Searching for a Stochastic Gravitational-Wave Background: The View from the Ground

John T. Whelan
The University of Texas at Brownsville
whelan@oates.utb.edu

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Outline

I Ground-Based Gravitational-Wave Detectors

- Interferometers
- Resonant Mass Detectors

II Techniques for Detecting a Stochastic Background

- Cross-Correlation Statistic
- Optimal Filter
- Overlap Reduction Function

III Ground-Based Stochastic Background Searches

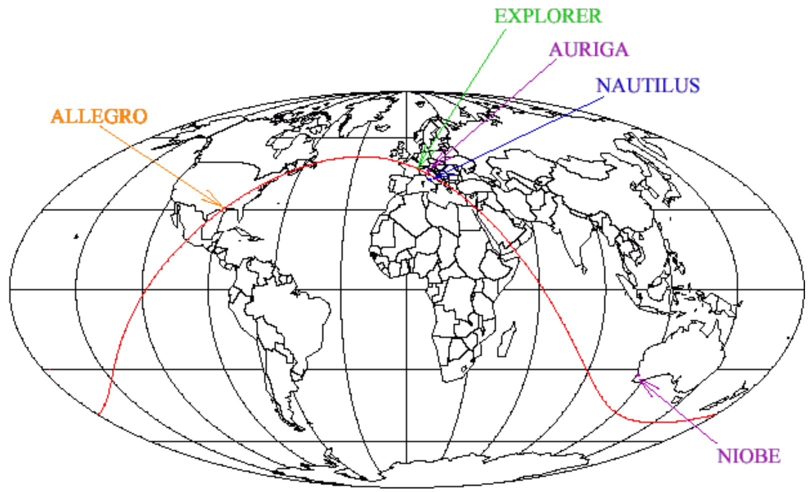
- Previous Results (bars and prototype IFOs)
- Plans for LIGO, ALLEGRO, and GEO

I. Ground-Based GW Detectors
Interferometers

Name	Location	Arm Length	On Line
Glasgow	Glasgow, Scotland	10m	1977
Caltech	Pasadena, CA	40m	1980
MPQ	Garching, Germany	30m	1983
ISAS-100	Tokyo, Japan	100m	1986
TAMA-20	Tokyo, Japan	20m	1991
TAMA-300	Tokyo, Japan	300m	1997
LIGO	Livingston, LA	4km	Shakedown
LIGO	Hanford, WA	2/4km	Shakedown
GEO-600	Hannover, Germany	600m	Shakedown
VIRGO	Pisa, Italy	3km	Construction

Typical sensitivity band 40–1000s of Hz

Resonant Bar Detectors



(figure from IGEC homepage)

Name	Location
ALLEGRO	Baton Rouge, LA
EXPLORER	Geneva, Switzerland
AURIGA	Padova, Italy
NAUTILUS	Rome, Italy
NIOBE	Perth, Australia

Sensitive in narrow band around 900 Hz

II. Techniques for Detecting a Stochastic Background

Stochastic Background

Backgrounds in 10–1000 Hz frequency band likely cosmological in origin, thus isotropic, unpolarized, gaussian, & stationary.

Describe i.t.o. GW contribution to $\Omega = \frac{\rho}{\rho_{\mathrm{crit}}}$:

$$\Omega_{\mathrm{GW}}(f) = \frac{1}{\rho_{\mathrm{crit}}} \frac{d\rho_{\mathrm{GW}}}{d \ln f} = \frac{f}{\rho_{\mathrm{crit}}} \frac{d\rho_{\mathrm{GW}}}{df}$$

Note $\rho_{\mathrm{crit}} \propto H_0^2$, so $h_{100}^2 \Omega_{\mathrm{GW}}(f)$ is independent of

$$h_{100} = \frac{H_0}{100\,\mathrm{km/\,s/\,Mpc}}$$

How to Tell Stochastic Signal from Random Noise

- Need correlations among detectors
  - Detector 1: $h_1 = s_1 + n_1$, Detector 2: $h_2 = s_2 + n_2$
- Assume noise uncorrelated with signal & between detectors
- Cross-correlation:

$$\langle h_1 h_2 \rangle = \langle n_1 n_2 \rangle + \langle n_1 s_2 \rangle + \langle s_1 n_2 \rangle + \langle s_1 s_2 \rangle$$

only surviving term is from stochastic signal

Optimally Filtered Cross-Correlation Statistic

$$
\begin{aligned}
Y_Q &= \int dt_1\, dt_2\, h_1(t_1)\, Q(t_1 - t_2) h_2(t_2) \\
&= \int df\, \tilde{h}_1^*(f)\, \tilde{Q}(f)\, \tilde{h}_2(f)
\end{aligned}
$$

Combine detector outputs using an *Optimal Filter* to maximize signal-to-noise ratio:

- Signal $\equiv$ mean of cross-correlation statistic $Y \propto T$
- Noise $\equiv$ variance of cross-correlation statistic $Y \propto \sqrt{T}$

Optimal Filter

$$\widetilde{Q}(f) \propto \frac{f^{-3}\Omega_{\mathrm{GW}}(f)\gamma_{12}(f)}{P_1(f)P_2(f)}$$

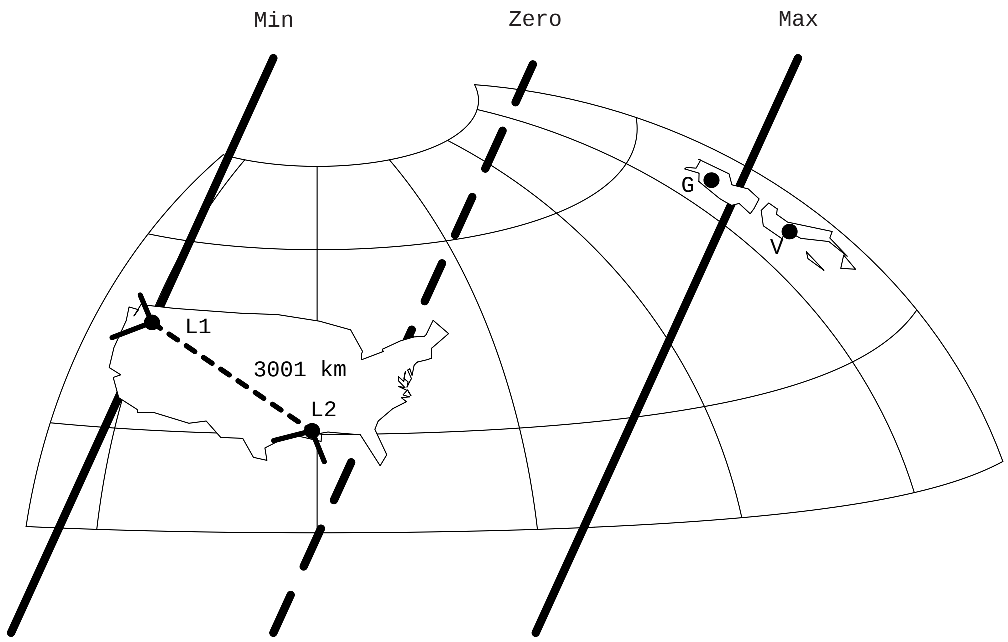
- Enhanced by signal $f^{-3}\Omega_{\mathrm{GW}}(f)$
  $\longrightarrow$ depends on target signal model

- Suppressed by noise $P_1(f)$,$P_2(f)$

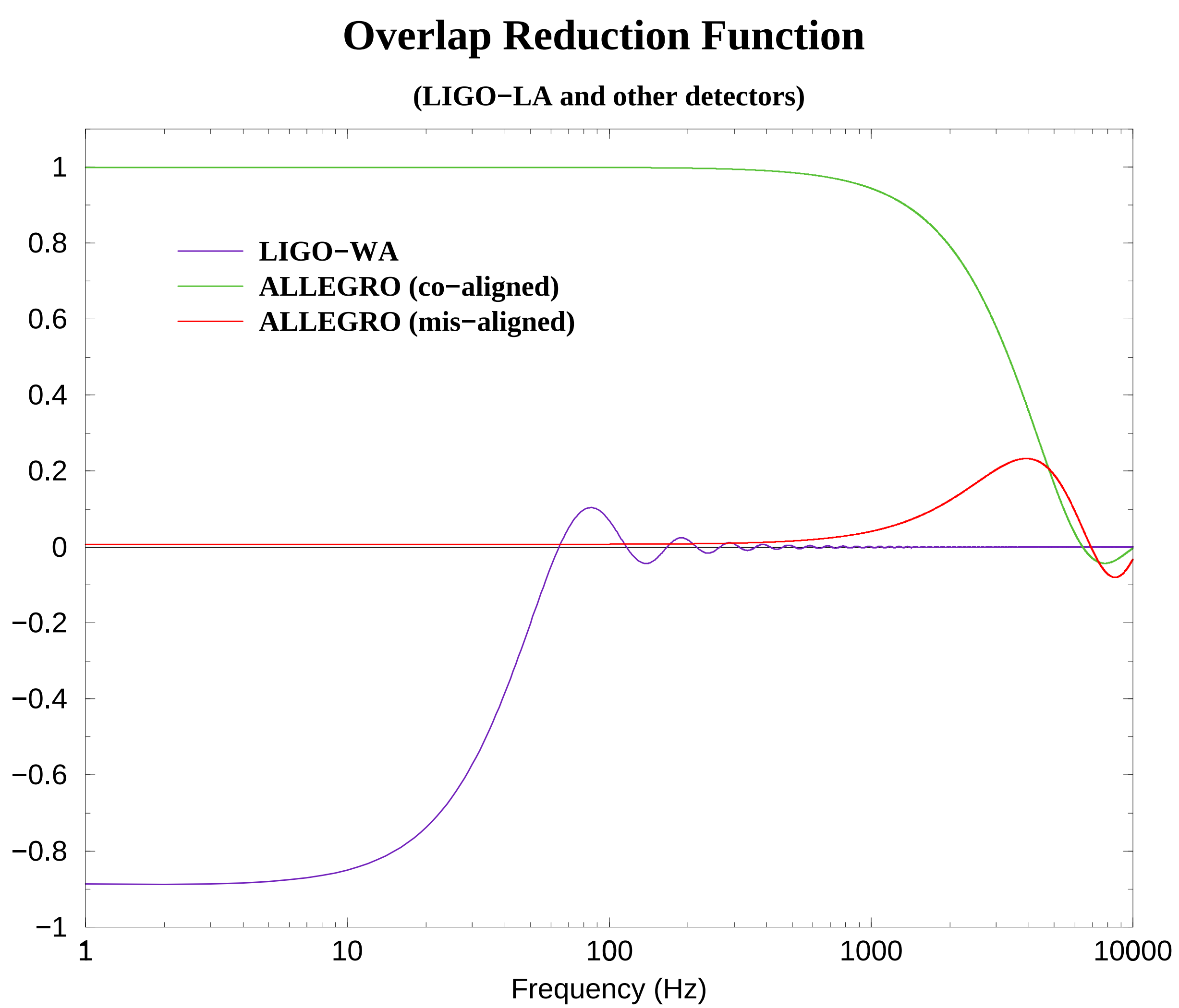
- Geometry via overlap reduction fcn $\gamma_{12}(f)$

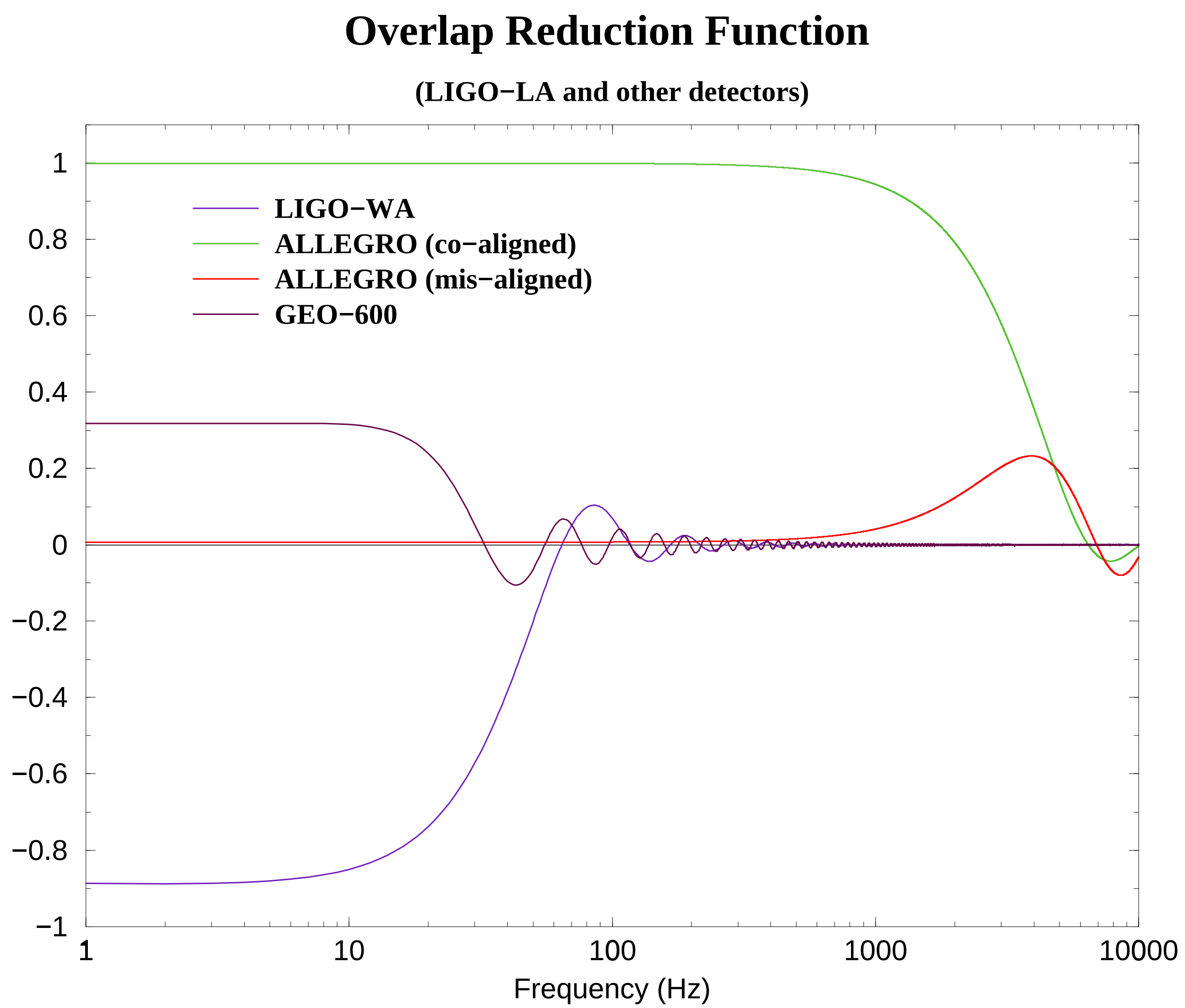
Overlap Reduction Function

Depends on distance between & relative alignment of detectors



(figure from Allen & Romano, gr-qc/9710117)


Overlap Reduction Function
(LIGO−LA and other detectors)
LIGO−WA
ALLEGRO (co−aligned)
ALLEGRO (mis−aligned)
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
1
10
100
1000
10000
Frequency (Hz)



Overlap Reduction Function
(LIGO−LA and other detectors)
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III. Ground-Based Stochastic Background Searches

Previous Results

- Current best upper limit: correlation between EXPLORER & NAUTILUS bars (Astone et al, 1999): $\Omega_{\mathrm{GW}}(907\,\mathrm{Hz}) \leq 60$
- Upper limit from single bar (Astone et al, 1996): $\Omega_{\mathrm{GW}}(907\,\mathrm{Hz}) \leq 100$
- Correlation between Garching & Glasgow prototype IFOs (Compton et al, 1994): $\Omega_{\mathrm{GW}}(f) \lesssim 3 \times 10^5$

Plans for LIGO Analysis

Timetable

- 2002: Science Run Begins

- End 2001: E7 Engineering Run:
  $\sim$ 2 weeks of coïncident data from LIGO-Hanford (LHO) & LIGO-Livingston (LLO); Four groups to set upper limits on Inspiral, Periodic, Burst, and Stochastic signals
  Coöperation with GEO-600 & ALLEGRO

Plans for E7

1. Set Upper Limit on Stochastic Background by Correlating LLO & LHO

- Use Optimally-Filtered Cross-Correlation Statistic
  (Look for $\Omega_{\mathrm{GW}}(f) = $const)

- Perform Analysis within LIGO Data Analysis System (LDAS)
  with codes from the LAL algorithm Library
  (also use for LLO/GEO-600 correlations)

- LHO/LLO Overlap Reduction Function kills correlations
  above ~300Hz; most information from 50–250Hz

2. Set Upper Limit on Stochastic BG by Correlating LLO & ALLEGRO

- ALLEGRO bar detector (Louisiana State Univ.) sensitive in narrow frequency band near 900Hz
- Overlap Reduction Function not a problem b/c ALLEGRO & LLO only ~40km apart
- Sensitive to correlations in different frequency band from LLO/LHO pair
- Test bar/interferometer collaboration model (using LDAS/LAL)
- Exciting future prospect: rotate ALLEGRO to callibrate cross-correlated noise (Finn & Lazzarini gr-qc/0104040)

Software Implementation

- One set of algorithms in LAL library
- Driven by two different "search engines": IFO-IFO and IFO-bar searches

Mock Data Challenge (Sept 4-10)

- Tested data analysis code & LDAS pipeline
- MDC tested IFO-IFO search engine in stand-alone & full LDAS pipeline enviroments; also tested data conditioning methods
- IFO-bar search engine tested subsequently

Summary

- To detect a stochastic GW background, look for a **cross-correlation** among detectors
- Maximize signal-to-noise using an **optimal filter**
- Plan to use LIGO engineering data to improve **upper limits**

References

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   Poster: LIGO graphical presentation G010246-00-E