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LIGO PROJECT MANAGEMENT PLAN

October, 1997

CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LIGO PROJECT

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Approved by:

______________________ Date 10/27/97
Gary H. Sanders, LIGO Project Manager

______________________ Date 10/27/97
Barry Barish, LIGO Principal Investigator

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- tests of General Relativity in the strong field and high velocity limit;
- direct measurement of the polarization and propagation speed of gravitational waves;
- direct observation of the dynamics of black holes.

Possible observations in astronomy and astrophysics which may not be measurable by other methods include:

- the final moments of the coalescence of extragalactic binary neutron star systems, which are the most reliably predicted sources and serve as the design benchmark for the sensitivity and spectral coverage of LIGO;
- the coalescence of black-hole/black-hole and black-hole/neutron-star binary systems;
- the inner dynamics of stellar collapse; the internal and surface dynamics of a neutron star;
- the dynamics of the primordial universe at the earliest stages of cosmic evolution;
- an inventory of the gravitational-wave sources distributed throughout the universe.

It is highly likely, as has been the experience in opening other branches of observational astrophysics, that LIGO will expose new classes of sources. The LIGO facilities are designed to accommodate a succession of detection systems with enhanced sensitivity and adjustable spectral response to retain flexibility in the exploratory phase of the science and to optimize the scientific returns once gravitational waves have been detected.

1.2.2. TECHNICAL OBJECTIVES

The initial phase of LIGO will encompass the minimum facilities necessary for successful detection of gravitational waves: a continuously operating triple coincidence detector comprising three broadband interferometers, operated at two widely separated sites. Initial interferometers are based on reasonable extrapolations from experience with current gravitational-wave detector prototypes, ancillary experiments and modeling. Specifications for the initial interferometers are given in Table 1-1. The projected rms strain sensitivity of $\sim 10^{-21}$ in a spectral region near a few hundred hertz is based on a detailed noise budget which gives the characteristic frequency dependence of interferometer noise. The spectral noise density and the noise budget are shown in Fig. 1-1, which is a reproduction of Fig. II-2 and V-3 of the LIGO Proposal, Volume I.[5] This projected sensitivity is an improvement of several orders of magnitude over the best current detectors, and according to theo-

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5. Please refer to the text associated with Fig. V-3 in the LIGO Proposal (Vol. I) for a discussion of the basis of the noise budget.

retical estimates, may allow detection of predictable sources at a rate of several per year. The nominal frequency band will cover the range of a few hertz to several kilohertz.

Table 1-1. Initial interferometer specifications

Strain Sensitivity [rms, 100 Hz band]	10^{-21}
Displacement Sensitivity [rms, 100 Hz band]	4×10^{-18} *m*
Fabry-Perot Arm Length	4000 *m*
Vacuum Level	< 10^{-6} *torr*
Laser Wavelength	1064 *nm*
Optical Power at Laser Output	10 *W*
Optical Power at Interferometer Input	5 *W*
Power Recycling Factor	30
Input Mirror Properties	Reflectivity = 0.97
End Mirror Properties	Reflectivity > 0.9998
Arm Cavity Optical Loss	≤ 3%
Light Storage Time in Arms	1 *ms*
Test Masses	Fused Silica, 11 *kg*
Mirror Diameter	25 *cm*
Test Mass Period Pendulum	1 *sec*
Seismic Isolation System	Passive, 4 stage
Seismic Isolation System Horizontal Attenuation	≥ 10^{-7} (100 *Hz*)
Maximum Background Pulse Rate	1 *per minute*

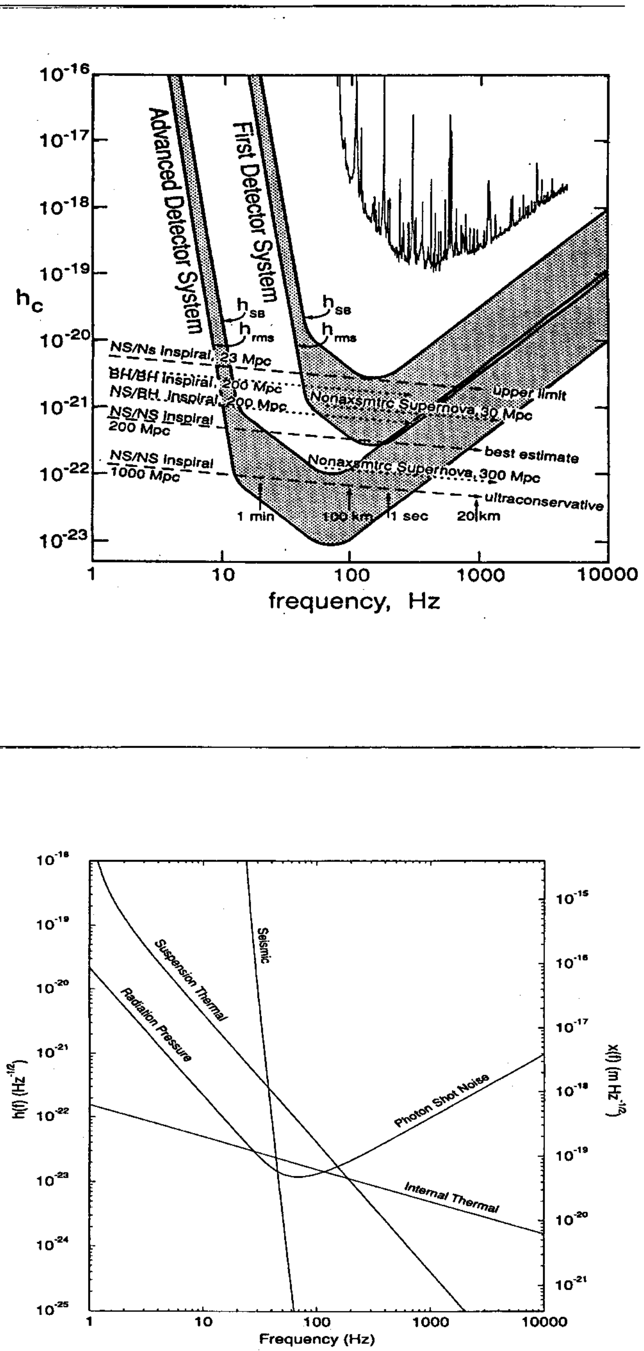

Figure 1-1. Initial interferometer spectral noise density (a) and noise budget (b). The uppermost curve on the top plot is the rms strain sensitivity of the 40m prototype as of October 28, 1994 displayed for comparative purposes.

1.2.3. PROJECT OBJECTIVES

The Project objective is to build LIGO (described in section 1.3) and to prepare it to operate as a gravitational-wave observatory. The essential characteristics of the facilities accommodating the interferometers are identified in Volume 1, Section IV of the LIGO Proposal:

- two widely separated sites under common management;
- vacuum systems to accommodate interferometer arm lengths of up to 4 km at each site;
- the ability to operate several interferometric detectors at each site simultaneously and without mutual interference;
- the ability to accommodate interferometers of two different arm lengths, at least at one site;
- a vacuum tube with a clear aperture of approximately 1 meter for the full length of the arms;
- the ability to produce a vacuum of order 10^{-9} torr of hydrogen and 10^{-10} torr of other gases;
- a minimum 20-year lifetime of the facilities; complete support instrumentation.

1.3. PROJECT DESCRIPTION

The major LIGO facilities consist of vacuum systems at two widely separated sites - Hanford, Washington and Livingston, Louisiana. The vacuum systems, in the shape of an *L* with 4 km arms, enclose laser interferometer beams. The beams originate and are detected at the vertex of the *L* (corner station) and are reflected from the ends of the *L* (end stations). At the Washington site, additional mirrors are placed at the midpoints (mid stations) of the arms to establish half length interferometers. The system comprising three interferometers, a full length and a half length at Washington and a full length at Louisiana operates in triple coincidence as a single gravitational-wave detector.

The vacuum system consists of two elements: the beam tubes running along the arms of the *L* and the vacuum chambers and associated tubing at the corner stations, end stations and mid stations (Washington). The vacuum chambers contain the test masses (end points of the interferometer) and their associated seismic isolation systems, the interferometer optics, the optics for beam injection and extraction from the interferometer and the electro-optic and mechanical instrumentation to maintain interferometer alignment and to detect the measured gravitational-wave signal.

The beam tubes are enclosed in a cover for protection and to reduce interferometer noise from scattered light due to wind driven motions of the tubes.

The buildings at both sites are designed to accommodate possible, but not yet proposed to NSF, expansion to a multiple detector phase of LIGO. In addition to the vacuum chambers and pumps, the corner station houses the facility and interferometer control systems, the laser power and cooling systems, the data archiving and facility computer systems, office space for staff and visitors, staging areas, equipment receiving areas and small electronic and mechanical shops. The mid station and end station buildings are smaller, containing only vacuum chambers, pumps, and equipment receiving and staging areas.

Full bandwidth analog strain signals from the interferometers will be digitized and recorded continuously for off-site analysis. Ancillary signals monitoring the state of the instrument, the facility and the environment will be archived continuously. Data will be analyzed for coincident bursts, periodic sources and a stochastic background of gravitational waves.

2.0 ORGANIZATION, RESPONSIBILITIES

2.1. INSTITUTIONAL ROLES AND RESPONSIBILITIES

The LIGO Project is conducted in accordance with the Cooperative Agreement between NSF and Caltech. The organizational hierarchy is shown in Figure 2-1.

NSF is responsible for providing funding, general oversight, monitoring, and evaluation to help assure project performance in accordance with approved plans. NSF will strive to obtain funding consistent with the Target Funding Level profile set forth in the Cooperative Agreement. The actual funding available for LIGO will be negotiated with the Project on the basis of the Annual LIGO Work Plan which, upon approval by NSF, will constitute the official operating plan for the year. Within the framework of the annual operating plan, NSF undertakes to provide the funding in a timely fashion and to provide the necessary document reviews and approvals as indicated in the Work Plan schedules.

Within the NSF, the LIGO Program Manager is responsible for scientific, technical, cost and schedule review and agency guidance. Review of progress and programmatic review of annual work plans is the responsibility of the LIGO Program Manager. Direct communication between the LIGO Program Manager and the LIGO Project is the method by which this review and guidance will be accomplished. Performance of work under the Cooperative Agreement is subject to the general guidance and monitoring of the NSF Program Manager for LIGO. This NSF involvement includes the following:

- provision of advice;
- review and, where required by the Agreement, approval of required subcontracts, reports, and plans submitted by Caltech;
- assessment of progress by the NSF Program Manager and external reviewers.

The NSF Division of Grants and Agreements is responsible for Cooperative Agreement matters between the NSF and Caltech. Formal communications related to contracts and required Cooperative Agreement designated approvals will be accomplished by the Division of Grants and Agreements and the Caltech Office of Sponsored Research. Annual funding increments and contractual obligations flow from the Division of Grants and Agreements (DGA), National Science Foundation (NSF) to Caltech, under the Cooperative Agreement. Excluding certain contractual arrangements, all subcontracts in excess of $100,000 issued by Caltech are subject to approval by DGA/NSF.

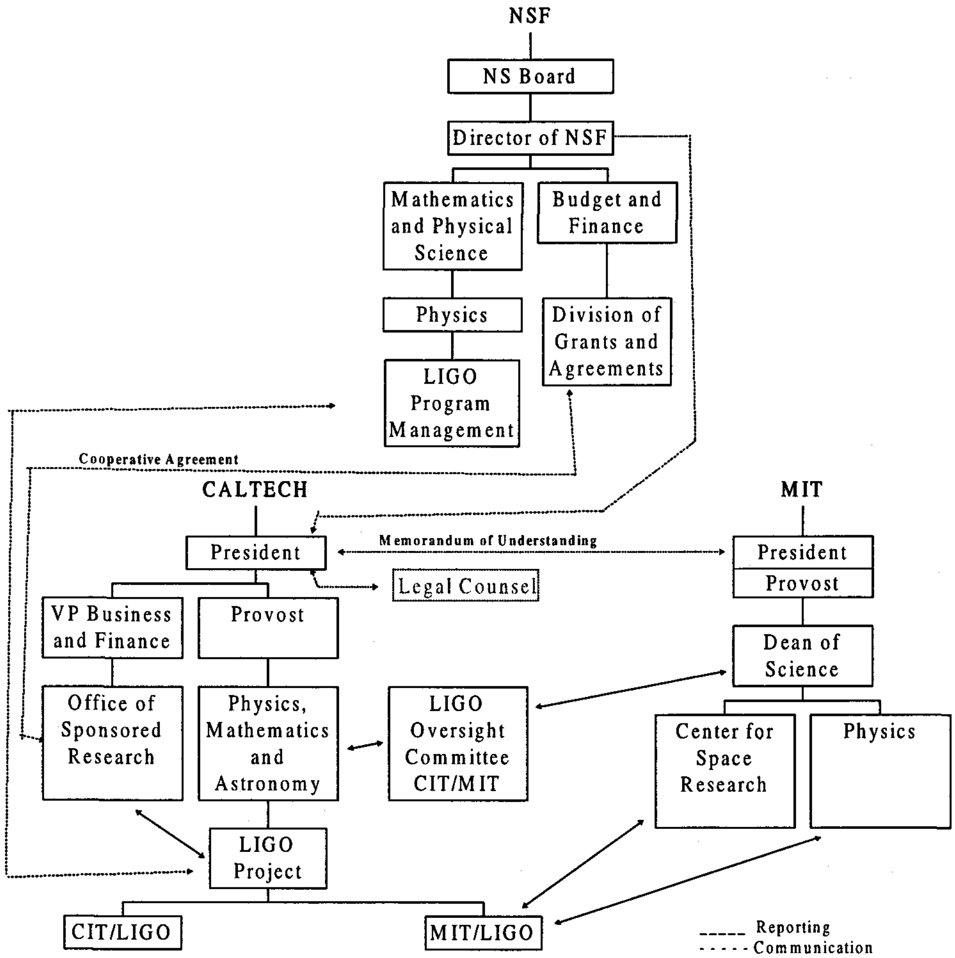

Figure 2-1. Organizational hierarchy.

Caltech is accountable, as the awardee, for the performance of the scientific research project, LIGO, as described in the LIGO Proposal as amended. Caltech is responsible for staffing the project, providing institutional support to the project and ensuring adequate oversight of the execution and performance of the project. 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 Treasurer, respectively.

The LIGO project encompasses a joint effort of Caltech and MIT. The MIT roles and responsibilities are defined through a Memorandum of Understanding (Appendix B) and subcontract with Caltech, with details defined in an attachment and updated as necessary. The MIT subcontract is subject to NSF approval. The MIT administration shares responsibility with the Caltech administration for overall oversight of the execution and performance of the LIGO Project 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 Management to have a fully integrated MIT participation with institutional boundaries minimized.

LIGO activities at Caltech, like other research programs directed by physics faculty, 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.

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

The presidents of Caltech and MIT have established a LIGO Oversight Committee, chaired by the Special Assistant to the Caltech President for LIGO and composed of two members from each institution appointed by their respective presidents after mutual consultation. 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 will regularly provide review of LIGO status and progress as required.

The LIGO Principal Investigator is appointed by the Caltech president in consultation with the MIT president and with the approval of NSF. The Principal Investigator performs his responsibilities in close association with the LIGO Project Manager, who is appointed by the Principal Investigator with the approval of the Presidents and the NSF. Other key personnel in the LIGO Project, as defined in the Cooperative Agreement, are appointed by Caltech and MIT with the approval of NSF.

The LIGO Principal Investigator, in association with the Project Manager, reports progress on a quarterly basis to the LIGO Oversight Committee.

2.2. ORGANIZATION OF THE LIGO PROJECT

The organization of the LIGO Project during the construction leading to the initial detector system is represented in Figure 2-2. An orderly transition to a new organizational structure more appropriate for operations is planned and will involve redefinition of the duties of the personnel executing the construction.

LIGO Project Management consists of the Principal Investigator and the Project Manager. As shown in Figure 2-2, both these positions appear in the same box. Although each has different well-defined <u>primary</u> responsibilities, the overall project management is fully shared and either can speak for the LIGO Project Management. Both the Principal Investigator and the Project Manager are fully informed on all major decisions and will be mutually involved in the decision making as appropriate. The LIGO Principal Investigator has overall responsibility for the LIGO Project. The Principal Investigator's <u>primary</u> responsibility is to ensure the development and implementation of the LIGO Project in a timely and cost effective manner with the goal of detecting gravitational waves as described in the LIGO Proposal as amended. The Project Manager is primarily responsible for executing the construction of LIGO and for organizing and directing the project team composed of Caltech and MIT staff. The Principal Investigator is the principal point for communication and interaction with NSF, through its LIGO Program Manager. The Principal Investigator is also responsible for maintaining interactions, and where appropriate, collaboration with the scientific community (both national and international).

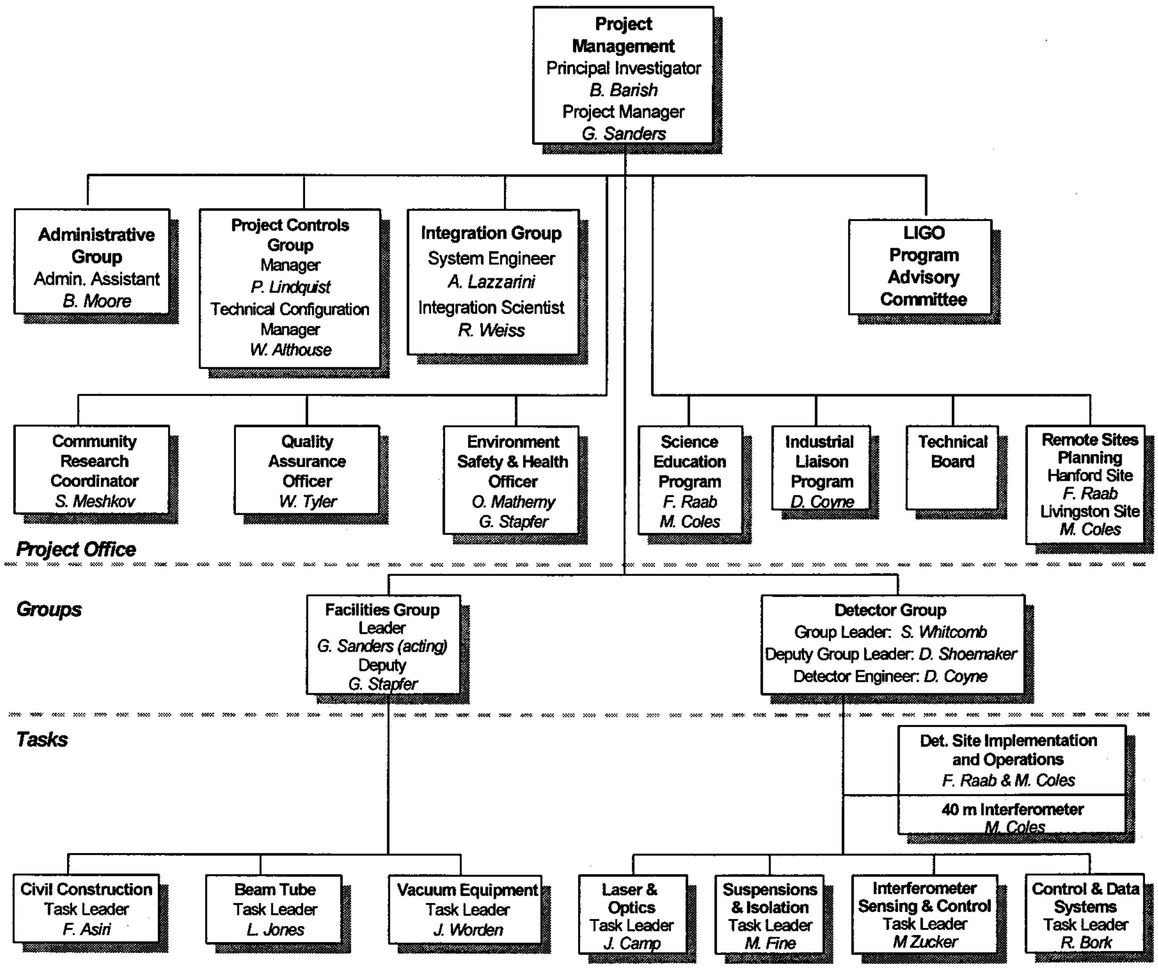

Figure 2-2. LIGO Project Organization.

In matters of policy, planning and scientific review, LIGO Project Management will be supported by a standing Program Advisory Committee (PAC), recruited from the scientific and engineering community outside the project. The PAC will review proposed scientific activities within the LIGO Project and external LIGO research and will support reviews of scientific progress, reporting to LIGO Project Management.

NSF will be invited to attend all PAC meetings and will receive all reports prepared by the committee.

The Technical Board is composed of ex-officio members (Project Controls Manager, Systems Engineer, Integration Scientist, Facilities Group Leaders, Technical Configuration Manager, Detector Group Leaders), who with the LIGO Project Management form the core management team. The Technical Board is chaired by the Principal Investigator in association with the Project Manager and it functions as the LIGO Change Control Board and advises LIGO Project Management on all aspects of the project's status and progress.

The Quality Assurance and Environmental, Safety and Health Officers report directly to the LIGO Project Manager.

Integration of the LIGO systems, including systems engineering, modeling and the coordination and interface control of the various subsystems of the physical facilities and the detectors is the responsibility of the Integration Group. The Integration Group reports to Project Management and is led by the Systems Engineer. Regularly scheduled Integration Meetings are the principal tool for assuring LIGO systems integration. These are attended by the Principal Investigator, Project Manager, Systems Engineer, Integration Scientist, Project Controls Manager, Technical Configuration Manager, Detector Group Leaders, Facilities Group Leader, and the Task Leaders and Lead Engineers for Civil Construction, Beam Tube, Vacuum Systems, and Detector. Other members of the LIGO Project, as needed, participate in Integration Meetings.

Definition, tracking and control of LIGO cost, schedule and technical configuration is the responsibility of the Project Controls Group, led by the Project Controls Manager. The Technical Configuration Manager maintains the LIGO schedule, organizes technical aspects of change control actions, organizes Technical Board meetings, and is responsible for maintaining engineering drawings and the description of the technical configuration. Establishment of the LIGO cost estimate, integrated project schedule, performance measurement baseline, and technical baseline configuration is managed by the Project Controls Group. Tracking and reporting of the Cost/Schedule Status, Estimate to Complete, Variances, and management of the Change Control Process is a responsibility of the Project Controls Group. Subcontract management, finance and documentation and contractual and purchasing actions are initiated and prepared by the Project Controls Group, and reviewed and formally implemented through Caltech's Office of Sponsored Research and legal, purchasing and accounting offices. Regular Project Control Meetings, chaired by the Project Manager, are a principal method of review of project status and progress, with emphasis on identification and early resolution of variances from the project plan. Typically, such meetings will be held weekly or biweekly and will be organized by the Project Controls Group and attended by all LIGO Task Leaders, Group Leaders, and LIGO Project Management.

Engineering and technical effort for Quality Assurance, Environment, Safety and Health, Integration, Project Controls and all Facility, and Detector efforts are accomplished by members of the Caltech or MIT staffs, and through purchased effort subcontracts[6], based upon cost, qualifications and duration of the required effort.

Scientific efforts are accomplished by scientists on the Caltech and MIT staff, and by LIGO scientific collaborators. A LIGO Community Research Coordinator is responsible for working with the Principal Investigator and Project Manager to communicate with the scientific community interested in LIGO and external to the LIGO Project and for facilitating scientific contributions by collaborators, for assisting in the development of collaborative Memoranda of Understanding, and organizing collaborative meetings and workshops. The LIGO Community Research Coordinator reports to LIGO Project Management.

As a national facility based upon an exciting scientific research mission, LIGO can provide a focus for educational programs in science. A Science Education Program will reach beyond the traditional university role of educating undergraduate and graduate students to reaching K-12 grade level students. A Science Education Program Manager will develop and lead programs in educational outreach to the general public, in on-site educational programs at the Washington and Louisiana sites, as well as Pasadena and Cambridge, and in supporting program development consistent with other NSF educational initiatives.

An Industrial Liaison Program will supplement the extensive industrial participation in LIGO construction. LIGO development of enabling technologies promises to provide new capabilities of interest to industry. These include advanced laser and optical technology, and new capabilities in vibration and acoustic isolation. A Program Manager will lead direct efforts to inform, collaborate and cooperate with industrial partners.

Planning for the scientific effectiveness and facility availability at Hanford and Livingston will be carried out within the Project Office in a Remote Site Planning team. Specific responsibilities for the planning for the two sites will be delegated to senior members of Project reporting to Project Management.

2.3. COLLABORATIVE RELATIONSHIPS

6. The LIGO Project also utilizes an arrangement with Caltech's Jet Propulsion Laboratory (JPL), allowing it to draw on JPL's technical divisions matrix on an as-needed basis. In addition, the project uses consulting services from a number of research and industrial organizations.

LIGO is being built by Caltech and MIT and will be operated for the scientific community as a national facility. Collaborative relationships with scientists outside the LIGO Project will be actively pursued for the benefit of science and as an opportunity for the scientific community. This will be organized as the LIGO Collaborative Program. The LIGO Community Research Coordinator will work with LIGO Project Management to implement the Collaborative Program. Various modes of collaboration will be possible, and these may evolve as the LIGO Project progresses from design and construction to operations.

2.3.1. LIGO COLLABORATIVE PROGRAM

Early in the design and construction of LIGO the US program for the development and construction of initial and advanced LIGO sensors is primarily conducted by the LIGO Project. The approved initial LIGO facilities will incorporate a single laser interferometric gravitational-wave detector, consisting of two interferometric sensors in Washington, operating in coincidence with a third sensor in Louisiana. This single detector will be operated by the LIGO Project and external collaborators, as defined below:

- LIGO Project: The LIGO Project is composed of staff from Caltech and MIT supported by Project funds to complete directed R&D and to provide defined deliverables which are part of the LIGO technical baseline.
- LIGO Research Community: The LIGO Research Community includes members of the LIGO Project and the group of external scientists and engineers with interest in the research to be carried out by LIGO. Its organization and charter will be developed following a series of workshops held to facilitate this formation. Its elected chair is a member of the LIGO Program Advisory Committee. External collaborators may propose to LIGO management any mode of scientific collaboration including development of enhancements to initial interferometers, development of advanced detectors and technology, and new scientific inquiries accessible to LIGO. Support of visiting scientists to LIGO will be included in the collaborative program.
- International Gravitational-Wave Network Partners: LIGO will be part of a future global network of gravitational-wave observatories. Plans for the construction of laser interferometer facilities in other countries are in various stages of preparation, including:

  - France/Italy (VIRGO Project)
  - United Kingdom/Germany (GEO600 Project)
  - Australia (AIGO)
  - Japan (TAMA)

- The LIGO Project will continue to actively pursue R&D collaborations with all international partners throughout the design and construction of the initial facilities in the global network, and in the joint development of improved interferometric sensors. This will initially be included in the LIGO Collaborative Program described above.

Participation in any collaborative effort can be arranged directly between interested parties and the LIGO Project. The responsibilities of the participants, such as periodic meetings or exchanges of information, will typically be specified in an MOU. Collaborative MOU's with international partners will require NSF approval. All collaborative MOU's involving costs greater than $100K will be submitted to NSF for review. NSF will have full visibility in all collaborative MOU's.

2.3.2. FULL OPERATIONS

The operation of LIGO offers a wide variety of opportunities for participation by scientists outside the LIGO Project. Enhancements to the initial interferometers and development of advanced interferometers will be a high priority. The scientific community will be encouraged, through the Collaborative Program, to propose research and development programs which will make optimal use of the LIGO facilities.

During full operations, the LIGO Principal Investigator will assign access to LIGO on the basis of time and beam line allocations based on recommendations from a Program Advisory Committee which will review all proposed experiments. LIGO expansion (see Appendix A) may result in additional beam lines for additional independent detectors. It is expected that the LIGO Project, with collaborators from the scientific community at large, will continuously operate one of the detectors (three beam lines at two sites) as a component of the international network.[7] This continuous operation as part of an international network, or any other mode of operation, will require submission to NSF of a proposal from LIGO, and review and approval by the NSF. Additional beam lines will be awarded competitively on the basis of proposals from the scientific community. The LIGO management will develop a written review process taking into consideration the recommendations of the LIGO Oversight Committee. NSF approval of this process is required.

Collaborative arrangements during this phase will continue as discussed in section 2.3.1.

The International Network partners, once their facilities are operational, will conduct global aperture-synthesis observations in conjunction with the detector operated by the LIGO team or any other operational LIGO detector, on the basis of protocols to be worked out

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7. Present plans by the French-Italian project (VIRGO), and all other international programs, envision the construction of a single-interferometer facility only, and rely on LIGO to provide the missing component for coincidence-mode operation and astrophysical source location in an ongoing capacity.

for particular investigations.

2.4. WORK BREAKDOWN STRUCTURE

The LIGO organization displayed in Figure 2-2 is designed to assign responsibility and accountability to the managers responsible to deliver parts of the LIGO project. The organization parallels the LIGO Work Breakdown Structure which organizes all effort within the LIGO project in a product oriented family tree of activities and components.

The level 3 Work Breakdown Structure (WBS) for the design and construction of the LIGO facilities and equipment, including the initial interferometers, is shown in Figure 2-3. A complete WBS Dictionary defines all elements of the WBS and underpins the technical, cost and schedule baselines. The WBS Dictionary will be part of the controlled LIGO configuration.

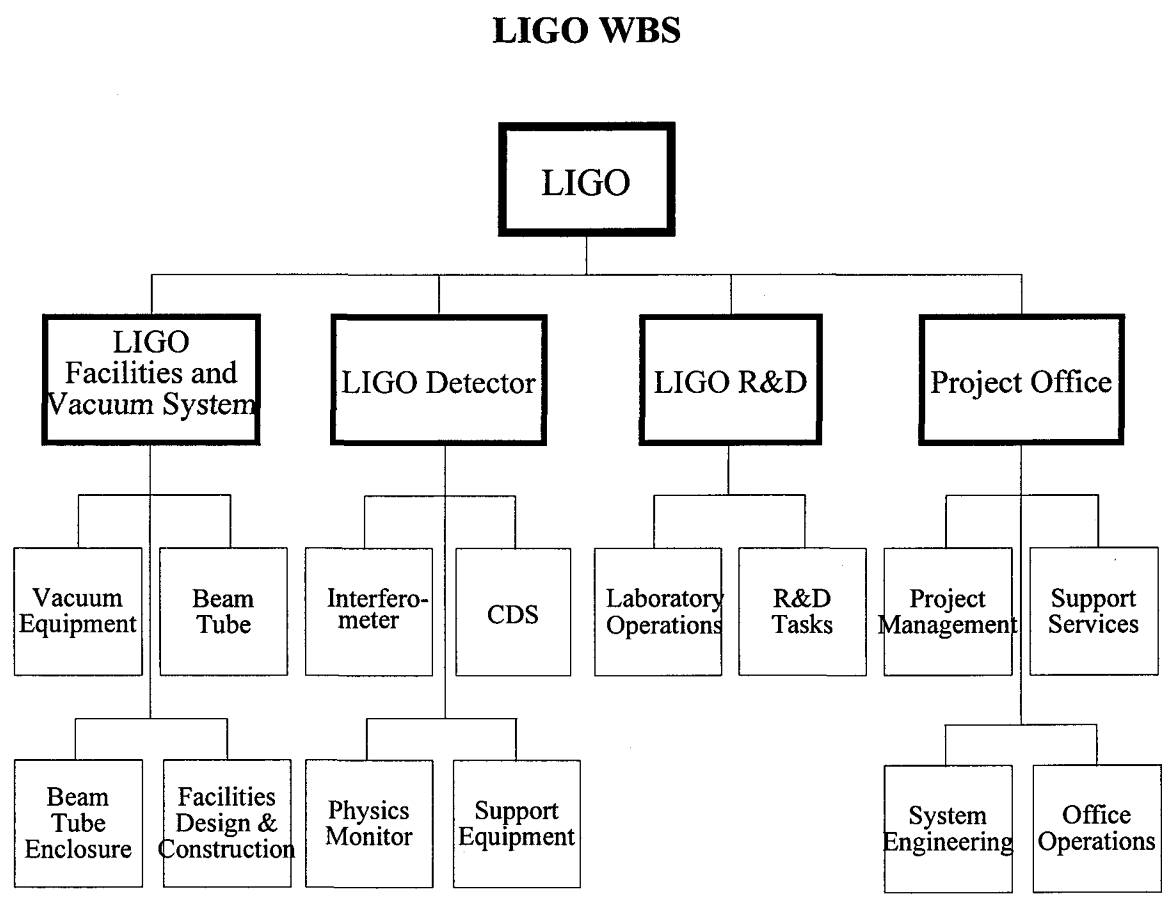

Figure 2-3. LIGO Work Breakdown Structure.

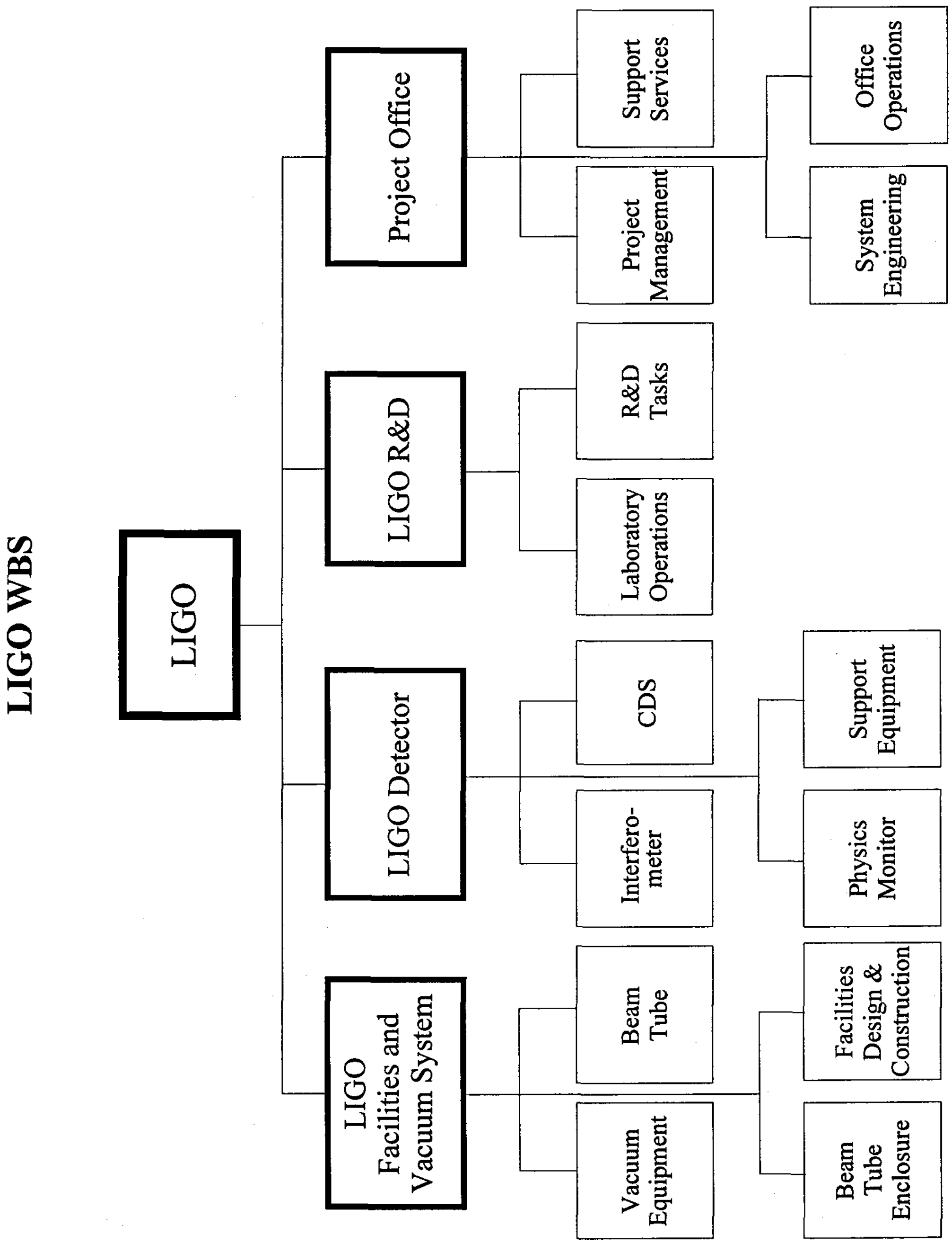

Figure 2-3. LIGO Work Breakdown Structure.

3.0 WORK PLAN

3.1. LIGO FACILITIES: CIVIL CONSTRUCTION, BEAM TUBE AND VACUUM EQUIPMENT FABRICATION AND INSTALLATION

3.1.1. OVERVIEW

The civil construction includes the buildings and the necessary infrastructure (e.g., roads, utilities) to support operations at the remote sites. The beam tube encloses the interferometer optical paths and contains most of the evacuated volume. The vacuum equipment requires a mixture of conventional high vacuum fabrication techniques and specialized low-cost manufacturing. Together these activities account for the largest part of the overall LIGO budget.

This work will be carried out by subcontractors operating under the direction of the LIGO Project. The LIGO Project will act as the top level system integrator --- approving designs, controlling interfaces, approving test plans and directing schedules.

3.1.2. OBJECTIVES

The objective of this effort is to provide for civil construction and the vacuum system housing the interferometers. The Project will:

- ensure that the civil construction and vacuum system designs meet the scientific and operational requirements of LIGO;
- manage the designs to keep the costs within total and annual allocated budgets;
- provide simple, well-defined interfaces among the various parts of the buildings, vacuum system and interferometers to permit a smooth integration;
- manage the schedules of the design, fabrication and installation to meet the overall project schedule.

3.1.3. APPROACH

The planned approach is to divide the majority of the civil construction and vacuum system effort into four major tasks and to subcontract each of these tasks with an appropriate industrial contractor. In general, the plan is to have contractors responsible for the design, fabrication/construction, and installation (vacuum equipment and beam tubes). This division into separate tasks is structured to afford the selected contractors the opportunity to influence the design to minimize construction costs, to give each subcontractor a set of testable deliverables, and to offer the simplest possible interfaces between different contractors. Details of each contract will be planned in an Acquisition Plan and a Request For Proposal.

Building architectural and engineering design and construction supervision: The LIGO Project will employ the services of a single firm, or several firms forming a team, with appropriate expertise for the design, trade studies, and construction management of the facilities. The contractor will initially provide design services consisting of conceptual design and requirements optimization, trade studies, detailed design and documentation covering site planning, corner-, end-, and mid-station buildings for both sites, under the supervision of the LIGO Project. The design-phase product will consist of construction documents (detailed drawings and specifications) suitable for obtaining fixed-price bids for construction. During the construction phase, the contractor will provide construction management services, maintain control of documentation, generate new documentation as required by design changes, and manage the review and resolution of nonconformances and claims. The contractor will also provide on-site inspection services and arrange for independent QA laboratory testing as required. The contractor will provide as-built documentation at the completion of construction. All activities at the LIGO sites in Hanford, WA and Livingston, LA will be conducted in accordance with the terms and conditions of the Cooperative Agreement and applicable land sale and lease documents.

Beam tube enclosure design and construction: The LIGO Project will employ the services of a single engineering and construction firm, or several firms forming a team, with appropriate expertise for the design and construction of the beam tube enclosures. This contractor may be the architecture and engineering contractor for the design phase, or the beam tube contractor or a third contractor. The contractor will be responsible for the design and construction of the beam tube enclosures at both sites, using lower-tier local subcontractors for on-site construction. Authority to proceed with on-site construction will be given after the design-phase work has been approved by the LIGO Project.

Vacuum equipment design and construction: A contract will be placed with a firm that has large scale vacuum system design and fabrication experience to design and integrate into a system the LIGO vacuum equipment, to perform detailed design of all vacuum equipment except for the beam tubes, and to fabricate, install, and test this equipment. Given the complexity of the LIGO vacuum equipment, it is planned that a single contractor or consortium be responsible for design, fabrication, installation, and testing of an integrated system. Authority to proceed with fabrication, installation, and testing will be given after the design phase work has been successfully completed, reviewed and approved.

Beam tube design and construction: A contract will be placed with a firm to provide detailed design engineering, fabrication, installation, and testing of the beam-tube modules. The design and fabrication of the beam tubes has been separated from the rest of the vacuum system because it departs substantially from that of conventional vacuum systems. The interfaces between the beam tube modules and the remainder of the vacuum system and beam tube enclosure have been identified and documented, and will be controlled by the LIGO Project. Authority to proceed with fabrication, installation, and testing will be given after the design phase work and a qualification test have been successfully completed, reviewed and approved. The fabrication, installation and testing may be procured as a separate, competitively bid contract, following a detailed Acquisition Plan.

The contract for each of these work packages will be based on specifications reviewed and approved by the LIGO Project, under the direction of the Project Manager. These specifications will have input from and will be reviewed by the Technical Board prior to release.

The technical work for each subcontract will be monitored by a designated Task Leader, who is a member of the LIGO Project staff reporting to the Facilities Group Leader. The Task Leader will have the support of other members of the LIGO Project and outside experts for consultation, for design reviews and to resolve any unexpected issues, and will have the support of a resident engineer at each site during construction and installation for on-site monitoring. The Task Leader and cognizant scientist will maintain frequent contact with the relevant subcontractor personnel, in order to establish a close working relationship between the subcontractor and the LIGO Project. This will enable the Task Leader to influence design decisions to meet the requirements of the LIGO Project and to identify issues which may have consequences beyond the immediate scope of the subcontract.

Design reviews of each subcontracted design effort will be held at appropriate times. The design review boards may include LIGO Project staff and external collaborators, members of the External Advisory Committee and other outside experts as appropriate. NSF shall be informed of the design reviews, invited to attend, and shall receive copies of relevant reports.

Smaller subcontracts for various aspects of site development work will be placed directly by the LIGO Project. These subcontracts involve activities which can be independently specified without elaborate interface controls. They will be monitored in the same way as the larger facilities and equipment contracts.

3.2. RESEARCH AND DEVELOPMENT

3.2.1. OVERVIEW

A research and development program will be maintained throughout the course of the project.[8] In the early phases of the program the prime emphasis is on the development, characterization, component level modeling and testing of the enabling technology for the initial LIGO interferometers. This effort leads to the definition of the initial interferometer

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8. Among the principal tools for this effort are a 40-m interferometer at Caltech and a 5-m interferometer at MIT. These interferometers serve as research and development test beds for the LIGO interferometers. Because of different length-scaling rules for different physical parameters, these interferometers can only be optimized to test individual subsystems or techniques. They are not suitable to test the full integration of a LIGO interferometer.

subsystems and their requirements. It also influences and is influenced by the facility design and facility/interferometer interfaces.[9] The initial phase of the research program ends with the design freeze for the interferometer subsystems. The research leading to improved interferometer performance is based in large part on the development of the initial interferometers. The continuing R&D will provide the technology for enhancements to the initial interferometer and toward more advanced detectors which will gain increased emphasis in the later phases of the project, during initial interferometer construction.

A substantive research and development effort is associated with design of data analysis strategies and algorithms both for overall system characterization and the initial gravitational-wave observations. Some of this work will be developed inside the LIGO project and some in collaboration with collaborative theory efforts.

3.2.2. OBJECTIVES

The objectives of the research program are to:

- support the development of specifications for the LIGO facilities;
- develop and validate technology required for the initial LIGO interferometers;
- develop techniques for enhanced and more advanced interferometer subsystems.

The Detector Group Leaders coordinate the detector development in consultation with LIGO Project Management. Budgeting and staffing allocations for tasks are negotiated as defined statements of work with deliverables, schedules and milestones agreed between the groups and LIGO Project Management. R&D issues are discussed at weekly meetings and further discussions and reviews are scheduled as needed. There are weekly interactions with LIGO Project Management to review status and troubleshoot problems.

Individual R&D tasks are typically managed by a scientist or engineer who is responsible for defining the scope of the task, for negotiating the staffing, budget, and schedule for the task and for documentation in a written Statement of Work. Reviews are held on scope and concept, technical designs, and for final acceptance of the completed task. Task documentation includes experimental and component modeling results, technical summaries and design drawings; these are archived for future reference and, if suitable, relevant parts are published.

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9. The requirements for civil construction and the vacuum system need to be frozen long before the detailed interferometer requirements can be fixed, placing subsequent constraints on the design, integration and operation of the interferometer.

3.3. DETECTOR DESIGN/FABRICATION

3.3.1. OBJECTIVES

The Project will design, fabricate, install and operate three interferometers: a full length and a half length interferometer at the Washington site and a full length interferometer at Louisiana. The three interferometers, operated in coincidence, constitute one gravitational-wave detector.

3.3.2. FABRICATION STRATEGY

The fabrication of the initial interferometers is divided into subsystems defined by the Detector Group. The Detector Group, working closely with the LIGO Integration Group, develops the subsystem requirements and specifies the interfaces and the subsystem test plan. A cognizant scientist and engineer are given the responsibility to deliver the subsystem to the project.

The transition from subsystem research and development to subsystem fabrication takes place at the design freeze (Preliminary Design Reviews). The design freeze for individual subsystems occurs at different times in the project depending on the state of readiness. The design freeze of a subsystem is followed by detailed engineering design, fabrication and test. The qualification test of a completed subsystem will take place in the interferometer prototypes when practical and applicable; otherwise the tests are carried out in special purpose facilities. The integration of the interferometers occurs at the LIGO sites.

The assembled interferometer, the control and data system and the facilities are tested together during the facility pre-operations phase by a set of diagnostic procedures prescribed by the Detector Group and approved by the LIGO Integration Group.

3.3.3. IMPLEMENTATION

The first key step in the implementation is the design freeze of a subsystem. In preparation for the design freeze, the cognizant subsystem scientist and engineer, in coordination with the Detector Group, will:

- assemble the experimental data and modeling results for the subsystem;
- review the subsystem requirements;
- review subsystem performance and interface specifications;
- review the conceptual design for the subsystem.

The planned design freeze (PDR) dates are milestones in the R&D schedule. Following the design freeze, the final engineering design of a subsystem is carried out by LIGO project engineers in coordination with the subsystem cognizant scientist. The product of the engineering design consists of:

- subsystem procurement and fabrication plan, including schedule, staffing and budget;
- drawings for subsystem fabrication;
- procedures for subsystem assembly and test;
- subsystem installation plan and schedule;
- subsystem integrated test plan.

The fabrication of the subsystems will be executed as much as is practical by external contractors monitored by the project engineering staff. The subsystem tests and qualification will be performed by project staff.

Subsystem installation and the integrated performance tests at a LIGO site will be under the direction of the site manager. The installation of a specific subsystem for all three interferometers will be carried out by the same subsystem installation team to the maximum extent feasible.

3.4. SYSTEM ENGINEERING AND INTEGRATION

3.4.1. OBJECTIVES

The objective of the system engineering and integration task is to ensure that all of LIGO's various subsystems meet their individual requirements and will operate as an integrated system. This task will refine and optimize the coherent LIGO design, detailed requirements and specifications, interfaces, technical aspects of configuration management, and systems issues such as reliability, maintainability and availability. Modeling of the complete LIGO system is an integral part of the integration task.

3.4.2. RESPONSIBILITIES

The overall system integration and engineering is the responsibility of the Integration Group. This Group is led by the Systems Engineer in association with the Integration Scientist. The Group reports to LIGO Project Management and ensures coordination between all technical activities. Specific system integration and engineering tasks are assigned to individual LIGO project members on a task by task basis.

3.4.3. *APPROACH*

The task 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 by the Integration Group. The requirements for the facilities, civil construction, beam tube and the vacuum system need to be frozen long before the detailed interferometer requirements can be established, placing subsequent constraints on the design, integration and operation of the interferometer.

For the civil construction, beam tube and vacuum system, the subsystem functional and interface requirements are incorporated into statements of work for the subcontracts. As the work in these areas progresses, the Integration Group ensures that the requirements are being met. If necessary, the Group reviews and identifies requirements which could lead to overall system conflicts, and makes recommendations to the LIGO Project Manager concerning their resolution.

For the development and fabrication of the detector, the Detector Group will define and maintain the detector subsystem requirements and establish the interfaces between them. The Detector Group will continuously assess the designs as they evolve through regular interactions with the subsystem task leaders and ensure the early resolution of any conflicting requirements.

The LIGO Integration Group will oversee 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.

3.5. QUALITY ASSURANCE

This section describes the policies being established to ensure that Quality Assurance (QA) considerations are adequately addressed within the LIGO project activities. QA is a line management responsibility represented by the QA Officer who reports to the Project Manager.

3.5.1. *OBJECTIVES*

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

3.5.2. RESPONSIBILITIES

The LIGO Project Manager has the responsibility to define the appropriate QA level for the different phases of the project. He will be supported by the Quality Assurance Organization of the Jet Propulsion Laboratory (JPL), which will provide its expertise to the LIGO project as required. The QA implementation is subject to review and audit by the LIGO QA Officer.

3.5.3. RELIABILITY, MAINTAINABILITY, AVAILABILITY

The goal of the LIGO project is to provide a national facility which will operate with a minimum of down time, for more than 20 years. Special attention is therefore devoted to any item which affects the operational reliability, maintainability and availability of the system and documented requirements will be developed and maintained as a part of the controlled LIGO configuration. To assure that these goals are met, the LIGO project has directed that all relevant QA aspects are constantly 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.

3.5.4. QUALITY CONTROL

Procedures will be in place, 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 audits and indoctrination/training of personnel.

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

3.6. ENVIRONMENTAL, SAFETY AND HEALTH PROTECTION

This section describes the policies being established to ensure that Environmental, Safety and Health Protection (ES&H) considerations are adequately addressed within the LIGO project activities. ES&H is a line management responsibility represented by the ES&H Officer who reports to the Project Manager.

3.6.1. OBJECTIVES

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

- to prevent personnel injury or loss of life during all phases of the LIGO project;
- to prevent any environmental contamination during the construction, shakedown or operation of LIGO;
- to prevent damage to equipment caused by accidents during all phases of the project;
- to comply with all federal, state and local laws, rules and regulations.

3.6.2. RESPONSIBILITIES

The LIGO ES&H program is the responsibility of the Project Manager. The Project Manager has responsibility to insure that the LIGO project members identify specific ES&H issues and risks, and establish appropriate safeguards and procedures for addressing those risks. To accomplish the detailed ES&H planning, documentation and surveillance, a LIGO ES&H Officer will be appointed. The ES&H Officer shall be responsible for all ES&H program activities and report to the Project Manager on matters pertaining to the ES&H program.

A major portion of the LIGO project will be performed by industrial contractors. These contractors will implement their own ES&H policies and procedures, which will be subject to review and audit by the ES&H Officer and the LIGO project staff. The project will be supported in its oversight function as needed, by employing the available expertise of JPL's Occupational Safety Office.

3.6.3. ENVIRONMENTAL PROTECTION

The LIGO project shall follow standards and practices which fully support the NSF environmental protection policies and requirements. The project will initiate activities necessary to ensure compliance with the Resource Conservation and Recovery Act (RCRA) and the National Environmental Policy Act (NEPA).

3.6.4. SAFETY AND HEALTH PROTECTION

Caltech has an established Safety Office, responsible for the Institute's overall safety and health program, and the LIGO management will implement the applicable health and safety program elements as outlined in the Caltech Safety Manual. The specific areas which will be addressed are hazards and safety requirements related to the construction of the facility, the installation and operation of the vacuum system and the installation and operation of laser equipment. For work performed at MIT, the safety and health protection measures adopted by MIT will similarly apply.

An order of precedence for resolving safety issues has been established by the LIGO

Project. Order of precedence shall be as follows:

Design for Minimum Risk: The primary means for mitigation of risk shall be to eliminate the hazard through design.

Incorporate Safety Devices: Fixed, automatic or other protective devices shall be used in conjunction with the design features to attain an acceptable level of risk. Provisions shall be made for periodic functional checks as applicable.

Provide Warning Devices: When neither design nor safety items can effectively eliminate or reduce hazards, devices shall be used to detect the condition, and to produce an adequate warning to alert personnel of a hazard. Devices may include audible or visual alarms, permanent signs or movable placards.

Procedures and Training: Where it is impractical to substantially eliminate or reduce the hazard or where the condition of the hazard indicates additional emphasis, special operating procedures and training shall be used.

3.6.5. EMPLOYEE TRAINING

LIGO project 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.

3.6.6. CONTRACTORS AND VISITORS

Contractors and visitors to the LIGO operational sites will be informed of ES&H rules and procedures applicable to the specific area. (See section 3.6.2 above for major contractors.) Hosts will be responsible for the safety of visitors.

3.6.7. DOCUMENTATION

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

3.6.8. GOVERNMENTAL CODE REQUIREMENTS

The LIGO Project, including its contractors, will comply with applicable US Federal Codes, laws and regulations, industrial codes and state rules, regulations and codes. The ES&H Officer, together with the Project Manager, will be responsible for clarifying compliance requirements and the resolution of safety issues.

3.7. PROCUREMENT AND SUBCONTRACTS

3.7.1. POLICY

LIGO procurements are of two types: equipment and supplies purchased to support the R&D efforts, and subcontracts and equipment purchases to support the construction of the LIGO facilities and equipment. R&D procurements occur at both Caltech and MIT. These are processed according to the procedures established by the Purchasing Department at the host institution and approved by the Office of Naval Research under OMB requirements..

All LIGO facilities and equipment procurements will be processed and administered by the Caltech or MIT Purchasing Department depending upon the institution originating the procurement, assisted by the LIGO project staff. Major procurements involving substantive efforts (subcontracts valued in excess of $100,000) will be submitted to NSF for approval or concurrence, in accordance with the Cooperative Agreement. Subcontract technical and programmatic management is performed by LIGO staff.

All procurements and subcontracts will be subject to the terms and conditions of the Cooperative Agreement and the requirements of land sale and lease documents pertaining to the LIGO sites.

3.7.2. RESPONSIBILITIES

The LIGO Project Manager is responsible for ensuring that all aspects of LIGO facilities and equipment procurement are managed and planned successfully. A written acquisition plan will support the procurement approach for major procurements in excess of $500,000. The Project Manager, in association with the Principal Investigator, shall approve all major subcontracts.

Procurement for the LIGO project is supported by the Project Controls Group which is responsible for preparing, facilitating and administering the procurement documentation associated with major LIGO procurements from industry.

Subcontracts and procurements will be initiated by the cognizant Task Leaders. Working closely with the Project Controls Group, the Task Leaders will be responsible that all procured components, items, services and construction are produced and delivered as required to support the LIGO project objectives. The Task Leaders will also provide technical direction and oversight of these contracts and procurements.

3.7.3. 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 in the LIGO project. This manual establishes compliance with NSF and Federal Acquisition Regulations, and ensures the use of competitive procurement techniques and small disadvantaged business subcontracting to the maximum extent. All major procurements which require NSF concurrence will be identified and scheduled in the annual Work Plan. Similarly, LIGO 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.

4.0 COST, STAFFING

4.1. COST ESTIMATE

A detailed cost estimate has been prepared for the LIGO Project and is documented in the LIGO Cost Estimate and the LIGO Cost Estimate Summary. The estimate has been prepared according to the LIGO Cost Estimating Plan. This estimate has been revised concurrent with the preparation of this Project Management Plan, and adopted as the cost baseline. The Cost Estimate will be maintained and reviewed in depth as a part of the preparation of the annual work plan (section 7.1.4). The total estimated cost for the LIGO construction phase,[10] including necessary R&D activities and contingency, is $276M in Fiscal Year (FY) 1994 dollars. Total run out cost, after adjustment for inflationary effects (section 4.2), is $292M. A breakdown of the cost baseline by WBS level 2 elements is given in Table 4-1.

4.2. FUNDING PROFILE

The run out cost for the project is consistent with the funding profile determined by NSF which governs the project schedule (section 5). Annual escalation rates are based on Gross Domestic Product (GDP) deflators provided by NSF.

Table 4-1. Estimated Construction Cost

WBS LEVEL	WBS No.	WBS TITLE	TOTAL COST (1994 K$)
1	1	LIGO	$276,216
2	1.1	Facilities and Vacuum Systems	$170,597
2	1.2	Detector	$57,812
2	1.3	Research and Development	$26,798
2	1.4	Project Office	$21,009

10. The LIGO construction phase covers the annual funding periods during which construction funds are appropriated and obligated, beginning in December 1991.

4.3. CONTINGENCY

A contingency budget item is identified to assure that technical, cost and schedule risks which develop during project execution can be successfully resolved. This contingency is estimated for each WBS element at the lowest possible level on the basis of a technical risk assessment for each item following the detailed methodology documented in the LIGO Cost Estimating Plan. All contingency funds are, however, retained by LIGO Project Management in a separate account.

Application of contingency funds will be initiated by a documented request from the appropriate task leader to the Project Controls Manager. The request for application of contingency will be reviewed by the LIGO Change Control Board and a recommendation will be made to LIGO Project Management. The Project Manager in association with the Principal Investigator shall issue a written decision memorandum on the request.

The granting of contingency funds is recorded as a change in the LIGO Cost Estimate and Performance Measurement Baseline. The Project Controls Manager is responsible to maintain an accurate accounting of the use of contingency.

Application of contingency will be reported at WBS level 3 in the Quarterly and Annual Reports to NSF (section 7.1) and tracked against allocation and against the project Earned Value. NSF will be notified monthly of any contingency allocation in excess of $1 million.

4.4. STAFFING

The primary responsibilities of the project staff are the development, design and construction of an advanced research facility capable of detection of gravitational waves and of astronomical research. The LIGO Project will be implemented through a combination of project staff at Caltech and MIT, and staff employed by subcontractors. LIGO benefits from the fact that the project is embedded in strong technical organizations (Caltech, MIT, JPL) from which specialized assistance can be drawn.

Additional staff will be attached to the project to cover two types of needs. The first is to provide specialized expertise (such as soil engineering during the site investigation and foundation design or metallurgical engineering during the beam tube design phase) which is not needed on a full time basis throughout the project. The second circumstance is to provide additional engineering support during peak demand periods (for example, additional mechanical engineering support during the detailed design phase). These people will be drawn preferentially from staff at Caltech, at Caltech's Jet Propulsion Laboratory (JPL) and at MIT.

Graduate students are involved in the LIGO Research and Development program. In addition, the project also employs a number of graduate and undergraduate students, primarily in summer positions assisting with the R&D activities. Participants in the LIGO Collaborative Program (section 2.3.3) contribute to the Project effort.

Subcontractors will be used for the major facilities design and construction tasks. The staffing plans for these activities are the responsibility of the selected subcontractor, whose work plans must be approved by the LIGO Project.

5.0 SCHEDULE

5.1. IMPLEMENTATION SCHEDULES

A fully integrated LIGO Project schedule will be developed and maintained under configuration control, consistent with the baseline cost estimate. Network logic will be utilized to develop and maintain schedules for all major elements of the LIGO Project at both intermediate and detailed levels. These schedules identify the major links and interfaces between the various tasks. These logic networks are the principal basis for tracking schedule performance and presenting status information.

The intermediate level schedules used to derive the milestone dates in Table 5-1 and Table 5-2 will be adopted as the baseline schedule. The baseline cost estimate and schedule will be integrated into a Performance Measurement Baseline which will be maintained under Configuration Control. A milestone for adoption of the controlled cost estimate, integrated schedule, and Performance Measurement Baseline is indicated in Table 5-1. Changes will be processed as described in the LIGO Configuration Management Plan (see section 6.3), subject to the approval of the LIGO Project Manager. Detailed level schedule baselines will be adopted and controlled, with changes approved by cognizant Group Leaders.

The schedule baseline and Performance Measurement Baseline will be revised annually based on available funding and summarized (with updated milestones) in the annual work plan and funding request submission to NSF (see section 7.1). Changes to these will be reviewed as formal changes to the LIGO configuration prior to this submission to NSF.

Table 5-1. Significant Facility Milestones

MILESTONE NAME	WASHINGTON LATE DATE	LOUISIANA LATE DATE
Initiate Site Development	03/94	08/95
Beam Tube Final Design Review	04/94	common
Select A/E Contractor	11/94	common
Complete Beam Tube Qualification Test	02/95	common
Select Vacuum Equipment Contractor	03/95	common
Complete Performance Measurement Baseline	04/95	common
Initiate Beam Tube Fabrication	10/95	common
Initiate Slab Construction	10/95	01/97
Initiate Building Construction	06/96	01/97
Accept Tube and Cover	03/98	03/99
Joint Occupancy	09/97	03/98
Beneficial Occupancy (Accept Buildings)	03/98	09/98
Accept Vacuum Equipment	03/98	09/98
Initiate Facility Shakedown	03/98	03/99

Table 5-2. Significant Detector Milestones

MILESTONE NAME	WASHINGTON LATE DATE	LOUISIANA LATE DATE
BSC Seismic Isolation Final Design Review	04/98	common
Core Optics Support Final Design Review	02/98	common
HAM Seismic Isolation Final Design Review	04/98	common
Core Optics Components Final Design Review	12/97	common
Detector System Preliminary Design Review	12/97	common
I/O Optics Final Design Review	04/98	common
Prestabilized Laser Final Design Review	08/98	common
CDS Networking Systems Ready for Installation	04/98	common
Alignment Final Design Review	04/98	common
CDS DAQ Final Design Review	04/98	common
Length Sensing/Control Final Design Review	05/98	common
Physical Environment Monitor Final Design Review	06/98	common
Initiate Interferometer Installation	07/98	01/99
Begin Coincidence Tests	12/00	common

6.0 MANAGEMENT: COST, SCHEDULE, TECHNICAL

6.1. COST AND SCHEDULE CONTROL

A consistent set of cost and schedule baselines (see sections 4.1, 4.2 and 5.1) will be maintained and used to manage LIGO project costs and schedules as described below.

6.1.1. OBJECTIVES

The following objectives guide the management of LIGO cost and schedule resources:

- to plan and schedule all activities to meet the technical performance goals, cost baseline and milestone dates;
- to routinely monitor and report cost and schedule status;
- to provide early warning of potential cost or schedule problems and to provide a basis for management actions.

6.1.2. RESPONSIBILITIES

All LIGO activities are assigned a cognizant Task Leader. Each Task Leader is responsible for monitoring cost/schedule experience-to-date for the activities within their domain[11] and for estimating cost-to-complete and scheduled completion on a monthly basis. The cognizant Task 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 (Facility Group Leaders, Detector Group Leaders, Project Manager).

LIGO Project Management has overall responsibility for cost and schedule monitoring, assessment, and reporting. These functions are supported by the Project Controls Group, which provides computer-automated cost and schedule tracking services, analysis assistance, and report generation.

6.1.3. APPROACH

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

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11. Based upon subcontract terms and schedules, or annual Work Plan, respectively.

apply contingency funds to solve the problem; (4) take any other available action deemed prudent under the circumstances. These latter actions constitute changes to the controlled LIGO configuration, and will be proposed and reviewed following the LIGO Configuration Management Plan.

Should problems arise that cannot be resolved within available resources without impacting essential LIGO features, the LIGO Principal Investigator, in association with the Project Manager, 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 descoping 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.

6.1.4. 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 Principal Investigator shall 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.

6.2. SUBCONTRACT MANAGEMENT

6.2.1. OBJECTIVES

The largest tasks which make up the LIGO Project are planned to be performed by subcontractors; these include the design and construction of the buildings, vacuum systems (including beam tubes), enclosures for the beam tubes, and utilities required to operate the facilities. It is the objective of the LIGO Project to accomplish these tasks in a timely fashion at the lowest possible cost.

The selected approach to accomplish this objective is to place several subcontracts with appropriate industrial contractors and to supervise these contracted efforts with a project engineering staff supported by LIGO scientists as required.

6.2.2. RESPONSIBILITIES

The LIGO Project Manager is responsible for ensuring that all aspects of the subcontracts are planned and managed successfully. The Project Manager, together with Caltech's Sponsored Research Office, shall identify those subcontracts which require NSF approval and ensure that such approval and/or concurrence has been received before legally binding contracts are executed. He will appoint the appropriate technical staff to be responsible for the technical management of the subcontracts.

Each of the major subcontracts is managed by a cognizant Task Leader (section 2.2). The Task Leader is responsible to the cognizant Group Leader for the day to day subcontract activities which require project attention. The Task Leader will provide the technical direction and oversight of the subcontract through regularly scheduled communication and on-site visits as required. The Task Leader is supported by the Project Controls Group which will prepare and facilitate contract documentation and analyze cost and schedule data as appropriate. When cost or schedule problems arise, the Project Manager, cognizant Group Leader and cognizant Task Leader, together with appropriate subcontractor personnel, will work together to resolve the problem. Subcontractor status is reported by the cognizant Task Leader at Project Control Meetings.

6.2.3. APPROACH

Major LIGO facilities design and construction 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. Subcontract terms will provide for technical direction, progress payments based upon measurable performance milestones, and require delivery of programmatic data characteristic of cost-reimbursable contracts (detailed technical status, cost experience, and estimated cost-to-complete) which allow the detection of potential problems and the implementation of early corrective action through technical directives. The cognizant Task 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) requirements, relevant technical expertise, and financial capability to accept the risks of the method of contracting. Technical and quality control, however, remain in the hands of the LIGO Project through requirements to review and approve subcontractor plans and procedures, contractually required formal design reviews, and provisions which permit LIGO Project inspection of work in progress.

6.3. CONFIGURATION MANAGEMENT, DOCUMENTATION AND CHANGE CONTROL

6.3.1. CONFIGURATION MANAGEMENT PLAN

A Configuration Management Plan (CMP) will be prepared as part of establishing a formal Performance Measurement Baseline.[12] It will describe the processes which will be followed to ensure coordination of changes and to assure that the technical, cost, and schedule impact of changes are considered. The CMP process involves configuration identification, change control and configuration accounting/verification.

12. Major subcontractors will be required to have a configuration management plan for their work, approved by the LIGO Project.

6.3.2. DOCUMENTATION

A technical, cost and schedule baseline will be established for the 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. These specifications will be accompanied by cost and schedule documentation which define the cost and schedule baseline. The cost and schedule baselines will be fully integrated into a Performance Measurement Baseline against which the progress of the project can be measured. Once approved by LIGO Project Management, these constitute the controlled LIGO baseline and can only be changed through the change control process.

A LIGO Document Control Center (DCC) has been established to support the project. The DCC will collect and maintain the documented LIGO baseline as a set of controlled documents. All other LIGO documents will be archived in the DCC. An orderly process for numbering and indexing all LIGO documentation will be established in the DCC.

The DCC is located and staffed in the Project Controls Group, which reports to the Project Manager. All documentation which has been identified to be controlled by formal configuration management is designated as Controlled Documents. Controlled documents will be maintained by the DCC in a form readily accessible for review, and will also file and store the originals of all such documentation.

For all of the subcontracted Civil Construction and Equipment Fabrication efforts, the requirements, specifications, interface drawings and documentation will be under formal configuration management throughout the contracted period. The interferometers, which require considerable research and development, will not be placed under full configuration management until the interferometer design freeze has occurred, but are subject to facilities interface constraints and to control of the top level specifications. For this reason, interface control documents and requirements and specifications associated with the detector will be controlled documents prior to the detector design freeze.

6.3.3. CHANGE CONTROL

Changes in the LIGO technical, cost and schedule baselines will be initiated by a documented request from the cognizant manager to the Project Controls Manager. Documented requests are required for all cumulative cost changes within a subsystem which exceed $50,000, all schedule changes to subsystem or LIGO system level milestones greater than one month, for all changes to interface control documents and for all subsystem level or system level specification and configuration changes. The cognizant manager will initiate the request, and if the need for a change control request is not certain, the burden on the cognizant manager shall be that the documented request will be made.

The Project Controls Manager will review the request for variance from the technical, cost and schedule baseline. The Technical Configuration Manager will support this review by reviewing all requests against baseline technical parameters and schedule. Baseline documentation in the DCC will be the primary review resource. Following the review, the request package, which shall include a memorandum summarizing the review, will be forwarded to the LIGO Change Control Board which is the Technical Board. The Change Control Board will review the request and the review comments and make a recommendation to the Project Management. LIGO Project Management will issue a written notice of decision on the requested configuration change. The Project Controls Manager will maintain a log and file of all approved Change Requests.

6.3.4. CONFIGURATION ACCOUNTING AND VERIFICATION

The primary objectives of configuration accounting are:

- to maintain a current list of all project baseline documentation;
- to maintain current and accurate records of the status of changes, both completed and in process;
- to track specific hardware and software configurations.

The DCC will maintain a Master Drawing List which identifies all controlled documents and their current revision status. This list will be made available to all project personnel.

The technical baseline is managed throughout the LIGO project to ensure that the system meets its specifications and that these specifications reflect the true configuration of the system. This is accomplished through periodic design reviews and physical configuration audits which will ensure that the technical documentation properly reflects the "as built" configuration.

7.0 REPORTING

7.1. REPORTS TO NSF

7.1.1. MONTHLY PROGRESS REPORT

A LIGO Project Monthly Report will be prepared and submitted to NSF. This report will include a statement of the LIGO Project cost and schedule status, a report of any contingency allocation in excess of $1 million, and a report of any schedule slippage of key milestones greater than 3 months.

7.1.2. QUARTERLY PROGRESS REPORT

Three LIGO Project Quarterly Reports will be prepared and submitted to NSF annually for the first three quarters of 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 including 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 LIGO/NSF responsibilities. This report shall also include management information such as changes to personnel, financial status report and other financial information including actual or anticipated underruns or overruns, and any other action requiring NSF or other Federal Agency notification."

The financial information in the Quarterly Report will include a summary at the reporting level of the Work Breakdown Structure (WBS), level 3 for Facilities and level 2 for the remainder of the WBS, of costs and obligations and a comparison with available funding. The forecast and actual completion of Project Level milestones will also be compared with the planned milestone completion dates presented in this plan. Performance data will include comparisons of "earned value" for work completed with a time-phased budget baseline and with actual costs accumulated to provide a "dollar" measure of the ahead or behind schedule position and the overrun/underrun status of each reporting level of the WBS. This data will be presented graphically to show trends at the top level of the WBS. A narrative "variance report" will discuss the causes and corrective actions to address significant variances from the plan. The report will also describe Change Requests approved by the Change Control Board during the reporting period and their affect on key milestones, contingency, or technical performance parameters.

7.1.3. ANNUAL REPORT

An Annual Report will be prepared and submitted to NSF, in lieu of a fourth Quarterly Report, containing: "1. a summary of overall progress, including results to date, and a comparison of actual accomplishments with the proposed goals of the period; 2. indication of any current problems or favorable or unusual developments; and 3. a summary of work to be performed during the succeeding year; and any other pertinent information." Financial and schedule status information similar to that given in the Quarterly Report will be included in the Annual Report.

7.1.4. ANNUAL WORK PLAN

Each year, through the Office of Sponsored Research, the LIGO Project shall negotiate and submit an annual Work Plan and funding request to the NSF on October 1 for the December 1 annual award date. The Annual Work Plan is prepared in accordance with the most current version of the NSF Grant Proposal Guide. This Plan shall discuss scientific and program achievements and compare achievements with the projected goals in the currently approved Work Plan. It will summarize the proposed goals for construction, R&D, science and collaborative programs for the program year for which funds are sought. Significant staffing changes, estimated costs and schedules will be presented for each level III WBS item and comparisons will be made to the LIGO cost/schedule baseline. An organization chart and description of the LIGO organization in the new program year will be presented, together with an explanation of any changes from the Project Management Plan. The Plan shall include a statement of the LIGO annual calendar including proposed dates for meetings of the LIGO Oversight Committee, advisory committees, scientific workshops and reviews. The Plan shall include an acquisition plan for all procurements in excess of $100K, including the proposed date of submission to NSF and the type of procurement.

Changes to the LIGO cost and schedule baseline, approved in the LIGO Change Control process will be identified in this annual work plan, and these changes may represent modifications to the cost and schedule information presented in this Project Management Plan. Any other changes in the Project Management Plan will similarly be considered in the Change Control process, as the Project Management Plan is a controlled document with the LIGO baseline. These changes will be fully reported in the Annual Work Plan for review and approval by the NSF in accordance with the terms and conditions in the Cooperative Agreement.

7.1.5. OTHER REPORTING

The Caltech Office of Federal Financial Activities submits to NSF a quarterly reconciliation report against the Letter of Credit 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 Project.

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

7.2. MEETINGS & REVIEWS

7.2.1. INTERNAL LIGO MEETINGS

Technical and design reviews within the LIGO project will be conducted by 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 will also be regularly scheduled Project Control Meetings, Integration Meetings, meetings of the Technical Board and of the Change Control Board.

7.2.2. PROGRAM ADVISORY COMMITTEE

The Principal Investigator shall convene the Program Advisory Committee as necessary, but at least once a year. The committee shall provide analysis and advice to the Principal Investigator and Project Manager. NSF shall be informed of all meetings, invited to attend, and shall receive copies of relevant reports. The charge and initial membership of this Committee will require the concurrence of the NSF Program Manager.

7.2.3. LIGO OVERSIGHT COMMITTEE

The LIGO Oversight Committee will hold regular meetings[13] to review progress and to resolve institutional issues. Special meetings may be held to resolve particular issues which must be resolved before the next scheduled meeting.

7.2.4. NSF REVIEWS

The NSF may convene a visiting committee to conduct periodic reviews of the LIGO Project, covering technical and management issues. NSF shall provide the Project with a copy of the charge to the review committee prior to the review, with adequate time to agree on the agenda and to prepare the necessary presentation material. We are informed that NSF intends to conduct two reviews annually. One review will concentrate on cost, schedule and management. The other, approximately six months later, will concentrate on the technical and scientific aspects of the project. There will be substantial continuity of membership on these review committees.

7.2.5. WORKSHOPS

As a means to foster greater interest and participation by the broader scientific community, the LIGO Project will sponsor or participate in workshops on specific topics relevant to

13. For planning purposes we have assumed that regularly scheduled Oversight Committee meetings will be held on a quarterly basis.

the development of gravitational-wave interferometers. The frequency of such workshops and the topics they address will be determined in consultation with interested outside scientists, such as LIGO R&D Collaborators (section 2.3) and the other international groups pursuing laser interferometer gravitational-wave detection.

7.3. TECHNICAL REPORTS

To enhance the participation of the general scientific community in gravitational wave research, the LIGO project will continue the publication of research results in refereed journals, and will make unpublished internal technical reports available to the general scientific community on request. A written LIGO Publication Policy will govern this process.

8.0 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 required responses to risks which 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.

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 performed in accomplishing a project.

APPENDIX A

OPERATIONS PHASE OF LIGO

This management plan describes the organization and controls for the LIGO project during the construction phase. Near the end of construction, the project will progressively enter the operations phase, during which the initial interferometers will be installed, integrated, and undergo shakedown. The initial goal during LIGO operations will be to make a single three-interferometer detector that will be operated and improved. At some point after satisfactory operation of the facilities and interferometers has been achieved, a proposal to expand the LIGO vacuum system to its full capability and to employ additional interferometers will be made.

Operations

The operation of the LIGO facility will begin at the time of acceptance of the first buildings and vacuum system and will proceed with the commissioning of the initial three interferometer detector. Two key milestones exist for the early operations phase. First, the milestone "Begin Coincidence Tests" identified in Table 5-2 corresponds to achievement of a strain sensitivity for the detector of 10^{-20}. A second key milestone at the end of FY2001 is the planned achievement of a detector strain sensitivity of 10^{-21}.

Once all three interferometers are operational the detector (consisting of three interferometers as required for coincidence detection) must serve the needs for both detector development and observations. This detector will be operated by the LIGO Laboratory in association with the LIGO Scientific Collaboration. The LIGO Scientific Collaboration will continue to carry out research to improve the sensitivity and operation of the interferometers. Substantial upgrades to the interferometer are envisioned. The division of time between detector operation and improvements will be made by LIGO Laboratory management, advised by the Program Advisory Committee.

Following the second key milestone, it will be possible to expand the initial vacuum system to accommodate additional interferometers. The LIGO facilities have been designed to permit expansion. The LIGO Scientific Collaboration will be involved early in the planning of the expanded facilities.

Access to the facilities will be granted on the basis of proposals, through an open competition. The LIGO Principal Investigator will employ the PAC to review the proposals and to recommend time and space allocations for the expanded facility. The LIGO Laboratory plans to continue to operate one detector (three interferometers) as a part of the international network.* Access to data from this detector and collaboration on its improvement and operation will continue to be available to outside scientists.

The LIGO staff will also provide supervision and support to outside users to ensure the safety of the facilities (in particular, to prevent contamination of the vacuum system) and to resolve interferences and conflicts between different uses.

* Present plans by the French-Italian project (VIRGO), and all other international programs, envision the construction of a single-interferometer facility only, and rely on LIGO to provide the missing component for coincidence-mode operation and astrophysical source location in an ongoing capacity.

APPENDIX B

MEMORANDUM OF UNDERSTANDING

BETWEEN THE

CALIFORNIA INSTITUTE OF TECHNOLOGY (CALTECH)

AND THE

MASSACHUSETTS INSTITUTE OF TECHNOLOGY (MIT)

ON THE

LIGO PROJECT

1) The LIGO project is a collaborative effort by Caltech and MIT scientists to design, build and operate an observatory to measure gravitational waves from astrophysical sources by laser interferometry. LIGO is a national facility for gravitational wave research.

2) Under the terms of a Cooperative Agreement with the National Science Foundation (NSF), Caltech is the responsible agent for the LIGO project. Caltech shares with MIT responsibility for oversight and implementation of the project, and both will share in the scientific benefit of LIGO

3) The presidents of Caltech and MIT will establish a LIGO Oversight Committee, chaired by the Special Assistant to the Caltech President for LIGO and composed of two members from each institution appointed by their respective presidents after mutual consultation. The Oversight Committee will report to the presidents through the Chair of Physics, Mathematics & Astronomy at Caltech and the Dean of Science at MIT.

4) The LIGO Principal Investigator is appointed by the Caltech president in consultation with the MIT president and in accordance with the terms of the Cooperative Agreement with NSF.

5) Selected members of the MIT LIGO science team will participate in the scientific and technical management of the project. One MIT member will serve in a senior, leadership role in the LIGO project and at least one will be designated as key personnel in the Cooperative Agreement. MIT will participate in NSF reviews of the project.

6) The MIT science effort is fully integrated into the LIGO Project. MIT activities on LIGO are listed in a Statement of MIT Roles to be negotiated by January 15, 1995 and updated by mutual agreement as necessary. MIT activities will be classified in two categories: Core LIGO Science and Technology, and LIGO Interferometer Subsystems. Core activities consist of research, development and project support in specific areas as negotiated with Caltech and noted in the Cooperative Agreement. Subsystem activities are associated with specific deliverable items for the LIGO interferometer. Both activities are funded by multiyear subcontract from Caltech, with budgets and statements of work as negotiated with Caltech; these will be renegotiated and updated as required.

7) The MIT group will share responsibility for establishing and maintaining interaction with the broader scientific community and for the operations phase of LIGO.

8) MIT will provide institutional, management and technical support to the MIT LIGO project through the Center for Space Research. Further institutional and academic support will be provided through the Department of Physics. The Director of the Center for Space Research and the Head of the Physics Department are the primary points of contact for institutional matters concerning LIGO. The higher level administrative contacts are the Chair of the Division of Physics, Mathematics and Astronomy at Caltech and the Dean of Science at MIT.

CALIFORNIA INSTITUTE OF TECHNOLOGY:

Barry C. Barish — Date: Sept 20, 1994
Barry C. Barish, LIGO Principal Investigator

Charles W. Peck — Date: Sept 20, 1994
Charles W. Peck, Chair, Physics, Mathematics & Astronomy

Thomas E. Everhart — Date: Sept 20, 1994
Thomas E. Everhart President

MASSACHUSETTS INSTITUTE OF TECHNOLOGY:

Claude R. Canizares — Date: Sept 12, 1994
Claude R. Canizares Director, Center for Space Research

Robert J. Birgeneau — Date: Sept 13, 1994
Robert J. Birgeneau Dean of Science

Charles M. Vest — Date: Sept. 18, 1994
Charles M. Vest President