Status of the LIGO-AURIGA Joint Burst Analysis

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Abstract. The recently upgraded AURIGA detector and the LIGO observatory were simultaneously acquiring data for the first time in a 2-weeks period during the LIGO S3 run. This coincidence run motivated a collaborative effort to test search methods for gravitational wave bursts on real data. The adopted method uses broad-band cross correlation for the LIGO interferometers triggered by AURIGA events in the 850-950 Hz band. This paper describes the analysis technique and gives a status report on the search, with emphasis on the tuning procedure. Preliminary network performance and background estimates will be provided.

1. Introduction

The first coincidence run between the LIGO observatory and the AURIGA detector (December 24, 2003 - January 9, 2004) motivated a collaborative search for gravitational wave bursts with the goal of testing on real data methods for joint burst searches between gravitational wave bars and interferometers [1]. The main advantages of adding the AURIGA detector to the LIGO network are related to the increased confidence in case of detection and to the extended coverage of the observation time. Since AURIGA has a much narrower sensitivity bandwidth than LIGO, these advantages will be actual only for gravitational wave signals featuring a suitable spectral content in the AURIGA bandwidth.

The short duration of the coincident data acquisition, combined with the presence of un-modeled noise sources in the AURIGA detector and instrumental transients in LIGO, forces this data set to be a bench test for future, longer joint observations.

During the LIGO third science run S3 (October 31, 2003 - January 9, 2004), the sensitivity of the LIGO interferometers was better than in S2, with suppressed environmental coupling between the two co-located Hanford detectors (H1 and H2) [2]. Throughout the run, the Livingston detector (L1) was affected by a significant noise variability (up to a factor 3 in amplitude) in the frequency band of interest for the joint search ($850 - 950\,\mathrm{Hz}$). The duty cycles were 77% for H1, 66% for H2 and 30% for L1.

In December 2003, AURIGA started its first data acquisition run (December 24, 2003 - January 13, 2004) after a considerable hardware upgrade [3, 4, 5]. The most significant improvement is the enlargement of the AURIGA sensitive band [3]. However during the coincidence run, the detector output was contaminated by un-modeled noise sources featuring spurious lines in the detection band. In figure 1 the best single-sided sensitivity spectra are shown referring to the common band ($800 - 1000\,Hz$). More details on the detectors' performances during the coincidence run is given in [6], together with the general lines of the proposed joint analysis methods.

This paper is organized as follows: section 2 describes the analysis method; the exchanged data sets are discussed in section 3, while section 4 describes the tuning procedures and offers preliminary estimates of the detection efficiency and of the accidental coincidence background. The paper concludes with a list of the steps still needed to bring this analysis to completion.

2. Analysis Method

The implemented method relies on the cross-correlation of data from the LIGO interferometers triggered by the AURIGA burst candidate events [6, 1]. This search targets burst signals with detectable spectral power in the AURIGA bandwidth ($850 - 950\,\mathrm{Hz}$), such as black hole ring-downs [10] and mergers of coalescing neutron star or black hole binary systems [12], but with no *a-priori* assumption on the shape and polarization of the signal or on the source location and distance, following the "eyes-wide-open" approach typically used in the LIGO burst analyses [13]. In fact, the target signals can show a so large variety of features that we cannot focus this search to specific signal templates. In order to perform a *blind search* in the statistical sense, the analysis evolves according to the following three steps:

(i) $\sim$ 10% of the total data set has been set aside as a *playground* to test and debug the analysis pipeline in its first implementation. The playground has been selected according to the LIGO criteria [7], in order to be representative of the whole run. This data set has later been excluded from the search.

(ii) The actual pipeline tuning takes place on *off-source* data on the remaining data set. The off-source condition is achieved with relative time-slides among data from the different detectors. These time-slides are larger than the sum of the maximum light travel time between detectors (27 ms) and the maximum duration of the target signal (100 ms). In this way, off-source data maintains the statistical properties of the coincident data set and allows an empirical estimate of the accidental coincidence background. Another important ingredient in the tuning of the analysis is the detection efficiency, measured through the simultaneous addition of simulated signals in all detectors.

(iii) Once the analysis procedure and thresholds are frozen, we "open the box" and search for gravitational wave bursts in the *on-source* original data set.

This paper provides details on the second step, which, at the time of writing, is still in progress.

AURIGA contributes to the data exchange a list of triggers produced by its Event Trigger Generator (ETG) after application of data quality vetoes. The ETG searches for local maxima in the output of a Wiener filter matched to a δ signal [11]. A candidate event is issued every time the filtered data stream passes an adaptive threshold. It exploits an interpolation between discrete samples to allow more accurate estimates of the event amplitude and arrival time. Statistical fluctuations of these estimators are monitored with Monte Carlo methods[1]. The Wiener filter has been modified to take into account the spurious noise lines in the detection band by means of adaptive algorithms and band-cut filters.[2]

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[1] A MonteCarlo simulation is used to estimate the distribution of the error on the event parameters (arrival time and amplitude) and the detection efficiency for a bank of signal waveforms. The method consists of adding, in software, signal waveforms to the filtered data and to compute the residuals of differences between simulated and measured event parameters.

[2] The spurious lines are fitted as additional Lorentzian curves in the measured noise power spectral density of AURIGA. Once they are parametrized, their effect is included in the whitening filter and in the δ signal filter of AURIGA. The parametrization is evaluated on time scales of about 43 min. Small fractions of the band have been cut by means of 4^{th} order Butterworth Filters to remove the remaining spectral disturbances. The overall effective sensitivity to burst signals is about 10% worse than that achievable in absence of the spurious noise lines.

In a following step, LIGO performs a cross-correlation search between pairs of interferometers around the time of the AURIGA triggers. The cross correlation is performed with the CorrPower code [8], with three integration windows: 20, 50 and 100 ms. Each of these time windows slides with 99% overlap around the AURIGA trigger time; the closer end of each sliding window is kept within $\pm[27\,\mathrm{ms} + \sigma_t]$ of the AURIGA trigger time, where σ_t is the estimated 1σ timing error of the event arrival time in AURIGA. The statistical significance of the cross-correlation is measured by Γ_i, being $10^{-\Gamma_i}$ the significance, S [3], of the null hypothesis test (data streams not correlated) in the detector pair i. Per each trigger, the analysis consider the maximum value of Γ_i with respect to the integration windows and time slides. When more than one pair of interferometers is available, the coherent statistic is Γ, the arithmetic mean of the Γ_i from each pair [9]. Instances of Γ above a fixed threshold, around the time of an AURIGA trigger, are treated as coincident candidate events, provided the cross-correlation between the co-located H1 and H2 detector is positive (as is expected for a real signal). LIGO also provides an estimate of the band-limited event amplitude at each interferometer: we expect in the future to be able to use this information to implement an amplitude consistency check among events in H1 and in H2.

3. Exchanged data set

The LIGO-AURIGA coincident data taking covers a period of $389\,hr$ between December 24, 2003 and January 9, 2004, decreased to $352\,hr$ after playground removal ($\sim 10\%$ of the total time). However, coincidence requirements and data validation procedures (both in LIGO and AURIGA) further reduce the analyzable time to about $36\,hr$ of the $4-$fold AURIGA-L1-H1-H2 coincidence and $110\,hr$ of $3-$fold AURIGA-H1-H2 coincidence.[4]

LIGO applied the same data quality flags and validation criteria that have been implemented in the S3 LIGO-only analysis: all periods of excessive seismic activity, dust in enclosures, timing errors and DAQ overflow have been removed from the data [2].

The data validation in AURIGA is based on the result of a Monte Carlo that monitors detection efficiency and noise statistics of the candidate events in time. This procedure has been developed *ad-hoc* to address the non-stationary and the non-Gaussian excess noise specific to this run. Data with the largest deviations from the expected behavior has been discarded, at the cost of $\sim 42\%$ of the total livetime. In addition, short anti-coincidence vetoes have been applied in the presence of wide-band electromagnetic glitches, for an additional 4% livetime loss.

3.1. AURIGA events

AURIGA selected its candidate events through an adaptive threshold on the amplitude signal-to-noise ratio: SNR ≥ 4.5 [5] . This threshold level ensures a satisfactory accuracy of the estimated events parameters in case of Gaussian noise statistic. However, during this coincident data run,

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[3]

$$S = 1 - Erf\left(\mid r \mid \sqrt{\frac{N}{2}} \right), \tag{1}$$

where r is the normalized covariance of two data streams of N samples.

[4] Other triple coincidence configurations were not considered for this analysis, mostly because during S3 the L1 interferometer had the lowest duty cycle.

[5] The signal-to-noise ratio SNR is defined, according to [10], as:

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

where $\tilde{h}(f)$ is the Fourier transform of the signal and $S(f)$ is the single-sided detector noise.

the AURIGA noise performance was far from the stationary Gaussian performance recently achieved [4]. Therefore, SNR ≥ 4.5 is to be interpreted as an *empirical* threshold for the triggers to be passed to a subsequent analysis. A more plausible threshold to assure a satisfactory accuracy of the events parameters during this coincident run would have been in the range $SNR \geq 7-8$.

Each AURIGA trigger is associated to a GPS arrival time with its uncertainty (standard deviation), an SNR and, finally, the estimated amplitude (with its uncertainty) and the estimated χ^2 value with respect to the template δ signal. A total of 182516 candidate events have been exchanged by AURIGA. Of these, 31676 triggers occurred in the 4-fold coincidence time.

In this run, the average uncertainty on the estimated arrival time is $\sigma_t \simeq 10\,\mathrm{ms}$. The largest uncertainty occurs when the signal has SNR close to threshold. However, the maximum error on the arrival time is always upperbounded by $\simeq 100\,ms$[6].

During the coincidence run, AURIGA featured a significant variability in its event rate. The event time distribution is non-Poissonian: triggers are clustered with auto-correlation scales of up to 300 s. This pathological condition is due to the presence of energetic noise spectral lines which are non-stationary on these time scales [7]. This effect could only partially be removed by the adaptive filters and MonteCarlo Vetoing system described in the previous sections. Figure 2 shows the SNR distribution of all the exchanged triggers and of the triggers in the 4-fold coincidence period.

3.2. LIGO events

LIGO events are selected by setting a threshold on the cross-correlation statistic Γ. The chosen value is $\Gamma \geq 4$, to be intended as a minimal threshold for the subsequent analysis. By comparison, $\Gamma \geq 3$ would have been a reasonable choice in Gaussian noise, while the threshold used in the LIGO-only S3 analysis is $\Gamma \geq 10$, driven by the presence of broadband instrumental transients during S3. The threshold condition needs to be satisfied for at least one of the three cross-correlation integration windows (20, 50 and 100 ms). Only the events which show a positive correlation between H1 and H2 detectors are then considered.

The LIGO cross-correlation event search and exchange has so far been performed only on time-shifted data: we considered 49 data sets with un-physical time delays between LIGO-Hanford (H1,H2), LIGO-Livingston (L1) and AURIGA[8]. The time lags were randomly chosen within $(7-100\,s)$. The resulting lists of LIGO-AURIGA coincidences from all time-slides are merged in a single list of background events, whose Γ distribution is shown in figure 3.

4. Analysis tuning

At the time of this writing, the tuning procedure for the AURIGA-LIGO analysis is still in progress. We have explored the accidental background of the 4-fold coincidences and we are now analyzing that of the AURIGA-H1-H2 triple coincidences. The aim is to find a compromise between false alarm rate and detection efficiency, before actually looking at the “on-source” information. The two most important parameters to be tuned are the thresholds on SNR for AURIGA and on Γ for LIGO. An additional feature, still under investigation, is an amplitude consistency test between the band-limited event amplitude measured in the two co-located detectors H1 and H2.

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[6] AURIGA ETG selects as a candidate event the maximum of the filtered data in a sliding time window of $\simeq 100\,ms$.

[7] The energy content of these spurious lines does not agree with the fluctuation/dissipation theorem: the current interpretation is that these fluctuations were coupled to the detector by means of up-conversion of seismic and acoustic noise through non linear terms in the suspension dynamics.

[8] H1 and H2 have not been time shifted with respect to each other, in order to account for their environmental and instrumental couplings in the background estimates.

Contour plots of the background false alarms measured over the 49 time shifted data sets are shown in figure 4 as a function of the two thresholds. One false alarm event corresponds to an expected average rate of $2 \times 10^{-7} Hz$. Lower expected rates of false alarms can be achieved either by increasing the Γ threshold (e.g. $\Gamma \geq 10.5$ keeping the minimal threshold on SNR) or by increasing the SNR threshold (e.g. SNR ≥ 12 keeping the minimal threshold on Γ). These preliminary background events contour lines are conservative: the ongoing studies of an H1-H2 amplitude cut are promising for further suppression of false events.

The network detection efficiency for band limited signals has been measured using sine-Gaussians [9]:

$$h_+(t; f_0) = h_{peak}\, \mathrm{e}^{-(t-t_0)^2/\tau^2}\, \sin(2\pi f_0 (t - t_0)) \ , \ \ h_\times(t; f_0) = 0 \, , \tag{3}$$

The parameters of this waveform have been chosen so that the central frequency is centered in AURIGA's band ($f_0 = 900\, Hz$) and the bandwidth is somewhat larger than the AURIGA bandwidth, $Q \equiv \sqrt{2}\pi f_0 \tau = 9$ ($\tau = 2.2\,\mathrm{ms}$).

We performed coordinated software injections of such signals according to the LIGO burst simulation procedure, by producing signals as they would appear in the different detectors, accounting for antenna pattern and polarization effects. These waveforms are then properly scaled and added to the detectors' data. The source population is assumed uniformly distributed in the sky and signals are randomly polarized. For each trial amplitude, h_{peak}, we considered 1348 injections, one per each $64s$ data segment, with an injection time randomized in the central half segment, $[16s, 48s]$. 17 h_{peak} values have been tested in the range corresponding to $h_{rss} = 5 \times 10^{-22} Hz^{-1/2} - 3 \times 10^{-17} Hz^{-1/2}$, where h_{rss} is an integral quantity related to $h(t)$:

$$h_{rss} = \sqrt{\int_{-\infty}^{+\infty} |h(t; f_0)|^2 \, dt} \approx 1.11952 \, \frac{h_{peak}}{\sqrt{f_0}} . \tag{4}$$

As expected, AURIGA dominates the network efficiency, given that the AURIGA exchange threshold corresponds to an higher absolute gw amplitude. Figure 4 shows the behavior of the signal amplitude at which the efficiency is 50%, $h_{rss50\%}$, as a function of the thresholds on Γ and SNR. Taking as a reference the $h_{rss50\%}$ corresponding to the minimal thresholds, the efficiency loss is limited to 10% by increasing the Γ threshold from 4 to 9.3. Alternatively, the same loss is produced by increasing the SNR threshold from 4.5 to 5.1. Preliminary studies on the introduction of an H1-H2 amplitude cut show that the loss in $h_{rss50\%}$ would be at most a $5-10\%$. We do not plan to further tune the AURIGA-LIGO time coincidence window, described in Sect.2, as it already ensures a satisfactory efficiency of detection.

Given the above results the best balance between false alarms rate and detection efficiency can be reached by increasing the LIGO Γ threshold and leaving the AURIGA exchange threshold unchanged SNR ≥ 4.5. In this preliminary stage we selected $\Gamma \geq 6$ as a trial threshold for illustrating the capabilities of this network. For this trial choice of thresholds, the false alarm rate is about $8 \times 10^{-7} Hz$. Figure 5 shows the resulting detection efficiency, with $h_{rss50\%} = 5.5 \times 10^{-20}\, Hz^{-1/2}$. As a comparison, the LIGO-only bursts analysis for S3, gives $h_{rss50\%} = 2.3 \times 10^{-20}\, Hz^{-1/2}$, using the Waveburst ETG and the r-statistic test by CorrPower with threshold $\Gamma_0 = 10$ [2]. Therefore, despite the large differences in overall sensitivity and bandwidth between AURIGA and the LIGO interferometers, for this specific waveform the efficiency of the LIGO-AURIGA network results about a factor $\simeq 2$ worse than that of LIGO-only.

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[9] Cosine-Gaussians have been tested, as well, giving fully equivalent results. Other waveforms, such as dumped sinusoids and gaussians have been injected, but the results of these latter injections have not been used for the tuning of the analysis.

5. Concluding remarks

The relevance of this work is mostly methodological. The analysis targets gravitational wave bursts and is based on a cross-correlation search on the LIGO interferometers triggered by AURIGA candidate events. We reported here on the exchanged data sets, the measured background of false alarms, the detection efficiency and the tuning procedures for this analysis. The tuning of the analysis is still under investigation, in particular for the implementation of an amplitude consistency check among detected events by the two Hanford detectors. The sensitivity of the observatory as a function of the incoming amplitude h_{rss} for some standard waveforms and source population has been measured and a sample is shown on Figure 5. We are not able to accurately convert the sensitivity of this network in terms of sources, because the expected signals can show a too large variety of features. Only a rough indication on the energy and distance of the detectable source is possible: assuming uniform distribution in the sky and random polarization, the fraction of energy converted to g.w. detectable with 50% efficiency is $\varepsilon_{gw50\%} \sim 5\ 10^{-2}\ (\ d/10\ kPc)^2\ M_\odot$ for the sample burst template.

Up to now, we considered the observation time during which all the four detectors were in coincidence. We are currently performing this analysis also on the three-fold coincidences among the Hanford detectors and AURIGA. The last part of this analysis will include a test of the compliance of the on-source results with the off-source distribution of false alarms and a further investigation on any event occurring on-source to better discriminate its features. Different analysis schemes, as for instance a directional coincidence search, will also be explored. The complete results of this analysis will be part of a future publication.

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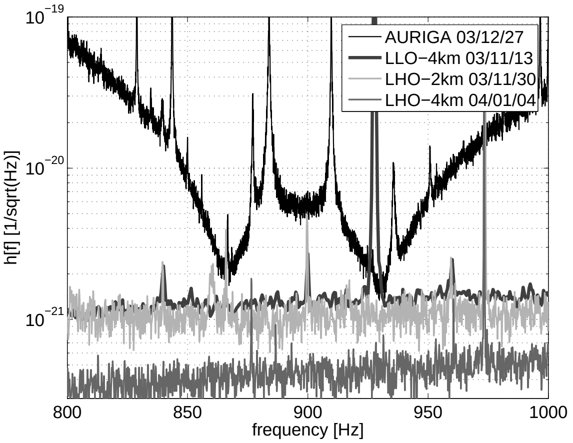

Figure 1. Single-sided sensitivity spectra for AURIGA, LH1, LH2 and LLO during the coincidence run. Only the band of interest for the analysis $(800 - 1000\,Hz)$ is shown. AURIGA spectrum was affected by some spurious lines. In the LIGO spectra, line at 973 Hz for the Hanford detectors and 927 Hz for LLO are calibration lines. Both these features have been filtered by the respective analysis of the 2 collaborations.

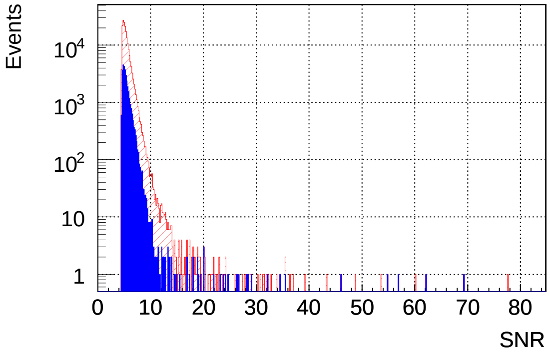

Figure 2. SNR distribution of the AURIGA triggers (SNR ≥ 4.5). Dashed histogram: all exchanged triggers (182516 events). Shadowed histogram: triggers in the periods of 4-fold coincidence (31676 events).

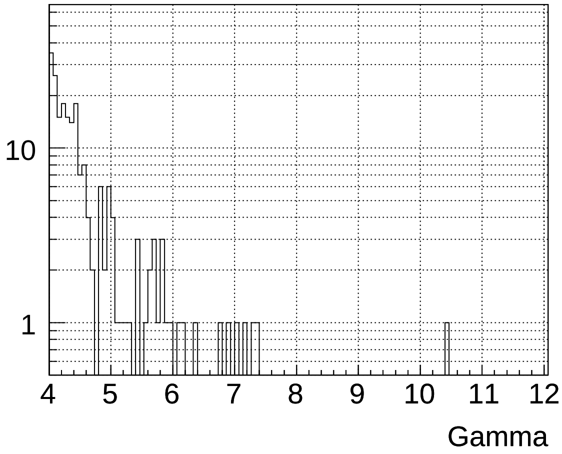

Figure 3. Histogram of the 4-fold background events of LIGO around the AURIGA triggers. The background has been estimated on 49 time shifted data sets, producing 209 coincident events over the minimal LIGO threshold, $\Gamma \geq 4$. A cut to ensure positive correlation among H1 and H2 responses has been applied.

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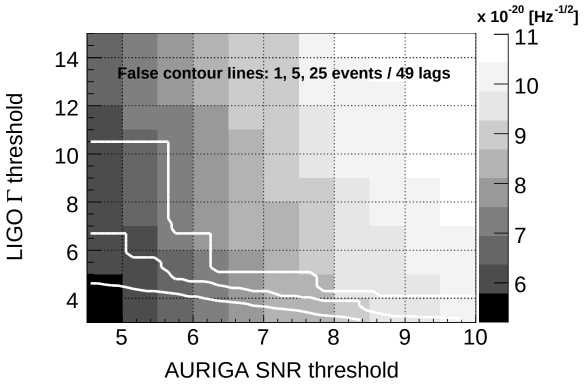

Figure 4. The gray-scale plot shows the dependence from the thresholds (AURIGA SNR threshold on the x axis and LIGO Γ threshold on the y axis) of the $h_{rss50\%}$, i.e. the h_{rss} amplitude at which the measured efficiency is 50% (units of $10^{-20}\,Hz^{-1/2}$). The contour lines show the dependence of the background false alarm rate on the thresholds, for the following values: 1, 5, 25 events over 49 time lags.

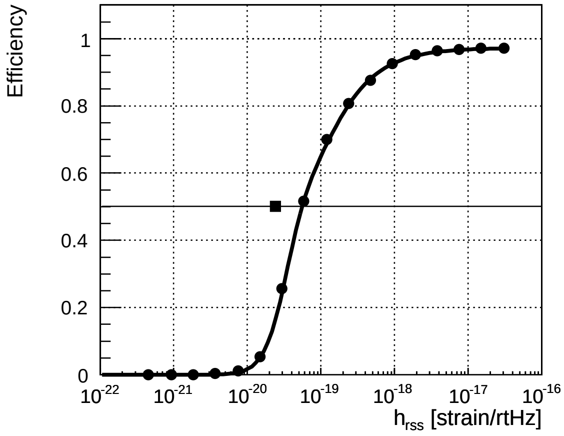

Figure 5. Preliminary efficiency of the network LIGO-AURIGA in 4-fold coincidence, using trial thresholds for SNR and Γ as described in the text. The detection efficiency is plotted as a function of the injected amplitude of the sine-Gaussians waveforms with central frequency $\nu_c = 900Hz$ and $Q = 9$ ($\tau = 2.2\,\mathrm{ms}$) and with random directions and polarizations. The square mark shows the $h_{rss50\%} = 2.3 \times 10^{-20} Hz^{-1/2}$ achieved by LIGO-only during S3.