LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

- LIGO –

CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
&

VIRGO EXPERIMENT

CNRS-INFN

Document Type Technical Note	LIGO-T040137-08-Z: VIRGO-PLA-DIR-1000-201	August 06, 2004

Proposal for joint LIGO-Virgo data analysis

Working group on joint data analysis
LIGO Scientific Collaboration
Virgo Experiment

VIRGO CNRS/INFN
Via E. Amaldi
56021 S. Stefano a Macerata
Cascina (PI), Italy
Phone (39) 050 752 521
Fax (39) 050 752 550
www: http://www.virgo.infn.it

California Institute of Technology
LIGO Laboratory - MS 18-34
Pasadena CA 91125
Phone (626) 395-212
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Laboratory - MS NW17-161
Cambridge, MA 01239
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

www: http://www.ligo.caltech.edu/

www: http://www.ligo.org/

INTRODUCTION

The similar design sensitivities of the LSC and Virgo interferometers make these instruments complementary for the search and exploitation of signals coming from astrophysical sources. By combining their data, we foresee to increase confidence in the observations and eventually deduce additional information such as source location.

During the next year, the commissioning of Virgo is expected to bring the interferometer to an operational state with sufficient sensitivity to enable useful scientific results to be produced from a combined analysis of coincident data taken simultaneously by Virgo and the LSC interferometers. This proposal defines the steps and goals for a joint collaboration between the LSC and Virgo Collaboration to scientifically exploit combined data in the search for burst or transient (un-modeled) events and for coalescence and mergers of compact binary systems.

In order for meaningful scientific results to be possible by such a joint analysis, it is imperative that the instruments being combined in a joint analysis have comparable detection expectations which usually require 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 detection expectations are achieved. The exact definition of “comparable” will, in general, be search-class dependent and will be defined accordingly.

Prior to this point, however, an early, preparatory phase of collaboration is needed to add confidence in the data analysis pipelines of the individual instruments. It is envisioned that there will be numerous possibilities for jointly publishing methodology papers.

There is much work to be done in preparation for successful joint analysis to become a reality. For this reason, this proposal defines a program of collaborative research and development whose goal is to establish the necessary mutual understanding of LIGO and Virgo data analysis approaches and philosophies. Furthermore, this proposal identifies those necessary steps which are needed well in advance of actual scientific analysis in order to make this possible and to ensure overall success. These steps, discussed in detail below, include:

- cross-calibration of analysis techniques and search algorithms;
- confirmation of the ability to integrate both analyses with commonly formatted data sets;
- definition of data products and their formats;
- steps to be taken in going from an initial event-based data exchange protocol to a subsequent, fully coherent network-based multi-interferometer analysis technique;
- identification of analysis infrastructure enhancements, modifications, or new developments that will be needed to pursue joint analysis;
- definition of analysis approaches and philosophies.

To achieve these steps, we propose to work together on a series of projects of increasing complexity. Each project will have a well defined goal, data set, analysis methods and must lead to at least a joint technical report and possibly a joined publication. The first projects will use simulated or technical data, while later projects will include the analysis of some science run data. 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 join data analysis team.

The first issue of the prototypical project is the definition of the scientific and/or technological goal. We believe that in the first stage of the collaboration project is more productive to address our efforts towards limited and well focused targets. This attitude will permit to verify the collaboration efficiency and then to approach more complex tasks.

The project definition implies also to state at the level of the proposal of each project which resources (personnel, hardware and new software) required.

The typical project will imply four different phases:

- Data preparation (reconstruction of the strain signal of each interferometer, data quality characterization and data distribution)
- Parallel analysis
- Result comparison and discussion
- Common report and publication

It is the mutual intent of the authors of this document to ensure that independence be maintained throughout all stages of the joint analysis. Both the LSC and Virgo believe that such goals are best served by a collaboration that emphasizes dual software pipelines and analysis techniques. Such independence of pipelines, software and post-processing helps to ensure to the maximum extent possible that any findings can be critically evaluated and independently verified in order to establish their validity and to thus maintain the integrity of their scientific and astrophysical interpretation.

2 OVERVIEW FOR INSPIRAL

The inspiral phase of the coalescence of compact binary objects offers Virgo and LIGO a signal source that can be accurately derived from general relativity. Knowledge of the functional form of a potential signal then gives investigators an advantage in the search for these types of events. The LIGO and Virgo detectors will soon be sensitive to the inspiral of binary neutron star and black hole systems out to distances that encompass the Virgo cluster of galaxies.

A joint analysis of LIGO and Virgo data should increase detection probability and statistical confidence; once a signal is detected, a joint analysis will also allow a better determination of the physical parameters. A number of practical issues enter into the detection task. First and foremost is knowledge and confidence in the operation of the interferometers and the character of the data. If LIGO and Virgo scientists are to conduct a joint search for binary inspiral events then there must be knowledge and understanding of each other's detectors. It is necessary to define the kind and depth of the data quality information to be exchanged, including information from possible veto channels. Further, the mutual understanding of calibration techniques, and calibration accuracy, will also be necessary for LSC and Virgo scientists. All this information will naturally provide confidence to the collaborative analysis.

The LSC [1, 2, 3, 4] and Virgo [5, 6] groups have independently developed analysis pipelines for the search for inspiral events. These analysis pipelines will remain independent, although the exchange of information, code, algorithms and techniques are welcomed. An important goal of the data analysis collaboration will be the cross validation of the binary inspiral search techniques of each group. These tasks will provide confidence to LSC and Virgo analysis groups individually. The LSC and Virgo analysis sides will each see immediate benefits through these collaborative efforts.

There are a number of similarities and differences between the LIGO and Virgo binary inspiral pipelines. At the most basic level, both implement matched filtering techniques that search over a grid in parameter space. LIGO presently uses a single grid based search method [7]; Virgo places their templates according to a 2D contour reconstruction technique based on the parameter space metric [8].

Virgo constructs the templates in time domain, whereas LIGO constructs them directly in frequency domain. This difference could ultimately become important for black hole searches as the detection family of BCV waveforms are defined in the frequency domain [9], while analytically derived waveforms, such as EOB, are obtained in time domain. Two kinds of template-based analysis are implemented in Virgo: the so-called "flat" search, and the "multiband" search. The flat search is similar to the LIGO approach, the major difference being the application of the "double whitening" technique in the time, rather than frequency, domain [10]. In the multiband search, the templates are split for efficiency into low and high frequency parts and then patch back together, possibly in a hierarchical way [6]. Pre-triggers, less dependent on the signal waveform, are also being investigated by Virgo [11].

The Virgo pipeline is constructed to read in calibrated data which is effectively proportional to the strain h(t) measured by the interferometer [12, 13]. The LIGO pipeline for their S1 and S2 analyses used an uncalibrated interferometer channel. The calibration to obtain h(t) was done offline as part of the analysis. Currently, LIGO is evolving to use calibrated h(t) data directly, similar to Virgo.

Both the LSC and Virgo inspiral groups use signal to noise ratio and χ^2 thresholds to determine their trigger lists. However, the algorithms for determining the precise times of triggers are different. It will be important to compare the two trigger generation methods, particularly their efficiencies and false alarm rates. Both groups are testing other signal based vetoes, specifically those based on the time domain behaviour of the SNR [14, 15]. The LSC has also done much work on the study of veto channels and data quality as part of its analysis pipeline [4].

The detectors for LIGO and Virgo are different, as are their data handling methods. However they share data format, hence this collaboration may ultimately allow (when both interferometers have comparable sensitivities) each group to analyze the other's data. Learning to process and analyze data from their counterpart in the collaboration are critical and important tasks. Working with artificial events injected into actual interferometer data will allow each side to learn how to process data from the other, a crucial step toward a coherent analysis.

The primary and immediate goal of each member of this collaboration is to confidently claim the detection of gravitational radiation. The simultaneous observation of an event by Virgo and LIGO will increase the statistical confidence of the detection. False alarms are unavoidable and deleterious; combining the data from LIGO and Virgo will decrease false events, and increase the statistical confidence for any events that are seen mutually by the LIGO and Virgo detectors.

When an event is detected the next step will be to estimate the astrophysical parameters of the source that emitted the gravitational radiation signal. Combining Virgo and LIGO data provides a better opportunity to accurately identify the location on the sky of the source. The relatively long baseline between the LIGO detectors and Virgo, as well as the different orientation, will ultimately provide better sky coverage. The mutual detection of an event will also increase the certainty in the determination of the astrophysical parameters. Parameter estimation code [16] will need to be tested and ultimately implemented by the Virgo and LSC analysis groups. An important goal of the LSC and Virgo analysis teams will also be the implementation of a coherent search for gravitational radiation events [[17, 18, 19] possibly as a follow-up of a coincidence analysis [20]; this important type of search will need to be developed and implemented in concert by the two sides of this collaboration.

3 OVERVIEW FOR BURSTS

The search for short-lived transients of gravitational radiation generally encompasses astrophysical phenomena whose source and exact waveform are not known in detail. Among the potential sources we are pursuing are the core-collapse supernovae, the merging and ring-down phase of compact binary coalescences, the ringing of accreting or perturbed black holes, neutron star instabilities, cosmic string cusps or gamma ray burst engines. This search employs generic methods (as opposed to match-filter techniques) and makes minimal assumptions on the time-frequency character of the expected signals. Astrophysical models for some of these sources provide some guidance as to what candidates waveforms might look like; we may use these models to benchmark our search sensitivity or extract detailed time-frequency features of candidate sources in order to perform specifically tuned searches.

Multi-detector analyses are of paramount importance for this type of search.

The goal of the LIGO-Virgo joint search for bursts is to establish confidence in claiming the first detections and use the information from the instruments in order to extract reliably the signal and source parameters. These considerations will be essential in operating a network of detectors as an astronomical observatory.

The Burst working groups within the LIGO and Virgo collaboration are undertaking the search for such signals using the data from their respective detectors. They have developed search pipelines and criteria for identifying candidate events. In the heart of the pipeline are the burst trigger selection algorithms. These can generally be divided into three main categories: time-domain, time-frequency and frequency-domain. The time-domain algorithms developed by the Virgo group [21] include a number of filters based on the mean and norm of the time series or on a linear fit of them. Time-domain matched filters were also put forward by the Virgo group for a templated search for Zwerger-Muller [22] supernovae waveforms as well as dumped sinusoids from black hole ringdowns.

Within the LIGO burst group a time-domain method –called BlockNormal [23] – that identifies change points of the time series by monitoring the mean and the variance of the time series is used. Excess Power [24], TFCLUSTERS [25], and WaveBurst [26] are three additional methods the LIGO burst group has invoked in selecting trigger events. They are all time-frequency methods looking for excess of power once the signal is decomposed in the Fourier or wavelet domain. Corresponding time-frequency methods have also been put forward by the Virgo group: Power Filter [27] is a classical power filter while Bursts-statistics [28] is a generalized Excess Power statistic [24] for the case of non uniform distribution of the signals in the noise as well as for multi-detector analysis.

Finally, the Virgo group has put forward a frequency domain filter [29] consisting of an adaptive Wiener filter followed by a battery of band-pass filters (first step), and an adaptive algorithm for the events selection (second step).

Several of these methods operate with higher efficiency when data are whitened. This is achieved in various steps and using a number of techniques depending on the search algorithm; they generally involve Kalman filtering and regression against auxiliary channels for line removal as well as linear filtering for whitening.

Simultaneously with the gravitational wave signal, thousands of auxiliary read-back channels of the servo control systems as well as of the instruments' physical environment are being recorded. These channels provide the means for establishing transients of non-astrophysical origin that can be used as vetoes. In the LIGO burst pipeline implementation [30], studies for the effect of such vetoes as well as ability to incorporate them in the final candidate event selection is provided. Moreover, in the same pipeline, hardware and software injections are used in order to establish the efficiency of the search while background estimation based on Poisson rates and time shifts of individual detector event triggers is used in order to establish a measurement of the gravitational wave burst foreground. The search is applied to all the data collected over periods when the instruments are well behaved and with the calibration lines present; these are established by the data quality criteria.

The joint working group for bursts will develop a multi-detector pipeline combining derived triggers and/or raw time-series from the LIGO and Virgo instruments that will best address the aforementioned goals, i.e., achieving improved (respect to separate searches) detection confidence as well as improved signal and source parameter extraction of a network of detectors that operates as an astronomical observatory.

As a first step toward this era, the LIGO-Virgo joint working group for bursts will address within the framework of this collaboration the mechanics of the exchange of raw and derived (triggers) simulated data. We will need to establish our ability to analyze and understand each other's simulated data.

In the process of analyzing that data we plan to exchange information and compare the performance of astrophysical search code for bursts by employing a common set of signal software injections and common set of figure of merits. The analysis of simulated interferometer data and signal injections will allow us to prototype a multi-detector search.

4 PROJECT 1: BENCHMARK TESTS

The primary purpose of our first project is for each group to learn from and gain a better understanding of the data analysis algorithms and procedures employed by the other group, and to develop a common analysis language.

Initially, we need to learn how best to exchange data products such as raw interferometer data and trigger files. The first should be relatively straightforward as both groups use frame files for the storage of data. However, triggers are stored in various different formats and some work will be necessary to understand the conventions. Secondly, we would like to gain experience in analyzing each others' data, and understanding any issue which may arise due to the different sampling rates and sensitivities of the two instruments.

Finally, we wish to compare the various search algorithms and their implementations for detection efficiency as well as computational efficiency. In particular, we would like to verify that both groups' detection algorithms identify the same injected events in the data streams and that the recovered parameters of these events are in good agreement with the injection parameters. This will provide confidence in both our injection and detection procedures. For the inspiral search, this will allow us to compare alternative implementations of matched filtering. For the burst search, this will provide the opportunity to compare a variety of alternative search algorithms.

4.1 Project Description

We propose that each collaboration creates three hours of single interferometer data consisting of coloured stationary Gaussian noise at their design sample rate with a spectrum matching their design sensitivity, including expected narrowband features. Additionally, each group will provide a series of non-coincident optimally oriented burst and inspiral injections to be added to the data. This injection data will be provided separately from the simulated detector noise data to allow for analysis with and without injections. Simulated inspiral waveforms will be performed over the range of masses anticipated for a joint search. Simulated burst injections will be performed for a variety of waveforms, both abstract as well as astrophysically motivated, in order to identify which algorithms are most suited to a particular class of waveform. All data will be stored and exchanged in frame format, with and without injections, and only calibrated strain data will be exchanged. Details of the injected signals will also be exchanged in advance of the analysis.

We will then run both the LSC and Virgo analysis codes over both sets of data. This will provide valuable experience in running on a different instrument's data. Wherever possible, to permit a fair comparison, the inspiral searches will be run with the same thresholds, such as signal to noise ratio or event rate. However, to allow comparison of the different burst search algorithms, they will be run over a range of thresholds in order to produce single detector receiver operator characteristics (ROCs) for each algorithm applied to each injected waveform and amplitude. In addition, the burst search algorithms will provide histograms of trigger properties to provide insight into their potential coincident performance.

Following the analysis, we will exchange triggers from the searches, and compare the detection efficiencies and false rates of the various algorithms used. In addition, although the various codes run in different environments and on different computers, we also hope to compare the computational costs of the various codes. This may help in identifying bottlenecks and techniques to optimize the analyses.

4.2 Timeline and Deliverables

We propose to complete this first project in time to present results at GWDAW 9. The conference proceedings will also provide an ideal place to publish the results of this project. In order to meet this deadline, we propose the following timeline.

- Prepare and exchange frame files containing simulated detector noise and simulated gravitational-wave signals by the end of August. This will be reviewed at a teleconference on August 31.

- Analysis of the data and exchange of results will take place prior to a tentatively scheduled face-to-face meeting on 16-17 October, at MIT to compare results and initiate a report.
- Preliminary results will be presented for review by the collaborations at the November 6-7 LSC meeting at MIT and the November 2-3 Virgo meeting at Orsay.
- Results will be presented at GWDAW 9 on 2004 December 15-18 in Annecy, France, with details published in the corresponding proceedings in a special edition of CQG.

4.3 Required Resources

The small amount of data proposed for this first project should limit the required personnel and computing resources. In addition, the tuning requirements are simplified by the absence of non-stationary noise. However, some modification and retuning of search algorithms will be necessary to permit operation on data with a different sample rates, noise spectra, and line frequencies. In addition, we will require some software development to enable the meaningful exchange and comparison of event triggers between the different trigger and injection formats used by each collaboration.

As a result, we anticipate that the proposed activities will require an average of 2 to 3 FTEs per collaboration, depending somewhat upon the number of search algorithms which are invoked. This includes data generation (0.5 FTE), analysis (1.25 FTE), and comparison and reporting of results (0.75 FTE). These will be split roughly equally between the burst and inspiral analyses.

5 PROJECT 2: SIMULATED SIGNAL INJECTIONS INTO REAL DATA

5.1 Goals

The primary purpose of the second challenge is to exercise our analysis techniques on real data from both the LSC and Virgo detectors, and to test the recovery of events coherently injected into the data. This will lead each analysis group to confront the specificities of the other detector(s), to exchange calibrated data, and to learn how to use extra information, such as data quality flags. It will also provide us with the opportunity to implement an automated data replication system.

The injection of coherent events will allow us to test the coincidence analysis pipeline in multiple ways. It will be possible for individual analysis groups to perform a fully independent analysis on the network data stream to produce independent lists of coincident events. It will also be possible to perform joint coincidence analyses by comparing the event lists produced by each algorithm applied to individual detectors. These studies will provide multiple opportunities to cross-check and validate our algorithms and their implementation. In addition, they will enable us to establish the optimal combination of analyses that maximizes detection efficiency while marginalizing false detections.

We also expect to be able to confront and understand issues related to the different sensitivity curves of the detectors, as well as their different orientations.

5.2 Project Description

We propose that each group identifies three hours of representative good quality data from each detector, not necessarily acquired in coincidence, to be exchanged for joint analysis. The data will be exchanged in frame format and will consist of calibrated dimensionless strain data as a function of time, which has been rescaled to yield comparable sensitivities for burst and coalescing binary events.

Additionally, the groups will agree on a series of simulated burst and inspiral signals. These injections will be performed coherently such that the signal timing, amplitude, and phase seen by each detector will be consistent with a source at a randomly selected sky position and orientation. This injection data will be provided separately from the detector noise data to allow for analysis with and without injections.

We will then run both the LSC and Virgo analysis codes over the full coherent data set from all detectors. Each collaboration will then provide single detector event lists for each algorithm and each detector.

The second stage will be to produce coincident event lists in three different ways:

1. Identify events which are coincident in all detectors by considering only event lists from a single collaboration or algorithm applied to all detector(s).

2. Identify events which are coincident in all detectors by considering only event lists from each collaboration's algorithms applied to their own detector(s).

3. Identify events which are coincident in all detectors by considering only event lists from each collaboration's algorithms applied to the other's detector(s).

The third stage will be to compare the resulting coincident event lists. We will first investigate possible discrepancies, namely events which do not appear on all the lists, or events which do not correspond to any injected signal. For the remaining events, we will compare the estimated and injected physical parameters. Additionally, we will investigate our background rate using a time-lag analysis. Finally, we will identify the optimal approaches for combining event lists that maximize detection efficiency for a particular waveform while minimizing false detections.

5.3 Additional tests on real data

In addition to the software injection study described above, we propose the following natural extensions, which will provide more challenging and thorough tests of our joint analysis pipeline.

5.3.1 Hardware injection study

As a first extension, we would like to perform coherent hardware injections of burst and inspiral signals. The analysis of coincident hardware injection data would provide the most complete possible test of our joint analysis pipeline. Alternatively, hardware injections could be made at predefined sidereal times to permit a coherent test without requiring coincident data. The analysis of hardware injection data will be performed by groups from both collaborations and the results combined by incorporating the strategies identified in the previous software injection study. This test is necessarily contingent upon the LSC and Virgo detectors operating with somewhat comparable sensitivities during the time frame of this project.

5.3.2 Blind injections study

As a final test of our joint analysis pipeline, we propose a blind or double-blind simulation. Each group will be given three hours of calibrated data from all instruments that may or may not contain an unknown number of coherent burst and/or inspiral injections. The groups will analyze the data and produce combined results based on the lessons learned in the previous studies. Any candidate detections will be followed up by both collaborations using their standard tests for data quality and by testing auxiliary channels for anomalous behavior. Finally, the groups will decide whether they are unanimously willing to declare a detection. This exercise will provide an excellent test of our detection criteria.

5.4 Timeline and Deliverables

We propose to complete the software injection and blind software injection components of this project in time to present results at the 6th Edoardo Amaldi conference in July 2005. The conference proceedings will also provide an ideal place to publish the results of these studies. In order to meet this deadline, we propose the following tentative timeline.

- Finalize the details of the calibrated data to be exchanged, the signals to be injected, and the format of the blind injection study at the December 2004 GWDAW 9 meeting in Annecy, France.
- Prepare and exchange the calibrated data files containing detector noise and signals to be injected by the beginning of February 2005.
- Analyze the software injection data and exchange events lists by the beginning of March. In addition, the data for the blind software injection study should be prepared and exchanged by this time as well.
- Review and compare results of the software injection study in time for a meeting at the beginning of April to initiate a report. In addition, event lists for the blind software injection study should be exchanged at this time.
- Review and compare results of the blind injection study in time for a meeting at the beginning of May to determine what, if any, action should be taken based on the results.
- Preliminary results of these studies will be presented for review by the LSC and Virgo collaborations in May 2005.
- Results of these studies will be presented at the 6th Edoardo Amaldi conference in Japan in July 2005, with details published in the corresponding conference proceedings.

If the commissioning status of the LSC and Virgo detectors permit it, the hardware injection study will be performed on a timeline similar to the software injection studies. Otherwise, hardware injections will be postponed until the time that the detectors are operating at sufficiently comparable sensitivity.

The effectiveness of vetoes may be partially confronted by the studies described above, particularly in the event of a candidate detection from the blind software injection study.

5.5 Required Resources

This project will require several software developments. Both experiments will have to upgrade and review their codes for exchanging calibrated data, and to upgrade their simulation codes to inject events coherently across all detectors. We will also need independent codes for identifying coincident events and for estimating the physical parameters of events, including source direction.

We anticipate that the proposed activities will require an average of 2-3 FTEs per project, which will be split roughly equally between the burst and inspiral analyses. However, we envision that the final blind injection study and subsequent followup will involve, at some level, a majority of the burst and inspiral groups of the LSC and Virgo.

REFERENCES

1 "Analysis of LIGO data for gravitational waves from binary neutron stars," B. Abbott, et al., *Physical Review D* **69**, 122001, (2004).

2 "Testing the LIGO inspiral analysis with hardware injections", D. Brown for the LSC, *Classical and Quantum Gravity* **21**, S797 (2004).

3 "Search for inspiralling neutron stars in LIGO S1 data", G.Gonzalez for the LSC, *CQG* **21**, S691 (2004).

4 "Vetoes for Inspiral Triggers in LIGO Data", N.Christensen, P.Shawhan, G. González for the LSC. gr-qc/0403114, *CQG* (2004) in press.

5 "A parallel Beowulf-based system for the detection of gravitational waves in interferometric detectors", P. Amico et al., *Computer Physics Communications* **153**, 179 (2003).

6 "Multi-band template analysis for CB search", F.Marion et al, GWDAW8, *CQG* (2004), to appear.

7 "Matched filtering of gravitational waves from inspiraling compact binaries: Computational cost and template placement", B.J. Owen and B. S. Sathyaprakash, *PRD* **60**, 022002 (1999).

8 "New contour reconstruction technique in template parameter space and associated placement", F. Beauville et al. *CQG* **20**, S789 (2003).

9 "Detection template families for gravitational waves from the final stages of binary–black-hole inspirals: Nonspinning case", A. Buonanno, Y. Chen and M. Vallisneri, *PRD* **67**, 024016 (2003).

10 "Whitening of non-stationary noise in gravitational wave detector", E. Cuoco et al. *CQG* **21** 801 (2004).

11 "IIR adaptive line enhancer filters for detection of gravitational waves from coalescing binaries", F Acernese, F Barone, R De Rosa, A Eleuteri, and L Milano. *CQG* **21**, S781 (2004).

12 "Search for inspiralling binary events in the Virgo Engineering Run data", F.Acernese et al., *CQG* **21**, S709 (2004).

13 "Multi-band search of coalescing binaries applied to Virgo CITF data", F.Marion et al, Proceedings of the Rencontres de Moriond 2003, Gravitational Waves and Experimental Gravity (2004), to appear.

14 "A time-domain veto for binary inspirals search", G.M.Guidi, GWDAW8, *CQG* (2004) to appear.

15 "A new waveform consistency test for gravitational wave inspiral searches", P Shawhan and E Ochsner, in press, Classical and Quantum Gravity, also gr-qc/0404064.

16 "A Metropolis-Hastings routine for estimating parameters from compact binary inspiral events with laser interferometric gravitational radiation data." N. Christensen, R. Meyer and A. Libson. *CQG* **21**, 317 (2004).

17 "Computational cost for detecting inspiralling binaries using a network of laser

---

interferometric detectors", Pai A, Bose S and Dhurandhar S., *CQG* **19,** 1477 (2002).

18 "A robust and coherent network statistic for detecting gravitational waves from inspiralling compact binaries in non-Gaussian noise", S. Bose, *CQG* **19**, 1437 (2002).

19 "Data-analysis strategy for detecting gravitational-wave signals from inspiraling compact binaries with a network of laser-interferometric detectors" Pai A, Dhurandhar S, Bose S, *PRD* **64** 042004 (2001).

20 "Network analysis for coalescing binaries: coherent versus coincidence based strategies" A Viceré, proceedings of GWDAW8, *CQG* (2004) to appear.

21 Pradier et al., Phys. Rev. D63, 042002 (2001).

Arnaud et al., Phys. Rev. D67, 102003 (2003).

Hello et al., Virgo Note 2001, VIR-NOT-LAL-1390-168.pdf.

Arnaud et al., PRD 59, 082002 (1999).

Arnaud et al., PRD 67, 062005 (2003).

T. Pradier, PhD thesis (Orsay, 2001).

http://www.lal.in2p3.fr/recherche/virgo/publications.

22 Zwerger and Muller, Astronom. and A.strophys, 320, 209 (1997).

Dimmelmeier et al., Astronom. Astrophys. 388, 917-935(2002).

23 McNabb et al. gr-qc/0404123.

24 Anderson et al. Phys. Rev. D 63 (2001) 042003.

25 Sylvestre, Phys. Rev. D 66 (2002) 102004.

26 Klimenko et al. gr-qc/0407025.

27 Guidi et al., Class. Quantum Grav. 21 (2004) S815-S820.

28 Vicere, PRD 66, 062002, 2001.

29 Brocco and Frasca, Class. and Quant. Grav. 21 (2004) S793-S796.

30 LIGO Scientific Collaboration, Phys. Rev. D 69, 102001 (2004)