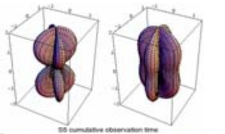
The QPipeline hierarchical coherent search for gravitational wave bursts

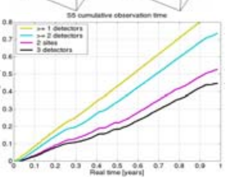
Shourov K. Chatterji[1,2], for the LIGO Scientific[3] and Virgo[4] Collaborations

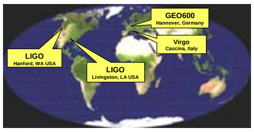
[1]INFN Sezione di Roma, [2]Caltech LIGO Laboratory, [3]http://www.ligo.org/, [4]http://www.virgo.infn.it/

Multi-detector burst search: motivation

- The gravitational wave burst search focuses on sources with incompletely understood waveform:
  - Core collapse supernovae
  - The merger binary compact objects
  - Gamma ray burst progenitors
  - Others…
- Cannot apply matched filtering since accurate waveform is not available
- Instead, search for statistically significant events
- Difficult to distinguish signals from detector artifacts and environmental disturbances
- Burst search greatly benefits from simultaneous observations by multiple detectors:
  - Increased sky coverage
  - Increased observation time
  - Increased signal to noise ratio
  - Increased detection confidence
  - Source direction and waveform reconstruction







Increased sky coverage and observation time of multi-detector burst searches. The top two figures (credit: D. Sigg) display the direction dependent sensitivity of interferometric gravitational wave detectors to the two polarizations of gravitational waves. The figure on the left (credit: wikipedia) identifies the location of the 4 LIGO and Virgo detector sites. Multi-detector analysis takes advantage of the wide angular acceptance of non-aligned detectors to provide good sky coverage as well as improved sky position reconstruction. The lower figure displays the total observation time available during the 1st calendar year of LIGO's fifth science run and demonstrates the increased observation time provided by a multi-detector network.

The QPipeline burst search algorithm

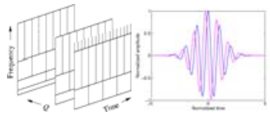
- The QPipeline is a multi-resolution time-frequency search for statistically significant excess signal energy
- Targets gravitational wave bursts of unknown waveform
- Projects whitened data onto an overlapping bank of complex valued sinusoidal Gaussians characterized by central time τ, central frequency ϕ, and Q (ratio of central frequency to bandwidth):

$$X(\tau,\phi,Q)=\int_{-\infty}^{+\infty} x(t)\,w(t-\tau,\phi,Q)\,e^{-i2\pi\phi t}\,dt$$

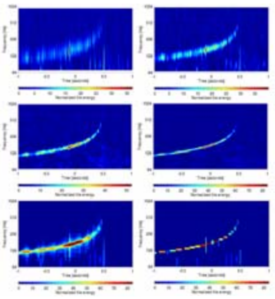
- Equivalent to a templated matched filter search for waveforms that are sinusoidal Gaussians *after* whitening
- Measures the normalized tile energy Z, matched filter SNR ρ, and white noise significance P, where

$$Z=-\ln P(Z'>Z)=\rho^2/2$$

- Reports the minimal set of non-overlapping templates that best describes the signal.



Sketch of the QPipeline signal space and bases functions. *The whitened data is projected onto a bank of overlapping complex valued sinusoidal Gaussian templates or "tiles". Since sinusoidal Gaussians have minimum time-frequency uncertainty, the QPipeline has maximal time-frequency resolution. The templates are overlapped in time, frequency, and Q such that the signal loss due to mismatch between an arbitrary sinusoidal Gaussian signal and the nearest template does not exceed a requested value.*



The QPipeline view of a simulated 1.4, 1.4 solar mass binary neutron star inspiral signal. *The top four panels are time-frequency spectrograms of the signal with 4 different choices of Q. The color represents normalized energy, Z, which is a measure of white noise significance and is proportional to SNR². The bottom left panel displays the significant tiles from all Q planes projected onto a single plane, while the lower right panel displays only the minimal set of non-overlapping tiles from all Q planes that best describes the signal. This particular signal is best detected at higher Q, but other signals may best match at lower Qs. The detectability of a signal is determined by its peak projection onto the space of sinusoidal Gaussians.*

Reference: *S. Chatterji, MIT Ph.D. thesis, September 2005*

Coincident analysis

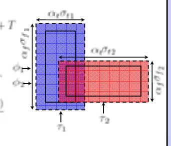
- Test significant tiles from single detectors for coincidence between pairs of detectors:
  - Temporal coincidence

$$\tau_1-\tau_2<\alpha_t\frac{\max(\sigma_{t1},\sigma_{t2})}{2}+T$$

    - Center times τ_1 and τ_2
    - Durations σ_{t1} and σ_{t2}
    - Dilation factor α_t
    - Speed of light travel time T
  - Frequency coincidence

$$\phi_1-\phi_2<\alpha_f\frac{\max(\sigma_{f1},\sigma_{f2})}{2}$$

    - Center times ϕ_1 and ϕ_2
    - Bandwidths σ_{f1} and σ_{f2}
    - Dilation factor α_f



- Sensitivity limited by the least sensitive detector
- The union of pairwise detector coincidences provides improved overall sensitivity due to increased sky coverage and observation time
- Estimate background accidental coincidence rate using non-physical time shifts between detectors

	HLV	HL	HV	LV	HL ∪ HV ∪ LV
max efficiency	19%	41%	22%	22%	60%
mean efficiency	12%	31%	13%	15%	41%

Simulated detection efficiency of coincident analysis using different detector networks. Percentage of detected signals from a simulated population of supernovae in the direction of the galactic center as a function of detector network at an approximate false rate of 1 μHz. The network consisted of the LIGO 4km Hanford (H) and Livingston (L) detectors and the Virgo (V) detector. The 2km Hanford detector was not considered. The union of pairwise detector coincidences provides increased sensitivity to the tested population over the triple coincidence case due to its greater sky coverage. See the reference below for more details.

Reference: *F. Beauville, et al., in preparation, arXiV:gr-qc/0701026*

Coherent analysis using collocated detectors: method

- Applicable to the two collocated LIGO Hanford detectors (4 km H1 detector and 2km H2 detector)
- Simple case of generalized coherent analysis
  - Coherent combinations independent of sky position
  - Computationally much cheaper than general case
  - Cannot fully recover sky position or waveform
- Forms the first stage of a hierarchical coherent analysis
- Combine data to form two new data streams:
  1. Optimal combination to maximize detectability depends on frequency dependent power spectral densities S_1 and S_2 in each detector:

$$H_+=\left(\frac{1}{S_1}+\frac{1}{S_2}\right)^{-1}\left(\frac{H_1}{S_1}+\frac{H_2}{S_2}\right)$$

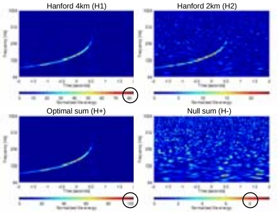
     The resulting SNR is the quadrature sum of SNRs

$$\rho^2_{H+}=\rho^2_{H1}+\rho^2_{H2}$$

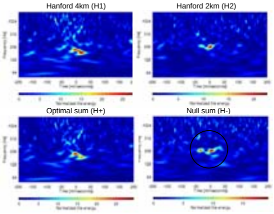
  2. Null combination to test for consistency:

$$H_-=H_1-H_2$$

     Require cancellation of the signal to the level of the background detector noise or an expected residual signal due to calibration uncertainties
- Must be consider the possibility of correlated events due to common environment of two Hanford detectors



Collocated QPipeline view of a simulated inspiral signal using the two LIGO Hanford detectors. *Simulated 1.4, 1.4 solar mass binary neutron star inspiral signal physically injected into the LIGO Hanford detectors with an optimally oriented distance of 5 Mpc. The signal was detected with sinusoidal Gaussian SNRs of ~12.9 and ~6.9 in the Hanford 4km (top left) and 2km (top right) detectors respectively. The optimal combination (bottom left) provided a ~10% increase in SNR over H1 for an combined SNR of ~14.4, while the null combination (bottom right) is consistent with the background detector noise.*



Collocated QPipeline view of a time-shifted detector glitch observed in the two LIGO Hanford detectors. *A coincident glitch observed in time-shifted background studies that exhibits similar time-frequency properties in the two Hanford detectors. In this case, the significant null sum signal indicates that this signal in the two detectors is not consistent with the expected properties of gravitational waves.*

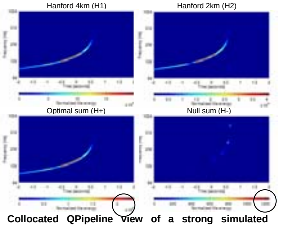
- Calibration uncertainty can produce a significant residual null stream signal for strong gravitational waves
- Compare null stream significance with the significance expected for the case of uncorrelated signals

$$Z_0=\frac{S_1Z_1+S_2Z_2}{S1+S2}$$

- In practice, Z_0 is replaced by the normalized energy of the reference sum H1+H2
- H- events are significant if

$$Z_->\alpha+\beta Z_0$$

- The parameter α fixes the false veto rate
- The parameter β accounts for calibration uncertainty
- Veto significant H+ events that overlap in time and frequency with a significant H- event.
- Veto a larger region of the time-frequency plane for highly inconsistent H- events.
- Does not exclude bursts which are detectable by the 4 km detector, but not the 2km detector
- Allows for coincident detection with other detector sites without limiting the sensitivity to that of the 2km detector



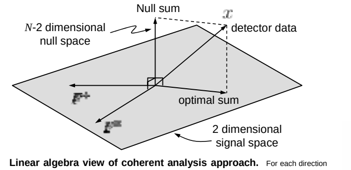
Collocated QPipeline view of a strong simulated inspiral signal using the two LIGO Hanford detectors. *Simulated 1.4, 1.4 solar mass binary neutron star inspiral signal physically injected into the LIGO Hanford detectors with an optimally oriented distance of 0.1 Mpc. A residual signal is present in the null combination (lower right) with a peak sinusoidal Gaussian SNR of ~50. This residual is ignored because it is much smaller than the peak SNR of ~300 observed in the optimal combination, as well as the peak expected SNR assuming uncorrelated signals (i.e., noise glitches) (not shown).*

Generalized coherent analysis: method

- A fully coherent analysis can be performed when data is available from three or more non-aligned detectors
- Generalization of collocated Hanford detector analysis to arbitrary networks
  - Produce optimal linear combinations of time-shifted detector data that maximizes the detectability of gravitational wave signals
  - Produce null linear combinations that cancel any gravitational wave signal to test for consistency
- For each direction on the sky, the data x in the n^{th} detector is described by:

$$\begin{bmatrix}x_1\\x_2\\\vdots\\x_N\end{bmatrix}=\begin{bmatrix}F_1^+&F_1^\times\\F_2^+&F_2^\times\\\vdots&\vdots\\F_N^+&F_N^\times\end{bmatrix}\begin{bmatrix}h_+\\h_\times\end{bmatrix}+\begin{bmatrix}n_1\\n_2\\\vdots\\n_N\end{bmatrix}$$

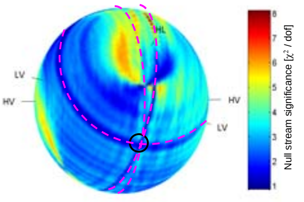
  - The two polarizations h_+ and h_x of the signal
  - The Antenna response F_n^+ and F_n^x of the n^{th} detector
  - The noise n_n in the n^{th} detector
- Construct the optimal sum by projecting the data into the F_+, F_x plane
- Construct the N -2 null sums by projecting the data out of the F_+, F_x plane.



Linear algebra view of coherent analysis approach. For each direction on the sky, the data from N detectors can be written as a linear combination of a signal component and a noise component. The signal component is constrained to lie in the column space of the antenna response matrix F, while the noise component is not constrained. The SNR of the signal can therefore be maximized by considering the projection of the data into the 2 dimensional column-space of the antenna response matrix, while the projection into the I-2 dimensional null-space should be consistent with the background detector noise and provides a useful consistency test. See reference below.

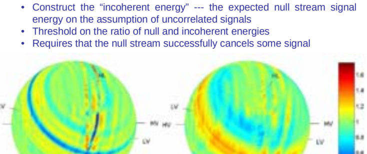
- Test is repeated for ~10⁴ directions on the sky
- Magnitude of optimal sum for each direction provides significance sky map
- Magnitude of null sums for each direction provides consistency sky map
- Computationally expensive due to need to repeat for multiple directions
- Implemented by the XPipeline coherent burst search algorithm

References: *Chatterji, Lazzarini, Stein, Sutton, Tinto, and Searle, Phys Rev. D **74** (2006) 082005*



Example null stream consistency map for a simulated supernova signal as seen by the LIGO and Virgo network. The A1B3G3 simulated supernovae waveform of Dimmelmeier, *et al.* was injected into simulated design sensitivity LIGO and Virgo detector noise with a SNR of ~20. The color represents the normalized null stream energy in units of chi-square value per degree of freedom. The ring-like features with approximately unity value (highlighted in magenta) correspond to the loci of constant time of arrival delay between pairs of detectors, and are indicative of a gravitational wave signal. The true sky position is at the intersection of the rings and is marked by a black circle. See reference below.

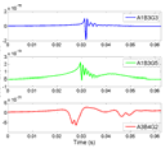
- Calibration uncertainties can produce a statistically significant null stream
- Similar to the collocated approach:
  - Construct the "incoherent energy" --- the expected null stream signal energy on the assumption of uncorrelated signals
  - Threshold on the ratio of null and incoherent energies
  - Requires that the null stream successfully cancels some signal



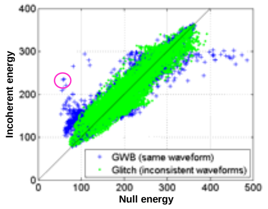
Comparison of consistency maps for a simulated burst and simulated detector glitch using null to incoherent energy ratio test. The left figure shows the ratio map for a simulated supernova signal, while the right shows the map for a simulated glitch using similar, but inconsistent, supernova waveforms. The ring structure is clearly evident in the burst case, while the ratio in the glitch map does not go below ~0.7. See reference below.

Generalized coherent analysis: simulation

- Study performance of null and incoherent energy consistency test using simulated bursts and detector glitches
- Bursts signals drawn from population of simulated supernovae waveforms with uniform distribution on the sky
- Detector glitches simulated by injecting different supernovae waveforms into the each detector
- Glitches are otherwise consistent in timing and in amplitude with a uniform distribution on the sky, providing "worst case scenario" test of the method.
- Signals are injected into simulated LIGO and Virgo detector noise at design sensitivity

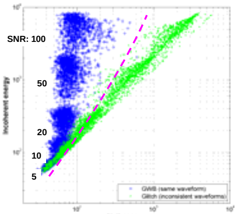


Supernovae waveforms considered in this study. The waveforms were taken from the catalog of Dimmelmeier, Font, & Mueller, Astronomy & Astrophysics 395 (2002) 523-542. The same signals were injected for both the burst and glitch population. Bursts were injected using a consistent waveform in all three detectors, while glitches were injections using a different waveform in each detector. Although the waveforms are different, they have an appreciable inner product and provide a "worst case scenario" test of the method. See reference below.

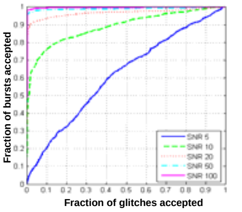


Example null stream consistency test for a simulated gravitational wave burst and a simulated detector glitch. Each point represents the measure null and incoherent energies for one direction on the sky. For the simulated detector glitch, all of the measurements fall along the diagonal corresponding to similar null and incoherent energies. For the simulated gravitational wave burst, there is a wider dispersion with some directions on the sky producing results far from the diagonal. The points corresponding to the minimum ratio of null to incoherent energies are marked by a black circle. See reference below.

References: *Chatterji, Lazzarini, Stein, Sutton, Tinto, and Searle, Phys Rev. D **74** (2006) 082005*



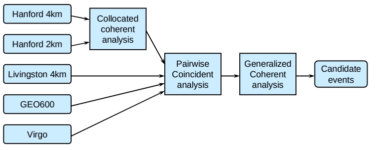
Example null stream consistency test applied to a population of simulated bursts and simulated detector glitches. The plot displays the measured null and incoherent energies of 5000 simulated bursts and 5000 simulated glitches corresponding to the sky direction with minimum ratio of null to incoherent energy. The burst and glitch populations are well separated for SNRs above ~10 by a threshold on the ratio of null and incoherent energies. See reference below.



Receiver operator characteristic (ROC) of null vs. incoherent energy consistency test for simulated population of glitches and bursts. Results along the diagonal of the plot are expected when the algorithm is not able to accurately distinguish between bursts and glitches. Results in the upper left region of the plot represent cases when the algorithm is able to reject glitches with out discarding true signals. See reference below.

Hierarchical coherent analysis

- Coincident methods are limited by the least sensitive detection, but computationally inexpensive
- Coherent methods make optimal use of multi-detector networks, but are computationally expensive
- The collocated Hanford search is computationally inexpensive subset of a generalized coherent analysis
- A hierarchical approach can achieve a sensitivity comparable to coherent methods for a computation cost comparable to coincident methods



Summary and plans

- The hierarchical coherent QPipeline burst search provides:
  - Performance of a coherent analysis
  - Computational cost similar to coincident analysis
  - Makes optimal use of the available detectors
- Coherent methods bring two features to the detection search:
  1. Optimal linear combination of detectors for increased SNR
  2. Null linear combinations of detectors for consistency testing
- Due to the presence of "glitches" in real detector noise, null stream consistency testing can significantly improve the performance of the gravitational wave burst search
- Coherent approaches for sky position and waveform recovery for candidate events are under development.
- A subset of the hierarchical QPipeline is currently being applied to analyze the first calendar year of data from LIGO's fifth science run:
  - Starts with the collocated Hanford analysis
  - Collocated Hanford triggers tested for time-frequency coincidence with Livingston triggers when available
  - Candidate events followed up by generalized coherent analysis when data is available from the Livingston and/or GEO600 detector
- The hierarchical QPipeline will also be used to analyze data from the GEO, LIGO, and Virgo network of 5 detectors
  - Agreement to begin sharing data starting 2007 May 18
  - Analyzing overlapping data from Virgo's first science run and LIGO's fifth science run
- A near real-time hierarchical search is under development and will be applied to future data sets

References

Publications

1. *S. Chatterji, MIT Ph.D. thesis, September 2005*
2. *S. Chatteriji, A. Lazzarini, L. Stein, P. Sutton, M. Tinto, A. Searle, Phys. Rev. D 74 (2006) 082005*
3. *Y. Gursel, M. Tinto, Phys. Rev. D 40 (1989) 3884*
4. *L. Wen, B. Schutz, Class.Quant.Grav. 22 (2005) S1321-S1336*
5. *Klimenko et al., Phys. Rev. D 72 122002 (2005)*
6. *P. Ajith, et al., Class.Quant.Grav. 23 (2006) S741-S749*
7. *F. Beauville, et al., in preparation, arXiV:gr-qc/0701026*

Related talks and posters at this meeting

1. *All-Sky Search for Gravitational Wave Bursts during the fifth LSC Science Run (I. Yakushin for the LIGO Scientific Collaboration)*
2. *Reconstruction of burst signals with networks of gravitational wave detectors (S. Klimenko, I. Yakushin, A. Mercer, S. Mohanty, and G. Mitselmakher)*
3. *Coherent waveburst algorithm for gravitational wave searches (S. Klimenko, I. Yakushin, A. Mercer, and G. Mitselmakher)*
4. *Robust Bayesian detection of unmodeled bursts of gravitational waves (A. Searle, S. Chatterji, P. Sutton, M. Tinto)*

Acknowledgements

The authors gratefully acknowledge the support of the United States National Science Foundation, the Italian Istituto Nazionale di Fisica Nucleare, the French Centre National de la Recherche Scientifique, the European Gravitational Observatory, the Caltech LIGO Laboratory visitors program, and travel support from Cornell University. The authors gratefully acknowledge the support of the United States National Science Foundation for the construction and operation of the LIGO Laboratory and the Particle Physics and Astronomy Research Council of the United Kingdom, the Max-Planck-Society and the State of Niedersachsen/Germany for support of the construction and operation of the GEO600 detector. The authors also gratefully acknowledge the support of the research by these agencies and by the Australian Research Council, the Natural Sciences and Engineering Research Council of Canada, the Council of Scientific and Industrial Research of India, the Department of Science and Technology of India, the Spanish Ministerio de Educacion y Ciencia, The National Aeronautics and Space Administration, the John Simon Guggenheim Foundation, the Alexander von Humboldt Foundation, the Leverhulme Trust, the David and Lucile Packard Foundation, the Research Corporation, and the Alfred P. Sloan Foundation.

LIGO-G070412-00-Z

7th Eduardo Amaldi Conference on Gravitational Waves, 2007 July 8-14, Sydney, Australia