

**Memorandum of Understanding (LIGO- M050292-00-M)**  
**between the**  
**Caltech Relativity Theory Group (CaRT)**  
**and the**  
**Laser Interferometer Gravitational Wave Observatory (LIGO)**  
**August 15, 2005**

The purpose of this Memorandum of Understanding (MOU) is to establish and define a collaborative relationship between the Caltech Relativity Theory Group (CaRT) and the Laser Interferometer Gravitational-Wave Observatory (LIGO). Both parties to this agreement share the broad goals of developing the instruments and techniques for detecting and studying gravitational waves, and subsequently using them as an astrophysical probe. Under this MOU, the CaRT Group will be a member group of the LIGO Scientific Collaboration.

1. The Caltech Relativity Theory Group (CaRT) consists of Professor Kip S. Thorne, who will serve as Principal Investigator for research in LIGO, and several graduate students and postdocs. The focus of the work done by the CaRT Group under this agreement will be those aspects of this group's work that deal with: a. Advanced detector design and modeling, b. LIGO noise modeling and control, c. LIGO data analysis and foundations for it. This agreement does NOT include our group's extensive research on the modeling of gravitational wave sources and numerical relativity foundations for that modeling.
2. LIGO comprises two parts: the LIGO Laboratory and the LIGO Scientific Collaboration. These two entities report to the LIGO Directorate, consisting of the LIGO Director, the LIGO Scientific Collaboration Spokesperson, and the LIGO Laboratory Deputy Director. The design and construction of the LIGO Observatories were carried out by California Institute of Technology (Caltech) and the Massachusetts Institute of Technology (MIT) under a Cooperative Agreement between the National Science Foundation (NSF) and Caltech. The LIGO Oversight Committee supervises the realization of LIGO.
  - A. The LIGO Laboratory is responsible for the operation of the LIGO Observatories, the development and implementation of future detector systems, and participates in all aspects of the research with the LIGO detectors. LIGO is a system of three interferometric Fabry-Perot antennas, two of them 4 kilometers long and the third one 2 kilometers long, aimed at the simultaneous detection of gravitational waves in the frequency range

40-6000 Hz. LIGO Observatories are located in Hanford, Washington and in Livingston Parish, Louisiana (USA) and began observations in the year 2002. The LIGO Laboratory is funded through a Cooperative Agreement between the National Science Foundation and Caltech, with the portion of the LIGO Laboratory at MIT funded through a subcontract from Caltech.

- B. The LIGO Scientific Collaboration (LSC) is organized as a separate entity from the LIGO Laboratory. It includes scientists from the LIGO Laboratory, and those from collaborating institutions, and has its own governance and leadership (which includes the LSC Spokesperson as a member of the LIGO Directorate). The Collaboration ensures equal scientific opportunity for individual participants and institutions. It organizes the research, publications, and all other scientific activities. The Collaboration reports to the LIGO Directorate for final approval of its research program, technical work, observational physics publications, and talks announcing new observations and physics results. This will be done through regular reports to the Directorate and its Program Advisory Committee. The organization of the LSC and its governance are defined in its Charter.
3. As a member group of the LSC, the CaRT Group will participate in the governance of the LSC and in setting its policies and procedures, as defined in the LSC charter. Similarly, it agrees to abide by the policies and procedures adopted by the LSC and posted on its website (<http://www.ligo.org/policies.html>), concerning publication, data access, software standards, and so on.
  4. Membership in more than one collaboration active in the same area of research may present complications. Members of the LSC contemplating joining other gravitational wave collaborations or participating in data analysis efforts with collaborations outside a framework established by the LSC should inform and consult with LSC and the LIGO Laboratory to ensure that no conflicts of interest exist.
  5. The LSC is the primary advocate of interferometric gravitational wave research in the U.S. To function effectively in this role, it needs to be informed in advance about major new initiatives. The CaRT Group agrees to inform the LSC of any major new proposals related to LIGO to be submitted to the NSF, and to consult with the LSC concerning the best approach to support the overall LIGO program. The final decision about the scope of any such proposal shall remain the prerogative of the CaRT Group.
  6. LSC Service Functions - Participation in the LSC brings with it responsibility for service functions to support the overall effort in achieving high detector sensitivity and high data quality. In particular, each LSC group is expected to assist in the staffing of scientific monitoring shifts during organized data runs. The staffing of these shifts is notable for both its importance and the travel burden it places on scientists. This burden makes an equitable shift allocation mechanism necessary.

A nominal guideline is that each LSC group should staff a fraction of the shifts comparable to its FTE fraction devoted to LSC activities. Kip S. Thorne (CaRT Group) will be responsible for interaction with the designated LSC Shift Organizer with respect to the CaRT Group's Service Function commitments.

Groups making extensive contributions to the LSC in other service efforts that involve a substantial travel burden may request a reduction in their nominal share of shift staffing. Those efforts can include:

- Commissioning and instrument improvement
  - Participation in on-site detector characterization investigations
  - Development/operation of analysis software/hardware infrastructure and validation of analysis software that requires travel away from the home institution.
7. Each party to this agreement continues to be responsible for all support of its staff including travel costs associated with the activities under this agreement. Exceptional support of travel by the other institution may be allowed for travel requested by that institution.
  8. Attachments to this MOU will be prepared annually to define the specific activities and responsibilities of the CaRT Group and to define any resources to be provided by the LIGO Laboratory to the CaRT Group in support of those activities.
  9. CaRT Group will provide an annual status report on its activities in support of LIGO. The report will consist of a summary status on research by topic as indicated in the Attachments for that period including progress against the milestones if any, significant accomplishments such as new insights/discoveries or publications, issues of concern if any, and an indication of invested time by each member of the group. The report will be due one month before the close of the period of performance under the Attachments in question.
  10. The LSC will review the progress report against the Attachments from the previous year and assess the Attachments for the up-coming year annually, under its established procedure, and recommend acceptance or rejection of each Attachment by the LIGO Director and the LSC Spokesperson.
  11. A list of CaRT Group members will be updated at least every six months. CaRT Group members and appropriate contact information will be provided in electronic form as Attachment Z to this Memorandum of Understanding. In cases where individuals who leave the group have had access to LIGO data and this access should be terminated, the CaRT Group Principal Investigator is responsible for timely notification to the Directorate and to the computing committee so access may be revoked.
  12. The LIGO Laboratory is responsible for obtaining NSF approval of collaborative Memoranda of Understanding where required. All Memoranda of Understanding will be provided to NSF for their information.

13. The rights to intellectual property developed under this Attachment using LIGO Laboratory resources will be subject to the National Science Foundation Grant Policy as indicated in Section 730, Intellectual Property.
- A. In the event a patentable invention is conceived or first actually reduced to practice during the work of a member(s) of the CaRT Group at LIGO Laboratory facilities, he/she will:
    - i) make prompt disclosure of the invention to the Director of the LIGO Laboratory; and
    - ii) cooperate with LIGO Laboratory and supply all information and execute all papers including invention reports, records of invention, patent applications and powers of attorney, necessary and proper to fulfill the obligations of the LIGO Laboratory to the U.S. Government sponsor.
  - B. The ownership of inventions conceived solely by members of the CaRT Group at LIGO facilities shall be owned by the Aaaa University, although the LIGO Laboratory shall be granted a license to use such invention for noncommercial research purposes at LIGO facilities. Inventions that are conceived by both members of the CaRT Group and LIGO Laboratory staff as part of the LIGO project shall be jointly owned and any income from commercial licensing shall be shared in proportion to the number of joint inventors from each institution.

In all other regards, the rights to intellectual property developed by members of the CaRT Group under this Attachment will be in accordance with the policies of Caltech University.

14. This MOU supersedes the previous MOU between the LIGO Laboratory and the CaRT group (LIGO- M950019-00) and its amendments and attachments. This MOU will remain in force until the parties mutually agree to terminate it, or until it is terminated in accordance with LSC procedures.

Approved:

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Barry Barish  
LIGO Director

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Kip S. Thorne  
Principal Investigator  
CaRT Group

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Peter Saulson  
LSC Spokesperson

**Attachment ACF to the**  
**Memorandum of Understanding (LIGO-M050292-00-M)**  
**between the**  
**Caltech Relativity Theory Group (CaRT)**  
**and the**  
**Laser Interferometer Gravitational Wave Observatory (LIGO)**  
**August 15, 2005**

This Attachment ACF to the Memorandum of Understanding LIGO-M050292-00-M defines the role of the Caltech Relativity Theory Group (CaRT) as a Member of the LIGO Scientific Collaboration (LSC) and a member of the Advanced Detector Configurations Development Group (ADCDG). The period of performance for the activities in this Attachment is from August 15, 2005 to August 15, 2006.

1. Advanced Detector Configurations Development Group - The Advanced Detector Configurations Development Group (ADCDG) is the scientific collaboration for defining and developing entirely new advanced interferometers. It is expected that this development group will pursue research in dual recycling, resonant sideband extraction, Sagnac interferometers, systems with non-transmitting optics and other advanced configurations. MOU Attachments define the roles and responsibilities of groups in this development group.
2. During the period August 15, 2005 to August 15, 2006, the members of ABC Group will participate in ADCDG in the following areas. *For background and details on most of these projects, see current and past CaRT Progress Reports and past MOUs.*
  - a. **Interferometer Configurations** – Having completed a six-month reading-group study of the literature on QND interferometers and related issues, Thorne, Mino, Mandel, and perhaps others in CaRT will begin exploring candidate optical topologies for LIGO-III and beyond.
  - b. **Testing Quantum Theory for Macroscopic Systems Using Future LIGO Interferometers:** Thorne, Mino, Mandel and perhaps others will continue their new project aimed at identifying ways in which future LIGO interferometers can be used to test the fundamental concepts of quantum mechanics for macroscopic systems. See the February and August 2005 CaRT Progress Reports for some details of this project.
3. Resource Sharing: The LIGO Laboratory will contribute resources including allocation of appropriate scientific and engineering personnel, research facilities and funding in support of the effort in Item No. 2, as indicated below.
  - a) Research accommodations for CaRT group members while on LIGO research assignment at any LIGO Laboratory site,
  - b) Access to LIGO data through established LSC channels in support of this work.

4. Coordination and Reporting – CaRT Group will perform this research within the structures established by the LIGO Laboratory and the LSC where appropriate. In particular activities described in Item 2 will be carried out within the Advanced Detector Configurations Development Group of the LSC. Coordination will include keeping the Group leaders informed of activities and plans, reporting to the group at meetings and telecons, and through technical documents submitted to the LIGO Document Control Center.

In addition, an annual report will be submitted with the update to this Attachment, giving a summary status on research by topic as indicated in Item No. 2, including progress against the milestones if any, significant accomplishments such as new insights/discoveries or publications, issues of concern if any, and an indication of invested time. This Attachment will be updated at least annually with a plan of activities for the succeeding on-year period. These documents will be due one month before the close of the period of performance under this Attachment.

Approved:

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Barry Barish  
LIGO Laboratory Director

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Kip S. Thorne  
CaRT Principal Investigator

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Peter Saulson  
LSC Spokesperson

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Ken Strain  
ADCDG Leader

**Attachment DAT to the**  
**Memorandum of Understanding (LIGO-M050292-00-M)**  
**between the**  
**Caltech Relativity Theory Group (CaRT)**  
**and the**  
**Laser Interferometer Gravitational Wave Observatory (LIGO)**  
**August 15, 2005**

This Attachment DAT to the Memorandum of Understanding LIGO-M050292-00-M defines the role of the Caltech Relativity Theory Group (CaRT) as a Member of the LIGO Scientific Collaboration (LSC), in particular, its activities in data analysis in support of the initial LIGO interferometers. The period of performance for the activities in this Attachment is from August 15, 2005 to August 15, 2006.

1. Together, the LIGO Laboratory and the LIGO Scientific Collaboration are responsible for implementing and exploiting the initial LIGO detector through its science data runs. The LSC has organized the data analysis effort into search groups which coordinate the analyses, perform detailed reviews, and prepare publications on behalf of the collaboration. LSC groups are encouraged to participate in one or more of these groups. MOU Attachments define the contributions of each participating group to the data analysis groups.
2. During the period August 15, 2005 to August 15, 2006, the members of CaRT Group will participate in the analysis of initial LIGO data in the following areas. *For background and details on most of these projects, see current and past CaRT Progress Reports and past MOUs.*
  - a) *Binary Inspirals* –
    - i) Non-spinning (BCV1) templates for BH-BH binaries in S2 and later searches:** Pan and Vallisneri, with Buonanno [UMd] and Chen [AEI-GEO], will continue their contribution to the implementation of BCV1-template searches for S3 and following runs, working in particular on template placement strategies with the Cardiff group.
    - ii) Spinning BCV2 templates for NS-BH and BH-BH binaries:** Pan and Vallisneri, with Buonanno and Chen, will continue their contribution to the implementation of BCV2-template searches for future runs, collaborating with the Inspiral Upper Limits Group and in particular with the Cardiff group.
    - iii) Quasi-Physical (PBCV) templates for NS-NS, NS-BH and BH-BH binaries:** Pan and Vallisneri, with Buonanno and Chen, will continue their study of the expected accuracies of parameter estimation for the quasi-physical template binaries, focusing on Monte Carlo simulations as well as the Fisher Matrix. This study will update previous work for parameter estimation in spinning binaries (NS-NS, NS-BH, and BH-BH), which includes spins only as constant terms in the waveform phasing.
    - iv) Extreme Mass Ratio Inspirals (EMRI's):** Fang and Thorne will continue their scoping of the ability of LIGO to extract science from EMRI waves. Duncan Brown [a

part-time member of CaRT who appears on the LIGO Lab-Caltech MOU] and others will develop a template family for EMRI searches with initial LIGO.

b) *Pulsars* --

**i) LALBarycenter LAL Routines:** Cutler [who is moving from AEI-GEO to CaRT] plans some improvements to the LALBarycenter LAL routines, which he wrote some time ago. These routines currently barycenter the data to within around 2-3 microsec; the improvements should decrease this error by about a factor of 2. Also, with Rejean Dupuis [a part-time member of CaRT who appears on the LIGO Lab-Caltech MOU], Cutler intends to document some tests of LALBarycenter based on comparisons to TEMPO. And Cutler intends to finish a 30-page document explaining how LALBarycenter works.

**ii) Detector-Network Search Routines for Pulsars:** With B. Schutz [AEI-GEO], Cutler recently wrote a paper (gr-qc/0504011) explaining how to generalize the F-statistic for gravitational-wave pulsars (the optimal frequentist detection statistic) to a network of detectors and/or to multiple sources. Along with Reinhard Prix and Iraj Gholami [AEI postdoc and grad student, respectively], Cutler intends to develop detector-network search routines for gravitational-wave pulsars, based on this generalized F-statistic, within the LIGO Software Library (with the goal of ultimately implementing them with [Einstein@Home](#)).

**iii) Hierarchical Search Routines for Pulsars:** With B. Krishnan and I. Gholami, Cutler recently completed a paper on optimized, multi-stage, hierarchical searches for gravitational-wave pulsars. Cutler and those co-authors will adapt that study to the Einstein@Home context.

3. Resource Sharing: The LIGO Laboratory will contribute resources including allocation of appropriate scientific and engineering personnel, research facilities and funding in support of the effort in Item No. 2, as indicated below.
  - a) Research accommodations for CaRT group members while on LIGO research assignment at any LIGO Laboratory site,
  - b) Access to LIGO data through established LSC channels in support of this work.
4. Coordination and Reporting – CaRT Group will perform this research within the structures established by the LIGO Laboratory and the LSC where appropriate. In particular activities described in Item 2a) will be carried out within the LSC Inspiral Search Group, Item 2b) will be carried out within the LSC Pulsar Search Group. Coordination will include keeping the Group leaders informed of activities and plans, reporting to the group at meetings and telecons, and through technical documents submitted to the LIGO Document Control Center.

In addition, an annual report will be submitted with the update to this Attachment, giving a summary status on research by topic as indicated in Item No. 2, including progress against the milestones if any, significant accomplishments such as new insights/discoveries or publications, issues of concern if any, and an indication of invested time. This Attachment will be updated at least annually with a plan of activities for the succeeding on-year period. These documents will be due one month before the close of the period of performance under this Attachment.

5. All computer code delivered to the LSC under this Attachment must be developed in consultation with the LSC Data Analysis Software Working Group (DASWG) and archived, documented and reviewed as determined by that group.

Approved:

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Barry Barish  
LIGO Laboratory Director

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Kip S. Thorne  
CaRT Principal Investigator

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Peter Saulson  
LSC Spokesperson

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Patrick Brady  
LSC Inspiral Search Group Leader

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Albert Lazzarini  
LIGO Laboratory Data and Computing  
Group Leader

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Mike Landry  
LSC Pulsar Group Leader

**Attachment OPT to the  
Memorandum of Understanding (LIGO-M050292-00-M)  
between the  
Caltech Relativity Theory Group (CaRT)  
and the  
Laser Interferometer Gravitational Wave Observatory (LIGO)  
August 15, 2005**

This Attachment OPT to the Memorandum of Understanding LIGO-M050292-00-M defines the role of the Caltech Relativity Theory Group (CaRT) as a Member of the LIGO Scientific Collaboration (LSC) and a member of the Optics Development Group (ODG). The period of performance for the activities in this Attachment is from August 15, 2005 to August 15, 2006.

1. Optics Development Group – The Optics Development Group (ODG) is the scientific collaboration for defining and developing improvements in optics for use in advanced subsystems for the initial LIGO interferometers or in entirely new advanced interferometers. MOU Attachments define the roles and responsibilities of groups in this development group.
2. During the period August 15, 2005 to August 15, 2006, the members of CaRT Group will participate in ODG in the following areas. *For background and details on most of these projects, see current and past CaRT Progress Reports and past MOUs.*
  - a) **Light scattering in the LIGO beam tubes and design of the baffles that control it:** K. Thorne and E. Flanagan [CURG; Cornell University] will complete their long paper on the theory of light scattering noise in beam tubes and its control by baffles with various shapes. They also will embark on writing a companion paper on beam-tube light-scattering noise for Advanced LIGO. As a foundation for this paper, they will update their 1995-96 computations making use of all available, relevant measurement data for beam-tube, baffle and mirror properties. Of particular concern will be the noise estimates for nearly concentric advanced-LIGO mirrors, which are expected to have larger microroughness than nearly flat mirrors. These noise estimates may lead to a necessity to place revised limits on the acceptable spectrum of mirror microroughness.
  - b) **Optimization of the Degeneracy of the Signal Recycling Cavity for Advanced LIGO:** Pan will continue his analysis of the optimization of the degeneracy of the signal recycling cavity for Advanced LIGO. In collaboration with Hiroaki Yamamoto and Phil Willems [LIGO Lab-Caltech], Pan will develop an FFT simulation code for the Advanced LIGO interferometer which will eventually provide more precise result on the optimal degeneracy. In collaboration with Willems, Pan will study possible modifications to the current design to achieve the optimal degeneracy.
  - c) **Influence of SR-Cavity Optical Losses on Noise Performance of Advanced LIGO:** Preliminary studies by Buonanno [UMd] and Chen [AEI-GEO] have shown that optical losses in the signal-recycling [SR] cavity of advanced LIGO can significantly degrade the performance of narrow-banded configurations. Pan, with Buonanno and Chen, will

- carry out a detailed theoretical investigation of this effect. They will explore the extent to which, by changing to a 4-kilometer-long SR cavity, this problem can be alleviated.
- d) **Duality Relations for Optical Cavities with Nearly Concentric and Nearly Flat Mirrors:** Savov, with Chen [AEI-GEO] and J. Agresti and E. D'Ambrosio [LIGO-Lab Caltech] will complete and submit for publication their paper presenting analytic proofs of the duality relation between nearly spherical and nearly concentric optical cavities, which Savov discovered numerically.
  - e) **Reshaping Mirrors to Reduce the Strength of the Parametric Instability:** Savov and Thorne will attempt to find new mirror shapes, and corresponding fundamental (TEM00) mode profiles, for which the number of parasitic Stokes modes with low diffraction losses is substantially lower than in the case of spherical mirrors and their Gaussian mode profiles. (This will substantially reduce the strength of the Braginsky-Strigin-Vyatchanin parametric instability.) They will attempt, simultaneously, to guarantee that the TEM00 mode has a near Mesa-beam shape so as to reduce thermal noise. See CaRT Progress report for background on this project.
3. Resource Sharing: The LIGO Laboratory will contribute resources including allocation of appropriate scientific and engineering personnel, research facilities and funding in support of the effort in Item No. 2, as indicated below.
    - a) Research accommodations for CaRT group members while on LIGO research assignment at any LIGO Laboratory site,
    - b) Access to LIGO data through established LSC channels in support of this work.
  4. Coordination and Reporting – CaRT Group will perform this research within the structures established by the LIGO Laboratory and the LSC where appropriate. In particular activities described in Item 2 will be carried out within the Optics Development Working Group of the LSC. Coordination will include keeping the Group leaders informed of activities and plans, reporting to the group at meetings and telecons, and through technical documents submitted to the LIGO Document Control Center.

In addition, an annual report will be submitted with the update to this Attachment, giving a summary status on research by topic as indicated in Item No. 2, including progress against the milestones if any, significant accomplishments such as new insights/discoveries or publications, issues of concern if any, and an indication of invested time. This Attachment will be updated at least annually with a plan of activities for the succeeding on-year period. These documents will be due one month before the close of the period of performance under this Attachment.

Approved:

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Barry Barish  
LIGO Laboratory Director

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Kip S. Thorne  
CaRT Principal Investigator

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Peter Saulson  
LSC Spokesperson

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David Reitze  
ODG Leader

**Attachment Number Z to the  
Memorandum of Understanding (LIGO-M050292-00-M)  
between the  
Caltech Relativity Group (CaRT)  
and the  
Laser Interferometer Gravitational Wave Observatory (LIGO) Laboratory  
August 15, 2005**

This Attachment to the Memorandum of Understanding LIGO-M050292-00-M lists the coordinates of the members of CaRT who will participate in the LIGO Scientific Collaboration (LSC) as members of LIGO Development Groups. The period of performance for the activities in this Attachment is from February 15, 2005 to August 15, 2005. This period may be modified by agreement to a revision of this Attachment.

<b>Name</b>	<b>Address</b>	<b>E-Mail</b>	<b>Phone Nos.</b>	<b>Begin Date</b>	<b>End Date</b>
Thorne, Kip S. 04-05: 40% 05-06: 40% Faculty Authorship: yes	Caltech 130-33 Pasadena, CA 91125	kip@ tapir.caltech.edu	626-395-4598 Fax:626-796-5675	Aug. 15, 2005	Aug. 15, 2006
Cutler, Curt 04-05: 30% in AEI-GEO group 05-06: 30% JPL: Sr. ResearchScientist Authorship: yes	Caltech 130-33 Pasadena, CA 91125; and JPL 169-237 Jet Propulsion Lab 4800 Oak Grove Dr Pasadena 91109	cutler@tapir.caltech .edu	Not yet known	Aug. 15, 2005	Aug. 15, 2006
Mino, Yasushi 04-05: 0% 05-06: 15% Sr. Postdoc Authorship: no	Caltech 130-33 Pasadena, CA 91125	mino@tapir.caltech. edu	626-395-2318 Fax:626-796-5675	Aug. 15, 2005	Aug. 15, 2006

Vallisneri, Michele 04-05: 25% 05-06: 25% JPL: Research Scientist Authorship: yes	JPL 169-237 Jet Propulsion Lab 4800 Oak Grove Dr Pasadena 91109	vallis@caltech.edu	818 393 7634 Fax: 603 506-6524	Aug. 15, 2005	Aug. 15, 2006
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Fang, Hua 04-05: 5% 05-06: 5% Grad Student Authorship: no	Caltech 130-33 Pasadena, CA 91125	hua@tapir.caltech.edu	626-395-8654	Aug. 15, 2005	Aug. 15, 2006
Mandel, Ilya 04-05: 0% 05-06: 15% Grad Student Authorship: no	Caltech 130-33 Pasadena, CA 91125	ilya@tapir.caltech.edu	626-395-8654	Aug. 15, 2005	Aug. 15, 2006
Pan, Yi 04-05: 100% 05-06: 100% Grad Student Authorship: yes	Caltech 130-33 Pasadena, CA 91125	ypan@tapir.caltech.edu	626-395-8654	Aug. 15, 2005	Aug. 15, 2006
Savov, Pavlin 04-05 10% 05-06 10% Grad Student Authorship: no	Caltech 130-33 Pasadena, CA 91125	<a href="mailto:pavlin@tapir.caltech.edu">pavlin@tapir.caltech.edu</a>	626-395-2151	Aug. 15, 2005	Aug. 15, 2006

Scientific Collaboration Council Delegate: Kip S. Thorne

Approved:

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Barry Barish  
LIGO Laboratory Director

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Kip S. Thorne  
CaRT Principal Investigator

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Peter Saulson  
LSC Spokesperson