



**Attachment DAT to the
Memorandum of Understanding LIGO-M050377-00
between the University of Wisconsin at Milwaukee (UWM)
and the
Laser Interferometer Gravitational Wave Observatory (LIGO)
For The Period
August 15, 2009 - August 14, 2010**

This Attachment DAT to the Memorandum of Understanding LIGO-M050377-00 defines the role of the University of Wisconsin at Milwaukee (UWM) as a Member of the LIGO Scientific Collaboration (LSC). In particular, it addresses data analysis activities in support of the initial LIGO interferometers. The period of performance for the activities in this Attachment is from August 15, 2009 - August 14, 2010.

1. Collaboration

Together, the LIGO Laboratory and the LIGO Scientific Collaboration (LSC) 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 analysis, review, and publication on behalf of the collaboration. LSC groups are encouraged to participate in one or more of these groups.

MOU Attachment DAT defines the contributions of each participating group to the data analysis development groups.

2. Participation

During the period August 15, 2009 - August 14, 2010, the members of UWM will participate in the analysis of initial LIGO data in the following areas:

- a. Binary Inspirals

1. Binary Inspiral Search

The UWM group (Brady, Biswas, Burguet-Castell, Clayton, Creighton, Fotopoulos, Goggin, Mercer, Vaulin and Yu) will work within the Inspiral Analysis Group on the following tasks:

- (a) The UWM group will continue to assist in the development of the general infrastructure for data analysis of compact binary systems whenever possible.
- (b) The UWM group (Clayton, Biswas, Burguet-Castell, Vaulin) will work with the LIGO-Virgo team to complete the joint S5/VSR1 analysis, the review, and the submission of a publication describing the search and the results.
- (c) The UWM group (Clayton, Biswas, Burguet-Castell, Vaulin) will assist in the analysis of S6/VSR2 data in the low-mass search for binary inspiral signals.
- (d) The UWM group (Brady, Burguet-Castell, Creighton, Fotopoulos) will work with the GRB team to complete the review of the S5/VSR1 search and the submission of a publication describing the search and the results. The group will also contribute to the running and enhancement of the GRB analysis during S6/VSR2 with the goal of providing preliminary results to the collaboration within hours of the GRB trigger and complete results within a week of the trigger. (The complete results require detailed simulations, hence the delay.)
- (e) The UWM group (Creighton, Goggin, Brady, Yu) will participate in the search for ringdown waves in S5 and S6/VSR2. Goggin will continue to coordinate the activities of the ringdown team. A complete analysis with improvements that have been commissioned since the S4 search will be carried out. This effort will also involve direct measurements of the effectiveness of this search in comparison to burst and matched filtering searches within the Inspiral-Merger-Ringdown team.
- (f) The UWM group (Creighton, Fotopoulos and Goggin) will extend the GRB analysis described above to also search for ringdown waves. This search may also be sensitive to the waves produced by long GRBs if they result in black-hole formation and significant ringing of the black hole.
- (g) The UWM group (Brady, Biswas, Goggin, Price and Vaulin) will document likelihood methods that can guide the development of new detection statistics within the CBC group. We anticipate two technical papers coming from this effort: the first will describe the general concepts and point out how the IFAR and effective likelihood fit into this system; the second will show how to use likelihood methods to present results from multiple searches which have some overlap in their ability to detect signals and their response to noise. The group will also contribute to the development of pipedown to include likelihood ranking as an option.
- (h) Biswas will continue his work in collaboration with Sarah Caudill to develop new background estimation techniques that can extend the range of time-slide background estimation. investigation of the reverse. This work will produce code that can be used in pipedown to improve our current false alarm probability

estimates. Biswas will also complete his studies of background estimation for the H1-H2 combination using reverse templates. These results will form part of his dissertation.

- (i) The UWM group (Brady and Price) will continue to contribute to sky localization studies and the integration of sky localization methods into the current pipelines. With Marion and Mours, they will provide sky position estimates based on MBTA triggers during S6/VSR2. The ultimate goal is to provide sky position information that can be used to point Swift and other telescopes later in the run. This will be coordinated with the sky localization team which will also carry out a comparative study of different methods and effects of systematic errors on position reconstruction.
- (j) The UWM group (Brady, Moe, Price) will integrate event candidates studies into the Gravitational-wave Candidate Event Databases (GraCEDb) including capturing information from intra-collaboration and external follow-ups.
- (k) The UWM group (Brady and Clayton) will participate in the GWHEN searches that are being negotiated at this time.
- (l) The UWM group (Brady and Price) will contribute to the optical follow-up projects that are under development. In particular, we will contribute to the sky localization studies, the galaxy catalog investigations, and integration of the gravitational-wave candidate event database into these programs.
- (m) The UWM group (Brady, Creighton, Mercer, Goggin) will engage in the Inspiral-Merger-Ringdown development activities. In particular, we will develop methods which allow information from complimentary searches to be incorporated into the final result.
- (n) Creighton will develop code that will produce coherent multi-detector strain data streams and null streams from single-interferometer strain streams that can be used as a pre-analysis stage for existing CBC (and burst) searches, thereby allowing existing searches to become fully-coherent searches.
- (o) Goggin, Mercer and Vaulin will participate in the continuation of Numerical Injection Analysis (NINJA-2) project, which will involve tests using data from S5/VSR1 science runs. This work will be done in the format of external collaboration to be negotiated.

b. Bursts

1. Burst Search

- (a) The UWM group (Creighton and Goggin) will continue development of the ring-down search code, will extend the frequency range of the search, and will integrate a ringdown variant of a signal based veto that was developed by Chad Hanna for inspiral signals.
- (b) The UWM group (Brady and Creighton) will develop an approach to determining upper limits on unmodeled sources of gravitational wave bursts. The approach could allow for direct comparison between results from different experiments; it would also allow interpretation of the search in terms of new waveforms which were not used directly in the original search.
- (c) The UWM group (Creighton and Siemens) will run a matched-filter search for cosmic string cusp radiation bursts in S5 data, in collaboration with Kipp Cannon (Caltech). Several refinements relative to the search done on S4 data are being explored including: likelihood-based coincidence scheme, signal-based vetoes, improved loudest-event statistic.
- (d) The UWM group (Creighton, Siemens, and Yu) will run a search to follow up bursts of radio waves in gravitational wave data. The work will be done as part of the the LVC's Radio Analysis Group (RAG).
- (e) Siemens will continue to serve as a burst group reviewer.

c. Stochastic

1. Stochastic Background Search

- (a) Siemens continued to work with the stochastic group to understand the bounds that the LIGO stochastic search places on cosmic string parameter space.
- (b) Siemens also worked on non-Gaussian stochastic background detection methods.
- (c) Anderson will serve as chair of the Stochastic Review Committee.

d. Continuous

1. Pulsar Search

- (a) Papa, Allen, Siemens and Hammer will continue to participate in the work of the CW Search group.
- (b) Papa and Allen will participate in the post-processing of the Einstein@Home results and in the development of new hierarchical scheme for wide parameter space searches.
- (c) Allen will continue to lead the Einstein@Home effort. Work will be continued in collaboration with the AEI group to implement a true hierarchical search using S5 data on Einstein@Home and in this way to obtain a new and higher level of sensitivity for future search work. The S5 post-processing pipeline will be developed, and the S5 analysis will be completed.
- (d) The group will hire a system administrators to move Einstein@Home towards a more professional level of development and support.
- (e) Hammer will continue to administer the Einstein@Home servers and database and to help in preparing data sets for distribution.
- (f) Siemens will continue to develop performance enhancements to the pulsar core search algorithm.
- (g) Siemens will assist with the pre-processing data selection and optimizing the S6 search design.

e. Other Contributions

1. LIGO Data Grid services and software

(a) Hardware resources and services

- i. Nemo is a 780-node beowulf-class parallel computer, built and operated by the LSC group at the University of Wisconsin - Milwaukee (UWM). Nemo will remain accessible to members of the LIGO Scientific Collaboration (LSC) by request through the LAMS. The job submission mechanism is Condor directly on the Nemo Condor pool. Wiseman will continue to maintain the physical facilities for the cluster.
- ii. If the UWM group's MRI proposal is successful, the computing facilities will be upgraded: CPU power will be tripled, storage will be doubled, networking will be upgraded to 10Gb/s, and a prototyping GPU facility will be deployed as a testbed for Advanced LIGO.
- iii. Servers are provided and maintained to host the following services for the LSC:
 - Web sites for the compact binary inspiral group, the burst group, the continuous wave group, and a number of other committees and working groups of the LSC. A development sandbox is provided for the LSC web site.
 - Wikis are also maintained for a number of LSC and Virgo committees and working groups.
 - Version control system access for LSCSOFT, ligovirgo, lscdocs, and a number of other projects undertaken by the LSC.
 - E-mail lists for a number of working groups and committees of the LSC.
 - Bug-tracking for software and hardware resources of the LIGO Data Grid.
 - Data related to these services are backed up nightly.
- iv. All the S5 and S6 LIGO RDS_C0X.L2 and RDS.L3 data will be hosted at UWM on file servers running RAID 6, along with calibrated strain VSR1 and VSR2 Virgo data. In the event of data corruption being discovered, an e-mail will be sent to the LSC notifying them of the epochs of files which were corrupted and any time during which the corrupt data was available for processing. The policy is to remove such data from available as soon as corruption is discovered so as to minimize impact on analysis work.

(b) System Administration

- i. Two full-time system administrators (Oldenburg and Skelton) will maintain and enhance the hardware resources and services over the period of this MOU.
- ii. System administrators will work with their counterparts at other institutions to insure proper integration of the resources and services described above into the LIGO Data Grid. The system administrators will attend the weekly teleconference for LDG administrators, chaired by Stuart Anderson at Caltech.

- iii. System administrators at UWM will support all LIGO Data Grid users on Nemo by helping to isolate, troubleshoot and, when possible, fix issues that cause problems in doing data analysis.

(c) Grid Services

- i. SCAT: Warren Anderson will continue to serve on the Security and Certificate Authority task force (SCAT) and continue to serve as a point of contact between the LDG and the DOEGrids Certificate Authority (CAT) for the purposes of communicating and addressing LIGO needs in this area. This effort involves developing clearly stated requests, which are approved by the Comp Comm, and working with the DOEGrids CA personnel and personnel from the Open Science Grid (OSG) to improve the service provided by the DOEGrids CA.
- ii. Metadata services: Brian Moe will continue to maintain the LDG available data service which provides one-stop shopping for the location of data around the LDG. The UWM group will continue the development of the prototype LIGO Archival System (LArS) and the gravitational-wave candidate event database (GraCEDb) in consultation with the DAC, the run committee, and the detection committee. This activity will take a view that covers enhanced LIGO and begins the process of development for the Advanced LIGO era.
- iii. Authentication and Authorization: Anderson will continue to lead the Authentication Working Group. which is charged to design, develop, and deploy a new authentication and authorization infrastructure for the collaboration in order to lessen the burden of managing credentials for users. Koranda will continue to contribute to that group. UWM will attempt to hire another person to work full time on this project under the supervision of Anderson. continue to serve on the AuthComm sub-committee of the Computing Committee, Anderson will continue to serve as a registration authority agent, issuing certificates for LIGO Data Grid (LDG) users, and as an LDG account manager, managing user requests for accounts on the LDG.
- iv. LIGO Data Replicator: Koranda and UWM will continue to design, develop, deploy, and support LDR, which is currently deployed on 9 sites around the LDG and now at the Virgo site in Cascina. A new model of LDR as a service provided by UWM to some LSC and Virgo sites will be pursued. Koranda is prototyping this direction with Birmingham University.
- v. Monitoring services: Koranda and Brady will continue to provide vision and input to the monitoring infrastructure for the LDG. This effort will ramp up over the next few months with the goal of having simple insight into the status of services and machines on the LIGO Data Grid. Oldenburg will deploy, support and enhance Nagios monitoring for servers, services, and networks.
- vi. Brian Moe will continue to serve as the LAMS operator and process requests for accounts and access to the LDG.

- vii. Open Science Grid: The UWM Nemo cluster is available as an OSG resource provided by LIGO. The UWM group will continue to support OSG users on Nemo and provide a level of access to resources for OSG users that is coordinated through the Computing Committee. Brian Moe will continue to serve as the primary OSG technical lead at UWM and will help support other LDG and LIGO sites, such as LSU, with their OSG technical needs. Brady serves as the LIGO representative on the OSG Council.
 - viii. Other: As the LSC moves into the era of gravitational-wave astronomy, there is a need for easy access to archived results from various searches. The UWM group, in consultation with the DASC, Comp Comm and DAC, will continue to design, document, and implement a prototype system over the period of this MOU. The system will be designed to use multi-site archival to insure data integrity and easy failover. The data will be generally read-only. An authenticated server will provide ability of designated individuals to move the data into the archive.
- (d) Data analysis software toolkits
- i. GLUE: UWM (Fotopoulos and Mercer) will collaborate on the development of GLUE to provide a toolkit for data analysts to use the LDG efficiently.
 - ii. LAL Software Suite: UWM (Creighton, Fotopoulos and Mercer) will continue to maintain the core infrastructure of LAL, LALApps and PyLAL. Efforts will continue to move functionality in LAL over to the LAL Spec that was approved by the SCCB in 2005. The following issues will be addressed in the course of this activity: separate core and analysis specific libraries for simpler deployment and use; improve documentation; support people moving over to the new XLAL function specification.
 - iii. Support/release: UWM (Amador and Mercer) will continue to release a unified build of the LSCSoft bundle for use by the LSC and other gravitational-wave scientists. This release method will be enhanced to include better support of platforms other than the cluster OS's decided by the Comp Comm and DASC. UWM will explore possible build and test harnesses for this software bundle with a view to activating it by summer 2010. Documentation relating to software installation will be updated and enhanced where appropriate.
 - iv. LIGO Data Grid Client: UWM will continue to provide and support certificate request, renewal and retrieval scripts to the LIGO Data Grid (LDG) software, and provide helpdesk support for users and diagnostics and analysis of related software issues for the LDG package maintainer (Greg Mendell, LHO).
- (e) S6 Online Infrastructure: The hardware, software and services will all form part of the S6 data analysis infrastructure. UWM will continue to support, enhance, and deploy tools in support of online analysis efforts.
- (f) Planning for AdLIGO data analysis infrastructure: Brady will initiate a planning exercise within DASWG for AdLIGO data analysis infrastructure. This exercise

will be closely coordinated with DAC, CompComm and DetChar to insure that plans for astronomical observations and analysis properly inform the infrastructure development effort.

2. Committees and working groups

- (a) Brady will continue to chair the DASWG committee of the LSC which is charged to coordinate software development activities for data analysis in the LSC.
- (b) Other contributors to DASWG at UWM include Warren Anderson, Jordi Burguet-Castell, Jolien Creighton, Nick Fotopoulos, Scott Koranda, Adam Mercer, Brian Moe, Xavier Amador, and Xavier Siemens.
- (c) Siemens will continue as a Burst reviewer.
- (d) Anderson will serve as chair of the stochastic review committee.
- (e) Anderson will serve as the lead on the AuthComm project.
- (f) Anderson will serve on the SCAT.
- (g) Anderson, Brady, and Koranda serve on the Computing Committee.
- (h) Koranda chairs the LIGO/Globus working group.
- (i) Anderson and Brady will serve on the Data Analysis Council. Papa co-chairs this council.
- (j) Brady will serve on the detection committee as one of two representatives for the CBC; the other is Steve Fairhurst.
- (k) Wiseman will continue as scimon shift coordinator.
- (l) Siemens will co-chair the Calibration Team.
- (m) Brady serves as the LIGO OSG Council representative.
- (n) Siemens will continue to serve on the LSC Publication and Presentation committee

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 UWM group members while on LIGO research assignment at any LIGO Laboratory site.

Not Applicable

- b. Access to LIGO data through established LSC channels in support of this work.

Not Applicable

4. Coordination and Reporting

UWM will perform research within the structures established by the LIGO Laboratory and the LSC where appropriate.

In particular, with reference to activities described above:

2a will be carried out within the LSC Inspiral Search Group.

2b will be carried out within the LSC Burst Search Group.

2c will be carried out within the LSC Stochastic Search Group.

2d will be carried out within the LSC Continuous Waves search Group.

This includes 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 one-year period. These documents will be due one month before the close of the period of performance under this Attachment.

5. Computer Code

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.

Signature Pending Approval

Jay Marx
LIGO Laboratory Director

A handwritten signature in black ink, appearing to read "Patrick R Brady". The signature is written in a cursive style with a large, stylized initial "P".

Patrick R Brady
Principal Investigator(s)
UWM

Signature Pending Approval

David Reitze
LSC Spokesperson