The STAMP all-sky search for long-duration gravitational-wave transients

Tanner Prestegard for the STAMP all-sky working group

University of Minnesota

October 9, 2015

LIGO-P1400138

STAMP all-sky S5/S6 paper

Paper draft on the DCC: LIGO-P1400138.

Further comments welcome!

Target journal: PRD.

Stochastic Transient Analysis Multi-detector Pipeline

- Looking for long-duration unmodeled GW transients (lasting from a few to thousands of seconds).
  - Accretion disk instabilities and fragmentation.
  - Rotational instabilities in PNS remnants, PNS convection, r-modes, and more.
- Procedure:
  - Cross-correlate data from multiple IFOs.
  - Make *ft*-maps of cross- and auto-power.
  - Parse *ft*-maps with a clustering algorithm to identify groups of pixels corresponding to GW transients.

STAMP all-sky working group:
Marie Anne Bizouard, Nelson Christensen, Michael Coughlin, Samuel Franco (graduated), Valentin Frey, Patrice Hello, Vuk Mandic, and Tanner Prestegard.

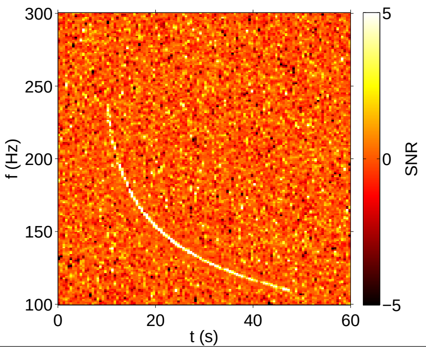


Figure 1: STAMP SNR *ft*-map, including a simulated GW signal. This is an energy SNR.

STAMP all-sky search

What:

- Use STAMP (designed for *targeted* searches) for an all-time/all-sky search.

Why:

- Search for GWs emitted without an EM counterpart.
- Search for GWs emitted by unknown/unmodeled mechanisms.

Challenges:

- Unknown source location and polarization.
- Computationally intensive.

Strategy:

- Clustering of positive and negative pixels.
- 5 randomly chosen sky positions which span the sky with ≈ 15% sensitivity loss.

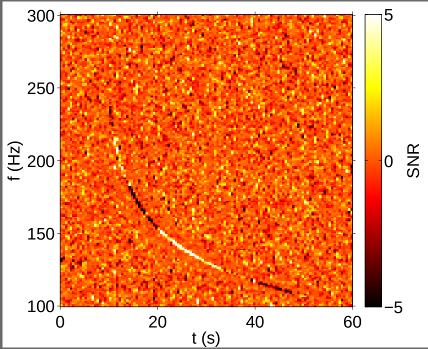


Figure 2: Recovery of a simulated GW signal when looking in the wrong direction.

Search description

Data selection:

- S5: 283.0 days of coincident H1-L1 data.
- S6: 133.2 days of coincident H1-L1 data.
- CAT 1 flags: from stochastic isotropic search.
  - Also added burst injection flags.
  - Almost identical to list used by burst all-sky searches.
- 100 time-slides from each science run.
- Data divided into 500 second-long *ft*-maps, 50% overlapping.
- Frequency range: 40 - 1000 Hz.

Data quality:

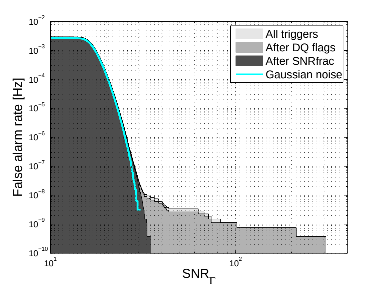
- STAMP glitch cut: checks for consistency between detectors using auto-power spectra[1].
- Frequency notches: primarily 60 Hz harmonics, violin modes, calibration lines.
  - S5: 47 1 Hz-wide bins.
  - S6: 64 1 Hz-wide bins.

[1] T. Prestegard et al., Class. Quantum Grav. **29**, 095018 (2012).

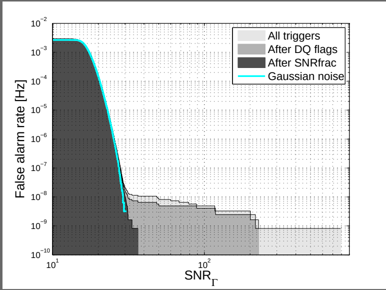
Background study results

Post-processing cuts:

- SNRfrac: veto triggers that deposit more than 45% of their power in a single time segment. Threshold tuned to maximize search sensitivity.
- CAT 2 DQ flags: chosen by estimating significance of coincidence with 100 loudest triggers from background studies. Used only for GW candidate follow up.



(a) S5, 100 time-slides.



(b) S6, 100 time-slides.

Waveform descriptions

All waveforms range between 9 - 250 s in duration and 50 - 900 Hz.

Physical waveforms:

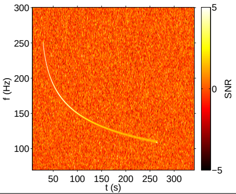
- Four accretion disc instability (ADI) waveforms[2,3].

Ad hoc waveforms:

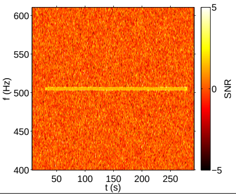
- Two monochromatic waveforms.
- Two linear (frequency-time evolution) waveforms.
- Two quadratic (frequency-time evolution) waveforms.
- Two sine-Gaussian waveforms.
- Three band-limited white noise burst waveforms.

[2] M. H. van Putten et al., Phys. Rev. D **69**, 044007 (2004).
[3] C. D. Ott and L. Santamaría, LIGO DCC T1100093 (2011).

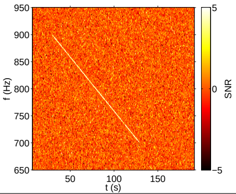
Waveform plots



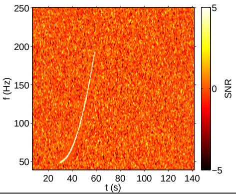
(a) ADI-C.



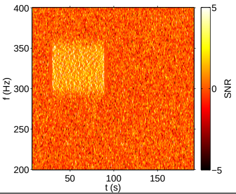
(b) MONO-B.



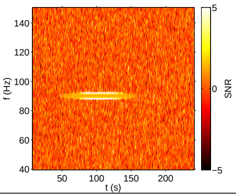
(c) LINE-B.



(d) QUAD-A.



(e) WNB-B.



(f) SG-A.

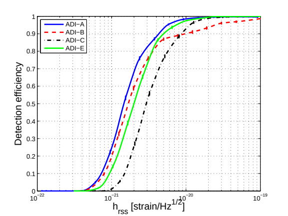
Injection studies

Details:

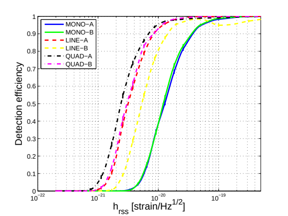
- Waveforms injected at 1500 random times in each dataset.
- Each waveform studied at 16 different signal amplitudes.
- Total: 1500 trials per waveform per amplitude per dataset.
- Random sky position and waveform polarization.

Injection study results

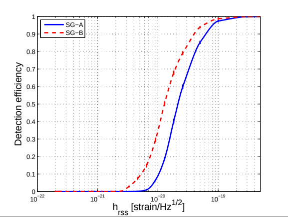
Efficiency vs. h_{rss} curves for all waveforms considered in the injection study. Curves shown are for S6 and include SNRfrac vetoes and CAT 2 data quality flags.



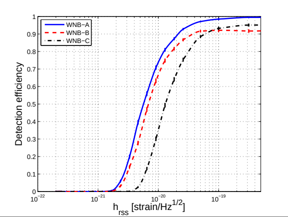
(a) ADI waveforms.



(b) Sinusoidal waveforms.



(c) Sine-Gaussian waveforms.



(d) White noise burst waveforms.

Zero-lag results

Loudest triggers:

Dataset	SNR_Γ	FAR [yr^{-1}]	FAP	GPS time	Freq. [Hz]
S5	29.65	1.00	0.54	851136555.0	129 - 201
S6	29.84	0.36	0.12	949728041.5	152 - 235

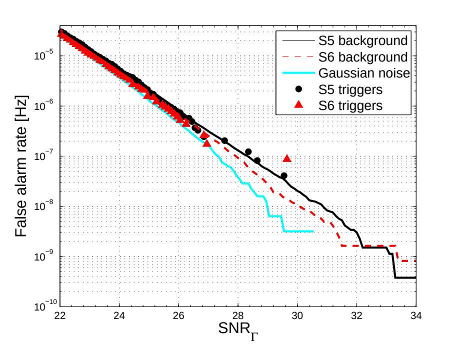


Figure 3: S5 and S6 zero-lag triggers superimposed on time-slide triggers.

Upper limits - visible volume

Visible volume: measure of volume of space accessible to search. Requires distance calibration, only calculated for ADI waveforms.
$V_{vis}(\mathrm{SNR}_\Gamma) = \int_0^\infty 4\pi\epsilon(\mathrm{SNR}_\Gamma, r) r^2 dr$

False alarm density (FAD): expected number of background triggers for a given visible volume. Useful for comparing triggers from different networks or searches.
$\mathrm{FAD}(\mathrm{SNR}_\Gamma) = \frac{\mathrm{FAR}(\mathrm{SNR}_\Gamma)}{V_{vis}(\mathrm{SNR}_\Gamma)}$

Rate upper limits: $R_{90\%,\mathrm{VT}} = \frac{2.3}{\sum_k V_{\mathrm{vis},k}(\mathrm{FAD}^\star) \times T_{\mathrm{obs},k}}$

Waveform	V_{vis} [Mpc^3] S5	V_{vis} [Mpc^3] S6	$R_{90\%,\mathrm{VT}}$ [$\mathrm{Mpc}^{-3}\mathrm{yr}^{-1}$]
ADI-A	1.6×10^3	3.2×10^3	1.0×10^{-3}
ADI-B	5.4×10^4	8.6×10^4	3.6×10^{-5}
ADI-C	7.0×10^3	1.4×10^4	2.4×10^{-4}
ADI-E	1.5×10^4	2.9×10^4	1.1×10^{-4}

Table 1: Visible volume upper limits on ADI waveforms. Uncertainties included; they are dominated by calibration error and marginalized over using a Bayesian method.

Upper limits - efficiency

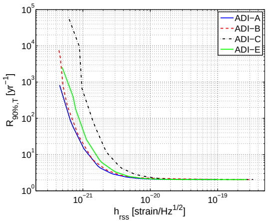
For waveforms that aren't distance calibrated, we use the efficiency to calculate rate upper limits:

$$R_{90\%,\mathrm{T}} = \frac{2.3}{\sum_k \epsilon_k(\mathrm{SNR}^{\star}_{\Gamma,k})\, T_{\mathrm{obs},k}}$$

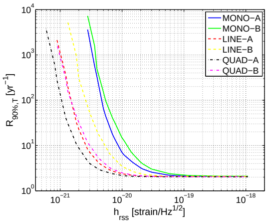
This results in an upper limit as a function of signal strength. Uncertainties are dominated by calibration error and are accounted for by adjusting the efficiency upward.

Upper limits - efficiency

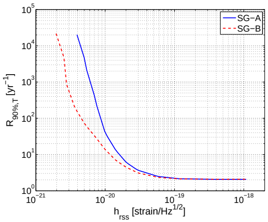
Rate upper limit vs. h_{rss} curves for all waveforms considered in the injection study.



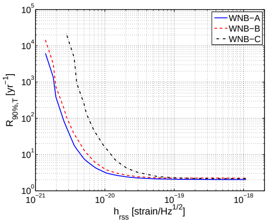
(a) ADI waveforms.



(b) Sinusoidal waveforms.



(c) Sine-Gaussian waveforms.



(d) White noise burst waveforms.

Discussion

Difficult to compare results directly to short-transient searches due to usage of different waveforms. Longer waveforms will require a more energetic source since the energy is more dispersed in time.

Can estimate isotropic energy for a pair of rotating point masses:

$$E_{\mathrm{GW}} \simeq h^2_{\mathrm{rss},50\%} r^2_{50\%} \pi^2 f^2_{\mathrm{GW}} \frac{c^3}{G}.$$

For *ad hoc* waveforms, we fix a fiducial distance of 10 kpc.

Results:

- ADI: $1.3 \times 10^{-7} - 1.2 \times 10^{-6}\ \mathrm{M_\odot c^2}$.
- Sinusoidal: $6.1 \times 10^{-7} - 2.3 \times 10^{-4}\ \mathrm{M_\odot c^2}$.
- Sine-Gaussian: $1.1 \times 10^{-5} - 2.5 \times 10^{-4}\ \mathrm{M_\odot c^2}$.
- White noise bursts: $2.1 \times 10^{-5} - 5.4 \times 10^{-4}\ \mathrm{M_\odot c^2}$.

Compare to a protoneutron star at 10 kpc developing matter convection over 30 s: $4 \times 10^{-9}\ \mathrm{M_\odot c^2}$.[4]

[4] E. Mueller et al., Astrophys. J **603**, 221 (2004).

Conclusions

First upper limits on long-lasting GW transients with LIGO data.

Connection to stochastic search: a GW transient lasting days or more could produce a signal in isotropic or directional stochastic searches.

Review has been completed (see Erik's talk).

Search is now focusing on O1 data.

Paper draft on the DCC, comments welcome! LIGO-P1400138

Target journal: PRD.

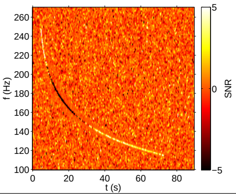
Extra Slides

Analysis description

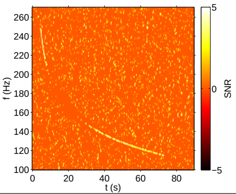
1. Calculate cross-power and auto-power *ft*-maps.
2. Notch problematic frequency bins.
3. Check each *ft*-map column with the STAMP glitch flag[5] and notch columns identified as glitchy.
4. Run clustering algorithm on SNR *ft*-map.
5. If a cluster was found, calculate cluster statistics.
6. Save results for post-processing.

[5] T. Prestegard et al., Class. Quantum Grav. **29**, 095018 (2012).

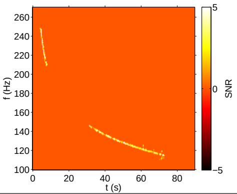
Clustering overview



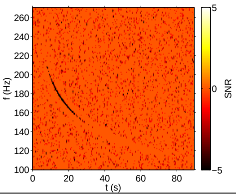
(a) SNR *ft*-map.



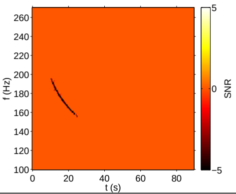
(b) Apply positive threshold.



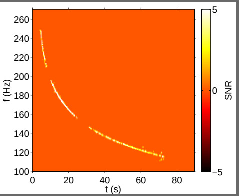
(c) Find positive clusters.



(d) Apply negative threshold.



(e) Find negative clusters.



(f) Form larger clusters, apply absolute value, calculate cluster statistics.

ADI waveform details

Waveform	$M[M_\odot]$	a^*	ϵ	Duration [s]	Frequency [Hz]
ADI-A	5	0.30	0.050	39	135 - 166
ADI-B	10	0.95	0.200	9	110 - 209
ADI-C	10	0.95	0.040	236	130 - 251
ADI-E	8	0.99	0.065	76	111 - 234

Table 2: List of ADI waveforms used to test the sensitivity of the search. Here, M is the mass of the central black hole, a^* is the dimensionless Kerr spin parameter of central black hole, and ϵ is the fraction of the disk mass that forms clumps. Frequency refers to the ending and starting frequencies of the GW signal, respectively. All waveforms have an accretion disk mass of 1.5 $M_\odot$.

Sinusoidal waveform details

Waveform	Duration [s]	f_0 [Hz]	$\frac{df}{dt}$ [Hz/s]	$\frac{d^2f}{dt^2}$ [Hz/s^2]
MONO-A	150	90	0.0	0.00
MONO-B	250	505	0.0	0.00
LINE-A	250	50	0.6	0.00
LINE-B	100	900	-2.0	0.00
QUAD-A	30	50	0.0	0.33
QUAD-B	70	500	0.0	0.04

Table 3: List of sinusoidal waveforms used to test the sensitivity of the search. Here, f_0 is the initial frequency of the signal, $\frac{df}{dt}$ is the frequency derivative, and $\frac{d^2f}{dt^2}$ is the second derivative of the frequency.

WNB and SG waveform details

Waveform	Duration [s]	f_0 [Hz]	τ [s]
SG-A	150	90	30
SG-B	250	505	50

Table 4: List of sine-Gaussian waveforms used to test the sensitivity of the search. Here, τ is the decay time of the Gaussian envelope.

Waveform	Duration [s]	Frequency band [Hz]
WNB-A	20	50 - 400
WNB-B	60	300 - 350
WNB-C	100	700 - 750

Table 5: List of band-limited white noise burst waveforms used to test the sensitivity of the search.