Earthquake Interferometer

Study earthquakes with
Virgo interferometer

Orientation Phase

Orienting and Asking Questions

Provide Contact with the content and/or provoke curiosity

Virgo Interferometer

The detection of Gravitational Waves (GW) and the discovery of their visible counterparts in 2016-17 has been one of the major scientific breakthroughs of the 21st century so far.

GWs has been predicted by the theory of general relativity. With that theory Einstein has changed our view of the force that apparently, physicists thought to know better: gravity.

He showed us that the concept of gravity that Newton introduced, had to be changed. Gravity is only a consequence of the change of geometry of space-time produced by all objects that have mass.

GWs are ripples of space-time, produced by the collapse of extremely dense astrophysical objects, like black holes of neutron stars. Those signals induce on the matter small variation of length (less than 10^{-18} m at 100 Hz) that can be detected only by the world most precise rulers, the interferometers.

Imagine to drop a glass of water in the ocean. Due to that the global level of all the seas on the Earth will increase by an extremely small amount. A rough estimate would lead you to this amazingly tiny displacement: 10^{-18} m!! This length is equivalent to the sensitivity of current gravitational wave (GW) detectors.

There only a few instruments on Earth that can reach such amazing level of sensitivity: the two LIGO detectors in the USA and Virgo, in Cascina, Pisa, Italy.

These detectors are huge! They have the shape of an L with a length of several kms on each side. Virgo, viewed from above in figure 1, is 3 km long while LIGO has of 4 km length.

Figure 1 Aerial View of Advanced Virgo (EGO/Virgo collaboration)

Virgo and LIGO changed the history of science twice: first, when they measured for the first time the gravitational waves in 2015, discovery that was awarded with the 2017 Nobel prize in physics, then, when, on August 17th, 2017, they were able to detect the signals produced by a binary neutron star.

This kind of binary star, composed by two extremely dense objects made only by neutrons, collapsing becomes a single object that emits gamma rays and visible light. The radiation produced by these strange objects were never detected before. In August 2017 Virgo and LIGO were able to localize the position of the gravitational wave source with such a precision that all the telescopes of the world were able to point a very narrow region of the sky. They all found a new star as shown in figure 2.

This discovery marks the beginning of a new era in the history of astronomy. Thanks to the gravitational waves now we are not only able to study the astrophysical objects already present in the Universe, we can also predict their birth!

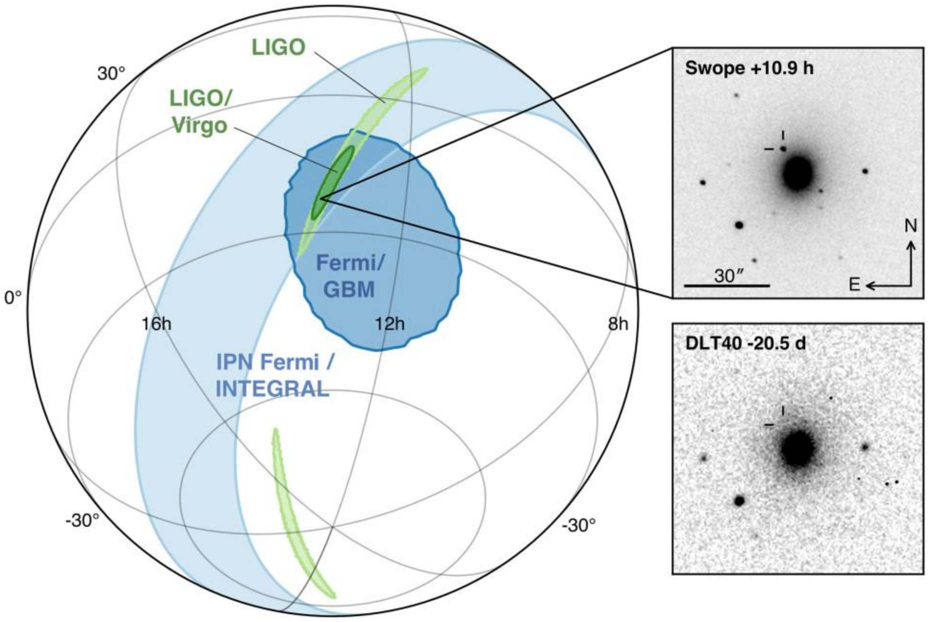


Figure 2 The impressive contribution of Virgo to the localization of the star, shown in top right plot, that was born after the GW signal of August 17th 2017.

Teacher Guidelines:

You may begin your lesson using the set of slides that will be provided. Trigger a small conversation with your class by asking your students the questions mentioned below and others like them.

- What is gravity? What Einstein understood about gravity?
- What are black holes? What are neutron stars?
- What are gravitational waves? Who won the 2017 Nobel prize for physics and why?
- What is Virgo?
- How does it work?

The answers will be given in the next sections and will constitute the introduction to the installation of your control room.

Exploratory Phase

Question or Statement

Define Goals and/or questions from current knowledge

- What are gravitational waves?
- How does a gravitational wave detector work?
- What are the problems that we need to tackle in order to build it?

Generation of Hypotheses or Preliminary Explanations

Teacher Guidelines:

- Very nice explanation by B. Greene interviewed in a talk show: https://www.youtube.com/watch?v=ajZojAwfEbs
- R. Weiss talks about relativity and GWs: https://www.youtube.com/watch?v=x7rjlm4SH5U
- Simple Explanation with comics: https://www.youtube.com/watch?v=4GbWfNHtHRg
- Simple Explanation with sketches: https://www.youtube.com/watch?v=YHS9g72npqA

Step 1

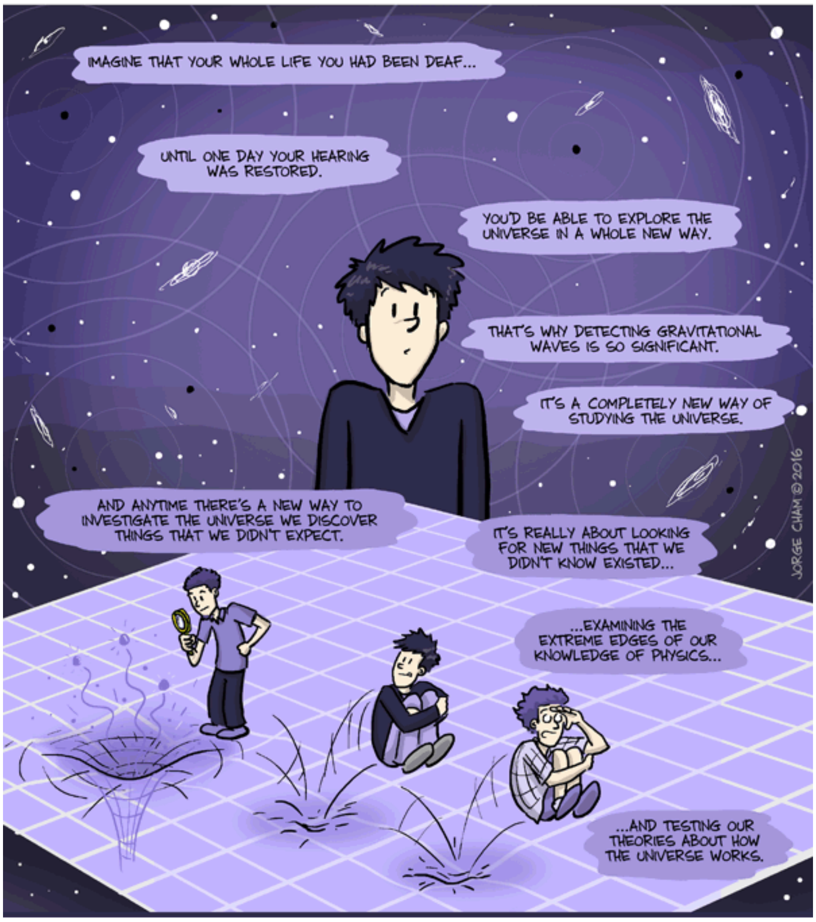


Figure 3 Astronomy status after gravitational wave detection.

What are gravitational waves?

Gravitational waves can be interpreted as the music of the universe. These signals have been predicted by general relativity, a scientific theory, widely confirmed experimentally, that Einstein finished conceiving almost exactly 100 years ago, in 1916.

Relativity provides the most accurate description available of the force that holds the whole Universe together, gravity. This force, studied since ancient times, reached its first mathematical formulation with Isaac Newton's Principia Mathematica of 1687. This description assumed that massive bodies were attracted by a force, inversely proportional to the square of the distance, which acted instantly on them. However, Einstein was the first to understand that no signal can propagate in nature at a speed higher than that of light. He also understood that time is not an absolute quantity but depends on the reference system in which we are. In particular, the faster we move, the slower the hands of our watch will be ticking. Putting these and other concepts together, Einstein came to a purely geometric description of gravity. He understood that this force is simply the effect of the curvature of the intimate structure of the universe, the so-called space-time.

We can imagine space-time as an extremely rigid mattress, as big as the universe (figure 4). In the absence of massive bodies on it, the mattress is perfectly flat; but as soon as we put down a heavy object, like a bowling ball, it will curve near the object, forcing every lighter body, for example a ping-pong ball, to slide towards it or to spin around it. In other words, light bodies tend to move towards heavy bodies, not because they are attracted by a force, but because bodies of small mass move through space-time that is deformed by bodies of large mass.

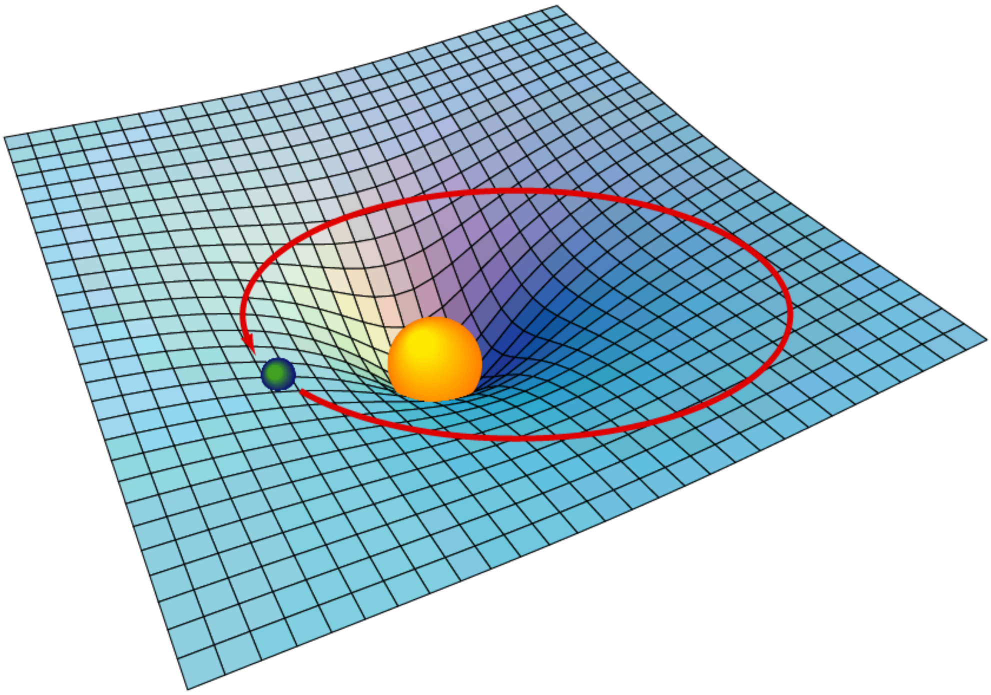


Figure 4 Space-time representation. A planet is orbiting around the Sun due to the geometrical deformation produced by the mass of the star.

If the mass of the objects and their speed are constant, the curvature produced does not change over time. However, if we imagine, for example, to instantly remove a massive body, the mattress, however rigid, will start to oscillate for a short time. These oscillations are called gravitational waves.

The astronomical events that produce gravitational waves of greater intensity are the explosion of supernovae or the fusion of the remains of dead stars like neutron stars or black holes. Near these latter objects the gravitational field is so intense that the light itself cannot escape them.

The effect of gravitational waves on matter is to dynamically distort space-time at the wave frequency, changing the size of the bodies the wave crosses. This deformation attenuates linearly with the distance and becomes very small when it reaches us. In fact, when Einstein foresaw the existence of gravitational waves, and calculated its effect, he concluded that no detector would be ever built sensitive enough to reveal them.

Step 2

We can actually detect gravitational waves!

Fortunately, Einstein was wrong: today three powerful optical instruments, called interferometers, can observe these signals produced by the universe and to localize their origin.

Two of these instruments, both called LIGO, are in the United States, one in Louisiana, the other in the state of Washington, while the third, Virgo, is in Italy, in Cascina, in the province of Pisa. The three experiments work together as a single detector sharing data.

Virgo was inaugurated in 2003 and was born thanks to the collaboration between the Italian National Institute for Nuclear Physics (INFN) and the French equivalent of the CNR (CNRS). Today, 400 physicists, engineers and technicians from five countries work there in turn. The center is administered and managed by a consortium called European Gravitational Observatory (EGO).

Let's understand how an interferometer work!!

A laser interferometer is a very high-precision ruler!

The operating principle of all interferometers is quite simple (see figure 5). The light produced by a very powerful LASER (25 W for Virgo) passes through a semi-transparent mirror called beam splitter.

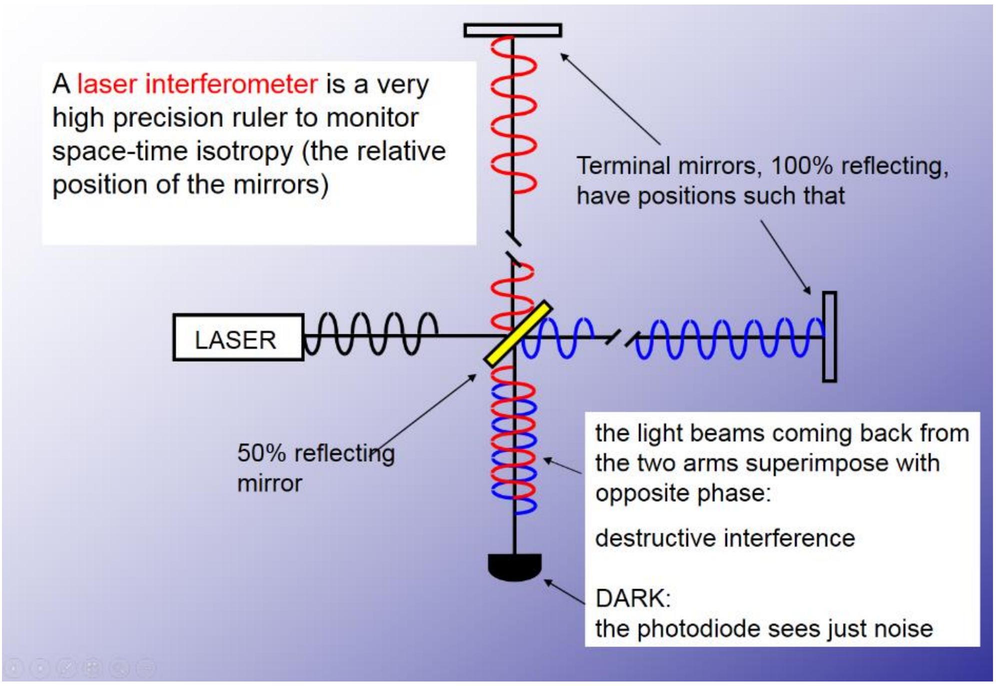
Why do we need a laser?

Using a LASER instead of a standard light source – like a LED for example - has several advantages. The main one is that the energy of the beam produced is concentrated almost entirely at one single frequency.

How does the interferometer work?

Half of the radiation emitted by the LASER crosses the beam splitter while the other half is reflected at 90 degrees. The two perpendicular beams run along the two arms of the L, 3 km long, at the end of which are reflected on two mirrors; they then go back, cross the beam splitter again and recombine on an optical bench equipped with a series of light sensors, called photodiodes.

The optical scheme is designed to have the two beams in phase opposition when they are recombined. The interferometer therefore works in an operating condition of destructive interference called dark fringe.



A laser interferometer is a very high precision ruler to monitor space-time isotropy (the relative position of the mirrors)

Terminal mirrors, 100% reflecting, have positions such that

50% reflecting mirror

the light beams coming back from the two arms superimpose with opposite phase:

destructive interference

DARK:
the photodiode sees just noise

Figure 5 Sketch of a Michelson interferometer

Step 2

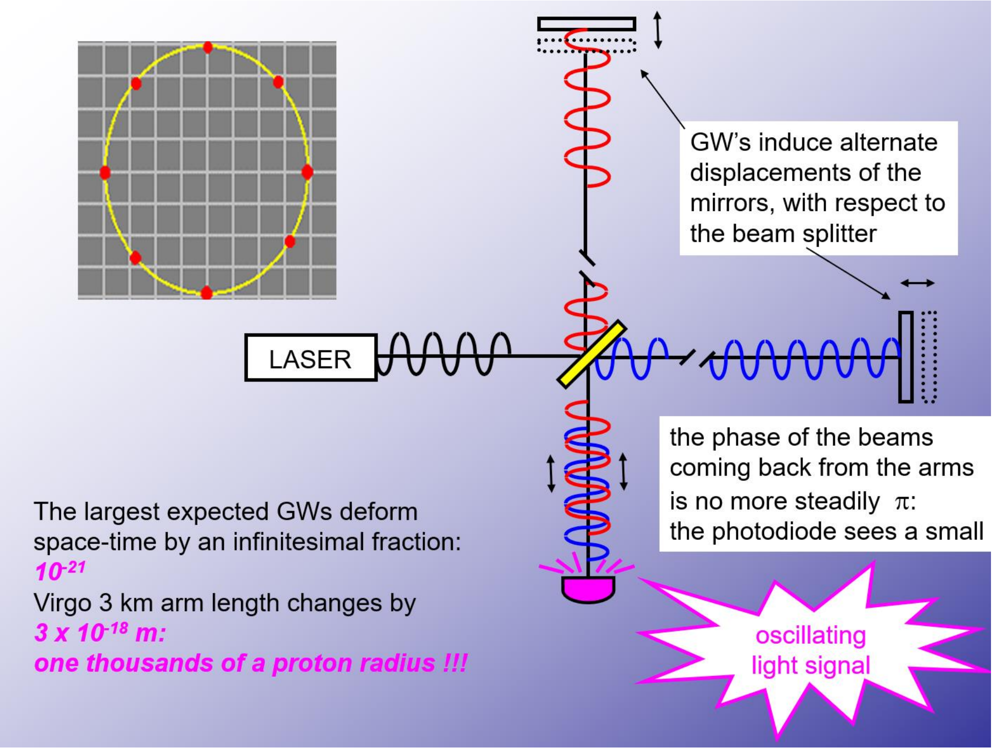
What happens when a gravitational wave arrives?

The incoming gravitational wave, deforming the space-time, produces a displacement of the end mirrors that misalign slightly the interferometer from the condition of dark fringe, producing a very weak light. This signal, that is measured by the photodiodes, contains all the information of the gravitational wave.

Each of the interferometer arms therefore works as a large 3 km ruler capable of measuring very small changes of its length. The length variations that Virgo and LIGO can measure are of the order of 10^{-18} m at 100 Hz, a quantity 1000 times smaller than the proton radius!

Teacher Guidelines:

- The sound of gravitational waves
  https://www.youtube.com/watch?v=QyDcTbR-kEA



GW's induce alternate displacements of the mirrors, with respect to the beam splitter

the phase of the beams coming back from the arms is no more steadily π: the photodiode sees a small

The largest expected GWs deform space-time by an infinitesimal fraction: ***10^{-21}***
Virgo 3 km arm length changes by ***3×10^{-18} m:***
one thousands of a proton radius !!!

Figure 6 Effects of gravitational waves on an interferometer

Step 3

How small is 10^{-18} m?

Imagine to drop a glass of water in the ocean. Due to that the global level of all the seas on the Earth will increase by an extremely small amount.

Let's assume that the Earth is a sphere having 70 % of its surface covered by water:

$$S = 70\% \text{ of } 4 \text{ x } \pi \text{ x } r^2 = 0.7 \text{ x } 4 \text{ x } 3.14 \text{ x } (6.37e6 \text{ m})^2 \sim 3.6e14 \text{ m}^2$$

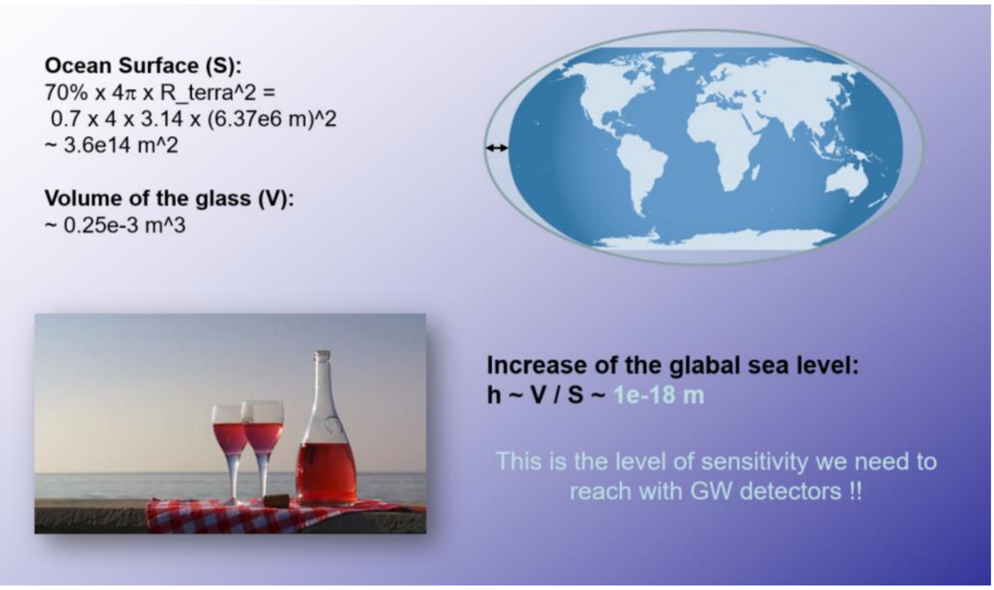
A volume of a glass can be assumed to be around

$$V = 25 \text{ cc} = 0.25e\text{-}3 \text{ m}^3$$

The ratio is therefore

$$V/S \sim 1e\text{-}18 \text{ m}$$

That is the same displacement sensitivity of modern GW detectors!!



Ocean Surface (S):
70% x 4π x R_terra^2 =
0.7 x 4 x 3.14 x (6.37e6 m)^2
~ 3.6e14 m^2

Volume of the glass (V):
~ 0.25e-3 m^3

Increase of the glabal sea level:
h ~ V / S ~ 1e-18 m

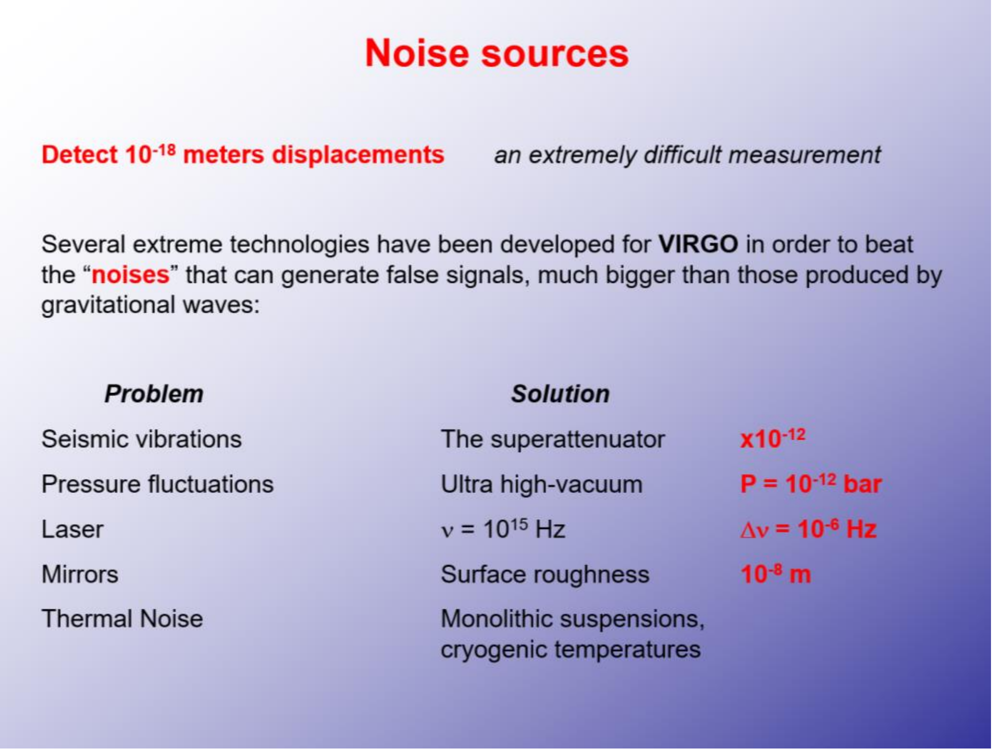
This is the level of sensitivity we need to reach with GW detectors !!

Figure 7 The impressive sensitivity of modern GW detectors

What are the noise sources of the GW detectors?

Many phenomena can mimic the effect of a gravitational wave by moving the interferometer mirrors or disturbing its beam.

Here you have a list of most important ones:



Noise sources

Detect 10^{-18} meters displacements *an extremely difficult measurement*

Several extreme technologies have been developed for **VIRGO** in order to beat the "**noises**" that can generate false signals, much bigger than those produced by gravitational waves:

Problem	***Solution***	
Seismic vibrations	The superattenuator	**x10^{-12}**
Pressure fluctuations	Ultra high-vacuum	**P = 10^{-12} bar**
Laser	$\nu = 10^{15}$ Hz	**$\Delta\nu = 10^{-6}$ Hz**
Mirrors	Surface roughness	**10^{-8} m**
Thermal Noise	Monolithic suspensions, cryogenic temperatures	

Figure 8 Noise sources of a GW detector

Step 4

The Earthquakes and the Seismic noise

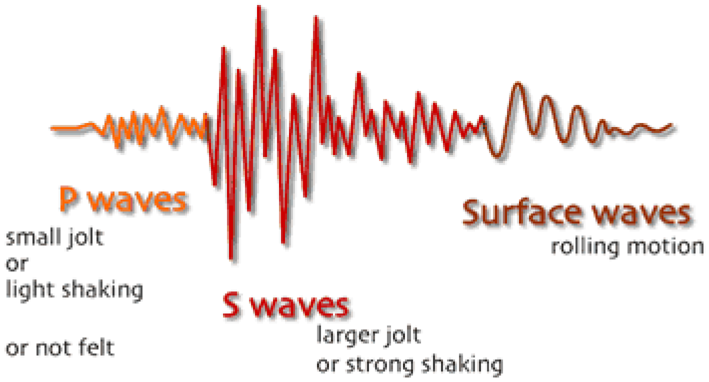
Introductory video

https://video.nationalgeographic.com/video/101-videos/00000144-0a2d-d3cb-a96c-7b2d6cd80000

What happen during an earthquake?

An earthquake is what happens when two blocks of the earth suddenly slip past one another. The surface where they slip is called the fault or fault plane. The location below the earth's surface where the earthquake starts is called the hypocenter, and the location directly above it on the surface of the earth is called the epicenter.

P and S waves



You can see what happens both on the surface and on the interior of earth crust using this web app developed by the Incorporated Research Institutions for Seismology (IRIS).

http://ds.iris.edu/seismon/swaves/

The propagation speed of S and P waves is different and changes with the depth as shown in fig. 9.

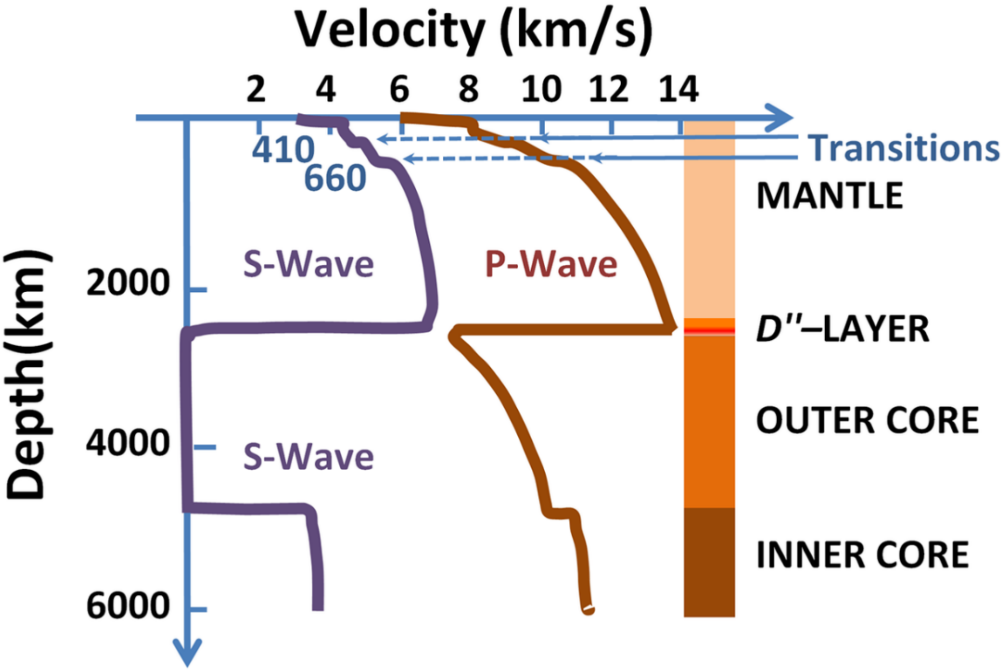
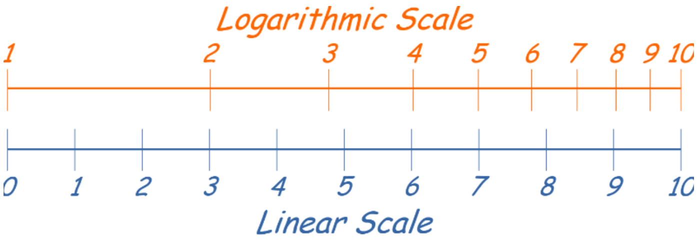


Figure 9 Propagation speed of S and P waves

Logarithmic scales

Logarithmic scales are used whenever you need to represent data that are spread over several orders of magnitudes. Instead of increasing in equal increments, each interval is increased by a factor of the base of the logarithm.



Examples are

- The equal temperament of western music
- The intensity of sound, measured in decibel
- Brightness of stars, called magnitude
- Acidity of substances, called pH

Richter scale

Several scales are used to measure the intensity of earthquakes. The most physically relevant one is the Richter scale, a logarithmic scale that gives a measurement of the energy released during an earthquake.

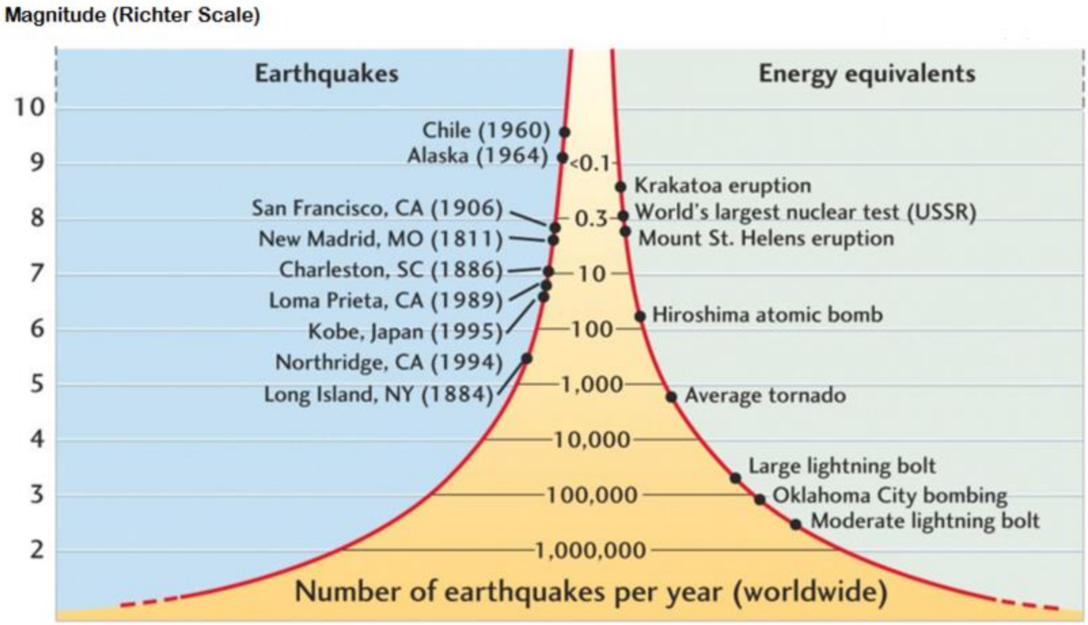


Figure 10 Intensity of earthquakes compare to the energy released

Is the ground moving when there are no earthquakes? If yes, why?

The ground moves continuously even when no earthquake is occurring. While the high frequency part (above 1 Hz) is caused by human activity, the low frequency noise is due to excitation produced by the sea waves on the earth crust. This continuous motion of the ground is called microseism or seismic noise.

Since the microseism is always present, it represents the biggest problem of gravitational wave detectors!

Seismic noise has both natural and human origins and can vary by few orders of magnitude from site to site. However, all ground motion displacement spectra observed worldwide share some common characteristics: they have essentially the same amplitude in all three orthogonal space directions and they exhibit a low pass behavior that follows the empirical law

$$\boxed{x(f) \sim A\,(1\,Hz/f)^2}$$

In 1993 J. Peterson collected and analyzed the data from 75 seismic stations around the world (shown in fig. 10) and developed two seismic noise models, the New Low Noise

Model (NLNM) and the New High Noise Model (NHNM) that geophysicists now commonly use as a reference. The models are hypothetical background spectra obtained from a composite of the lowest spectra (NLNM) and from the average of the noisiest sites (NHNM) in the seismometer network.

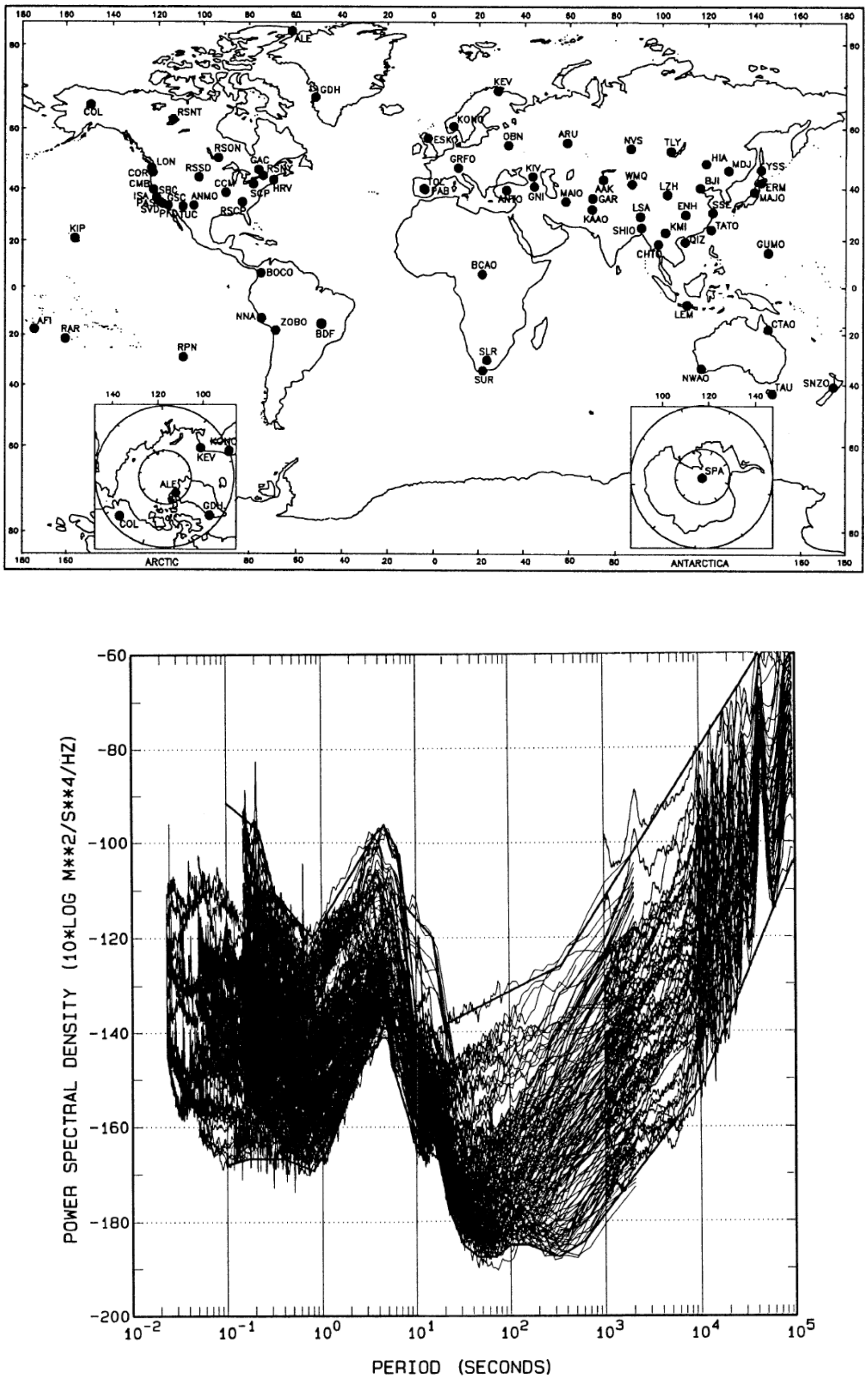


Figure World seismic data used by Peterson to develop his models. Top: locations of the stations. Bottom: Seismic data as function of the period. The top and bottom continuous lines are the NHHM and NLNM.

There are two main peaks present in Peterson's NLNM and NHNM models. The broad resonance in the 0.1-0.5 Hz range, called microseismic peak, is generated by the interactions of ocean waves at sea and is prominent in all seismic noise spectra measured all over the world. The peak is caused by a nonlinear process [17] through which ocean waves couple energy into elastic waves, called microseisms. The interaction of water waves with similar frequencies but opposing directions generates a second order pressure wave with half the period and an amplitude proportional to the product of the wave heights. Unlike the pressure field generated by traveling waves, this pressure wave does not wane with depth and efficiently couples with the Earth's crust to generate seismic surface oscillations that propagates primarily as Rayleigh waves.

The resonance between 0.05 Hz and 0.1 Hz is called single-frequency microseismic peak because it's generated by the same process but it doesn't show the frequency doubling of the microseismic peak.

Teacher Guidelines:

- Earthquake 101
  https://www.usgs.gov/natural-hazards/earthquake-hazards/science/science-earthquakes?qt-science_center_objects=0#qt-science_center_objects
- Wikipedia
  https://en.wikipedia.org/wiki/Microseism
- Simple and well done paper on Science magazine:
  https://science.sciencemag.org/content/307/5710/682

The Superattenuators

Springs and pendula are seismic isolators!!

A spring or a pendulum are simple mechanical systems, called harmonic oscillators, in which a body of mass M, connected to a support through an elastic element of mass m, when displaced from its equilibrium position, experience a restoring force *f* proportional to its displacement x (fig. 11). The motion of these systems repeat itself after a fixed amount of time called *period* of the system that depends by the stiffness of the elastic element. The inverse of the period is called *resonance frequency* of the system.

If the support is moved by an amount x_0 by an external force, the displacement of M, as shown in fig. 12, have a magnitude that depends by the frequency.

In particular, if the support moves at frequencies lower than the resonance frequency of the oscillator, ω_o, the mass M simply follows the motion of the support. If the support moves instead at a frequency close to ω_o the motion of M will be amplified (by a factor 10 as shown in the plot). However, if the support moves at higher frequencies, the motion of the mass is attenuated by several orders of magnitude: the greater is the frequency the higher is the attenuation!!

Imagine now that the support is the earth itself. The displacement of the support will change depending on the earthquakes or seismic noise but if you choose a spring with a stiffness that is low enough then your oscillator will attenuate the ground motion. *This is the basic principle of every seismic isolator!!*

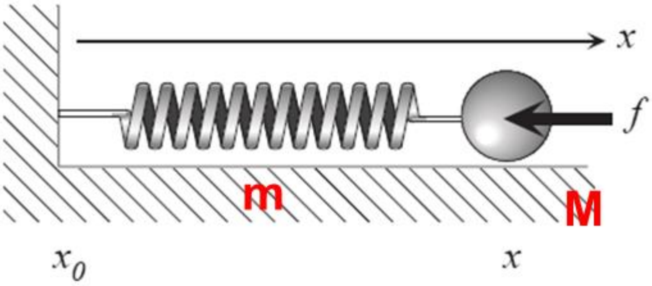


Figure 11 Harmonic oscillator

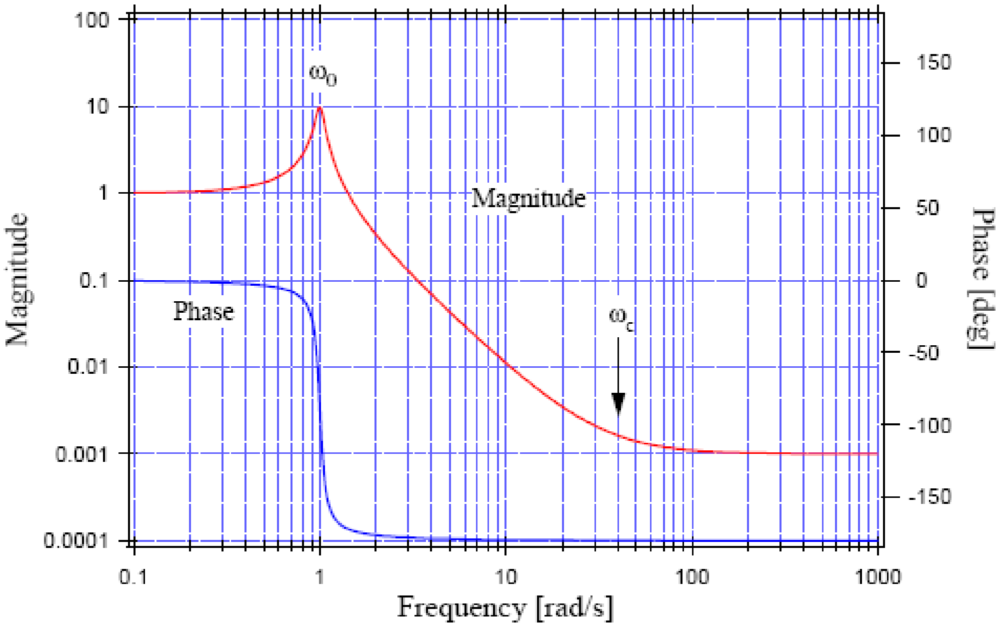
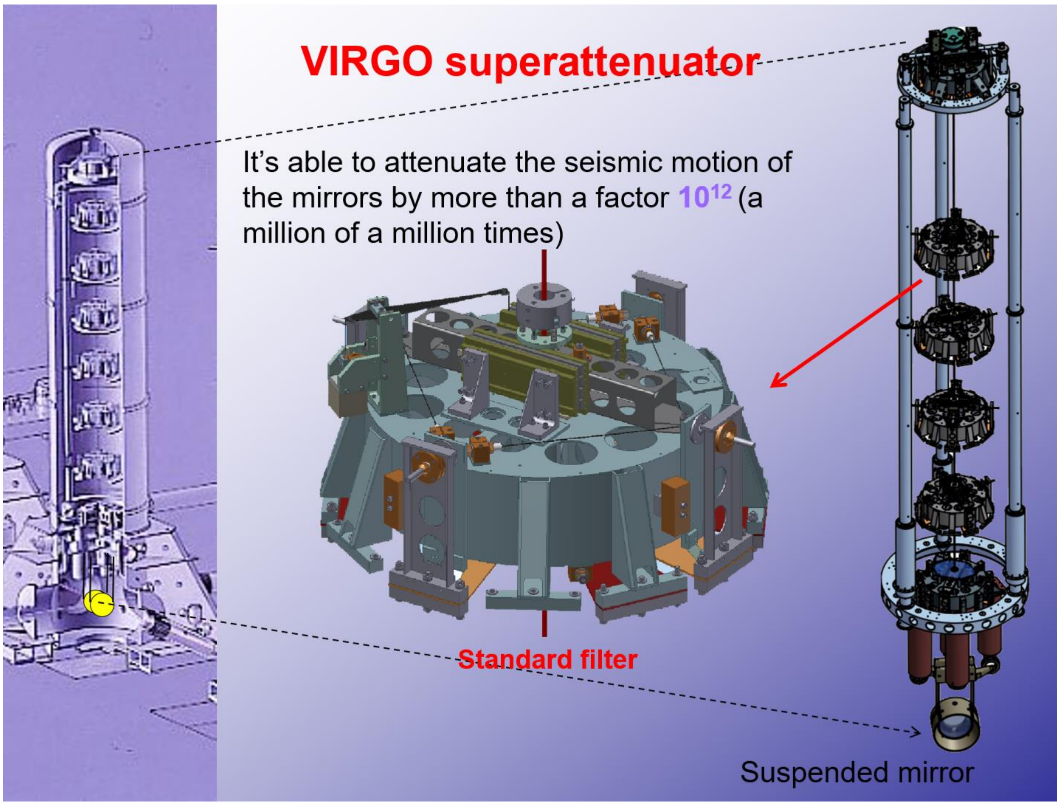


Figure 12 Transfer function of a spring

Superattenuators

Seismic noise constitutes the main limitation at low frequency for the detection of gravitational waves on the Earth.

For this reason, all the main optical components of the interferometers must be suspended from ground. Virgo uses an 8m-long chain of pendula called Superattenutor. The idea of the superattenuator is simply to put in series several harmonic oscillators in order to obtain an extremely high level of attenuation above their resonance frequencies. This mechanical device can indeed reduce the motion of the ground by a factor 10^{12} that is a million of a million times for frequencies above a few Hz.



VIRGO superattenuator

It's able to attenuate the seismic motion of the mirrors by more than a factor 10^{12} (a million of a million times)

Figure 13 Virgo impressive seismic isolator: the superattenuator

Step 4

How a modern gravitational wave detector is made?

As shown in figure 10 a modern gravitational wave detector like Advanced Virgo is much more complex respect to a Michelson interferometer.

However, the basic parts are still there

- The LASER

- The Beam Splitter (BS)
- The end mirrors. They are called North End (NE) and West End (WE) since the arms are approximately aligned with North-South and East-West directions
- The photodiode

The input mirrors, called North Input (NI) and West Input (WI), constitute the most important difference: at the beginning of each arm, a mirror almost completely transparent is added. This trick allows to keep the light confined inside the arms, virtually increasing the effective optical length by a factor of about 400.

This means that Virgo interferometer is equivalent to a Michelson interferometer with 400 x 3 km = 1200 km long arms!!

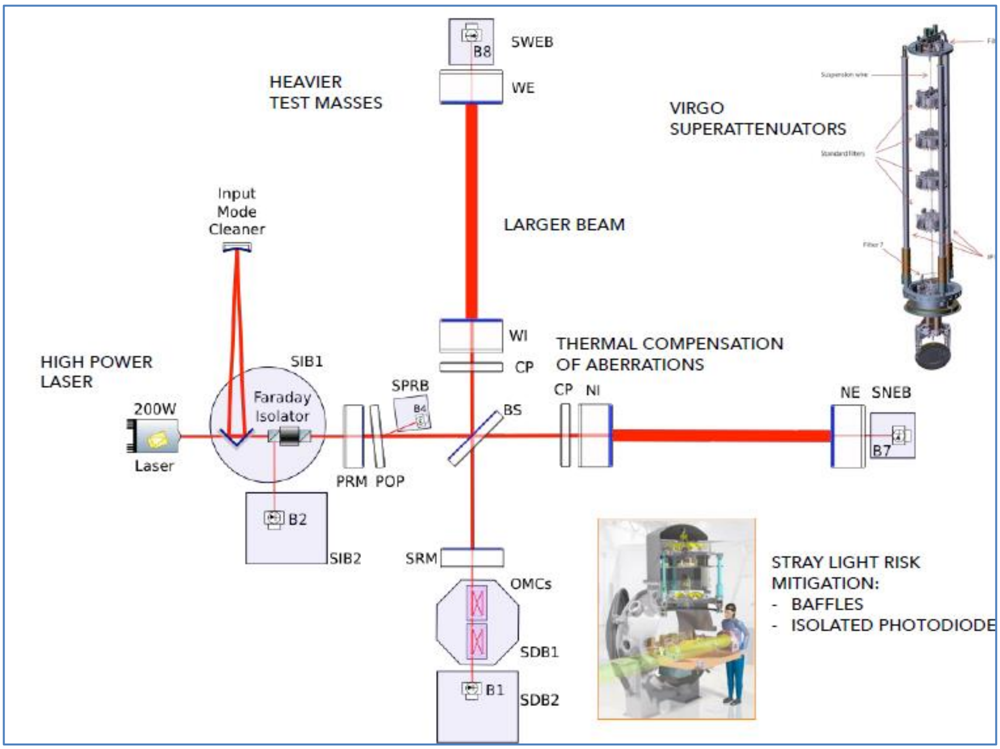


Figure 14 Optical scheme of Advanced Virgo, a modern GW detector

Teacher Guidelines:

- Very good video made by NIKHEF about Virgo: https://www.youtube.com/watch?v=h_FbHipV3No

Step 5

The Virgo control room

The control room is where all the magic happens! Here all the troubles, successes, joy and despair of the experimental physicist life are concentrated.

In this room, shown in the photos of fig. 11, tens of people work day and night together to improve the sensitivity of the detectors.

The improvement process that takes the interferometer to the performance required in order to detect gravitational waves is called ‘commissioning’. The detector is not like a commercial device that is guaranteed to work as expected after you have mounted it, installed, connected and turned on. When all the components of the detector are installed and tested the interferometer does not work. You need to work months or even years in order to see the detector starting to work properly.

What happens always after this initial phase is that the noise is too high to detect gravitational waves. Therefore, more months of hard work are required until you slowly approach the sensitivity you wanted to reach. This phase of continuous improvement of the sensitivity, called ‘noise hunting’, essentially never ends. It is only temporarily stopped when the data taking runs are ongoing.

Figure 15 Virgo control room

Detector Data

As shown in fig. 11 in the Virgo control room many screens continuously showing the data of the detector. With your setup you will reproduce the set of screens and information shown in the control room using a set of monitors and small computers called Raspberry PI.

Here is the list of the interferometer data shown in control room that you will also display in your screens:

Live Video Stream 1:

- NE, WE: video stream of the laser beam reflected from the Virgo end mirrors, 3 km far from the laser.
- IMC, MC: video streams that show the status of the laser, before entering the detector. They are acquired inside the so-called mode cleaner cavity.

Live Video Stream 2:

- B1, B1p, B1s2: video stream of the laser beam reaching the output photodiodes. Here the signals containing the gravitational waves are acquired. Depending on the status of the detector, interference fringes can be clearly seen.
- B4: The interferometer guardian angel: The power recycling pick-off photodiode. It is used to monitor the light sent back to the laser and gives an indication of the overall alignment of the detector.

Virgo Dashboard (DMS): live monitoring system of all interferometer subsystems. This screen gives an idea of the complexity of the detector. In a fully working interferometer all the flags should be green.

Sensitivity Curve (figure 12): Current noise of the detector as a function of frequency (Hz). The extremely small numbers on the y axis, if multiplied by the length of the arm (3000), give the differential displacement in meters the interferometer is able to measure. This plot gives an idea of the incredible sensitivity of this amazing ruler. At the minimum of the curve (100 Hz) we have for example $3000*2*10^{\wedge-23}=6*10^{\wedge-20}$ m, that is about 1/15000 of the proton radius!!

Binary Neutron Star Horizon (BNS Range): This number express the radius of the universe in which the interferometer is currently able to detect binary neutron star gravitational-wave signals, such as the GW170817 last year event. The number is expressed in Mpc: 1 Mpc = 3000000 light years!!

Suspensions: In the six top row plots the position of the Virgo superattenuator stages of the end mirrors are plotted. The signals sent to their relative coils in order to move the mirrors are plotted in the bottom row. The effect of ground motion caused by the moon gravitational attraction can be seen on time scales of the order of 48 hours.

Earthquakes and Sea Activity: This plots show the seismic noise of the last 24 hours measured by seismometers located close to the end mirrors. The plots on the left column show the noise caused by nearby or remote earthquakes, while on the right the ground motion due to the sea activity is displayed.

Weather: These plots shows the summary of the weather conditions of the last 24 hours at Virgo site. In the left column plots, the wind speed, its direction and the intensity of rain dropped are shown. The left column plots display the relative humidity of all Virgo buildings.

Spectrogram: This plot shows how much the various frequency components of the output signal of the detector had changed in the last 24 hours.

Noise Budget: This complex plot is a summary of all the noise sources affecting the interferometer sensitivity. They come from both the environment and the detector components.

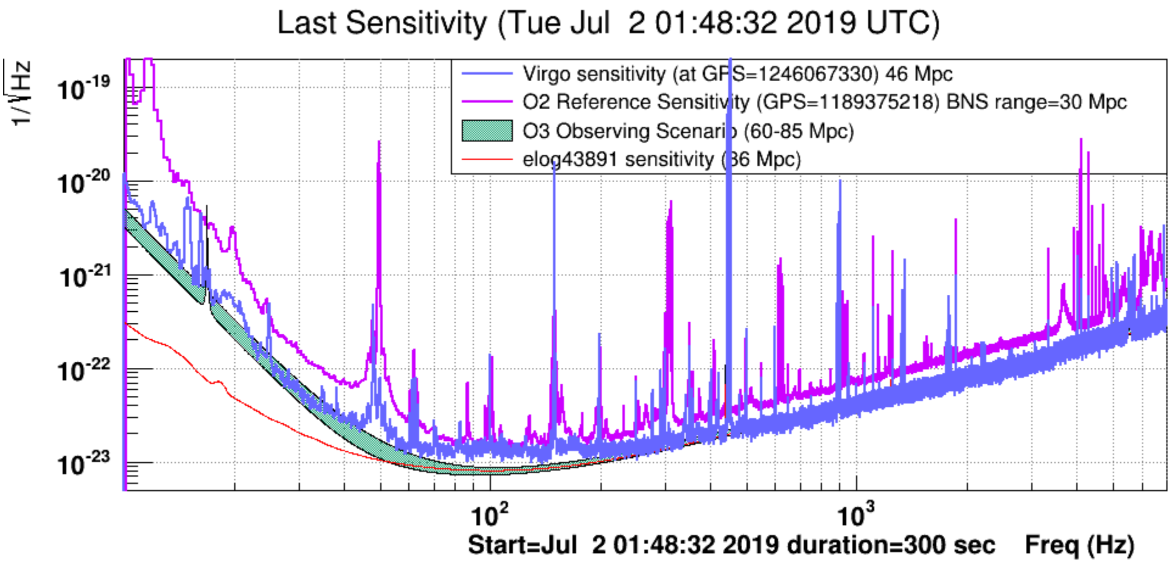


Figure 16 Virgo Sensitivity curve

Evidence

Technical Requirements

- A set of 11 **Raspberry PIs** (v3 or v4): one for each screen plus one for h(t)
- A set of 10 monitors with HDMI input
- Fixed IP of your school to be added to VIRGO firewall white list
- In order to reload the screens containing the VIM data, a plugin called AutoRefresh had to be installed in the RPi default browser (chromium).

What is a Raspberry PI?

Teacher Guidelines:

- The official site of the RPi documentation https://www.raspberrypi.org/education/
- The official guide for beginners https://www.raspberrypi.org/magpi-issues/Beginners_Guide_v2.pdf

Figure 17 Raspberry PI (v4)

A Raspberry PI is a small low-cost fully functional computer developed in the UK to promote teaching. It uses both open-source hardware and software.

As shown in fig. 13, it is simply constituted by a single board and can be connected to the internet using both Wi-Fi and ethernet cable and to an enormous number of devices through USB and HDMI ports.

The most common operating system used is the so-called RaspbianOS, a special version of Linux Debian distribution dedicated to the Raspberry. Since it is an open project, the documentation available on the web on both its hardware and software is very big.

Links

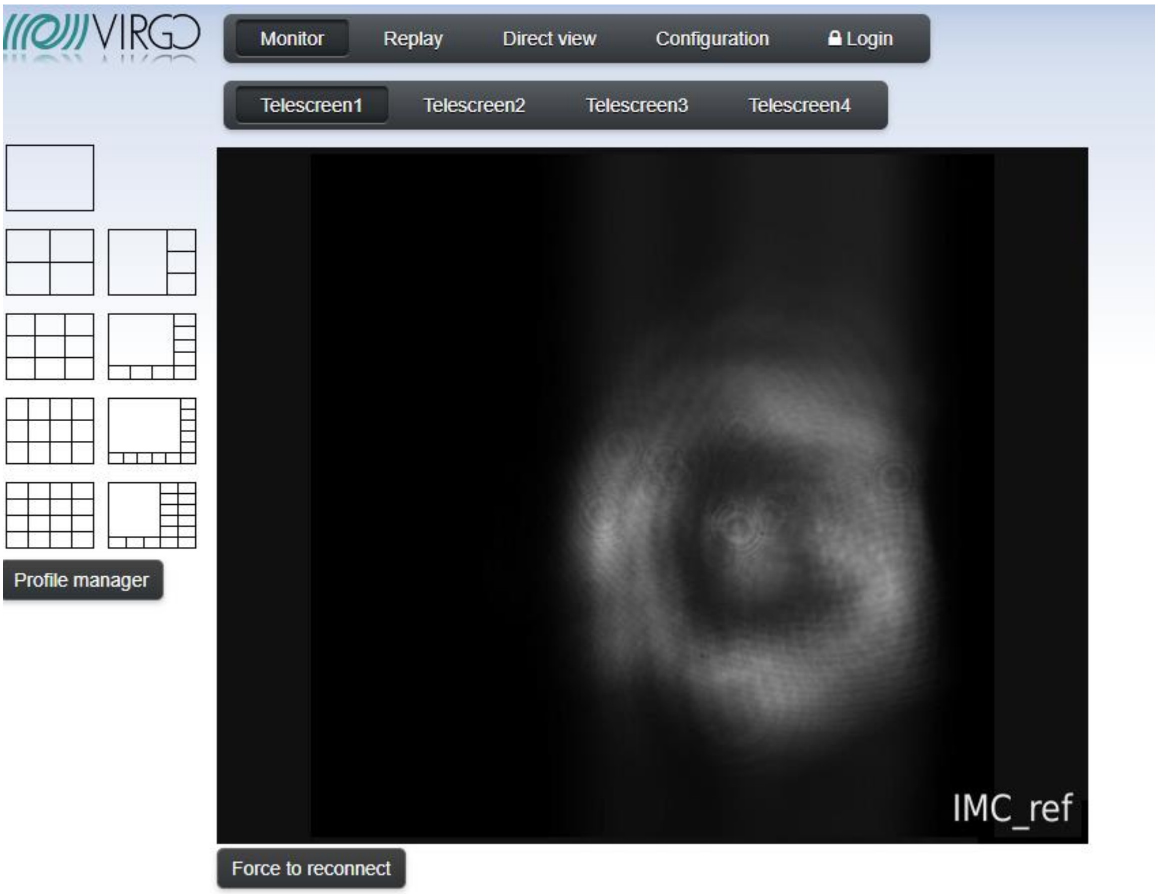
Once you have connected your Raspberry to a monitor, to the network, to a mouse and keyboard, you just need to launch the default browser called Chromium. You just need to write these links, one for each RPi, in the address bar and put the window in full screen with F11.

- Live Video Stream 1: https://vid03.virgo.infn.it:8084/display.html?monitor=1&update=0
- Live Video Stream 2: https://vid03.virgo.infn.it:8084/display.html?monitor=2&update=0
- DMS: https://dms.virgo-gw.eu/
- Sensitivity: https://vim-online.virgo-gw.eu/?config=65
- BNS Range: https://vim-online.virgo-gw.eu/?config=65
- Suspensions: https://vim-online.virgo-gw.eu/?config=68
- Earthquakes and Sea Activity: https://vim-online.virgo-gw.eu/?config=69
- Weather: https://vim-online.virgo-gw.eu/?config=70

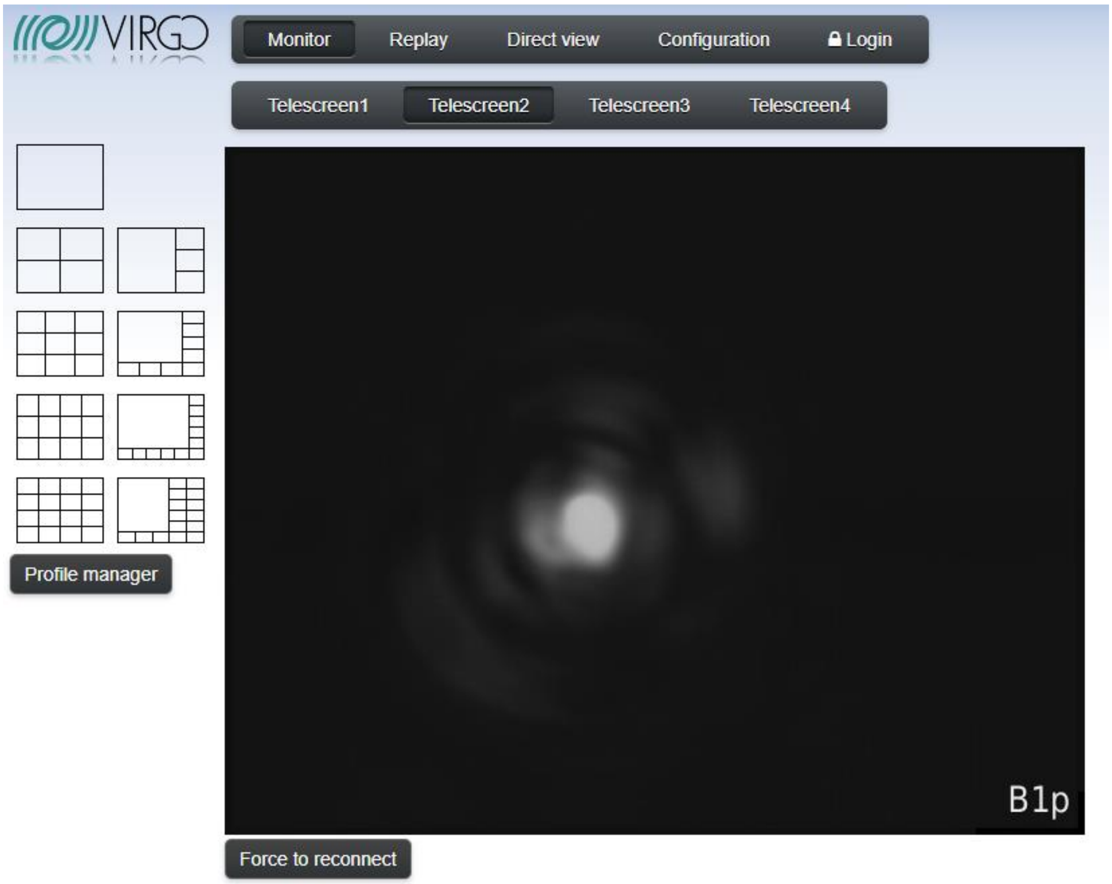
Photos of the screens

This is a list of the screen you will have after you have configured properly the Raspberries:

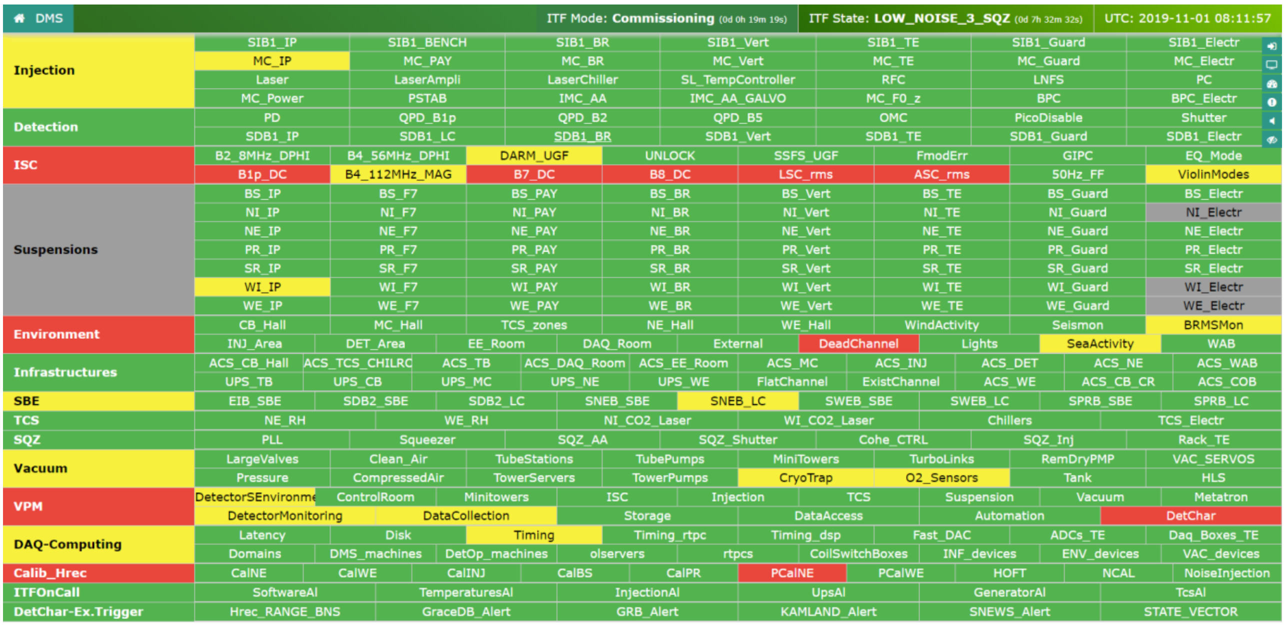
Live Video Stream 1



Live Video Stream 2



Virgo Dashboard (DMS)



DMS

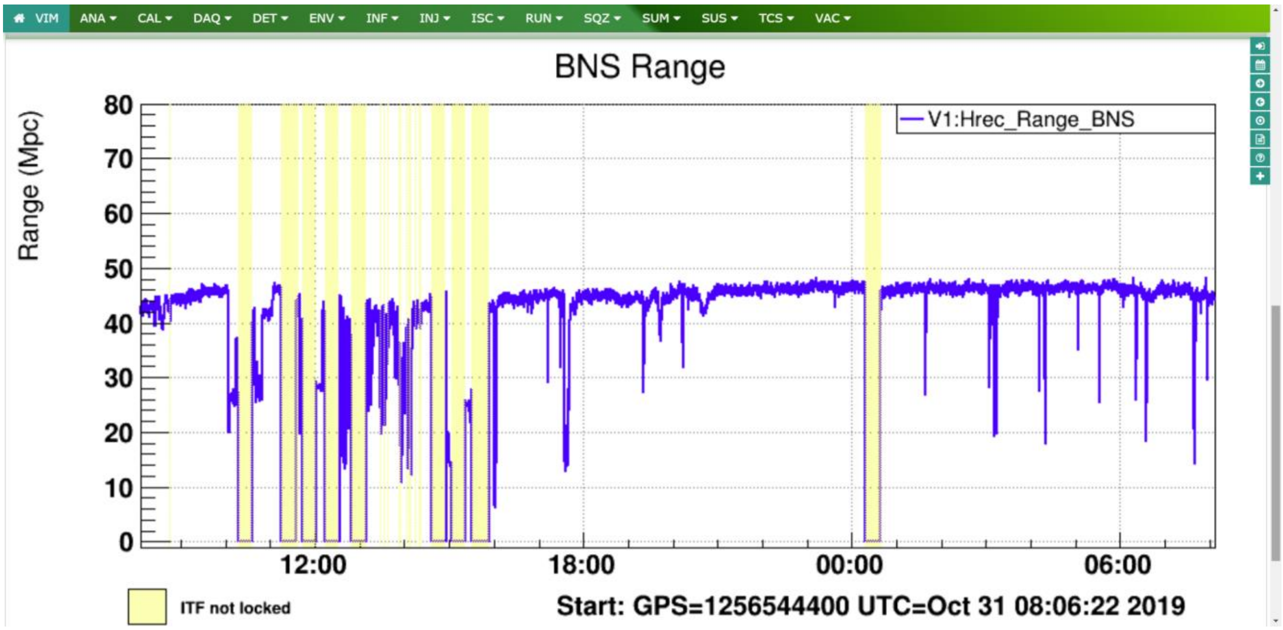
ITF Mode: **Commissioning** (0d 0h 19m 19s)

ITF State: **LOW_NOISE_3_SQZ** (0d 7h 32m 32s)

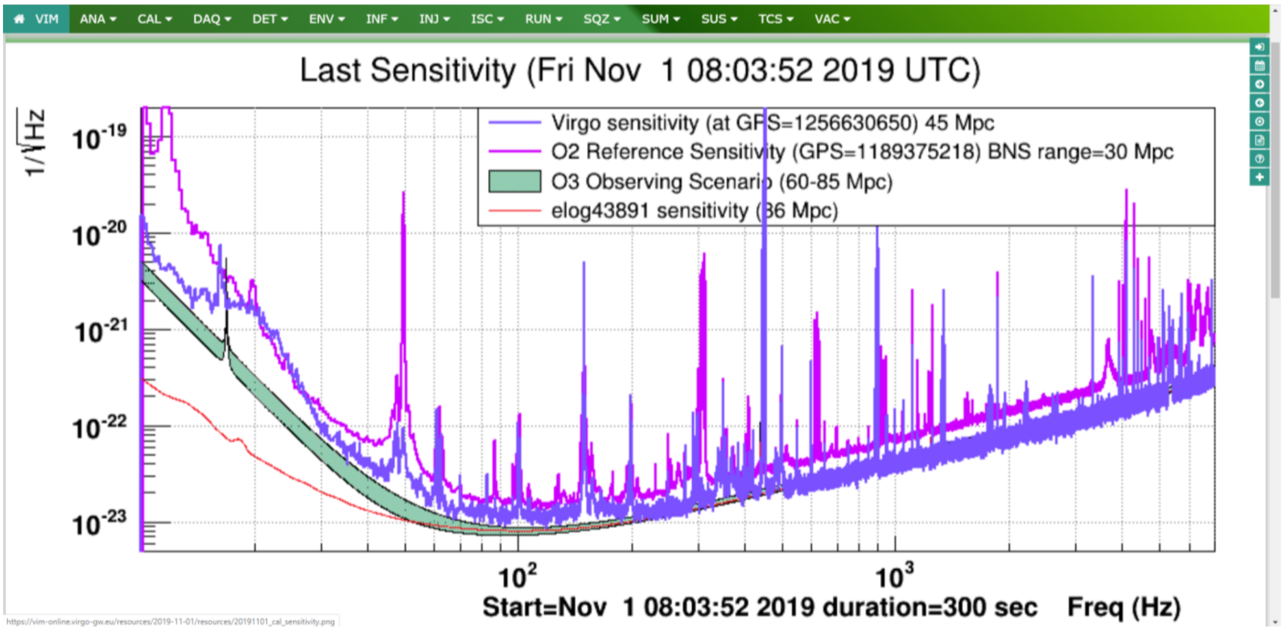
UTC: 2019-11-01 08:11:57

Injection	SIB1_IP	SIB1_BENCH	SIB1_BR	SIB1_Vert	SIB1_TE	SIB1_Guard	SIB1_Electr			
	MC_IP	MC_PAY	MC_BR	MC_Vert	MC_TE	MC_Guard	MC_Electr			
	Laser	LaserAmpli	LaserChiller	SL_TempController	RFC	LNFS	PC			
	MC_Power	PSTAB	IMC_AA	IMC_AA_GALVO	MC_F0_z	BPC	BPC_Electr			
Detection	PD	QPD_B1p	QPD_B2	QPD_B5	OMC	PicoDisable	Shutter			
	SDB1_IP	SDB1_LC	SDB1_BR	SDB1_Vert	SDB1_TE	SDB1_Guard	SDB1_Electr			
ISC	B2_8MHz_DPHI	B4_56MHz_DPHI	DARM_UGF	UNLOCK	SSFS_UGF	FmodErr	GIPC	EQ_Mode		
	B1p_DC	B4_112MHz_MAG	B7_DC	B8_DC	LSC_rms	ASC_rms	50Hz_FF	ViolinModes		
Suspensions	BS_IP	BS_F7	BS_PAY	BS_BR	BS_Vert	BS_TE	BS_Guard	BS_Electr		
	NI_IP	NI_F7	NI_PAY	NI_BR	NI_Vert	NI_TE	NI_Guard	NI_Electr		
	NE_IP	NE_F7	NE_PAY	NE_BR	NE_Vert	NE_TE	NE_Guard	NE_Electr		
	PR_IP	PR_F7	PR_PAY	PR_BR	PR_Vert	PR_TE	PR_Guard	PR_Electr		
	SR_IP	SR_F7	SR_PAY	SR_BR	SR_Vert	SR_TE	SR_Guard	SR_Electr		
	WI_IP	WI_F7	WI_PAY	WI_BR	WI_Vert	WI_TE	WI_Guard	WI_Electr		
	WE_IP	WE_F7	WE_PAY	WE_BR	WE_Vert	WE_TE	WE_Guard	WE_Electr		
Environment	CB_Hall	MC_Hall	TCS_zones	NE_Hall	WE_Hall	WindActivity	Seismon	BRMSMon		
	INJ_Area	DET_Area	EE_Room	DAQ_Room	External	DeadChannel	Lights	SeaActivity	WAB	
Infrastructures	ACS_CB_Hall	ACS_TCS_CHILRC	ACS_TB	ACS_DAQ_Room	ACS_EE_Room	ACS_MC	ACS_INJ	ACS_DET	ACS_NE	ACS_WAB
	UPS_TB	UPS_CB	UPS_MC	UPS_NE	UPS_WE	FlatChannel	ExistChannel	ACS_WE	ACS_CB_CR	ACS_COB
SBE	EIB_SBE	SDB2_SBE	SDB2_LC	SNEB_SBE	SNEB_LC	SWEB_SBE	SWEB_LC	SPRB_SBE	SPRB_LC	
TCS	NE_RH	WE_RH	NI_CO2_Laser	WI_CO2_Laser	Chillers	TCS_Electr				
SQZ	PLL	Squeezer	SQZ_AA	SQZ_Shutter	Cohe_CTRL	SQZ_Inj	Rack_TE			
Vacuum	LargeValves	Clean_Air	TubeStations	TubePumps	MiniTowers	TurboLinks	RemDryPMP	VAC_SERVOS		
	Pressure	CompressedAir	TowerServers	TowerPumps	CryoTrap	O2_Sensors	Tank	HLS		
VPM	DetectorSEnvironme	ControlRoom	Minitowers	ISC	Injection	TCS	Suspension	Vacuum	Metatron	
	DetectorMonitoring	DataCollection	Storage	DataAccess	Automation	DetChar				
DAQ-Computing	Latency	Disk	Timing	Timing_rtpc	Timing_dsp	Fast_DAC	ADCs_TE	Daq_Boxes_TE		
	Domains	DMS_machines	DetOp_machines	olservers	rtpcs	CoilSwitchBoxes	INF_devices	ENV_devices	VAC_devices	
Calib_Hrec	CalNE	CalWE	CalINJ	CalBS	CalPR	PCalNE	PCalWE	HOFT	NCAL	NoiseInjection
ITFOnCall	SoftwareAl	TemperaturesAl	InjectionAl	UpsAl	GeneratorAl	TcsAl				
DetChar-Ex.Trigger	Hrec_RANGE_BNS	GraceDB_Alert	GRB_Alert	KAMLAND_Alert	SNEWS_Alert	STATE_VECTOR				

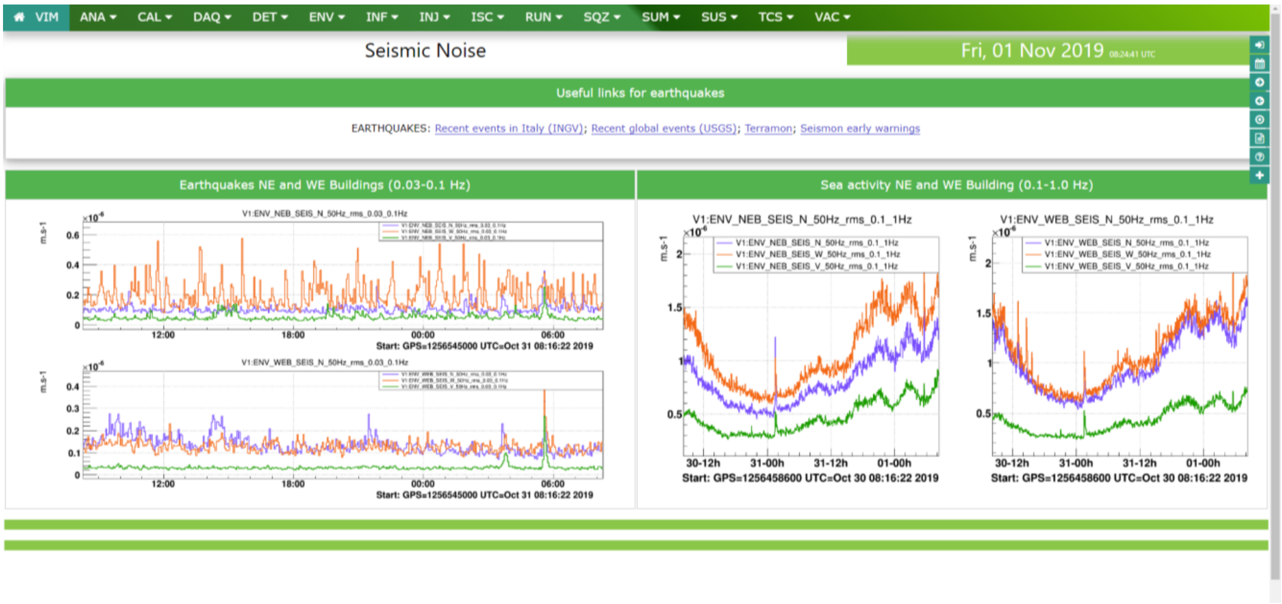
Binary Neutron Star Horizon (BNS Range)



Sensitivity



Earthquakes



Seismic Noise

Fri, 01 Nov 2019 08:24:41 UTC

Useful links for earthquakes

EARTHQUAKES: Recent events in Italy (INGV); Recent global events (USGS); Terramon; Seismon early warnings

Earthquakes NE and WE Buildings (0.03-0.1 Hz)

Start: GPS=1256545000 UTC=Oct 31 08:16:22 2019

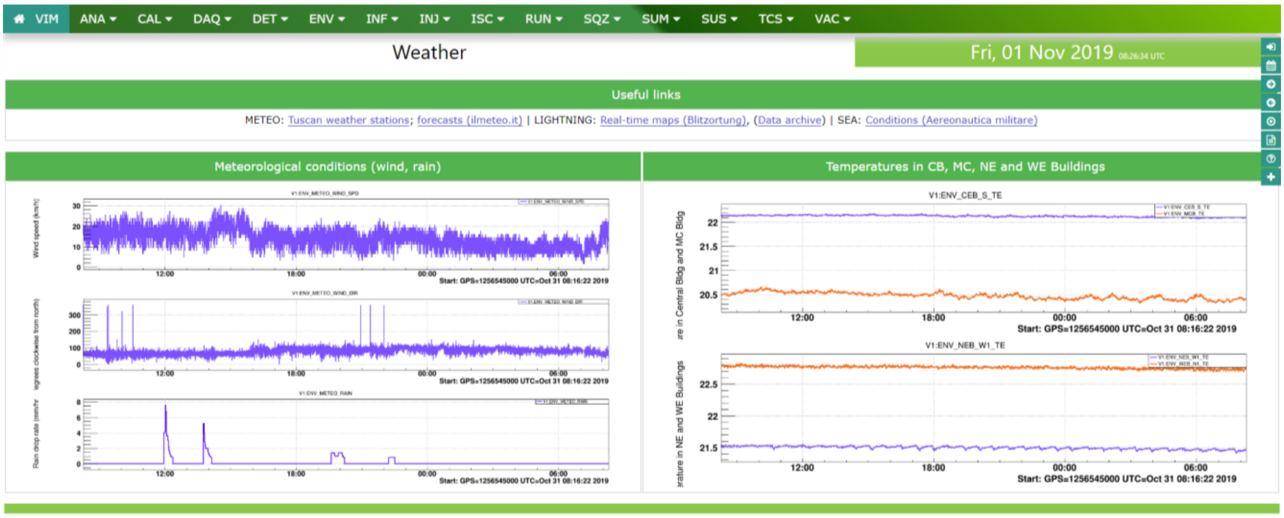
Start: GPS=1256545000 UTC=Oct 31 08:16:22 2019

Sea activity NE and WE Building (0.1-1.0 Hz)

Start: GPS=1256458600 UTC=Oct 30 08:16:22 2019

Start: GPS=1256458600 UTC=Oct 30 08:16:22 2019

Weather Conditions



Weather

Fri, 01 Nov 2019 08:26:34 UTC

Useful links

METEO: Tuscan weather stations; forecasts (ilmeteo.it) | LIGHTNING: Real-time maps (Blitzortung), (Data archive) | SEA: Conditions (Aereonautica militare)

Meteorological conditions (wind, rain)

Start: GPS=1256545000 UTC=Oct 31 08:16:22 2019

Start: GPS=1256545000 UTC=Oct 31 08:16:22 2019

Start: GPS=1256545000 UTC=Oct 31 08:16:22 2019

Temperatures in CB, MC, NE and WE Buildings

Start: GPS=1256545000 UTC=Oct 31 08:16:22 2019

Start: GPS=1256545000 UTC=Oct 31 08:16:22 2019

Perform Investigation

Mount your components

Follow the beginners guide instructions to mount the RPi into an external cover. You then need to connect it to its power supply, to an HDMI monitor, an USB mouse and an USB keyboard.

Configure the RPis

You can now insert the SD card and start the operating system. You will need to configure the network properly in order to browse the web and see the Virgo data.

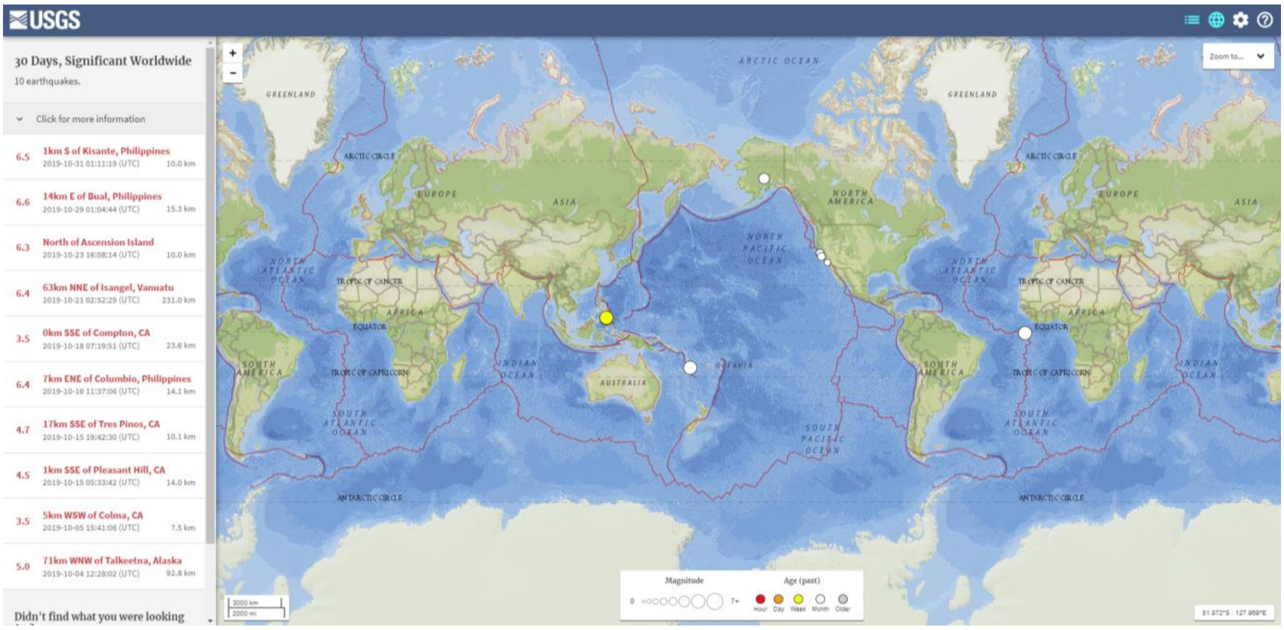
Analysis and Explanation

Analysis: Analyze evidence to discover a possible answer

Since you have now all the information a Virgo scientist has available in front of him you can perform a lot of investigations

Let's find an earthquake!

- Go to https://earthquake.usgs.gov/ and find the list of latest strong earthquakes



30 Days, Significant Worldwide

10 earthquakes.

Click for more information

6.5	1km S of Kisante, Philippines	2019-10-31 01:11:19 (UTC)	10.0 km
6.6	14km E of Bual, Philippines	2019-10-29 01:04:44 (UTC)	15.3 km
6.3	North of Ascension Island	2019-10-23 16:08:14 (UTC)	10.0 km
6.4	63km NNE of Isangel, Vanuatu	2019-10-21 02:52:29 (UTC)	231.0 km
3.5	0km SSE of Compton, CA	2019-10-18 07:19:51 (UTC)	23.6 km
6.4	7km ENE of Columbio, Philippines	2019-10-16 11:37:06 (UTC)	14.1 km
4.7	17km SSE of Tres Pinos, CA	2019-10-15 19:42:30 (UTC)	10.1 km
4.5	1km SSE of Pleasant Hill, CA	2019-10-15 05:33:42 (UTC)	14.0 km
3.5	5km WSW of Colma, CA	2019-10-05 15:41:06 (UTC)	7.5 km
5.0	71km WNW of Talkeetna, Alaska	2019-10-04 12:28:02 (UTC)	92.8 km

Didn't find what you were looking

- Calculate the distance between Virgo (Cascina, Pisa, Italy) and the earthquake epicenter.
- Calculate the expected time of arrival of S and P waves using the date of fig. 9
- Analyze the data shown in VIM at the expected time of arrival
- What happens when the earthquake arrives?
    - When an earthquake is about to arrive, you will see this flag in the DMS screen that becomes red

Seismon

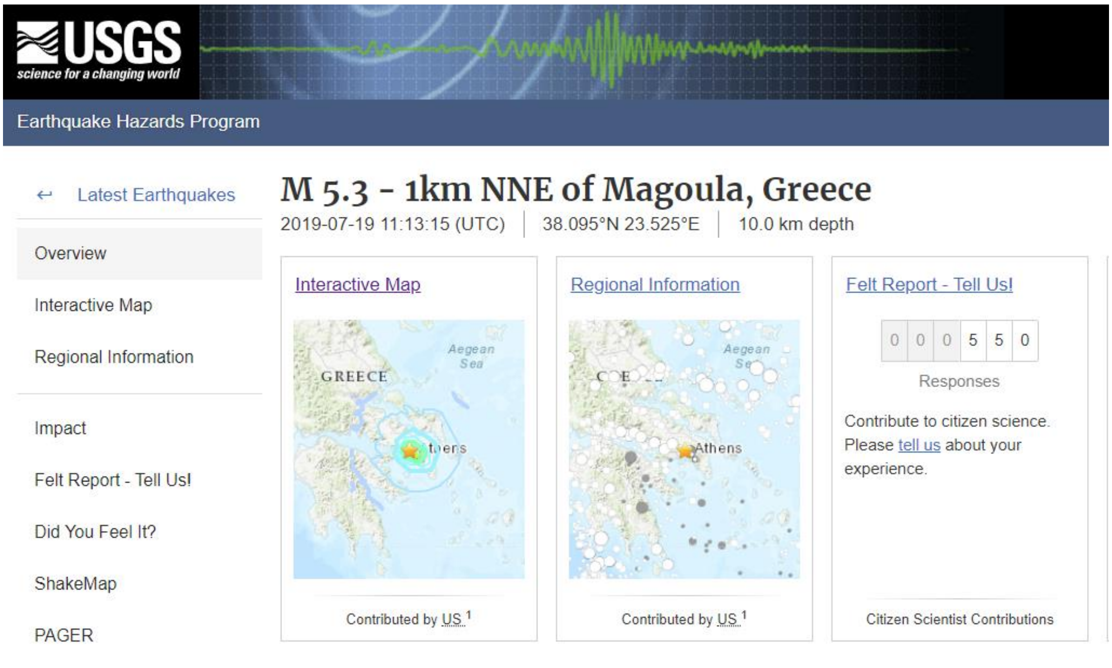
- What is the difference between S and P waves?
- How does the sensitivity of the interferometer changes depend from the intensity and distance of the earthquake?

An Example: the effect on Virgo of an earthquake in Greece!

On July 19th at 11.13 UTC an M5.3 earthquake, shook Athens, Greece.

Let's find out the effect on the interferometer:

1. Find out the time, depth and position of the event



USGS
science for a changing world

Earthquake Hazards Program

↩ Latest Earthquakes

Overview

Interactive Map

Regional Information

Impact

Felt Report - Tell Us!

Did You Feel It?

ShakeMap

PAGER

M 5.3 - 1km NNE of Magoula, Greece

2019-07-19 11:13:15 (UTC) | 38.095°N 23.525°E | 10.0 km depth

Interactive Map

Contributed by US [1]

Regional Information

Contributed by US [1]

Felt Report - Tell Us!

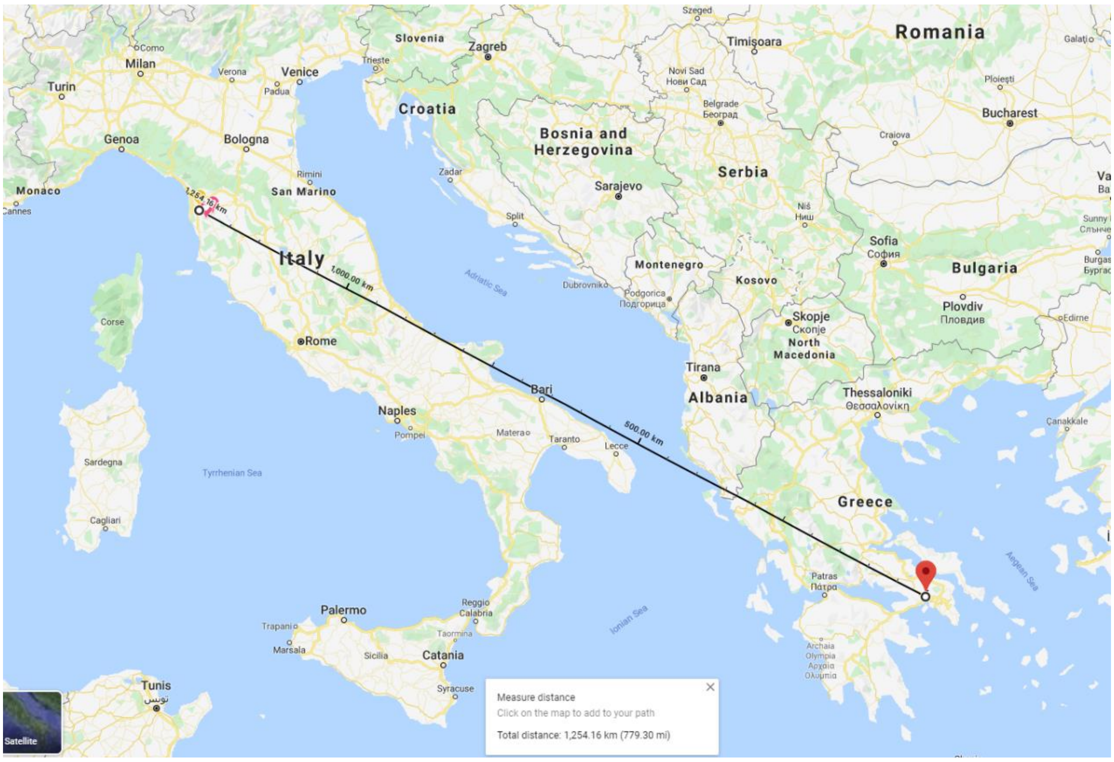
0 0 0 5 5 0

Responses

Contribute to citizen science. Please tell us about your experience.

Citizen Scientist Contributions

2. Calculate the distance between the epicenter and Virgo. You can simply use Google Maps to do that copying and pasting the coordinates given by USGS



Measure distance

Click on the map to add to your path

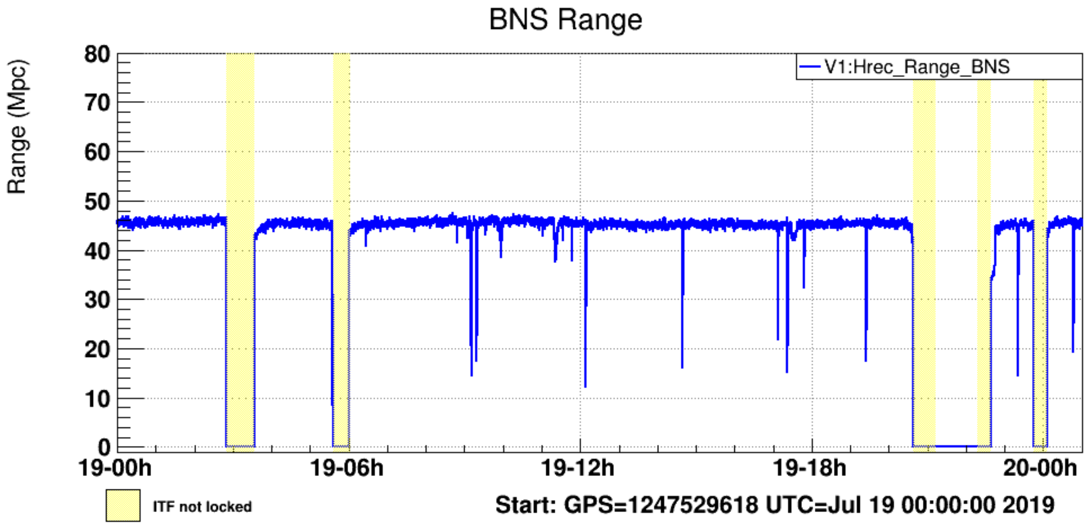
Total distance: 1,254.16 km (779.30 mi)

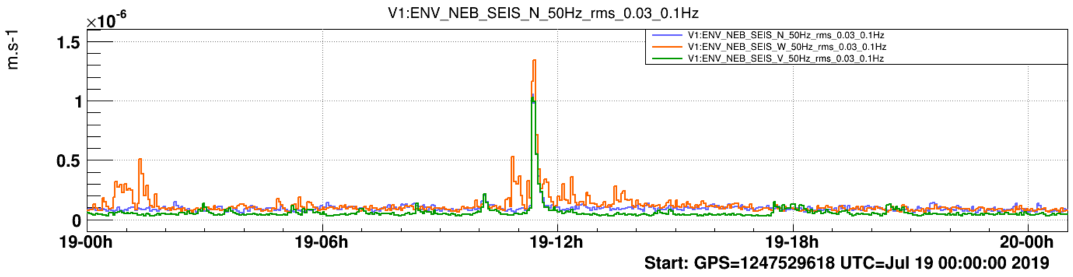
The distance obtained is 1254 km.

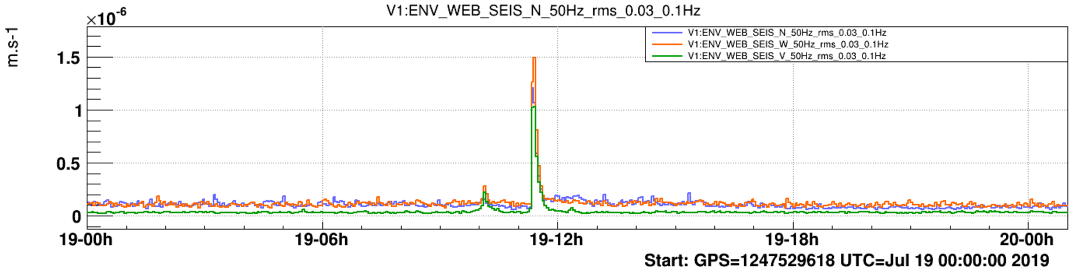
3. Knowing that the depth is 10 km, using fig. 9, we can estimate a propagation speed for the S waves of around 3 km/s.

4. The expected time of arrival of S waves is therefore 1254 /3/60 about 7 minutes after the earthquake.

This is confirmed by both the decrease in the BNS range and by the sudden increase of seismic noise measured by the local seismometers in Virgo at 11:20 UTC







Explanation: Formulate an explanation based on the analysis of your evidence

Given the information you have about the noises that disturb the detection of gravitational waves, try to explain the behavior of the interferometer when a specific event happens (earthquake arrival, wind speed increase…)

Consolidation Phase

Connect

Connect explanation with current scientific knowledge

Do the same work Virgo researcher does. Look at all the data you have and try to understand them and correlate them with what you have understood about the interferometer and its noises.

Communicate

Communicate and justify your explanation

Exactly like an actual researcher would do in a meeting, show the results of your investigations on the detector data in a set of slides you will present to your class.

Reflect

Reflect on what you have learned from the learning process

You can now understand how a detector sensitivity is correlated with the environment. Even earthquakes happening very far from Virgo, like in Japan or Australia, can disturb the detection of gravitational waves.