Gravitational wave detection with Virgo and LIGO experiment - Case of the long bursts

Samuel Franco
Supervisor: Patrice Hello

Laboratoire de l'Accélérateur Linéaire (Orsay)

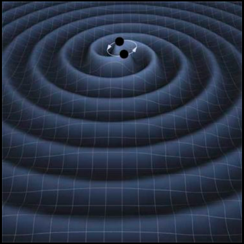
06/12/2013

Outline

1. A word about gravitational waves
2. The Virgo and LIGO experiments
3. Data analysis: detection of long transients (a.k.a. my thesis)

You said gravitational?

- Gravitational waves are perturbations of the space-time metric.



Credit: K. Thorne (Caltech), T. Carnahan (NASA GSFC)

- **Their advantage:** they interact very weakly with the rest of the Universe. They can therefore be a precious vector of information about their emitters.
- **Their disadvantage:** they interact very weakly with the rest of the Universe.

What are you looking for?

- The power emitted by a gravitational wave source is given by:

$$P_{GW} \sim \frac{c^5}{G}\left(\frac{R_s}{R}\right)^2\left(\frac{v}{c}\right)^6\epsilon^2$$

  where R is the radius of the object, R_s its Schwarzschild radius, v its velocity, ϵ a parameter characterizing its asymmetry.
- An efficient emission implies a compact, relativistic and asymmetric progenitor.
- Impossible to create a gravitational wave emittor in a laboratory: for $\varepsilon = 1, R = 1\ m, M = 10^3\ kg, v = 300\ m.s^{-1}$ the resultant wave should have a luminosity of about $10^{-14} W$...
- Just compare to a 10 $M_\odot$ black hole collision: 10^{50} W!

Gravitational zoology

We can split up the gravitational waves sources into three main categories:

- **Stochastic background:** incoherent sum of waves in the close-by universe, primordial gravitational waves.
- **Continuous sources:** pulsars which emit gravitational waves continuously.
- **Transient sources:** excited compact objects. For instance:
  - Merging of a compact binary system
  - A proto-neutron star, directly after its formation during a supernovæ.
  - A black hole when formed or when perturbed by an infalling object.
  - Instabilities in accretion disks, cosmic strings...
- All of them are rare objects/events. We need a detector which "sees" far *i.e.* a very sensitive detector.

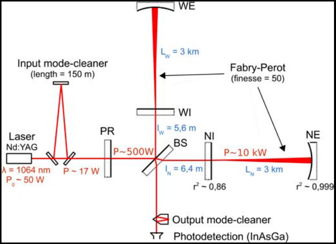
The Virgo Experiment, part I

- Located in *Cascina*, near Pisa, Italy.

Credit: Virgo

- It is basically a Michelson interferometer with arms 3 km long.

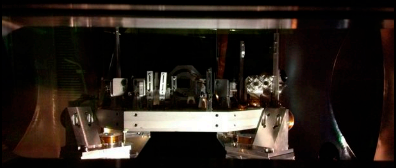
The Virgo Experiment, part II



Credit: Virgo

- When a wave goes through the interferometer, the space-time metric changes (differently) in each arm. Thus the optical path of the photons in each arm is different. This implies:
  - A phase shift of the laser, hence a shift of the interference pattern.
  - So a change in the detected power.
- The light intensity's change at the level of the dark fringe is proportional to the amplitude of the wave which induced it!

How does it actually look like?

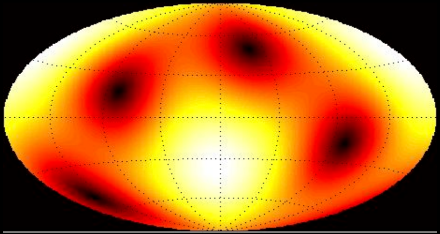


How sensitive?

$$\frac{\delta L}{L} = 10^{-21}$$

But how do you do astronomy?

- With one experiment: impossible. Each experiment has an antenna factor. For a source located in the direction of the arms' bisectors, the phase shift is null, this direction is blind.
- So you need at least 3 different interferometers to be able to triangulate your signal.



Virgo antenna function at a given date in galactic coordinates

The LIGO-Virgo network

From left to right: LIGO Livingston (Louisiana), LIGO Hanford (Washington) and Virgo

Long transients

- Signals of duration from a few seconds to a few weeks.
- Standard transient analysis focus on very short ($<$1s) signals.
- Astrophysical sources of long transients:
  - Eccentric black hole binaries
  - Accretion disk instabilities (ADI)
  - Neutron stars r-modes
  - and more...

The STAMP pipeline

- STAMP computes the auto and cross-correlation of the data from a couple of interferometers, and then generates frequency-time maps
- The most significant pixels are then clusterized generating the triggers.

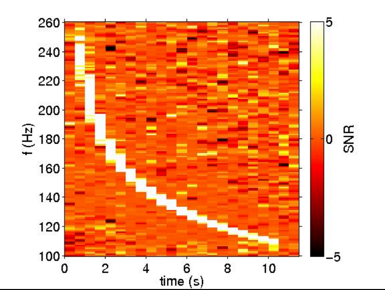


Figure : ft-map containing an injected Accretion Disk Instability waveform in Gaussian noise.

All-sky pipeline

- The purpose of the STAMP All-Sky (or STAMP-AS) pipeline is to adapt STAMP in order to cover the case of an unknown source position.
- The all-sky analysis, for a given pair of detectors, is structured as follows:
  1. A grid of sky positions to scan is chosen
  2. On each of these positions, we perform a STAMP search, which gives triggers.

Background estimation

- As in other fields, make a detection is to catch a signal significantly louder than the background noise, which is not due to an abnormal instrument behavior or to the direct environment (glitches).
- The more data, the more efficiency background can be estimated.
- To get an acceptable false-alarm rate (FAR), of the order of 10^{-9} Hz, (about three false alarms in a hundred years), we cannot wait until enough science data is produced, and we cannot simulate them either (because of the glitches).

Timeslides

- With a physical signal, you should have power left almost simultaneously in each experiment.
- To estimate the background *i.e.* accidental coincidences between power in the two experiments, we introduce a time shift between the two data strains before the correlation.
- All physical coincidences are removed, we have only accidental coincidences.

First results: Efficiency studies

- Results for a false alarm rate of 10^{-6} Hz (rate estimated over a week of S5 data, shifted a 100 times).
- Pipeline begins to be sensitive to our signals for sources distant from 5 to 20 Mpc, depending on the waveform we use (reminder: 1 pc = 3.26 light-years)

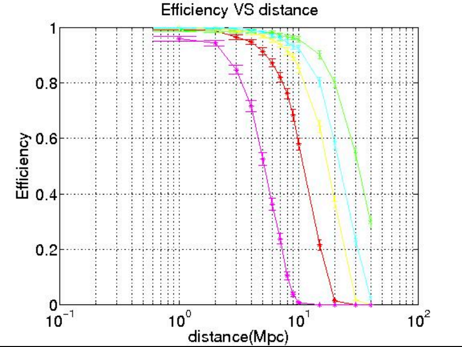


Figure: Efficiency curves for different ADI waveforms.

What's next?

- Pursue the study over an entire science run (about 1 year of data). Beginning this week! Results in March.
- Look at the non-shifted data. If we have a candidate: a lot of work to do to understand it.
- If we don't, we can set upper limits: knowing the state of our detector, we can say that the event rate of the sources we are studying cannot be higher than a certain threshold, otherwise we would have seen something.
- Even with a non detection, there is good physics to be done!

Summary

- Gravitational waves are a new astronomical messenger. They are emitted by dense, relativistic and asymmetric objects (neutron stars, black holes..)
- Virgo is a Michelson interferometer designed to detect gravitational waves.
- STAMPAS is a new analysis pipeline dedicated to the search of signals never studied so far. Results coming soon!

On the paper

- In General Relativity, space-time structure is defined by a quantity named metric tensor, defined as:

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

where ds is the infinitesimal length element, dx the infinitesimal changes in coordinates vector and g the metric tensor.

- In a "flat" space, this metric tensor is:

$$g_{\mu\nu} = \eta_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

On the paper (II)

- A GW can be described, at first order, as a first order perturbation of the metric tensor:

$$g_{\mu\nu} = \eta_{\mu\nu} + \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+(t) & h_\times(t) & 0 \\ 0 & h_\times(t) & -h_+(t) & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

- The amplitude of the GW is defined as $h(t) = \sqrt{h_+(t)^2 + h_\times(t)^2}$

But are these things real?

- The Hulse-Taylor (PSR 1913+016) binary pulsar is the most famous evidence of their existence: this binary system has been observed for more than 30 years, and its orbital period is slowly decreasing with time.
- The GR predicts that the two pulsars are getting closer because the system loses energy due to the emission of gravitational waves.
- This prediction agrees remarkably well with the data (it is not a fit, it is a predicition!).

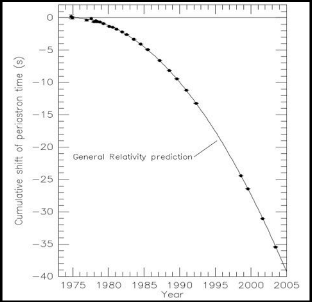
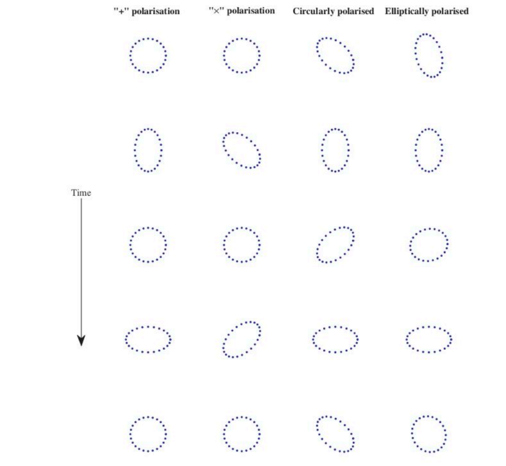


Figure : Decrease of the orbital period of the Hulse-Taylor binay pulsar, from arXiv:astro-ph/0407149

Effect of gravitational waves

- Consider a wave propagating in the direction orthogonal to the screen.
- The scheme presents the effect of a gravitational wave on a ring of test masses, according to its polarization (+, ×, circular or elliptical).



Credit: J. Clark (University of Glasgow)

Beauty of the design

- Each mirror of the experiment is suspended to a series of pendula to reduce the seismic noise above 10 Hz, to a level compatible with our designed sensitivity.
- Each arm is a Fabry-Perot cavity, which traps the light of the laser, making it travel a longer distance into the arms, which increases our sensitivity. It is equivalent to build a simple Michelson with 100 km long arms.
- Our design sensitivity: we are able to detect relative distance changes of about 10^{-21}!

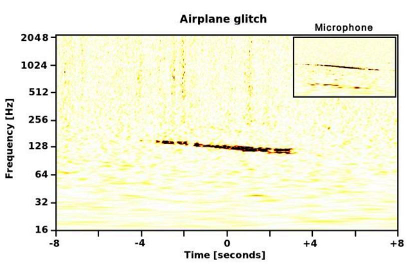
Data characterization

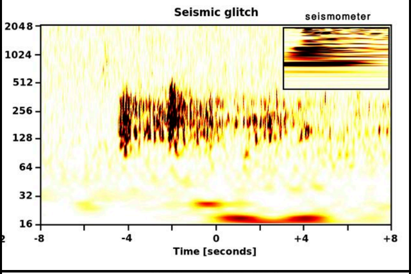
- An experiment like Virgo is extremely sensitive to noise, due to the fact that the signal we are looking for is very weak. Typically we look for a relative distnace change of 10^{-21}.
- To be able to raise our chances to actually make a detection, it is extremely important to know the noise in our detector, to understand it source, to be able to cancel it as quickly as possible. This is called noise hunting.

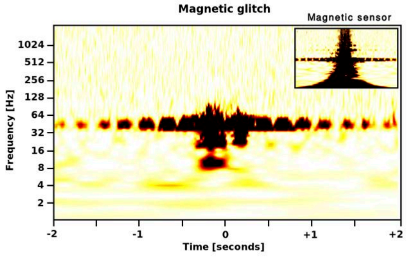
Noise Hunting

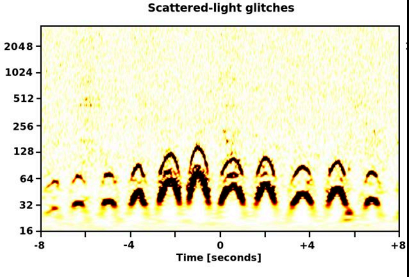
1. An event or a family of events with similar properties are detected in the physical channel
2. A check is done to correlate this event to either unusual detector behavior or human activities.
3. If it is not the case, we look for correlations between the physical channel and one or several auxiliary channels. This helps identifying the origin of the noise.
4. When the noise is understood, we try to either remove its source or lower its coupling with the physical channel.

Example of time-frequency maps

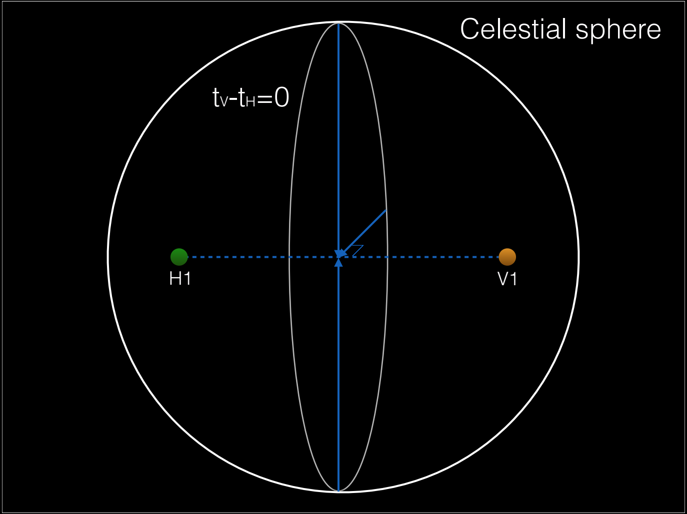








About phase degeneracy



The signals we are interested in

- Eccentric black hole binaries: signals emitted by a couple of black holes with eccentric orbits.
- Essentially accretion disk instabilities: generated by matter falling onto a dense body, forming a ring around it, in which instabilities occur.

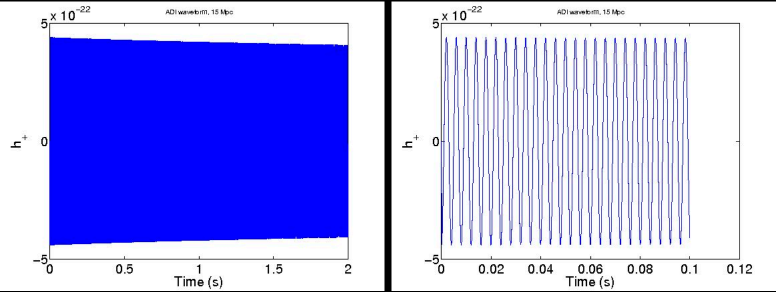


Figure : Accretion disk instability waveform

Example of skymap

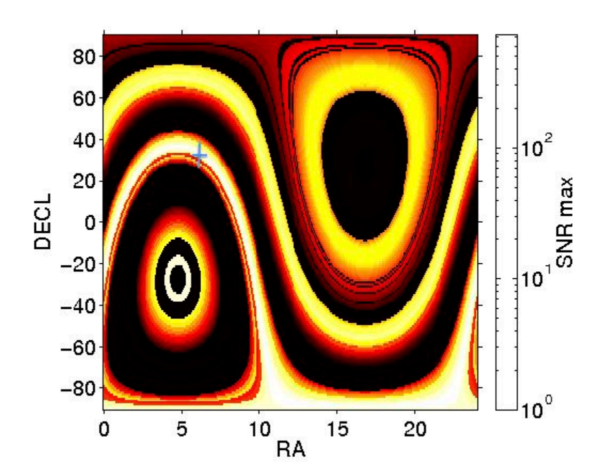
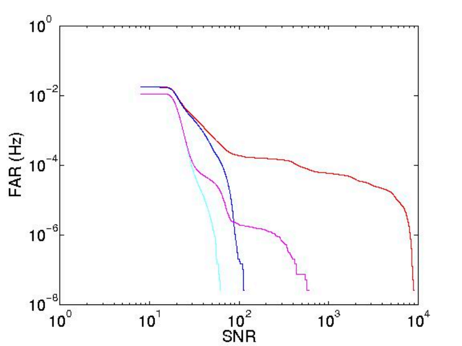


Figure : Skymap obtained with Hanford and Livingston detectors, with a strong injection at $\alpha = 6h$, $\delta = 30\ deg$.

First results: Background studies

False alarm rate estimate over one week of data from Hanford and Livingston experiments.

1. Red: Raw data
2. Magenta: Triggers with frequencies above 200Hz
3. Blue: Triggers with loudest identified glitches removed
4. Cyan: (2) and (3) combined



Advanced Detector Era

- So far no detection has been made. Which was expected.
- On-going technical upgrades of both Virgo and LIGO will make them 10 times more sensitive:
  - New mirrors
  - New suspension cables
  - New lasers ...
- The Advanced LIGO and Virgo detectors should be operational in respectively 2015 and 2016.
- Seeing 10 times further means we observe a volume 1000 times wider, and expect a detection rate between 1 event per year and a few events per month.