Polgraw – Virgo group

and its contribution to gravitational wave searches

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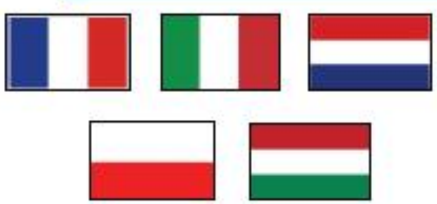
SMART INSTRUMENTS

DCC: G1400665

APC Paris
ARTEMIS Nice
EGO Cascina
INFN Firenze-Urbino
INFN Genova
INFN Napoli
INFN Perugia
INFN Pisa
INFN Roma La Sapienza
INFN Roma Tor Vergata
INFN Trento-Padova
LAL Orsay – ESPCI Paris
LAPP Annecy
LKB Paris
LMA Lyon
NIKHEF Amsterdam
POLGRAW(Poland)
RADBOUD Uni. Nijmegen
RMKI Budapest

5 European countries
19 labs, ~200 authors



- Advanced Virgo (AdV): upgrade of the Virgo interferometric detector of gravitational waves
- Participated by scientists from Italy and France (former founders of Virgo), The Netherlands, Poland and Hungary
- Funding approved in Dec 2009
- Construction in progress. End of installation: fall 2015
- First science data in 2016

Polgraw-VIRGO

Institutions in Poland:

Białystok: UwB

Toruń: UMK

Warsaw: CAMK, IMPAN, NCBJ, OA UW

Wrocław: SI sp. z o.o. , UWr

Zielona Góra: WFiA UZ

Members:

7 scientists , 1 engineer, 1 PhD, 3 technicians

Main contribution:

Data analysis, electronic engineer , vacuum system

Main tasks:

Data analysis, astrophysics, organizations of meetings

Funding: 2010-2014 (grants from NCN and FNP)

The GW network of the Advanced detectors

Collaboration with LIGO Scientific Collaboration (LSC)

Virgo project collaborates closely with the American LIGO project which has two large interferometric detectors with 4km arms.

Like Virgo detector, the LIGO detectors are currently being upgraded to advanced configuration and are expected to start collect data at the end of the year 2015.

By memorandum of understanding between the two projects all analysis of data from the Virgo and LIGO detectors is performed jointly by common data analysis groups.

All publications concerning searches of gravitational wave signals in data of the detectors are signed by all members of the collaborations.

FUNCTIONS:

A.K. – Member of Virgo Steering Committee and LSC-Virgo Data Analysis Committee
A.K. - Virgo co-chair of LSC-Virgo Continuous Waves Group
Tomek Bulik – Virgo co-chair of LSC-Virgo Burst Group review committee

F-statistic all-sky search for continuous gravitational waves in Virgo VSR1 data

Andrzej Królak

On behalf of the

LIGO Scientific Collaboration

and

Virgo Collaboration

http://arxiv.org/abs/1402.4974 (CQG in print)

Continuous GWs from spinning neutron stars

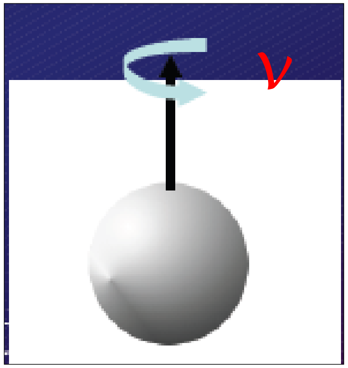
Characteristics:

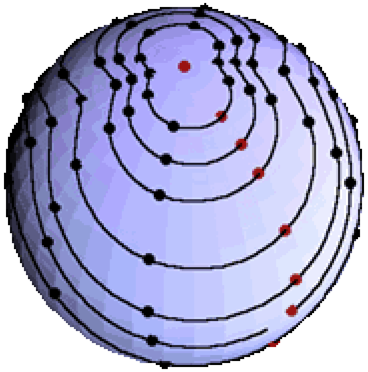
1. Long-lived: $T > T_{obs}$

2. Nearly periodic: $f_{GW} \sim \nu$

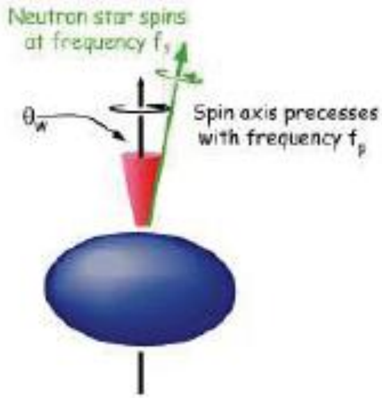
Generation mechanisms (we need a time varying quadrupole moment):

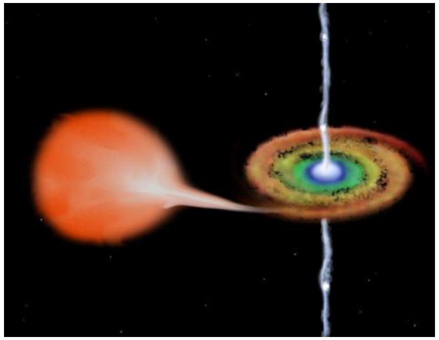
1. *Mountains*
   (elastic stresses, magnetic fields)
2. *Oscillations*
   (r-modes)
3. *Free precession*
   (magnetic field)
4. *Accretion*
   (drives deformations from r-modes, thermal gradients, magnetic fields)





Courtesy: B. J.Owen





Courtesy: McGill U.

List of people from Polgraw-Virgo group that contributed to this work:

M. Bejger, K. Borkowski, P. Jaranowski, A. Królak, O. Dorosh, M. Piętka (reviewers: D. Busculic, M. Pitkin)

Introduction and data from the Virgo's first science run

- Paper presents results from a wide parameter search for periodic gravitational waves from spinning neutron stars using data from the Virgo detector.

- Data were produced during Virgo's first science run (VSR1) which lasted more than four months.
  VSR1 run
  - started on May 18, 2007 at 21:00 UTC,
  - ended on October 1, 2007 at 05:00 UTC.

- Detector was running close to its design sensitivity with a duty cycle of around 81.0%.

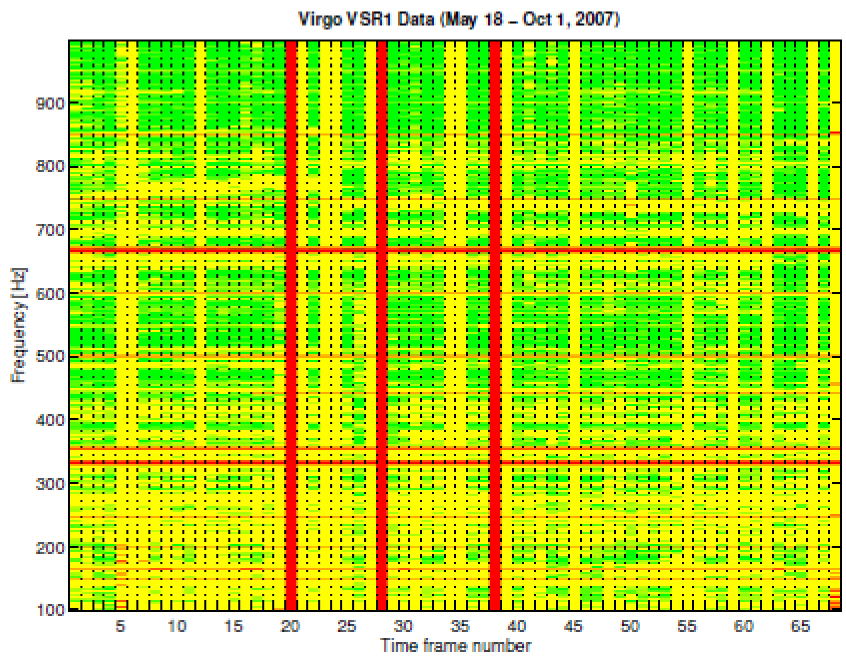
Data selection

- Input - 2-day long, 1 Hz wide time domain segments of VSR1 data with $N = 344656$ data points each

- Segment analyzed if two criteria are met:
  1. $N_0/N < \frac{1}{4}$,
  2. $S_{\max}/S_{\min} \leq 1.1$,

  where N_0 is the number of zeros in a given data segment, $S_{\max}$ and $S_{\min}$ are the minimum and the maximum of the amplitude spectral density in the segment band.

20419 data segments were selected for the analysis by the two criteria:



Response of the detector and the $\mathcal{F}$-statistic

Based on P. Jaranowski, A. Królak and B. F. Schutz 1998 Phys. Rev. D 58 063001

Response of the detector

- ⋆ Detector response is a nearly periodic amplitude and phase modulated function
- ⋆ There are two amplitude modulation functions $a(t)$ and $b(t)$. They depend on the location and orientation of the detector on the Earth and on the position of the gravitational-wave source in the sky, (right ascension α, declination δ angles). They are periodic functions of time with the period of one and two sidereal days.
- ⋆ The phase modulation reads

$$\phi(t) = \omega_0 t + \omega_1 t^2 + \frac{\mathbf{n} \cdot \mathbf{r}_d(t)}{c}(\omega_0 + 2\omega_1 t),$$

$\mathbf{r}_d(t)$ - vector joining SSB with the detector
$\mathbf{n} = (\cos\delta\cos\alpha, \cos\delta\sin\alpha, \sin\delta)$.

Response of the detector and the $\mathcal{F}$-statistic cont.

$\mathcal{F}$-statistic (generalized periodogram)

For the observation time T_{obs} equal to an integer multiple of days it takes the simplified form:

$$\mathcal{F} = \frac{2}{\sigma^2}\left(\frac{|F_a|^2}{\langle a^2\rangle} + \frac{|F_b|^2}{\langle b^2\rangle}\right),$$

where σ^2 is the variance of the data $x(t)$,

$$F_a := \sum_{t=1}^{N} x(t)\, a(t) \exp[-\mathrm{i}\phi(t)],$$

$$F_b := \sum_{t=1}^{N} x(t)\, b(t) \exp[-\mathrm{i}\phi(t)],$$

$$\left\langle a^2 \right\rangle = \sum_{t=1}^{N} a(t)^2, \;\; \left\langle b^2 \right\rangle = \sum_{t=1}^{N} b(t)^2.$$

Description of the search

The search consists of two parts:

A coherent search

of 2-day data segments over a 4-parameter space spanned by

- ⋆ angular frequency ω_0,
- ⋆ angular frequency derivative ω_1,
- ⋆ declination δ,
- ⋆ right ascension α.

We set a fixed threshold of 20 for the $\mathcal{F}$-statistic for each data segment corresponding to a threshold of 6 for the signal-to-noise ratio ρ. All the threshold crossings are recorded together with corresponding 4 parameters of the grid point and the signal-to-noise ratio.

Post-processing stage

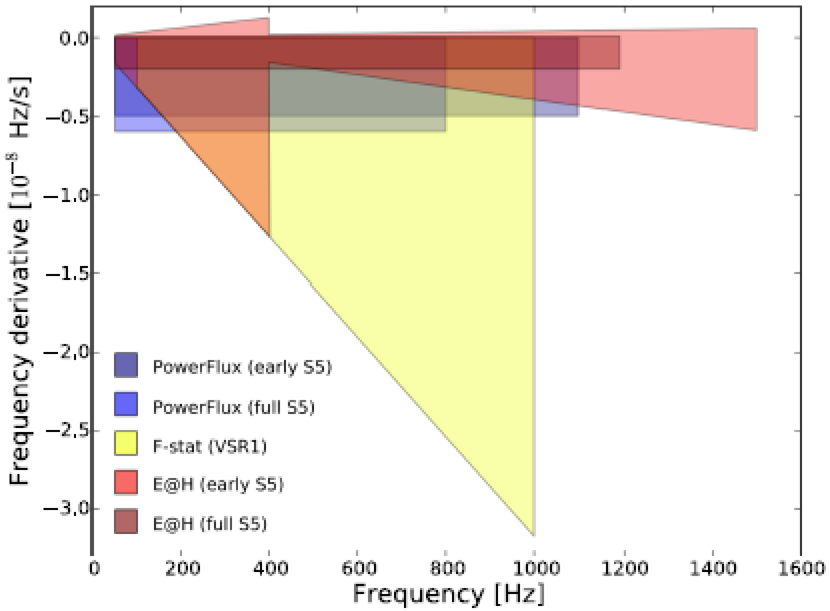
consists of vetoing of the candidates and a search for coincidences among the candidates.

Parameter space

- ⋆ All-sky search
- ⋆ Frequency band f_0: $[100, 1000]$ Hz.
- ⋆ Spin-down f_1 range:

$$[-1.6 \times 10^{-9} \frac{f_0}{100\text{Hz}},\ 0]\ \text{Hz s}^{-1}$$

Comparison of the $f_0 - \dot{f}$ plane searched (yellow) with that of other recent all-sky searches:



Efficient calculation of the $\mathcal{F}$-statistic on the grid in the parameter space

P. Astone, K. M. Borkowski, P. Jaranowski, M. Piętka and A. Królak 2010
Phys. Rev. D 82 022005

Two methods:

a) Resampling of the data to barycentering time according to

$$t_b := t + \frac{\mathbf{n} \cdot \mathbf{r}_d(t)}{c}$$

($\rightarrow$ $\mathcal{F}$-statistic can be evaluated with the FFT).

b) Application of an approximate (so called *linear*) model h_{lin} of the response where we neglect the amplitude modulation as well as the part of vector $\mathbf{r}_d(t)$ perpendicular to the ecliptic:

$$h_{lin}(t) = A_0 \cos[\phi_{lin}(t) + \phi_0],$$

where A_0 is constant and ϕ_{lin} is a linear function of the 4 parameters.
($\rightarrow$ The optimal uniformly spaced grid can be constructed).

Grid constraints:

1. Grid points coincide with the Fourier frequencies (for FFT)
2. Resampling for each sky position only once for all the spindowns (for speed)

Resulting lattice has only 20% more grid points than the optimal lattice.

Coincidences

Candidate follow-up method was a search for coincidences among candidates in different time frames. This method was applied in the first two E@H searches.

1. Firstly we transform all frequencies ω_0 of the candidates to a common fiducial reference time t_f chosen to be the time of the first sample of the latest time frame that we analyzed *i.e.* the 67th time frame.

$$\omega(t_f) = \omega_0(t_l) + 2\,\omega_1(t_l)[67\,T_{\mathrm{obs}} - t_l],$$

   where t_l is the time of the first sample of the lth time frame.

2. Secondly we divide the parameter space into cells. To construct the coincidence cell we use the reduced Fisher matrix $\tilde{\Gamma}$ for the linear signal model. We define the cell in the parameter space by the condition:

$$\sum_{k,l} \tilde{\Gamma}_{kl}\kappa_k\kappa_l \leq 2.$$

   where κ_k are the 4 parameters. Because $\tilde{\Gamma}$ has constant coefficients the coincidence cell grid is uniform.

Coincidence algorithm

1. Transform astrophysical parameters to coordinates of the reduced Fisher matrix $\tilde{\Gamma}$
2. Coordinates are rounded to the nearest integer. In this way we sort candidates efficiently into adjacent 4-dimensional hypercubes. If there are more than one candidates form a given data segment in a hypercube we select the candidate with ~~has~~ the highest SNR. We do sorting for each time frame in the band. If there is more than one candidate in a given hypercube we register a coincidence.
3. We shift cubes by 1/2 of their size in 2^4 directions, and for each shift we search for coincidences.

Step 3 takes into account cases for which the candidate events are located on opposite sides of cell borders, edges, and corners and consequently coincidences that could not be found just by packing candidates into adjacent cells.

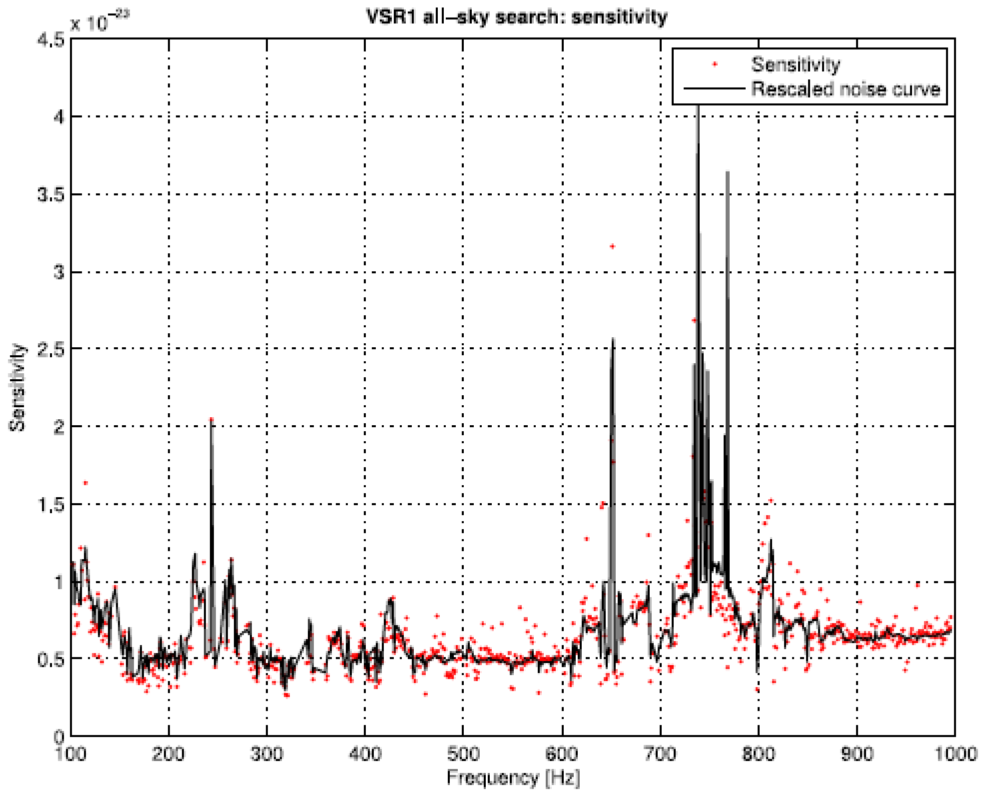
The search

- 20419 two-day time segments of data narrowbanded to 1 Hz searched using the $\mathcal{F}$-statistic
- 9.10×10^{16} templates applied (the number of $\mathcal{F}$-statistic values computed)
- 20419 candidate files obtained containing 4.21×10^{10} candidates.
- Vetoing applied using the three veto criteria: *line veto, polar caps veto, and stationary line veto*. 24% of the candidates vetoed (mostly by line veto), leaving 3.19×10^{10} candidates.
- Candidate searched for the significant coincidences.
- The most significance coincidence occurred in the frequency band [488.4, 489.4] Hz. It had multiplicity = 5 and its false alarm probability was 14.5%.

By adopting a criterion similar to the one used by E@H searches that the background coincidences correspond to the false alarm probability of 0.1% or greater we conclude that we have found no significant coincidence and thus no viable gravitational wave candidate.

Sensitivity of the search

Sensitivity of the search estimated through the Monte Carlo simulations by injecting signals to the data:



Sensitivity reflects the instrumental noise curve

$$h_0^{90\%} = R_{\mathcal{D}} \sqrt{\frac{S_h(f)}{48 \text{ hours}}},$$

where $15.6 < R_{\mathcal{D}} < 22.4$, and depends on the frequency band and the number of the data segments in the band.

For large parts of the VSR1 data band we achieve sensitivity in the range $5 - 6 \times 10^{-24}$

Conclusions

We plan to use our pipeline to search for GW signals from rotating neutron stars in data form Observational Run 1 (O1) of LIGO detectors that should start in September (June) 2015.

At the moment we are testing our pipeline by analysisng simulated gravitational wave signals added to LIGO S6 data.

We are optimizing our codes and adpating them to run on very big computing clusters.
In paper: *Architecture, implementation and parallelization of the software to search for periodic gravitational wave signals,* submitted to Computational Physcis Communications, we present a parallelized version of our basic code that can run on 1Pflops machines.