Report of the Review of the

Laser Interferometer Gravitational Wave Observatory (LIGO)

By the

Operations and Scientific Research Sub-Panel

For the National Science Foundation

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Table of Contents

	Page
Executive Summary	**3**
1. Introduction	**5**
2. Scientific Justification and Broader Scientific Impact	**5**
3. Commissioning Progress and Readiness for Scientific Data Taking	**7**
4. Balance Between LIGO I Operations and Advanced R&D	**8**
5. Education, Public and Industrial Outreach	**9**
a. Industrial and Technical Outreach	**9**
b. Integration of Research and Education	**10**
c. Integration of Diversity and Outreach	**11**
6. LIGO Laboratory Infrastructure	**12**
7. The LSC Collaboration and Relation to the LIGO Laboratory	**14**
8. International Cooperation Among Gravitational Wave Detector Groups	**15**
9. Budgets and Manpower	**17**
10. Schedules and Milestones	**19**
Appendices:	
A - Charge to the Review Panel	**21**
B - Panel Members and NSF Participants	**25**
C - Agenda for the Review	**27**
D - Report of the Advanced R&D Panel	

Executive Summary

As the LIGO program moves toward fruition, it heralds the beginning of a new way to "see" the universe using gravitational waves. The Review Panel was extremely impressed with all aspects of the LIGO Program and feels that it should receive the highest possible rating. The scientific goals of the program to study the universe using gravitational radiation are of revolutionary importance. The technical progress and management are excellent. The overall scientific and technical expertise of the participants is of the highest caliber. The construction of the laboratory and the instrument has been completed on time and on budget, and the prospects for successful operations of the LIGO I interferometers and the R&D for the advanced LIGO detector are excellent.

The panel's response to the questions posed in the charge are the following:

- The proposed budgets for LIGO Laboratory Operations, the scientific research program, and the R&D for Advanced LIGO are justified and adequate to carry out the proposed activities.

Recommendation:

The Review Panel recommends that the NSF, even in the eventuality of overall fiscal pressures, support the LIGO program at the requested level.

Discussion:

The Panel felt that the requested budget was carefully thought out and is the minimum required for the successful and timely implementation of the two goals of the next five years of the program, namely, the operation of the LIGO I interferometers and the R&D for Advanced LIGO. Compromising either of these efforts would have the undesirable consequences of

a. endangering the continuity of the key personnel who are crucial to the success of the program, and

b. endangering the leadership position of the U.S. in this fundamental area of science.

- The proposed LIGO Laboratory infrastructure, including facilities and manpower, is appropriate and adequate for effective participation in the science by LSC members, and the plan for wide access to LIGO data seems appropriate.

Recommendation:

NSF should continue to fund the LSC member institutions and gravitational wave research at a level that makes it possible to exploit the full scientific potential of the LIGO facility.

Discussion:

The LIGO Program has organized itself into the LIGO Laboratory and the LIGO Scientific Collaboration (LSC). The Panel feels that this organization has been successful and very fruitful in opening up LIGO to all interested scientists, bringing in much needed expertise, and separating the day to day construction and operating effort from a strategic consideration of the scientific issues.

- The schedule and milestones for the LIGO Laboratory commissioning and scientific running are achievable with the proposed resources. The milestones in the past have been achieved, and sufficient and significant milestones have been provided for the future.

- The proposed outreach and education plans are well designed and the proposed manpower and funds are adequate to carry out the plan. LIGO outreach efforts would be substantially enhanced if there were modest additional funding allocated for this activity.

- There is a well thought out plan for international collaboration between LIGO and other gravitational wave programs around the world. This plan, in the form of the Gravitational Wave International Committee (GWIC), is well along the path of implementation.

The two goals of the program for the next five-year period were described to the Panel. The first goal is the operation of the LIGO I interferometers to search for gravitational waves with the strain sensitivity of $h=10^{-21}$. This sensitivity is sufficient to make plausible, but not to guarantee, significant discoveries. The second goal is to pursue the R&D necessary for the design and construction of the Advanced LIGO interferometers with a 15-fold sensitivity improvement. Since the number of detectable sources is expected to scale as the cube of the sensitivity, Advanced LIGO is crucial in realizing the scientific goals of the program. The Review Panel felt that both of these goals are of paramount importance, and that the balance between the resources planned by LIGO on these two efforts is about right.

1. Introduction

A Panel has been constituted by the National Science Foundation to review the proposal "Continued LIGO Operations for FY2002 – 2006" by the Laser Interferometer Gravitational Wave Observatory (LIGO). The panel was divided into two sub-panels, the " Detector Research and Development Sub Panel" and the "Operations and Scientific Research Sub Panel". The charge to the panel and the membership of the operations sub panel are included as Appendix A and B respectively. The R&D sub panel met at Caltech, Pasadena, California on January 29 – February 1, 2001, and the Operations Sub Panel met at Hanford, Washington on February 26 – March 1, 2001. The agenda of the meetings of the operations sub panel is included as Appendix C. The final report of the R&D Sub Panel (Appendix D) was available to the Operations sub-panel at the February meeting in Hanford. One member of the R&D panel attended the Hanford meeting and led a thorough discussion of the findings in that report. These findings formed an integral and useful part of the deliberations of the Operations sub panel.

The following nine sections detail the findings, comments and recommendations of the Review Panel.

2. Scientific Justification and Broader Scientific Impact

LIGO is a facility designed to open a new window on the universe – the gravitational wave window. Detection of gravitational waves will allow for the first time, fundamental physics tests of general relativity theory in the strong field regime. It will also enable the study of the universe with radiation that gives information not obtainable with electromagnetic or neutrino signals.

The decision by the National Science Board and the U.S. Congress to proceed with LIGO envisioned a two-stage process. The first stage ("LIGO-I") was to build the facilities for LIGO and install in them a conservatively designed set of interferometers, with which it is plausible, but not probable, that gravitational waves will be detected. A several year search with these initial interferometers will give us the experience necessary for moving to the second stage. The second stage ("Advanced LIGO") is to upgrade the interferometers to a sensitivity at which it is probable that we will detect a number of sources, and begin extracting rich information about the gravitational–wave universe. The rationale for this two-stage process has not changed; if anything, developments in astrophysics have strengthened the case since the construction decision was made.

The proposed upgrade will improve the sensitivity of the detector by a factor of about 15. This increases the event rate for distant extragalactic sources by a factor of 15^3, or about 3000. The first 2.5 hours of operation of Advanced LIGO will exceed the integrated observations of the 1-year LIGO-I science run. The advanced interferometers will also have a wider frequency range, enabling them to study sources not accessible to the initial LIGO.

A prime target for LIGO is the inspiral and coalescence of a pair of neutron stars in binary orbit. This is a source that we know exists – 3 such systems have been identified in our galaxy as radio pulsars, and they will coalesce about 10^8 years from now. The only uncertainty is how to extrapolate this rate to include larger volumes of the universe that are observable by LIGO. There is now reasonable consensus that the event rate is very conservatively 1 per year for Advanced LIGO, and possibly as high as several hundred per year. (For LIGO-I, the most optimistic estimate is 1 per 3 years.)

Neutron star–black hole binary inspiral and black hole–black hole binary inspiral are other prime targets. We have no observational evidence that such objects exist. Indeed, black hole binaries are unobservable except with gravitational waves. However, theoretical estimates of the event rates range from 1 to several thousand per year for Advanced LIGO. It is important to point out that these various estimates are being made by mainstream astrophysicists not connected with LIGO or even with research in general relativity theory, and are published in the general astrophysical literature.

One of the most exciting prospects is the detection of gravitational waves from events involving black holes. Black holes are a fundamental prediction of Einstein's theory. The black hole candidates identified so far in nature are objects with a lot of mass in a small volume. We say they are black holes because general relativity says that is what such compact objects must be. But we have no direct evidence that these objects are in fact the black holes of Einstein's theory, objects with an event horizon, and which distort the geometry of spacetime around them into that of the Schwarzschild or Kerr metrics. By confronting gravitational wave signals from black hole events with the predictions of general relativity we will finally be able to test the theory in the strong-field, nonlinear regime.

Many other classes of sources have been proposed. These include low-mass X-ray binaries, fast spinning pulsars with a slight ellipticity, unstable r-modes in newborn neutron stars, supernovae, gamma ray bursts, and a stochastic background from the early universe. Detection, or even non-detection, from these sources will enable a wealth of astrophysical information to be gleaned. There is even the potential to learn details of the nuclear equation of state from observations involving neutron stars.

Some of these potential sources, such as unstable r-modes, have only been discovered in the past few years. Moreover, there have been speculations about cosmological sources, such as cosmic strings or coherent excitations of our 3+1 dimensional universe regarded as a "brane" in a higher dimensional universe. Each of these speculations is plausible, though not highly likely. Perhaps their greatest value is to remind us how ignorant we are of physics and astrophysics in the domain that the advanced LIGO interferometers will probe. Our ignorance may well be even greater than that of the pioneering radio astronomers of 1940 and X-ray astronomers of 1960; and as there, so also here, the first waves to be discovered may well be from sources that were previously unknown. Advanced LIGO could bring us a revolution of insights into the universe, and even into gravity, comparable to the revolutions wrought by radio and X-ray astronomy.

Besides revolutionizing the field of gravitation physics, LIGO will impact many other areas of science. In astrophysics, our knowledge of events involving objects like neutron stars, black holes, gamma ray bursts, supernovae, and X-ray binaries will be dramatically increased. Nuclear physics may gain significant information as we learn about the nuclear equation of state. Fundamental theories of physics that postulate extra dimensions or cosmic strings or other phenomena that are difficult to observe may be constrained by observations of the stochastic gravitational wave background.

3. Commissioning Progress and Readiness for Scientific Data Taking

This section addresses the charge item requesting comments on the proposed commissioning plan and its supporting resources for the LIGO observatories and the LDAS data processing system as these bear on the readiness for the planned accomplishment of the proposed engineering and scientific data taking runs in the period 2002-2006. Here, we report our findings on this topic.

Findings:

The LIGO installation and commissioning activities at the two observatories and at the two university centers, CIT and MIT, have progressed well and have made good and systematic progress toward the LIGO commissioning and operations goals. The most significant recent milestones for the overall program are the achievement of full interferometer lock in both arms of the 2Km interferometer at Hanford and the achievement of single arm lock in the 4Km interferometer at Livingston. Of comparable importance is the maturing of the computing infrastructure and the successful completion of the first mock data challenge. The achievement of these milestones implies the successful achievement of many underlying goals and indicates the good general health of the program as it progresses to reach operational status and to carry out the planned engineering and science runs on the planned baseline schedule.

Comments:

These recent accomplishments indicate that the Laboratory has the planning capability and performance track record to successfully plan and propose the continuing LIGO commissioning activities, as well as to successfully carry out the upcoming engineering and scientific data runs. The submitted proposal presents a well thought-out plan for these activities in the resource context of the existing CIT and MIT based Laboratory staff, the LSC collaborating groups and the LHO and LLO observatory staff and infrastructure. The serial interferometer commissioning philosophy has proven itself, especially when technical problems have arisen during the installation and commissioning work performed so far.

The schedule has been held and problems have been addressed without holding up the overall commissioning effort and schedules. The proposed resources, including the increases for incremental staff at the observatories and other materials and services

budgets, are fully adequate for ensuring that the engineering and scientific program can be successfully accomplished as proposed. There are adequate control mechanisms and milestones in the management plans to assure that the planned program is accomplished on-schedule and within the proposed resources.

The Sub-panel concludes that the proposed funding and manpower resources are adequate for the successful engineering and scientific running of the LIGO program in the period 2002-2006. We also conclude that the incremental operating resources proposed for site operations starting in 2002 are necessary for site operations needs.

4. Balance between LIGO I operations and Advanced LIGO R&D

Findings:

A breakout of proposed costs (in all budget categories) associated with Advanced LIGO R&D corresponds to about $54 M, whereas the share allocated to basic facility operation (including support of LIGO-I science runs) corresponds to about $121 M. (For example, a substantial portion, about half, of Advanced R&D expenditure appears in the proposal budget as “Basic Operations R&D Support”). The Advanced R&D effort pursues new technology on many fronts to achieve a major increase in sensitivity for Advanced LIGO. The basic operations include funding to turn both observatory sites into round-the-clock observing facilities.

Comment:

The panel finds that the balance of resources between LIGO I operations and Advanced LIGO R&D is about right.

The panel finds that the organization of the LIGO Laboratory and the LSC is remarkably healthy and flexible, with good decision-making and communications channels. As long as these attributes are maintained, an optimal allocation of resources should remain assured for the duration of the proposed activity.

The challenges of Advanced LIGO R&D, in addition to their eventual large scientific payoff, are important to retaining the most creative scientific and technical staff--- who are naturally drawn to the most important and difficult (but solvable) problems. At the same time, the exquisite and unique LIGO I data will exert a powerful draw compelling these same individuals, who are most knowledgeable with the details of the apparatus, to become engaged with the rest of the LSC in analyzing the engineering and science run data. The committee feels that the appropriate relationships and institutions are in place for highly effective direction and coordination of effort for both individuals and the collaboration as a whole to divide their effort optimally between these activities. One panel member called the level of cooperation in the program "breathtaking".

The overall plan of the program to make the Advanced LIGO enhancements "all at once," rather than incrementally, will optimize the observational runtime available for the LIGO I science run. The program management is flexible enough to adapt the precise schedule to various exigencies which cannot be predicted at this time, such as the running status of other detectors.

The technical goals of Advanced LIGO are well motivated and largely independent of any astrophysical signals which may be detected by LIGO I. The schedule of the Advanced LIGO R&D is set by available personnel, by long-lead-time items, and by the uncertainties which necessarily accompany new technologies. The proposed work plan sets the best course with currently available information.

The panel endorses the priority given to the support of the LIGO I science run. The incremental funding requested for conversion to 24/7 operations is fully justified. At the same time, the new funding requested for advanced R&D is at the right level to empower the team to work through to the level of a working engineering prototype for Advanced LIGO, with fully functional systems ready for implementing a construction phase. This level of effort is needed to maintain the integrity, leadership and the momentum of the LIGO team at its current world-class level.

5. Education, Public and Industrial Outreach

a. Industrial and Technical Outreach

The LIGO activities to date have already spurred an advance of technological capabilities outside of the scientific venue.

Findings:

LIGO has successfully developed a number of cooperative ventures with commercial firms that have been of significant importance in the assurance of high-quality innovative components required for meeting its technical goals. This has occurred by the transfer of LIGO's unique technical competencies via some of its members working closely with colleagues in industrial concerns. One example of this was the development of an enhanced Nd:YAG laser by Lightwave Electronics, Inc. that has now appeared in its product line. New optical techniques have been developed and are expected to have industrial applications. Other industrial partners include Veeco, Inc., Barry Controls, Inc. and Research Electro-Optics, Inc. working on the development of key precision isolation, optical and telecommunications technologies.

The requirements of LIGO optics are pushing the envelope in the development of new coatings and polishing techniques. These advanced technological requirements have also had an impact on the metrology in such optical devices that have led to new techniques for measurement of tolerances. The development of some of these capabilities in LIGO industrial partners has had the result that contracts have been let with NASA JPL and some of the high quality optics may play a role on the NASA Space Interferometer Mission (SIM).

b. Integration of Research and Education

Findings:

The LIGO program has engaged in a number of activities to foster integration of academic and educational programs, which are related to its core scientific mission.

A partial list of the already established activities along this line include;

(a) High School Student and Teacher Research (LHO/HSST)

(b) Distance Learning (LHO/DL)

(c) Education Material Development (LHO/LLO/EdMat)

(d) K-12 In-Service Teacher Program (LLO/K12)

(e) Research Experience for Undergraduates Program (LHO/PNNL/REU)

(f) Summer Undergraduate Research Foundation Program (Caltech/SURF)

(g) Public Open House (LLO)

(h) Public Lectures (LHO)

(i) Web-based Activities (Caltech/MIT/LH0/LLO)

The LIGO-Caltech and LIGO-MIT groups have hosted numbers of K-12 students from their respective metropolitan areas permitting the students to learn, through hands-on activities, about the properties of observable wave phenomena and, by analogy, gravitational wave phenomena.

Comments:

The situations of the research sites LHO and LLO with regard to such opportunities are strikingly different. The LHO is located within a community that has for a long period of time been the host of other large scientific activities. The nearby Pacific Northwest National Laboratory (PNNL) as well as the Schlumberger organization have long offered the local community and their school systems the opportunities for active academic and educational engagement in a dynamic state-of-the-art scientific research effort. Within its immediate community, LHO is in the midst of an already well served group. This makes it harder for LHO to have a substantial local impact but under the direction of Fred Raab, it has definitely taken steps (e.g. LHO/HSST, etc.) to be of service in less well served and more distant areas in the northwest region of the U.S.

The situation of LLO is very different. Its location does not possess a pre-existing large scientific infrastructure and thus affords it major opportunities for having a substantial impact within its local community. Under the leadership of Mark Coles, LLO has made progress in offering a new facility for spurring increased levels of scientific awareness. The support by the State of Louisiana for the construction of a telescope facility on-site is an example of the impact that this program is starting to have. The possibility of a visitor center, built around this telescope, seems very real. The number of colleges and universities within an hour's drive of LHO is significant and should be viewed as additional opportunities for outreach.

Recommendation:

LIGO efforts at outreach would be substantially enhanced if there were *additional funding* allocated for this activity. How this could be achieved should be explored between LIGO and the National Science Foundation.

c. Integration of Diversity and Outreach

With regard to broadening opportunities and enabling the participation by a wider segment of the population in scientific research, the LIGO team has moved commendably to address these issues.

Findings:

Members of LHO have undertaken efforts to offer opportunities for the Native-American community to become involved in LIGO activities. Presentations at an AISES (American Indian Science and Engineering Society) meeting, Heritage College, Salish Kootenai College and high schools with considerable Native American populations have taken place.

With regard to the African-American community, it is noted that progress seems to be occurring through the LSC membership of Southern University at Baton Rouge.

Comments:

The presence of the LIGO facility in Louisiana may allow for a potentially large and unusual opportunity for the newly emerging scientific community of gravitational wave observers to create a strong bridge to increase its diversity. Particularly, it should be noted that this is *not* just potentially a student related activity, but could be an effective way to bring research into a new environment.

An equivalent role for the Hispanic and Latin-American communities is being played by the LSC membership of the University of Texas @ Brownsville. Certainly within the greater Los Angeles metropolitan area, large communities of such U.S. residents live and would appear to offer a target of opportunity for LIGO-Caltech.

The operating centers of LIGO are particularly well suited to undertake outreach efforts to three under-represented communities. The LHO site serves as a `gateway' to the Native-American community. LIGO-Caltech and LHO sites serve this role for the Hispanic and

Latin American communities. Finally, LIGO-Caltech and LLO serve the role to the African-American community.

The Jefferson Laboratory/Hampton University (JLab/HU) experience is a pre-existing model where the creation of an enhanced national laboratory was coupled with an enhanced scientific *research* program at a historically black college. To some large degree, the NSF created this model. The NSF played a substantial role in the success of this effort through its support of the Nuclear and High Energy Physics (NuHEP) Center at Hampton University.

Recommendation:

LIGO, in conjunction with the NSF, should investigate ways in which the highly successful JLab/HU model might be replicated. This should be considered as widely and creatively as possible and all opportunities, including those outside of the MPS directorate, should be explored.

6. LIGO Laboratory Infrastructure

Findings:

The panel reviewed the proposed budget for LIGO Laboratory operations as well as the infrastructure, including manpower and facilities, available to support participation in the science by LSC members.

The staff at the Livingston and Hanford sites have the following responsibilities: installation of the remaining components of the interferometers; operation of the facility for data acquisition; trouble shooting and maintenance of the scientific equipment; on site data processing and temporary storage of data before it is archived at Caltech; maintenance of the physical plant; related research and development; and educational outreach.

The on site staffing requested for the period 2002-2006 to cover these activities is 60 FTEs for the two sites combined. This represents an increase of 13 people over the staff funded at the current budget level. The increased staff will support continuous (24x7) operation; the operation and maintenance of the LDAS; site support of visiting scientists from the LSC; computer and network systems administration; and educational outreach ($1,063K annually for all of these functions). Additional funding is also requested to support data distribution via OC3 connections ($540K annually) and to maintain and replace LIGO Data Analysis and Computing hardware on a 4-year cycle ($1380K annually).

Significant steps have already been taken that should help to limit operations costs. The fact that the equipment at the two sites is identical means that each site can benefit from the experience of the other, and that improvements made at one site can be translated directly, without additional redesign and testing, to the other. Techniques for diagnosing system problems and identifying sources of noise have been worked out in advance. A data archiving system is available for recording environmental perturbations and other key diagnostic data for subsequent analysis. An end-to-end model of the system is being refined and can be applied to noise analysis; one advantage of the availability of this model

is that the analysis can be carried out away from the site by people who are unfamiliar with the details of the experimental design and operation of the facility, thereby in effect providing an extension of the on site staff.

There was also evidence of good attention to safety, particularly laser safety.

The staff at the sites relies heavily on personnel and support services available at MIT and particularly at Caltech. Senior scientists and engineers resident at these institutions have in-depth knowledge of system design that will be essential for diagnosing problems at the sites. Centralized oversight also makes it possible to enforce configuration control and to keep the facilities at the sites as nearly identical as possible. Staff at Caltech are responsible for providing nearly all administrative support. There appears to be good response to requests from operating sites.

Comments:

The increases requested are closely linked to increased program requirements for continuous operation for extended periods of time, support of LSC scientists, data management, and educational outreach and appear to be well justified. The proposed overall staffing for operations appears to be lean but adequate given the current understanding of requirements. It is, however, too early in the operational phase to have established any real experience with how reliable the instrumentation will be. Therefore, there remains some uncertainty about what level of effort will ultimately be required to maintain a high duty cycle and complete the goal of one year of operations at the desired sensitivity level of 10^{-21}. Over the next year or two as experience is gained with the operation of LIGO, staff should assess whether the currently predicted personnel requirements are adequate to achieve robust performance at the desired sensitivity.

The high speed data links that are proposed will be important not only for data distribution but also for enabling better real time communication among the multiple sites, including videoconferencing, remote engineering diagnosis of problems, and remote monitoring of data acquisition.

The level of funding requested for replacement of computers is adequately justified, but there are likely to be more items in this category of capital replacement as the facility ages. For example, the budget for the types of facility maintenance that must be conducted routinely at intervals of a year or less appears to be adequate. However, the panel was given estimates that beginning in about five years time, items normally referred to as deferred maintenance, that is maintenance that is required less frequently than annually such as resurfacing of roads, re-roofing, painting, etc., is likely to require an annual expenditure of about $600K for Hanford and Livingston combined. There is probably not yet enough experience base to determine the costs of repair, replacement and sparing the key components of the interferometer.

Recommendation:

LIGO staff should develop a schedule and cost estimate for deferred maintenance and capital replacement for all components of the facility.

7. The LSC Collaboration and Its Relationship to the LIGO Laboratory

Findings:

In 1997 the LIGO Program decided to split into two entities, the LIGO Laboratory and the LIGO Scientific Collaboration (LSC). The LIGO Laboratory, with its directorate and hierarchical structure, was organized to carry out the civil construction of the two laboratory sites, construct the instruments, and operate them. The LSC, with its own elected spokesman and organization, in collaboration with the LIGO laboratory, was intended to:

- Determine the scientific needs of the program
- Set priorities for research and development
- Present the scientific case for the program
- Carry out the scientific and technical research program
- Carry out the research program and validate the scientific results
- Establish the long term needs of the field

The collaboration now consists of 35 institutions and 355 members. The scientific staff of the LIGO Laboratory is also members of the LSC. Membership in the Collaboration is open to all scientists interested in the study of gravitational waves internationally. However, membership is conditional on all members contributing in some way to the overall effort of LIGO. These contributions are defined in MOUs between the program and each member institution.

The funding of the LSC member institutions is covered in a minor part through the LIGO Laboratory, but mostly directly from the NSF in the US or other funding agencies abroad.

Comments:

The Review Panel feels that the LSC concept has been successful and its relationship to the LIGO Program has been fruitful in many ways:

- The members of the LSC and the LIGO Laboratory appear to be working together smoothly and in a coherent fashion.

- Membership in the LSC has opened up the LIGO program and science to all interested scientists internationally.

- The LSC has brought into the program much needed talent and expertise, both from the US and abroad.

- The structure of the LSC and the Laboratory has effectively separated the need to respond to immediate needs of the construction program from the more strategic thinking about longer range scientific issues.

- The requirement that members of the LSC contribute to the overall effort of the program is very healthy. This arrangement contributes much needed effort to a very complex program, and it also provides a feeling of equity that everyone who enjoys rights to the data contributes to generating it.

Recommendation:

The NSF should continue to fund the LSC member institutions and gravitational wave research at a level that makes it possible to exploit the full scientific potential of the LIGO facility.

8. International Cooperation Among Gravitational Wave Detector Groups

Findings:

1) There is large degree of cooperation in the technology R&D program among the major gravitational detectors based on laser interferometers.

2) There is an emerging collaboration between gravitational wave detector experiments as they explore coordinated data taking as a global detector array.

3) The most evolved technology R&D cooperation exists between the GEO program and LIGO. Joint R&D is being done on suspensions, interferometer configurations and pre-stabilized lasers. Discussions have started on a possible financial contribution of the GEO groups to the construction of Advanced LIGO.

4) A major collaborative program exists between LIGO and ACIGA on laser development, sapphire development and high power issues. The full ACIGA collaboration has joined the LSC and is fully integrated into the physics research and the technology R&D programs.

5) The TAMA collaboration has an MOU with LIGO on modeling and on a coincidence run with the 40 Meter interferometer at Caltech. LIGO has provided a new isolation system prototype for testing at TAMA. A growing collaboration exists between TAMA and LIGO on cryogenic detectors. One of the TAMA institutes has joined the LSC.

6) There exists collaboration with several experts in Russia on thermal noise, quantum sensing and non-linear optics.

7) The early steps in collaboration are now starting with the VIRGO Program. Peer to peer efforts have occurred in optics and beam tube technology. Coatings are being explored as a joint program and discussions have started on how to run the detectors as a phased array.

8) GWIC was formed in 1997 and comprises the directors of the major gravitational wave detectors. It is a forum for collaboration and joint planning. It operates as a sub-panel of IUPAP Working Group 4. The director of LIGO is currently the chair of GWIC.

9) GWIC promotes coordination and sharing of technical R&D and the development of gravitational wave detection as an astronomical tool. It has led to the adoption of a common data format adopted by all IFO programs.

10) GWIC is promoting the development of a worldwide detector network. The exchange of the Physical Environment Monitoring (PEM) data has been implemented and work is ongoing on cooperative analysis of data by the various gravitational wave detector programs as well as with other astronomical observatories.

Comments:

A great deal of attention and effort has been invested in developing international collaborations both in the technical R&D and in the beginnings of coordinated data taking and analysis. Several of the collaborations are already well developed and the technical work in these is highly integrated. Others are starting to develop as the effectiveness of the various collaborative efforts is demonstrated. Initial discussions are underway to coordinate the downtime of individual detectors in order to maintain significant observational capabilities at all times once a number of detectors become operational. The efforts of LIGO in developing these collaborations and providing leadership within the community of gravitational wave detectors are to be commended. We see the development of international collaboration among the various interferometer-based detectors proceeding along a very good track.

9. Budgets and Manpower

Findings:

The submitted proposal is for a combined program of LIGO observatory operations and advanced LIGO interferometer R&D for the period 2002-2006. The proposal also includes a budget for significant equipment items provided in support of research by LSC collaborators through the Laboratory for the three-year period 2002-2004. The total budget proposed for the five-year period is $175,566,236. The proposal divides this amount into 4 categories: “Currently Funded Operations” @ $125.5M; “Increase for Full Operations” @ $25.0M; “Advanced R&D” @ $14.7M; and “R&D Equipment for LSC Research” @ $10.3M. However, the “Currently Funded Operations” category includes a substantial amount for manpower related to the Advanced R&D effort. When this is taken into account, the total request for LIGO I Operations is $121.3M and the request for Advanced R&D is $54.2M.

The sub-panel concluded that the proposed amounts were adequate to fully fund the proposed activities and, in fact, would make up for a significant under-budgeting situation encountered by the Laboratory in the fiscal years 2000 and 2001. The resulting 2002 budget for Laboratory operations plus advanced R&D rises from its full-year value of $25.62M in 2001 to $34.91M in 2002 and maintains this approximate level through the year 2006.

After a considerable amount of discussion, the sub-panel concluded that the separation of these budget categories into “operations” and “R&D” categories had been comprehensibly made and that the incremental requests for operations costs at the two observatories were needed and fully justified. These increases totaled about $3.4M in 2002 for “basic operations” plus $1.7M for “operations in support of advanced R&D”. Comparable amounts were request in subsequent years under this category.

In the home laboratories, CIT and MIT, the permanent staff levels remained approximately constant, although the skill mix evolved to a somewhat different profile during the past two years. Declines in the engineering staff associated with vacuum and mechanical infrastructure were experienced with the completion of the large vacuum systems; growth of the computing professional staff was also realized as the LDAS enterprise was increased to its full strength for supporting the LIGO data analysis load. The technical staffs at CIT and MIT, except for the LDAS operation, are largely devoted to advanced R&D activities with about 25% or less of their effort applied to direct support of site operations activities. This site support is likely to decline over the proposal period as the fraction of time devoted to scientific observation increases and engineering runs decrease. The management and administrative staff levels are approximately unchanged from prior years.

Significant numbers of temporary and contract staff are proposed in the submitted budget and these are for both scientific activities (data analysis) and for advanced R&D. Both scientist positions and engineering positions are requested. Some of these positions are included in the 2001 level of operations and some are new slots as yet unfilled.

The sub-panel concluded that the staffing levels are adequate for and consistent with the full proposed program of site operations and advanced R&D. The site operations program has as its goal, an integrated year of scientific observation time in the LIGO I configuration. The remaining calendar time in the 2002-2006 period will be devoted to engineering studies. Given the complexity of the interferometers this is a reasonable planning goal.

The advanced R&D program proposed has as its goal, the realization of a set of design and hardware improvements to the LIGO I interferometer complement that would be ready for installation in 2006 and that would increase the strain sensitivity by a factor of 15, hence expanding the discovery capability of the LIGO observatories by a factor of about 3000 due to the increased volume of space accessible at a given signal sensitivity level.

Comments:

The sub-panel concluded that the proposed budgets are consistent with these goals and would be limited by the technical rate of progress that can be reasonably foreseen. At the proposed budget level, the R&D program is limited primarily by technical and manpower considerations.

Realization of the full scientific promise of the LIGO program has been predicated from the program's beginning on the realization of the interferometer sensitivity benefits of the Advanced LIGO upgrade. The sub-panel strongly supports this goal and the associated budget levels proposed for the period 2002-2006. We urge the NSF in the recommendation below to exert vigorous efforts to provide the proposed levels of support for the LIGO operations and advanced R&D.

We observe, however, that the advanced R&D program faces significant technical challenges and that it has development areas where the desired advances will require large funding investments. The three areas where this is especially true comprise: sapphire crystal optics development; optical coating improvements; full-scale seismic suspension improvements. The present plan is to make only one upgrade when all the improvements have been realized. This is anticipated to provide the full factor of 15 improvement in observatory sensitivity. We suggest that this policy be revisited in the event that one or more of the advanced R&D improvement goals falls significantly behind the others on the 2006 time scale and threatens to hold back the time frame for the upgrade to Advanced LIGO. Given the great scientific benefit of even a factor of 2 or 3 in sensitivity improvement of the LIGO interferometers, the sub-panel notes that it may be advisable to make even a partial upgrade after the LIGO I has run for its integrated year of observing.

Recommendation:

The Review Panel recommends that the NSF, even in the eventuality of overall fiscal pressures, support the LIGO program at the requested level.

10. Schedule and Milestones

Findings

1) The LIGO I Detector Operation is on schedule. All relevant milestones have been met with the goal of a first science run with the three interferometers in mid 2002. This final milestone has been kept throughout the program from the start in 1994.

2) In some cases intermediate milestones have not been kept when compared with the original plans; this has been due to a change in strategy from completing all three interferometers concurrently to completing them in series, thus applying the experience learned in one to the commissioning of the others. The committee agrees that this change of strategy was correct and effective. The change in the ordering of completion has shifted milestones without delaying the overall target of a three-interferometer science run in mid 2002.

3) The recent commissioning experience has developed consistently along the lines and with the set of milestones shown a year ago.

4) In the R&D plan there is a comprehensive set of milestones. These milestones take the various elements of the R&D plan from conceptual design to first engineering prototypes. At the end of the R&D program, all interferometer systems R&D is meant to be complete so that Advanced LIGO construction could proceed without any additional R&D.

5) Change in milestones will be handled through the change control process established for the full R&D program.

Comments:

The LIGO program has an excellent record of program management. Schedules and costs have been controlled over a long period. This period will be roughly eight years from the beginning of the program to the first science run with three interferometers in mid 2002.

The process of commissioning now enters a period of some uncertainty, as the sensitivity of the instrument has to be brought to the designed values. While the 2-KM interferometer has locked, the sensitivity at this time is orders of magnitude from the design sensitivity. Several orders of magnitude are understood, from the present effects of electronic noise (prevalent now because of the low power of the laser beam) to the fact that not all control servos have been implemented yet. These large but understood effects mask other potential

sources of noise. The period to achieve full design sensitivity is somewhat unpredictable since we do not know whether un-anticipated sources of noise may be encountered. A reasonable time for commissioning has been allowed and an extensive set of simulations and debugging tools exist for understanding the interferometers. We understand, however, that we enter a period of some uncertainty in maintaining milestones that will last until the instruments reach design sensitivity values.

The successful experience gained during the construction of LIGO is being carried over to the management of the R&D program for Advanced LIGO. Being an R&D program the milestones cannot be controlled as rigidly as they would be in a construction program. The approach to manage milestone changes through a well-defined change-control process is a good idea.

The proposed schedule and milestones for the LIGO Laboratory commissioning and running are achievable with the available and proposed resources.

The set of milestones proposed for the Advanced LIGO R&D are largely determined by the expected rate of technical developments and not by funding. Even at this technology-limited rate, it will be several years before Advanced LIGO will be ready to be constructed. It is important for the NSF to provide the resources necessary to be as close as possible to this expected technology-limited rate in order to maintain the scientific leadership position that LIGO has established. As the field of gravitational astronomy comes into our horizon, many more players will come into the field. The field will become more exciting but also more competitive. The NSF is to be commended for the way it has supported LIGO in the past, allowing the program to successfully establish a position of leadership in the world. This hard gained advantage should not be dissipated by a timid approach to Advanced LIGO. The sensitivity gain that will be achieved by Advanced LIGO is sufficiently vast that operating LIGO I for a protracted period of time before the construction of Advanced LIGO is highly inefficient from both a scientific and an economic perspective.

Recommendation:

The committee recommends that the NSF provide funding at a rate that enables the proposed schedule to be met.

APPENDIX A.

Charge to the LIGO Review Panel

The NSF Grant Proposal Guide (http://www.nsf.gov/pubs/2001/nsf()12/toc.html) contains instructions and guidelines for individual investigator proposals. The National Science Board approved review criteria are included in the section from the Proposal Guide reproduced below and they should be followed in this review:

III. NSF Proposal Processing and Review

Proposals received by the NSF Proposal Processing Unit are assigned to the appropriate NSF program for acknowledgement and, if they meet NSF requirements, for review. All proposals are carefully reviewed by a scientist, engineer, or educator serving as an NSF Program Officer, and usually by three to ten other persons outside NSF who are experts in the particular fields represented by the proposal. Proposers are invited to suggest names of persons they believe are especially well qualified to review the proposal and/or persons they would prefer not review the proposal. These suggestions may serve as one source in the reviewer selection process at the Program Officer's discretion. Program Officers may obtain comments from assembled review panels or from site visits before recommending final action on proposals. Senior NSF staff further review recommendations for awards.

A. REVIEW CRITERIA

The National Science Board approved revised criteria for evaluating proposals at its meeting on March 28, 1997 (NSB 97-72). The criteria are designed to be useful and relevant across NSF's many different programs, however, NSF will employ special criteria as required to highlight the specific objectives of certain programs and activities.

On September 20, 1999, the NSF Director issued Important Notice 125, Merit Review Criteria. This Important Notice reminds proposers of the importance of ensuring that, in addition to the criterion relating to intellectual merit, the criterion relating to broader impacts is considered and addressed in the preparation and review of proposals submitted to NSF. The Important Notice also indicates NSF's intent to continue to strengthen its internal processes to ensure that both criteria are appropriately addressed when making funding decisions.

The merit review criteria are listed below. Following each criterion are considerations that the reviewer may employ in the evaluation. These considerations are suggestions and not all will apply to any given proposal. While reviewers are expected to address both merit review criteria, each reviewer will be asked to address only those considerations that are relevant to the proposal and for which he/she is qualified to make judgments.

What is the intellectual merit of the proposed activity?

How important is the proposed activity to advancing knowledge and understanding within its own field or across different fields? How well qualified is the proposer (individual or team) to conduct the project? (If appropriate, the reviewer will comment on the quality of prior work.) To what extent does the proposed activity suggest and explore creative and original concepts? How well conceived and organized is the proposed activity? Is there sufficient access to resources?

What are the broader impacts of the proposed activity?

How well does the activity advance discovery and understanding while promoting teaching, training, and learning? How well does the proposed activity broaden the participation of underrepresented groups (e.g., gender, ethnicity, disability, geographic, etc.)? To what extent will it enhance the infrastructure for research and education, such as facilities, instrumentation, networks, and partnerships? Will the results be disseminated broadly to enhance scientific and technological understanding? What may be the benefits of the proposed activity to society?

PIs should address the following elements in their proposal to provide reviewers with the information necessary to respond fully to the above-described NSF merit review criteria. NSF staff will give these elements careful consideration in making funding decisions.

Integration of Research and Education

One of the principal strategies in support of NSF's goals is to foster integration of research and education through the programs, projects and activities it supports at academic and research institutions. These institutions provide abundant opportunities where individuals may concurrently assume responsibilities as researchers, educators, and students, and where all can engage in joint efforts that infuse education with the excitement of discovery and enrich research through the diversity of learning perspectives.

Integrating Diversity into NSF Programs, Projects, and Activities

Broadening opportunities and enabling the participation of all citizens -- women and men, underrepresented minorities, and persons with disabilities -- are essential to the health and vitality of science and engineering. NSF is committed to this principle of diversity and deems it central to the programs, projects, and activities it considers and supports.

Specific Charge to the LIGO Review Panel.

The proposal includes three major activities: operations of the LIGO facilities; scientific research; detector research and development. To address this wide range of activities, the Review Panel will be divided into two sub-panels. The first will concentrate on detector research and development. The second will concentrate on operation of the LIGO facilities and scientific research. The broader issues of scientific merit and the overlap in manpower and other resources assigned to the three activities will require both sub-panels to consider the total proposal in their evaluations.

A. Detector Research and Development Sub-Panel

This sub-panel will concentrate on detector research and development to improve the science reach of the LIGO observatories. A major contribution to this R&D program is provided by members of the LSC at institutions other than Cal Tech and MIT. Funds to support those LSC member research programs are provided directly to the LSC institutions.

- While this sub-panel is not charged with reviewing each of the LSC proposals, it is asked to evaluate the total detector R&D plan as presented by the LIGO Laboratory in this proposal. Are the LSC R&D activities (including Cal Tech and MIT) appropriate to achieve the scientific goals of the proposal and are they well coordinated ?

- The Sub-Panel should review the schedule and milestones for progress in the detector R&D program. Is the schedule achievable with the available and proposed resources and are there sufficient significant milestones provided?

- The sub-panel is asked to review the LIGO Laboratory R&D program (Cal Tech and MIT) in detail, including manpower allocation and budget.

The final report of this Sub-Panel is to be completed at this meeting so that it can be made available to the Operations and Scientific Research Sub-Panel before the meeting of that sub-panel.

B. Operations and Scientific Research Sub-Panel

The activities to be reviewed by this sub-panel include completion of installation and commissioning of the interferometers, operation of the facility for engineering and science runs, creating and maintaining the infrastructure for data acquisition and analysis by the LIGO Scientific Collaboration (LSC), and scientific research proposed by the LIGO Laboratory. The Sub-Panel is asked to review and evaluate the proposal with regard to each of the following items:

- Are the proposed budget for LIGO Laboratory operations and the scientific research program justified and adequate to carry out the activities listed above?
- Is the proposed LIGO Laboratory infrastructure, including manpower and facilities, adequate for effective participation in the science by the LSC members?
- Are the schedule and milestones for LIGO Laboratory commissioning and for proposed engineering and scientific running achievable with the available and proposed resources? Are there sufficient significant milestones provided?
- Is the proposed outreach and education plan well designed and are proposed manpower and funds adequate to carry out the plan?
- What is the status of international collaboration between LIGO and other gravity wave centers around the world?
- Is the plan for public access to LIGO data appropriate?

The final report of the Detector Research and Development Sub-Panel will be provided as input to the Operations and Scientific Research Sub-Panel, which is requested to determine if there are issues involving allocation of manpower or other resources between the major activities presented in the proposal. If there are, one member of the R&D Sub-Panel (Dr. John Hall, NIST) will attend this review and other members (Dr. Roger Falcone, UC Berkeley) and Dr. Frances Houle (IBM, Almaden) will be available by teleconference to discuss these issues.

APPENDIX B.
Panel Members and NSF Participants

Operations and Scientific Research Panel

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National Science Foundation Participants

Name	Affiliation
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Victor Cook	Division of Physics Program Manager for LIGO
Adriaan de Graaf	Executive Officer Mathematical and Physical Sciences Directorate
Robert Eisenstein	Assistant Director, Mathematical and Physical Sciences Directorate
Carol Langguth	Office of Budgets, Finance and Award Management Division of Grants and Agreements
Richard Isaacson	Division of Physics Gravity Program Director
Margaret-Anne Wampamba	Division of Physics Gravity Program Administrative Assistant

APPENDIX C.

Agenda for the Review

AGENDA

Monday February 26, 2001

8:30 - 9:00	Panel Executive Session
9:00 - 9:15	Introduction of Panel and Reading of Panel Charge
9:15 - 9:50	LIGO Overview (Barish)
9:50 -10:45	LIGO Science (Thorne)
10:45 - 11:00	Break
11:00 - 11:45	LIGO Installation/Commissioning (Coyne/Whitcomb)
11:45 - 12:30	Advanced R&D Overview (Shoemaker)
12:30 - 1:30	Lunch
1:30 - 2:15	LSC and its Role (Weiss)
2:15 - 2:50	Organization and Budget (Sanders)
2:50 - 3:30	Operating the LIGO Sites (Coles)
3:30 - 5:00	Laboratory Tour (Raab)
5:00 - 6:00	Parallel break-out sessions meet.
6:30	Dinner

Tuesday February 27, 2001

8:30 -10:00	Executive Session ; Discussion of R&D Panel report with John Hall.
10:00 -12:30	Parallel Breakout Sessions
12:30 - 1:30	Lunch
1:30 - 3:00	Presentation for Full Panel a. International Cooperation (Sanders) b. How will LIGO-I reach 10^{-21} strain sensitivity? (Whitcomb)
3:00 – 6:00	Executive Session – begin writing report.

Wednesday February 28, 2001

8:30 - 12:30	Executive Session – Discussion and report writing
12:30 - 2:00	Lunch (assemble first draft of report).
2:00 - 8:00	Executive Session; reading of first draft, discussion, write final report.

Thursday March 1, 2001

9:00 - 10:00	Executive Session final discussion for close out.
10:00 - 11:00	Close-out session with Panel and LIGO/LSC Staff.
11:00	Adjourn

APPENDIX D.

Report of the LIGO Detector Research and Development Sub-Panel

Review Report from the NSF Detector Research and Development Sub-Panel

regarding the proposal

"Continuing LIGO Operations (FY2002 - 2006)"

from the

Laser Interferometer Gravitational Wave Observatory (LIGO) Laboratory

Review conducted for the National Science Foundation at the
California Institute of Technology
Pasadena, CA
January 29 – February 1, 2001

Date of Report

February 1, 2001

Table of contents

Executive summary		3
Background		5
Intellectual merit		5
Broader impacts		6
Integration of research and education, diversity, and outreach		7
Management		7
Budget		8
Manpower		9
The LIGO Science Collaboration (LSC)		9
Seismic Isolation		9
Suspension		11
Interferometer configurations and controls		12
Lasers		14
Optics		15
Appendix A	Charge to the LIGO Review Panel	18
Appendix B	Panel Members and NSF Attendees	21
Appendix C	Agenda for LIGO Panel Review – R&D Sub-Panel	22

Executive Summary

A review of the proposal "Continuing LIGO Operations (FY2002 - 2006)," submitted to the National Science Foundation by the LIGO (Laser Interferometer Gravitational Wave Observatory) Laboratory, was conducted by a panel of experts at the California Institute of Technology in Pasadena, CA from January 29 – February 1, 2001. This review panel was constituted as the Detector Research and Development Sub-Panel, and it focused on evaluating the R&D plan for an advanced LIGO detector.

The NSF charge to the Panel, names of members of the Panel and observers from the NSF, and the agenda for the review are included as Appendices A, B, and C to this report.

The LIGO proposal was provided to the Panel before the review. For background, the Panel was also provided with the report of the Special Emphasis Panel for the Review of the LIGO II Conceptual Plan (October 1999). During the review, oral presentations were heard, and subgroups of the Panel met with appropriate members of the LIGO team to explore details of the proposal. Additionally, the Panel met with five members of the international LIGO Scientific Collaboration (LSC) who were present at the review.

The Sub-Panel has the following summary observations and recommendations:

1) The proposal for research and development regarding an advanced LIGO detector contains a set of significant technical challenges that, if met, will provide a design for a gravitational wave detector that should be capable of yielding extremely exciting science.

2) We believe that the LIGO Laboratory, in consort with the LSC, is capable of carrying out, and is ready to carry out, the R&D program described in the proposal.

3) Advanced LIGO will require a level of control system complexity that considerably exceeds that required for initial LIGO. Recent locking of the Michelson Fabry-Perot 2–km detector at Hanford represents a significant demonstration of a multi-dimensional control system, and builds confidence in the ability of the LIGO team to deal with its even more complex design challenge in advanced LIGO.

4) A critical path item for advanced LIGO is a set of new optics. Advanced LIGO requires increased size of the test masses, dealing with the absorptivity of optical coatings, and better mechanical Q optimization of the mirrors. This part of the R&D program will require new partnerships with vendors. The availability of increased expertise for the LIGO program, especially in optical materials and system integration in the optics area, is crucial to the success of this effort.

5) The requirement for stable, single-mode, 80 - 180 W lasers for advanced LIGO represents a significant challenge to the state-of-the-art. Attention should be given to the tradeoffs between a potentially more reliable but lower power laser system (or a phased-locked ensemble of lower power laser systems), and the potentially increased high-frequency performance of the detector at higher power.

6) Higher average power on the input optics of advanced LIGO presents a challenge to the current technology of crystal modulators and isolators. An aggressive testing program will be required to understand the limitations and potential of these important optical elements.

7) Forces exerted on the mirrors due to the higher average power stored in advanced LIGO cavities may introduce alignment instabilities. The planned inclusion of these effects in the end-to-end model and the planned testing program are essential elements of the program.

8) Success of advanced LIGO will be (in part) measured by its uptime. The reliability of the in-vacuum components (such as the active seismic isolation system) is crucial, and design for reliability should be kept at the forefront of the R&D effort.

9) Suspension of test masses by ribbons represents a novel solution to test mass suspension noise. However, effects such as creep (leading to potential excess noise) in the expected load regime, should be carefully evaluated.

10) The review panel finds that the proposed balance between operation of initial LIGO and R&D on advanced LIGO, as described during the review, is appropriate for optimizing the probability of programmatic success.

Background

Construction of LIGO is 98% complete. Optics, vacuum, and partial pressures in the detector have met requirements, and lock has been achieved on the 2–km LIGO Michelson Fabry-Perot interferometer at Hanford, Washington for tens-of-minutes. Interferometers in Washington and Louisiana are being commissioned in 2001, and sensitivity studies with the detectors are expected in 2002. A data run is planned for LIGO during 2003 – 2006, with a planned strain sensitivity of $h \cong 10^{-21}$ and a goal of conducting a broad search for astrophysical sources of gravitational waves.

Concepts for an advanced version of a LIGO detector, with increased strain sensitivity, have been studied for a number of years by a variety of national and international groups. The current LIGO proposal details a funding request for both the continued operation of the initial LIGO detector and the research and development effort needed for an advanced detector (in conjunction with a significant effort by the LSC), over the 5-year period FY 02–06. The proposed advanced detector would be implemented in the vacuum tube and other facilities constructed under the initial LIGO construction project, with an expectation of installation of the advanced LIGO detector in 2006.

Key technological changes in advanced LIGO, compared to initial LIGO, include improved core optics, a higher laser power, the addition of signal recycling, a fully active seismic isolation system, and a new multiple pendulum suspension. This upgrade to the LIGO detector should yield a major increase in sensitivity.

Intellectual merit

The rationale for a sensitive gravitational wave detector has been discussed in a number of previous reviews. The potential for increased scientific discovery with an advanced detector is great, since the number and type of available astrophysical sources will increase enormously with increased detector sensitivity. The appropriate scaling suggests a volume of probed space that increases as the third power of the sensitivity increase. Design sensitivity for advanced LIGO of $h \cong 10^{-22}$ or better implies an increased annual rate of detected coincidences of several thousand, essentially enabling the originally envisioned observatory function of the LIGO program. This will yield a high probability of gravity wave detection for a wide variety of astrophysical models. In addition, the ability to improve the detection sensitivity in a narrow frequency band provides a good probability of detection of specific sources such as neutron star tidal disruption or binary star inspiral..

Increased sensitivity is to be achieved by lowering the thermal noise in the hundred-Hz range, through improvement in the suspension and optics, accompanied by the lowering of photon shot noise. One of the obvious ways to fight the shot noise limit is to raise the laser power on the beamsplitter. The recycling configuration of the interferometer allows an increase of this power by increasing the input light power and/or by increasing the recycling power. Since the recycling power is limited by the total loss of the interferometer, which is a technical issue, the scheme of advanced LIGO is to increase the power of the laser. Some of the committee members were unsure that a single more-powerful laser approach is desirable, as opposed to use of a phase-coherently-added ensemble of injection-locked laser subsystems of lower

individual power, which is the approach initially adopted by the other Gravitational Wave Detector groups worldwide.

Broader impacts

An advanced LIGO detector research and development program will require significant technological advances in the areas of high-average-power lasers, seismic isolation, optical components including mirrors and light modulators, control systems, and data analysis. These are technologies that will impact, as well as benefit from, a variety of industries and scientific programs. The advanced mirror coatings being developed by LIGO may benefit interferometers used in precision measurements. Active seismic isolation technologies could be useful to a variety of scanned probe instruments and sensitive low temperature physics experiments. Complex data analysis techniques may find use in other astrophysical experiments with large data rates.

Technological impacts of R&D on advanced LIGO designs are expected in optical materials and coating technology, scientific instruments, and various commercial instruments including laser gyros, telecom narrow line filters, optical measurement technology (high precision measurement of large optics), and remote sensing. There is also potential applicability to UV / X-ray optics for lithography. There are a range of commercial applications in system control, and nonlinear dynamic control systems. Precision interferometry and signal processing to extract astrophysics signals from noise are potential applications of the LIGO R&D work for a variety of measurements. Finally, vibration isolation applications are probable for industry for the semiconductor business and physics (precision mechanical measurements, accelerators). The effort to develop a 100-200 W class laser with good beam parameters may be useful for precise cutting because the beam can be focused to a very small size.

The LIGO, VIRGO, GEO, TAMA and other major-scale gravitational wave detectors (under construction), represent intellectual and technical challenges of the first order. These activities have attracted perhaps a majority of people worldwide with appropriate skill sets. As these projects approach their full-scale operation, the intellectual attraction will surely draw in some of the best and brightest young people. As the LIGO-developed precision measurement techniques are diffused into and become more widely applied in the wider industrial and research world, these young people will be well poised to make their contributions within a variety of different environments. Ph.D. students graduating from LIGO (even during the construction phase) have found opportunities in both academia and industry.

Another important outreach is the program attracting teachers to the labs for summer interactions at Hanford. This education dimension of the LIGO enterprise could represent a valuable interest payback into the larger scientific and technical community, quite apart from the expected astrophysical discoveries.

It appears that LIGO is conducting a well-organized and effective effort to make the taxpayers participants in the science and technology related to the project, with particular attention in promoting interest and popularizing science within the next generation. In the case of high-tech industries and research institutions, such an effort takes the shape of an indirect technology transfer. When former LIGO Ph.D. students go to work in those environments, they carry with them all the training and expertise acquired in LIGO.

Integration of research and education, diversity, and outreach

Findings:

The proposal outlines a series of ongoing and planned activities to expose K-12 students and teachers, local communities, and college students from regional institutions to the excitement of gravity wave research and technologies. It is clear that the observatories are in regions of the country that could benefit from active local science centers, and LIGO seems to be responding to that need.

Students are currently brought to the sites, and bring knowledge and enthusiasm back to their schools. We heard that perhaps the most successful outreach program results from the approximately 25 undergraduates, from a variety of institutions, who are brought to work in the project each summer through a variety of funding programs; more than half of these students are from institutions other than CIT and MIT.

In a broader context, articles discussing LIGO science have been written for magazines such as Scientific American and Sky and Telescope. An informative and engaging book "Einstein's Unfinished Symphony; Listening to the Sounds of Space-Time" has been written about the LIGO program by Marcia Bartusiask. LIGO operates a variety of web sites for the dissemination of information.

Observations:

LIGO has a variety of activities that have engaged researchers in outreach activities. It appears that this is a decentralized effort. The integration of education and research activities at many universities often benefits from assistance from university offices that are tasked to assist researchers who appear to have the interest and energy to participate in outreach activities. Other national centers have also benefited from a coordinator with specific responsibility for organization of education and outreach activities.

Management

Findings:

LIGO management has been structured in an effective manner. Staff roles have been flexibly defined, which is appropriate to the missions of the project. The proposed transition to a flatter structure, and the redefinition of roles should be accomplished relatively seamlessly. Morale seems high.

Observations:

One example of an issue facing management is that the staffing of the SEI engineering effort out of LLO may be problematic; strong demand and high salaries are offered nationally by industry for experts in real time controls, structural dynamics, and optics. The hiring of real time controls and software experts will have to be aggressive to avoid schedule slip due to lack of expert staffing.

Another challenge to LIGO management is the identification of the leader of the Advanced R&D effort.

Budget

Findings:

The Panel requested a different cut through the budget, and received the following figures:

$M	FY 01	**FY 02**		**FY 04**	**FY 05**	**FY 06**	**02-06 TOTALS**
Adv. R&D	2.7	2.8	2.9	3.0	3.0	3.1	14.8
Ops - R&D	≈3.0	4.1	4.2	4.3	4.5	4.7	21.7
Incr. Ops. - R&D	-	1.7	1.7	1.3	1.3	1.4	7.4
LSC - R&D(equip)	-	3.3	3.8	3.1	-	-	10.3
SUM	≈5.7	11.9	12.6	11.7	8.8	9.2	**54.2**

TOTAL 02-06 Advanced LIGO R&D $ 54.2 M

TOTAL 02-06 Proposal Request $175.6 M

Observations:

The Panel did not validate budgetary items in detail. However, the Panel notes that the total request, the continuity of the funding request, the clarification of R&D costs actually contained within "operations manpower," and the proposed balance between operation of initial LIGO and R&D on advanced LIGO as described during the review, seem appropriate for optimizing the probability of programmatic success.

The Panel agrees with LIGO management's attempt to deal with evolving technical issues through the use of funds built into the budget and held in the Director's office.

Manpower

Observations:

The Panel believes that staffing for the R&D effort is adequate but lean. One example of issues relating to manpower can be given for the laser development effort. Responsibilities for R&D and prototyping are shared among four groups outside the LIGO Lab, which of course has the ultimate role of specifying needs. The Stanford and Hanover/LZH groups are playing

particularly important roles. Two FTE are missing this year in LZH, and one has recently left Stanford. At LZH there is a recognized and serious need to find replacements, mostly to benefit from the experience of one key-person who also might leave at the end of the year. The significant experience of these labs cannot hide the fact that the experimental feasibility of the high-power laser has to be demonstrated, there are potential technical delays due to late delivery of diodes, YAG crystals, etc., and there is limited availability of human resources; these are important factors to be taken into account.

The Panel shares the concern of the LIGO team for continued training of next generation of scientists and technical personnel as a response to this on-going issue. However the Ph.D. training period is rather long and one can easily anticipate a serious shortfall in manpower, in view of dramatic opportunities in biophysics and telecommunications, as well as the approaching retirements within the LIGO-related programs nationwide. As the national focal point of this kind of precision work, LIGO and the LSC colleagues need a vigorous recruiting campaign to identify and attract and train appropriate students earlier, rather than later. This reality is being addressed as LIGO's student participants increase from ~20 Ph.D.s awarded over 10 years, to the present involvement of ~20 students/year.

The LIGO Science Collaboration (LSC)

Observations:

The resources and expertise of the world gravitational science community outside of the funded LIGO project is enormous. The Panel is impressed by the coordination of efforts and the spirit of cooperation evidenced among the relevant parties (NSF, LIGO, and the members of the LSC). The intellectual and technical contributions of the LSC are crucial to the R&D effort for advanced LIGO.

Seismic isolation

Findings:

The seismic isolation sub-system (SEI) attenuates environmental induced motions on the test masses and other suspended optics. The baseline design has completed conceptual development and consists of a two-stage active isolation with low noise sensor feedback. An external low bandwidth, large stroke stage is also in the design.

A "soft passive" SEI design, which evolved from the VIRGO design and will have shortly found a full test in VIRGO and in TAMA, has been abandoned here in favor of an "active" system, which successfully passed a technology demonstration. Prototypes will be tested under condition close to final implementation.

The effort undertaken to down-select between the new "stiff" more active system and the heritage "soft" more passive system is admirable. The systems approach (with requirements and prototype testing) to both the technical and programmatic aspects of the decision were smart.

The analysis of the current SEI conceptual design for advanced LIGO, backed up by measurements recently completed at MIT on a two-stage isolation system, support the required amplitude spectral density at 10 Hz and above. RMS motion of the test masses also appears to meet requirements based on tests and analysis to date.

The design similarities between the BSC and HAM isolation systems will drive cost and complexity savings in advanced LIGO.

The development plan for demonstrator tests at Stanford (4Q01) and HAM prototype testing in LASTI (3Q02) is aggressive in schedule, but appears to have adequate funding.

The FY 2002 allocation of 27.3 FTE and $1.6M of equipment is adequate for a well planned and managed research and development program for the SEI, SUS, TNI and STO elements of the R&D program.

The collaboration between the CIT and MIT campus efforts with those of the GEO group, Stanford, LSU, and JILA is commendable.

Observations:

The current baseline controls involve roughly 44 actuators (of 8 types) and 69 sensors (of 10 types) controlling 39 degrees of freedom in each of about 30 chambers in 3 interferometers at 2 sites. This control system is at or above the complexity of several national efforts such as the Stellar Interferometer Mission (SIM), and the Airborne Laser (ABL).

The most stressing driver in the LIGO seismic isolation system is to design for system reliability on in-vacuum components to prevent significant down time of the Advanced LIGO observatory (both sites).

The vender-specified 300,000-hour mean time between failure of the STS-2 would lead to a failure of one every 140 days. This is probably more than would be acceptable, but the specified MTBF is for “field use” and would hopefully be much less in the more benign LIGO operation. Other in-vacuum components need to be more closely analyzed for reliability.

It is not clear that the 10 Hz “wall” is a valid design criterion. It is possible that the programmatic cost and schedule impacts to validate performance at 10 Hz would not be worth the additional “science” gain. For example, if a strong knee in the cost curve appears between 10 Hz and 15 Hz, then 15 Hz would be acceptable.

The UHV compatibility with the large numbers of cables required for actuator and sensors is a design issue that may have not been addressed. RF transmission may be required.

Acoustic disturbance sources may have not been addressed.

Recommendations:

1) Elevate the "design for reliability" aspects of the R&D program for the in vacuum components of Advanced LIGO. In particular the STS-2 seismometer and the first stage (active) geophones should have reliability analyses under the thermal-vac conditions and continuous operation.

2) Study, perhaps on the existing hardware, the electromagnetic coupling between the voice coil actuators and the various sensors (especially the GS-13).

3) Contact Dave Redding at JPL and arrange for a tour and demonstration of the NGST wavefront control test bed (WCT) at NASA Gadded. This represents the state of the art for control of a very complex controlled optical dynamic test article with a high level (push button) human interface and operation over the Internet.

4) The integration of the seismic isolation and suspension dynamics and controls models with the end to end simulation should not be allowed to slip.

Suspension

Findings:

The suspension of test masses and other optics creates a "free" mass with actuation and provides several orders of magnitude of seismic isolation. Silica fibers or ribbons hold the test masses through a multiple pendulum chain.

The suspension design capitalizes on the results of an aggressive R&D of the GEO project, which will be fully tested in the coming operation of the GEO 600 interferometer. R&D is needed to scale up to the larger masses to be suspended. The preferred SUS design allows for keeping pendulum and violin modes clear of the maximal sensitivity frequency range between 10 Hz and 500 Hz, with a small sacrifice in sensitivity.

Fused silica ribbons, silicate-bonded to suspend the mirrors, are planned to operate at a significant fraction of the breaking load. There is little experimental evidence to date on the creep of such a highly stressed design.

The LIGO lab's collaboration with the GEO team in suspension research is an outstanding example of cross-lab and international cooperation. The rich mix of expertise and experience on both sides of the ocean is a critical element of advanced LIGO R&D.

The development schedule for suspension (2Q03 for installation in LASTI) appears adequate.

The schedule for the Thermal Noise Interferometer (1Q03 Sapphire/fused silica results) appears adequate with the caveat about material and coating vendor timeliness expressed elsewhere in this review.

Observations:

The most stressing performance index for the suspension system is to maintain the good thermal noise performance.

The SUS concept adopted from GEO is considered most innovative in the field, for delivering the overall high mechanical quality factors needed.

Thermal noise measurements (at the Thermal Noise Interferometer) will allow possibly the first direct comparison with predictions, for systems with this class of materials and mass.

Recommendations:

1) Understand the impact of the removal of the violin modes above 500 Hz on the SNR in specific signal searches.

2) Study, on top of the thermal noise, the ill understood effects of mechanical creep phenomena in the loaded suspensions, giving attention to the impact that such an “excess” noise may have on the false alarms in the whole observatory.

3) Study the effect of pickup on the penultimate mass magnetic actuators from the actuator fields from other SEI and SUS magnetic actuators as well as other environmental fields.

Interferometer configurations and controls

Findings:

Considering only presently-known noise sources, the recycled power and signal interferometer configuration for advanced LIGO has the potential to provide the desired increase in gravity wave signal sensitivity. This configuration also allows tuning of the sensitivity spectrum to optimize response to specific types of signal sources.

The configuration change results in a substantial increase in complexity, in particular of the control system. The number of control system degrees of freedom is increased by the addition of the signal-recycling mirror. The forces from the high stored optical power may introduce instabilities not yet seen in lower power interferometers. In particular, light power-introduced angular instabilities may be problematic. These changes will increase the speed and low noise requirements of the data acquisition and control system. They also bring a new coupling between axial-motion cavity locking and mirror-suspension subsystems.

The current LIGO control system uses a set of VME crates with VxWorks controllers. High-speed communication between crates and data collection is implemented using reflective memory. Straightforward upgrades to the current LIGO control system hardware and software should be able to provide the required data bandwidth and computation for the controls for the advanced LIGO. The LIGO group is continuing to monitor developments in control system technology, and plans to adopt those that are applicable. R+D is underway to resolve some remaining technical issues with the high-resolution analog to digital converters. These issues probably do not represent significant risk.

The existing software configuration control system has been successful for initial LIGO. An interconnected control system of this complexity has the risk that software errors can result in

significant downtime or data corruption. It may be necessary to implement more formalized configuration control in the future.

The control system algorithm for the high power interferometer may be very complex. The stored optical power produces very large forces on the mirrors. These forces are nonlinearly dependent on the mirror position and angle. In addition to instability under operating conditions, the optical back pressure may complicate the system locking procedure. They plan to initially study these effects with an upgrade to their "end to end" simulation. (Unfortunately, the 40M interferometer does not provide an ideal test bed for these nonlinear effects, as it operates at lower power, uses optics of smaller diameter, and has a 100-fold shorter lever arm.)

Considerable work has been done, and is being planned to control thermal distortions in the advanced LIGO optics. This work will be critical if the preferred optical absorption specification cannot be met. The ring heating compensation appears likely to work as designed. The "laser writer" thermal compensation scheme is potentially much more flexible, but is also more technically challenging and could bring unwanted noise.

Observations:

Efforts to mitigate both the photon backpressure effects and the thermal distortion compensation would benefit from a more complete end-to-end simulation. Work on this is underway.

The development and maintenance of a control system requires a trade off between the adoption of new higher performance technology, and the need to limit development costs. The LIGO group appears to have found good balance.

The use of reflective memory for the control system, and the software development process has proven very efficient. However, there is a concern that neither provides good assurance against data corruption and software bugs.

The advanced LIGO interferometer is an exceptionally complex combination of optical and control systems. The LIGO group is aware of the potential difficulties with a system of this complexity, and they have allocated reasonable resources to R+D. The techniques developed to design and manage such a complex optical system will have applicability to other precision optical measurement systems. It is likely that the management solution to the complex nonlinear control problem will also have wide applicability.

Recommendations:

1) The mirror control problem in the presence of high optical power is our most serious concern. The LIGO group is aware of this issue, and we support their use of calculations and simulations to model this problem and to guide appropriate diagnostic experiments.

Lasers

Findings:

The laser system planned for the advanced LIGO is a 180 W laser coming from either an injection-locked system or a MOPA system using a two-step amplifier, and starts from an injection-locked laser with 20 W. R&D will be carried out by the GEO people (University of Hanover), Stanford, and University of Adelaide. The industrial company selected is the LZH that is already building the lasers for the GEO and the Virgo projects. The laboratory version of a MOPA is being built and tested in Stanford, while LZH is concentrating on the achievement of the 20 W injection-locked laser: a 100 W version is planned for 4/02 while a 200 W version is for 2/04. Meanwhile, Adelaide might offer another possibility with unstable-stable laser, and a final version phase is planned at the beginning of 2006 after a long-term test at Hanover and LASTI. The GEO, Stanford and Adelaide teams are experts in that field.

Observations:

A decision will be required between three basic alternatives for the laser system: 1) A Master Oscillator/Power Amplifier configuration; 2) an injection-locked, full-power system (which benefits from laser cavity filtering); and 3) the phase-coherent addition of an ensemble of lower power phase-locked laser sub-systems. This last solution implies multiple servos (which is well known technology) to lock the injection of the multiple lasers, and has been the baseline approach considered by all the other Gravitational Wave Detector groups worldwide. Solutions 1 and 2 use a single laser powerful amplifier medium as either a power amplifier (1) or as an injection-locked oscillator (2). Beyond the undesirable single-point failure problem, the amplifier case absolutely will need a pre-mode cleaner, one that will have to withstand the full amount of power and will need to employ a wavefront servo. Indeed, the power-with-standing capability needed for the mode cleaner mirrors is of equal quality as needed for the core optics of the IFO itself. Added complexity is coming in this approach also from the fact that this MOPA needs wavefront compensation of the beam through adaptive optics, with wavefront sensing for the feedback. Though these techniques have been used extensively in other fields, here they just add complexity to the system and this has to be analyzed in terms of duty cycle. The difficulty of the injection locked single oscillator is the reliability of keeping the 200 W laser operating monomode (transverse), so it will also need dynamic wavefront observation/correction. The third approach, with multiple lasers coherently added, may also need long-term active beam steering to provide the excellent beam quality as needed for LIGO, but these controls would be only for two angular adjustments and would have a time scale for the correction of days or weeks, rather than a few milliseconds to ~1 second as needed for the MOPA approach.

Raising laser power always comes along with raising of thermal effects and thermal induced birefringence inside the optical components that are crossed by the main beam. These effects do not scale linearly with the power, when optical components like Pockels cell modulators and Faraday isolators are reaching their limit. All the position controls systems are based on the modulation - demodulation concept, and rely on the very good operation of these essential elements. A compromise in their quality could compromise the signal-to-noise ratio of the IFO, as it will most probably induce extra noise in the strain curve. Optical feedback into the laser, coming from the different cavities, is minimized thanks to the Faraday isolators, and currently,

only one Faraday material (TGG) is available for the 1.06 micron laser light. We note that the reliability of each type of components has to be ensured.

The ultimate power chosen for the laser (here up to 200 W) is perhaps not so critical, as it will only degrade slightly the strain curve in a small frequency range. Unfortunately, the heating effects are so severe that the main optics have to be pre-compensated for these aberrations. Though this topic is off the critical path, clear planning around this difficulty and, perhaps, a fallback solution for the advanced LIGO has to be defined.

Recommendations:

1) Milestones for progress on some key-points in the R&D program require better definition. The margin between selecting the best technology to achieve the lowest noise, and keeping the schedule on time, is thin. On one hand, funding should not be delayed because of a potential loss of experts; on the other hand, delay in achievements of the R&D could result in adopting solutions that will not lead to a significant improvement of the strain sensitivity of the interferometer. Intermediate progress milestones and technical reviews should be established.

Optics

The optics program for advanced LIGO builds on the current state of the art for LIGO, and makes some important changes in order to meet the more stringent requirements of the new design. The physical size of the optics will be substantially larger, there are performance requirements that can be better met by switching from fused silica to sapphire for certain optical elements, and coating specifications have been made more stringent to address thermal and mechanical requirements. The success of this program is critical to the success of advanced LIGO.

Findings:

The optics team at LIGO lab is a highly skilled and experienced group and is well qualified to address the numerous optical engineering challenges posed by the advanced LIGO design. The optics R&D process involves multiple institutions. Metrology will be carried out by LIGO lab team members while raw materials, coatings and polishing will be provided by vendors. Accordingly, the success of the optics R&D is dependent on the successful management of relationships with the vendors, the business model of the vendors, and the ability of vendors to execute due to availability of skilled personnel and raw materials of sufficient quality. This arrangement had been successful for LIGO, but has become more complex for advanced LIGO because Research Electro Optics (REO), the LIGO coatings vendor, has withdrawn and a new vendor must be brought in. This new vendor (in process of being identified at the time of this review) must perform as well as REO, and also be willing to work towards a considerable advancement of the state of the art. The optics R&D program for advanced LIGO has been active for the order of two years, and has made considerable progress in elucidating the issues that need to be resolved.

Observations:

The current status of the optics R&D is as follows. It has been determined that the performance of fused silica is comparable to that of sapphire in terms of thermal noise, but sapphire may be a better material for operation at the high powers that will be used in advanced LIGO. Over the next 18 months it will be determined whether large blocks of sapphire can be made transparent enough to be used in advanced LIGO, and a final decision between sapphire and fused quartz will be made. This choice presumes that the coating vendor will be able to successfully coat large sapphire blanks with coatings of acceptable quality, an issue that is not currently resolved.

There are additional coatings R&D issues. To reduce thermal effects, it has been determined that the absorptivity of the coatings must be reduced by a factor of 10 (to 0.05 ppm/cm), and that they must not significantly degrade the mechanical Q of the optics. It has been found that the coatings are not inert in this regard and that if this problem cannot be overcome then the advantage of using sapphire is reduced. As noted earlier, should the goals for reducing absorptivity not be met, thermal compensation schemes are being developed as an alternative.

Although not discussed in the proposal, it is clear the coatings must retain their optical and physical properties while being exposed to large power densities in vacuum over a period of years. Thus the coatings R&D program is more challenging than just reducing absorptivity on fused silica, which may be possible incrementally. Absorptivity, mechanical characteristics, and stability must all be optimized in a coordinated way. Qualification of the coatings must be a well-planned activity to ensure that the ultimate materials performance meets requirements. As the timeline for ordering optics is short, it is essential that a detailed plan to develop the coatings be in place as early as possible.

The engagement with a new coatings vendor will almost certainly require that LIGO lab purchase a deposition tool, to be housed at the vendor's facility, capable of coating two 40-kg optics at a time. It is expected that the tool will be installed and commissioned by the third quarter of 2003. It is planned that all optics are to be ordered in early 2004 and be ready for installation in the first interferometer by the end of 2005. Since deposition processes are generally tool dependent there is a risk that use of new tooling in this time frame will significantly disrupt progress if it happens that the coatings produced in the tool cannot be made identical to the coatings that had been under study up until that time.

Recommendations:

1) According to the proposal and presentations, a specific plan to address absorptivity has been made, but it does not include stability and mechanical properties. The panel recommends that the team expand their agreement with their coatings vendor (to be selected) to include significant materials R&D. They should also engage with a group with expertise in optical materials science to ensure that all necessary characterization is being done and to facilitate communications with the vendor concerning process-property optimization of the coatings process. They should explicitly address mechanisms of coating degradation such as slow deposition of contaminants and chemical or structural aging. These issues need to be resolved before final commitment to a schedule for the construction plan is made.

Charge to the LIGO Review Panel

The NSF Grant Proposal Guide (http://www.nsf.gov/pubs/2001/nsf()12/toc.html) contains instructions and guidelines for individual investigator proposals. The National Science Board approved review criteria are included in the section from the Proposal Guide reproduced below and they should be followed in this review:

III. NSF Proposal Processing and Review

Proposals received by the NSF Proposal Processing Unit are assigned to the appropriate NSF program for acknowledgement and, if they meet NSF requirements, for review. All proposals are carefully reviewed by a scientist, engineer, or educator serving as an NSF Program Officer, and usually by three to ten other persons outside NSF who are experts in the particular fields represented by the proposal. Proposers are invited to suggest names of persons they believe are especially well qualified to review the proposal and/or persons they would prefer not review the proposal. These suggestions may serve as one source in the reviewer selection process at the Program Officer's discretion. Program Officers may obtain comments from assembled review panels or from site visits before recommending final action on proposals. Senior NSF staff further review recommendations for awards.

REVIEW CRITERIA

The National Science Board approved revised criteria for evaluating proposals at its meeting on March 28, 1997 (NSB 97-72). The criteria are designed to be useful and relevant across NSF's many different programs, however, NSF will employ special criteria as required to highlight the specific objectives of certain programs and activities.

On September 20, 1999, the NSF Director issued Important Notice 125, Merit Review Criteria. This Important Notice reminds proposers of the importance of ensuring that, in addition to the criterion relating to intellectual merit, the criterion relating to broader impacts is considered and addressed in the preparation and review of proposals submitted to NSF. The Important Notice also indicates NSF's intent to continue to strengthen its internal processes to ensure that both criteria are appropriately addressed when making funding decisions.

The merit review criteria are listed below. Following each criterion are considerations that the reviewer may employ in the evaluation. These considerations are suggestions and not all will apply to any given proposal. While reviewers are expected to address both merit review criteria, each reviewer will be asked to address only those considerations that are relevant to the proposal and for which he/she is qualified to make judgments.

What is the intellectual merit of the proposed activity?

How important is the proposed activity to advancing knowledge and understanding within its own field or across different fields? How well qualified is the proposer (individual or team) to conduct the project? (If appropriate, the reviewer will comment on the quality of prior work.)

To what extent does the proposed activity suggest and explore creative and original concepts? How well conceived and organized is the proposed activity? Is there sufficient access to resources?

What are the broader impacts of the proposed activity?

How well does the activity advance discovery and understanding while promoting teaching, training, and learning? How well does the proposed activity broaden the participation of underrepresented groups (e.g., gender, ethnicity, disability, geographic, etc.)? To what extent will it enhance the infrastructure for research and education, such as facilities, instrumentation, networks, and partnerships? Will the results be disseminated broadly to enhance scientific and technological understanding? What may be the benefits of the proposed activity to society?

PIs should address the following elements in their proposal to provide reviewers with the information necessary to respond fully to the above-described NSF merit review criteria. NSF staff will give these elements careful consideration in making funding decisions.

Integration of Research and Education

One of the principal strategies in support of NSF's goals is to foster integration of research and education through the programs, projects and activities it supports at academic and research institutions. These institutions provide abundant opportunities where individuals may concurrently assume responsibilities as researchers, educators, and students, and where all can engage in joint efforts that infuse education with the excitement of discovery and enrich research through the diversity of learning perspectives.

Integrating Diversity into NSF Programs, Projects, and Activities

Broadening opportunities and enabling the participation of all citizens -- women and men, underrepresented minorities, and persons with disabilities -- are essential to the health and vitality of science and engineering. NSF is committed to this principle of diversity and deems it central to the programs, projects, and activities it considers and supports.

Specific Charge to the LIGO Review Panel

The proposal includes three major activities; operations of the LIGO facilities; scientific research; detector research and development. To address this wide range of activities, the Review Panel will be divided into two sub-panels. The first will concentrate on detector research and development. The second will concentrate on operation of the LIGO facilities and scientific research. The broader issues of scientific merit and the overlap in manpower and other resources assigned to the three activities will require both sub-panels to consider the total proposal in their evaluations.

C. Detector Research and Development Sub-Panel

This sub-panel will concentrate on detector research and development to improve the science reach of the LIGO observatories. A major contribution to this R&D program is provided by

members of the LSC at institutions other than Cal Tech and MIT. Funds to support those LSC member research programs are provided directly to the LSC institutions.

- While this sub-panel is not charged with reviewing each of the LSC proposals, it is asked to evaluate the total detector R&D plan as presented by the LIGO Laboratory in this proposal. Are the LSC R&D activities (including Cal Tech and MIT) appropriate to achieve the scientific goals of the proposal and are they well-coordinated ?

- The Sub-Panel should review the schedule and milestones for progress in the detector R&D program. Is the schedule achievable with the available and proposed resources and are there sufficient significant milestones provided ?

- The sub-panel is asked to review the LIGO Laboratory R&D program (Cal Tech and MIT) in detail, including manpower allocation and budget.

The final report of this Sub-Panel is to be completed at this meeting so that it can be made available to the Operations and Scientific Research Sub-Panel before the meeting of that sub-panel.

D. Operations and Scientific Research Sub-Panel

The activities to be reviewed by this sub-panel include completion of installation and commissioning of the interferometers, operation of the facility for engineering and science runs, creating and maintaining the infrastructure for data acquisition and analysis by the LIGO Scientific Collaboration (LSC), and scientific research proposed by the LIGO Laboratory. The Sub-Panel is asked to review and evaluate the proposal with regard to each of the following items:

- Is the proposed budget for LIGO Laboratory operations and the scientific research program justified and adequate to carry out the activities listed above?
- Is the proposed LIGO Laboratory infrastructure, including manpower and facilities, adequate for effective participation in the science by the LSC members?
- Are the schedule and milestones for LIGO Laboratory commissioning and for proposed engineering and scientific running achievable with the available and proposed resources? Are there sufficient significant milestones provided?
- Is the proposed outreach and education plan well-designed and are proposed manpower and funds adequate to carry out the plan?
- What is the status of international collaboration between LIGO and other gravity wave centers around the world?
- Is the plan for public access to LIGO data appropriate?

The final report of the Detector Research and Development Sub-Panel will be provided as input to the Operations and Scientific Research Sub-Panel which is requested to determine if there are issues involving allocation of manpower or other resources between the major activities presented in the proposal. If there are, a teleconference will be arranged during the meeting of the Operations and Scientific Research Sub-Panel and members of the Detector Research and Development Sub-Panel to discuss these issues.

Appendix B

Panel Members and NSF Attendees

Title	Name	Institution
Prof.	Roger Falcone (Chair)	UC Berkeley
Prof.	Massimo Cerdonio	INFN University of Padova
Dr.	Josef C. Frisch	SLAC Stanford University
Dr.	John L. Hall	NIST University of Colorado
Dr.	Frances Houle	IBM Almaden Research
Dr.	T. Tupper Hyde	Honeywell Space Systems
Dr.	Catherine Nary Man	CNRS Observatoire Côte d'Azur

NSF Attendees

Dr.	David Berley	University of Maryland
Dr.	Victor Cook	NSF U. of Washington
Dr.	Adriaan de Graaf	NSF
Dr.	Joseph Dehmer	NSF

Appendix C

AGENDA for LIGO PANEL REVIEW - R&D Sub-Panel

Monday January 29, 2001

8:30 - 9:00	Panel Executive Session
9:00 - 9:15	Introduction of Panel and Reading of Panel Charge
9:15 - 9:30	LIGO Status and Introduction- B. Barish
9:30 -10:15	Overview of R&D Proposal- G. Sanders
10:15 -10:45	Advanced LIGO Science- K. Thorne
10:45 -11:00	Break
11:00 -12:30	LIGO R & D Program- D. Shoemaker
12:30 - 2:30	Lunch and tour of Caltech facilities
2:30 - 4:00	Parallel Detector R&D Sessions
4:00 - 6:00	Panel Executive Session *[Reports from Panel members attending parallel sessions; request for info. to LIGO/LSC Staff at end of Session.]*
6:30	Dinner

Tuesday January 30, 2001

8:30 - 9:00	Panel Executive Session *[Review requests for info.; make writing assignments.]*
9:00 -12:00	Response of LIGO/LSC Staff to Panel Request.
12:00 - 1:00	Panel meeting with LSC members.[R.Weiss(MIT), D. Reitze(U. Fla), J. Giaime(LSU), Norna Robertson(GEO), Brian Lantz(Stanford), Benno Wilke(GEO)
1:00 - 4:00	Lunch and Panel Exec. Session *[discuss outline of report; begin writing]*.
4:00 - 6:00	Panel formulates questions for LIGO/LSC Staff
6:30	Dinner

Wednesday January 31, 2001

8:30 - 9:00	Panel Executive Session
9:00 -11:00	Break-out sessions with LIGO/LSC Staff
11:00 - 12:00	Panel Executive Session *[panel members write break-out reports]*.
12:00 - 1:30	Lunch presentation on LIGO outreach –B. Barish, G. Sanders
1:30 - 2:30	Panel Executive Session *[panel members complete report sections]*.
2:30 - 5:00	Panel Exec. Session *[discuss general report items; integrate break-out reports]*.
5:00 - 6:00	Panel Executive Session *[complete report; discuss close-out presentation]*.
6:30	Dinner

Thursday February 1, 2001

9:00 - 10:00 Panel Executive Session *[Final discussion of report and close-out presentation]*.
10:00 -11:00 Close-out; adjourn

Parallel meetings and assignments

Suspensions and Isolation - Hyde and Cerdonio
Lasers and Optics - Houle and Man
Interferometry, Controls and Electronics - Frisch and Hall