Updates on the AURIGA-LIGO Joint Burst Search

Francesco Salemi for the LIGO Scientific Collaboration and the AURIGA Collaboration
Dip. Fisica and INFN - Ferrara
mailto: salemi@fe.infn.it

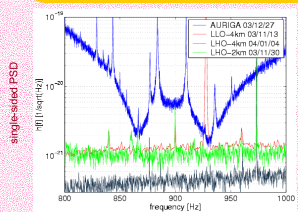
Abstract: We completed the tuning of the analysis procedures of the AURIGA-LIGO joint burst search and we are in the process of verifying our results. This analysis is the first test of methodologies for burst searches on real data within a hybrid observatory consisting of resonant and interferometric detectors. We investigated the periods of four-fold coincident operation between AURIGA and the three LIGO detectors as well as the periods of three-fold coincidence operation between AURIGA and the two LIGO-Hanford detectors during the LIGO S3 run. We describe the analysis tuning procedure and present the false alarm rate estimated on time-shifted data, the efficiency of the observatory and plans to combine the results from four-fold and three-fold coincidences.

Keypoints

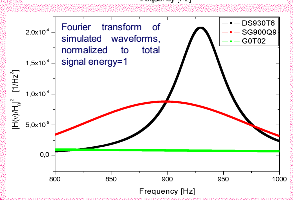
SCOPE

The first coincidence run between the LIGO observatory and the AURIGA detector motivated a joint effort aimed at a collaborative search for gravitational wave bursts. The main purpose of this analysis is to test, on real data, methods for joint burst searches between gravitational wave bars and interferometers. The short duration of the coincident data acquisition, combined with the presence of unmodeled 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.

References
AURIGA-LIGO white paper (**LIGO-T040202-00-Z**)
Proceedings paper for GWDAW9 (published on **Class. Quantum Grav. 22 (2005) S1337 - S1347; LIGO-P050011-00-R**)
Proceedings paper for Amaldi 2005 (submitted to cqg)



Single-sided sensitivity spectra for AURIGA, LH1, LH2 and LLO during the coincidence run. Only the band of interest for the analysis (800 — 1000Hz) is shown.



- Sine gaussians and cosine gaussians with ν_c = 900 Hz and Q=9 (τ = 2.2 ms)
- Gaussians with τ = 0.2 ms
- Damped sinusoids with ν_c = 930 Hz and damping time τ = 6 ms.

DATA SET

The first AURIGA-LIGO coincident data set covers a period of 389 hours during the LIGO S3 science run, between **December 24, 2003** and **January 9, 2004**. The useful time for joint observation consists of :

- **36 hours of 4-fold coincidence operation** AURIGA & all LIGO detectors
- **74 hours of 3-fold coincidence operation** AURIGA & LIGO Hanford detectors

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

Coincidence run (after removal of 10% playground data set):	352 h
After AURIGA wide-band (4%) and epoch (42%) veto:	190 h
LIGO triple coincidence (with DQ flags):	61 h
Intersection (AU-H1-H2-L1):	36 h
LIGO H1H2-noL1 (with DQ flags):	132 h
Intersection (AU-H1-H2-noL1):	74 h

THE TARGET SIGNALS

Target signals have to show detectable spectral power in the AURIGA bandwidth (850-950 Hz). **Joint software injections have been performed on 3 test waveforms** (see the plot on the left and the final table at the bottom).
To show the spectral selection due to AURIGA, we performed software signal injections with linearly polarized waveforms of different spectral shape on a more recent AURIGA data set. The signal was assumed to arrive from optimal direction and with optimal polarization.
The Table below refers to **Cosine-Gaussian pulses** (**Optimal direction and polarization**) for **5 central frequencies** in the band of AURIGA and **3 values of Q**.
The delta-matched filter has been used with an event search threshold at SNR = 4.5.
The injections have been performed on recent data of AURIGA (end of July 2005).
The detector performance was stationary and the noise was gaussian: hrss50% is almost a factor 2 better than during the coincidence run.
The detection efficiency shows significant variations as a function of the central frequency of the signal within 850-960 Hz, when the signal duration is longer than ~ 50 ms.

$hrss_{50\%}[\frac{1}{\sqrt{Hz}}]$	$f_0 = 850$	$f_0 = 867$	$f_0 = 900$	$f_0 = 930$	$f_0 = 960$
Q = 3	1.86e-20	1.85e-20	1.86e-20	1.91e-20	1.95e-20
Q = 9	1.31e-20	1.21e-20	1.13e-20	1.16e-20	1.27e-20
Q = 100	5.03e-20	9.75e-21	2.94e-20	5.81e-21	7.52e-20

THE ANALYSIS METHOD

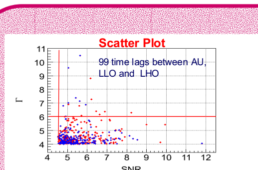
The implemented method relies on the **cross-correlation of data from the LIGO interferometers triggered by the AURIGA burst candidate events.**

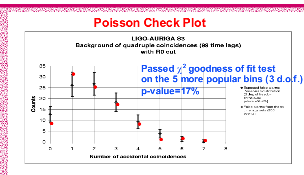
The algorithm:
1. Start from the AURIGA triggers with SNR above threshold
2. Apply r-statistic test in CorrPower :
   - cross correlation over the interval:
   Auriga arrival time ± uncertainty ± 27 ms (=flight time)
   Max AU uncertainty =100ms, typical <<100ms
   with sliding windows of 20, 50, 100 ms duration
3. Use Γ (LIGO cross-correlation statistic) to make a statement on the coherence between the LIGO interferometers.
4. Impose H1-H2 consistency criteria:
   Sign of the H1-H2 correlation (R0 cut)

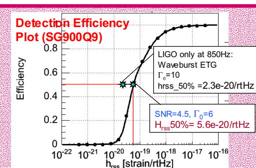
In order to perform a **blind search**, the analysis evolves according to the following four steps:

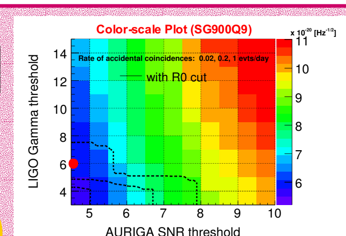
- 10% of the total data set has been set aside as a **playground** to test and debug the analysis pipeline in its first implementation. The playground has been selected according to the LIGO criteria, in order to be representative of the whole run. This data set has later been excluded from the search.
- The actual pipeline **tuning takes place on off-source data** on the remaining data set. The off-source condition is achieved with relative timeslides among data from the different detectors. These timeslides are larger than the sum of the maximum light travel time between detectors (27 ms) plus 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.
- **freeze the analysis** procedure and thresholds, **then "open the box"** and search for gravitational wave bursts in the on-source original data set.

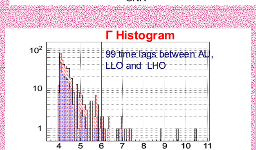
4-Fold Analysis











4-fold AU-H1-H2-L1

AU-H1-H2-L1

MEASURING THE EXPECTED RATE OF ACCIDENTAL COINCIDENCES USING TIME LAGS

- **Scatter Plots** of Γ (LIGO cross-correlation statistic) vs SNR (SNR from delta-matched filter for AURIGA triggers) for background events: Blue dots for accidental coincidences above minimal thresholds & passing the R0 cut; Red dots for accidental coincidences above minimal thresholds excluded by the **R0 cut (cut on the sign of the H1-H2 cross correlation)**
- **Γ Histograms**: Blue for accidental coincidences above minimal thresholds & passing the R0 cut; Red for accidental coincidences above minimal thresholds excluded by the R0 cut.
- **Poisson Check Plots**: We need to check if the statistics of the accidental coincidences is Poisson, to be able to use the Poisson distribution as a noise model. Red dots: histogram of the 3 and 4-fold accidental coincidences considering all the events above minimal thresholds passing R0 cut. Diamonds with error bars: fitted Poisson distribution with ± 1σ expected fluctuations per each bin.

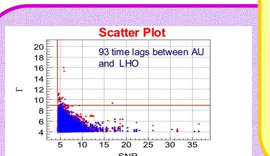
MEASURING EFFICIENCY OF DETECTION

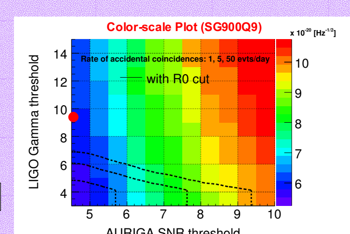
No a priori assumptions are made on the source location and on the signal polarization. Our test bench of source population is uniformly distributed in direction and polarization.

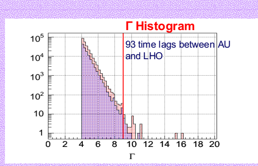
- **Detection Efficiency Plots** of the network LIGO-AURIGA in 3 and 4-fold coincidences, using the chosen thresholds for SNR and Γ. The detection efficiency is plotted as a function of the injected amplitude of a linearly polarized **SG900Q9** waveform, i.e. **sine-Gaussians** with central frequency **900Hz** and **Q = 9** (τ = 2.2 ms), and with random directions and polarizations. **Efficiency curves for the joint analysis are dominated by AURIGA**.
- **Color-scale plots** show the dependence from the thresholds (AURIGA SNR threshold on the x axis and LIGO Γ threshold on the y axis) of the **hrss50%**, i.e. **the hrss amplitude at which the measured efficiency is 50%** for SG900Q9. Red dots: indicate the chosen working points. The contour lines show the dependence of the background false alarm rate on the thresholds.

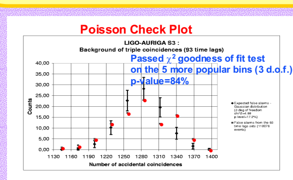
3-Fold Analysis

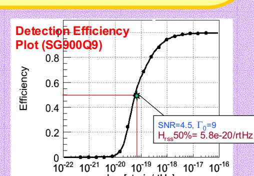
AU-H1-H2











3-fold AU-H1-H2

Concluding Remarks

AU-H1-H2-L1:
Γ>=6; SNR_A>=4.5; R0 cut;
False rate: 8 events in 3323.0 h hours
0.67±0.23 μHz (1σ error bars)
0.09±0.03 zero lag events expected

Waveform	hrss_50% [1e-20/rtHz]	hrss_90% [1e-19/rtHz]
SG900Q9+ CG900Q9	5.6 (5.3 at Γ ≥ 4)	4.9 (4.7 at Γ ≥ 4)
GA0d2	15 (15 at Γ ≥ 4)	10 (10 at Γ ≥ 4)
DS930T6	5.7 (5.5 at Γ ≥ 4)	3.3 (3.2 at Γ ≥ 4)

AU-H1-H2:
Γ>=9; SNR_A>=4.5; R0 cut;
False rate: 12 events in 6598.0 hours
0.51±0.14 μHz
0.14±0.04 zero lag events expected

Waveform	hrss_50% [1e-20/rtHz]	hrss_90% [1e-19/rtHz]
SG900Q9+ CG900Q9	5.8 (5.3 at Γ ≥ 4)	5.3 (4.7 at Γ ≥ 4)
GA0d2	15 (15 at Γ ≥ 4)	11 (10 at Γ ≥ 4)
DS930T6	5.7 (5.5 at Γ ≥ 4)	3.4 (3.1 at Γ ≥ 4)

The selected thresholds allow a comparable false alarm rate in 4-fold and 3-fold operation

The analysis has been tuned. Next step, we will look for the results from 3-fold and 4-fold coincidence observations separately as well as for a combined result for the entire observation time
Since 3-fold and 4-fold coincident operation show very similar :
efficiencies to selected signals
false alarm rates
=> near optimal combination of 3-fold and 4-fold results can be very simple:
- false alarms: just add the number of accidental coincidences and normalize to the total observation time
  false alarm rate 0.56±0.13 μHz (σ error bars)
  expected mean number of accidental coincidences in the total observation time 0.23±0.05
- Consider the worst efficiency curve to interpret the results

Remarks on the sensitivity of AURIGA LIGO joint observations.
Even though the S_h curves of the LIGO detectors have been better than the AURIGA one during S3, the resulting amplitude sensitivity of the joint search is only about a factor 2 worse than the LIGO only search (for SG900Q9). Moreover, this joint search allows also to analyse that part of LIGO observation time during which the Livingston detector was not operating.
Future searches would benefit from the impressive improvements on LIGO sensitivities during S4 and S5 and from the very significant progresses achieved as respect noise outliers on all detectors. Though, in this case, we would have to develop a new scheme for the coincidence search algorithm, since this specific kind of triggered search would not be efficient any more.

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