Characterization of the LIGO detectors during their sixth science run

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2014/11/18 by T.Yokozawa

DetChar meeting

Abstract

Abstract. In 2009-2010, the Laser Interferometer Gravitational-wave Observatory (LIGO) operated together with international partners Virgo and GEO600 as a network to search for gravitational waves of astrophysical origin. The sensitivity of these detectors was limited by a combination of noise sources inherent to the instrumental design and its environment, often localized in time or frequency, that couple into the gravitational-wave readout. Here we review the performance of the LIGO instruments during this epoch, the work done to characterize the detectors and their data, and the effect that transient and continuous noise artefacts have on the sensitivity of LIGO to a variety of astrophysical sources.

LIGO operation with Virgo and GEO600
sensitivity was limited by combination of noise sources
performance of the LIGO instruments during S6

(退屈になってしまうかもしれませんが、)かなり詳細まで詳しく説明してくださっていたのでレビューでも少し詳細に書いています。

1. Introduction

- LIGO S6 operation during July2009 - October2010
- collaboration with GEO600 and Virgo
- many short-duration noise events(glitches)
    - environmental
    - mechanical
    - electronic mechanism ... they are not fully understood
- improved data quality through ‘vetoes’

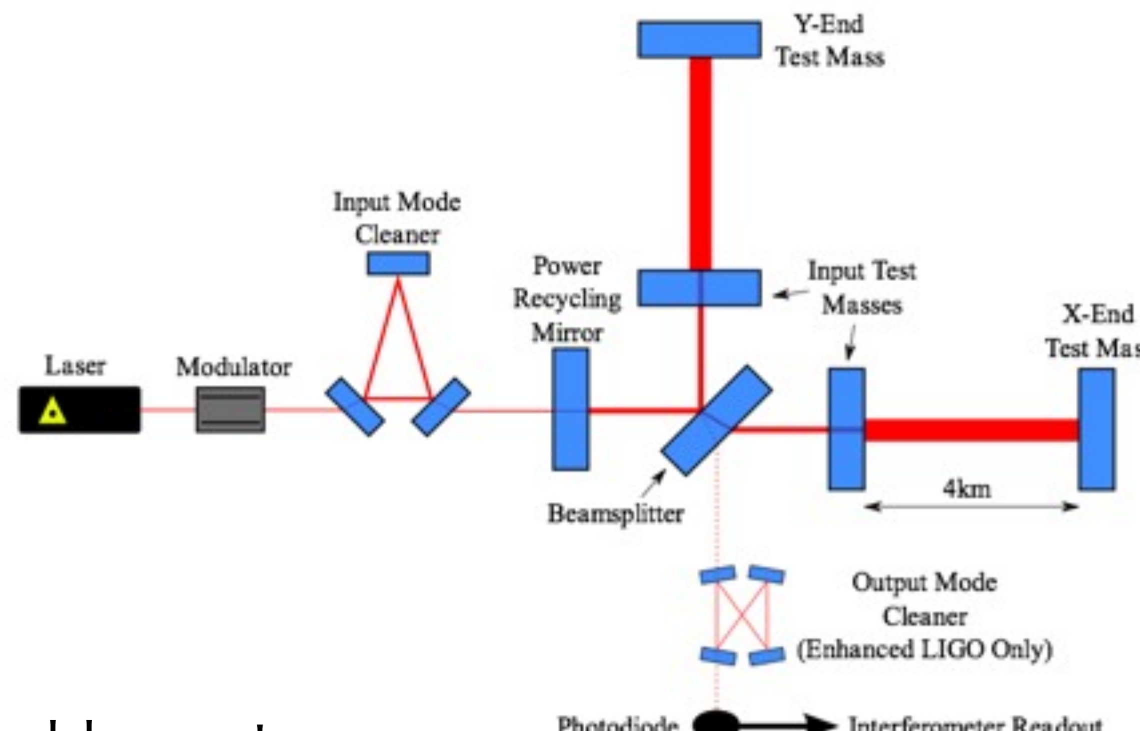


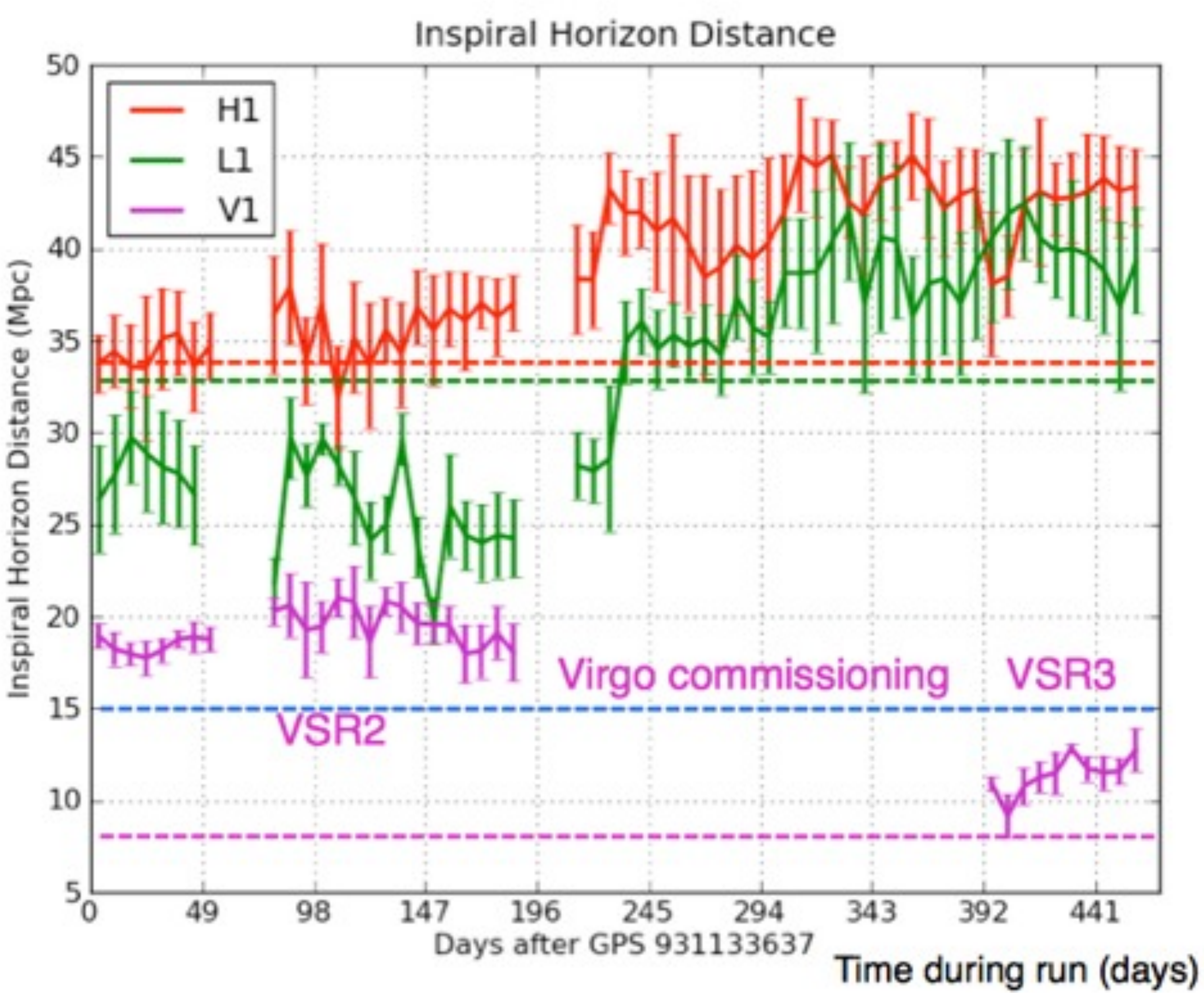
Fig1. LIGO optical layout

2. Configuration of the S6 LIGO

- diode-pumped power-amplified Nd:YAG laser at 1064nm
- S6 improvement
  - initial input laser system 10W to maximum of 35W
    - improved the sensitivity at high frequencies(>150Hz)
  - improved CO2 laser thermal compensation system
  - alternative GW detection system
    - replacing to so called ‘DC readout’
    - output mode cleaner(OMC) was installed to filter out the higher order mode content of the output beam
    - seismic feed-forward to a hydraulic actuation system
  - The detail will be described in each reference

3. Detector sensitivity during S6

- Split into four epoches A-D
  - A,B run alongside the VSR2(second Virgo Science Run)
  - Between A,B and B,C … a long instrumental commissioning break
  - C,D continuous period and D alongside the VSR3

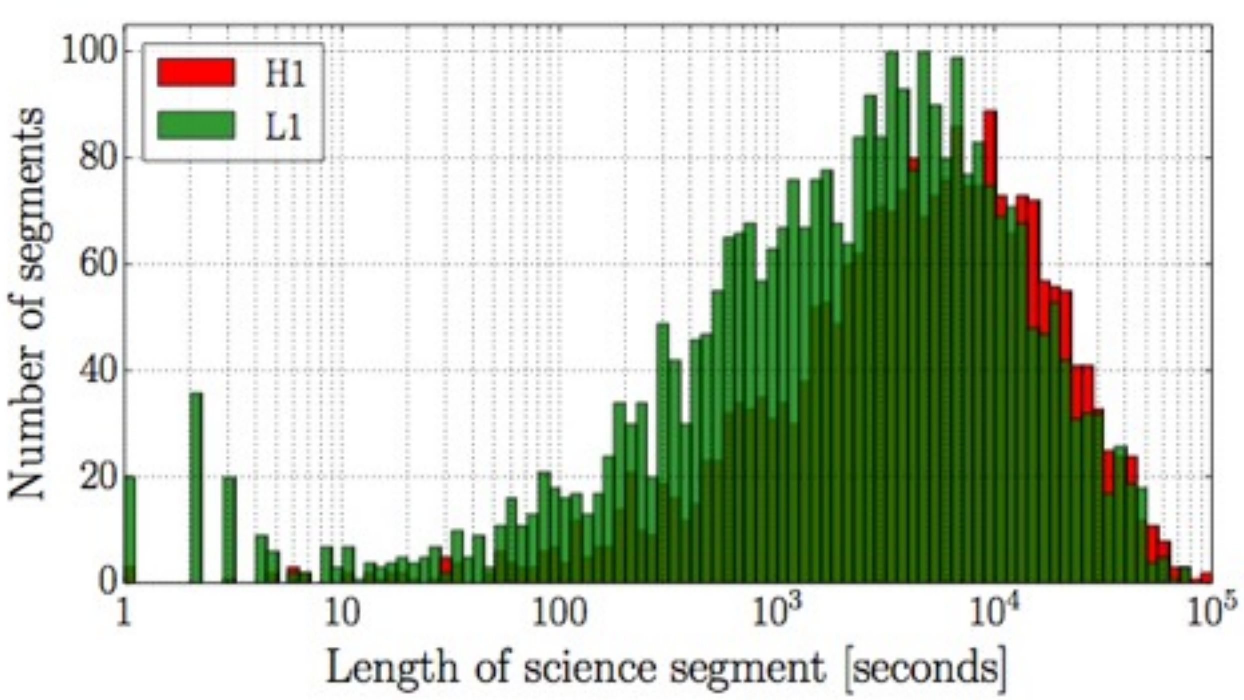


- Distance where (1.4, 1.4) $M_{\odot}$ inspiral with optimal geometry gives SNR=8
- Dotted lines show modes of S5 and VSR1 ranges
  - » LHO 4km
  - » LLO 4km
  - » LHO 2km
  - » Virgo

Fig3'. LIGO phase A-D
(inspiral range will explain later)

3. Detector sensitivity during S6

- Detector duty factor
  - the fraction of the total run time
  - a science segment i typically ended by lock-loss(large noise level)
  - short time is stop due to maintenance, calibration measurement
  - L1 shorter than H1, due to poor detector stability during the early part
  - Stability developments in understanding the critical noise coupling and their affect operation of the instruments(see Sec.4)



Epoch	Median duration (mins)	Longest duration (hours)	Total live time (days)	Duty factor (%)
S6A	54.0	13.4	27.5	49.1
S6B	75.2	19.0	59.2	54.3
S6C	82.0	17.0	82.8	51.4
S6D	123.4	35.2	74.7	63.9

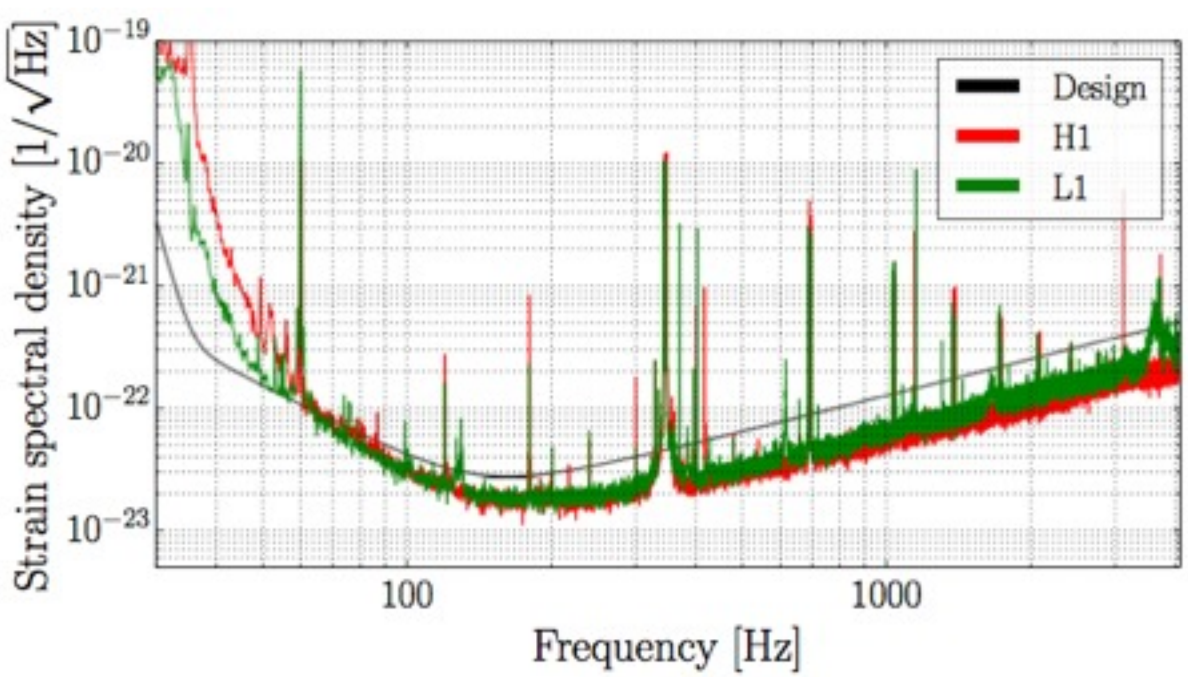
(a) H1 (LIGO Hanford Observatory)

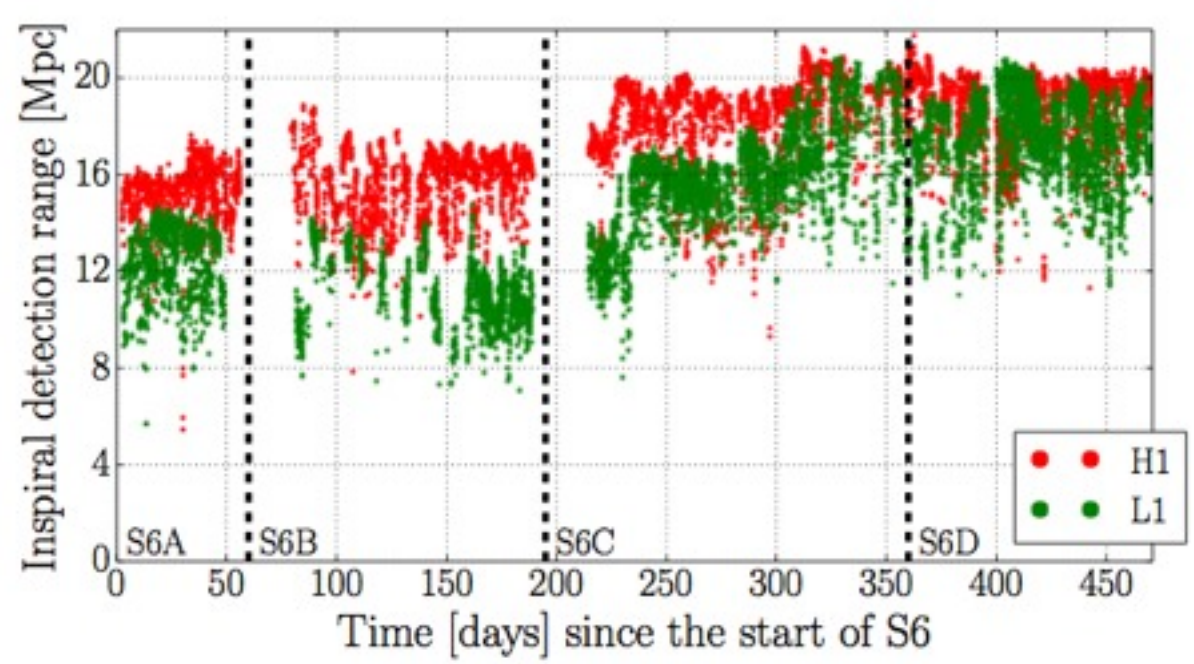
S6A	39.3	11.8	25.6	45.7
S6B	17.3	21.3	40.0	38.0
S6C	67.5	21.4	82.3	51.1
S6D	58.2	32.6	75.2	64.3

(b) L1 (LIGO Livingston Observatory)

3. Detector sensitivity during S6

- The sensitivity to GWs, strain amplitude spectral density
- dominant Noise source
  - seismically-driven motion of the key interferometer optics(<40Hz)
  - Brownian motion - mechanical excitation and their suspension due to thermal energy (50-150Hz)
  - variation in incident photon flux(>150Hz)
  - narrow-band line structure(See Sec.4.7)
- Detection range (SNR>8, sky average, 2048sec of data)

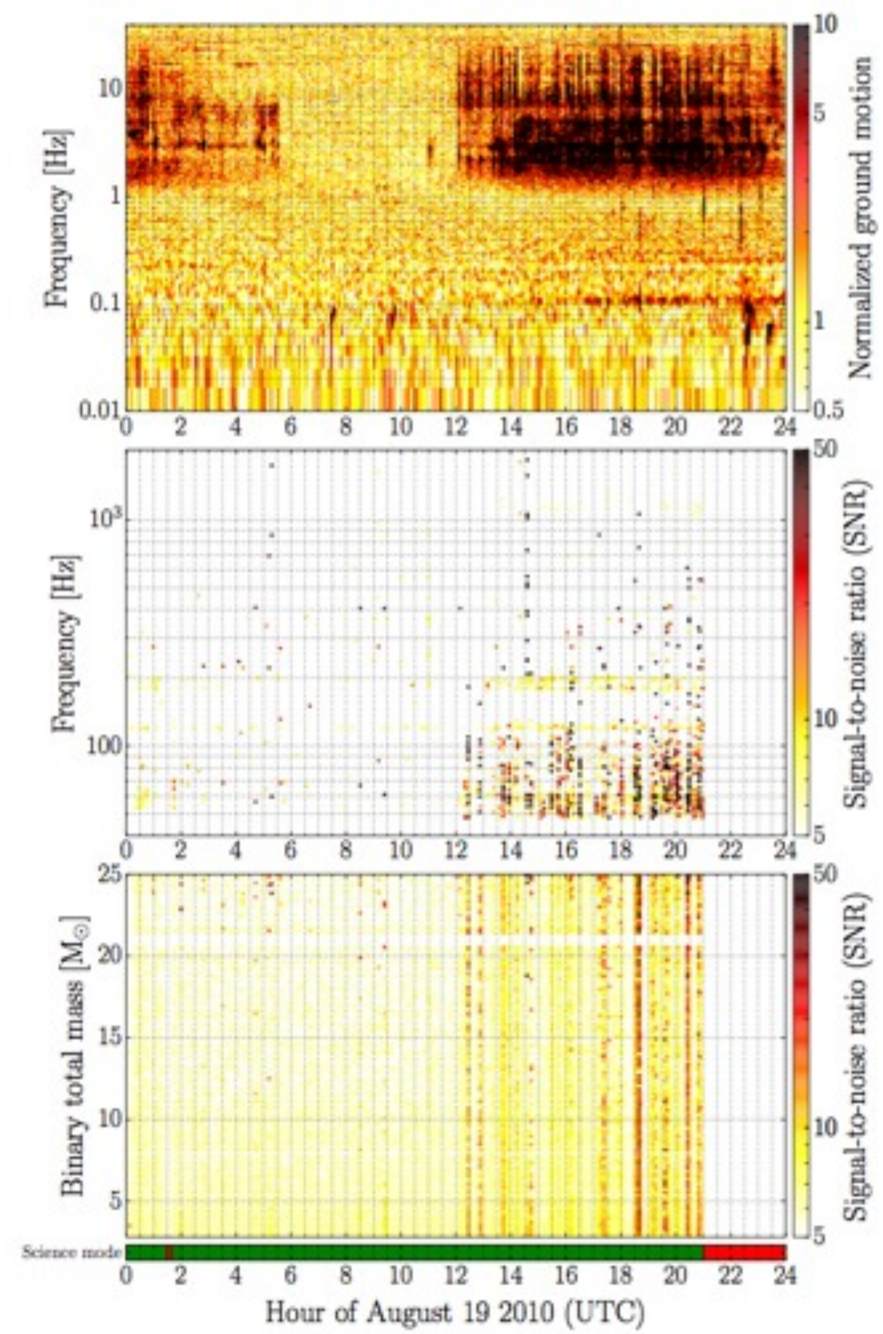




4. Data-quality problems in S6

- ideal condition … all excess noise can identify quickly, but difficult..
- The data quality flags and their associated time segments were used
- details a representative set of specific issues that were present

- 4.1 Seismic noise
  - fundamental limit to the sensitivity below 40Hz
  - observed to be strongly correlated with glitches(100-200Hz)
  - (top)seismic ground motion
  - (middle) GW burst, Ω pipeline
  - (bottom)CBC analysis, daily ihope
  - With great efforts -> can reduce the coupling

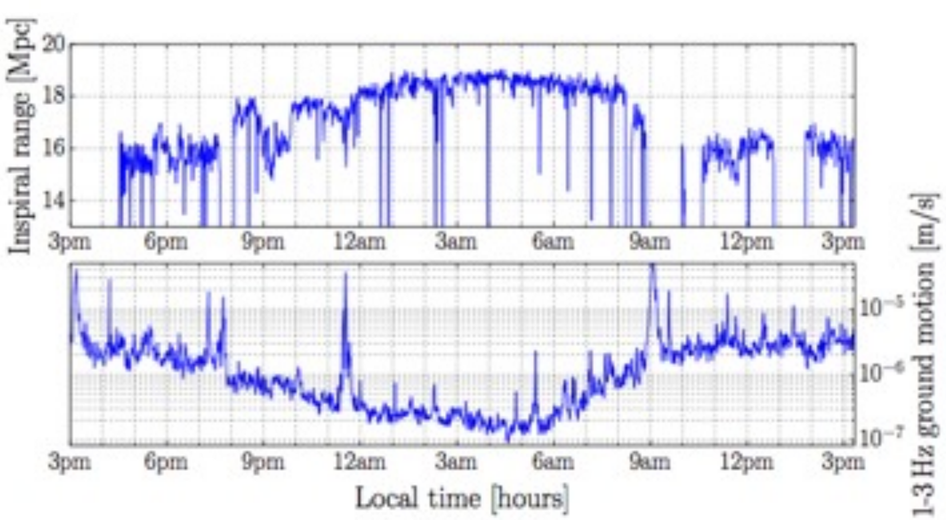


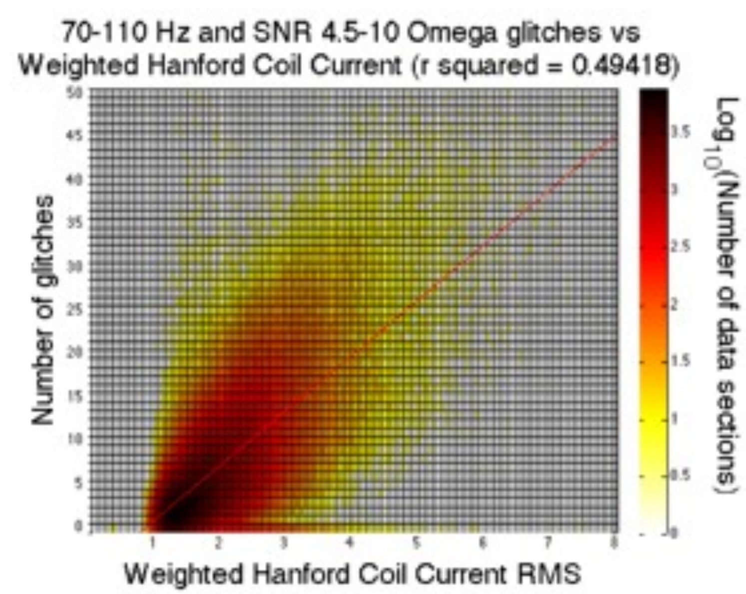
4. Data-quality problems in S6

- 4.2 Seismically-driven length-sensing glitches
  - correlated with noise in the length control signals of two short length degree of freedom
    - the power recycling cavity length(PRCL)
    - short Michelson formed by the beam-splitter and the input test masses(MICH)
  - Simulated and these glitches were correlated with 70% with GW data
  - discovered that high microseismic noise was driving large instabilities
  - eliminated via commissioning of a seismic feed-forward system
    - decrease the PRC optic motion by a factor of three
  - Identified by both Hierarchichal Veto(HVeto) and Used Percentage Veto(UPV) algorithms

4. Data-quality problems in S6

- 4.3 Upconversion of low-frequency noise due to the Barkhausen effect
  - In the earlier phase, below 10Hz motion was associated with increases in noise in the 40-200Hz
  - seismic upconversion noise was produced by passing trucks, distant construction activities seasonal increases in water flow over dams, high wind, and earthquakes
  - (left figure) : anti-correlation between ground motion and inspiral range
  - An empirical, frequency-dependent function was developed to estimate upconversion noise from low-frequency noise -> produce flags
  - (right figure) : correlation between # of glitches and test mas actuation current, upconversion noise affect tot unmodelled GW burst search





4. Data-quality problems in S6

- (continued) evidence that was Barkhausen noise
  - magnetic filed fluctuation produced by changing magnetic fielis
- 4.4 Beam jitter noise
  - one of the upgrade was the output mode cleaner
  - the mode transmission of this cavity is very sensitive to angular fluctuation of the incidnet beam
    - misalignment of the beam would cause non-linear power fluctuations
  - low-frequency seismic noise and vibrations of optical tables were observed to mix with higher-frequency beam jitter
  - changing with the amount of alignment offset
  - additionally, several other methods were used to mitigate and control beam jitter noise throughout the run.

4. Data-quality problems in S6

- 4.5 Mechanical glitching at the reflected port
  - caused by electronics failures associated with the LHO interferometer
  - servo actuator -> coupled GW data at ~37Hz -> identified with HVeto
  -

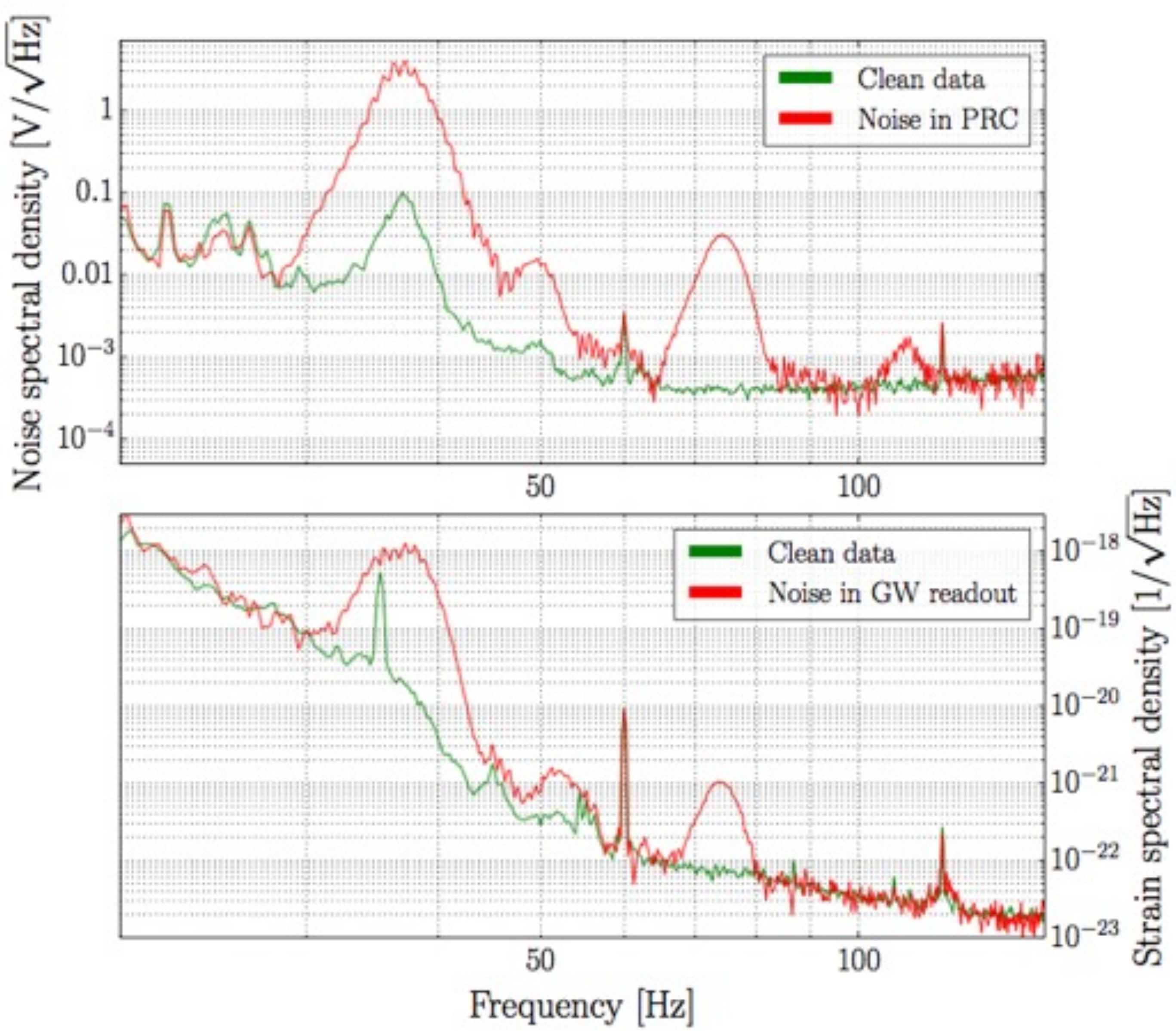


Figure 8
(upper figure) : the power recycling cavity length signal

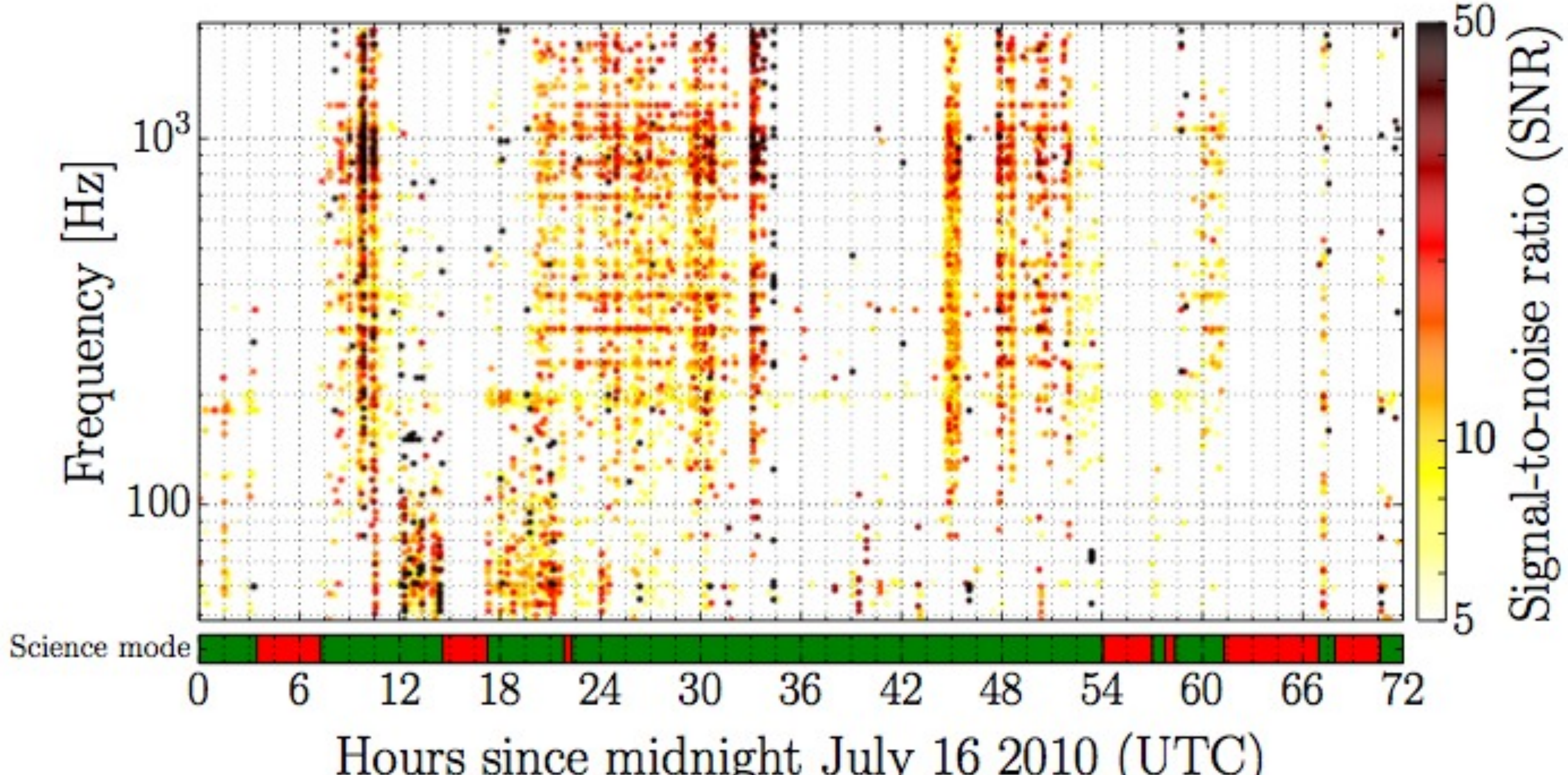
(lower figure) : GW output error signal

strong correlation at ~37Hz

also I can see in ~75Hz, but no description in paper..

4. Data-quality problems in S6

- 4.6 Broadband noise bursts from poor electrical connections
  - repeated, broadband glitching
  - The main diagnostic clues(ヒント) were coincident with quadrant photo-dodes
    - unlikely detect a glitch in the beam more sensitively than GW data

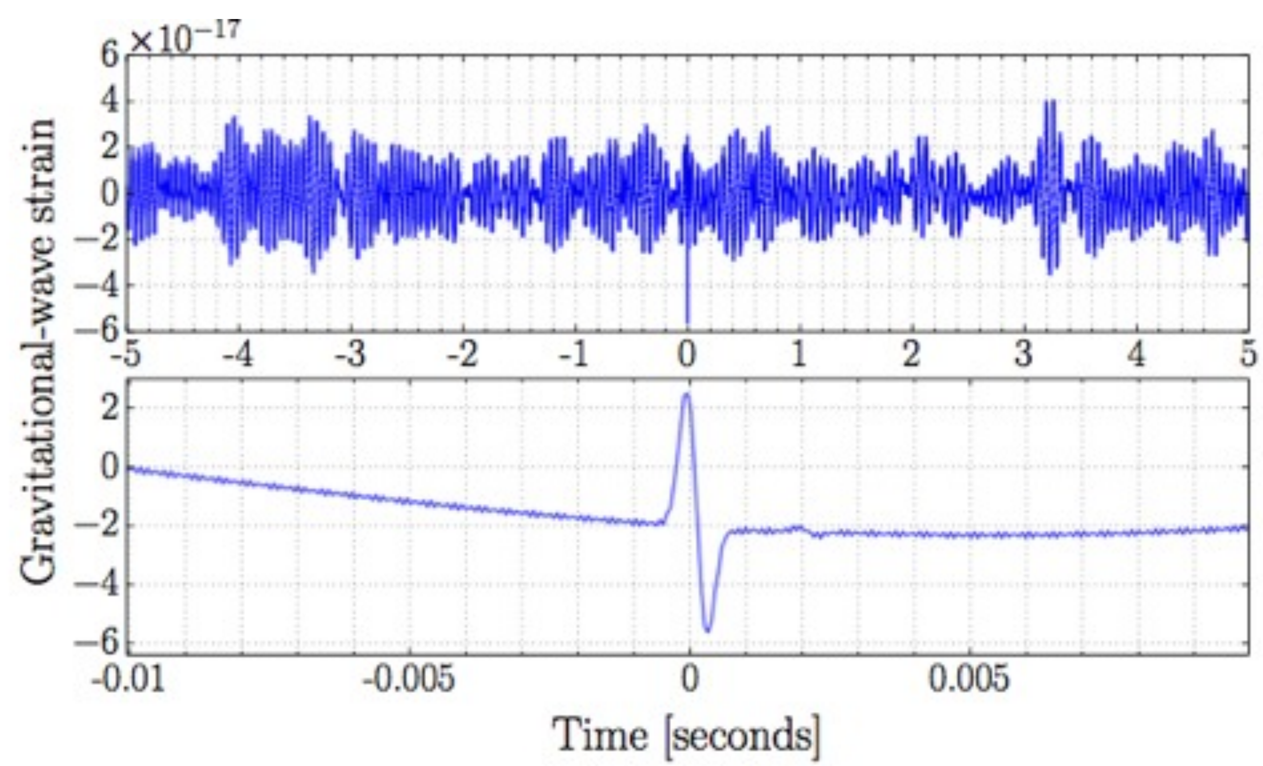


4. Data-quality problems in S6

- 4.7 spectral lines
  - Many spectral lines are fundamental to the design and operation
    - alternating current(AC) power line 60Hz
    - violin modes from core-optic suspensions ~350Hz
    - various calibration lines used to measure the interferometer response functions
    - unintended sources, magnetic and vibrational couplings
    -

4. Data-quality problems in S6

- 4.8 The ‘spike glitch’
  - They were characterized by a distinctive shape in the time series of the signal oon the GW output photodiode
  - (example fig.11) often visible in the raw time series, SNR from 200 to 20,000 with Ω pipeline
  - investigated, light did not enter the arm cavities but went almost directly into the OMC ~0.2miliseconds wide
  - But, there are many unknown glitch sources.



5. The impact of data quality

- The impact of non-Gaussian, non-stationary noise in the LIGO detectors on searches for GWs is significant.
    - loud glitches, high rates of lower SNR glitches, spectral lines, continued glitching in a given frequency range.
- Non-Gaussian noise in the detector outputs that can be correlated with auxiliary signals
- 5.1 Data quality vetoes for transient searches
    - the low-mass CBC search ‘ihope’
    - the all-sky cGW algorithm(coherent)
    - they need multi-detector with better data quality
- Data Quality flag were highly effective, time-domain DQ flag->deadtime
- performance is checked by efficiency-to-deadtime ratio(EDR)

5. The impact of data quality

- 5.1.1 Category 1 vetos
  - The most egregious interferometer, should not be included any analysis
  - Data Monitoring Tools(DMT) automatically identify
    - such as cavity resonance, error h(t) calibration..
- 5.2.2 Category 2, 3
  - the higher category flags were used to identify likely noise artefacts.
  - Category2 veto from auxiliary data
  - generated in low-latency by the DMT, photodiode saturations, digital overflows, high seismic, environmental noise
  - Category3 veto from less well understood statistical correlation
  - generated HVeto, UPV bilinear-coupling veto(BCV) algorithms

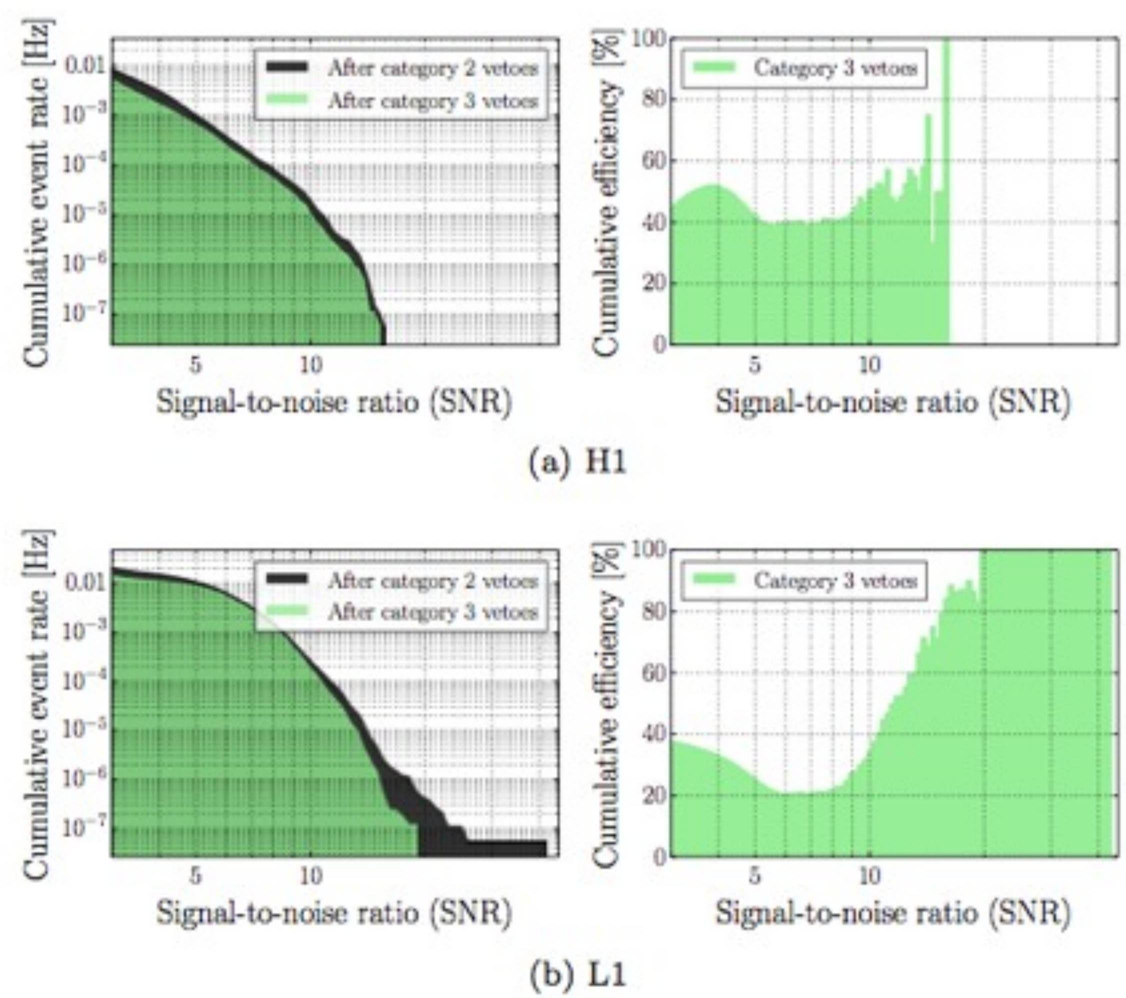
5. The impact of data quality

- Deadtime and veto effects

Instrument	Absolute deadtime % (seconds)		Search deadtime % (seconds)	
	cWB	ihope	cWB	ihope
H1	0.3% (53318)	0.4% (176079)	0.4% (77617)	3.8% (786284)
L1	0.4% (75016)	0.1% (20915)	0.7% (137115)	6.2% (1180976)

Absolute deadtime : fraction of science-quality data removed
Search deadtime : fractional reduction in analysable time after category 1vetoes and segment selection.

Deadtime type	Cat.	H1		L1	
		cWB	ihope	cWB	ihope
Absolute % (s)	2	0.26%	0.77%	1.59%	1.53%
	3	7.90%	9.26%	8.54%	7.03%
Relative % (s)	3	7.73%	9.00%	7.06%	6.10%
Cumulative % (s)	3	7.97%	9.71%	8.54%	7.54%



(a) H1
(b) L1

the background is dominated by low SNR events.
EDR>5@SNR3 and can remove tails at SNR~20

5. The impact of data quality

- 5.2 Data quality in searches for long-duration signals
    - both continuous GWs and SGWB
        - duration and stationarity of data were the key factor
- 5.2.1 Searches for continuous GWs
    - The PowerFlux pipeline
        - the final seven month of the S6 dataset to minimize the impact of poor detector performance from the earlier epochs
        - ~20% of frequency bands has been identified as non-Gaussian
        - beam jitter has had a detrimental effect around 180-200Hz
        -

5. The impact of data quality

- 5.2.2 Searches for a SGWB
  - eliminate data, too noisy, too non-stationary apparent correlated noise between detectors
  - excluding those times flagged as category 1 or category 4 veto.
  - stationary noise assumption, depending on frequency
    - ~117 days of coincident live time are remained
  - correlated magnetic field noise from the Schumann resonances was observed in correlation between magnetrometers in H1, L1, Virgo
    - level of correlation noise did not effect the S5 and S6 search

6. Conclusion and outlook for aLIGO

- regularly affected by both non-Gaussian noise transients and long-duration spectral features.
    - some problems are identified during S6
    - increasingly stable and sensitive instruments
        - See in improvement of run segments and detection range
    - Data quality flag help to identify backgrounds
- Still exist high SNR events -> need more deep study, also line noise
- One major goal of the aLIGO is to contribute to multi-messenger astronomy -> EM neutrino, both burst and CBC search
    - real-time characterization of instrumental data
    - reduce the latency of EM follow-up requests
- Best estimate predict ~40 binary neutron star merger per year
    - a great effort will be required in commissioning the now instruments