LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

AURIGA EXPERIMENT
ISTITUTO NAZIONALE DI FISICA NUCLEARE (INFN)

Document Type	**LIGO-T040202-00**	2004/10/13
Proposal for the First AURIGA-LIGO Joint Analysis		
L. Baggio, L Cadonati, S. Heng, W. Johnson, A. Mion, S. Poggi, G. Prodi, A. Ortolan, F. Salemi, P. Sutton, G.Vedovato, M. Zanolin		

Istituto Nazionale di Fisica Nucleare (INFN)
INFN of Ferrara, Firenze, Legnaro, Padova, Trento
Universities of Ferrara, Firenze, Padova, Trento
Experiment AURIGA
via dell'Universitá, 2
I-35020 Legnaro, Padova
Phone +39-049-8068473
Fax +39-049-8068824
E-forum: http://www.auriga.lnl.infn.it/cgi-bin/SP2/YaBB.cgi
WWW: http://www.auriga.lnl.infn.it/

California Institute of Technology
LIGO Project - MS 51-33
Pasadena CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project - Room NW17-161
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

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

Processed with LaTeX on 2005/01/25

1 Introduction

Over the course of a two-week period, starting on Christmas Eve 2003, the recently upgraded AURIGA and the LIGO observatory were simultaneously acquiring data. This represents the first coincident run between the two projects and an important opportunity for a collaborative analysis.

In July 2004 a Memorandum of Understanding (MOU) for joint data analysis was signed between the two projects [1]. Attachment 1 [2] describes the protocols for a coincident burst search between LIGO and AURIGA, to be performed on data acquired between December 24 2003 and January 9 2004. The data set is part of the third LIGO Science run (S3) and the first run of the upgraded AURIGA detector (AU1).

This document, a provision of Attachment 1, describes the methodologies that the AURIGA-LIGO Joint Working Group (JWG) plans to implement in the coincidence analysis. This proposal is submitted to the attention of the AURIGA Collaboration and of the LIGO Scientific Collaboration. Its approval is conditional for the actual data exchange.

2 Scientific Motivation for an AURIGA-LIGO Joint Analysis

The principal focus of this analysis is the search for gravitational wave bursts. The search will be performed only once both the AURIGA and LIGO Collaborations have approved the general methods described in this document and have reached confidence on the quality of the exchanged data.

Due to the short duration of the S3/AU1 overlapped observation time, the JWG does not expect the results of this analysis to have a significant impact when compared to those obtained by longer data-taking. Nevertheless this effort is important to lay the path for future, longer coincidence runs.

The initial plan is to perform a trigger-based coincidence search, following the methods described in section 4. As a general remark on strategy, all decisions on the analysis will be made while *blind* to the final result. The final interpretation of the result (upper limit vs detection) will be performed in a frequentist approach. The JWG will agree on a method for the construction of the confidence belt and a test of the null hypothesis that will be applied to the results. If when the whole data set is analyzed some crucial issues, such as the background statistics, are still not understood, the JWG reserves the right to stop the interpretation at an earlier stage and, if necessary, forego deriving a publishable result.

The JWG is also considering the exploration of coherent analysis techniques for burst searches on playground data sets, making contact with other studies of global network coincidence methodologies. This will not be explored in this first proposal, but will be the focus of a possible next round of studies.

The addition of a gravitational wave detector to a network offers three principal advantages.

First and foremost is the suppression of the false alarm rate. Long term observations aiming to the first measurement of gravitational wave signals must ensure a satisfactory statistical confidence in the detection. This requires the predicted false alarm rate to be several orders of magnitude below the rate of detectable signals or, in more practical terms, much less than one false detection over the entire observation time. The long term observations of the IGEC [3] network of gravitational wave antennae demonstrated that adding a detector to the network lowers the false alarm rate by few orders of magnitude at the same sensitivity level, in agreement with back-of-the-envelope predictions.

Another general advantage of adding detectors is an increase of the effective observation time.

The live time of an individual detector depends on its reliability and stationarity. In a coincidence network analysis, we can require that at any time a minimum number of detectors is operating (for instance, at least three out of four); this was the approach used in the IGEC analysis [3] and in the LIGO-TAMA S2 analysis [4]. In such a scenario, the total observation time increases as more detectors are added to the network.

Finally, the addition of detectors with different directional sensitivity improves the network's sky coverage and its potential to detect linearly polarized transient signals, as expected for gravitational wave bursts[1]. A good sky coverage for each polarization component is also needed to fully measure the properties of the incoming gravitational wave. General Relativity (GR) states that a plane gravitational wave is fully described by four independent parameters: direction (two coordinates) and amplitude (in two polarizations). A network of at least three detectors in simultaneous observation with different directional sensitivities, such as LHO, LLO and AURIGA, can provide enough information to measure all four of these parameters. Additional participating detectors with different directional sensitivities would allow to do this more efficiently over a wider portion of the sky. This larger network could perform consistency checks on such fundamental wave properties as the propagation speed, the wave transversality and the absence of a scalar component of the wave (i.e. tracelessness of the Riemann tensor). A complete characterization of the wave properties would offer a fundamental advantage to the analysis: the statistical significance of a detection would not be based exclusively on timing/morphology information, but on the actual gravitational wave signature.

In order for the network to achieve its potential, all the detectors must have comparable sensitivity for the target signals. In our case, the addition of a resonant bar (AURIGA) to a network of long-baseline interferometers (the LIGO observatory) can provide significant benefits only for signals with a detectable spectral component in the bar's narrower sensitivity band. Therefore, the AURIGA-LIGO joint search will focus on bursts with high frequency content, such as black hole ring-downs [22] and mergers of coalescing neutron star or black hole binary systems [6].

It is likely that the detectors will show different sensitivities to the same target signals. In this case, the observatory can still take advantage of the least sensitive detectors if they happen to cover sky regions and polarization angles where the more sensitive detectors have poor directional sensitivity. An important point to remember is that resonant bar detectors can also be re-oriented, as was done by ALLEGRO [10]. This feature could be exploited in the future either to improve the coincidence efficiency with LIGO or the detection efficiency with respect to some target sky region.

3 Performance of AURIGA and LIGO during the Coincidence Run

3.1 The AURIGA AU1 Run

The AURIGA detector has been upgraded since its first run (1997-1999)[24]. The principal improvements have been achieved on the signal amplifier and signal matching network, on the cryogenic suspensions and on the data analysis system [23]. The initial phase of AURIGA run 2 is being carried out at liquid Helium temperatures (4.5 K during the overlapping period with LIGO S3). Due to the higher operating temperature, the minima of the noise power spectrum S_{hh} are higher than during run 1. Nevertheless, the sensitivity to transient signals has improved in run 2, thanks to the significant enlargement of the sensitivity band. The spectral sensitivity is much flatter, allowing

[1] The simplifying assumption that gravitational wave bursts are linearly polarized is a very good approximation for most of the present simulations/models of burst sources (e.g. [22, 8]).

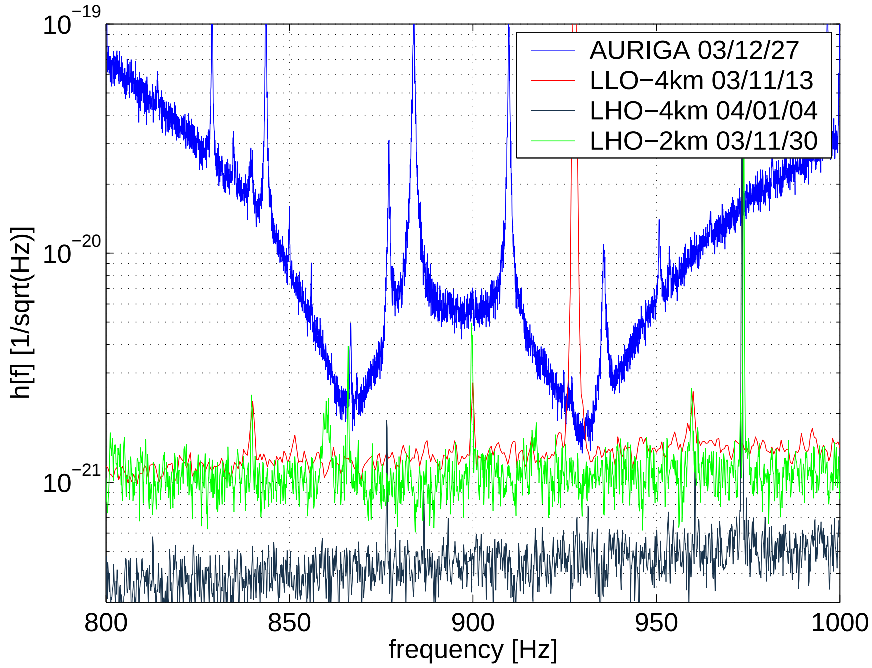


Figure 1: Single-sided sensitivity spectra for AURIGA and the three LIGO interferometers during the AU1 and S3 science runs, in the 800-1000Hz band. Notice, in the AURIGA spectrum, the presence of spurious lines, as described in section 3.1. For LIGO, the Hanford spectra are quite representative, but the Livingston spectra was at times a factor 2-3 worse than shown here (on this topic, see also figure 2). In the LIGO spectrum, notice also the calibration lines at 973 Hz for the Hanford detectors and 927Hz at Livingston, inconveniently centered in one of the two AURIGA dips. AURIGA's spurious lines and LIGO's calibration lines need to be filtered in the analysis.

a useful bandwidth close to 100 Hz, and the energy sensitivity to millisecond transients in AU1 is about three times better than the best performance achieved during run 1.

The AU1 run was the first continuous period of data acquisition in the target configuration for the upgraded AURIGA. It started on December 24 2003 at 11:06 UTC, and ended on January 13 2004 at 08:30 UTC. During this period the AURIGA spectrum featured various spurious noise lines, whose amplitude is affected by human activities (exhibiting day-night oscillations), and which turn off for periods of approximately one minute. These spurious lines do not appear in the mechanical or electromagnetic transfer functions, and are generated by up-conversion of low frequency noise. Four of them are prominent in the sensitivity band (see figure 1); therefore, the AURIGA data analysis had to be modified to take their effect into account. This has been accomplished through an adaptive algorithm which tracks the variation of the spurious lines and (partially) whitens the spectrum. If the non-stationarity is too rapid for the algorithm to work, the spurious lines are notched by narrow Butterworth band-reject filters. Apart from the spurious lines, the noise spectrum in the sensitive band is well accounted for by modeled noise sources, mainly the thermal noise of resonators and of the amplifier.

During the AU1 run no maintenance was needed by AURIGA, so that the duty cycle, defined as the fraction of time in operation, was close to 100%.

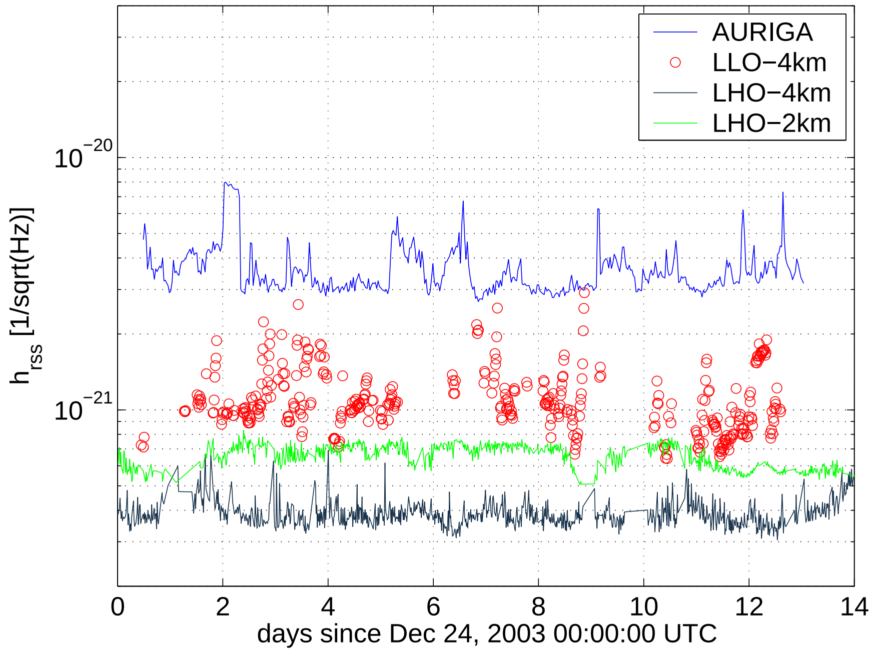


Figure 2: Root-sum-square amplitude (h_{rss}) of a 900 Hz Sine-Gaussian with Q=8.9 (defined as in equation 1) with SNR=1 in AURIGA and in the LIGO interferometers over the period of interest for this analysis. h_{rss} is defined in equation 3; the SNR is defined in equation 2.

3.2 The LIGO S3 Run

The third LIGO Science Run (S3) started on October 31 2003 at 16:00 UTC, and ended on January 9 2004 at 16:00 UTC.

The fundamental improvement from the previous S2 run is a reduction on H1-H2 correlated noise, thanks to the suppression of acoustic coupling. H1 offers the best spectral improvement since S2, although it presents an increased rate of transient glitches. L1 was arguably the most problematic of the three interferometers, as it had the lowest duty cycle and variability in spectral shape: the noise floor in the band of interest for this analysis fluctuated by up to a factor 3. For the period of interest, between GPS 756259213 (Dec 24) and 757699213 (Jan 9) the duty cycle was 30% at L1, 77% at H1 and 66% at H2, for a total triple coincidence time of 92 hours (23% duty cycle).

3.3 Sensitivity and Stationarity

Figure 2 shows the root-sum-square amplitude required for a test waveform to have signal-to-noise ratio SNR=1 in each detector over the analysis period. The test waveform is a sine-Gaussian of the form

$$h(t) = h_0 \sin\left[2\pi f_0 (t - t_0)\right] \mathrm{e}^{-\frac{(t-t_0)^2}{\tau^2}} , \tag{1}$$

with central frequency $f_0 = 900$Hz and $\tau = 2/f_0$, corresponding to quality factor $Q = 8.9$. The SNR ρ is defined, according to [22], as:

$$\rho = \left[4 \int_0^{\infty} df \, \frac{\left|\tilde{h}(f)\right|^2}{S(f)} \right]^{1/2} \tag{2}$$

where $S(f)$ is the single-sided detector noise[2]. The root-sum-square amplitude h_{rss} is defined as:

$$h_{rss} = \left[\int_{-\infty}^{\infty} dt \, |h(t)|^2 \right]^{1/2} = \left[2 \int_0^{\infty} df \, \left|\tilde{h}(f)\right|^2 \right]^{1/2} \tag{3}$$

The actual amplitude or SNR at which a signal is detectable with a specified efficiency depends on the details of the search algorithm, on the non-Gaussianity of the data and on the thresholding scheme, which in turn is regulated by the allowed false alarm rate and by the bias we allow on the estimated event parameters (amplitude and arrival time). Knowledge of the minimum detectable amplitude as a function of time will be essential to define the actual live time of a measurement at a given threshold, as an additional data selection criterion after all data quality requirements are satisfied.

3.4 Data Quality Criteria

Prior to the data exchange and coincidence analysis, a data quality assessment must be performed within each experiment. In the following we describe the strategies traditionally adopted by the two projects.

- **AURIGA**: *first level vetoes* are time intervals when the detector is not operating or when the acquisition is interrupted by maintenance operations (cryogenic, electronic, etc.). None of these occurred during AU1. *Second level vetoes* can be applied in a second step, on the basis of data quality monitors (e.g. Gaussianity of data) or considerations about efficiency; we shall try to limit the use of second level vetoes.

- **LIGO**: there are multiple levels of data quality criteria applied to the LIGO data. The first cut takes place online, in the control room, where the operators define data to be in *science mode* if a set of requirements on a number of figures of merit is satisfied. Most notably, the inspiral range, defined as the distance to which we would be sensitive to a neutron-star binary system, needs to be above a pre-defined threshold. Data quality flags are then raised offline in a second step, in correspondence with pathologies that have been identified by the detector characterization team (see for instance [11]). These two levels of data quality assessment define a set of time segments that can be used in the analysis. A third level of veto is applied when coincident transients are simultaneously identified in the gravitational wave channel and in auxiliary diagnostic channels.

From current information on data selection criteria, we expect no more than 92 hours of simultaneous observation with 4 detectors (AU-L1-H1-H2) and no more than 175 hours with 3 detectors only (mostly from the combination AU-H1-H2).

[2]With this convention, the variance of the noise with power spectral density $S(f)$ is given by $\sigma^2 = \int_0^{+\infty} S(f) df$

4 Analysis Procedures

In this section we describe the analysis proposed by the JWG. Details are provided on the methods, the algorithms, and their current status.

The fundamental idea for a network search is to compare the information from the different detectors through a conveniently chosen *test statistic*. We also need a reliable estimate of the background (off-source) distribution of the test statistic, to be used as reference when estimating the significance of the measurement. In principle, the reference distribution of the test statistic could be known theoretically. In practice, since the detectors are non-stationary, it needs to be computed numerically through a *resampling*[3] procedure, which consists of computing the test statistic on a different data set with the same statistical features as the original one. We accomplish this by shifting the time axis of one or more detectors by an un-physical delay, which is larger than the maximum light travel time between detectors but small enough to preserve stationarity.

Given the measured test statistic and its estimated background distribution, one can set a confidence interval, for instance, on the number of gravitational waves that crossed a minimum number of detectors within a given time period.

The interpretation of the final result requires assumptions on the source properties: location, polarization angle, and waveform. In order to calibrate the results and their statistic, we compute the detection efficiency for selected signal classes and source distributions using Monte Carlo methods. Alternatively, we can optimize the search by making some assumptions on the source characteristics.

In this context, we propose two alternative pipelines. The first is optimized for a target source direction and polarization, with the assumption that different angular combinations will be probed in order to map the sky. The second one makes no assumptions on source direction or polarization, and only assumes an upper bound on the signal duration. The level of dependence (or *correlation*) of the results obtained by the two pipelines will be tested on the same resampled data produced for the background estimation (see for instance the final discussion in [3]). We will then explore the possibility of combining them into a single result.

The actual analysis setup will require some tuning on real data. We plan to perform a *blind search* to avoid biases due to *a posteriori* choices, which would jeopardize the statistical interpretation of the results[4]. This could be accomplished by inserting an un-physical delay (unknown to the analyst) between the detector responses. The analysis of the zero-delay data would be performed only at the very end, after all tuning has been fixed. This approach presents the advantage of reproducing the statistical features of the full data set. However, the JWG can adopt the method currently used by the LSC and perform all tuning and analysis choices over a *playground* data set (600 seconds of data sampled every 6370 sec, covering 10% of the full set).

---

[3]In this context, the term *resample* is drawn from the mathematics/statistics language, not to be confused with the similar term in signal processing language. It means to *get a new statistical sample*, either from the data or from a simulated ensemble suggested by the data.

[4]The concept of a *blind search* is used as opposed to *exploratory search*. In an *exploratory search* the experiment is tuned on the basis of its results in an attempt to improve the compliance of the results with some priors of the experimentalists. With this procedure, however, the statistical interpretation of the final results is very difficult and is practically lost. The *blind search* method has been adopted by high energy physics experiments such as BABAR [5]. In the case of gravitational wave detection, since it is generally expected that the first detection will be made just on the basis of statistical rarity, the adoption of *blind searches* seems mandatory.

4.1 Method 1: Trigger-Based Directional Analysis

The first proposed approach is a trigger-based directional analysis that follows the main guidelines of the IGEC procedure [3]. Data collected at each detector site is analyzed locally, taking into account environmental disturbances and data quality issues. Lists of burst candidate events are produced and vetted independently by each Collaboration.

In order to produce a meaningful comparison between different detectors and perform a directional analysis, the exchanged quantities need to comply with standardized definitions. The minimal set of quantities to be exchanged includes the event peak time, a calibrated amplitude, which from now on we will label A, and their errors. In addition, it is important to also exchange the sensitivity of the detectors at all times. We refer to this quantity as A_T, the minimum detectable amplitude, i.e. the amplitude above which the event parameter estimation is trustworthy (this can be estimated with negligible bias). Only events with amplitude exceeding A_T will be exchanged.

The definition of the calibrated amplitude A is a particularly delicate point. In the IGEC analysis, which only included bar detectors with similar narrow-band sensitivity and orientation, events were identified by matched filtering the whitened data with a δ-function template. The filter provided an optimal estimate of arrival time and calibrated amplitude. In the AURIGA-LIGO network, the situation is complicated by the fact that some of the detectors are broad-band and more freedom in the choice of templates is needed. The JWG is exploring different approaches. In a template-based analysis, the event amplitude would first be estimated by the event trigger generator in the frequency range where each detector is sensitive (narrow-band for the bar and broad-band for the interferometers). For each template, this quantity can be scaled into a calibrated amplitude to be used in the network coincidence. Alternatively, a completely template-less search can be performed in the narrow band where all detectors have comparable sensitivity (850-950 Hz), although this would constitute a limitation for the LIGO interferometers, whose best sensitivity is at lower frequencies. A third possibility is to make general assumption on the shape of the waveform, such as smoothness or asymptotic spectral slope at high frequency, in order to use all out-of-band LIGO events and extrapolate the narrow-band component of the signal that is to be used in the network analysis.

The JWG plans to adopt the parameter estimation technique first introduced in the LIGO burst analysis [13], where the event time is estimated through a maximum likelihood fit and the band-limited event amplitude $A_{measured}$ is defined as the square root of the excess power, in this case band-limited to 850-950 Hz[5].

The exchanged data (time and $A_{measured}$ for each event and A_T at all times) are fed into the network coincidence module that is optimized for a given direction (the Galactic Center is a good starting point, but the complete analysis would explore different directions, to map the sky) and signal polarization[6]. The key point is to apply to $A_{measured}$ an antenna pattern correction for the chosen direction and polarization (this correction is a function of time), and obtain the corresponding A_{source}, a quantity that can be directly compared in all detectors. In order to enhance the detection confidence, the live time is constrained to periods when A_T, scaled by the antenna pattern factor, is comparable between detectors, as exemplified in figure 3 and its caption[7].

[5] The LIGO power spectral density can considered approximately flat. Hence, the comparison with AURIGA estimates will be done by computing the event parameters using band-limited LIGO data, using the AURIGA power spectral density to shape the band-pass filter.

[6] IGEC involved only co-aligned bar detectors, therefore the source polarization did not need to be taken into account.

[7] Even with no antenna pattern correction, this data selection step would be necessary to compensate for fluctua-

The final test statistic is the number of coincidences between a minimum number of detectors (for instance, three out of four); the result thus depends on the temporal separation of the candidate events with A_{source} above a given threshold in different detectors.

In summary, three new aspects will make this analysis different from the IGEC one:

1. the polarization angle of the wave can not be neglected, as one could do with almost parallel and identical detectors;

2. the power spectral density of the detectors are significantly different;

3. the ability to search without a target template, at the cost of reduced power of wide-band detectors.

4.1.1 Software Requirements

Triggers are produced by the experiments separately and no further code development is needed on top of what each group is already doing.

- **AURIGA**: AURIGA is currently testing a template-less search algorithm based on the Karhunen-Loeve decomposition [14, 15], which would be on a similar footing as the algorithms used by LIGO. However, for this first coincident analysis AURIGA will continue to use its classical max-hold search on the Wiener-Kolmogorov optimal filter output. Since this algorithm requires the specification of a template, AURIGA will use a small bank of templates representative of the properties of signals of interest *within its bandwidth*. For the purpose of interpretation of results, efficiency for a wider class of interesting signals will be quantified (see discussion in section 6).

- **LIGO**: on the LIGO side, the all-sky burst search is being performed with WaveBurst [16], run in a configuration that only produces triple coincident events. The analysis we propose benefits from the availability of all single-interferometer triggers, which implies the need for a trigger production different from the standard LIGO burst search. There are currently a few options, which will be decided on depending on the status of the algorithm validation. One option is to use the new release of WaveBurst, which can produce triggers from a single interferometer. TFclusters is a viable alternative, as well as the Q-pipeline and KleineWelle, two multi-resolution algorithms that also can produce single-interferometer triggers [17].

The parameter estimation code is currently being debugged and validated within the LIGO burst group and should be available by the end of October. The post-processing code that was used in IGEC will need to be edited for the scope of the AURIGA-LIGO analysis. Finally, for the estimation of $A_{50\%}$ we are planning to use the BurstMon algorithm in LIGO and an equivalent code in AURIGA, if they will be available by the end of October. Alternatively, we will perform the estimation of the detector sensitivity versus time from the spectrum, as it was done to produce the plots in figure 2.

4.2 method 2: All-sky triggered search

The alternative analysis pipeline follows the "eyes wide open" approach typically used in the LIGO burst analyses [18], where no assumptions are made on the event waveform, polarization, or direction. We plan to implement it as a coherent search within the LIGO interferometers triggered by the AURIGA events.

---

tions of the detector sensitivity.

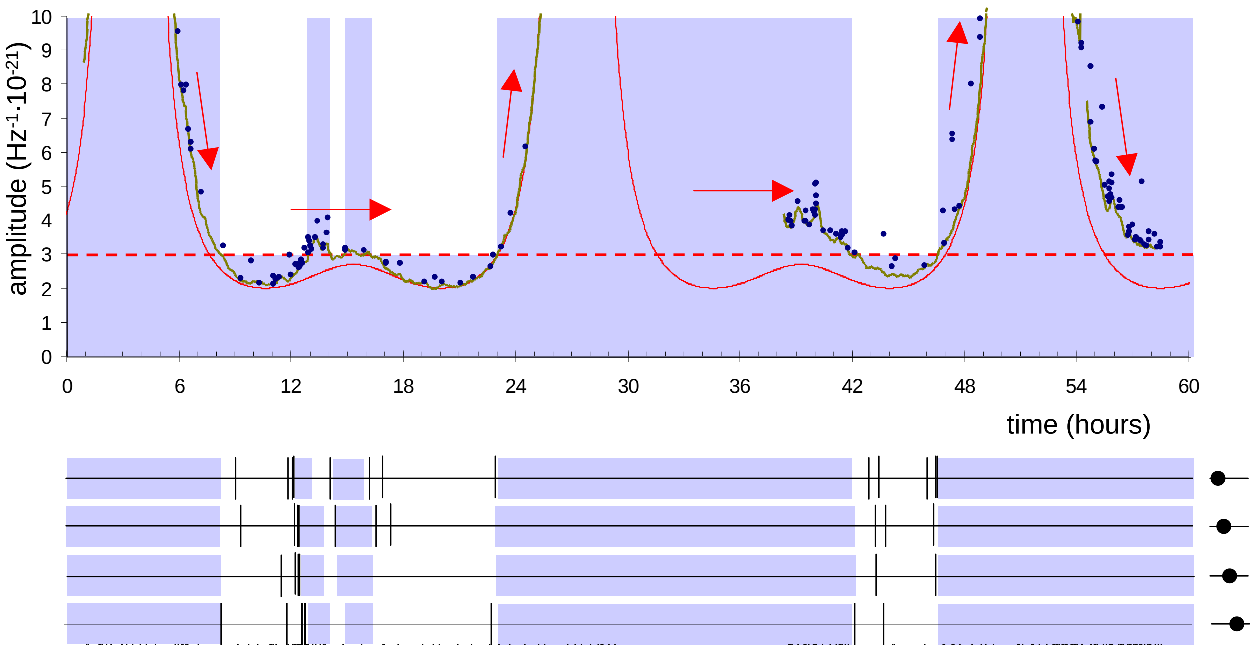


Figure 3: Trigger-based directional analysis: (*top*) illustration of the proposed data selection mechanism over a period of a few hours, using the AURIGA antenna pattern. In this example, the amplitude A is the spectral density of gravitational wave strain at a frequency $\sim 900Hz$, assuming one direction (the galactic center), and neglecting polarization, although this is not restricting for the purpose of illustration. The *dots* represent the measured event amplitudes after angular sensitivity modulation (A_{source}). Only events with A_{source} above a fixed common absolute threshold (*dashed line*) are retained. Periods when the local detector threshold (*solid jagged curve*) is above the common threshold are removed from the observation time (*vertical solid shadows*). This generates the "on-source" time series (*bottom, first row*). To obtain resampled ("off-source") event selections (*bottom, under the first row*), the local time coordinate at the detector site is shifted by a given amount (*arrows*). Note that the background event density drops exponentially toward larger amplitudes. The event amplitude density is more or less constant in time *relative to the local threshold*, but it is highly non-stationary *with respect to the fixed common threshold*. In fact almost all events are cut out by the selection mechanism except for when the local threshold approaches closely the common threshold from below –i.e. near the edges of the live time spans. The angular sensitivity modulation enhances this mechanism of artificial clustering. The described resampling procedure preserves the correlation pattern.

AURIGA will provide a list of events produced with the δ-matched filter and LIGO will perform a search around those times with *CorrPower*, a cross-correlation algorithm developed for detecting excesses of coherent power between the three LIGO interferometers [19].

This procedure has the potential to optimize the detectability of signals that are weaker in LIGO than in AURIGA due to antenna pattern orientation. For example, the antenna pattern plots in figure 4 show that AURIGA is sensitive to a larger fraction of the sky than the LIGO interferometers; signals from the shadowed region could be detected by AURIGA but not by the LIGO trigger analysis, or they are more likely to be detected in the LIGO "sweet spot" than in the 850-950 Hz band.

CorrPower will report an estimate of the coherent component of the power of the event, which is good within 50%, not enough for an accurate directional analysis. We may repeat the procedure of method 1 for a directional analysis, however this method is intrinsically more suited for an "all-sky" search, where no assumptions are made on the relative amplitude of the LIGO and the AURIGA events.

The detection efficiency will be determined through Monte Carlo simulations, which will assume either an isotropic or a galactic-plane population model, as is typically done in the LIGO burst search [18, 20].

4.2.1 Software Requirements

AURIGA will be using the well-tested match filtering code with a delta function, so no further coding will be needed. The *CorrPower* code is currently in debugging mode and is expected to be operational by the end of October. The simulations for threshold setting and efficiency determination will be performed through the MDC-frame mechanism used by LIGO.

5 Expected performances

Figure 4 shows the directional sensitivities for the AURIGA, Livingston, and Hanford detectors averaged over the polarization angle: $\sqrt{F_+^2 + F_\times^2}$. Although these plots give a general idea of what regions in the sky the detectors are most sensitive to, they should not be used to determine whether a signal is detectable simultaneously by more detectors. In fact, since gravitational waves bursts are expected to be polarized signals, the directional sensitivities should be compared separately for each polarization. While a more complete study is ongoing, figure 5 already shows the temporal variation of the directional sensitivities for two sample orthogonal polarizations, for sources from the Galactic Center, the first target direction of the coincidence search using method 1. The detector with the best orientation for a given polarization changes in time and the overlap time for coincidence analysis is reduced to a fraction of the sidereal day.

In order to quantify the daily coverage of the Galactic Center direction for signals with random polarization, we compute for each detector pair and as a function of the signal amplitude the fraction of sidereal time selected according to the rules of the coincidence method 1. Figure 6 shows the resulting efficiency under the simplifying assumption of equal and stationary detector thresholds. The efficiency gets close to 1 only for high ratios of signal amplitude to threshold, and drops to zero as the signal amplitude approaches the threshold. In addition to this calculation, we need to perform end-to-end Monte Carlo simulations to determine the detection efficiency of the network. Waveforms which have most of their power centered around the resonant frequencies of AURIGA will be chosen when performing these simulations. Examples of such waveforms are the Lazarus black hole merger waveforms for a pair of 15 solar mass black holes and black hole ring-downs, as well as ad hoc waveforms, such as sine-gaussians and damped sinusoids (see Section 6).

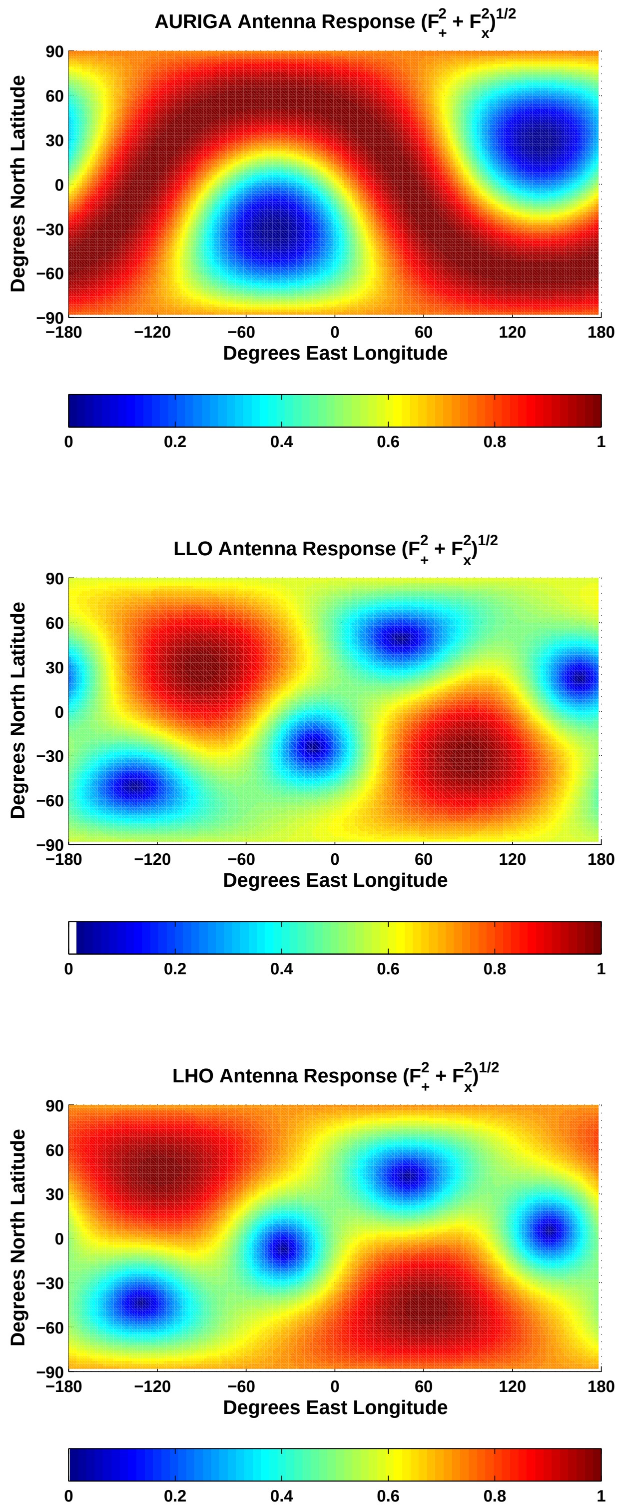
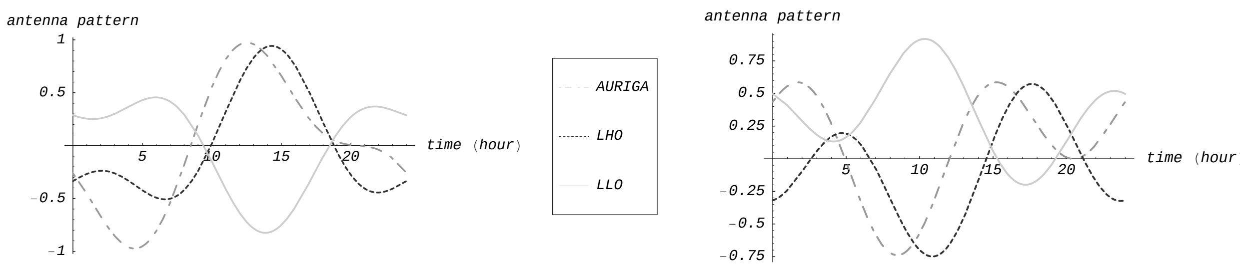


Figure 4: Amplitude directional sensitivities averaged over polarization ($\sqrt{F_+^2 + F_\times^2}$), in Earth-based coordinates.



(a) (b)

Figure 5: Directional sensitivities of LHO, LLO, and AURIGA for the Galactic Center during the sidereal day Sep 23 2004. The two plots refer to two independent polarization components: (a) $\times$-component is along the projection of the Earth rotation axis on the wavefront; (b) + component is oriented 45° clockwise as seen looking at the source.

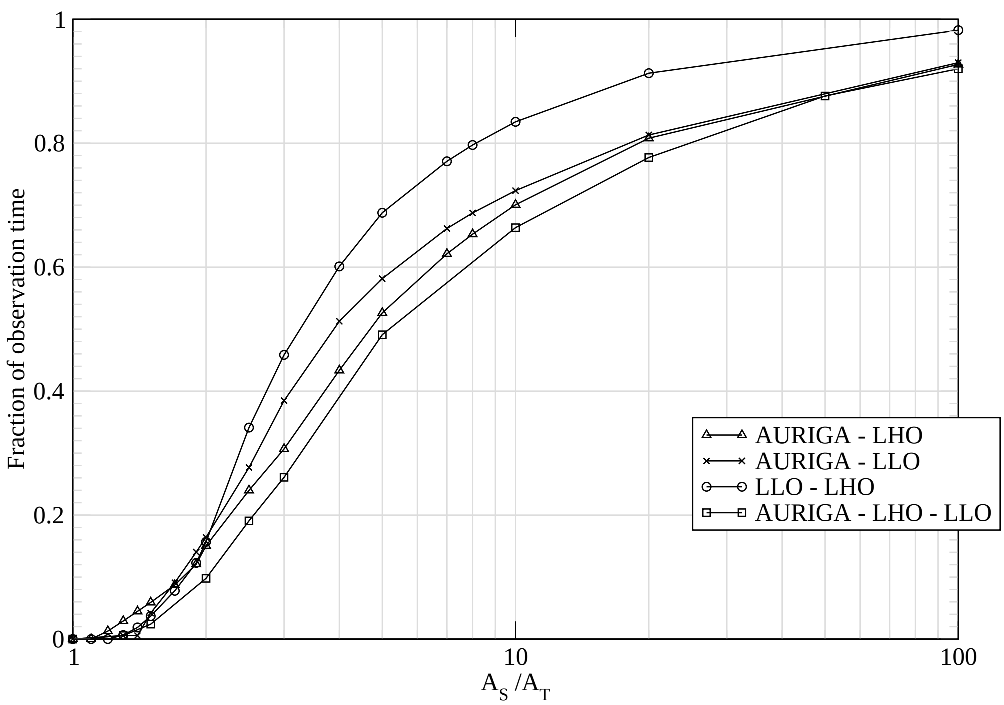
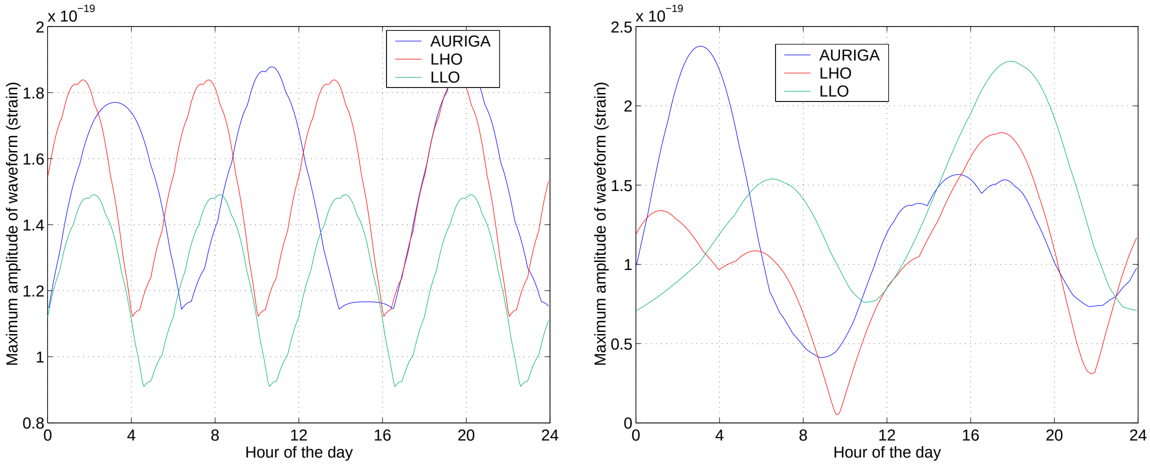


Figure 6: Directional efficiency for various combination of detectors as a function of the signal amplitude A_S for the case of Galactic Center direction, uniformly distributed polarization, and equal detector thresholds. The directional efficiency is expressed as the fraction of the sidereal day that can be used for the coincidence search, averaged over the possible signal polarization. The signal amplitude is normalized to the detector threshold A_T.



(a) (b)

Figure 7: The peak signal amplitude observed by AURIGA, LHO, and LLO for a Lazarus black hole merger waveform for a pair of 15 solar mass black holes (circularly polarized) at a distance of 1 megaparsec. Figure *a* shows the detector responses for a source location with a polarization angle of 180 degrees (the south pole) where AURIGA observes a larger peak response than LLO for 80% of the day. Figure *b* shows the detector response for a source location with a polarization angle of 85 degrees (near the equator) where AURIGA observes a larger peak response than LHO for 62% of the day.

The inclusion of AURIGA observations can potentially increase the sky coverage of LIGO. There are source directions and polarizations for which AURIGA is more sensitive than either of or both LIGO detectors over a 1 day cycle. Examples of such sky locations are illustrated in figure 7, where AURIGA observes a larger signal than one of the LIGO detectors for a significant portion of the day. For these figures, Lazarus black hole merger waveforms (polarization angle of 45 degrees) for a pair of 15 solar mass black holes at a distance of 1 megaparsec were projected to the detector locations of AURIGA and the two LIGO sites. In figure 7a, the peak signal amplitude observed at each detector for a source location with a polar angle of 180 degrees (Earth's south pole) over 24 hours is plotted. In this direction, AURIGA observes a larger peak signal amplitude than LLO for about 80% of the day. If we consider a source location with a polar angle of 85 degrees (almost at Earth's equator), the peak signal amplitude observed by AURIGA, as plotted in figure 7b, is larger than that observed by LHO for 62% of the day.

With this in mind, we can perform a triggered search where a trigger observed by AURIGA is used as an indicator to perform a more thorough search in LIGO data around the time of the AURIGA trigger. The search parameters of the *CorrPower* would be tuned to dig deeper into the LIGO noise curve and the threshold will be lowered. Simulations and signal injections will need to be performed to characterize this kind of triggered analysis and allow for the *CorrPower* search parameters to be re-tuned *a priori.*

Given the sensitivities shown in figures 2 and the short duration of the overlapped observation time, we can expect to improve the previous IGEC rate versus strength upper limit on incoming gravitational wave bursts only for amplitudes for which the current limit is of the order of 1 event per day or larger[8] However, the actual improvement will depend strongly on the measured false alarm rate.

6 Template Waveforms

The AURIGA burst search has traditionally used δ-pulses both in Monte Carlo simulations and event searches [12]. The LIGO burst group has instead adopted ad hoc Gaussian and sine-Gaussian waveforms to tune its search algorithms, and astrophysically motivated waveforms from the supernova catalogs [7, 8, 9] and the Lazarus project [6] to estimate the efficiency of the analysis and interpret the results [20].

For the scope of the AURIGA-LIGO network analysis, the focus will be on a class of waveforms with significant power in the AURIGA band. This set will include both linearly and circularly polarized signals, which is important for testing the robustness of our coincidence and cross-correlation techniques.

We plan to start with a set of waveforms with a fixed set of parameters (amplitude, direction, polarization) in order to validate the simulation procedure and understand the effects of the antenna pattern and thresholding scheme used in the efficiency estimation. Ultimately, though, the simulations should be performed using random polarization angles and (for the all-sky search) a source distribution over the entire sky.

The exchange of injection signals will take place using the so-called mock data challenge (MDC) frames. These are frame files that contain the simulated gravitational-wave burst signals as they would be seen by each detector. That is, the gravitational waves are projected onto the antenna patterns of each of the detectors and time-shifted by the appropriate delay to account for the sky direction of the source. For the LIGO detectors, the signals are also inverse-calibrated into AS_Q counts using the most up-to-date version of the calibration. In each case, the channels are sampled at the rate of the corresponding detector. To include these simulations in an analysis, the MDC data for the appropriate detector(s) are simply added to the raw detector data stream(s) before they are analyzed.

Following is the list of waveforms we are planning to use in the AURIGA-LIGO joint analysis.

6.1 Gaussians and Sine-Gaussians

Gaussians and sine-Gaussians are *ad-hoc* waveforms, with no specific astrophysical meaning, but they are very useful for reference and tuning of the analysis algorithms. The detection efficiency for these waveforms is also particularly simple to understand, as they are linearly polarized.

The standard format for the Gaussian waveforms adopted by LIGO is

$$h_+(t) = h_{peak}\, \mathrm{e}^{-(t-t_0)^2/\tau^2}\,, \tag{4}$$

$$h_\times(t) = 0\,. \tag{5}$$

Although these waveforms are not particularly well-suited for AURIGA, as they are broad-band, we are still planning to use them, as they are a standard reference function. We select $\tau = 0.2$ms, for which the maximum fraction (5%) of the signal energy is in the [850, 950]Hz band.

Most of the tuning will be performed using sine-Gaussians of the form

$$h_+(t) = h_{peak}\, \mathrm{e}^{-(t-t_0)^2/\tau^2}\, \sin(2\pi f_0(t-t_0))\,, \tag{6}$$

$$h_\times(t) = 0\,, \tag{7}$$

[8] See figure 14, page 13, in reference [3].

where $f_0 = 900\,\text{Hz}$, $\tau = 2/f_0 = 2.2\text{ms}$ and $Q \equiv \sqrt{2}\pi f_0 \tau = 8.9$. Such waveforms are standard for the LIGO burst analysis [20]. The central frequency is set in the middle of the band of interest for the joint analysis.

6.2 Damped Sinusoids

Damped sinusoids are also, technically, *ad-hoc*, but they are expected to be representative of the generic behavior of perturbed systems, such as ringing black holes in their late stages. There should be some overlap with the Lazarus waveforms (below) for appropriate choices of central frequency and damping time, so these may be somewhat redundant; we will decide whether to include them in the set of interpreted results as time and practical considerations allow.

The form of the damped sinusoids which we will use is:

$$h_+(t) = h_{peak}\,\frac{1}{2}(1+\cos^2\iota)\,e^{-t/\tau}\,\cos(2\pi f_0 t+\delta) \qquad t \geq 0\,, \tag{8}$$

$$h_\times(t) = h_{peak}\,\cos\iota\,e^{-t/\tau}\,\sin(2\pi f_0 t+\delta) \qquad t \geq 0\,, \tag{9}$$

where δ is an arbitrary phase and ι is the inclination angle of our (presumed rotating) perturbed system to the line of sight.

As for the sine-Gaussians, we will use a central frequency of $f_0 = 900\text{Hz}$, which is in the middle of our analysis band. The signal bandwidth approximately matches our analysis bandwidth of 100Hz for damping time $\tau = 3\text{ms}$; we will test $\tau = 3\text{ms}$ and $\tau = 6\text{ms}$. For a black-hole ring-down, these correspond to masses and spins of approximately $(M, a) = (25M_\odot, 0.9)$ and $(M, a) = (30M_\odot, 0.98)$ respectively [21, 22].

6.3 Lazarus Black-Hole Mergers

The Lazarus waveforms [6] are from numerical simulations of the merger and ring-down of binary black holes. The characteristic frequency of a Lazarus waveform for black-hole mergers is about half that of the corresponding ring-down:

$$f_{char} \sim (10M_\odot/M)\,1400\,\text{Hz}\,. \tag{10}$$

Masses in the $10-20M_\odot$ are the ones which put the largest fraction of their energy (5-20%) in $[850, 950]\,\text{Hz}$, the band of interest for the AURIGA-LIGO joint analysis.

These merger waveforms are of particular interest since they are motivated by astrophysics, and their sources should be detectable to Mpc distances with the S3 data.

6.4 Supernovae

The LIGO full-band sensitivity to waveforms from the Zwerger-Muller [7] and Dimmelmeier-Font-Muller [8] catalogs will likely be $\sim 1\,\text{kpc}$ or less, and worse for the Ott-Burrows-Levine-Walder waveforms [9]. Although we will conduct exploratory work with them, we consider these waveforms a lower priority for the AURIGA-LIGO joint analysis, and we don't commit to doing large-scale simulations with them.

7 Protocol for Data Exchange

The previous sections provided a general description of the analysis, with reference to quantities that will need to be exchanged. In this section we summarize the information into a protocol for data exchange.

1. **candidate event triggers.** LIGO and AURIGA will exchange burst candidate event triggers detected by their respective search algorithms. Standardized quantities will be provided for each event, such as the arrival time, the band-limited amplitude A, and their errors, as described in section 4.

2. **sensitivity vs time.** LIGO and AURIGA will exchange minute-trend information on the detector's sensitivity. This quantity is chosen as A_T, to be estimated with Monte Carlo simulations (using LIGO's BurstMon and an equivalent code for AURIGA, if they are ready in the proper time frame) or computed from first principles from the spectrum, as shown in figure 2. This information will be used in the directional analysis method described in section 4.1.

3. **simulation frames.** These are standardized frame files containing simulated waveforms as they would appear in the LIGO interferometers or in AURIGA for events according to a predefined source population, as described in section 6. They will be produced by LIGO, using the same software currently used for LIGO simulations. The waveforms contained in these files will be added to the detector noise and analyzed according to the procedures defined in section 4.

All intermediate results of the analysis will be shared within the Joint Working Group.

8 Code Validation

As stated in the MOU, the software to be used in the joint analysis is open to each party to this agreement for cross validation and consistency in the output results.

The event search algorithms are independently validated within each collaboration. A reciprocal validation will be performed through a set of standardized tests, among which is a performance estimation with simulated data (MDC frames) and white Gaussian noise.

All other code written by the JWG for the post-processing analysis and antenna pattern computations will be archived in a CVS repository and will undergo a careful scrutiny, including a "walk-through."

9 Divulgation of Results

As stated in the MOU, the formal presentation and publication of results from the joint data analysis effort are subject to prior approval by both the AURIGA and the LIGO Collaboration, through the AURIGA and LSC Spokespersons and the LIGO Director. The advance approval requirement includes invited talks, seminars, colloquia and conferences.

The AURIGA Spokesperson and the LIGO Director agree to notify and receive each other's approval prior to initiating work on any manuscript for publication that involves results from the AURIGA-LIGO coincidence data analysis. Once results of the joint AURIGA/LIGO data analysis are in the public domain, they may be freely used.

At the time of publication, the AURIGA and LIGO leaderships will establish their own contribution to the authorship for joint AURIGA/LIGO scientific publications.

References

[1] LIGO-M040010-00-M

[2] LIGO-M040191-00-M

[3] P. Astone et al.(IGEC collaboration), "Methods and results of the IGEC search for burst gravitational waves in the years 1997-2000", Phys. Rev. D 68 (2003) 022001, also on astro-ph/0302482

[4] P. Sutton *et al* "Upper Limits from the LIGO and TAMA Detectors on Gravitational-Wave Bursts" - in preparation

[5] F.C.Porter (BABAR collaboration), "Statistical issues in particle physics - a view from BABAR", Proc. PHYSTAT2003, eds. L.Lyons, R.Mount and R.Reitmeyer (SLAC, CA, Sept.2003) p.186; also in SLAC-R-703 eConf C030908 as WEAT002 (http://www.slac.stanford.edu/spires/find/hep/www?r=PHYSTAT-2003-WEAT002)

[6] J. Baker, M. Campanelli, C. O. Lousto, R. Takahashi, "Modeling gravitational radiation from coalescing binary black holes," Phys. Rev. **D 65** 124012 (2002) [arXiv:astro-ph/0202469].

[7] T. Zwerger and E. Muller, "Dynamics and gravitational wave signature of axisymmetric rotational core collapse," Astron. Astrophys. **320** 209 (1997).

[8] H. Dimmelmeier, J. A. Font and E. Muller, "Relativistic simulations of rotational core collapse. II. Collapse dynamics and gravitational radiation," Astron. Astrophys. **393** 523 (2002) [arXiv:astro-ph/0204289].

[9] C. D. Ott, A. Burrows, E. Livne and R. Walder, "Gravitational waves from axisymmetric, rotational stellar core collapse," Ap. J. **600** 834-864 (2004) [arXiv:astro-ph/0307472].

[10] see for instance: W.Johnson et al., "Status of the ALLEGRO detector", GWDAW-9 2004, http://lappc-in39.in2p3.fr/GWDAW9/Program.html

[11] http://tenaya.physics.lsa.umich.edu/ keithr/S3DQ/

[12] A. Ortolan et al., Data analysis for the resonant gravitational wave detector AURIGA: optimal filtering, chi-square test, event timing and reconstruction, in the proceedings of the "Second Edoardo Amaldi conference on gravitational wave experiments", (CERN - Switzerland, 1997), edited by E. Coccia, G. Veneziano, G. Pizzella, World Scientific, Singapore (1998) p. 204.

[13] See Chapter 37.1 of http://www.lsc-group.phys.uwm.edu/lal/lsd.pdf

[14] A. Vicere, Phys Rev D 66, 062002 (2002)

[15] A. Ortolan *et al.* "Optimal reconstruction of the input signal in resonant gravitational wave detectors: data processing algorithm and physical limitations" Phys Rev D 50 (1994) 4737-47-43

[16] S Klimenko and G Mitselmakher "A wavelet method for detection of gravitational wave bursts" 2004 Class. Quantum Grav. 21 S1819-S1830

[17] S. Chatterji et al. "Multiresolution techniques for the detection of gravitational-wave bursts" 2004 Class. Quantum Grav. 21 S1809-S1818

[18] LIGO Scientific Collaboration, "First upper limits from LIGO on gravitational wave bursts" Phys. Rev. D 69 (2004) 102001

[19] Laura Cadonati and Sz. Marka, "CorrPower: a cross-correlation-based algorithm for triggered and untriggered gravitational burst searches", GWDAW-9 2004, http://lappc-in39.in2p3.fr/GWDAW9/Program.html

[20] LIGO Scientfic Collaboration "Upper Limits on Gravitational Wave Bursts in LIGO's Second Science Run" - in preparation

[21] F. Echeverria, Phys. Rev. **D 46** 5236 (1992).

[22] E.E. Flanagan, S.A. Hughes, Phys. Rev. **D 57** 4535 (1998).

[23] http://www.auriga.lnl.infn.it

[24] J. P. Zendri et al., Status report of the gravitational wave detector AURIGA, in "Gravitational waves", proceeding of the "Third Edoardo Amaldi Conference", (CalTech - California, 1999), edited by S.Meshkov, AIP Conference Proceedings, New York (2000) p. 421-422