Search for Gravitational Wave Bursts in LIGO Science Run 2 Data

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- The S2 untriggered analysis Pipeline
- Upper limit on rate of detectable GW bursts.
- Rate limits versus Gravitational Wave strain.
Science Run 2

Improvements over S1 important for Burst Search
- 60 days of running (vs. 19 in S1)
- ~318 hrs triple coincidence (34 in S1)
- Sensitivity ~1 order of magnitude better than S1.

*S2 Science Mode Running*

<table>
<thead>
<tr>
<th>IFO</th>
<th>hrs</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>1043.7</td>
<td>73.7</td>
</tr>
<tr>
<td>H2</td>
<td>821.8</td>
<td>58.0</td>
</tr>
<tr>
<td>L1</td>
<td>536.4</td>
<td>37.9</td>
</tr>
<tr>
<td>H1·H2·L1</td>
<td>318.0</td>
<td>22.5</td>
</tr>
</tbody>
</table>
Data Selection

- Use triple coincidence science mode segments
- Data quality cuts eliminate sections with:
  - DAQ errors / Missing data
  - Non-standard/noisy IFO
  - Missing/unreliable calibration
- Pipeline inefficiencies:
  - Processing granularity
- No effective vetoes (significant reduction in single IFO triggers) found in playground.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>hours</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total H1·H2·L1</td>
<td>318.0</td>
<td>100.0</td>
</tr>
<tr>
<td>After data quality</td>
<td>304.9</td>
<td>95.9</td>
</tr>
<tr>
<td>No playground</td>
<td>277.2</td>
<td>87.2</td>
</tr>
<tr>
<td>Pipeline</td>
<td>239.5</td>
<td>75.3</td>
</tr>
<tr>
<td>After Acoustic Veto</td>
<td>237.8</td>
<td>74.8</td>
</tr>
</tbody>
</table>
Analysis Pipeline

- Use all three LIGO interferometers (H1, H2, L1)
- Wavelet domain event search using WaveBurst (WB)
- Consistency check between IFO pairs using r-statistic test
- Search in frequency band 100-1100 Hz
- Tune analysis cuts using playground sample (~10% of triple coincidence data)
- Background estimate from time-shifted data
- Upper limit calculated from the upper bound of a Feldman-Cousins interval.

![Diagram showing analysis pipeline with H1, H2, L1, Sim, WB, Delta t, Coincidence/Global Significance, and r-statistic]
WaveBurst pipeline

Wavelet transform, data conditioning, rank statistics

channel 1

channel 2,…

wavelet transform, data conditioning, rank statistics

10% bp “coincidence” bp

IFO1 event generation IFO2 event generation

Δf × Δt = 64 Hz × 1/128 sec

band 64-4096 Hz

coincidence likelihood > 1.5, cluster likelihood > 4

Threshold on combined significance of triple coincidence events.

Ref: Class. Quantum Grav. 21 (2004) S1819;
r-Statistic Test

- Waveform consistency test using r-statistic
  \[ r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}} \]
- Effectively a measure of the cosine of an angle in signal space
- Significance: \[ C = \text{erfc} \left( \sqrt{\frac{r^2 N}{2}} \right) \]
- Combine significance of IFO pairs \[ \Gamma = -\log_{10} \left( \prod_{i<j} C_{ij} \right) \]
- Unknown incident direction (\(\Delta t\)), signal duration (\(\tau\))→search valid \{\(\Delta t, \tau\)\} to maximize \(\Gamma\).
- Reference: L. Cadonati, Class. Quantum Grav. 21 S1695-S1703
Pipeline Tuning

- Pipeline tuned on ~10% “playground” sub-sample (not used in final analysis)
- Search code global significance tuned to produce ~20µHz coincidence rate.
- r-Statistic aims at ~99% reduction in final rate. Threshold set to $\Gamma > 4$.
- Expected background ~0.05 events.
Background Estimation

- Background estimated using time shifted 3-fold coincidences.
  - LLO data shifted relative to LHO data
  - 46 × 5s time shifts (5s ≤ |Δt| ≤ 115s)
  - Data time shift internal to WaveBurst and r-statistic
- Identical pipeline, cuts for all shifted data
Detectable Burst Upper Limit

- Blind procedure gives one event candidate
  - Event immediately found to be correlated with airplane over-flight
  - Airplanes have been seen to in PEM channels for ~5 years.
  - Acoustic mitigation before S3 reduced coupling.
- Background estimate is 0.05.
- Our Feldman Cousins 90% upper limit for one event would be 4.3
Airplane at LHO

LIGO-G040542-00-Z

GWDAW9 December 17, 2004
LSC is currently debating whether we can make a statistically reliable confidence limit made after a post analysis veto.

Statistical issues under discussion include:

» Does upper limit with “airplane” event adequately state the measurement we wish to make?
» Will post analysis veto necessarily cause under coverage?
» How does veto procedure affect background estimate?
» Simulation needs probability that a believable veto will be found for real GW events.

We quote the 0 foreground event limit with a band of systematic uncertainty that includes the limit inferred from one event.
**Acoustic Veto!**

- Acoustic veto based on power in 65-115Hz band in H2 PSL table microphone.
- Vetoes ~0.7% of live-time.
- Eliminates $\Delta t=0$ event and one background ($\Delta t\neq0$) event.
- Feldman Cousins 90% upper limit for 0 events over a background of 0.05 is 2.4.
- Rate upper limit = $2.8 \times 10^{-6}$s$^{-1}$ =0.24/day.
Rate Upper Limits vs $h_{rss}$

- We infer rate upper limits vs. strength for test wave-forms
  - sine-Gaussians
  - Gaussian
  - Lazarus and Zwerger-Muller (not shown here)
- Use $h_{rss}$ to indicate strength, where:
  $$h_{rss} = \sqrt{\int |h(t)|^2 dt}$$
- $R(h_{rss}) = \frac{\eta}{\varepsilon(h_{rss}) \times T}$
- We present results as a band limited by $0 \rightarrow 1$ foreground event
- Bands include 11% calibration uncertainty
Detection Efficiency vs. $h_{rss}$

- Measure test waveform efficiencies vs. $h_{rss}$
  - sine-Gaussian
  - Gaussian
- Software injections: signal added to digitize IFO output
- Hardware injection: signals added to length servo signal
- All-sky (random orientation)
- Fit to asymmetric sigmoid

Q=9 sine-Gaussian Efficiencies
Rate vs. $h_{rss}$ ($Q=9$ sine-Gaussians)
Rate vs. $h_{\text{rss}}$ (Gaussians)

- $\tau = 0.1$ ms
- $\tau = 0.5$ ms
- $\tau = 2.5$ ms
- $\tau = 1.0$ ms
- $\tau = 4.0$ ms
- $\tau = 6.0$ ms
Summary

- LIGO S2 triple-coincidence data were searched for gravitational wave burst events.
- The analysis improved on the S1 untriggered pipeline
  » A new wavelet-based search code was used.
  » The r-statistic was used to test signal consistency in the 3 IFOs.
- One event remained at the end of the pipeline
  » Event traced to an airplane flying over LHO
- An 90% confidence upper limit for detectable bursts in the 100-1100Hz band of 0.24/day was inferred from zero events (with systematic uncertainty extending to 0.43/day)
- Rate vs. strength curves were calculated for Gaussian and sine-Gaussian waveforms.