LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

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CNRS-INFN

Document Type Technical Note	LIGO-T050264-07-Z: VIRGO-PLA-DIR-1000-217	January. 04, 2006

Proposal for joint LIGO-Virgo data analysis to search for stochastic sources

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1. INTRODUCTION

This plan proposes to extend the joint data analysis collaboration between the LIGO Scientific Collaboration (LSC) and the Virgo experiment to include the search for a stochastic gravitational wave background (SGWB).

The stochastic background results from the superposition of a large number of unresolved signals from the very early stage of the Universe up to the limits of the Planck era and the big bang (the cosmological contribution) or from the beginning of the stellar activity (the astrophysical contribution).

Because the stochastic background cannot be easily distinguished from the intrinsic noise in the output of a single detector, the optimal detection strategies involve coherent analysis, which means that data from two or more detectors are combined and analyzed together. Consequently, at the outset, our approach is fundamentally different from a coincidence-based search for transient events, where the data from each detector are analyzed independently and candidate event lists are compared to identify coincidences.

By cross-correlating Virgo with the LSC network of interferometers (by LSC we mean LHO, LLO, and GEO600), we expect to improve the sensitivity to both isotropic and anisotropic backgrounds at frequencies above ~200 Hz. By collaborating in our efforts, we expect to become more efficient in improving the existing search methods and developing new analysis methods.

In order for meaningful scientific results to be possible by such a joint analysis, it is imperative that the instrument pairs combined in a joint analysis have comparable sensitivities over at least a portion of their respective bands. Thus, while it is necessary to embark on the preparatory phases for joint LIGO-Virgo analysis at this time, the actual analysis leading to an astrophysical interpretation will await such a time when comparable sensitivities are achieved. The exact definition of "comparable" will depend on correlations between GEO-Virgo and LIGO-Virgo. It will also depend on whether sky-averaged or spatially resolved searches are undertaken.

An early, preparatory phase of coordination is needed to cross-validate the existing LIGO data analysis pipeline with the new pipeline being developed by Virgo. In addition, any modifications to either pipeline that are needed to accommodate differently sampled data streams will also have to be validated.

It is envisioned that there will be researcher and student exchange visits, co-supervised Ph.D projects resulting in numerous possibilities for jointly publishing methodology papers.

In this proposal, we give the outlines of a collaborative research program, for the all sky survey (Section 2) and for the directed search for anisotropic backgrounds (Section 3). After a brief description of the expected sensitivity, we define the main objectives and provide estimated timetables.

To achieve these steps, we propose to work together on a series of projects of increasing complexity. Each project will have specific goal, data set, analysis methods and will lead to a joint technical report. The first project will use the same simulated or technical data generated during Phase I of the burst and inspiral effort. The second phase proposes to use archival data taken during epochs of coincident operation from the LIGO A4 and Virgo C7 runs. This document will describe the issues we expect to face in a prototypical project and then define the first projects. The detail of the projects involving science data will be defined after an experience has been gained through a few months of working together as the LSC Virgo joint data analysis team.

2. OVERVIEW FOR THE ALL-SKY AVERAGED SEARCH

In this section, the SGWB is assumed to be Gaussian, stationary, unpolarized and isotropic. The optimal detection strategy (the cross correlation statistic) is described in details in Allen and Romano (1999).

The sensitivities (in term of a constant GW strain spectrum S_{gw}) for the different pairs of detectors in 100 Hz wide frequency bands up to 600 Hz are summarized in Table 1 for the design sensitivities (GEO-600 collaboration, Lazzarini & Weiss 1996, Punturo 2004). We assumed an integration time of four months, a false alarm rate of 5% and a false dismissal rate of 5%. In these tables, H1 refers to LIGO Hanford 4km, L1 to LIGO Livingston, G1 to GEO and V1 to VIRGO.

Table 1 sensitivity of different band limited stochastic measurements using different combimations of the 4km interferometers at LHO(H1) and LLO(L1), the GEO(G1) and the Virgo(V1) interferometers at their design sensitivity with a 5% false alarm and 5% false dismissal rate for four months of observation.

Frequency (Hz)	Observable $S_{gw}(f)^{1/2}$ (10^{-24} Hz)			
	H1-L1	**G1-V1**	**H1-V1**	**L1-V1**
0-100	2.0	4.4	3.0	2.8
100-200	1.5	3.3	2.1	1.9
200-300	2.7	2.5	2.7	2.5
300-400	5.0	2.8	4.0	3.6
400-500	7.8	3.7	5.0	4.5
500-600	11	4.0	6.2	5.7
0-600	**1.4**	**2.0**	**1.8**	**1.7**

The table presents calculations based on expected design sensitivities of the various instruments. It suggests two types of analysis:

- The LHO/LLO and the LIGO/Virgo pairs have comparable sensitivities above ~200 Hz. Thus, a correlation in one pair should appear at the same level in the others, which provides an important way of checking an eventual detection. In addition, we can improve single pair upper limits by optimally combining all possible pairs.
- At higher frequencies, the difference in orientations ceases to matter for GEO/Virgo and their proximity implies better observing geometry (see Figure 1, showing the overlap reduction functions for the different pairs, which makes the two pairs complementary to set the strongest upper limit over a wider range of frequency).

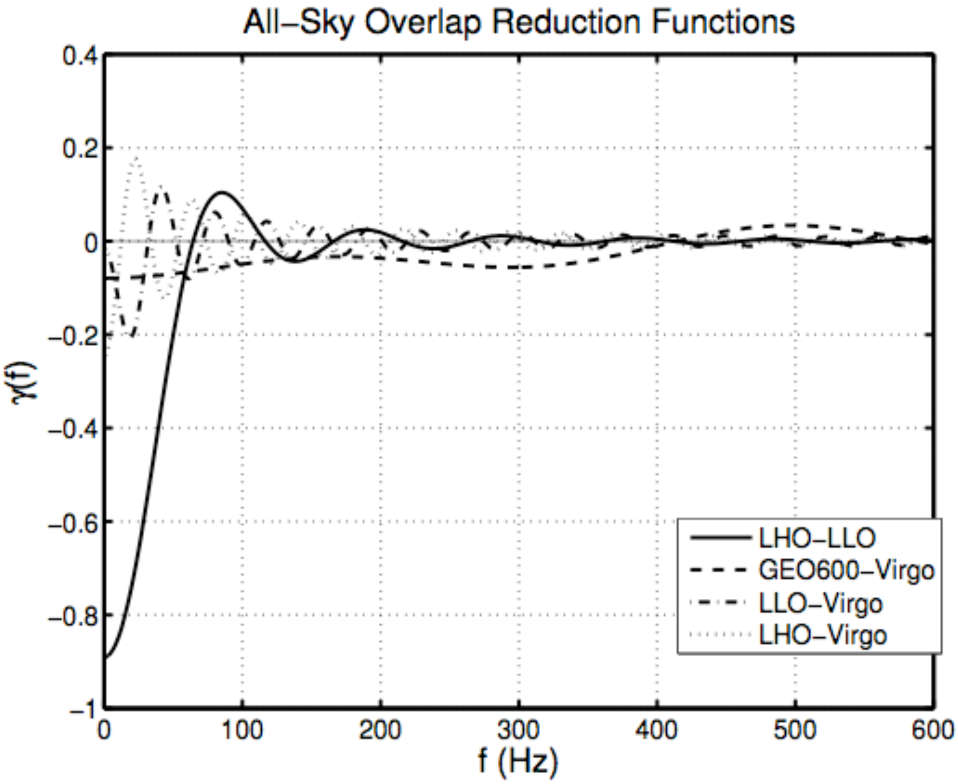

Figure 1 The overlap reduction function for various pairs of gravitational wave detectors. The detectors used are the interferometers at the LIGO Hanford Observatory (LHO) in Hanford, WA, the LIGO Livingston Observatory (LLO) in Livingston, LA, the GEO-600 detector near Hannover, Germany, and the Virgo interferometer near Pisa, Italy. Note that there are actually two interferometers at LHO, and the overlap reduction function between them is unity at all frequencies. At low frequencies, the LHO-LLO overlap reduction function is close to -1 because the detectors are as nearly anti-aligned (rotated 90 degrees with respect to one another) as possible given the planes in which they lie. The oscillation and damping associated with cancellations in the all-sky average happens at higher frequencies for LHO-LLO than for LHO-Virgo or LLO-Virgo because the two LIGO detectors are closer together than either is to Virgo. Virgo and GEO-600, both located in Europe, are closer still, but they are sensitive to very nearly independent GW polarizations, with corresponding arms making nearly 45 degree angles with one another, which suppresses their low-frequency sensitivity. However, their observing geometry is still superior to that of LHO-LLO's at frequencies above 200 Hz.

2.1. Approach: Timeline and deliverables

Before the instruments reach comparable sensitivities, preparatory work is required to make a joint data analysis possible. The main steps of the first phase are summarized below.

PHASE I

1. In order to facilitate the communication between the LSC and the Virgo groups, we will organize common teleconferences weekly. The weekly teleconferences will be separate from the other LSC-Virgo teleconferences in order to enable us to focus on the stochastic

search. Our activities will be reported regularly to the LSC-Virgo joint working group. One option is to extend the existing LSC stochastic teleconference to accommodate a standing agenda item to discuss progress on the joint analysis and including Virgo members in the last part of the teleconference. We propose to begin this immediately.

2. We will use this forum to exchange conceptual approaches to performing the stochastic analysis. We will develop presentations to describe how each group's pipeline functions: data conditioning, calibration, resampling, etc. In this process, we will identify any issues that need to be resolved in order to successfully incorporate each other's data into the other group's pipeline. We propose to review each group's pipeline by 1 April 2006.

PHASE II

3. Once the pipelines are understood by each side, we will proceed to perform tests using simulated data (we propose to use the same Project 1B dataset created for burst and inspiral comparisons) to make sure that the codes can process the data without problems. This will provide an opportunity to confirm consistent results are obtained by both pipelines. Both pipelines will be designed to allow injection into data streams (both simulated and real) of simulated SGWB signals verify we can extract the strength of their injection SGWB. We propose to complete this task by 1 June 2006.
4. We will then perform a number of tests using coincident archival data from LIGO A4 astrowatch data and Virgo C7. At this stage we also will investigate search parameters such as the frequency range, frequency masks or filter parameters. As in #3, we will inject simulated SB in software to verify that we recover the expected point estimate. We propose to complete this task by 1 August 2006.

Results will be presented at respective LSC and Virgo teleconferences as the milestones are achieved. We will present results at the August LSC Meeting and at a suitable meeting hosted by Virgo at about the same time.

3. OVERVIEW FOR TARGETED OR SPATIALLY RESOLVED SEARCHES

The method described in the previous section assumes that the SGWB is isotropic. While this assumption is reasonable for the cosmological contribution, it may fail for astrophysical foregrounds, in particular because the distribution of galaxies in the local Universe up to ~100 Mpc is strongly concentrated in the direction of the Great Attractor.

The objective of the targeted search is to generate a sky map of the SGWB, which show may show anisotropies not detectable in an all-sky averaged measurement.

For an appropriate set of discrete sky locations, characterized by their right ascension and declination, the GW signal can be estimated by cross correlating the data streams of a given interferometer pair with a (sidereal time dependent) time shift corresponding to the time travel of GW between the two detectors. In this case, the overlap reduction function depends on the sky directions and evolves throughout the sidereal day. The systematic errors are estimated by comparing the measurements of nearby pixels using different time delays (LSC Collaboration Proposal 2004, Ballmer 2005, Allen & Ottewill 1997, Cornish 2001).

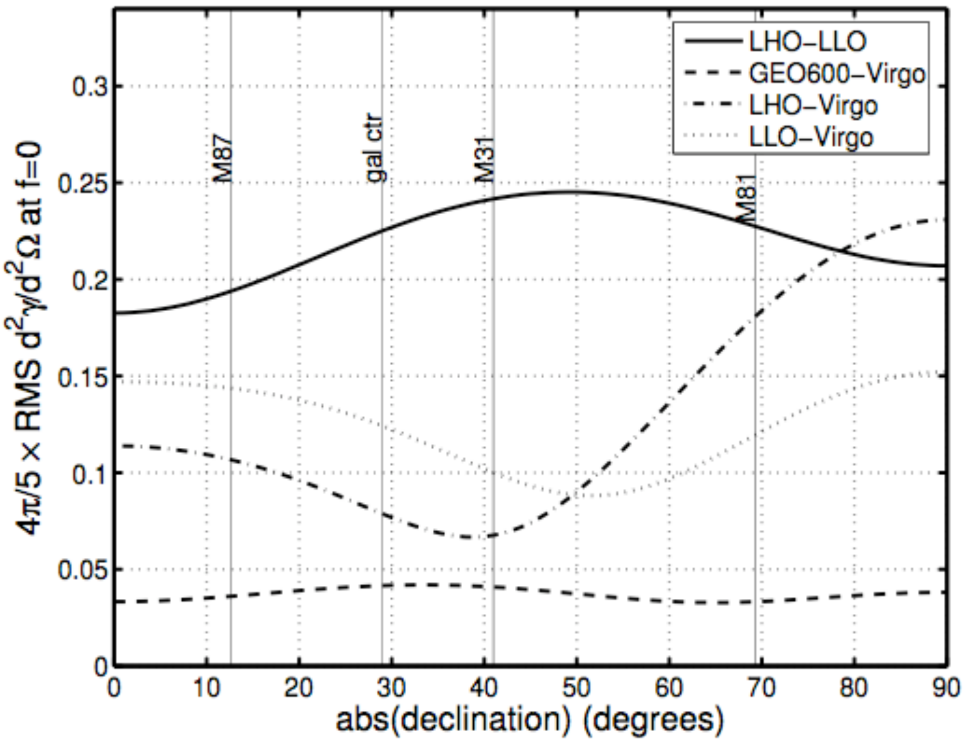

Figure 2. The root-mean-absolute-square of the DC antenna pattern, which is the magnitude of the differential overlap reduction function, for the same gravitational wave detector pairs considered in Figure 1. This quanitity depends on the declination of the target source. The declinations of the Virgo cluster (M87, 12^O 40'), the galactic centre (gal ctr, -28^O 55'), Andromeda (M31, 40^O 0'), and M81 (12^O 40').

The relative sensitivities of directed searches for particular sky locations can be compared by considering the overlap reduction functions associated with pointlike objects at those sky locations. The differential overlap reduction function $d^2\gamma/d^2\Omega$ consists of a frequency-dependent phase and a real prefactor known as the DC (f=0) antenna pattern. For a particular pair of detectors, these quantities depend on both the sky position of the target source and the sidereal time of the observation, with sidereal time being degenerate with right ascension. Because of this degeneracy, the root-mean-square of the DC antenna pattern (which is the root-mean-absolute-square of $d^2\gamma/d^2\Omega$) depends only on the source's declination. This is plotted in Figure 2 for the detector pairs under consideration, with the declinations of several objects of interest indicated.

3.1. Timetable and deliverables

As for the all-sky search, the targeted search method will become efficient when Virgo and the LIGO interferometers reach comparable sensitivities, but in the meantime, much preparation work is needed.

5. As a first step, we will exchange conceptual approaches to performing spatially resolved stochastic analysis. We will develop presentations to describe how each group’s pipeline

functions: data conditioning, calibration, resampling, etc. In this process, we will identify any issues that need to be resolved in order to successfully incorporate each other's data into the other group's pipeline. We propose to review each group's pipeline by 1 September 2006.

6. In the meantime, we will plan and develop a list of targeted sources to be searched for. We will focus on selected targets (such as the galactic centre or the Virgo cluster) to verify that the pipelines run correctly on LIGO/Virgo data and to investigate the optimal search parameters (size of the pixels etc.). We will use catalogs of Galaxies (for instance HYPERLEDA) and astrophysical background models to identify potential targets, their frequency range and their sky distribution. We propose to complete this task by 1 September 2006.
7. Once again, the first stage will use simulated data produced for burst and inspirals investigations. Simulated signals from sptatially resolved stochastic sources will be injected into the data streams by both pipelines to verify the sources can be located and localized. We propose to complete this task by 1 November 2006.
8. To date, LIGO has focused on a single baseline measurement. With multiple baselines, different independent pairs of instruments become available. We will develop the optimal method for combining maps from the different pairs of interferometers. We propose to complete this task by 1 November 2006.

4. REQUIRED RESOURCES

This project will require some software development. Both collaborations will have to determine the abilities of their cross-correlation codes to use calibrated strain data sampled at different rates (16384 samples per second [sps] for LIGO/GEO, 20000 sps for Virgo). The LSC's code within the matapps library (http://www.lsc-group.phys.uwm.edu/daswg/projects/matapps.html) is designed to handle those features, but they have so far only been exercised in the context of a search using LIGO data with data from the ALLEGRO resonant bar detector. (Whelan et al 2005)

We anticipate that the proposed activities will require an average of 2-3 FTEs per phase from each collaboration. The Virgo group does not yet have a validated pipeline for stochastic analysis. This needs to be developed in order to enable independent comparisons to be made. However, we envision that the final implementation of this search will eventually involve, at some level, a majority of the stochastic groups of the LSC and Virgo.

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