Development of Non-Gaussian Noise Characterization System

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Motivation

The presence of Non-Gaussian noise is known from TAMA and LIGO experience

- Detector sensitivity may be limit by non-Gaussian noise
- Noise event at tail of distribution see like GW event

Quantitative modeling of gaussianity of detector noise

- Specifying time and frequency in bad gaussianity
- Narrow down the candidate of noise sources
- Make a list of non-Gaussian noise sources

These things will be progress in real time during KAGRA Commisioning and Observation
Motivation

Understanding state of detector and surrounding environment
Use obtain information to detector and data analysis

For detector: Narrow down of noise sources
  Early achievement to the target sensitivity
  Contribution for stable operation

for analysis: Evaluating data quality
  Usable/Un-usable
  Stationary/Non-Stationary
  Gaussian/Non-Gaussian
Example of Non-Stationarity Monitor

Result of Omega pipeline

There are features of each noise source in TF-plane

Figure 3. Omega time–frequency maps of six examples of glitches seen in the DF channel. Glitch families are identifiable by their unique time–frequency morphology. When identified, the glitch in the auxiliary channel is shown in the inset plot. The first plot shows a 50 Hz power-line glitch also detected by the magnetometers. The second map shows a series of glitches caused by scattered light induced by seismic activity. The third glitch is caused by a TCS instability. The fourth plot presents an airplane event with a clear Doppler effect. The fifth event is due to a glitch in the laser stabilization loop. The last glitch with an undefined shape is due to a seismic event up-converted to higher frequencies.

J. Aasi, et. al., Class, Quantum Grav 29 (2012)
Classification of Noise

TAMA R142

Looks like non-stationarity

Non-stationary?

or

Tail of distribution?
Classification of Noise

Looks like non-stationarity

Non-stationary? or Tail of distribution?

Changing appearance by time window

V [volt]

TAMA R142
Classification of Noise

The gap from gaussian noise

- Stationary-Gaussian + Non-stationary
- Stationary-Non-Gaussian
- Stationary-Non-Gaussian + Non-stationary etc...

Non-stationarity monitor tools: KleineWelle, Omega (LAL)...

Non-gausianity monitor tools: We implemented new tool for real time monitoring

LAL: LIGO/LSC Algorithm Library
Non-Gaussian Noise Model

Gauss Noise Model

Re[n(f)] and Im[n(f)] follow Gaussian distribution
and |n(f)| follows Rayleigh distribution

\[
f(x) = \frac{x}{\sigma^2} \exp\left(-\frac{x^2}{2\sigma^2}\right)
\]

Non-Gaussian Noise Model : Using Student-t Noise Model

Re[n(f)] and Im[n(f)] follow Student-t distribution
This distribution has heavier tail
and is characterized only 1 parameter (\( \nu \))

\[
f(t) = \frac{\Gamma((\nu + 1)/2)}{\sqrt{\nu \pi} \Gamma(\nu/2)} (1 + t^2/\nu)^{-(\nu+1)/2}
\]

When \( \nu = \infty \), Student-t is equal Gaussian

Modeling noise event at tail of distribution using a clear indicator
In Student-t noise model, 

\[ |n(f)| \text{ follows Student-Rayleigh distribution} \]

\[ f_{SR}(x|\sigma, \nu) = \frac{x}{\sigma^2} f_F(2, \nu) \left( \frac{x^2}{2\sigma^2} \right), \quad (A18) \]

\[ f_F(x): \text{F-distribution function} \]


When \( \nu = \infty \), Student-Rayleigh distribution is equal Rayleigh distribution.
Non-Gaussianity Monitor

[1] Calculating spectrogram of detector signal (Short Fourier Transform)

[2] Estimating $\nu$ using Student-Rayleigh distribution each frequency bin

**chunk time:** $T$ (128 sec)

**stride:** $dT$ (1 sec)

<table>
<thead>
<tr>
<th>$s_0(t)$</th>
<th>$s_1(t)$</th>
<th>$s_2(t)$</th>
<th>...</th>
<th>$s_N(t)$</th>
<th>Input signal: $s(t)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s_0(f_0)$</td>
<td>$s_1(f_0)$</td>
<td>$s_2(f_0)$</td>
<td>...</td>
<td>$s_N(f_0)$</td>
<td>$\nu(f_0)$</td>
</tr>
<tr>
<td>$s_0(f_1)$</td>
<td>$s_1(f_1)$</td>
<td>$s_2(f_1)$</td>
<td>...</td>
<td>$s_N(f_1)$</td>
<td>$\nu(f_1)$</td>
</tr>
<tr>
<td>$s_0(f_2)$</td>
<td>$s_1(f_2)$</td>
<td>$s_2(f_2)$</td>
<td>...</td>
<td>$s_N(f_2)$</td>
<td>$\nu(f_2)$</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>$s_0(f_M)$</td>
<td>$s_1(f_M)$</td>
<td>$s_2(f_M)$</td>
<td>...</td>
<td>$s_N(f_M)$</td>
<td>$\nu(f_M)$</td>
</tr>
</tbody>
</table>

$dF = 16 \text{Hz}$

Output: $\nu(f)$
How do we estimate $\nu(f_{j=x})$ from samples $s_i(f_{j=x})$?

1. Decide base quantile $\alpha (=0.99)$
2. Sorting $s_i(f_{j=x})$
3. Pickup quantile data $s_i=\alpha M(f_{j=x})$ from sorted $s_i(f_{j=x})$
4. Calculating theoretical quantile value of Student-Rayleigh distribution $s_{\text{theory}}(\alpha;\nu)$ varying $\nu$
5. Employing empirical $\nu$ as $\nu(f_{j=x})$
   where $\nu(f_{j=x})$ give $s_{\text{theory}}(\alpha;\nu)$
   which is the most closest to $s_i=\alpha M(f_{j=x})$
Quantile of Student-Rayleigh Distribution

The position of 99% Quantile on the probability density function (right) and cumulative distribution function (below) of Student-Rayleigh distribution.
Performance test with known $\nu$

- Generating simulation signal with $\nu = 4, 8, 16, 64$
- Confirmed detectability of difference of $\nu$
Non-Gaussianity Monitor ~ Long Time Run

\[ s'(t) \rightarrow s(t) \]

Ave. spectrum \( \rightarrow \) Sn(f) \n
\[ \text{SFT} \]

\[
\begin{array}{cccc}
S_0(f_0) & S_1(f_0) & \cdots & S_N(f_0) \\
S_0(f_1) & S_1(f_1) & \cdots & S_N(f_1) \\
S_0(f_2) & S_1(f_2) & \cdots & S_N(f_2) \\
\cdots & \cdots & \cdots & \cdots \\
S_0(f_M) & S_1(f_M) & \cdots & S_N(f_M) \\
\end{array} \rightarrow \begin{array}{c}
\nu(f_0) \\
\nu(f_1) \\
\nu(f_2) \\
\cdots \\
\nu(f_M) \\
\end{array}
\]

In this time
1 chunk = 128 sec.
shift 16 sec. at a time
Non-Gaussian Monitor ~ using LIGO S5 Data

Using LIGO S5 data(https://losc.ligo.org/start/)

GPS Time : 842747904

dt = 16 [sec], df = 16 Hz

Gaussianity is **constantly bad**

Gaussianity is **suddenly bad**
Non-Gaussian Monitor ~ using LIGO S5 Data

Applied monitor tool to continuous data (about 5 hrs.)

average spectrum

GPS: 842752000

GPS: 842756096

GPS: 842760192
Toward to commissioning phase, we are developing DetChar tool named HasKAL

HasKAL is Haskell base library to run various monitor tools on CUI or GUI

https://github.com/gw-analysis/detector-characterization
Summary

Developed a monitor tool to evaluate non-Gaussianity of signal

- Confirmed detectability of difference of $\nu$ using simulation noise
- Applied monitor tool to continuous data (about 5 hrs.)

Future Work

- Searching correlation of non-Gaussianity during multi-channels
- Classification of non-Gaussian and non-Stationary noise using Gaussianity and stationarity monitor