caltech). For these activities, an Advanced LIGO MOU will be prepared between the group and the LIGO Laboratory which covers this

Project scope and ensures adequate oversight and control by the Advanced LIGO management for this scope.

3 Advanced LIGO Project Organization

The LIGO Laboratory has established a separate organization within the Laboratory to carry out the Advanced LIGO Project. The organization of the Advanced LIGO program is represented in Figure 3. This organization is responsible for the planning, preparations, execution, and reporting of the Advanced LIGO Project. Although some personnel such as the project planning and controls staff are hired only for the duration of the Advanced LIGO Project and are directly assigned to this organization, the majority of Advanced LIGO personnel will be 'matrixed' to the project organization from other LIGO Laboratory groups and from the LIGO Scientific Collaboration.

When the project ends and Advanced LIGO moves into the commissioning and operations phases, the organization will transition from a construction-oriented organization to an operational organization.

3.1 Advanced LIGO in the context of the LIGO Laboratory and the NSF

The Advanced LIGO Project is a structure set up in the LIGO Laboratory to carry out the Project, and thus the relationship of the Project to the host institutions and the NSF is defined via the LIGO Laboratory Charter. The Advanced LIGO Project Leader reports to the LIGO Executive Director, and all communication of substance between the LIGO Laboratory and the Advanced LIGO Project Organization will include the Advanced LIGO Project Leader. While it is planned for there to be significant contact between the management of Advanced LIGO and the NSF Advanced LIGO Program Office, all official NSF communication on Advanced LIGO is via the LIGO Executive Director.

The LIGO PAC (see above) advises the Advanced LIGO Project Leader, and the Project Leader participates in defining the charter given to the PAC on questions relevant to the Advanced LIGO Project.

3.2 Advanced LIGO Project internal organization

The organization follows the Work Breakdown Structure of the Advanced LIGO Project, with "lead personnel" indicated though the detector subsystem level; please see Figure 2. The Project Leader reports to the LIGO Laboratory Executive Director. The Leader supervises the Project Manager and the System Engineer, and this senior management group runs the project. For each project subsystem, a lead engineer and a lead scientist are designated, with one acting as the subsystem leader. The definition of these positions is given in Table 1. In several cases, a leader for a subset of related or integrated subsystems has been designated to coordinate activities within those subsystems. The assignment of staff (engineers, scientists, technicians, etc.) below the subsystem "lead personnel" are not shown in the organizational chart; these assignments will in general change with time and project needs.

The Advanced LIGO Senior Management consists of the Project Leader, Project Manager, and Systems Engineer. This group will meet at least weekly (by telephone/video). The Project Leader will meet at least weekly (by telephone/video) with the LIGO Lab Directorate.

3.3 Advanced LIGO advisory mechanisms

3.3.1 LIGO Program Advisory Committee

As noted above, the LIGO Program Advisory Committee (PAC) advises the Advanced LIGO Leader, and the Leader participates in forming the charge to the PAC on Advanced LIGO issues. The composition of the PAC will be made in consideration of the needs for technical and organizational advice for the Project.

3.3.2 Advanced LIGO Change Control Board

Changes in the Advanced LIGO budget baseline are initiated through a documented request submitted by the Subsystem Leader to the Project Manager, who chairs the Advanced LIGO Change Control Board. A recommendation is made to the Project Leader, who holds the project contingency. Please see section 6.3 for more detail.

3.3.3 Advanced LIGO Technical Review Board

Changes in the Advanced LIGO technical baseline are initiated through a documented Technical Review request from a subsystem manager or the Project management to the System Engineer, who chairs the Advanced LIGO Technical Review Board (AdLTRB). Requests are required for all technical changes with impact on the scope or performance of the Advanced LIGO detectors, or technical changes whose cost impact exceeds $50,000; subsystem leaders are also encouraged to bring other complex technical issues to the TRB.

The System Engineer logs each request and schedules meetings of the Technical Review Board (AdLTRB) to conduct reviews of open requests. The AdLTRB is an ad-hoc board, with membership from within and external to the Project (and Laboratory) as deemed appropriate by the System Engineer for the question at hand. The System Engineer is responsible for preparing the agenda and meeting minutes. The AdLTRB reviews each request and makes recommendations to the AdL Leader. The System Engineer maintains a log of the status of all Technical Review requests and retains a file of all TRB recommendations in the LIGO Document Control Center (DCC).

If the TRB recommends a technical change which requires a change to one or more cost accounts in excess of the threshold for CCB approval, then the Subsystem Leader(s) that manages the associated cost account(s), submits a request to the CCB for approval (see sections 3.3.2 and 6.4).

If a technical baseline change is approved, the change will be incorporated into the Technical Baseline document and the impact on performance, scope, and subsystems recorded in the appropriate system and subsystem technical documentation.

Any change impacting the overall Advanced LIGO performance or scope will be brought to the attention of the NSF via the LIGO Laboratory Directorate for their approval.

3.3.4 Advanced LIGO Quality Assurance/Quality Control

The Quality Assurance Program, as applied to the Advanced LIGO Project, encompasses Reliability, Maintainability, Interferometer Availability, and Quality Control. QA is a line management responsibility represented by the QA officer who reports to the Project Manager. Please see section 6.5 for a description.

3.3.5 Advanced LIGO Safety

See Section 7, Safety and Health Protection, below.

3.3.6 Advanced LIGO Risk Management

Risks are managed through the Risk Management Team, chaired by the Project Leader, which maintains and regularly reviews a threat list and implements mitigation actions. Please see section 6.1 below.

3.4 LIGO Support Services – Business and Administration

The Advanced LIGO Project receives support for its business activities from the LIGO Laboratory Business Office and the MIT and Caltech Institutional administrative services. The Laboratory Business Office is supported by the LIGO Laboratory Operating Cooperative Agreement in this role.

3.5 Domestic and International Partners

The Advanced LIGO Project is the result of contributions in concepts, design, and instrument science from the greater LIGO Scientific Collaboration (LSC). Several of the groups of the LSC wish to continue their contribution into the Project phase by taking on significant responsibilities for deliverables to Advanced LIGO. Two models for this engagement will be used.

International Partners: LSC Groups who have received commitments of funds from their non-NSF funding agencies to make a material contribution of deliverables to Advanced LIGO. These deliverables can take the form of any or all of manpower, designs ready for fabrication, and equipment for installation.

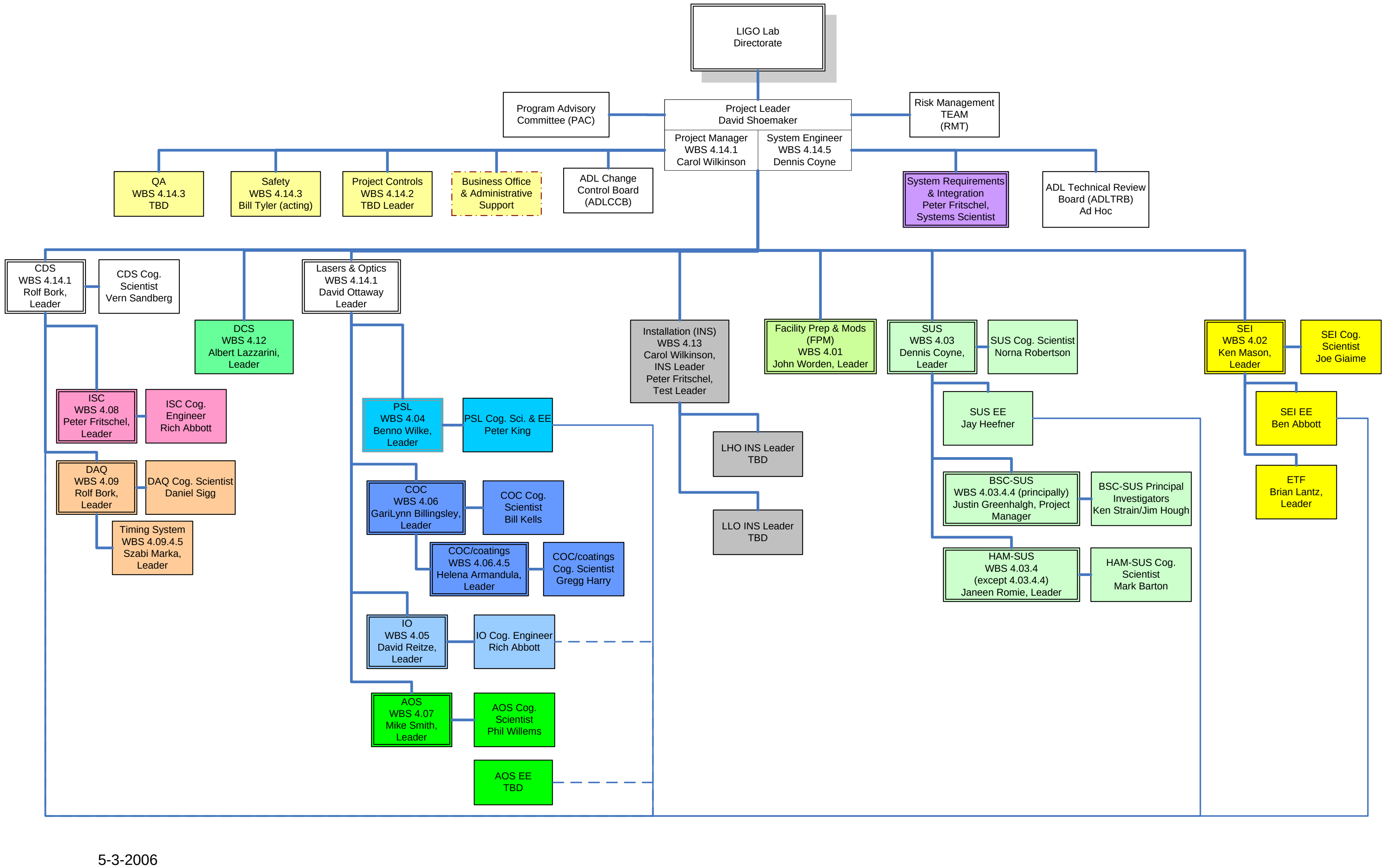
Capital Partners: LSC Groups who wish to subcontract from the LIGO Laboratory to produce deliverables for Advanced LIGO, adding value from their institutional support and/or funding agencies. These deliverables can take the form of any or all of manpower, designs ready for fabrication, and equipment for installation.

In both cases, a Memorandum of Understanding (MOU) between the LIGO Laboratory, the LSC group(s), and the institutions housing the group(s) will be established. This MOU describes the deliverables and any cost implications of the arrangement, and indicate clearly the responsible individuals for the agreement. All such arrangements are cost-neutral or cost-advantageous to the Project (including oversight of the activity by the Project).

The NSF will be informed of all such MOUs, and in particular attention will be drawn to any Advanced LIGO scope which is paid for by others to adjust, if necessary, the Advanced LIGO NSF support appropriately.

To manage each non-Lab Partner, an individual in the Lab will be assigned a Liaison responsibility. There will be weekly Lab Liaison contact with the Partners (in general through normal weekly meetings for relevant subsystems), and monthly contact between the leaders of the Partner group and the Advanced LIGO senior management. We will incorporate selected, mutually agreeable and useful milestones into the Advanced LIGO schedule plan. The normal progress reporting and performance tracking process will be followed, but at the milestone rather than the activity level. Earned value and variance reports will be generated at the milestone level.

Figure 2: Advanced LIGO Project Organization



Project Leader

Scope: The Advanced LIGO Construction Project.
Reports to: The LIGO Laboratory Executive Director
Responsibilities:

- Accountable for the Advanced LIGO Project and its deliverables
- Define and modifies overall strategy for completing project
- Assures all QA, safety, and reporting requirements are met
- Advocates for Advanced LIGO in the context of the Laboratory

Authority:

- Provides leadership for Advanced LIGO in Lab and LSC
- Manages project contingency
- Acts on advice from the Advanced LIGO CCB, TRB
- Chairs the RMT (Risk Management Team)
- Directly supervises the Advanced LIGO Project Manager and Systems Engineer
- Has approval (signature) authority on all accounts (to a limit of $1,000,000 for each purchase order)

Project Manager

Scope: The Advanced LIGO Construction Project
Reports to: The Advanced LIGO Leader
Responsibilities:

- Develops & Maintains WBS, schedule, cost estimate, and resource plan
- Reports on performance measures to the Advanced LIGO Leader
- Prepares quarterly progress reports for the NSF
- Implementation of Advanced LIGO safety policies, direction of personnel engaged in safety concerns
- Implementation of Advanced LIGO QA/QC

Authority:

- Directs the efforts of the subsystem leaders to manage project scope, cost, and schedule goals
- Directs the Advanced LIGO project controls office and its personnel
- Chairs the Advanced LIGO CCB
- Has approval (signature) authority on all accounts (to a limit of $250,000 for each purchase order)

Project Systems Engineer

Scope: The Advanced LIGO Construction Project
Reports to: The Advanced LIGO Leader

Responsibilities:

- Oversees all engineering for Advanced LIGO, including systems engineering
- Manages interface definition and control, and configuration control
- Performs/directs system tradeoffs in concert with the Systems Scientist
- Makes technical/engineering decisions at the system level
- Decides on technical readiness for reviews
- Decides on acquisition/procurement strategy in concert with Advanced LIGO Project Manager and Leader
- Delivers all system engineering documentation

Authority:

- Final approval of all design configuration controlled documentation, standards, subsystem interface agreements
- Direction of all system engineering staff and resources

- Chairs the Advanced LIGO TRB
- Has approval (signature) authority on all accounts (to a limit of $250,000 for each purchase order)

System Scientist

Scope: The Advanced LIGO Construction Project
Reports to: The Advanced LIGO Leader

Responsibilities:

- Oversees all subsystem scientific requirements for Advanced LIGO
- Creates and evaluates proposals to changes in the Reference Design for TRB consideration
- Directs the systems-level modeling and simulation effort
- Manages inter-subsystem trades of requirements
- Performs/directs system tradeoffs in concert with the Systems Scientist
- Delivers all system-level requirements documentation

Authority:

- Final approval of all subsystem requirements

Integrated Subsystems Systems Leader

Scope: Limited to a designated set of related subsystems
Reports to: The Advanced LIGO Project Manager

Responsibilities:

- Manages/directs the overall assigned resources (hardware and personnel) to perform the tasks for the designated set of subsystems
- Acts as point-of-contact for the leaders of the designated set of subsystems and the Advanced LIGO Management for reporting against the plan. Analyzes progress against the plan for the subsystems to optimize the assigned resources and to help to identify problems and solutions across the designated set of subsystems
- Participates in the Interface Working Group (IWG)
- Participates as reviewer or reviewee in all reviews of the designated set of subsystems
- Oversees major subcontracts for the designated set of subsystems
- Advises subsystem leaders on acquisition/procurement strategy (e.g., make or buy)

Authority:

- Manages/directs the overall assigned resources (hardware and personnel) to perform the tasks for the designated set of subsystems
- Has approval (signature) authority on all supervised subsystem accounts (to a limit of $100,000 for each purchase order).

Subsystem Leader[2]

Scope: Limited to the associated subsystem.
Reports to: The LIGO Project Manager
Responsibilities:

- Defines & maintains the subsystem development plan
- Manages/directs the assigned resources (hardware and personnel) to perform the tasks
- Tracks and reports progress against the plan to management
- Makes decisions (programmatic and technical) at the subsystem level based on advice from staff (in particular the cognizant engineer and cognizant scientist)

[2] In the UK organization, these "Subsystem Leader" is referred to as "Project Manager" for their subset of the project.

• Represents the subsystem in interface discussions as part of the Interface Working Group (IWG), or delegates this responsibility. • Decides on the readiness for formal and informal subsystem reviews and organizes these reviews • Manages major subcontracts (as a Technical Monitor), or delegates this responsibility • Decides on acquisition/procurement strategy (e.g., make or buy) Authority: • Has approval (signature) authority for all configuration controlled documents authored/originated by the associated subsystem. • Has approval (signature) authority for interface agreements in the Interface Control Document (ICD). • Has approval (signature) authority on all subsystem accounts (to a limit of $50,000 for each purchase order).
Cognizant Engineer[3] Scope: Limited to the associated subsystem. Reports to: The Subsystem Leader Responsibilities: • Oversees all technical aspects of the subsystem implementation • Advises the Subsystem Leader of technical or engineering issues • Oversees all form, fit, function assessment (CAD, simulation and test) • Performs trade studies and value engineering as deemed necessary • Provides input to the Subsystem Leader for decisions (programmatic and technical) Authority: • Has approval (signature) authority for all configuration controlled documents authored/originated by the associated subsystem. • Has approval (signature) authority on all subsystem accounts (to a limit of $5,000 for each purchase order).
Cognizant Scientist[4] Scope: Limited to the associated subsystem. Reports to: The Subsystem Leader Responsibilities: • Establishes the subsystem requirements in collaboration with the System Scientist • Advises the Subsystem Leader of any science or performance related issues • Oversees all performance related assessment (via analysis and test) • Provides input to the Subsystem Leader for decisions (programmatic and technical) Authority: • Has approval (signature) authority for all configuration controlled documents authored/originated by the associated subsystem. • Has approval authority for all critical (e.g., supporting design reviews) science and performance documentation (technical memos, test reports, etc.)

Table 1: Advanced LIGO Project Roles and Responsibilities

[3] In the UK organization, there is no equivalent "Cognizant Engineer" defined.
[4] In the UK organization, the "Project Scientist" is equivalent to the LIGO Lab "Cognizant Scientist".

4 Project Work Breakdown Structure

The Work Breakdown Structure (WBS) for the Advanced LIGO Project is divided into twelve major subsystems or elements. Summary descriptions of each subsystem are given in this section. A detailed Advanced LIGO Project Work Breakdown Structure is to be maintained as controlled document in the LIGO Document Control Center.

The Project work plan is aimed at accomplishing the LIGO Laboratory goal of minimizing the amount of downtime for scientific observations and optimizing the use of limited key personnel. There are three phases of activity for each observatory site: fabrication and assembly, installation, and integration and testing. Development activities through final design are completed outside the project before production begins. During the fabrication and assembly phase, sites are prepared and components are fabricated and assembled until a sufficient stock of elements is ready for installation for one interferometer. The initial LIGO detector in one observatory site is then decommissioned and installation commences. The second site continues observations until the remaining detector components are ready approximately nine months later. The delay in installation at the second site optimizes the deployment of limited key personnel and experts by allowing tasks at the first site to be completed before commencing similar activities at the second site. The three installed instruments, one four kilometer interferometer at the Livingston Observatory and two at Hanford, are integrated and tested. The Project is complete when all equipment is installed, tested, and integrated, and each interferometer is capable of being brought to an operational state (‘locking’) for multi-hour periods.

4.1 Facility Modification and Preparation

The Facility Modification and Preparations (FMP) subsystem encompasses modifications to the permanent facility infrastructure and the site preparations required for the assembly and installation of new detector instruments. It does not include other facility additions or modifications carried out as normal operations or maintenance tasks.

Preparation for on-site assembly of detector components includes providing clean assembly and staging space, materials cleaning and handling equipment, and soft wall clean rooms. The staging, inventory control, and storage of parts and completed sub-assemblies are the responsibilities of this subsystem leader.

Preparation for installation includes the development of installation and testing plans, the design and fabrication of installation tooling, and the procurement of soft wall clean rooms for installation. Other deliverables are the design and fabrication of vacuum beam tube replacements for two modifications to the existing vacuum infrastructure. The conversion of the two-kilometer interferometer at Hanford to four kilometers will require replacement spool pieces in the original locations when the existing mid-station chambers are moved to the end stations. Larger diameter beam tubes in the input and output optics sections are required to accommodate the larger, Advanced LIGO optical beams. Actual installation of replacement beam tube sections occurs under the Installation subsystem.

Work Plan

Preparation of clean assembly space and the purchase of assembly clean rooms and cleaning equipment and supplies must be completed in time for commencement of assembly in late FY2008**.** Contracts for these preparations will be awarded as soon as project funding is available. Procurement of installation tooling and vacuum equipment replacements must be completed in time for decommissioning activities commencing in FY2011 and can be completed as personnel and funds become available. This subsystem is complete when all assembly staging is finished, the installation and vacuum equipment materials and hardware for both sites have been procured, and the installation planning for both sites is complete.

4.2 Seismic Isolation

The seismic isolation subsystems serve to attenuate ground motion in the observation band (above 10 Hz) and also to reduce the motion in the control band (frequencies less than 10 Hz). They also provide the capability to align and position the load. The Seismic Isolation (SEI) subsystem for Advanced LIGO consists of the production of hydraulically-actuated external pre-isolators (HEPI) as well as active internal seismic isolation (ISI) systems located inside the vacuum chambers. It delivers all components of active and passive elements including programmable controls items, and software specific to local control of this subsystem. It does not include general controls for the interferometer, nor shared controls infrastructure.

The deliverables for the external pre-isolator include the production of twenty-one HEPI units ready for installation based on an existing and operating design. The total complement of HEPI units is thirty, with ten installed in each interferometer. Nine Advanced LIGO design HEPI units are already installed and operating at the Livingston Observatory, leaving twenty-one units remaining to be produced.

The deliverables for the internal seismic isolation (ISI) entails the production of installation-ready units for the test mass suspension chambers (BSC) and for the cavity and auxiliary optics chambers (HAM). There are five each of these chambers in each of the three interferometers, leading to a total of fifteen BSC ISI units and fifteen HAM ISI production units. Production designs are completed in the development phase and are not a part of this project.

Work Plan

Seismic Isolation production will be staged to match available funding, personnel, and assembly space. Production subcontracts for the HEPI components will be placed as soon as funding becomes available in FY08. Assembly of the units will take place at the various LIGO sites and is scheduled to start in late FY2008. Clean room space is not required for HEPI assembly. Production of the BSC ISI components will commence as soon as funding becomes available in FY2009. Production of the HAM ISI seismic subsystems will follow in late FY2009. Production start dates for both ISI series rely upon the completion of the final design in the development program outside the project envelop. The delivery of the installation-ready HAM ISI units is on the critical path for maintaining the installation start dates. This subsystem is complete when all pre-assembled and tested seismic isolation systems have been delivered to the sites, ready for installation.

4.3 Suspensions

The suspension forms the interface between the seismic isolation and the suspended optics. It provides seismic isolation and the means to control the orientation and position of the optic while minimizing the amount of thermal noise from the suspension elements.

The Suspensions (SUS) subsystem includes all hardware for Advanced LIGO suspensions, including intermediate masses, suspension fibers and attachment to the optics. It contains all physical hardware for sensing and control (including the electrostatic actuator, but not the photon actuator) of suspended masses. It includes all components of active elements including programmable controls items, and software specific to local control of the suspensions. It does not include general controls for the interferometer, nor shared controls infrastructure. It does not include controls hardware and software specific to other suspended elements provided by other subsystems.

Responsibility for this subsystem is shared by the LIGO Laboratory and the Advanced LIGO United Kingdom (ALUK) group, a consortium of the University of Glasgow, University of Birmingham, and Rutherford Appleton Laboratory. Scope documents and an MOU[5] detail the responsibilities of ALUK and LIGO with respect to the suspensions systems. ALUK is responsible for supplying the test-mass suspensions for Advanced LIGO, using UK funds granted in 2003 by the Particle Physics and Astronomy Research Council (PPARC). Other suspensions are the responsibility of the US members of SUS. The ALUK efforts are integrated into the overall Advanced LIGO schedule but the costs are not included in the NSF MREFC funding baseline.

<u>Work Plan</u>

The ALUK test mass suspension production is scheduled to start in mid FY07, with delivery of all hardware to the observatory sites by early FY2009. LIGO personnel will be trained in the assembly and testing and will perform the majority of the test mass suspension assembly. The ALUK responsibility for this subsystem element ends when all hardware has been delivered to the sites, LIGO personnel have been trained, and the integrated first article testing with the seismic isolation system is completed. The test masses themselves will not be installed until installation phase. The US production of the suspensions will be staged to match available funding, personnel, and assembly space. It starts as soon as FY2008 funds are accessible with the fabrication of the assembly tooling, fibers and attachments, penultimate masses, and the US component of the test mass suspension electronics. Assembly of the UK produced test mass suspensions, as mentioned above, starts in FY09. Fabrication of the HAM cavity and auxiliary suspensions starts in mid-to-late FY2009, with assembly at the sites starting in FY2010. The majority of the assembly is planned to finish by the time the first interferometer is decommissioned in FY2011, allowing staff to move on installation tasks. The US

---

[5] Memorandum of Understanding between the Advanced LIGO United Kingdom (ALUK) Group and the Laser Interferometer Gravitational Wave Observatory (LIGO), LIGO- M060022-00-M

subsystem element is complete when all suspensions have been assembled and tested, and are on-site and ready for installation.

4.4 Pre-Stabilized Laser

The pre-stabilized laser (PSL) provides the frequency and intensity stabilized light for the Advanced LIGO interferometers, at the specifications required at the entrance to the Input Optics (IO) system.

The PSL subsystem includes the high power Nd^{3+}:YAG laser and all hardware, local controls, and controls software for the pre-stabilized laser subsystem upgrade (one operational PSL per interferometer, one spare per site, and one engineering prototype/first article). All necessary electronics, optics and optical mounting hardware required to implement the first level of frequency stabilization are part of the PSL. All necessary electronics, optics and optical mounting hardware required to stabilize the intensity fluctuations of the Advanced LIGO Laser are parts of the PSL. The optical table and its surrounding laser safety table enclosure, acoustic enclosure and laser area enclosure are included in the WBS element. Not included are the suspended input and output mode cleaners, any transition optics to the mode cleaners, general controls for the interferometer, or shared controls infrastructure.

Responsibility for the Advanced LIGO Laser and the PSL will be led by the Max Planck Albert Einstein Institute, Hannover, Germany (AEI), the group responsible for the design of the high power laser. AEI is responsible for the production of the laser, its controls, and the frequency stabilization, using German funds granted in 2005 by the Max-Planck Gesellschaft. Scope documents and an MOU[6] detail the responsibilities of Max Planck and LIGO with respect to the laser systems. The AEI efforts are integrated into the overall Advanced LIGO schedule but the costs are not part of the NSF MREFC funding baseline. The LIGO Laboratory is responsible for the interface with the laser controls, the PSL intensity stabilization, and the infrastructure such as optical tables and laser enclosures.

Work Plan

The AEI Pre-Stabilized Laser production is scheduled to start no later than mid FY09, with delivery of all hardware from AEI to the LIGO Laboratory by FY2010. LIGO Laboratory elements of the PSL are produced starting in late 2009 and completing in late 2010. Pre-assembly, checkout, and shipping for all interferometer Pre-Stabilized Laser components are completed by early 2011, accomplished with a combination of AEI and LIGO Laboratory staff.

The WBS element is complete when all PSL parts, including spares, have been delivered to the observatory sites. Final assembly of the PSL will occur at the time of installation.

---

[6] Memorandum of Understanding between the Max-Planck-Institut fuer Gravitationsphysik (Albert-Einstein-Institut) and the Laser Interferometer Gravitational Wave Observatory (LIGO), in preparation

4.5 Input Optics

The Advanced initial LIGO subsystem will be an extension of the initial LIGO Input Optics design to the higher specified power and lower noise level of Advanced LIGO. The IO conditions and matches the light from the Pre-Stabilized laser to the Core Optics, applying phase modulation, and reducing the frequency, intensity, and geometric fluctuations in the process.

This element includes all fabrication, assembly, stand-alone alignment and test of the hardware of the input optics subsystem (IO). This includes the phase modulators, Faraday isolators, suspended input mode cleaner, and the input mode-matching telescope. Suspensions are provided by the suspension subsystem. Controls are designed by the interferometer sensing and controls subsystem. As in initial LIGO, the University of Florida will take the responsibility as a subcontractor to the LIGO Laboratory for the scope of this subsystem. Scope documents and an MOU[7] detail the responsibilities of the University of Florida LIGO Group and LIGO with respect to the laser systems.

Work Plan

The subsystem fabrication starts in early FY2008 to produce optics first used in the integrated testing of the Input Optics subsystem at the MIT Campus LASTI testbed; on completion of testing in mid-FY09, production of hardware is enabled. The first completed deliverables are the modulation elements which are complete in early FY10, and delivery of all components is complete by mid-FY11. Installation will commence in 2011.

4.6 Core Optics

The Advanced LIGO Core Optics comprise the test masses, beamsplitter, recycling mirrors and folding mirrors (to allow the sharing of the beam tube by two interferometers at the Hanford Observatory), as well as the reflective dielectric coatings on these optics. The test masses must serve a combination of mechanical and optical functions, leading to requirements for low mechanical loss in the substrate and coatings, low optical absorption in the bulk material and optical coating, and stringent figure and roughness specifications. A large mass is needed to hold the motion due to the quantum and technical fluctuations in the light power to an acceptable level. Fused silica substrates are used.

This element includes purchase of materials, polishing, coating, metrology, cleaning and preparation and transport of the core optics and spares. It includes preparations of the optic for installation in the suspension, but it does not include physical elements attached to the optics required for suspension fiber attachment.

---

[7] Memorandum of Understanding between the University of Florida and the Laser Interferometer Gravitational Wave Observatory (LIGO), in preparation

Work Plan

As part of the PPARC-funded UK Capital Contribution to the Core Optics Subsystem, four test mass substrates have been delivered to LIGO. These substrates are to be used as part of a ‘pathfinding’ process, and then (after re-work, if required) to be installed in the Advanced LIGO interferometers.

Work starts for the Core Optics subsystem as soon as Project funds are available at the beginning of FY08, due to long lead items. Blanks are complete for all interferometers by mid-FY10, polishing is complete by early FY11, and coating and final metrology complete by mid FY11.

4.7 Auxiliary Optics

The Auxiliary Optics is responsible for (a) transport of interferometer output beams, (b) stray light control, (c) thermal compensation (including diagnostic wavefront sensing), (d) optical levers for alignment reference, (e) initial alignment system/equipment, and (e) a photon calibration/excitation system. The unifying theme for the AOS work is in-vacuum optical layout and beam transport. The optical transport function includes beam reducing telescopes, large pick-off mirror assemblies, small in-vacuum relay mirrors and mounts, and optical view ports. Stray light control is accomplished with beam dumps and baffles and Faraday isolator assemblies. The active thermal compensation element generates compensatory heating of core optics in order to cancel thermal distortion induced by absorbed laser power.

This element covers all hardware, assembly, stand-alone testing, and delivery of the auxiliary optics subsystem. This includes the Stray Light Control (beam dumps and baffles for ghost beams, arm cavity baffle for small angle scattered light, input test mass and output test mass errant beam baffles to protect suspension fibers, attenuators for pick-off beams); Thermal Compensation (ring heaters for recycling & arm cavity mirrors, CO_2 laser, shaped heating beam for the input test mass, wavefront probe/sensor optical system for real-time thermal compensation), the pick-off mirror and telescope (suspended pick-ff mirror to extract core optics pick-off beams for wave-front sensors, non-suspended beam-reducing telescope and steering mirrors, suspended existing end-test-mass telescope), Initial Alignment System (replace or upgrade existing surveying equipment, visible & IR laser autocollimators, theodolites, optical squares, etc.), Optical Levers and piers, Photon Calibrator, Output Mode Matching Telescope (suspended beam reducing telescope for dark port gravitational-wave signal, Faraday isolator), and the View ports (interferometer sensing beams, video camera, chamber illumination, optical lever, thermal compensation system).

Work Plan

Production of the elements starts early in FY08 due to the possible long lead time for custom-fabricated off-axis parabaloids used in the telescopes. The output mode-matching telescopes are finished in early FY10, for integration with their suspensions. The equipment for the first two interferometers is complete by mid-FY10, with some float before installation in early FY11. The third interferometer components are complete by early FY11, well before the 3rd-quarter readiness of that instrument for the components.

4.8 Interferometer Sensing and Control

This subsystem comprises the length sensing and control, the alignment sensing and control, and the overall servo-controls infrastructure modifications for the Advanced LIGO interferometer design. The infrastructure elements will be replaced to accommodate the additional control loops in the reference design. The single most significant difference in the Advanced LIGO subsystem is the addition of the signal recycling mirror and the resulting requirements on the controls.

This WBS element includes all hardware, software and test for the sensing, signal conditioning and digital conversion electronics, programmable items, computers, and software for the servo control of the Advanced LIGO interferometer systems. These include control and coordination of all degrees of freedom of the interferometer up to the interface points with the PSL, AOS, SUS, and SEI subsystems, and sensing and readout of lengths and angles of optical elements.

The LIGO Laboratory will manage the design and fabrication of the controls subsystem as it did during initial LIGO construction.

Work Plan

Development work, exploiting the Caltech 40m Interferometry Testbed, continues through FY08, with final design toward the end of that year. Production begins in early FY09, with RF electronics completed in early FY10. By mid-FY10, all components (electronic and optical) have been delivered to the sites, and assembly commences. In parallel, real-time controls software is in production, and by the beginning of FY11 the subsystem deliverables are complete.

4.9 Data Acquisition Systems

The differences between the initial LIGO and Advanced LIGO Data Acquisition, Network & Supervisory Control (DAQ) requirements derive from the greater channel counts in Advanced LIGO, and the lessons learned from initial LIGO in terms of infrastructure layout, EMI/RFI, etc.

This element includes all hardware, software, integration and testing for the analog and digital signal conditioning electronics, computers, networking, sensors, actuators and excitation devices for reading Advanced LIGO data and diagnostic data and operating diagnostic systems. Common elements of the supervisory control and human interface for subsystems, and the infrastructure (cable plant, servers, etc.) are also in this subsystem. The element includes all additions and modifications to the LIGO Global Diagnostics System (GDS) and the Physics Environmental Monitor (PEM) system.

For one sub-element of the Data Acquisition System, the Timing system, the Columbia Experimental Gravity Group (GECo) will take the responsibility as a subcontractor to the

LIGO Laboratory. Scope documents and an MOU[8] detail the responsibilities of Columbia and LIGO with respect to the laser systems.

Work Plan

The DAQ subsystem starts production early in FY09, with the equipment and software for the first interferometer complete by early in FY11. The remaining interferometers complete in second and third quarters of FY11.

4.10 Data and Computing Systems

The Advanced LIGO data analysis computational load is increased over that for initial LIGO due to the broader range of detector sensitivity. The enhanced frequency range means that sources whose characteristic frequency of emission varies with time will be observable in the detection band for longer periods. Combined, these enhancements provide both greater range and in-band dwell times. These improvements imply that the rate of detectable events with Advanced LIGO will be orders of magnitude greater than initial LIGO.

This element includes all incremental upgrades to data analysis systems and computational infrastructure needed to support the analysis of data from Advanced LIGO. It includes neither software nor computing nor network hardware supported normally by the LIGO Laboratory operations program (WBS 2.0). It does include the LIGO Data Analysis System (LDAS) infrastructure development for Advanced LIGO. Cybersecurity during the Project (e.g., protection against code or document loss) and after the end of the Project (for the operating Advanced LIGO detector) will be the responsibility of the LIGO Laboratory Cybersecurity organization, and Advanced LIGO staff will follow their direction.

Work Plan

Due to the rapid evolution of computing technology, it is a strong advantage to purchase the computing equipment 'just in time'. Thus, this subsystem is scheduled for the end of the project, with timing of the system acquisition, integration, and test to just match the need for acquiring overall interferometer test data at the end of the hardware effort. Production begins in mid-FY14, and by early FY15, all equipment is accepted and ready for use.

4.11 Installation and Testing

The installation and testing of the Advanced LIGO detector systems is planned to be as rapid as possible in order to minimize the observatory downtime. It requires the installation of all detector elements in all three LIGO interferometers in a phased approach to best utilize the infrastructure and manpower in the Laboratory and LSC. The

[8] Memorandum of Understanding between Columbia Experimental Gravity Group (GECo) and the Laser Interferometer Gravitational Wave Observatory (LIGO), LIGO- M050453-02-M

subsystem teams are expected to have pre-assembled and pre-tested components available for installation when needed (much assembly and test can take place at the observatory sites in advance); all assembly is within the subsystem scope, not INS WBS scope.

The scope of the work includes the decommissioning and disposal of the initial LIGO components, the implementation of the vacuum equipment modifications for all interferometers, the installation and initial checkout of the Advanced LIGO subsystems, and the integration, testing, and demonstration of locking for each interferometer. The deliverables are three Advanced LIGO interferometers that have demonstrated full lock status. All installation planning, staging and fixture/jig fabrication/procurement is in the FMP WBS scope.

<u>Work Plan</u>

The subsystem starts in early FY11 with the shutdown of the first initial LIGO interferometer, followed in late FY11 by the shutdown of the second and third interferometers. In mid-FY13 the first interferometer is accepted, and the second two interferometers by mid FY14. The 'just-in-time' installation of the Data and Computing systems follows. Commissioning of the interferometers starts after each acceptance and is supported by operations funds. Both sites expect to return to operations funding by late-FY14.

This is the baseline plan. The status of the global observing networks, agreements between projects, and scientific and technical developments may motivate altering the order of upgraded interferometers or the interval between installations of the successive interferometers. The NSF will be involved in any re-planning of this effort.

4.12 Project Management

This element includes Project management and controls, QA, ES&H, Contract procurement, and systems engineering including modeling and simulation.

4.12.1 Project Management and Controls

The scope of this activity covers the project and technical direction and control. It includes the functions of the project management office as well as of the change control processes. The Project Management WBS element provides support for the project leader, project manager, intermediary technical managers, the project controls team, and the incremental procurement and contracts management personnel. The project management office directs and benefits from the functions of the Risk Management Team (RMT) and Risk Register, the Change Control Board (CCB), and the Technical Review Board (TRB), but does not provide financial support for the various members of these control mechanisms. The project controls staff is responsible for the application of project management tools for planning and tracking the project and for the implementation of Cost/Performance Tracking and Reporting (Earned Value Reporting and Management). Business and financial controls are provided by the LIGO Business Office, with incremental subcontract and procurement management staff supported by this WBS element. The LIGO Business Office, under the direction of the project management, is responsible for subcontract and procurement management. It is responsible for ensuring that the correct funding source is used for activities (MREFC Project funds as opposed to R&RA).

The project office provides support and direction for a Quality Assurance and Quality Control officer, and is responsible for the project QA/QC Plan. Support and direction for the project Safety Officer also fall under the responsibility of the project office. The definition and the implementation of the project Safety Plan are the responsibility of the project management.

The LIGO Staffing Transition Plan is a joint effort of the Advanced LIGO Project Management and the LIGO Laboratory Operations management. The Staffing Plan integrates the staffing plan for operations and Project and includes a transition plan to move people in and out of Project and Operations.

4.12.2 System Engineering and Integration

The scope of system engineering and integration is to define, establish and control individual subsystem requirements and interface requirements between subsystems. These requirements are documented in Interface Control Documents (ICD), which are controlled and maintained by the Systems Engineering Group. The System Engineering Group will define and maintain the detector subsystem requirements and establish the interfaces between them, and oversees the development of interferometer system level modeling and analysis, and the initial interferometer integration and test plan, and will ensure that facility interfaces and implementation maximize the capability to operate advanced interferometers. Note that the system integration and test is executed under the INS WBS elements in accordance with the Systems Engineering plans and guidance.

Work Plan

The Project management effort is effectively continuous throughout the Project. There is a reduction in Project Controls and procurement management staff as the procurement winds down, to match the needs of the Project.

5 Baseline Project Definition

5.1 Project Cost Estimate

5.1.1 Basis of Estimate

The Advanced LIGO Project Cost Estimating Plan (CEP), LIGO M-990310-06, defines the guidelines and methodology that is used to prepare and update the Advanced LIGO cost estimate. This guidance is provided to assure that the final product is complete, consistent, and well documented. The cost estimate is assembled and maintained in an Advanced LIGO Cost Book.

The current Advanced LIGO estimating plan is based on the structure established in an earlier version of the LIGO Cost Estimating Plan. The cost estimates are prepared by technical experts who are experienced in the fields of specialization required to accomplish the Advanced LIGO upgrade. Vendor quotations, engineering calculations, catalog pricing, drawings, and other pertinent data which are used to support the cost estimate, are collected and organized into a Basis-of-Estimate (BOE). A copy of the BOE is provided to Project Controls and maintained in the Cost Book with the cost estimate. The Cost Book is organized according to the Advanced LIGO Work Breakdown Structure (WBS).

The cost estimate developed according to the CEP is a detailed bottom-up estimate performed at the lowest reasonable or “activity” level of the WBS. The base year for the current estimate is FY 2006. The original Advanced LIGO Proposal was based on FY 2003 dollars. Escalation will be applied at the top level to adjust costs to the anticipated Funding Year basis. Wherever possible, the bottom-up estimates are improved or verified by top down comparisons to actual costs for initial LIGO construction, installation, integration and testing. The cost estimates are also informed by comparisons to experience gained in prototyping Advanced LIGO subsystems, or in the case of the seismic pre-isolator (HEPI), with installation and operation of an Advanced LIGO subsystem at the observatories.

5.1.2 Contingency Estimates

A risk analysis is used to calculate contingency, using a formal graded approach to assess technical, cost and schedule risk as defined in the Advanced LIGO Cost Estimating Plan. Contingency is developed at the same level of the WBS used to prepare cost estimates. The method is based on estimator evaluation of the technical, cost, and schedule risk against standard risk factors for every activity.

An additional contingency factor was determined using the information from the technical, cost, and schedule risk analysis and a Monte Carlo simulation of cost and schedule variances generated by input from a Risk Register. The Risk Register is a compilation of potential events that may have a negative impact on the overall project objectives, along with an evaluation of the probability of occurrence and possible impacts. The Risk Register is described in more detail in section 6.1.2 Risk Management

Process. The Monte Carlo analysis increased the overall project contingency by 3%, leading to an average contingency of 26.3% for the NSF request amount. The actual contingency used in initial LIGO construction for similar scope was 26.1%, leading to additional confidence in the estimated contingency.

While contingencies are estimated at the same level as the bottom-up cost estimate, the project contingency will be held at the top level and allocated as needed to address problems and items or activities that have been overlooked during the estimating process. A formal change control process will be used to allocate contingency to specific activities.

5.1.3 Total Project Cost in Base Year Dollars

The baseline project cost for the NSF-funded portion of the Advanced LIGO Project is shown by sub-system in Table 2. The NSF-funded project cost totals $172.21M in base year dollars (2006$).

The total cost of the Advanced LIGO project, including effort and hardware contributions by international partners, is given in Table 3. The overall project cost, with international partner contributions, is $186.2M in 2006$.

The costs shown for the international partner contributions represent the value to the LIGO Laboratory to replace those contributions. They are estimated following the Advanced LIGO Cost Estimating Plan for the supplied equipment, labor, and related costs. Due to differences in labor rates, overhead costs, contingency estimating, and currency exchange rates, the LIGO replacement value may differ slightly from the costs as estimated provided by the contributing partner. The Albert Einstein Institute in Germany is funded by the Max Planck Gesellschaft (MPG) to provide the pre-stabilized lasers (PSL) with a value of $7.13M. The Advanced LIGO United Kingdom group, ALUK, is funded by the Particle Physics and Astronomy Research Council as well as by the German-English Observatory (GEO) to provide the test mass suspensions and one set of test mass substrates. Their effort is valued at $6.87M. The total contribution from international partners to the project has a value of $14.0M in 2006$.

WBS	Sub-System	Funding Agency	Baseline Control Cost 2006 ($M)	Contingency 2006 ($M)	Contingency %	Total 2006 ($M)
4.01	FMP	NSF	7.01	1.40	20.0%	8.41
4.02	SEI	NSF	34.34	9.91	28.8%	44.25
4.03	SUS	NSF	12.27	3.59	29.3%	15.86
4.04	PSL	NSF	2.10	0.67	31.8%	2.77
4.05	IO	NSF	2.75	0.60	21.6%	3.35
4.06	COC	NSF	12.57	3.26	25.9%	15.83
4.07	AOS	NSF	7.33	1.71	23.4%	9.04
4.08	ISC	NSF	6.02	2.02	33.5%	8.04
4.09	DAQ	NSF	3.63	0.53	14.7%	4.17
4.12	DCS	NSF	9.78	1.47	15.0%	11.24
4.13	INS	NSF	24.17	7.89	32.6%	32.06
4.14	PM	NSF	14.44	2.78	19.2%	17.21
		Totals	**136.39**	**35.82**	**26.3%**	**172.21**

Table 2: NSF-Funded Advanced LIGO Project Costs in 2006 Dollars by project subsystem.

Summary Costs by Subsystem

2006 Base Year Dollars

Funding Agency	WBS	System	Hours	Labor $	Travel $	Equipment $	Subtotal	Contingency $	Cont %	Total $
MPG										
	4.04	PSL	10,385	1,217,760	309,127	3,945,518	5,472,405	1,662,079	30.4%	7,134,484
		Subtotal	**10,385**	**1,217,760**	**309,127**	**3,945,518**	**5,472,405**	**1,662,079**	**30.4%**	**7,134,484**
NSF										
	4.01	FMP	16,672	1,081,042	49,296	5,875,141	7,005,479	1,401,568	20.0%	8,407,047
	4.02	SEI	55,939	4,445,672	368,492	29,526,288	34,340,452	9,905,469	28.8%	44,245,920
	4.03	SUS	44,498	3,528,233	450,774	8,289,847	12,268,854	3,591,113	29.3%	15,859,966
	4.04	PSL	8,105	597,003	30,968	1,471,906	2,099,877	666,915	31.8%	2,766,792
	4.05	IO	8,490	519,354	101,900	2,130,955	2,752,209	595,010	21.6%	3,347,219
	4.06	COC	18,484	1,872,652	261,016	10,436,847	12,570,515	3,257,095	25.9%	15,827,610
	4.07	AOS	17,622	1,411,148	157,930	5,757,161	7,326,239	1,713,360	23.4%	9,039,599
	4.08	ISC	26,670	2,580,685	83,160	3,355,864	6,019,709	2,018,935	33.5%	8,038,644
	4.09	DAQ	13,230	1,074,591	260,700	2,295,567	3,630,858	534,999	14.7%	4,165,857
	4.12	DCS	5,344	457,928	39,500	9,280,001	9,777,429	1,466,614	15.0%	11,244,043
	4.13	INS	325,982	19,375,366	2,695,323	2,095,402	24,166,092	7,889,251	32.6%	32,055,343
	4.14	PM	123,556	14,167,531	267,810	0	14,435,341	2,776,811	19.2%	17,212,151
		Subtotal	**664,592**	**51,111,203**	**4,766,869**	**80,514,979**	**136,393,051**	**35,817,140**	**26.3%**	**172,210,191**
UKGEO										
	4.03	SUS	6,914	536,302	267,980	4,089,218	4,893,500	1,510,546	30.9%	6,404,046
	4.06	COC		0	0	396,000	396,000	73,260	18.5%	469,260
		Subtotal	**6,914**	**536,302**	**267,980**	**4,485,218**	**5,289,500**	**1,583,806**	**29.9%**	**6,873,306**
		Grand Total	**681,891**	**52,865,265**	**5,343,976**	**88,945,715**	**147,154,956**	**39,063,025**	**26.5%**	**186,217,981**

Table 3: Table of total project costs including collaborators

5.1.4 Cost and Funding Profiles

Escalation was applied to the cost totals for each year to obtain then-year or funding year cost profiles, shown in Table 4. Escalation factors were derived from the NSF recommended CPI-W tables for Laboratory labor and travel and the NSF recommended value for MREFC construction for equipment. A single factor for each year was calculated by forming the weighted sum of the NSF factor times the ratio of the cost category to the total project cost. Yearly factors derived from the current NSF tables range from 4.16% to 4.20%. The escalated total cost of the NSF request is $205.12M.

Advanced LIGO must have sufficient funds on hand before placing large contracts. A procurement commitment profile was generated to determine the funding profile necessary to support contract awards on a timely basis. This profile was generated by placing the costs associated with equipment procurements in the year in which procurement starts rather than as spent or disbursed. Table 5 and Figure 3 show the commitment profile for Advanced LIGO. The second line in the table, 'commitment shift' shows the amounts that shift forward into the designated year by front loading the procurements.

	Spending Profile - NSF Request								
Category	TOTAL ($M)	FY 2008 ($M)	FY 2009 ($M)	FY 2010 ($M)	FY 2011 ($M)	FY 2012 ($M)	FY 2013 ($M)	FY 2014 ($M)	FY 2015 ($M)
Equipment (2006$)	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
Grand Total 2006$	**172.21**	**30.19**	**45.51**	**39.33**	**12.41**	**18.58**	**11.64**	**14.26**	**0.29**
Escalated Grand Total	**205.12**	**32.75**	**51.43**	**46.30**	**15.21**	**23.73**	**15.50**	**19.78**	**0.42**
Escalated Cum. Spending		**32.75**	**84.19**	**130.49**	**145.69**	**169.43**	**184.92**	**204.71**	**205.12**

Table 4: Spending profile for NSF request, including totals per year for costs in base year dollars and as-spent, then-year dollars.

	Commitment Profile - NSF Request								
Category	TOTAL ($M)	FY 2008 ($M)	FY 2009 ($M)	FY 2010 ($M)	FY 2011 ($M)	FY 2012 ($M)	FY 2013 ($M)	FY 2014 ($M)	FY 2015 ($M)
Committed Equipment (2006$	101.03	26.89	44.29	16.49	1.09	1.59		10.67	
Commitment shift		2.97	12.42	2.49	0.25	0.12	0.01	0.00	
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
Grand Total 2006$	**172.21**	**33.16**	**54.96**	**29.40**	**10.17**	**18.44**	**11.54**	**14.25**	**0.29**
Escalated Grand Total	**205.12**	**36.11**	**62.69**	**34.73**	**12.48**	**23.56**	**15.36**	**19.76**	**0.42**
Escalated Cum. Commitment		**36.11**	**98.80**	**133.53**	**146.02**	**169.58**	**184.94**	**204.71**	**205.12**

Table 5: Commitment or funding profile for NSF request, including totals per year for costs in base year dollars and as-spent, then-year dollars. Commitment profile is

obtained by assigning total costs for equipment procurements to the year contracts are awarded.

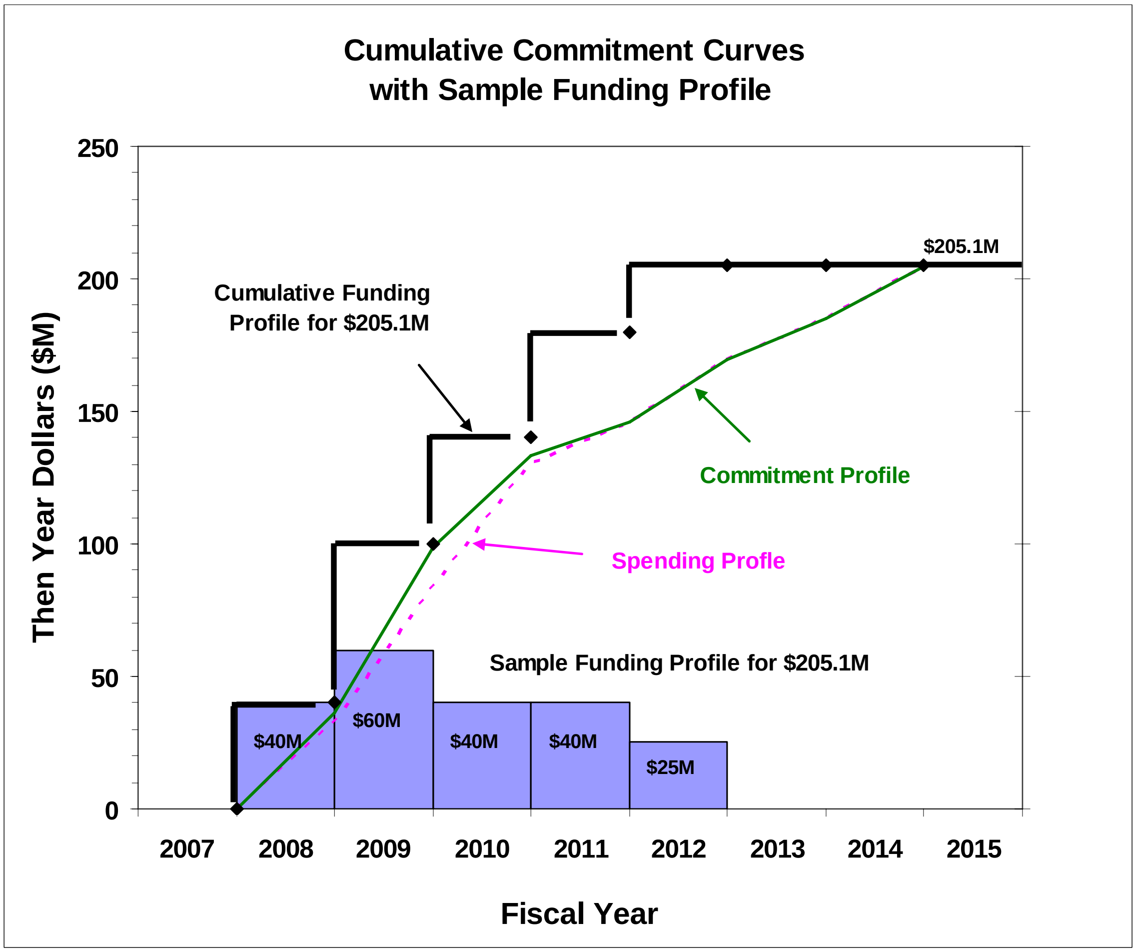


Figure 3: Cumulative spending and commitment profiles for the Advanced LIGO NSF request in then-year dollars. A sample funding profile is also shown.

5.2 Project Schedule

5.2.1 Schedule Estimates

The Advanced LIGO schedule estimates were prepared by an experienced team of specialists who participated in the initial LIGO project and/or who are actively involved in the design and development stage of the Advanced LIGO program. Estimators developed the flow of work in the linked activities in the Work Breakdown Structure (WBS). Schedule durations were estimated based on input data such as resource availability, vendor quotes, and past experience with initial or Advanced LIGO systems, as well as on engineering judgment.

The estimator's evaluation of the range of possible durations for the lowest level WBS elements and potential schedule impacts from the Risk Register was used in a Monte Carlo simulation to obtain the uncertainty in the overall project schedule. The simulation yielded a five month overall schedule contingency. The schedule contingency is held at the project level and is managed by the project leader through a change control process.

5.2.2 Project milestones

The Advanced LIGO schedule control milestones for performance measurement are shown in Table 6. Funding is scheduled to start in October 2007 (start of FY08). The project duration includes an additional 5 months added to the final interferometer acceptance date as overall project schedule contingency.

Procurements of long lead items and site preparations for assembly space start as soon as funds are available. Procurement and assembly of other subsystem components are staggered to match the completion of design work and the availability of assembly space and personnel. The fabrication is planned so that the majority of components for each interferometer is pre-assembled, tested, and ready for installation before that interferometer is shutdown from operations. The HAM internal seismic isolation systems, closely followed by the HAM auxiliary optical suspensions, are the driving activities (critical path) for scheduling the start of installation activities at both observatory sites. See Figure 4 for a schedule cartoon detailing the project flow of work.

Installation is planned to start at the Livingston Observatory in early 2011, followed approximately nine months later by installation at the Hanford site. Both interferometers at Hanford will be shutdown at the same time, but installation will be staggered to allow crews to finish tasks on the first interferometer before moving to the second. Integration and testing of subsystems will occur as systems become available. The final acceptance of each interferometer will occur when full lock has been obtained and maintained for a period of hours. Installation and testing-to-acceptance activities become the critical path once the sites are shut down. The final project activity is the procurement and installation of the data and computing systems, which is planned to occur just after final acceptance to leverage cost and performance opportunities in the market. This just-in-time activity is not on the critical path.

The project is complete when all three interferometers have been accepted and all equipment is installed and ready for operations.

Advanced LIGO Project Control Milestones	
NSF Funding Start for Advanced LIGO Construction	Oct 2007
Installation Begins At Livingston (LLO)	Jan 2011
Installation Begins At Hanford (LHO)	Sep 2011
Acceptance at Livingston (LLO)	May 2013
Acceptance at Hanford (LHO)	Mar 2014
LLO Commissioning Starts (Operations funds)	Oct 2014
LHO Commissioning Starts (Operations funds)	Aug 2014
Data and Computing Systems Ready at CIT, MIT, LLO, LHO	Dec 2014

Table 6: Advanced LIGO Project Control Milestones

5.2.3 Schedule

A high level summary schedule of Advanced LIGO is found in Figure 5. A complete version of the Advanced LIGO Project Schedule can be found in the Advanced LIGO Cost Book or on the Advanced LIGO Project Center website at http://www.ligo.caltech.edu/~advligo/ .

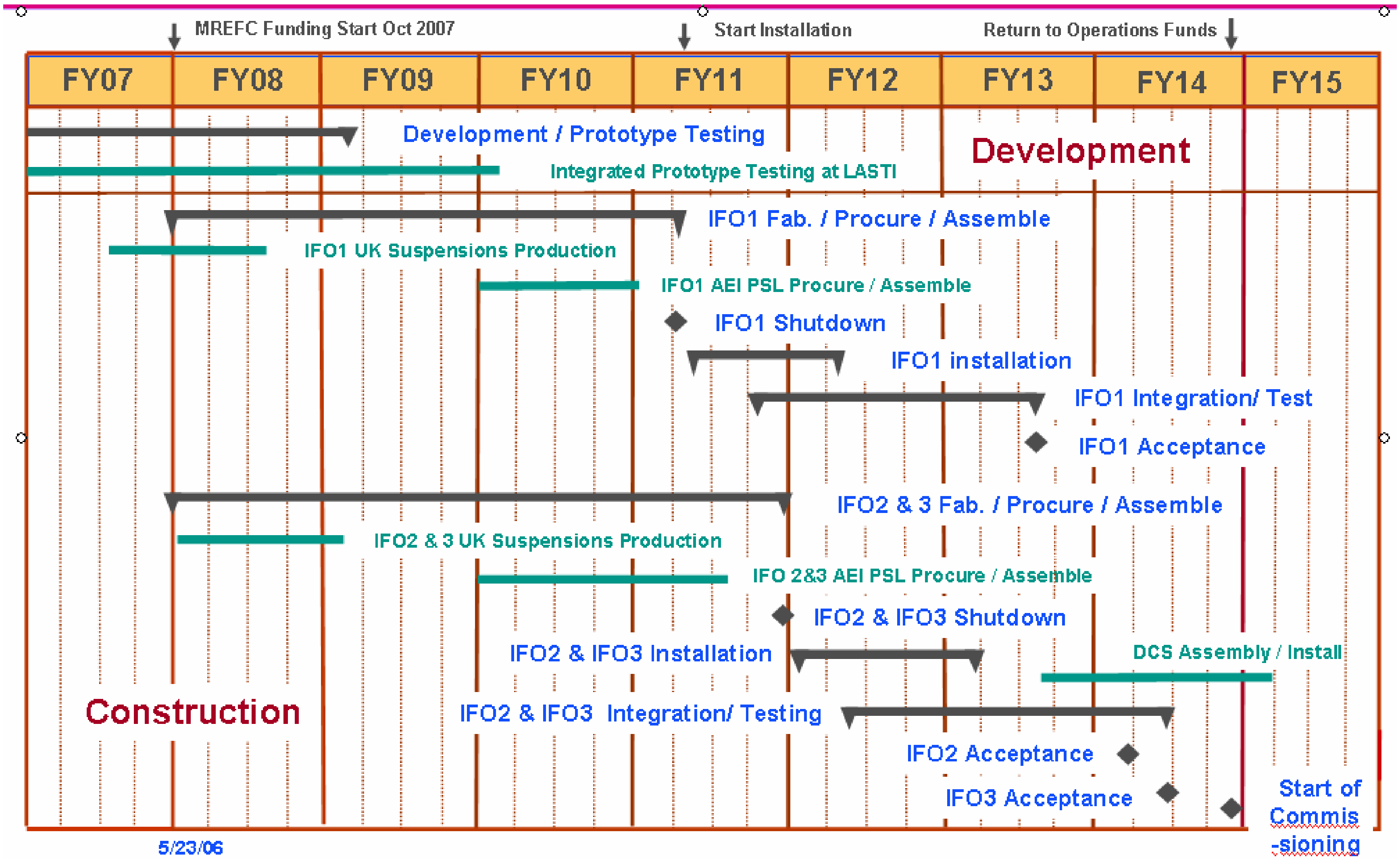


Figure 4: Schedule cartoon showing project sequence of activities by Interferometer (IFO). Activities by LIGO International Partners are included.

Activity ID	Activity Description	Funding Agency	Early Start	Early Finish	Total Float
LIGO					
LIGO.4 Advanced LIGO					
+ LIGO.4.01 Facility Modifications & Preparation (FMP)					
		NSF	01OCT07	02SEP11	0
+ LIGO.4.02 Seismic Isolation (SEI)					
		NSF	31JAN08	19AUG11	0
+ LIGO.4.03 Suspension (SUS)					
			17APR07	07JUL11	31
+ LIGO.4.04 Prestabilized Laser (PSL)					
			17JUL09	05MAY11	74
+ LIGO.4.05 Input Optics (IO)					
		NSF	31JAN08	19APR11	86
+ LIGO.4.06 Core Optics Components (COC)					
			01JUL05A	24MAY11	36
+ LIGO.4.07 Auxiliary Optics (AOS)					
		NSF	14MAY08	21JUL10	171
+ LIGO.4.08 Interferometer Sensing and Control (ISC)					
			26NOV08	07DEC10	160
+ LIGO.4.09 Data Acq., Diag. & Controls (DAQ)					
		NSF	19NOV08	01AUG11	14
+ LIGO.4.12 Data and Computing Systems (DCS)					
		NSF	20JUN13	23DEC14	0
+ LIGO.4.13 Installation (IN)					
		NSF	22DEC10	18MAR14	0
+ LIGO.4.14 Project Management (PM)					
		NSF	01OCT07	23DEC14	0

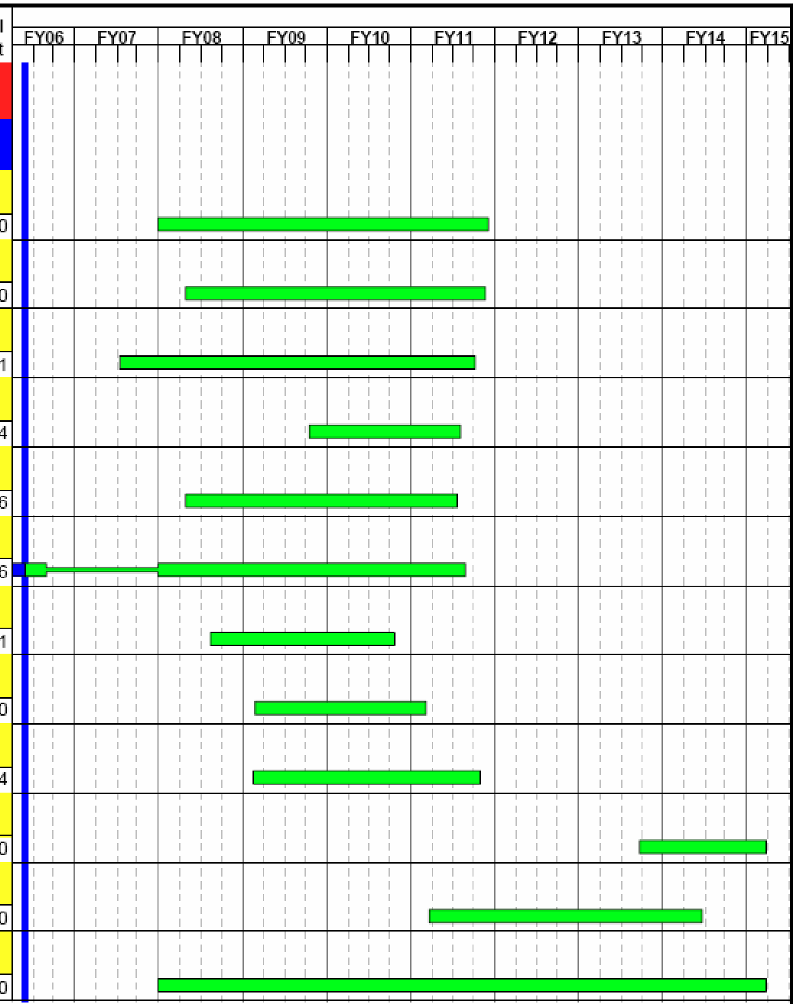


Figure 5: Summary Schedule for the Advanced LIGO Project

5.3 Staffing profile

Advanced LIGO will be implemented by a combination of project staff at Caltech and MIT, staff employed by subcontractors, and LIGO Scientific Collaboration (LSC) collaborators. LIGO benefits from the fact that the project is embedded in strong technical organizations (Caltech, MIT, and LSC Institutions) from which specialized assistance can be drawn. Additional staff will be attached to the project to provide specialized expertise which is not needed on a full time basis throughout the project, and to provide additional engineering support during peak demand periods. Craft laborers and temporary help will be employed when project demands exceed the resources within the laboratory. A project staffing profile is shown in Table 7.

The project also employs a number of graduate and undergraduate students. Most of their efforts will take place during the integration and testing period, which offers significant opportunities for scientific contributions. Care will be taken to ensure that the undertakings of students are well-matched to their academic needs and that the Project is robust against changes in student focus.

LIGO Laboratory will continue to operate during the project and will provide infrastructure, business, and administrative support. The Advanced LGIO project will provide any incremental personnel required beyond the administrative staff normally employed by the Laboratory in the absence of the project. Management and administration of the Laboratory will provide important support for Advanced LIGO and the other activities of the Laboratory. Education and Outreach will be active, as will future R&D which must go on in parallel with AdLIGO construction and commissioning, just as AdLIGO R&D accompanied initial LIGO commissioning. It is anticipated that this will be an important adjunct to Advanced LIGO Project activities, providing risk reduction to the project and upgrades to Advanced LIGO in a timely way.

RESOURCE	FY 2008	FY 2009	FY 2010	FY 2011	FY 2012	FY 2013	FY 2014	FY 2015	TOTAL FTE YRS
Administration	1.0	1.0	1.0	1.0	0.5				4.5
Engineer / Sr. Technician	10.7	17.2	20.0	14.5	21.8	13.9	3.5	0.9	102.4
Graduate Student	0.5	0.5	1.1	0.8	3.7	5.0	1.2		12.7
Craft Laborer	0.4	0.4	0.4	6.0	13.2	0.2			20.6
Mgt/Senior Personnel	2.4	2.7	2.7	2.4	2.3	2.3	1.8	0.3	16.9
Post-Doctoral Fellow	0.7	0.7	1.9	1.5	4.4	6.1	1.6		17.0
Scientist	1.1	2.3	4.1	3.3	12.6	8.4	2.5	0.2	34.5
Sr Engineer	8.4	13.8	15.2	11.7	11.4	8.1	2.8	0.3	71.6
Sr Scientist	1.4	2.9	4.1	3.8	10.6	6.7	1.7		31.2
Technician	2.8	7.2	10.1	6.5	24.2	6.1	1.0		57.8
TOTAL	**29.3**	**48.7**	**60.6**	**51.5**	**104.6**	**56.9**	**16.1**	**1.5**	**369.3**

Table 7: Staffing plan for Advanced LIGO Project

Project Controls

6.1 Risk Assessment and Management

The Risk Management Program, implemented through LIGO-M060045-00-M, *The Advanced LIGO Risk Management Plan*. This document provides a formalized approach to actively identify and manage risks to the successful completion of the Advanced LIGO Project.

Project risk management entails the systematic process of identifying, quantifying, handling, tracking, and reporting risk events. Risk events are defined as individual occurrences or situations that are determined to have potential negative impacts to a project. The Advanced LIGO risk management plan uses a multi-step, iterative process that requires continued involvement of all project members.

6.1.1 Risk Management Responsibilities

Accountability for Advanced LIGO risk management is a responsibility of each individual working on the Advanced LIGO Project. The Project Leader has overall responsibility for Advanced LIGO risk management. Implementation and management of risk management processes is the responsibility of the Project Manager. The Project Leader and Project Manager work in conjunction with the Risk Management Team (RMT) to administer Advanced LIGO risk management processes.

6.1.2 Risk Management Process

The risk management process begins with the identification of risks and the generation of a comprehensive list of potential project risk events. Project risks are analyzed by considering their likelihood or probability of occurring together with the consequence to one of the four project objectives: cost, schedule, scope, or technical performance baselines. A risk assessment matrix of likelihood versus consequence provides a qualitative scoring of an event as a high, medium, or low project risk.

The management team decides, for each event, whether to adopt a mitigation strategy or to accept a risk without further action. Strategies may involve developing a contingency plan that will be executed should the risk be realized or waiting until a risk is realized before formulating a plan. The strategy and threshold for accepting a risk is made on a case-by-case basis. After appropriate risk mitigation measures have been implemented, a re-evaluation of the event may result in residual risk. The risk mitigation strategy for each risk event may include measures to address this residual risk.

The collected list of risk events, along with the risk assessment evaluation and mitigation strategies, forms the Advanced LIGO Risk Register. It is the main tool used to implement the Risk Management Processes. A selected subset of the highest priority risks or those requiring the closest monitoring forms the Advanced LIGO Major Threat List. The current Risk Register and Advanced LIGO Major Threat List are located on the Advanced LIGO Project Center Website and are maintained by the PM. Both are active documents that are reviewed on a periodic basis: monthly for the Major Threat List and quarterly for the Risk Register. New risk events are added to the register as they are identified and existing risks are retired as mitigations are completed or the events become obsolete. During the review process, completed mitigation actions are noted, risk events and mitigation strategies are re-evaluated, and future mitigation activities are verified.

The Advanced LIGO risk management plan is a simple, organized, and systematic, decision-making process that allows managers to focus attention and resources on the possible events that will have the greatest likelihood of occurring and the greatest impact if it does occur. It is forward looking, so that uncertainties can be identified and managed before impacts are realized.

6.2 Earned Value Tracking

Advanced LIGO will use an Earned Value Management System (EVMS) to plan, track, organize, report, analyze, control, and manage the Project. The cost, schedule, and technical baselines are integrated into a Performance Measurement Baseline to facilitate earned value (EV) measurement. EV performance measurement and reporting provides Project Management a method of tracking progress as well as obtaining early detection of potentially unfavorable baseline impacts. Corrective actions can be determined and implemented in a timely manner.

The Advanced LIGO Project Manager (PM) is responsible for implementing EVMS on the project. The project scope of work is planned and organized by Work Breakdown Structure (WBS) to create a cost and schedule baseline. Baseline schedule, cost, and scope are incorporated into a tracking system which represents the Performance

Measurement Baseline. Cost accounts are created to manage the work and facilitate tracking. Progress status is collected on a monthly basis, including schedule progress and actual cost from CIT Accounting. EVMS software provides performance tracking and reporting which keeps management informed on the state of the Project. Reports include variances, and forecasted estimate to complete (ETC) information. Project Management uses this information to track progress and determine corrective actions. Performance reports, analysis, and corrective actions are distributed to the Advanced LIGO Project team. This information is provided to NSF on a quarterly basis.

EVMS controls changes to the baseline plan. It controls and manages contingency assignments that are approved by the Advanced LIGO Change Control Board (CCB) actions. It incorporates and controls any approved Performance Measurement Baseline changes.

6.3 Configuration Management and Change Control

Advanced LIGO will follow the same configuration control processes employed currently in the LIGO Laboratory[9]. The LIGO Laboratory configuration management process has been implemented to ensure coordination of changes and to assure that the technical, cost, and schedule impact of changes are considered. The configuration management process involves configuration change control and configuration accounting/verification.

A controlled technical, cost and schedule baseline will be established for the Advanced LIGO Project. The technical baseline consists of the approved documentation used to define the physical and functional requirements of the system and subsystems, including specifications, interface control documents and drawing packages.

The technical baseline is managed throughout the Advanced LIGO project to ensure that the system meets its specifications and that these specifications reflect the true configuration of the system. Periodic reviews, physical configuration audits, and configuration change control ensures that the technical documentation properly reflects the "as built" configuration.

---

[9] Configuration control in the LIGO Laboratory is defined in the following documents:

R. Bork, Detector Configuration Control Procedures, E000037-00, 1/14/2000; (except the ECR process has not been implemented).

R. Bork, CDS Software Development Plan and Guidelines, T960004-A, 12/1/97; (has a section on software configuration management)

D. Coyne, C. Torrie, Drawing Requirements, E030350-A, 5/24/05; (defines configuration control and archiving requirements for drawings).

W. Althouse, Procedure for Release of Controlled Drawings and Specifications, L970164-02, 4/9/97; defines the procedure for establishing and changing configuration controlled documents (using the Document Change Notice (DCN)).

The approved cost and schedule baselines will be fully integrated into a Performance Measurement Baseline against which the progress of the project can be measured. The LIGO Document Control Center (DCC) collects and maintains the documented Advanced LIGO baselines as a set of controlled documents. Earned Value and variance tracking, as described in Section 6.2, ensure that the project is executed according to the baseline plans.

6.3.1 Document Control

A LIGO Document Control Center (DCC) has been established to support the laboratory. All Advanced LIGO documents are archived in the DCC. An orderly process for numbering and indexing all LIGO documentation has been established in the DCC. The DCC is located and staffed in the LIGO Business Group, which reports to the Laboratory Deputy Director. The Document Control Center (DCC) will maintain an electronic database all controlled documents with meta-data including the current revision status. The status of all documents is available to all project personnel. The DCC will also file and store the electronic copies of all such documentation. For all subcontracted efforts, the requirements, specifications, interface drawings and documentation will be under formal configuration management throughout the contracted period.

6.3.2 Configuration Control

Changes in the Advanced LIGO technical, cost and schedule controlled baselines will be initiated by a documented request from the cognizant manager to the Advanced LIGO Project Controls Leader. The Project Controls Leader will review the request for variance from the technical, cost and schedule baseline. Following the review, the request package will be forwarded to the appropriate Advanced LIGO control board. All requests against baseline technical parameters, configuration, and interface documents go to System Engineer for review. If the change is potentially significant, the Systems Engineer will convene the Advanced LIGO Technical Review Board (ALTRB). Requests against project baseline cost, schedule, and scope go to the Advanced LIGO Change Control Board (ALCCB), if the proposed change exceeds project defined thresholds. Baseline documentation in the DCC will be the primary review resource. The appropriate board will review the request and any review comments and make a recommendation to the Advanced LIGO Management. The chair person of the board, in association with the Project Leader, will issue a written notice of the decision. The Advanced LIGO Controls Leader will send out announcements of the ALCCB action and will maintain a log and file of all approved Change Requests.

6.4 Contingency Management and Change Control

Contingency for cost and schedule is generated by a detailed risk analysis for each project WBS element as described in Sections 5.1.2 and 6.1. Each subsystem has a Performance Measurement Baseline for cost and schedule that does not include contingency. All contingency resources are controlled by the Project Leader and are retained in separate accounts. Documented requests for reassignment of contingency resources are required for all cumulative cost changes within a subsystem which exceed $50,000 and all schedule changes to subsystem or Advanced LIGO project level milestones greater than one month.

Requests for Adjustments to the Performance Measurement Baseline are submitted by the cognizant subsystem leader to the Advanced LIGO Project Controls Leader. The Project Controls Leader submits the change request to the Advanced LIGO Change Control Board (ALCCB). The ALCCB will review the request for application of contingency and provide a recommendation to Advanced LIGO Project Management. The Project Manager chairs the Change Control Board and, in association with the Project Leader, will issue a written decision on the request. The granting of contingency resources is recorded as a change in the Advanced LIGO Performance Measurement Baseline. The Project Controls Leader is responsible for maintaining an accurate accounting of the use of contingency and maintaining a log and file of all approved change requests. Application of contingency will be reported to the NSF at WBS level 2 (project) in the Quarterly and Annual Reports (section 10) and tracked against the project Earned Value. NSF will be notified immediately of any contingency allocation in excess of $ 2.0 million or 2 months.

6.5 Quality Assurance and Quality Control

The Quality Assurance (QA) activity for the Advanced LIGO Project is a vital component in the delivery of a successful detector. A QA Officer will be designated who has the technical skills and background to address the issues in the context of Advanced LIGO. QA is a line management responsibility represented by the QA officer who reports to the Project Manager.

The Quality Assurance Program, as applied to the Advanced LIGO Project, encompasses Reliability, Maintainability, Interferometer Availability, and Quality Control. It is an integral part of the design, procurement, fabrication, and construction phases. The program objective is to ensure the completion of high quality, reliable advanced detectors. Achieving this goal requires all project participants to employ sound and accepted engineering practices and to comply with all applicable procedures.

6.5.1 Responsibilities

The Advanced LIGO Project Manager is responsible for defining the appropriate QA level for the different phases of the project. QA implementation is subject to review and audit by the LIGO QA Officer.

6.5.2 Reliability, Maintainability, Availability

The goal is to provide a long-lived and flexible interferometer, which will operate with minimum downtime for more than 10 years, and which will support a range of to-be-determined upgrades during its lifetime. Special attention is therefore devoted to any item which affects the operational reliability, maintainability, and availability of the detectors, and documented requirements will be developed and maintained as a part of the controlled Advanced LIGO configuration. To ensure that these goals are met, the

Advanced LIGO project has directed that all relevant QA aspects be continuously analyzed, evaluated, and incorporated during the design, material selection, fabrication, and construction phases. To ensure compliance with this directive, all relevant issues will be identified and specifically addressed as an integral part of each design review.

6.5.3 Quality Control

Procedures will be implemented describing the processes to be followed for all aspects of Quality Control (QC). Procedures will be established by the project to cover procurement, construction inspection, documentation, component inspection, parts inspection, vendor audit, and indoctrination and training of personnel.

Contractors performing design, fabrication, assembly, and construction tasks for the LIGO project will implement their own QC procedures and processes. These programs, procedures, and processes will be subject to review and audit by the LIGO QA Officer or his/her designees.

6.6 Business and Financial Controls

Administrative functions are provided at four levels: the University, the Department (Physics, Math, and Astronomy at Caltech and the Kavli Institute of Astrophysics and Space Research at MIT), the LIGO Laboratory, and the Advanced LIGO Project. Advanced LIGO will rely on existing infrastructure to the greatest extent practical to minimize costs and to assure adherence to commercial practices and government requirements. In some cases the university environment does not provide the infrastructure needed to manage a large development and construction effort. In these cases special systems are implemented at the LIGO Laboratory or Advanced LIGO Project level to buttress existing systems.

The support provided by the Universities includes:

- Finance (including data processing, the general ledger, and Cost Reporting)
- Procurements
- Accounts Payable
- Timekeeping
- Payroll
- Office of Sponsored Research
- Human Resources
- Legal
- Internal Audit
- Property Accounting
- Travel Services and Audit

Departmental support includes Visitor Appointments as well as administration of student and post doctoral assignments. The department is also involved in proposal review and approval and administration of non-site facilities.

The LIGO Laboratory Business Office located at Caltech is responsible for:

- Staffing (interfaces with the University Human Resources Departments for most needs. The size of the LIGO organization requires the assignment of individual specifically to track and support our staffing effort.)
- Time Reporting (entering data into the University systems)
- Subcontracts Management (involves a strong collaboration with the University Procurement Departments.)
- Finance (interfaces with the University Financial Systems to monitor costs and resolve problems)
- Preparation of budgets and Actual Cost reports for internal reporting
- Document Control
- Proposal Preparation
- Preparation of reports for LIGO Management, Advanced LIGO Project, and NSF
- LIGO Property Accounting (implements the special property requirements needed for Government Owned Equipment; closely integrated with the Caltech Property Accounting Group)

The Advanced LIGO Project Controls is responsible for:

- Maintaining the Budget Baseline
- Maintaining the Schedule Baseline
- Maintaining the Earned Value System
- Maintaining the Cost Estimate Database
- Change Control
- Preparing the Project Status Reports for the Advanced LIGO Project, LIGO Management, and the NSF
- Contingency Management
- Proposal Preparation

6.6.1 Cost Control

A consistent set of cost and schedule baselines (see sections 5.1 and 5.2) will be maintained and used to manage LIGO project costs and schedules. The following objectives guide the management of LIGO funds:

- all activities are planned to meet the technical performance goals, cost baseline, and milestone dates;
- all costs are properly recorded and applied against the appropriate funds;
- the status is routinely monitored and reported against the plan and value of work accomplished;
- early warning of potential cost or schedule problems provides a basis for management actions.

6.6.1.1 Responsibilities

All Advanced LIGO activities are assigned to a Subsystem Leader. Each Subsystem Leader is responsible for monitoring cost/schedule experience-to-date for his activities and for estimating cost-to-complete and scheduled completion on a monthly basis. The Subsystem Leaders shall take immediate corrective actions necessary to minimize projected deviations from cost and schedule baselines, without modifying the technical scope of their assigned tasks (or subcontracts). These corrective actions, when required, shall be assisted by the supervisor of the activity. Advanced LIGO Project Management has overall responsibility for cost and schedule monitoring, assessment, and reporting. These functions are supported by the LIGO Business and Advanced LIGO Project Controls Groups, which provide computer-automated cost and schedule tracking services, analysis assistance, and report generation and distribution.

6.6.1.2 Approach

When cost or schedule problems arise, the Project Manager (or his designee) will investigate and work with the cognizant Subsystem Leader (and Integrated Subsystem Leader when relevant) and subcontractor to take steps necessary to correct the situation within the resources allocated to the task. If the problem cannot be satisfactorily resolved in this manner, it may be necessary to

1. descope the task in question;
2. descope an unrelated task in order to divert resources to the task in question;
3. apply contingency funds to solve the problem;
4. take any other available action deemed prudent under the circumstances.

These actions may constitute changes to the controlled Advanced LIGO baseline, and will be proposed and reviewed following the Advanced LIGO change control procedures. Should problems arise that cannot be resolved within available resources without impacting essential Advanced LIGO features, the Advanced LIGO Leader and the LIGO Executive Director, in association with the Deputy Director, after consultation with the LIGO Oversight Committee, shall propose alternative choices to the NSF which include an assessment of supplemental funds required to preserve the current project scope, and recommended de-scoping of one or more essential features needed to complete the project within current resources. NSF shall then decide upon the action(s) to be taken.

6.6.1.3 Allocation of Costs

A requirement for LIGO and the NSF is that all LIGO costs during the Advanced LIGO Project must be recorded appropriately against the various funds provided, specifically MREFC and R&RA funds. The Standard Institutional (Caltech or MIT) Cost Allocation Systems will be used wherever possible.

The Caltech financial systems accrue costs in accordance with an account number tied uniquely to an award. LIGO will establish separate account numbers for each source of funding thereby properly segregating costs. The account number further reflects a project defined structure that allows us to identify and report costs for the various elements in our work breakdown structure and, further, to compare those costs with budgeted values at that level.

LIGO will use the Caltech systems for reporting labor and allocating labor costs. A web-based system (‘Kronos’) is used to report time worked and personal or lost time. Time allocation is entered directly into ORACLE. To properly allocate labor costs, LIGO has established a simple labor allocation report. The Caltech labor reporting system is based on a two-week cycle for most employees.

The labor allocation report comprises a list of all employees charging to LIGO Operations or Advanced LIGO. A default account allocation is identified on the report. This list will be distributed each labor reporting period to supervisors to approve and modify as needed.

The LIGO Business Office will distribute this report, collect the modifications, and enter any adjustments when required for direct employees. This is consistent with the system that has been used during Initial LIGO Construction and during LIGO Operations.

The LIGO Business Office will also provide the information concerning contract labor allocation to our subcontracts and payments personnel to assure that invoiced costs for contract labor are properly allocated. Occasionally contract modifications will be required.

6.6.1.4 Agency and Institutional Directives

In the event that NSF, Caltech, or MIT offer direction which significantly alters the scope, cost or schedule of planned activities, the LIGO Executive Director will notify NSF, in writing, of the cost and schedule impact of such alterations. Any significant changes, including changes in scope, require approval by the NSF Grants and Agreements Officer.

6.6.2 Subcontract Management

The largest tasks comprising the LIGO Project will be performed by sub-contractors (equipment represents over 60 percent of the total costs); these include modifications to the facilities and vacuum systems (including the beam tubes), and the fabrication of detector subsystems. Our objective is to accomplish these tasks in a timely fashion at the lowest possible cost. Competitive bidding will be used wherever possible. Firm-fixed price contracts will also be used whenever possible to minimize the risk of cost growth.

6.6.2.1 Responsibilities

The Advanced LIGO Project Manager is responsible for ensuring that all aspects of the subcontracts are planned and managed successfully. An acquisition plan will be prepared to support the procurement of major items as defined in the Advanced LIGO cooperative agreement. The Advanced LIGO Leader, in association with the LIGO Laboratory Executive Director, shall approve all major subcontracts. The LIGO Business Group is responsible for preparing, facilitating and administering the documentation associated with major LIGO procurements. The Subsystem Leaders will initiate subcontracts and procurements. Working closely with the Business Group, the Subsystem Leaders will be responsible to assure that all procured components, items, services and construction are produced and delivered as required to support the LIGO Laboratory objectives. The Subsystem Leaders will also provide technical direction and oversight of these contracts and procurements.

The Advanced LIGO Project Manager shall identify those subcontracts that require NSF approval and ensure that such approval and/or concurrence has been received before legally binding contracts are executed.

Advanced LIGO management will appoint the appropriate technical staff to be responsible for the technical management of the each subcontract.

Each major subcontract is managed by a Subsystem Leader (see Table 1). The Subsystem Leader will provide the technical direction and oversight of the subcontract through regularly scheduled communication and on-site visits as required. The Subsystem Leader is supported by the LIGO Business Group, which will prepare and facilitate contract documentation and provide cost and schedule data as appropriate. When cost or schedule problems arise, the Advanced LIGO Leader, Project Manager, cognizant Group Leader, and cognizant Subsystem Leader, together with appropriate subcontractor personnel, will work together to resolve the problem. The Subsystem Leader reports subcontract status during subsystem meetings.

6.6.2.2 Approach

Major Advanced LIGO fabrication will be performed using selected contracting methods (Firm Fixed Price, Cost Reimbursable Contracts, etc.) appropriate for each contract based upon detailed, documented acquisition planning. Subcontract terms will incorporate applicable flow-down requirements from the Cooperative Agreement. Sub-contract terms will provide for technical direction, progress payments based upon measurable performance milestones, and require delivery of programmatic data characteristic of cost-reimbursable contracts when used (detailed technical status, cost experience, and estimated cost-to-complete), which foster awareness of potential problems and permit the implementation of early corrective action through technical directives. The Subsystem Leader participates in regularly scheduled meetings at the subcontractor's facility to monitor technical progress and ensure that decisions are made in a timely manner. Technical specifications are identified up-front. Subcontractors are selected based upon their responsiveness to Request for Proposal (RFP) or Request for Quote (RFQ) requirements, relevant technical expertise, and financial capability to accept the risks related to the method of contracting. Technical and quality control, however, remain in the hands of the Advanced LIGO Project through requirements to review and approve subcontractor plans and procedures, contractually required formal design reviews, and provisions which permit Advanced LIGO Project inspection of work in progress.

Major procurements involving substantive efforts (corresponding to a dollar threshold to be determined with the NSF) will be submitted to NSF for approval or concurrence, in accordance with the Cooperative Agreement. LIGO Laboratory staff performs subcontract technical and programmatic management. All procurements and subcontracts will be subject to the terms and conditions of the Advanced LIGO and LIGO Laboratory Cooperative Agreements and the requirements of land sale and lease documents and Memoranda of Understanding pertaining to the LIGO Observatory sites.

6.6.3 Procurement and Subcontracts

Advanced LIGO procurements occur are executed at both Caltech (including the Caltech-managed Observatory sites) and MIT. These are processed according to the procedures established by the Purchasing Department at the host institution and approved by the appropriate government audit agencies.

All Advanced LIGO procurements will be processed and administered by the Caltech or MIT Purchasing Department depending upon the institution originating the procurement, assisted by the LIGO Laboratory staff.

Major procurements involving substantive efforts (corresponding to a dollar threshold to be determined with the NSF) will be submitted to NSF for approval or concurrence, in accordance with the Cooperative Agreement. Advanced LIGO Laboratory staff performs subcontract technical and programmatic management. All procurements and subcontracts will be subject to the terms and conditions of the Cooperative Agreement.

6.6.3.1 Approach

Procurement policies and procedures, embodied in the Caltech Purchasing Policy and Procedure Manual, will be utilized for all facilities and equipment procurement actions originating at Caltech or the Observatories. This manual establishes compliance with the NSF Cooperative Agreements. All major procurements that require NSF concurrence will be identified and scheduled in the annual Work Plan.

Similarly, procurements originating at MIT may be placed using corresponding policies and procedures at MIT. Both Caltech and MIT have procurement systems approved by the Office of Naval Research under OMB requirements.

7 Environment, Safety, and Health Protection

ES&H is a line management responsibility. The LIGO Laboratory Deputy Director is responsible for the overall ES&H programs for the Laboratory during the Advanced LIGO effort. At each Observatory site, the Observatory Head has responsibility for implementing ES&H programs at the Observatories. The Observatory Head will appoint a Safety Officer to coordinate and oversee E, H &S issues on a day-to-day basis.

During the Advanced LIGO Project, the Advanced LIGO Leader will be responsible for the ES&H aspects of the Advanced LIGO Project activities, under the coordination and overall responsibility of the Deputy Director. All policies and procedures for the overall Laboratory program will be followed for the Advanced LIGO Project. We describe the Laboratory policies and procedures below.

The LIGO facilities shall also comply with all policies and procedures in effect at the appropriate host institutions (Caltech for Caltech, Livingston, and Hanford; and MIT for MIT).

The LIGO ES&H program has the following specific objectives:

- to prevent personnel injury or loss of life;
- to prevent any environmental contamination;
- to prevent damage to equipment caused by accidents;
- to comply with all federal, state and local laws, rules and regulations.

7.1 Responsibilities

The LIGO ES&H program is the responsibility of the Deputy Director, who has responsibility to insure that LIGO staff members and collaborators identify specific ES&H issues and risks, and establish appropriate safeguards and procedures for addressing those risks.

7.2 Environmental Protection

The LIGO Laboratory shall follow standards and practices that fully support all applicable environmental protection policies and requirements.

7.3 Safety and Health Protection

Caltech has an established Safety Office, responsible for the Institute's overall safety and health program, and LIGO management will implement the applicable health and safety program elements as outlined in the Caltech Safety Manual. The Caltech Safety Office policies will be applicable to the Observatory sites, supplemented by additional policies developed by LIGO staff in consultation with the Caltech Safety Office. For work performed at MIT, the safety and health protection measures adopted by MIT will similarly apply.

The environmental health and safety personnel at Caltech and MIT will be used to help establish and review processes and procedures as well as to conduct facility audits.

7.4 Employee Training

Laboratory employees will be provided with procedures, training and information to ensure their safety. Briefings and presentations will be made to managers and supervisors to communicate ES&H policies and procedures.

Contractors, Collaborators and Visitors: Contractors and visitors to the LIGO operational sites will be informed of ES&H rules and procedures applicable to the specific area. Hosts will be responsible for the safety of visitors.

7.5 Documentation

The LIGO Laboratory shall provide hazard assessments, safety analyses and evaluations as required. Specific procedures and training documents will be prepared and released.

7.6 Governmental Code Requirements

The LIGO Laboratory, including its contractors, will comply with applicable US Federal Codes, laws and regulations, industrial codes and state rules, regulations and codes. The Administration Group, together with the Deputy Director, will be responsible for clarifying compliance requirements and the resolution of safety issues.

8 System Testing and Acceptance

The definition of subsystem test and evaluation, including acceptance criteria, are the responsibility of the associated subsystem development teams, subject to the review and approval of the Systems Engineering group. System and subsystem testing, evaluation and acceptance are incorporated into the Installation and Integrated Testing (INS) element of the Work Breakdown Structure (WBS). Individual subsystems will be reviewed and accepted (by Systems Engineering) as they meet acceptance criteria, while operating in-situ, after installation. Testing in-situ helps assure testing the as-built configuration, with the realized interfaces and in the operating environment. For subsystems comprised of multiple, stand-alone, testable implementations or instances of major sub-assemblies (e.g. SEI and SUS), the test, evaluation and acceptance is likely to be done on a sub-assembly basis.

Each interferometer (IFO), or overall detector system, will be tested, evaluated (by Systems Engineering) and accepted when all subsystems are installed, integrated, tested, accepted and the interferometer achieves “full lock”. “Full lock” is defined as achieving optical resonance in all optical cavities simultaneously for a period of at least 2 hours. The project will be complete when all three interferometers have achieved full lock and all Advanced LIGO equipment has been installed and accepted.

9 Transition to Operations

Operations of the LIGO Laboratory, supported by the R&RA under cooperative agreements, will continue throughout the duration of the Advanced LIGO Project. Initial LIGO observation will continue during the first three years of project funding. Through 2008, LIGO Laboratory staff supported under the existing Cooperative Agreement will be carrying out the remaining portions of the LIGO R&D program related to Advanced LIGO. As the R&D activities are concluded, some of the LIGO Laboratory staff will move on to Advanced LIGO fabrication and assembly tasks. Advanced LIGO construction funds will support the LIGO and the incremental staff required to carry out Advanced LIGO fabrication and assembly.

Following shutdown of the initial LIGO detector systems, a significant portion of the LIGO Laboratory staff becomes available to support Advanced LIGO installation and testing. In addition, incremental contractor staff will be added to support installation. These contractors are budgeted in the Advanced LIGO construction estimate.

Those LIGO Laboratory staff not involved in Advanced LIGO at any given time will continue to operate the two Observatory sites, maintaining the infrastructure, and supporting the Advanced LIGO use of the sites. LIGO Laboratory staff will be staffing the ongoing data analysis of initial LIGO data and data from collaborating instruments, the business office, and supporting research into upgrades for Advanced LIGO and other future detector development.

Participating LSC members from outside the LIGO Laboratory (supported by their own NSF and other funding) are expected to augment the instrument-science-focused aspects of integration and test of Advanced LIGO during the Project phase, and the commissioning after the end of the Project.

As individual subsystems are installed, tested and accepted, some of the LIGO staff will transition onto operations funds as they perform pre-operations activities such as commissioning and characterization of the accepted subsystems. Operators will begin to staff the control room once a sufficient subset of accepted interferometer subsystems enable interoperability (e.g., once a Seismic Isolation System (SEI) and an associated Suspension assembly are both accepted).

Following the completion of Advanced LIGO, many of the personnel involved in the design, fabrication, installation, and testing of those systems will become responsible for subsequent operations.

Details are provided and maintained in the Advanced LIGO Staffing Plan.

10 Reporting and Reviews

10.1 Annual Report

The LIGO Laboratory through the Caltech Office of Sponsored Research will submit an Annual Report to the NSF by August 1 summarizing overall progress during the past year, including results to date, and a comparison of actual accomplishments with the proposed goals in the latest approved Project Execution Plan; an indication of any current problems or favorable or unusual developments, and any other pertinent information. The Annual Report will also summarize the proposed goals for scientific and collaborative programs for the next program year. Proposed staffing levels, significant staffing changes, an organization chart, and an explanation of changes in the LIGO organization will be provided.

Advanced LIGO activities will be included in the Laboratory Annual Report, as a distinct section, reporting on the technical progress, cost, schedule, and management status and plans.

The Annual Report shall include a calendar of major scientific workshops and reviews, and an acquisition plan for all procurements in excess of $250,000, including the proposed date of submission to NSF and the type of procurement.

10.2 Quarterly Progress Reports

Advanced LIGO Project Quarterly Reports shall be prepared and submitted to NSF for each fiscal year. This report is prepared in accordance with the Cooperative Agreement and shall consist of a summary of work accomplished during the reporting period. The quarterly report will include major scientific and technical accomplishments, an assessment of current status against scheduled status, a review of current or anticipated problem areas and corrective actions, and a status of action items affecting participant responsibilities. This report shall also include management information such as changes in personnel, a financial status report and other financial information including actual or anticipated underruns or overruns, and any other action requiring NSF/IOG notification.

The financial information in the Quarterly Report will include a summary (to WBS level 2) of actual costs compared to the baseline estimated costs and graphs showing actual costs versus time compared with the planned budgeted cost profile. A narrative discussion of construction and R&D progress will be provided and referenced to the baseline schedule. The Report will include a description of all Change Control actions for key milestones or contingency usage, and any changes in the annual acquisition plan.

10.3 Technical Reports

To enhance the participation of the general scientific community in gravitational wave research, the LIGO Laboratory will continue the publication of research results in refereed journals, and will make unpublished internal technical reports available to the NSF and to the general scientific community on request.

10.4 Other Reporting

The Caltech Office of Financial Services submits to NSF a quarterly reconciliation report covering all NSF sponsored grants at Caltech, including LIGO. This report identifies the incurred expenditures for the quarter, cumulative expenditures effective at the close of the quarter, and the available balance against the allocation for the LIGO Laboratory.

Caltech will submit for approval by NSF all collaborative Memoranda of Understanding.

11 Meetings and Reviews

11.1 Internal LIGO Meetings

Technical and design reviews within the Advanced LIGO Project will be conducted by Advanced LIGO Project Management on a regular basis, to assess the status of design, construction and R&D activities, to update plans for future activities, and to resolve technical problems. Reviews of acquisitions and procurements and source selection meetings will be scheduled as required. There are also regularly scheduled meetings of the Advanced LIGO subsystem leaders, Integration Meetings, and meetings of the Risk Management team, Technical Review Board and of the Advanced LIGO Change Control Board.

11.2 The Program Advisory Committee

The LIGO Laboratory Executive Director shall convene the Program Advisory Committee as necessary, and the subcommittee on Advanced LIGO will meet at least once per year. The subcommittee shall provide analysis and advice to the LIGO Executive Director and the Advanced LIGO Leader. NSF shall be informed of all meetings, invited to attend, and shall receive copies of relevant reports.

11.3 The External Oversight Committee

The LIGO External Oversight Committee will hold regular meetings to review progress and to resolve institutional issues. Special meetings may be held to resolve particular issues that must be resolved before the next scheduled meeting.

11.4 NSF Reviews

The NSF will convene a visiting committee to conduct periodic reviews of the Advanced LIGO Project, covering technical and management issues. NSF shall provide the Project with the charge to the review committee prior to the review, with adequate time to agree on an agenda and to prepare the necessary materials.

It is desirable that there be substantial continuity of membership on these review committees.

11.5 Workshops

The LIGO Laboratory will sponsor or participate in workshops on specific topics relevant to the development of gravitational-wave interferometers, and specifically on Advanced LIGO topics. The frequency of such workshops and the topics they address will be determined in consultation with interested outside scientists, such as the Gravitational Wave International Committee (GWIC), the LIGO Scientific Collaboration (LSC), and the other international groups pursuing laser interferometer gravitational-wave detection.

12 GLOSSARY

BASELINE - A specific and quantitative expression of projected costs, schedule, or technical configuration to serve as a base or standard for measurement during the performance of an effort; the established plan against which the status of resources and the progress of a project can be measured.

CHANGE CONTROL - A documented process applying technical and management review and approval of changes to technical, schedule and cost baselines. Along with con-figuration identification at the beginning of a project and configuration audit at a project's conclusion, this process represents the way in which the project baseline is modified in a disciplined manner during the execution of a project.

CONFIGURATION MANAGEMENT - The formal process by which the baseline technical description of a project is identified and recorded, formally reviewed for proposed changes in a documented and auditable process, and verified at completion for conformity with the final documented baseline.

CONFIGURATION MANAGEMENT PLAN - The written plan establishing the detailed procedures to be followed in carrying out the configuration management of a project.

CONTINGENCY - A portion of the total project cost estimated to represent the technical, cost and schedule risks, which may emerge during project execution. The contingency is estimated on each component of the project and withheld in a single pool of funds to support the necessary responses to risks that actually emerge.

EARNED VALUE - The sum of the budget (estimated cost) for completed work, including scheduled work packages and the portion of level-of-effort work completed. Earned Value is used interchangeably with the term Budgeted Cost for Work Performed. It is the quantitative expression of the fraction of the project completed.

ESTIMATE TO COMPLETE - The cost estimate developed to represent a realistic appraisal of the cost estimate of the remaining work in a project.

INTEGRATED PROJECT SCIIEDULE - The comprehensive combination of all schedules in a project, including all subprojects, subsystem schedules and contracted work schedules.

MILESTONE - Finite defined events in a project schedule that constitute start, completion of a task or occurrence of an objective criterion for accomplishment. Milestones are discretely measurable; the passage of time itself is not sufficient to be a milestone. Milestones should be associated with a schedule date so that it can be determined when the milestone is to occur.

NETWORK - A flow diagram in a prescribed format consisting of the activities and events which must be accomplished to reach project objectives and showing their planned sequence and interrelationships.

PERFORMANCE MEASUREMENT BASELINE - The combination of the cost estimate for every element in the Work Breakdown Structure with the scheduled tasks in the Integrated Project Schedule. This produces a detailed, time phased budget plan for all work to be accomplished during project execution against which the project performance is measured.

WORK BREAKDOWN STRUCTURE - A product-oriented family tree division of activities and components which organizes, defines, and displays all of the work to be per-formed in accomplishing a project.