Preliminary results of noise canceling on searches for continuous gravitational waves

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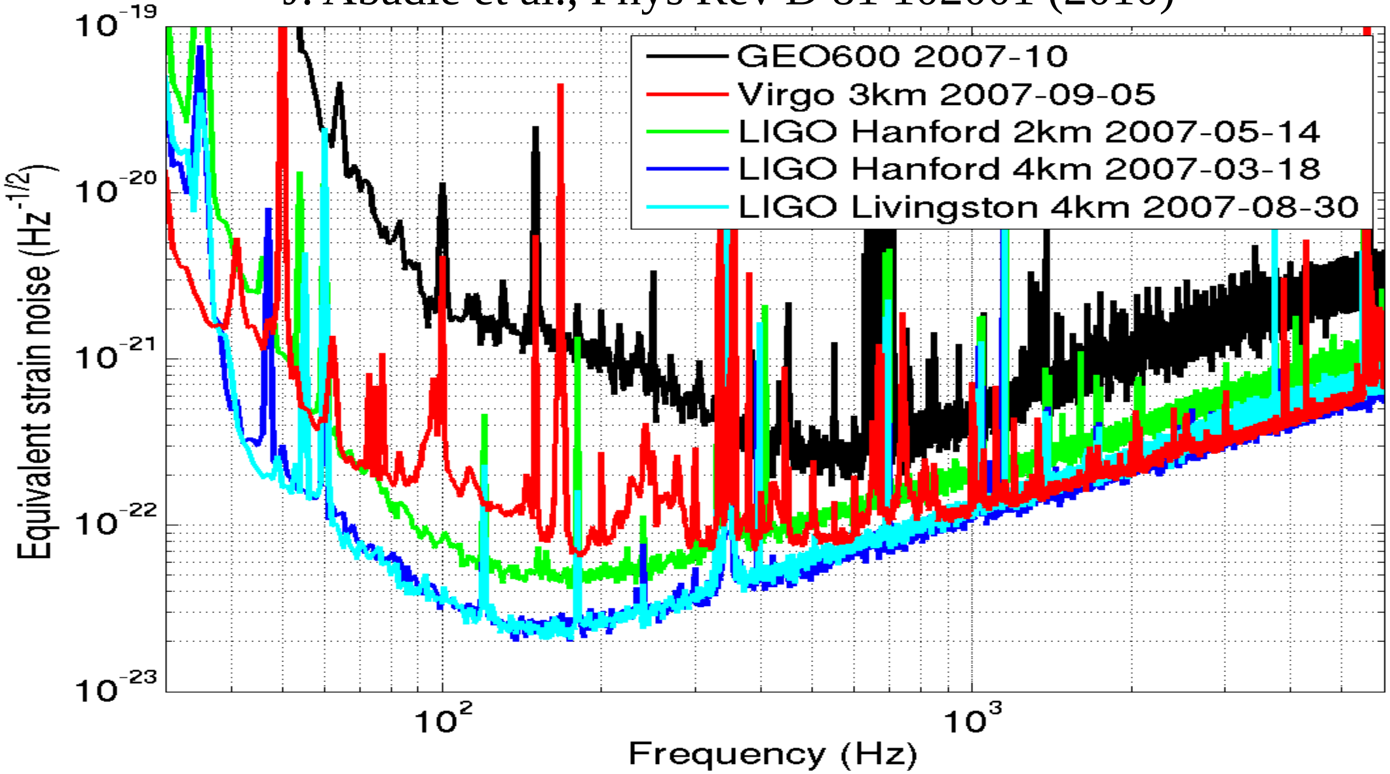
Outline

- Introduction
- Method
- Preliminary results on searches for continuous waves
  - On real data from the first joint LIGO-Virgo run (2007)
- Future plans

Detectors noise

J. Abadie et al., Phys Rev D 81 102001 (2010)



- Highly variable behavior
- Up-conversion and other non linear couplings
- Some artifacts not well understood

Many monitors used to measure environmental disturbances

REGRESSION METHOD

1. Characterize noise disturbances of h(t) in linear or bilinear correlation to auxiliary channels
(environmental or instrumental monitors)
2. Clean noise disturbances of h(t) correlated to by auxiliary channels

Regression Basics

Wiener-Kolgomorov filter (*)

- Simple case: considering one auxiliary channel

- Estimating which features of h(t) can be predicted by its correlation with a witness channel x(t):
  - s: prediction
  - L: filter length

$$s_i = \left(\sum_{j=-L}^{L} a_j x_{i+j} \right)$$

a: predicting filter
i, j : time indexes

- Least square minimization of the residuals:
  - N: filter training length

$$\sum_{i=1}^{N} e_i^2 = \sum_{i=1}^{N} \left[h_i - \left(\sum_{j=-L}^{L} a_j x_{i+j} \right) \right]^2$$

* [Rev. Sci. Instrum. **83**, 024501 (2012)]

Wavelet transform

[V. Necula et al., LIGO-P1100152]

- Allows to reduce the computation in small sub-bands
  - Calculate a bank of Wiener filters instead of a big one
  - Reduce computational complexity
- Use of Wilson-Daubechies-Meyer transformation
  - Orthonormal, invertible, very low spectral leakage
- Filters are built separately for each target frequency band
  - 1 Hz for this work

Multiple witness channels

- Enhance regression (more information)
- **But** add noise to prediction

$$\sum_{i=1}^{N} e_i^2 = \sum_{i=1}^{N} \left[h_i - \left(\sum_{j=-L}^{L} a_j x_{i+j} \right) - \left(\sum_{j=-L}^{L} b_j y_{i+j} \right) - \ldots \right]^2$$

$$\begin{pmatrix} R_{xx} & R_{xy} & \cdots \\ R_{xy} & R_{yy} & \cdots \\ \cdots & \cdots & \cdots \end{pmatrix} \begin{pmatrix} \mathbf{a} \\ \mathbf{b} \\ \cdots \end{pmatrix} = \begin{pmatrix} C_{hx} \\ C_{hy} \\ \cdots \end{pmatrix}$$

$$R_{xy}^{jk} = \sum_{i=1}^{N} x_{i+j} y_{i+k}$$

$$C_{hx}^{k} = \sum_{i=1}^{N} h_i x_{i+k}$$

- Cross-correlation matrix R can be constructed using:
  - Combination of more witness channels (x, y, …) describe linear noise disturbances
  - Multiplication of different witness channels: can describe up-conversion of low frequency signals

Regulators

[V. Tewari et al., LIGO-G1200288-v1]

- R matrix can be written considering related eigenvalues λ and eigenvectors O

$$\begin{pmatrix} a_{-L} \\ a_{-L+1} \\ \cdot \\ \cdot \\ a_L \end{pmatrix} = O \begin{pmatrix} 1/\lambda_{-L} & 0 & \cdots & 0 \\ 0 & 1/\lambda_{-L+1} & \cdots & 0 \\ \cdot & \cdot & & \\ \cdot & & \cdot & \\ 0 & & & 1/\lambda_L \end{pmatrix} O^T \begin{pmatrix} C_{yx}(-L) \\ C_{yx}(-L+1) \\ \cdot \\ \cdot \\ C_{yx}(L) \end{pmatrix}$$

Typically, few eigenvalues are significant

- Regulators: Impose a threshold on eigenvalues

hard: $$\begin{pmatrix} a_{-L} \\ a_{-L+1} \\ \cdot \\ \cdot \\ a_L \end{pmatrix} = O \left(\begin{array}{cccc} 1/\lambda_{-L} & 0 & \cdots & 0 \\ 0 & 1/\lambda_{-L+1} & \cdots & 0 \\ \cdot & \cdot & & \\ \hline \cdot & & 0 & \\ 0 & & & 0 \end{array}\right) O^T \begin{pmatrix} C_{yx}(-L) \\ C_{yx}(-L+1) \\ \cdot \\ \cdot \\ C_{yx}(L) \end{pmatrix}$$

soft: $$\begin{pmatrix} a_{-L} \\ a_{-L+1} \\ \cdot \\ \cdot \\ a_L \end{pmatrix} = O \left(\begin{array}{ccccc} 1/\lambda_{-L} & 0 & \cdots & \cdot & 0 \\ 0 & \cdot & \cdots & \cdot & \cdot \\ \cdot & \cdot & 1/\lambda_l & \cdot & 0 \\ \hline \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & \cdot & \cdot & & 1/\lambda_l \end{array}\right) O^T \begin{pmatrix} C_{yx}(-L) \\ C_{yx}(-L+1) \\ \cdot \\ \cdot \\ C_{yx}(L) \end{pmatrix}$$

- Avoid unphysical solutions
- Reduce filter noise
- Suppress irrelevant channels

PRELIMINARY RESULTS

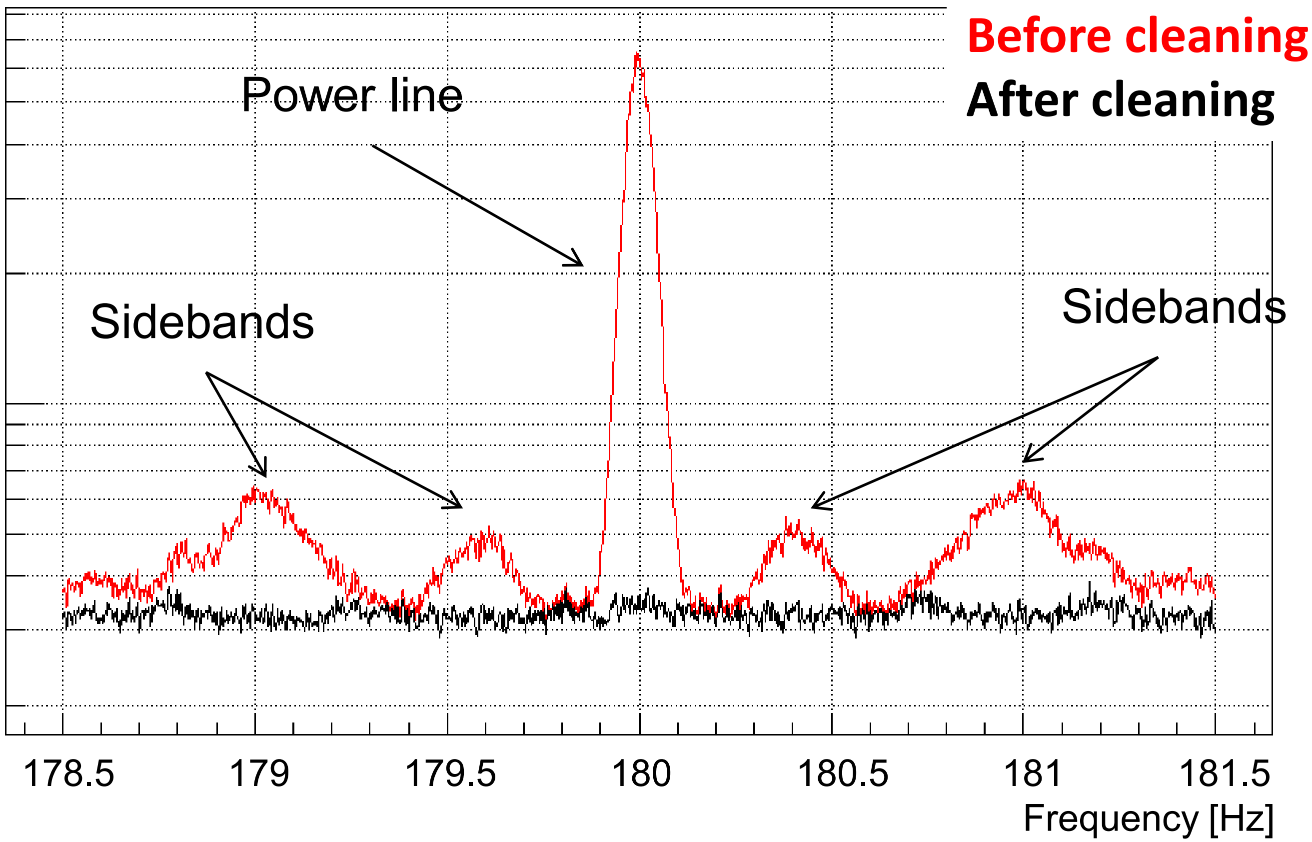
The following tests are performed on
8 days of data collected by
LIGO Hanford 4km detector
on May 2007 scientific run

Power lines + sidebands cleaning

- Simple case
  - Power lines are well monitored by power monitors or magnetometers
  - Sidebands originated by non linear coupling with low frequency disturbances
  - Sidebands can be predicted by mixing two channels:
    - $b_{xy}[i] = x[i] \cdot y[i]$

      b: channel predicting side-bands
      x : "power line" monitor
      y: "low frequency" monitor
    - "low frequency" monitor channels: coil actuators on input and end mirrors (see extra slides)

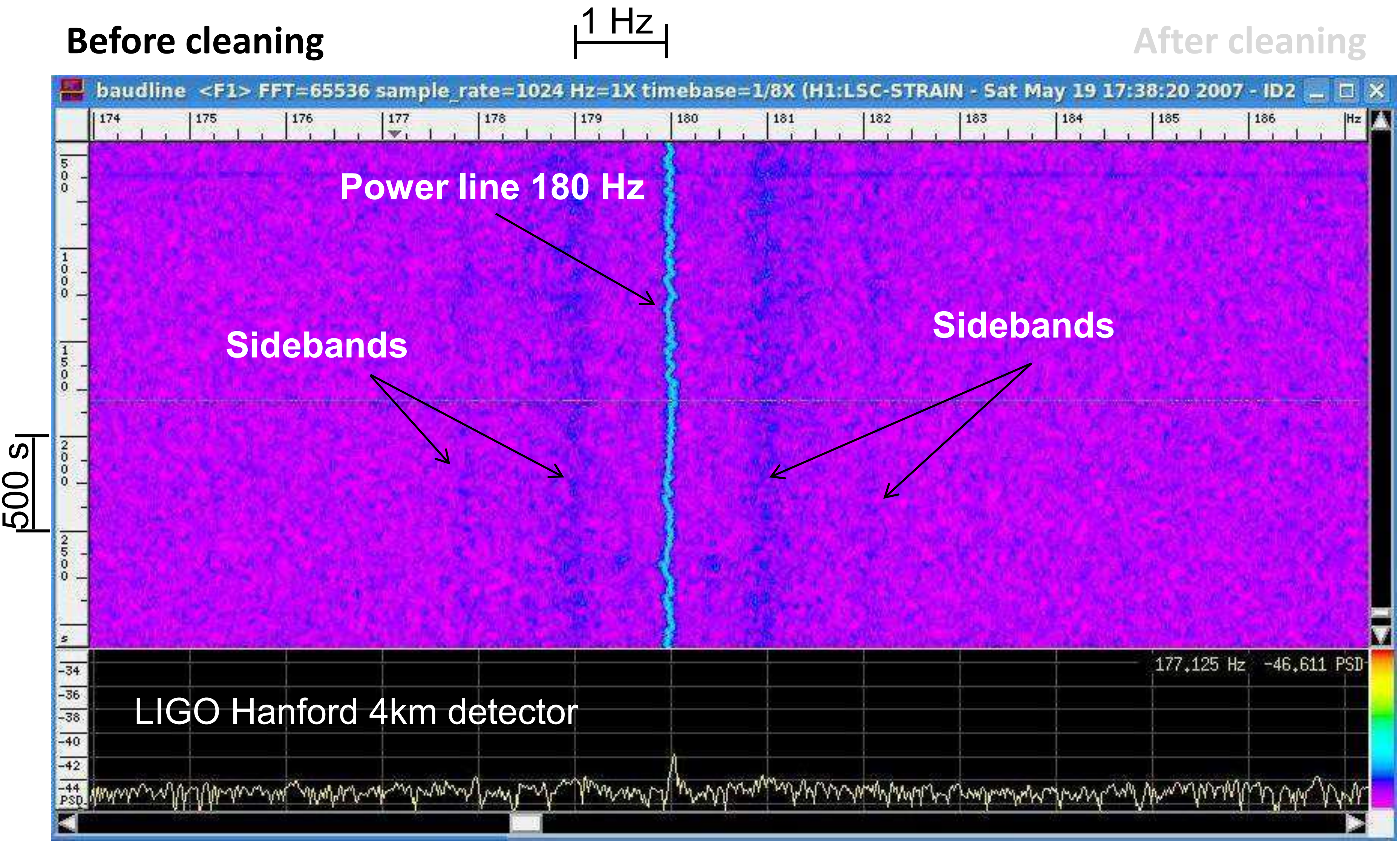
Example: Power line + sidebands (1)



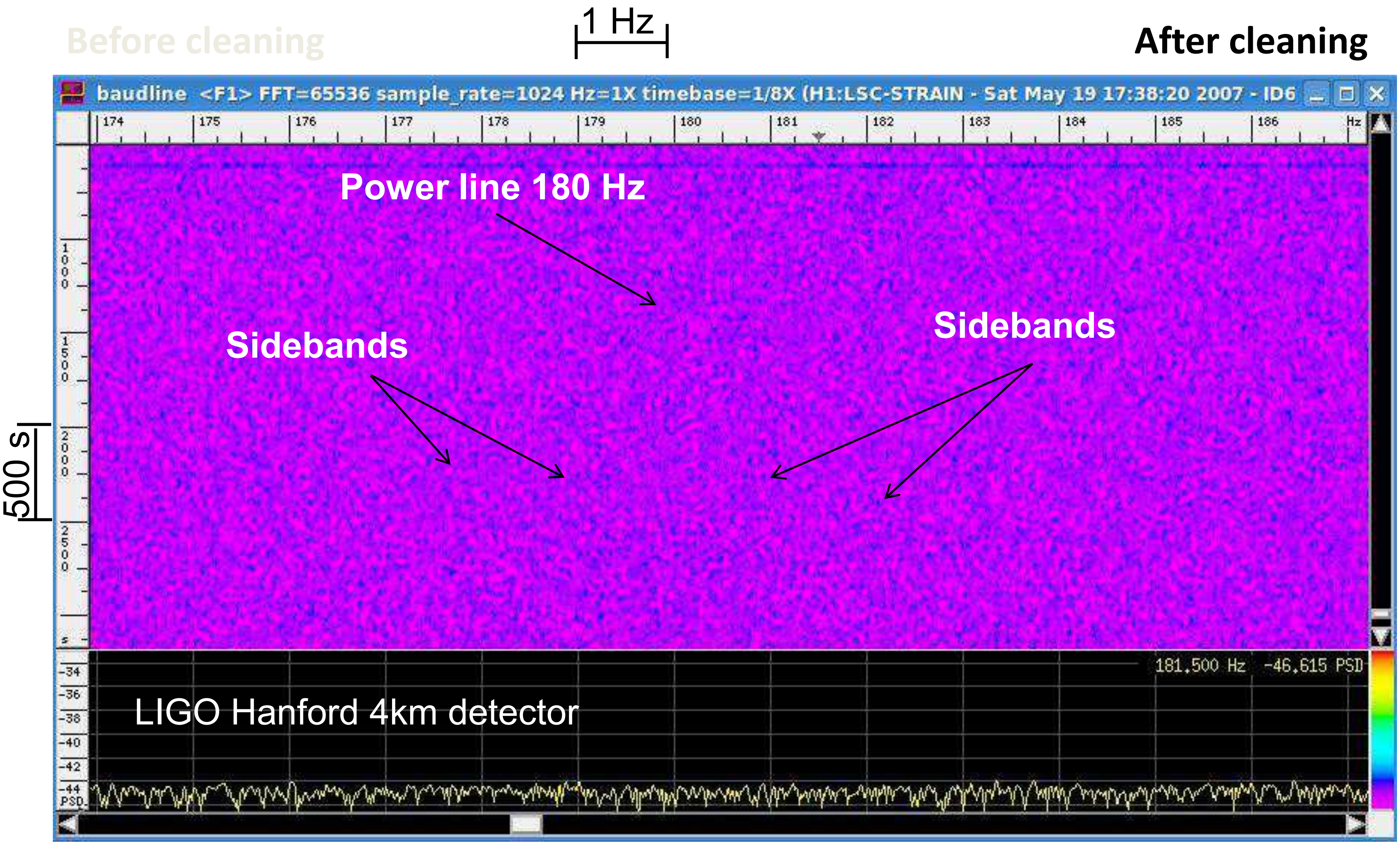
LIGO Hanford 4km detector
[LIGO-G1200288-v1]

Example: Power line + sidebands (2)

Before cleaning After cleaning



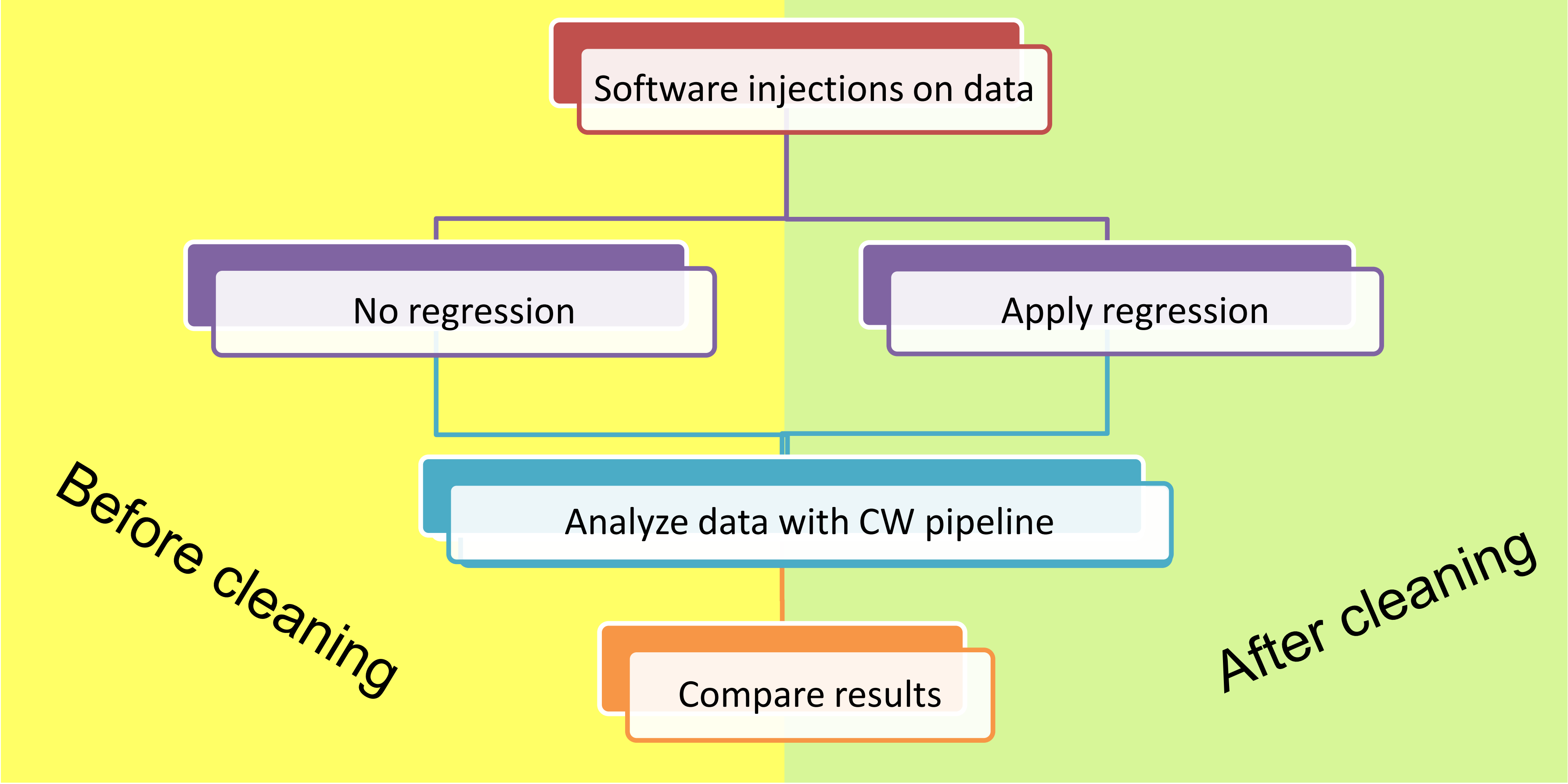
Example: Power line + sidebands (2)



Analysis Procedure

Inject Continuous Waves (CW) “pulsar-like” waveforms and verify the performances of search pipelines before and after the cleaning

Two search pipelines:	incoherent	[CQG 25, 184015 (2008)]
	coherent	[Astrophys. J. 737 (2011) 93]



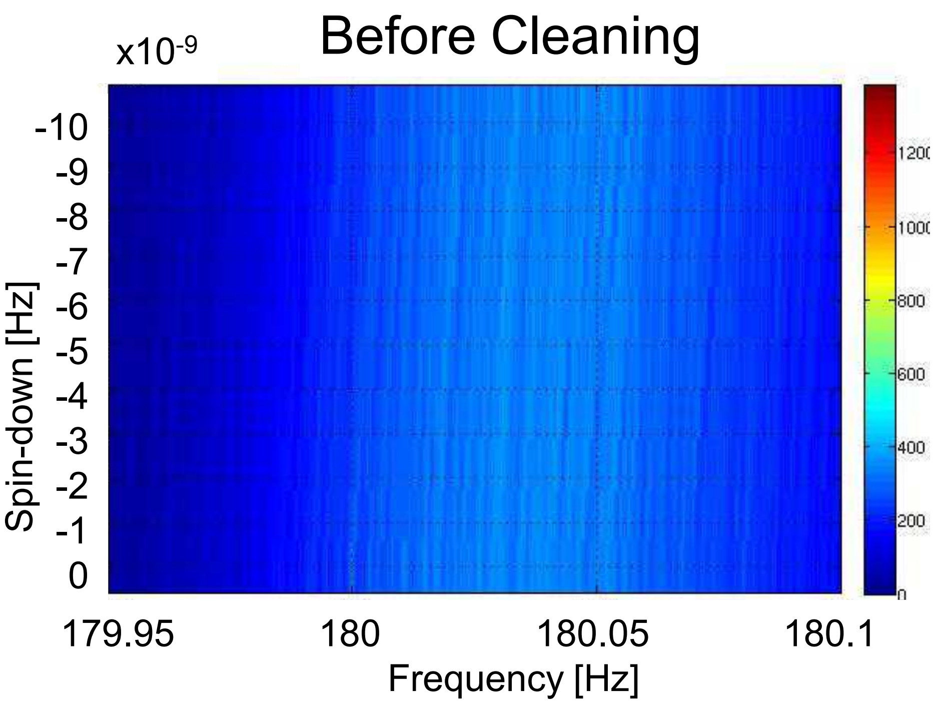
Software injections

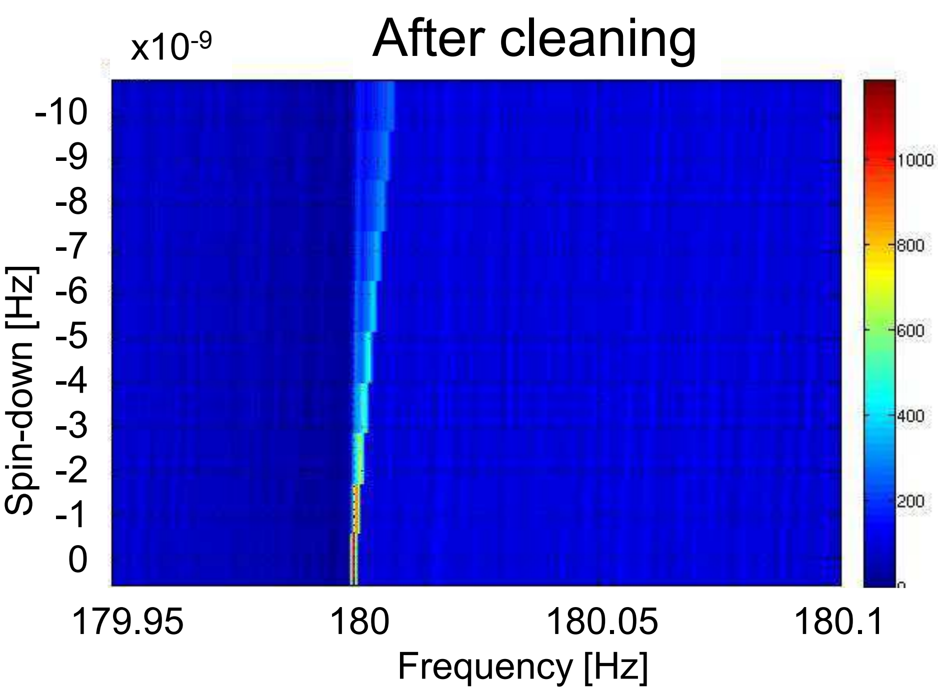
- Fifteen CW "pulsar-like" at frequencies near power lines
  - Same parameters for all (except H_0 e F_0)
    - H_0 *see table*
    - $\cos(\iota)$ 0.4629676
    - ψ (rad) -0.36395
    - ψ_0 (rad) 5.11905
    - RA_J (hh:mm:ss) 20:10:30.376
    - DEC_J (deg) -83:50:6.662
    - F_0 *see table*
    - $\dot{F}$ (Hz/s) -4.03e-18
    - P_{EPOCH} (mjd) 54239

F_0 (Hz)	H_0 (10^{-24})
30.00	30.0
29.74	30.0
60.00	6.5
60.49	19.0
59.55	6.5
90.51	14.0
90.29	14.0
90.00	14.0
89.55	4.9
120.47	6.5
120.00	19.0
119.44	19.0
150.48	23.0
150.00	8.2
149.50	8.2

Hough maps 180 Hz

Assuming the actual direction of the injected signal



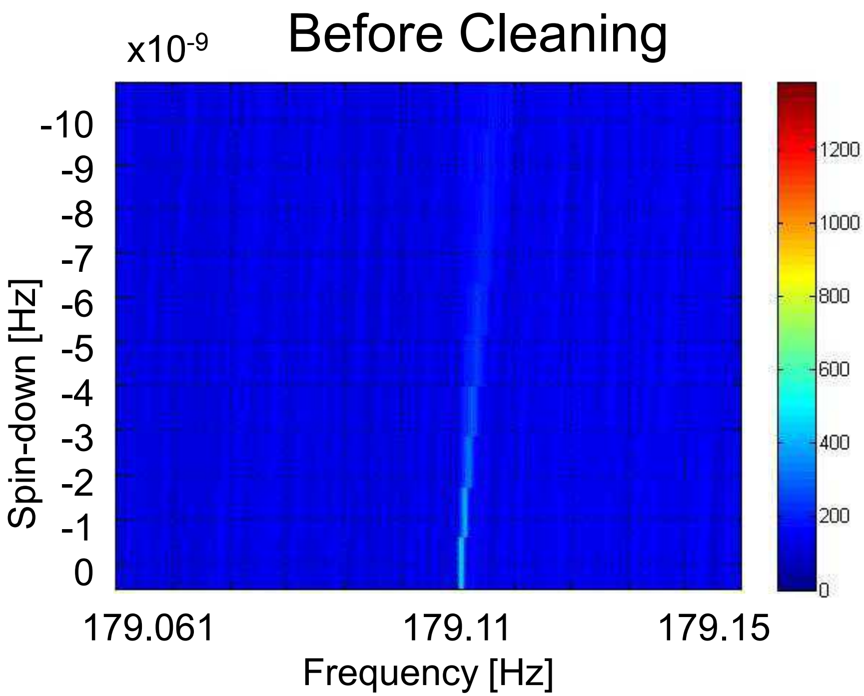


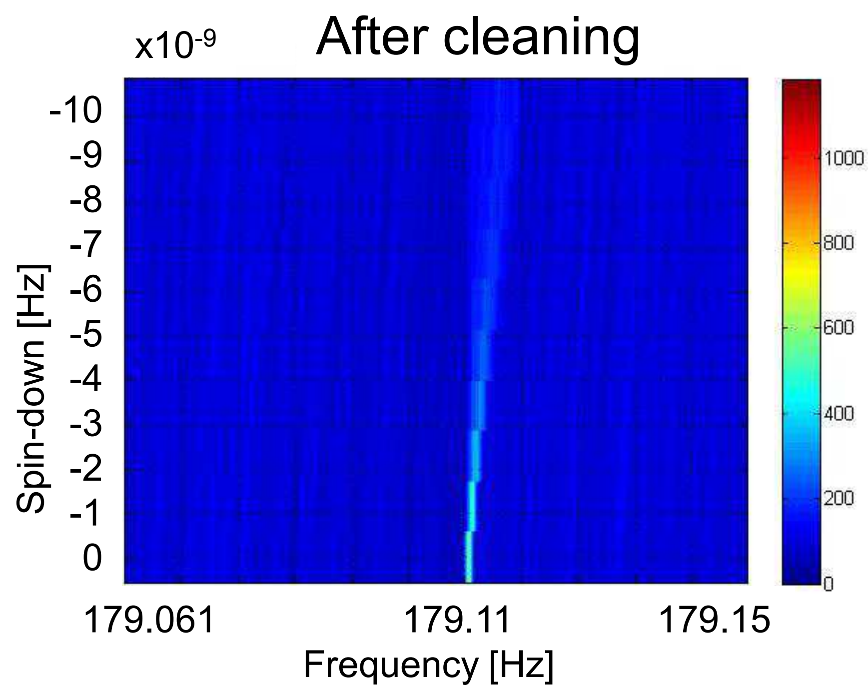
The injection below the power line becomes visible after cleaning

For other power lines performances are similar

Hough maps 179.11 Hz

Assuming the actual direction of the injected signal

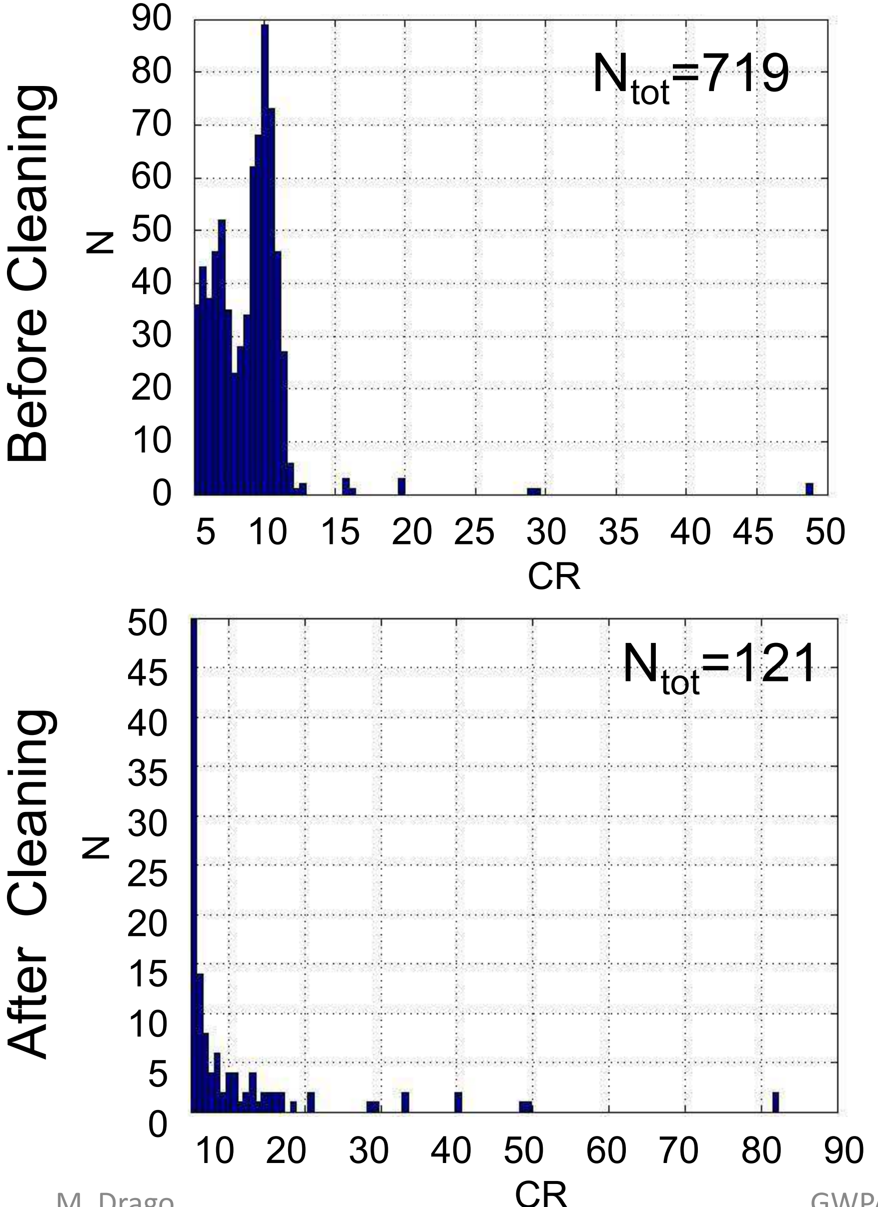




Injection below sidebands shows higher signal to noise ratio after cleaning.

This effect depends on noise suppression for each sideband

Hough candidates [115-125 Hz]



Critical Ratio (CR): ratio of excess signal to noise

- General observations:
  - Cleaning does not introduce artifacts
  - The number of candidates (N_{tot}) decreases after the cleaning

- *The decrease of spurious candidates is not crucial for the results of the analysis.*
  (This stage is a preliminary selection)

PRELIMINARY RESULTS

Critical Ratio (CR)

Injected pulsar Frequency (Hz)	Before cleaning	After cleaning
59.4923	19.0	38.5
119.1132	19.5	40.1
120.0	-	16.3
120.9851	49.0	82.3
179.1107	12.2	29.6
180.0	11	68.2
180.5992	46.3	71.0
181.0347	41.2	71
238.8843	44.8	75.8
240.0	12.3	78.7
240.9532	12.6	40.3
299.0056	25.6	42.1
300.0	18.3	37.4
300.9755	76.2	86.9

Power lines

Assuming the actual direction of the injected signal

General observations:

- CR is systematically increased after the cleaning
- Greatest effect under the power lines (red)

PRELIMINARY RESULTS

Estimated waveform amplitude

Before cleaning (yellow rows) / After cleaning (blue rows)

Frequency	H_0/h_{inj}	SNR gain
59.4923	0.87	1
	0.86	
119.1132	0.96	1.18
	0.95	
120.9851	0.96	1.23
	0.94	
179.1107	0.96	1.44
	0.96	
180.5992	0.98	1.02
	0.98	
181.0347	0.97	1.58
	0.96	
180.0	1.02	9.3
	0.89	
120.0	1.06	5.0
	0.93	

General observations on sidebands:

- Estimated amplitudes before and after the cleaning are compatible (within 1% systematic)
- The estimated SNR after the cleaning is greater than before of a factor 1.2 ÷ 1.5

Results on power lines should be better studied

PRELIMINARY RESULTS

Estimated waveform parameters

Before cleaning

After cleaning

Frequency	$\Delta\eta$	$\Delta\psi/90$
59.4923	-0.020	0.011
	-0.009	0.022
119.1132	0.030	-0.013
	0.004	-0.037
120.9851	0.002	0.011
	0.0008	0.012
179.1107	-0.007	0.011
	-0.007	0.009
180.5992	-0.005	0.0026
	-0.007	0.0048
181.0347	0.007	-0.019
	-0.02	0.001
180.0	0.03	0.082
	-0.004	0.0033
120.0	0.038	-0.068
	-0.0076	0.007

η: $-h_x/h_+$
ψ : polarization angle
Δ: difference between estimated value and injected one

General observations:
- The parameter reconstruction is not worsened by the cleaning. For most cases (especially for η) it is equal or improved (red numbers)

PRELIMINARY RESULTS

Summary and plans

Preliminary tests are encouraging

Must be extended:

- Test on over longer times (more than 8 days)
- More CW injections
  - Study parameter reconstruction
  - Study possible biases or artifacts induced by regression
- Test on Hardware injections
- Collaborate with commissioners to extend the cleaning to other frequency bands
  - Trace relevant environmental channels
- Development of the method
  - Optimizing filter length and training time
  - Optimize the coupling estimator