



**Application to the NSF for funding the experimental
gravitational group at Columbia University**



Szabolcs Márka

for the GEC0 group
at Columbia University

December 2, 2004
PAC meeting, Boston, MA



Outline



- Columbia University
- GEC0 group and LSC membership
- Proposed contribution
- Broader impacts
- Conclusion

Encyclopedia: Columbia University



Alternate uses: [Columbia](#) ([disambiguation](#))

Columbia University, officially known as *Columbia University in the City of New York*, is a private institution of higher education. It is one of the world's foremost research universities, and a member of the [Ivy League](#). Founded in [1754](#) under a royal charter granted by [England's King George II](#), Columbia has grown over time to comprise 20 schools and affiliated institutions.



Columbia's main campus occupies six blocks in the [Morningside Heights](#) neighborhood of [Manhattan](#), and its largest satellite campus, Health Sciences, is situated some fifty blocks uptown in the island's [Washington Heights](#). This makes Columbia not only [New York City's](#) only [Ivy League](#) school but also, by some accounts, the city's second largest landowner after the [Catholic Church](#).

University data

In lumine tuo videbimus lumen
(*In thy light we shall see light*)

Established	1754
School type	Private
President	Lee C. Bollinger
Location	New York City, New York, United States
Enrollment	7,114 undergraduate, 16,536 graduate and professional
Faculty	3,224
Campus	Urban , 32.6 acres (Morningside)
Sports teams	29
Mascot	Royal Lion
Homepage	www.columbia.edu

Shield image © Columbia University in the City of New York



Physics and Astronomy at Columbia



Pupin Laboratories, home of the Columbia Physics Department (dedicated in 1927). Named for Serbian-American inventor and scholar, Michael Idvorsky Pupin, and also houses the Astronomy Department and the Rutherford Observatory

- Graduate Students: ~160
- Faculty/research:
 - Astronomy: ~12
 - Astrophysics: ~5
 - Condensed Matter/Laser: ~7
 - Nuclear: ~2
 - Particle: ~11
 - Theory: ~15



Experimental Gravity Group at Columbia University (GEC0)



- 1 faculty
- 1 associate research scientist (being hired)
- 2-3 undergraduates
- 2-4 graduate students (1 on board, 2 pending)

Great opportunity for collaborative work with
colleagues at Columbia !



History of the group, LSC membership



- The GEC0 group of Columbia University joined the LSC on the August 2004 LSC meeting
- GEC0 is a newly formed (albeit small) group with
 - Significant LIGO experience
 - Strong potential to grow
 - Expected good students
 - High interest/investment in LIGO results
 - Commitment for specific results
- Laboratory space is expected to be ready by January 2005
- Easy access to machine shop (member of Department's Machine Shop Committee) and electronics shop



Proposed contribution to the work of LSC/LIGO



- I. Timing verification studies and **timing diagnostics** system design
- II. Participation in the support and future development of **detector diagnostic tools** and physical environmental monitoring systems, LIGO **service work**
- III. Execution and development of even more sensitive and specialized **analysis** strategies utilizing astrophysical triggers from external sources



Timing Diagnostics: Motivation



- Past experience in timing verification studies and timing diagnostics
- Continuation of timing verification studies and development of timing performance diagnostics tools are critical for both LIGO and Advanced LIGO
- Verifiable and closely monitored timing is essential for reliable data analysis as the presentation of results is based on coincidence
- Important to have both a primary system and a completely independent verification system that both deliver the required accuracy



Timing Diagnostics: Current System I.



- Network of independent Global Positioning System (GPS) based clocks:
 - timing signals for data taking at the corner, mid (LHO only) and end stations
 - a quartz oscillator is phase locked to the GPS's 1PPS signal and serves as the main clock signal for the ADC and DAC boards
 - data are collected in short segments before they are assembled into 16 second long frames
 - the exact time mark is provided by the front-end hardware
 - the GPS master clock is also read out to provide the time stamps of the 1/16s long data segments
 - to monitor the accuracy of the sampling process a several samples long ramp signal (precisely aligned with the GPS 1PPS) is read in on an auxiliary channel
 - to check the time stamp of the data, we also read in an IRIG-B timing signal that is derived from the same GPS master clock



Timing Diagnostics: Current System II.

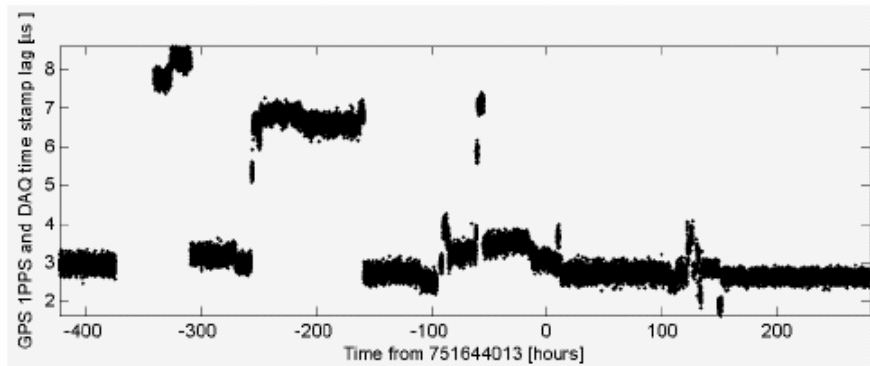


- Internal consistency checks (interferometer length sensing and control software):
 - Is there enough time to process the data before the next sample arrives?
 - Is each and every sample actually seen by the ADC?
 - Are the mid and end stations synchronized with the corner station?
- Timing Performance Monitor
 - proven to be very useful in catching various faults ranging from hardware failures through firmware bugs to software errors/glitches
 - identified built-in limitations of the GPS based timing system

We cannot simply rely solely on a single timing solution/system to achieve the desired redundancy in detector timing.



Timing Diagnostics: Timing Accuracy



Long term (~700 hours) timing accuracy of the LIGO Livingston Length sensing and Control system at the end of 2003. Due to software features the timing accuracy varied at reboots of subsystems.

- The trend provided by the timing monitoring system
- enabled us to correct these fairly large deviations to “repair” the time stamps of the data.
 - helped us to identify the source of the fault.



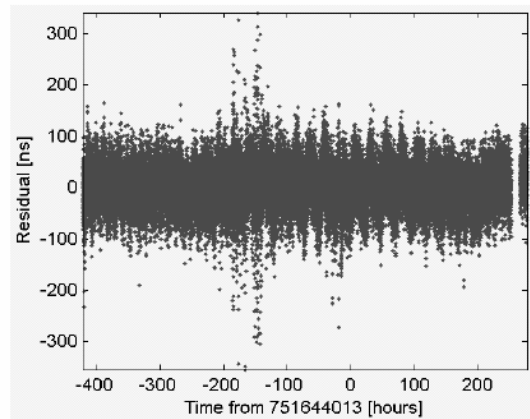
Timing Diagnostics: Atomic Clock System



- A second independent timing system based on a caesium clock
- Designed and installed in 2003
- Complements the existing GPS-based system with the following purposes:
 - (1) Provides a diagnostics system to verify the accuracy of the GPS-based timing system
 - (2) Enables a NIST traceable calibration of the absolute timing of the LIGO detectors (highly desirable in the case of a detection or in coincident observations with other gravity wave detectors abroad or when receiving external triggers).
 - (3) Proves that we understand the arrival time of gravitational waves from an astrophysical point of view.



Timing Diagnostics: Complementary Systems



Long term (~700 hours) relative timing accuracy of the LIGO Hanford Y Mid-Station timing as derived from the **comparison of the local GPS and (central) Caesium clock signals** at the end of 2003. (The predictable linear trend due to the frequency offset of the Caesium clock was removed.)

- Agreement between the systems can be routinely verified to $\pm \sim 100$ ns.
- Even GPS timing glitches of $\pm \sim 200$ ns can be easily caught.



Timing Diagnostics: Proposed Activities I.



1. Continuous monitoring of timing performance during data taking runs:
 - to guarantee that faults are identified and corrected as soon as possible.
2. Install, integrate and test enhancements to the present
 - new ideas and fault types may surface.
 - timing faults must be discovered and dealt with in a timely and permanent fashion.
 - improve the timing diagnostics tools in order to enhance its real time response.
 - develop an expert system, which utilizes our expertise with detection, identification and repair of timing faults and incorporate it into the timing software (the software will be able to advise the operator for solutions to possible timing problems).
3. Equip and precisely monitor the timing accuracy of all systems and subsystems
 - there are still significant parts of the detector electronics (e.g. parts of the angular sensing and control (ASC) and physical environmental monitoring (PEM) system) which are not adequately monitored.



Timing Diagnostics: Proposed Activities II.



4. Timing diagnostics system design, prototyping, testing, installation and calibration for Advanced LIGO:
 - Current requirement for timing accuracy is set to $\pm 1\mu\text{s}$ to allow for uncertainties in translating this time to the response of the interferometers.
 - A significant refinement of the **timing base** and **timing distribution** system (fiber based) is considered for Advanced LIGO.
 - We will continue to take full advantage of the redundancy of the current timing diagnostics system with **two independent subsystems** (GPS and atomic clock) while incorporating the latest advances in GPS technology and atomic clock design.



Detector Diagnostics and Physical Environmental Monitoring Systems I.



- Continue to support the Data Monitoring Tool (DMT) infrastructure and development:
 - concentrate on tools and areas originally developed by GEC Co group members
 - web interface layers of the Data Monitoring Tool
 - the operator alarm interface
- Low-frequency acoustic noise:
 - A possible disturbance, not yet monitored.
 - It happens in natural environment but it is below the sensitive frequency range of the currently installed microphones.



- **Real time evaluation of the spectral shape**
 - Needed for timely identification of unexpected features and unusual detector behavior.
 - Spectral shapes serve as the only "fingerprints" one can use to ensure that the correct kind of data is being recorded via the proper data acquisition channel.
 - The current version of such monitor (also written by Marka) alerts operators when the data acquisition system mixed up various data channels (such problem would lead to significant data loss).
 - Design an expert algorithm that
 - will enable it to detect more subtle problems
 - monitors a wider selection of channels
 - advises the operator on the recommended course of action upon detecting a problem.



Additional LIGO Service Work



- **Perform regular duties during Science Runs**
 - Participating in shifts
 - Providing input for the Calibration and Data Quality Teams
- **Help in hardware signal injection studies as need arises** (in the past Shawhan (Caltech) and Marka attended these duty during the LIGO science runs)
 - Extremely important to verify the integrity of the data analysis pipelines
 - Used in quantifying the agreement between software injected simulated signals and expected gravity wave signatures. (It is reasonable to believe that the thumbprint of hardware injections in the data closely resembles that of a real gravity wave.)
 - All present Upper Limit groups rely on these hardware injections for their analysis and this effort is only expected to grow.
 - It is foreseen that the astrophysical trigger based analyses will have their special needs concerning hardware signal injections.



Data Analysis: External Trigger Based Searches



- ExTrig Group
- Motivation for external trigger based searches
- Analysis strategy
- Analysis example: GRB030329
- Proposed activities



ExTrig Group



- Marka will continue to coordinate the work of the Externally Triggered (ExtTrig) search group within the LSC
- One of the first groups (grassroots effort!) formed to exploit LIGO scientific data
- Takes advantage of existing and readily available data from other astronomical/astrophysical channels (GRBs, optical supernovae, neutrino detectors)
- GEC0 will continue to perform work in close collaboration with members of contributing LSC institutions
- Continue strong cooperation with the Burst Upper Limits Group



Motivation for Externally Triggered Searches



- Astronomical discoveries (GRB, supernovae) often coincide with LIGO data runs
- Increase in the number of GRB/supernova discoveries is expected with the launch of new satellite (SWIFT).
- Improvements in the sensitivity of the LIGO detectors should also increase the probability of a gravitational wave detection and certainly lead to **scientifically significant upper limits**.
- Motivation and limitations (GRB):
 - GRBs are the result of the core collapse of massive stars resulting in black hole formation which have long been proposed as a potential source of gravitational waves.
 - No detailed waveform simulations exist, and there are no gravitational waveform predictions that could be reliably used as templates for a matched filter search. =>Detection of gravitational waves associated with a GRB would likely provide new input for GRB astrophysics.



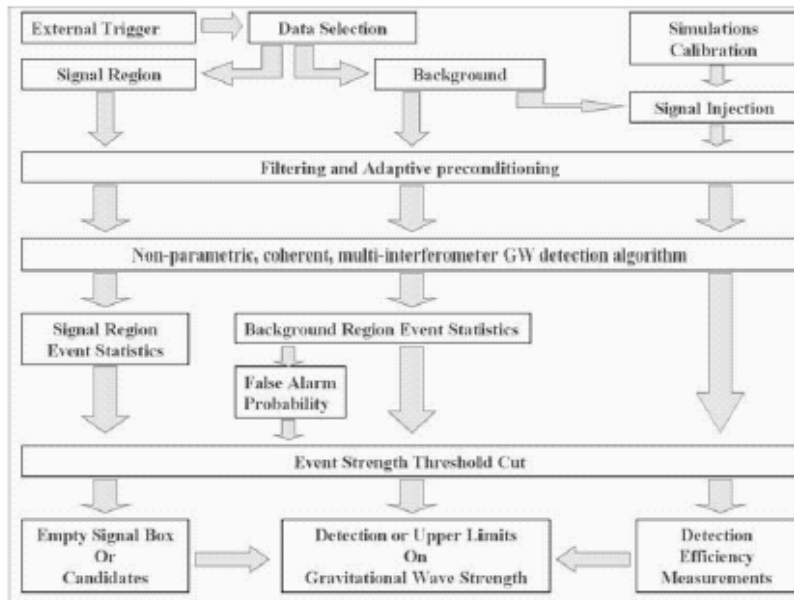
Analysis Strategy



- Goal:
 - either to **identify significant events** in the signal region or,
 - in the absence of significant events, to **set a limit on the strength of the associated gravitational wave signal**.
- The general external trigger based analysis pipeline developed for LIGO takes advantage of the additional information provided by the astrophysical trigger
 - direction
 - timing
 - event type.
- The search algorithm looks for excess correlated power between the two interferometers and thus makes minimal assumptions about the gravitational waveform while being very sensitive.
- Simulations and background data are used to determine the detection efficiency for various ad-hoc and model-based waveforms and the false alarm rate of the detection algorithm respectively.



Analysis Pipeline



Analysis Example: GRB030329



- Search uses data taken by the two detectors at the LIGO Hanford Observatory during the Second Science Run (S2).
- Frequency dependent upper limits on the strength of the gravitational waves associated with GRB030329 were determined.
- Near the most sensitive frequency region, around 250 Hz, our root-sum-square (RSS) gravitational wave strain sensitivity for optimally polarized short band-limited bursts was better than $h_{\text{RSS}} \cong 6 \times 10^{-21} \text{ Hz}^{-1/2}$.
- Significant contribution to existing literature on searches for gravitational waves associated with GRBs.
 - Other GRBs though may be fainter than GRB030329 ($z=0.1685$, distance ~ 800 Mpc) was, but could be significantly closer (e.g. 1998bw ($z=0.0085$, ~ 35 Mpc)).
 - Can also hope for sources with more optimal direction than GRB030329 was.
 - Possibility of a coincidence between three or four observing interferometers.



Proposed Data Analysis Work



(1) Develop and implement a **triggered, prompt, automatized analysis** based on our existing method to search for gravitational wave signature of GRBs and optical supernovae.

- Start ~45 minutes after the reception of the astrophysical trigger.
- Should take less than 12 hours to get the preliminary results and nominally 24-36 hours to have an executive summary for the collaboration (depending on human schedule).



Proposed Data Analysis Work



(2) Continue to execute **high sensitivity, off line searches for short duration GW signatures of GRBs** within the data recorded during LIGO science runs around the received trigger times.

- Evaluate the most promising GRB candidate events first.
- Work in close collaboration with foreign detectors, taking data in coincidence with LIGO.



(3) Search for long duration GW signatures of GRBs
based on promising models by Maurice van Putten and Rafael Araya-Gochez.

- These models significantly differ from the rest of the models described within the traditional literature.
- Predict relatively strong gravitational wave signatures and significantly different waveforms.
- Exploratory work has already started and it is clear that we will have to develop a somewhat different pipeline for optimal results.



(4) Develop, implement and execute a specialized search algorithm to **search for gravitational signature of observed optical supernovae.**

- These events provide different information requiring us to slightly modify the present pipeline.
- Excellent directional information.
- Uncertainty on the timing of the trigger is fairly high.
- As the LIGO detectors become more reliable, the length of stable lock stretches significantly increases, thus making triggered searches with longer timeframes feasible.



- (5) Prepare and maintain a prompt and automatic analysis pipeline to take immediate advantage of a **possible trigger from neutrino detectors**.
- Limited probability for a trigger.
 - Pointing information may not be accurate; timing information should be very precise (neutrinos are expected to leave the collapsing core within ~ 0.1 s of the gravitational waves).
 - A close by event would have enormous scientific payoff (e.g. direct measurement of the neutrino mass).
 - Automatic analysis pipeline should present preliminary findings within 45 minutes of the time of the neutrino trigger.



Overall goal for the GEC0 Group:



Contribute to and further LIGO science !

- Marka will continue to coordinate the work of the Externally Triggered (ExtTrig) search group within the LSC
- To produce concrete, scientifically significant results (e.g. improving upper limits) by implementing externally triggered searches associated with
 - GRBs (almost certainly will yield new results)
 - optical supernovae (requires greatly increased reliability for the LIGO detectors)
 - neutrino detectors (low probability for trigger but huge scientific payoff)
- Further the sensitivity and reliability of the LIGO detectors
 - Continue to support and improve on detector diagnostic systems (e.g. timing, spectral shape monitor) and perform regular duties at the Observatories.
 - Contribute to the Advanced LIGO effort by designing, prototyping, installing and calibrating the timing distribution/diagnostic system for AdLIGO.



Modest Budget



Personnel:

- 2 months of Summer salary for Marka (\$16,178 - year 1 \$16,825 - year 2 and \$17,498 - year 3)
- 12 months of salary (\$56,500 - year 1, \$58,760 - year 2 and \$61,110 - year 3) for Associate Research Scientist
- 1 undergraduate student full time Summer salary of 3 months (\$3,780 - year1, \$3,931 - year2 and \$4,088 - year3)
- Part time salary for the academic year (9 months) for two additional undergraduate students (\$10,368 - year 1, \$10,783 - year 2 and \$11,214 - year 3)

Equipment:

- Year 1

\$5,000 is requested for local data analysis prototyping computer under the Linux operating system.

- Year 2

Raid disk array (\$3,400 and 8 IDE disks (250GB each) to load the rack for \$1,600) to expand our data storage capabilities.

- Year 3,

Taking into account the amortization of the original computing equipment and the expected increase in the group size, more computing equipment (\$4,350) with additional software licenses (\$650) are required.

Travel:

- Domestic

2 domestic conferences per year (one for the PI and one for the research scientist (\$2,340/year))

Main LSC collaboration meetings (2/yr * 2 attendees, \$3,900/yr)

Short LSC collaboration meetings (2/yr * 1 attendee for \$1,950/yr)

Total of 4 trips/yr to the observatories (\$3,750/yr)

- Foreign

1 foreign conference per year (\$1,950/yr) with alternating participation between the PI and the research scientist.

\$1,755 for one group member to participate in the foreign LSC meeting (expected during year one)

1 foreign joint data analysis meeting or a foreign observatory visit for each year (\$1,950/year).

Other Direct Costs:

Publications \$1,900/yr, Computing supplies \$2,500/yr, Machine shop \$950/yr, Office supplies \$500/yr,

Telecommunications including long distance charges \$1,300/yr.



Broader impact



- Our proposed work spans projects from data analysis through detector characterization, to hands on experimental work with the detectors, thus offering talented students a diverse education and experience in the forefront of experimental research.
- The group already has two undergraduates contributing.
- Marka puts strong emphasis on continuously bringing his research into the classroom even during his regular classes.
- The unique setting of Columbia University enables the group members to participate in extra curricular activity of the neighboring community and schools.
- Marka is getting involved in the Columbia Robots for Academic Inspiration mentoring program, targeting underrepresented ethnic and social groups.
- Marka advocates the field of gravitational wave astronomy and the exciting beauty of its science to students through the classroom and to general audiences in the USA and abroad through invited talks.



Conclusion



We believe that we have interesting agenda

We are dedicated to improve LIGO and its science

We are also determined to involve students

**NSF support would enable us to
contribute most
PRODUCTIVELY!**