Third Generation Gravitational Wave detectors: the challenge of Einstein Telescope in Europe

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Abstract

In 2010 the concept design of ET was released. Gravitational waves had not been observed yet and most of the efforts were leading to achieve higher sensitivity exploiting the infrastructures developed for LIGO and Virgo. Today we are re-examining more operatively the possibility to study an actual proposal of Einstein Telescope, in the context of 3^{rd} generation (3G) detector network. The discovery of gravitational waves, the observation era using a detector network and the birth of multi-messenger astronomy is the basis on which such an engagement relies. At the end of the process Einstein Telescope project will be compliant with the worldwide scenario as it appears today in order to keep the European scientific role in this context.

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Introduction

In gravitational wave observation run O3 (1-April 2019/30 April 2020), network operation is ensured, in spite of the different sensitivities strongly favouring LIGO devices [**?**]. Trustable source reconstruction and initial polarisation studies are allowed by triple-detector observations [2]. Several improvements are foreseen for both LIGO and Virgo, and the joining of KAGRA in a four-detector network [1] widens the sky coverage aims in the medium term. The upgrades are usually called “plus” (or “+”), and observation runs encompassing the foreseen implementations with increasing nominal sensitivities are scheduled for the next years. The purposes of those improvements are not merely observational, leading to produce scientific results until the high-sensitivity phase is achieved with next generation detectors (3G). Those upgrades are also strongly focused on exploiting current infrastructures, which impose structural limitations on envisaged hardware implementations and, after two decades, can even reach technical obsolescence. From the experimental and technological viewpoint, two are the considerations that make urgent the actual feasibility study meant to start-up 3G engagement:

- current infrastructures will limit the sensitivity of future upgrades
- current infrastructures will be obsolete in 2030

The path leading to 3G

The undoubted success of second generation Advanced detectors was achieved by means of infrastructures built for first generation detectors. Even via strategically different paths, and significantly different financial budgets LIGO versus Virgo, the overall process from project approvals by funding agencies to the scientific run of initial detectors took roughly 15 years, from 1992-1994 to 2006-2007. From that point roughly another decade was required to reach a networked operation with detections. Indeed, this second term was needed due to two main reasons A) acquisition of matured experience with km-scale interferometers and B) gravitational wave science-case based just upon astronomical counterparts, mainly electromagnetic (binary system population, BH mass demography and distribution). Nowadays, the prediction process is expected to be much more accurate thanks to direct gravitational wave observations.

The overall path delineated for the future suggests, as a strategic priority, operating in a network. The relevance of the network was clear since the beginning of GW detectors, at the old times of resonant bar antennas, but, up to recent times, was most focussed on the first detection claims. Nowadays, that aspect appears the main character of GW astrophysics performed from the Earth's ground.

The European path to 3G idea initiated very early, in 2004, within the ILIAS (EU-FP6, Framework Programme 6), starting from thermal noise R&D for next generation detectors and then projected in the ET conceptual design issued in 2011 [4] as a deliverable of EU-FP7. The main concepts are the following:

- Wide detection bandwidth, with special attention to achieve high sensitivity from few Hz. In order to reach the result, two different technologies, leading to high frequency performance and to low frequency performance, are adopted by two different interferometers, hosted in a common infrastructure and operating as a single hybrid-instrument.

- Capable to work alone. Indeed, ET was the first detector conceived to beat the nominal sensitivity of Advanced Detectors, and being the first, it was designed to provide localisation capability and redundancy, exploiting equilateral triangular shape. This brigs the number of interferometers to six.

- The detector infrastructure was requested non to be obsolescent for 50 years.

Due to the difference in the structures of Virgo and LIGO communities, the paths aimed to 3G, in the two continents, were quite different. The main efforts done in Europe (Einstein Telescope), collected worldwide experience on ground based interferometers and about the techniques to be adopted, delivering a preliminary conceptual design. At the time of the first GW observation, in fall 2015, a comparison between the DCC archive of LIGO [3] and the homologous (TDS) used by Virgo community, shows up that LIGO community was effectively involved in cryogenic R&D programs, by a factor 3 times larger with respect to Virgo (the total number of entries in DCC is more than 140 so far). This shows how, while Virgo collaborators were strongly concentrated on the achievement of Virgo operation, LIGO community had human resource margin to invest in future plans towards 3G. Nevertheless, In Europe further sporadic studies were done, concerning intrinsic noise sources as Newtonian, Thermal and test mass-sites seismic background. Remarkably, new optical strategies to overcome quantum noise and meant to be adopted in 3G detectors schemes, have been developed for 2G advanced detector upgrades.At the same time, thanks to the KAGRA startup, the field concerning cryogenics and payloads embedding 3G essentials (Low frequency and low temperature, ET-LF) underwent to a fruitful period. In Europe the activity was mainly supported by EC programs, initially dedicated to R&D and, later on, via exchange programs directed to KAGRA, as a technological bridge towards ET.

It must be remarked that even if it started few years later, US path towards 3G expressed by Cosmic Explorer (CE) [5] was inspired since the beginning to different features. Different views were matured estimating logistic (sites) and technological aspects (e.g. cryogenics), investment time-scales, and were certainly influenced by the experience gained with two almost-identical Advanced LIGO detectors. It is quite important not to spoil the precious impulse of ET concept and pass to a realistic proposal in Europe. In order to do it, a dedicated science-case accounting for the result provided by Advanced detectors, was the first step to be accomplished. This study has been done accounting for different kinds of 3G detectors.

3G Network and Science case

In 2019 the first science-case study was issued by the Gravitational Wave International Committee dedicated to 3G (GWIC 3G) [6] . The document considered a network of 3G detectors, two L shaped Cosmic-Explorer-like and one triangular ET like, at the edge of the technology envisaged so far. According to the estimates, an impressive reach is achieved concerning binary coalescence detection. Based upon actual evidence in the current observation runs (02-03), at the nominal sensitivity of 3G network from 10^5 to 10^6 events per year should be detected, which goes well beyond redshifts at which electromagnetic telescopes are able to observe individual sources. The science-case, under reasonably simplified hypotheses demonstrates that 3G projects deserve a priority attention by funding agencies and that by means of a 3G network the real era of GW observational astronomy would be definitely be open.

3G network, with ET in Europe and two Cosmic Explorer (CE) detectors one in the Norther hemisphere and the other in the Southern, has several intriguing themes strongly related to cosmology, multi-messenger astrophysics and high energy physics. Few examples, according to GWIC-3G are outlined below.

- Merging stellar-mass Black Holes throughout the whole universe and reconstructing BH formation process and actual demography.
- Exploring new physics in gravity and fundamental properties of compact objects, by accessing at high frequency (1-10 kHz) a sufficient statistics of BNS mergers (high and low deformability).
- Investigating the connection between high energy processes in radiation/particle with respect to gravitation. In case of GRBs associated to BNS, so far it is unclear what are the jet properties and progenitor features as well as the remnant characteristics.
- Large scale universe studies, as multi-messenger BNS and NSBH studies will be based upon increased reach.
- Investigating the primeval universe through GW stochastic background and connections with particle physics.
- Continuous wave emission detection from non-spherical isolated NS sources with rotation axis misaligned with respect to their symmetry.

- Presence of non-GR polarisation components, by combining GW network observations with EM sources.

Most of the items cited above exploits the presence of a network of three 3G detectors. Taken for granted those golden purposes, the actual scenario has to face the real complexity of present detectors, whose infrastructures have to be in operation responding to the demanding sensitivity targets at least for the next 15 years and in the first phases of initial low-performance operation of one 3G detectors. Reasonably, their operation should last even more, until the completion of a network of three 3G detectors. More conservatively, the community has to consider the scientific outcome of a particular detector network, constituted by 2.5G detector units plus an initial 3G unit, balancing the long-term infrastructure investment and the need of producing relevant scientific outcomes on the way.

Choices for the future

Speeding-up the constitution of a large collaboration in Europe promising long term investment is the main issue. Once science-case studies have been provided, the decision about location is the major one. But the strategy has also to consider the aimed technological targets. As said earlier, ET detector embeds two different technologies, with two interferometers, each accommodated in a triangular shape, which implies, redundancy by locating at each vertex two beam splitters, one featured to have best sensitivity at low frequency (LF) and the other at high frequency (HF), meaning in total six interferometers hosted by the same underground infrastructure, i.e. three hybrid detectors (HF+LF), Fig. 1.

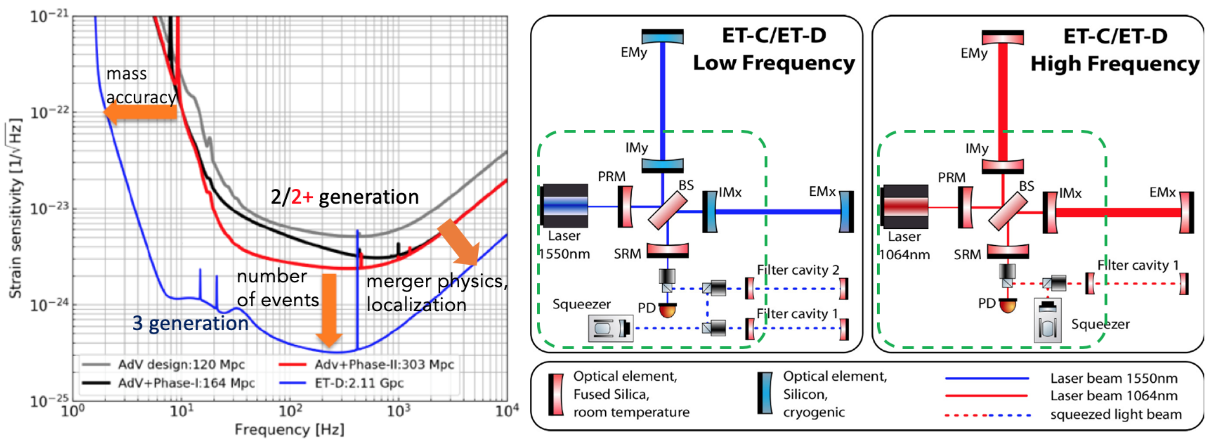

Figure 1: Left: sensitivity achievements passing from 2G to ET (HF+LF). Right: according to the present design of ET, each of the three detectors is a hybrid one, composed of two interferometers one dedicated to low frequency sensitivity (ET_{LF}) and the other enhanced at high frequency (ET_{HF}) (the triangular shape implies 60 deg angle between the arms). A major effort is being spent to design a suitable infrastructure capable to host the optical elements in the green dashed boxes around the same vertex, together four end stations of the other two hybrid interferometers. (credits: M. Punturo et al. (GWIC 3G), (2019) [6])

The design is modular, hence facilitating the implementation of identical interferometer pairs and provides a powerful internal veto channel, intrinsically related to the equilateral triangle shape, as the sum of the three output channels is not affected by gravitational waves [7]. For a triangular shape, prioritising the implementation schedule is a very relevant issue. Indeed, reaching fast the operation two hybrid interferometers (two ET vertexes) seems mandatory to join the network with two 40-km-long detectors. If, as CE is ready only one vertex of triangular ET is completed, its contribute of the latter will not go much beyond source localisation for many years, also delaying further installations.

However, a sequence of configurations to reach the full operation of ET has been delineated in three phases: A) starting with a single detector made of two interferometers with two arms at 60 deg, HF and LF; B) adding the second pair HF, LF (to resolve polarisation and, finally, C) adding the third one to have the null stream veto [7]. Considering also the nine Fabry-Perot filter cavities foreseen to overcome quantum noise (more demanding to rotate the squeezing ellipse at low frequency, as in that case two cavities in series should be adopted), a total of 33 cavities with suspended mirrors should be locked to operate the full ET detector. Beyond the science-case motivation, further GWIC-ET studies [6], constantly in progress, are expected to deal with the practical approach, leading to a viable schedule for setting-up the network. They will drive to suitable strategic decisions concerning both the proposal and the construction.

A key element of the ET project plan is the decision about the site, which is presently meant to be taken by mid 2023. This topic is nowadays under animated scientific and technical debate and somehow interlaced with the aimed constitution of the ET international collaboration and its financial aspects. A first campaign carried out over 18 sites (12 underground) was concluded in 2013, by M. Beker [8]. Newtonian noise originating at the surface, and associated to the seismic background, is significantly reduced by subtraction techniques [9, 10] already under study with 2G detectors, but such a task is naturally made much easier in the underground sites. The decision to build ET in an underground site is mainly driven by the fact that at few Hz, the seismic noise background is roughly two orders of magnitude lower.

In 2019 the characterisation is focussed on two sites separated by 1600 km:

- *3-border site* , located in Terziet (NL) in the flat territory near Epen on the B-D-NL border [11].
- *Sardinia site* , located in Sardinia island (IT) near the village of Lula in the hilly area of the old mine of Sos Enattos, no longer in use. [12].

Terziet is under suitable characterization from March 2019. This work is done by means of deep bore holes in the soil, suitably structured and protected to host seismic sensors. Initial results published [11] about the 3-border site, concerning the seismic background. The good point of this analysis is that since the surface of the site is flat and known only through preliminary geologic campaigns, a standard plan of investigation in the area, lasting 2-3 years will be performed by means of standardised 250 m deep bore hole campaign. Terziet area is relatively quiet but still significantly affected by antropogenic vibration noise, as day/night difference is seen even at 250 m depth., which is attenuated in underground, as expected by geological models. However, joining the result registered at 250 m (close to the ET specs), with Newtonian noise subtraction techniques would make the site compliant with ET requirements.

Sardinia site was under study since 2011, allowing easy access to underground through an existing mine. Remarkably, tectonic microplate of Sardinia island is almost decoupled from current geodynamics of the Mediterranean domain (including Italy), it is made of old rocks (Variscan basement, 360-290My) and is characterized by very low infra-plate horizontal velocities [12]. Comparing the Sardinian site to Terziet results, drove to the urgent need of starting also in such a quiet place a standardised campaign to qualify the site exactly with the same methods adopted in 3-border site (starting in 2020). Indeed, the measurements done in the Sardinian mine site so far are non-optimized and sensitive to activity in the mine (visits/excursions). Thinking to Sardinian site, a dedicated and promising study has been performed, to investigate the possibility of building a triangle (10 km sides) versus an L-shape (15 km arms) infrastructure [12]. The result of a standard bore-hole campaign in Sardinia are expected to be excellent and the hilly orography appears convenient from practical points of views (e.g. descending access), but the decision on the site will be a trade-off of several aspects, and it is still too early to guess the resulting choice. In the underground a very good performance is probed at the available position at -111 m (right). Below 0.1 Hz and above 3 Hz instrumental and environmental noise around the seismometers in the mine worsen the low-noise performance.

Many environmental and structural elements that may impose strict constraints affecting the proposal are nowadays being considered for ET. Among the structural ones, the problem of installing a considerable number of seismic suspensions in a reasonably large excavated cavern plays a central role, especially because cryogenics implementation is foreseen and tall suspensions are supposed to be installed, inspired by Virgo design (passive systems with advanced active damping). A first analysis, reported in [4], and based to a Virgo-like seismic attenuator, brought to 17 m tall system, roughly twice that of Virgo, but thanks to the recent developments on modelling tools is has been possible to keep the height like that of Virgo (9 m) Fig. 2, further enhancing low frequency cut-off [13], Fig. 3. This latter research is interlaced with that concerning cryogenic payload design and cryostats, which indeed appears at the moment the leading point concerning R&D plans for ET-LF technologies. The main issues are the following:

- *Cryogenics and size of cryostats*, strongly based upon KAGRA experience, but surely revised to achieve compactness and better structural dynamics, not to spoil the low-seismic-background of the floor, where the cryogenic shields and, in turn, the heat links to cool down the test masses are connected. KAGRA has accomplished the result gradually, starting from a design pre-tested in Kamioka with CLIO interferometer [14], but passing to the size of ET, and especially if the triangular shape will be finally chosen, quite significant developments have to be pursued. In fact, due to the limited volume of caverns and the concentration of large hardware apparatuses at the vertexes, preserving the low seismic potential ensured by the underground implementation is a challenge.

- *Seismic suspension*, the development needed are not so dramatic as it seems, the major issue is how to make the assembling and maintenance operation compliant with the room size and with infrastructure servicing without too many constraints.

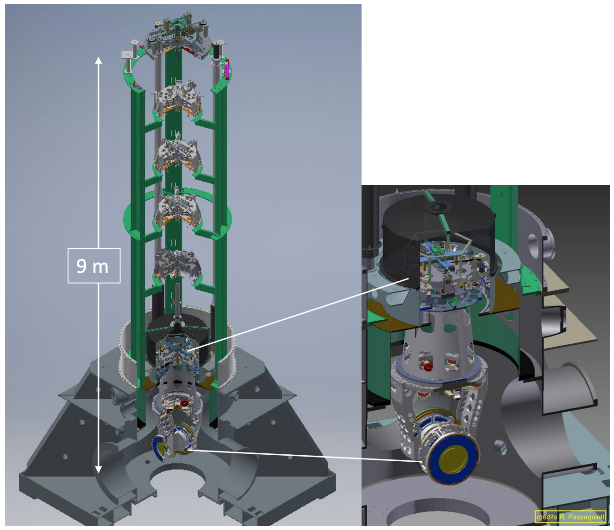

Figure 2: The scheme of passive seismic attenuator of Virgo, a cascade of vertical and horizontal stages with digital control of internal modes, is in the baseline of ET conceptual design proposed in 2011. The overall length from the top stage of the inverted pendulum to the test mass into the payload is 9.06 m (vacuum chamber not shown).

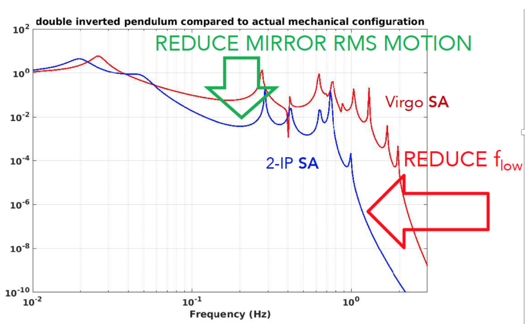

Figure 3: GWDAW, G. Losurdo [13], newly compact seismic attenuators modelled for Einstein telescope implementation. Based upon Virgo experience, both stronger attenuation of background RMS and lower frequency cut-off are conceptually possible.

Conclusions

Stimulated by the experience gained with 2G detectors and by the conceptual ideas underlaying Cosmic Explorer, at the 9th ET Symposium (2018), a very preliminary study (by SWS Engineering [15]) focused on Sardinia site, provided a rough estimate and comparison of L-shape configuration versus triangular shape. For the first time it was pointed out the alternative concept of L-shape as an alternative to ET conceptual design. Comparison studies concerning geological aspects are still going on. In 2019, after the 10th ET Symposium, another (independent) study, focussed on triangular-shape (original ET conceptual design) in 3-border site in central Europe, was committed (Implenia [16])). This is meant to provide more realistic feasibility study of the triangular shape originally foreseen in the ET. Even though the ET community is a common platform, at the moment

European paths are differently articulated and start to be locally funded. For instance, Maastricht ET-Pathfinder technology pole [17] and Terziet site characterization. In Italy by INFN, concerning Sardinia underground environment and site studies. These are just seeds of a much wider scenario that is going to grow up in the next years. Indeed, after the imminent ET submission (spring 2020) to ESFRI board (European Strategic Forum for Research Infrastructures), and if European consensus is achieved, it will be urgent to make the due choices about realistic final design and site locations (end of 2023).

The development horizon, compared to the timeline of 1G and 2G detectors, must be shorter. This is in principle possible, because science-case predictions should be now much more reliable than in the past, thanks to the parallel work provided by current detectors [2, 18] . ET is nowadays conceived as a part of a network. However, its concept is still based upon a conceptual design (2011), before the detection, and inspired by strong optimal design principles for a leading large detector. On the other hand, the network turned to be the key feature of 2G devices, leading to multi-messanger fundamental astrophysics, and has to be considered a priority.

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