

LIGO Laboratory / LIGO Scientific Collaboration

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A+ Project Execution Plan

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This is an internal working note
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Signature Sheet

The following Digital Signatures are established in the LIGO Document Control Center for this document at <https://dcc.ligo.org/LIGO-M1800264>

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Revision Log

Date	Revision	Revision notes
3/11/19	-v1	Initial Release

1) A+ Project Overview

Advanced LIGO (aLIGO) has transformed gravitation, astrophysics, and cosmology by opening the gravitational-wave window on the universe and establishing a new paradigm for multimessenger observations. These achievements were based on novel and innovative precision-measurement technology that affords continuous, sub-attometer position measurement over multi-kilometer baselines, and spanning a broad range of astrophysical source frequencies.

Further advances in quantum optics and materials science now inspire improvements that can be implemented with modest incremental investment. These include an enhanced quantum-nondemolition readout employing frequency-dependent squeezing, and improved dielectric mirror coatings to suppress Brownian thermal noise. The *A+ Project* aims to implement these improvements in the LIGO instruments and return them to observational status as soon as 2024. Once operational, A+ will survey four to seven times more space, depending on the type of source, than the unmodified aLIGO detectors would cover, in effect collecting up to seven years worth of scientific data per future observing year.

Approximately 35% of the required equipment, and significant effort, will be contributed by UK-based LIGO Science Collaboration (LSC) groups, echoing both their historic roles in aLIGO and the corresponding support that was provided by the UK Science and Technology Facilities Council (STFC). Additional key hardware and effort will be provided by aLIGO partners at the Australian National University and the University of Adelaide, both of which are currently and proactively funded by the Australian Research Council (ARC) to support A+. The balance of the A+ upgrade, including overall coordination and management of the program will be the responsibility of the Caltech-MIT LIGO Laboratory on behalf of the U.S. National Science Foundation (NSF).

During some phases of its implementation, activities of the A+ Project will displace astrophysical observing and other select activities of the LIGO Laboratory, which is funded for continuing operations under a separate NSF cooperative service agreement. With concurrence of NSF, Laboratory personnel are thus at times made temporarily available to assist in execution of the A+ Project. The number of full-time-equivalent LIGO Laboratory staff members assigned to A+ will vary over the period of performance, with peak contributions occurring during the two planned observatory installation phases described below.

a) Scientific goals

The A+ upgrade can vastly improve the discovery potential of Advanced LIGO. Taking specific examples, the detection range for inspiral of compact binary systems will increase by a factor of approximately 1.9 for twin 1.4-solar-mass neutron stars, and by 1.6 for twin 30-solar-mass black holes, expanding surveyed volumes and detection rates, by factors of 6.6

and 4.1, respectively. Based on estimates derived from aLIGO detections made during its first two observing runs, A+ can be expected to see between 1 and 13 binary neutron star (BNS) events, and between 17 and 300 binary black hole (BBH) events, per month.

In addition, events similar to those previously detected in the early aLIGO runs will register in A+ with signal-to-noise ratio (SNR) exceeding 100:1. This degree of signal fidelity will permit resolution of subtle strain waveform details, supporting deep explorations of source and spacetime physics. Not least, the expanded horizon of A+ will increase the chance of opening up completely new discovery spaces through detection of unpredicted phenomena.

b) Technical Project Description

The Advanced LIGO baseline configuration confronts quantum noise at both high and low signal frequencies, while at intermediate frequencies (from about 50 to 200 Hz) it is constrained by thermal noise in interferometer mirror coatings. To address these limiting factors, A+ takes two lines of attack:

1. Reduction of broadband quantum noise through frequency-dependent squeezing and enhanced optical efficiency: Squeezed light injection, a means to control quantum uncertainty, has been tested in LIGO and GEO600, a 600 meter interferometer facility in Germany. A fully engineered squeezed-light injection system developed jointly with Australian National University has been installed in both LIGO instruments for the upcoming O3 observing run. An augmented technique, called frequency-dependent squeezing, has now also been demonstrated in the laboratory. This technique affords simultaneous reduction of both quantum phase noise in the high-frequency range, and quantum radiation pressure noise at lower frequencies. The introduction of an isolated, narrowband filter cavity, housed in an auxiliary vacuum enclosure, will allow simultaneous tuning of the effective quantum noise reduction quadrature to suit each band. In addition, increased apertures (including the interferometer's main beamsplitter), improved transmission efficiencies for optical elements such as Faraday isolators, and a new "Balanced Homodyne" (BHD) fringe readout technique will afford a greater depth of quantum-noise suppression overall, by further reducing the optical losses through which contaminating vacuum fluctuations enter.

2. Reduction of coating thermal noise through improved reflective coatings: At middle frequencies, aLIGO is limited by Brownian thermal fluctuations in the effective thickness of the interferometer's dielectric mirror coatings. The LSC and the NSF Center for Coating Research have embarked on a targeted program to develop compatible coatings with as little as one quarter the elastic dissipation of current examples. Substituting core optics with those equipped with such coatings will halve the contribution of thermal fluctuations to LIGO strain noise at mid-band frequencies.

c) Project Flow

Research and development (conducted off-Project) provides the technical basis for final designs of each A+ Project deliverable. In addition to performance, cost, and overall schedule, two further constraints specific to LIGO drive the Project flow: 1) a desire to minimize the observing down-time of the observatories, which are effectively the cornerstones of worldwide gravitational wave research, and 2) limits on the highly-skilled LIGO Laboratory manpower needed to assemble, install, and test the equipment, which predominantly comprises custom specialized instrumentation that is not available commercially.

The program sequence is envisioned as follows. Final design for facility and vacuum system modifications, seismic isolation, suspensions, control and data systems, interferometric sensing and control, and core optics will begin after award (with exception of test mass coating design, which is delayed to permit optimization from ongoing R&D).

Procurement, design, fabrication, and assembly of the primary infrastructure components, including observatory facility modifications, vacuum system extensions, and seismic isolation systems, are expected to be sufficiently complete within 18-24 months to permit installation during the planned LIGO observing hiatus immediately following O3, LIGO's third astrophysical observing run. This will set the stage for subsequent integration of the remaining suspensions, optics, and sensing and control components, which will be ready for installation following O4, LIGO's fourth observing run. By retiring conventional heavy construction well in advance, the A+ Project can sharply reduce the risk of delays in bringing the interferometers to observational readiness.

As applicable for each deliverable, Project scope comprises Final Design, Procurement and/or Fabrication, Assembly, Test, and Installation phases, including subsystem-level functional verification. Integrated joint commissioning with legacy aLIGO systems (i.e., as a complete interferometer at each site), sensitivity characterization and improvement, and operation for astrophysical observations will be the responsibility of LIGO Operations and Maintenance, and are excluded from Project scope.

d) Project Completion

The A+ Project will formally conclude upon successful demonstration that each included component and subsystem complies with its individual specifications. These specifications, along with testing methods and criteria for verification, are included in each subsystem's approved Final Design. Acceptance is based on completion of all subsystem tests and on delivery of associated procurement, process, QA, and test documentation. Upon acceptance, Project deliverables become the responsibility of LIGO Operations and Maintenance.

2) Project Organization

a) LIGO Laboratory Context

The A+ Project is managed and executed as a program of the LIGO Laboratory. The *LIGO Laboratory Charter* (LIGO-M060323) describes its mission, institutional relationships, chain of command, and infrastructure. LIGO Laboratory is managed by the California Institute of Technology and the Massachusetts Institute of Technology.

Within LIGO Laboratory, the A+ Project is configured as a LIGO Detector Improvement (DI) Program reporting against Laboratory Operations WBS category ALTS.DI. A+ engineering, human resource, planning, and business practices therefore conform with those of LIGO Laboratory, and typically share its common infrastructure. A+ Project Management will report to the LIGO Laboratory Directorate and is subject to all Laboratory oversight requirements, in addition to those specific to the A+ award.

LIGO Laboratory comprises approximately 170 full-time equivalent staff working at four geographical sites. The LIGO Hanford Observatory in Washington and the Livingston Observatory in Louisiana primarily maintain and operate the LIGO observing instruments and site facilities. The LIGO MIT and LIGO Caltech campus groups perform instrumentation research and development, instrument commissioning and detector characterization, detector engineering, scientific analyses, and overall Laboratory program management. All sites participate in education and public outreach. During periods of A+ installation, certain Observatory and campus group operations will be interrupted, making Laboratory technical personnel available to support the Project at its peak of activity.

b) A+ Project Organization

A+ is executed by the California Institute of Technology (Caltech) under U.S. National Science Foundation award PHY-1834382, with period of performance from 1 October, 2018 through 30 September, 2023. The Principal Investigator is Dr. David H. Reitze. Dr. Albert Lazzarini and Dr. Michael E. Zucker are Co-Principal Investigators. These individuals are designated as Key Personnel under the A+ award, and are thus committed to the Project under authority of the NSF Program Officer.

The A+ Project Management Team comprises the following individuals:

- Michael Zucker, Project Leader and Co-PI
- GariLynn Billingsley, Project Lead Engineer
- Hannah Hansen, Project Manager
- Bailey Toon, Project Planning and Controls Analyst

Group roles are described in detail below.

For efficiency, A+ participants and the Project Management Team will draw upon the existing LIGO Laboratory management, business, and technical resource matrix, such as budget analysis, procurement, human resources, travel, technical review, vacuum review, engineering change, fault tracking, and safety. A portion of planned additional Project labor will be allocated to augment such services, particularly under Business Office, System Engineering, Control and Data Systems, and Vacuum Engineering groups, in recognition of the increased Project-related demand during the period of performance. In order to capture corresponding contributions to Project earned value, tracking of defined Project effort will employ the existing LIGO Laboratory activity-based time reporting system.

c) LIGO Support Services – Business and Administration

The A+ Project receives support for its business activities from temporary hires, from the LIGO Laboratory Business Office, and from the MIT and Caltech Institutional administrative services. Support services personnel hired specifically for the Project are supervised by the project managers. Existing Laboratory staff are 'matrixed' to and supported by the Project as appropriate.

d) A+ International Partners

The A+ plan builds on the expertise and synergy of the joint international team that delivered Advanced LIGO (aLIGO). As before, realizing this benefit depends on coordinated support from their respective national funding agencies. Approximately 35% of the total required equipment value and significant effort for the Project will be contributed by UK-based collaborating groups, echoing both their historic roles in aLIGO and the corresponding support that was provided by the UK Science and Technology Facilities Council (STFC). Additional key hardware and effort will be provided by partners at the Australian National University and the University of Adelaide, which are each funded to support A+ under Australian Research Council (ARC) awards. The balance of the A+ upgrade, including overall coordination and management of the program, will be the responsibility of the Caltech-MIT LIGO Laboratory on behalf of the NSF. The Laboratory maintains fiducial responsibility for managing the Project and maintaining overall scope and schedule.

International partners will report to the A+ Project Lead and Project Lead Engineer, and each has pledged to contribute staff hours to shared A+ Systems Engineering and Project Management functions in addition to their designated deliverables. International contributions are subject to all applicable LIGO Laboratory engineering standards and practices, oversight, and configuration control requirements. International contributors will also provide periodic schedule status updates for integration with the master Project schedule. International participants will not be subject to Earned Value tracking.

UK participants in A+, funded under independent UKRI/STFC funding, include members of the following research groups:

Glasgow University (UK lead institution),

UKRI/STFC Rutherford Appleton Laboratory
 Birmingham University
 University of Strathclyde
 Cardiff University

Australian participants in A+, funded under independent Australian Research Council (ARC) award, include:

Australian National University (Australia lead institution)
 University of Adelaide

A Memorandum of Understanding codifying roles, responsibilities, key deliverables, and performance milestones will be executed between LIGO Laboratory and the lead institution of each international partner.

e) A+ Project Work Breakdown Structure

The Work Breakdown Structure (WBS) for the A+ LIGO Project is divided into nine major subsystems or elements. Summary descriptions of each subsystem are given below. A detailed A+ Project Work Breakdown Structure Dictionary is maintained as a controlled document in the LIGO Document Control Center.

Code	Title	Subsystem Lead	Description	US	UK	AUS
1. PM	Project Management	Zucker	Resource management, safety, budget, scheduling, earned value reporting, contingency allocation, procurement, travel	✓	✓	✓
2. SYS	Systems Engineering	Torrie	System integration, interface control, standards compliance, integrated layout and ray tracing, stray light control, installation tooling, installation and test coordination, quality assurance	✓	✓	✓
3. VAC	Vacuum System Modifications	Romel	Decommissioning, rearrangement and recycling of legacy H2 vacuum chambers, creation/adaptation of new 300m auxiliary beamtube, vessels, and support systems to house FDS filter cavity at each site	✓		
4. FAC	Facility Modifications	Oram	Alterations to corner stations and creation of new FC beamtube enclosures and end station laboratory structures at each site; support for interferometer subsystem installation	✓		
5. CDS	Control and Data Systems	Abbott	Electronic modules, sensors, cabling, feedthroughs and software to support control and operation of ISC, SUS, and SEI components	✓	✓	

6. COC	Core Optic Components	Billingsley	Filter cavity mirrors, enlarged main beamsplitters, and input and end test masses bearing reduced-dissipation reflective coatings	✓	✓	
7. SUS	Suspensions	Robertson	Isolated suspensions for beamsplitters, filter cavity mirrors, readout components, and beam relays; improved suspension fiber infrastructure, and tooling for core optics installation	✓	✓	
8. SEI	Seismic Isolation	Mason	Active single-stage seismic isolation platforms for filter cavity end mirrors	✓		
9. ISC	Interferometric Sensing and Control	Barsotti	Balanced homodyne antisymmetric port readout, adaptive mode matching, high-efficiency optical isolators, squeezed light injection adaptation, and frequency-dependent squeezing filter cavity control	✓	✓	✓

Table 1: Project work breakdown structure (WBS) and definitions, denoting areas of US, UK and Australian participation.

i) WBS 1: Project Management (PM)

The Project Management group includes the A+ Project Leader, Lead Engineer, Project Manager, Cost-Schedule Analyst, and Procurement Official. This group is responsible for the budget and schedule baseline and change control as well as earned-value reporting for the Project. Project Management also carries responsibility for cost contingency allocation, staffing and resource management, Project procurements, and all Project travel. Finally, Project Management oversees health and safety for all aspects of the A+ Project.

ii) WBS 2: Systems Engineering (SYS)

The A+ System Engineering group is responsible for defining, auditing, and controlling subsystem performance and interface requirements. To accomplish this, A+ Systems oversees integrated system performance modeling and analysis, and builds and maintains the Integrated Optomechanical Layout which captures the physical arrangements of A+ deliverables within the as-built Advanced LIGO context. Systems Engineering is responsible for all Engineering and Fabrication standards, including Quality Assurance/Control (QA/QC), Contamination Control, ElectroMagnetic Compatibility (EMC), Software Version Control, and Engineering Configuration Management. Systems manages the review of proposed engineering changes by convening the Technical Review Board (TRB).

In addition to these global functions, A+ Systems Engineering is also responsible for furnishing general-use installation tooling as needed to accommodate new installation scenarios and protocols of the A+ design. The Systems Engineering team will also furnish the integrated stray light baffling required to protect new in-vacuo A+ optical elements and

existing aLIGO legacy elements which become displaced or exposed by the A+ implementation.

iii) WBS 3: Vacuum Equipment (VAC)

The Vacuum (VAC) subsystem for A+ comprises modifications and additions to the LIGO vacuum equipment at LHO and LLO to accommodate the A+ filter cavity and ancillary support equipment. This includes decommissioning, removal and/or reuse of certain H2 chambers, adapters spools and heads, and rigging and shipping such recovered items to Livingston as needed. It also includes a new 300m beam tube along with tube supports, transitions, expansion joints, pumping, and instrumentation at each observatory. Finally, it includes provision for volume isolation and for piecewise vacuum bakeout.

iv) WBS 4: Facilities Modification (FAC)

The A+ Facility (FAC) subsystem oversees the design and construction of Facility modifications to accommodate A+ Filter Cavity (FC) vacuum system additions at Livingston and Hanford, and to support installation and operation of corresponding internal components. Specific deliverables include minor modifications to each site's corner station Laser and Vacuum Equipment Area (LVEA); a new foundation slab and enclosure building for the FC beam tube, paralleling the Y arm for approximately 250m at each site; and a new utility-equipped laboratory building to house the FC endstation assembly.

v) WBS 5: Control & Data Systems (CDS)

The A+ Control & Data Systems (CDS) consists of all custom and commercial electronics assemblies, in-air and in-vacuum cabling, and vacuum feedthroughs associated with the Single Stage Internal Seismic Isolation (ISI); various types of Suspensions; Readout Cavity (RC) alignment and length sensing controls; Filter Cavity (FC) alignment; and length sensing controls. It also includes a category for shared components including DC Power Supplies, 19-inch racks, vacuum controls, and Realtime Computing.

vi) WBS 6: Core Optic Components (COC)

The Core Optics Components (COC) subsystem will provide design, fabrication oversight, characterization and transportation of six end test masses (ETMs), six input test masses (ITMs), three beamsplitters (BS), and 8 Filter Cavity optics. COC provides for a coating pathfinder phase, assuming a scientific solution for low thermal noise coating is found and supplied by the Center for Coating Research (PHY-1708175.) Scaling of that solution occurs on the A+ Project during the pathfinder phase to meet the remaining aLIGO coating requirements.

vii) WBS 7: Suspensions (SUS)

This WBS element comprises the following suspensions for optics in A+: triple suspensions for the 300m filter cavity based on the current aLIGO HSTS design. This element does not include other electronics and cabling for suspensions. Those items are covered in the CDS

WBS element. It also does not include the optics for these suspensions, which are in the COC WBS element. Liaison for various other suspensions and suspension-related items in the SUS element are being contributed by the UK. The UK contributions for this element are:

- a) Beamsplitter (BS) suspensions for large BS optic (design and production)
- b) Compact triple suspensions for relay optics, to a design provided by the U.S.
- c) Vacuum optical parametric oscillator (VOPO)-style suspensions as part of the readout system, based on a design provided by the U.S.
- d) B-type Optical Sensor Electromagnetic Motors (BOSEMs) for all of the UK-delivered suspensions
- e) Upgrades to the existing aLIGO silica fiber pulling and welding systems for improved performance

viii) WBS 8: Seismic Isolation (SEI)

The A+ Seismic Isolation (SEI) scope includes four HAM ISI isolation platforms to be installed in re-located HAM chambers, along with the structure supporting the platforms to the ground. This element includes the masses needed to balance the payload but does not include internal cabling and feedthroughs, which will be supplied by the CDS group.

ix) WBS 9: Interferometer Sensing and Control (ISC)

This WBS element comprises equipment for the (a) filter cavity optical components - opto-mechanical components for the filter cavity tables, (b) mode-matching and relay optics for static mode-matching telescopes for the squeezer and filter cavity - this covers the 2" curved optics, manufacture, and coating, (c) low-loss Faraday isolators replacing the Output Faraday Isolator (FI) optical elements - polarizing beam splitters and crystals - and for FIs that are integrated into the squeezer, and (d) actuators and sensors for active wavefront control to maximize mode-matching between (i) squeezer (SQZ) and FC, (ii) FC and interferometer (IFO), (iii) IFO and output mode cleaner (OMC), and (iv) local oscillator (LO) and OMC.

3) Project Controls

a) Environment, Safety and Health Protection

The A+ Project Leader is responsible for ensuring that A+ activities conform to the *LIGO Observatory Operational Safety & Environmental Protection Manual*, [LIGO-M980242](#). In particular, this protocol requires that subsystem designs and installation procedures be subjected to formal Hazard Analysis as part of their approval cycles, and that any required mitigations are certified before the activity may proceed. Compliance is monitored by the LIGO Laboratory Safety Officer, who reports to the Laboratory Deputy Director and maintains delegates at all LIGO worksites. The LIGO Safety Officer also coordinates

mandatory safety awareness education and safety training for all A+ participants, including foreign contributors and visitors to LIGO worksites.

b) Risk Management

The objective of A+ risk management is to anticipate, mitigate and retire risks proactively and thus avoid adverse Project impacts. A+ employs a risk management paradigm modeled on that of the Advanced LIGO Project. It is fully coordinated with the concurrent LIGO Laboratory Operations and Maintenance risk management system. Accountability for A+ risk management is a defined duty of each Project participant. The Project Lead, Project Lead Engineer, and Project Manager carry joint supervisory responsibility for risk management.

The primary vehicle for anticipating, dynamically tracking, and assessing A+ risks is the *A+ Project Risk Register* ([LIGO-M1900020](#)). This repository is continuously reviewed and updated by A+ Management in collaboration with A+ Subsystem Leaders as possible threats are identified, mitigated and retired throughout the performance of the Project. The Risk Register comprises a database of identified threats, each of which is characterized by its estimated probability, potential severity or mission impact, feasibility, cost and time to effect possible mitigations, and other details pertinent to formulating a response that best avoids adverse consequences.

Risk register entries may be proposed by any participant and are collectively reviewed on a monthly basis. This review updates each threat in light of new data and assesses the effectiveness of applied mitigation. The Project Management team may demote in priority or fully retire risk entries which are shown to have been mitigated. A subset of active entries, deemed *Significant Risks*, will be highlighted and tracked in periodic reports. These are the risks which carry substantial potential for adverse mission impact but have not been fully mitigated as of the reporting date.

c) Document Revision Control

All A+ Project documents are entered in the LIGO Laboratory Document Control Center (DCC), which supports electronic storage, dissemination, indexing, search, and archiving of LIGO documentation. The DCC is located and staffed in the LIGO Business Group, which reports to the Laboratory Deputy Director. The DCC includes an electronic database of document meta-data which affords document revision control and authenticated signature approval. For all subcontracted A+ efforts, the requirements, specifications, interface drawings, documentation, and contract deliverables will be under formal configuration management throughout the contracted period.

d) Technical Configuration Control

A+ configuration management is the joint responsibility of A+ Project Management and A+ Project Systems Engineering under concurrence of the LIGO Laboratory Systems Engineer and Systems Scientist. Engineering standards, practices, and documentation protocols for

A+ will conform to existing LIGO standards. These standards include establishing approved baseline designs, typically at Final Design approval, which are thereafter placed under formal configuration control. A+ will follow the existing engineering configuration and change control protocol used for all design aspects of LIGO detectors. This is established in *A+ Upgrade Engineering Process* ([LIGO-M1800239](#)), which affirms compliance with *Guidelines for Advanced LIGO Detector Improvement (DI) Project Reviews* ([LIGO-M1500263](#)), and *Engineering Change Request (ECR) Process* ([LIGO-M1200274](#)).

e) Earned Value Tracking

A+ will use Earned Value Management (EVM) 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 measurement. Earned Value 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 A+ Project Manager is responsible for implementing EVM on the project. The project scope of work is planned and organized by Work Breakdown Structure (WBS) to create a cost and schedule baseline. Microsoft Project is utilized to develop and maintain the Project baseline schedule. Progress status is collected on a monthly basis, including schedule progress and actual cost from CIT Accounting. Earned Value Management reporting will be at Level 2 of the Work Breakdown Structure (WBS). Discussion of variances and plans for recovery when variances exceed +/-10% or revisions of a Level 1 schedule milestone by more than 1 month are a requirement of the NSF award. Reports include variances and forecasted estimate to complete (ETC) information that will be generated on a monthly basis by the A+ Project Planning and Controls Analyst. Performance reports, analysis, and corrective actions are distributed to the A+ Project team. This information is provided to NSF on quarterly and annual bases per the reporting requirements in award PHY-1834382.

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

f) Budget and Schedule Change Control

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 a separate account. Documented requests for reassignment of contingency resources are required for all cumulative cost changes within a subsystem which exceed \$75,000 and all schedule changes to subsystem or A+ Project level milestones greater than one month.

Budget control will be exercised through the existing LIGO Laboratory budget change process (LIGO-M1400104). For A+ Project scope, the *Change Control Board* will comprise:

- David Reitze, PI
- Albert Lazzarini, Co-PI
- Michael Zucker, Project Lead and Co-PI
- GariLynn Billingsley, Project Lead Engineer
- Hannah Hansen, Project Manager
- Calum Torrie, Systems Engineer

g) Management and Application of Project Contingency

Contingency budget is retained in a separate account under Project Management. Use of the contingency budget is for equipment, materials, and services only. The use of contingency is subject to the change control process, as described above. Any contingency greater than \$250k must also be approved by the NSF prior to dissemination. As noted in the award, in the event of an emergency that threatens imminent harm to life or property, NSF authorizes the Awardee to use contingency exceeding \$250,000. NSF will be informed with a detailed rationale as soon as practicable and no later than 24 hours of the emergency.

h) Quality Assurance and Quality Control

A+ Quality Assurance is governed by LIGO-M960076, *Advanced LIGO Quality Assurance Plan*. This plan establishes and maintains a program to administer the quality aspects of the LIGO Project. The plan is applicable to the development, design, qualification, procurement, acquisition, test, and installation of equipment that together, comprise the LIGO observatories. The provisions of this plan encompass all parts and assemblies including tooling, consumables, and services that are used in the development of the LIGO observatories. For the A+ project, the authority of the QA officer for each Project deliverable is assigned by the Project Lead Engineer.

i) Business and Financial Controls

Administrative functions are provided at four levels: the Institutes (Caltech and MIT), the Departments (Physics, Math, and Astronomy (PMA) at Caltech, and the Kavli Institute of Astrophysics and Space Research at MIT), the LIGO Laboratory, and the A+Project. The Business Office of the LIGO Laboratory is based at the LIGO Hanford Observatory and at Caltech. The A+ Project will rely on existing infrastructure to the greatest extent practical to minimize costs and to assure adherence to commercial practices and government requirements.

The support provided by the Universities includes:

- Finance (including data processing, the general ledger, and cash drawdowns)
- A certified Procurement System with large dollar value procurement review and approval (over \$500k)

- Accounts Payable processing
- Time Reporting Software (Kronos)
- Payroll
- Office of Sponsored Research
- Human Resources
- Office of General Council
- Internal Audit
- Property Accounting
- PCard Report processing: Audit and Payment

PMA Departmental support includes Visitor Appointments as well as administration of undergraduate students, graduate students and postdoctoral assignments. The department is also involved in proposal review and approval and administration of non-site facilities.

The LIGO Laboratory Business Office supports the project with the following responsibilities:

- 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.)
- Travel Services
- Procurement Management Oversight and any required NSF Procurement Approvals
- Time Reporting (entering data into the University systems)
- Finance (interfaces with the University Financial Systems to monitor costs and resolve problems)
- Preparation of budgets and Actual Cost reports for internal reporting
- LIGO Property and Logistics (implements the special property requirements needed for Government Owned Equipment; closely integrated with the Caltech Property Accounting Group)

The A+ Project Controls and Administrative Services staff are responsible for:

- Subcontracts Management (involves a strong collaboration with the University Procurement Departments)
- Procurement Services
- Maintaining the Budget Baseline
- Maintaining the Schedule Baseline
- Maintaining the Cost Estimate
- Change Control
- Preparing the Project Status Reports for the A+ Project, LIGO Management, and the NSF
- Contingency Management

i) Cost Control

A consistent set of cost and schedule baselines will be maintained and used to manage A+ 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.

(1) Responsibilities

Each Subsystem Leader (refer to Table 1) is responsible for monitoring cost/schedule experience-to-date for their 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. A+ Project Management has overall responsibility for cost and schedule monitoring, assessment, and reporting. These functions are supported by the A+Project Controls and Administrative Services staff, which provide cost and schedule tracking services, analysis assistance, and report generation and distribution.

(2) Approach

When cost or schedule problems arise, the Project Manager (or designee) will investigate and work with the cognizant Subsystem Leader 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.

In extreme cases, an unforeseen adversity may ultimately force alterations to the controlled A+ Project baseline. Should A+ award resources be deemed insufficient to address such an obstacle without compromising essential A+ Project objectives and features, the A+ Leader, Principal Investigator and Co-Principal Investigator(s) will formulate a proposal for consideration by the NSF Program Officer. This proposal will include an assessment of supplemental funds that would be required to maintain original Project scope, as well as feasible options to de-scope one or more essential Project features or objectives so as to carry on under existing resource constraints. NSF will be asked to evaluate this proposal and provide appropriate direction.

(3) Allocation of Costs

A requirement for LIGO and the NSF is that all LIGO costs during the A+ Project must be recorded appropriately against the various funds provided. In order to accomplish this in an auditable way, 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 structures. These costs include labor, procurements, and other costs incurred in the execution of the project.

LIGO will use Caltech and LIGO Laboratory systems for reporting labor and allocating labor costs incurred at Caltech and the LIGO sites at Hanford Washington and Livingston Louisiana. A web-based system ('Kronos') is used to report time worked for overtime-eligible (OTE) staff and for all other exempt bi-weekly staff to record full day absences. Caltech has developed an application for LIGO to record percent effort by account number on a bi-weekly basis. This application will interface directly with Oracle Labor Distribution to ensure effort is reported within Oracle, Caltech Accounting System. A labor allocation report will be distributed monthly to supervisors to review. The report comprises a list of all employees charging to LIGO Operations or the A+ Project. The LIGO Laboratory Financial Analyst will distribute this report, collect the modifications, and enter any adjustments when required for direct employees.

This approach is consistent with the system that is being utilized by the corresponding LIGO Operations & Management award.

Procurement costs related to A+ will be charged to the appropriate accounts linked to the A+ award. All A+ LIGO work performed at collaborating institutions outside of Caltech and MIT will be through subcontracts.

(4) Agency and Institutional Directives

In the event that NSF, Caltech, or MIT offer direction that 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.

ii) Procurement and Subcontract Management

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 routed to NSF for approval prior to award. An acquisition plan will be included in the Annual Work Plan.

The largest tasks comprising the A+ Project will be performed by subcontractors; these include modifying the facilities and vacuum systems, and fabricating 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.

The procurement group within the Business Office is responsible for preparing, facilitating, and administering the documentation associated with major A+ LIGO procurements. The A+ Project Manager shall approve all major A+ subcontracts. The A+ Project Planning and Controls Analyst along with the Procurement 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. Major procurements involving substantive efforts and/or which exceed \$250K will be submitted to NSF for approval or concurrence in accordance with the Cooperative Agreement.

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 Office Procurement Group, which will prepare and facilitate contract documentation and provide cost and schedule data as appropriate. When cost or schedule problems arise, the A+ Project Leader, Project Manager, buyer, and Subsystem Leader, will work together to resolve the problem. The Subsystem Leader reports subcontract status during project meetings.

4) 4 Reporting

a) Annual Report

The LIGO Laboratory, through the Caltech Office of Sponsored Research, will submit an A+ LIGO Annual Report to the NSF by the due dates outlined in the Cooperative Support Agreement summarizing overall progress during the past calendar 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.

A+ LIGO activities will be covered in the Annual Report, reporting on the technical progress, cost, schedule, and management status and plans.

b) Annual Work Plan

The LIGO Laboratory through the Caltech Office of Sponsored Research will submit an A+ LIGO Annual Work Plan (AWP) to the NSF by the due dates outlined in the Cooperative Support Agreement summarizing overall planned tasks for the upcoming fiscal year. The AWP will include goals/objective, activity-based budget that traces the budget for the coming year, and schedule for work to be performed to the current project baseline. The AWP will include a Basis of Estimate for planned expenditures and labor.

The Annual Work Plan shall include an acquisition plan for all procurements anticipated to exceed \$250,000, including the proposed date of submission to NSF and the type of procurement.

c) Quarterly or Monthly Report

A+ LIGO Project Quarterly Reports shall be prepared and submitted to NSF for each fiscal quarter. This report is prepared in accordance with the Cooperative Agreement, LIGO-M1800243 and shall consist of a summary of work accomplished during the reporting period. The quarterly reports will include major scientific and technical accomplishments, an assessment of current status against scheduled status, and a review of current or anticipated problem areas and corrective actions. 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 notification. Beginning in FY2020 the cadence of these reports will be monthly.

d) NSF Reviews

The NSF will convene a visiting committee to conduct periodic reviews of the A+ LIGO Project covering technical and management issues. The project progress will be reviewed annually during the corresponding panel reviews of the related award for LIGO Operations & Management.

5) 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 configuration 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 SCHEDULE- 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.

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 performed in accomplishing a project.