PART B

B1 Concept and objectives, progress beyond state-of-art. S/T methodology and work plan

B1.1 Concept and project objectives

This project concerns the study and the conceptual design for a new infrastructure that will bring Europe to the forefront of the most promising new development in our quest to understand the history and future of the Universe, the emergence of the field of Gravitational Wave Astronomy.

Currently, several first generation gravitational wave (GW) detectors are active in Europe. There are three cryogenic resonant bar detectors, the GEO600 laser interferometric GW detector operating close to Hannover as a German-UK collaboration and the 3km laser Interferometric GW Virgo detector, located in Cascina near Pisa (Italy) and managed by a French-Italian-Dutch scientific collaboration. These interferometers pool their data with the three American LIGO interferometers and are currently doing extensive searches for gravitational waves from astrophysical systems. Searches for gravitational waves from these data sets and the algorithms used in the analysis are the result of many years of research and development in Europe and today European scientists are leading several of the analyses efforts in this international context. During the next decade all of these interferometers will be upgraded to second-generation instruments. The large interferometers (VIRGO and LIGO) will gain a factor of about ten in sensitivity at lower frequencies (up to about a kilohertz) using technology largely developed in Europe. The smaller GEO instrument will pioneer high-frequency wide-band observing above one kilohertz, again deploying new technologies. If the current instruments do not make the first detections of gravitational waves, it can confidently be expected that this will be done by the second-generation interferometers. However, all these detector designs have limitations in sensitivity and bandwidth that must be overcomed in order to develop a detector system truly capable of fully characterizing GW signals from all possible kinds of sources observable from the ground. While the first and second generation detectors will open up the field of gravitational wave astronomy, third-generation detectors will be required to create gravitational wave observatories that are capable of complementing optical and X-ray observatories in the study of fundamental systems and processes in the Universe. These third-generation detectors should potentially cover the complete frequency range from about 1 Hz to 10 kHz that is observable from ground.

The main objective of the ET design study is the realization of the conceptual design of a 3rd generation gravitational wave detector, with the specifications of the site and infrastructure characteristics and the description of the requirements of the detector main components.

This main objective will be reached centring on three specific targets, as described in the following text.

Current detectors are limited, in the low frequency range, by the seismic noise that enters in the detector sensitivity both directly, passing through the seismic filter chain used to suspend the main optics of the interferometer or by direct coupling of the vibrating soil with the suspended masses (so called Newtonian noise or gravity gradient noise), and indirectly, making the control of the seismic filter chain more noisy and more difficult (the so called control noise).

The first target of this design study is to identify the strategies to reach a further reduction of the seismic noise effects with respect to the second generation detectors expectations. This is expected to be attained trough in two parallel ways:

- identification of a site with a lower seismic (and Newtonian noise)
- improvement of the mirror vibration isolation and of the controllability of the suspension.

The first one is the <u>main activity of the first work package</u>: the definition of the site requirements and the proposition of the possible sites in Europe, having satisfactory specifications. The need to reduce both the seismic and Newtonian noise seems to be fulfilled by an underground site, where the low seismic activity and the uniformity of the soil could play a dominant role in the site identification process. This possibility requires the study and the design of a complex underground facility that satisfies the requirements of the observatory:

- multi-kilometres tunnels to host the interferometer arms
- cryogenic plants
- safety of the infrastructure users

The second target of the ET design study is the identification of the specifications of the last stage suspension and test mass that can satisfy the thermal noise requirements of a third generation GW detector. These specifications must take in account the requirements in terms of loss angle of the test mass and possibly reflective optical coatings, mechanical Q and stress strength of the suspension system, optical absorption and heat extraction capability needed to support a multi-megawatt circulating power in a cryogenic environment. The definition of these specifications determines the characteristics of the cryogenic system that must be designed. The cryogenic system (conceptual) design must be compliant with the detector thermal noise requirements, with the limits in terms of artificial seismic noise reintroduction into the optics suspension, with the power extraction requirements, due to the laser power circulating in the Fabry-Perot cavities and to the optical absorption of the mirrors, and, possibly, with the underground location.
The third target is the definition of a detector design that minimizes the so-called quantum noise (the shot noise component of the quantum noise is currently limiting all the GW detectors in the high frequency range). Many technologies are currently under study and some of them are still in a too embryonic phase to be adopted in a second generation GW detector. The activity in the third work package (related to this target) is the identification of the technologies that can be adopted in a third generation detector to suppress the quantum noise:

- signal recycling techniques
- squeezed light techniques
- very high power lasers

and to cross-check their compatibility with a 3rd generation GW detector global design.

B1.2 Progress beyond the state of the art

The last two decades have seen the emergence of broadband interferometric gravitational-wave detectors that are presently reaching unprecedented levels of sensitivity. Recently, the construction of several long arm-length interferometers has been completed: the Laser Interferometer Gravitational-Wave Observatory (LIGO) in the US (a project now with significant involvement from the UK and German groups), VIRGO, funded by France and Italy, and GEO600, funded by Germany and the UK. The Japanese TAMA interferometer has been alternating commissioning and detector improvement, acquiring data for several years. The interferometer network is now operating with a greater sensitivity and bandwidth than that of resonant bars, paving the way to search for a much broader class of potential sources. There is a mature plan to upgrade existing detectors to create ‘enhanced’ and ‘advanced’ systems. Indeed, the observation of gravitational waves is expected in the first weeks or months of operation of advanced detectors at their design sensitivity. GEO600 and Virgo completed construction in 2003. They are now in the late stages of commissioning and, although they are not yet operating at their design sensitivity, they have already achieved sensitivities better than the resonant detectors.
LIGO and GEO600 began their long data taking science run in November 2005, with the aim of acquiring at least a year's worth of triple-coincident data over two calendar years. The LIGO interferometers, built with less sophisticated suspensions and optical configurations, are now operating at design sensitivity. GEO600 participated in this science run from January to October 2006 and then went back to detector commissioning to cover LIGO’s downtime during late 2007

and 2008 with improved sensitivity, when the LIGO detectors will be upgraded to create an enhanced LIGO system. Virgo just concluded (October 2007) its first science run in parallel with LIGO and after it is continuing the commissioning process (end 2007, beginning 2008). The upgrade of Virgo to Virgo+ in the summer 2008 will be followed by an extended science run with worldwide participation. The expected sensitivity gain for the "enhanced" detectors is typically a factor 3 (in amplitude), which converts to an increase by a factor of 27 in the event rate, as gravitational wave detectors observe signal amplitude, which falls off as 1/distance. The "advanced" Virgo and LIGO upgrades have a more ambitious goal: a sensitivity improvement of roughly one order of magnitude with respect to the initial instruments (about 3 orders of magnitude rate improvement for extragalactic events). The construction and then installation phase of the advanced detectors is expected to occur around 2011. The advanced interferometers are expected to be in operation around 2013. On a similar timescale and with similar target sensitivity an underground, cryogenic interferometer, 'LCGT' is proposed for installation in the Kamioka mine in Japan.

The baseline of the ET design study is the expected performance of the advanced detectors; any further improvement of the design concepts must be compared with the expected sensitivity of the advanced LIGO and advanced Virgo detectors. The aim is to arrive to the conceptual design of a 3rd generation GW detector showing a sensitivity curve roughly an order of magnitude better than the advanced detectors, at least in the medium and high frequency range, opening, in this way, the astronomy era for the GW radiation. A quantitative way to evaluate the advance respect the baseline of the project is represented by the sensitivity curve, reported in the following figure.

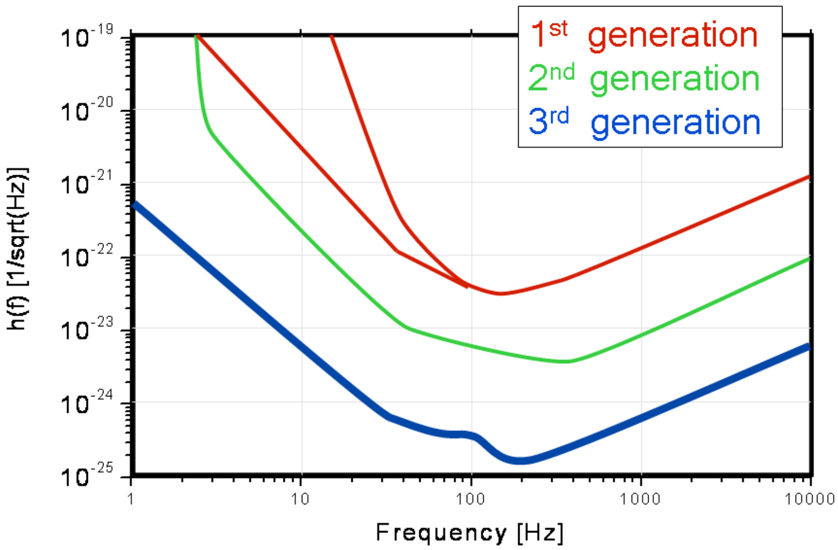

Figure 1 - Comparison between the sensitivity curves of the different GW interferometric detectors. The 3rd generation curve represents, probably, the envelope of the maximum improvement attainable for this kind of detectors.

B1.3 S/T Methodology and associated work plan

B1.3.1 Work plan strategy description

The activities of this design study are grouped in four "Scientific" working packages (WP1-WP4) and one management working package (WP5). This kind of grouping is driven by the typical noise characteristics of a gravitational wave detector and permits the parallel start of intrinsically related activities. In general, each scientific working package starts analyzing the status of the art of the current technologies, the on-going evolutions and its first objective is the definition of the requirements needed for a 3rd generation GW detector (on the specific item analyzed in the working package). After the definition of the requirements, the activities of each working package start to be related with the progress of the activities ongoing in the other working packages. The final part of each working package must converge to the realization of the conceptual design study of the main components of the future detector, with particular attention to the needed infrastructures and cost evaluation. An intense activity of meeting is foreseen, meanwhile the overall scientific activity is coordinated by a scientific coordinator that address the efforts of the scientists involved in the project. The progresses of the activities are verifiable through a regular report activity (roughly every 6 months).

B1.3.1.1 WP1 strategy description

Interferometric gravitational wave detectors are large and complex and the selection for their site is an issue of great importance. Ideally, the site should feature minimal seismic, seismic gradient and cultural noises (now and in the future), while proximity to an existing laboratory would be an advantage. Most of the seismic and cultural noise propagates over the surface, but exponentially attenuates with depth. Consequently, the ideal site may be located underground at sufficient depth.

Presently, the advanced interferometric detectors such as LIGO and VIRGO are placed on the surface of the earth and, consequently, are sensitive to seismic disturbances. In fact, their operation is limited by seismic displacement noise and their sensitivity rapidly deteriorates for frequencies below about 10 Hz. From a mathematical point of view ground motion is a random process and can be represented by a power spectrum. At a moderately quiet site on or just below the surface of the earth, seismic motion in all three dimensions follows a spectrum of ~ 10^{-7} m $(1\ \mathrm{Hz/f})^2$/Sqrt(Hz) above ~ 1 Hz. Measurements at the LCGT facility located at the Kamioka underground site (1000 m underground from the top of the mountain) reveal an average reduction of seismic noise of about 10^2 (with 10^3 at 4 Hz) compared to surface sites. Since seismic displacement noise is driven by wind, volcanic and seismic activity, ocean tides and human activity (e.g. logging, cars, heavy machinery) we intend to carry out a careful site selection. Part of this study will be performed in collaboration with the European geoscience groups, as the Italian National Institute for Geophysics and Volcanology. The use of active control systems with feedback of information from seismometers, accelerometers, strainmeters, tiltmeters, rock thermometers and piezometers to the test masses will be studied.

To suppress the influence of seismic displacement noise, the test masses will be suspended in sizable and complex attenuation chains. Nevertheless, fluctuating gravitational fields couple directly to each stage of this chain and in particular to the test masses themselves, in this way bypassing all previous attenuation stages. These time-varying contributions to the Newtonian background are driven by seismic compression waves, ground-water dynamics, slow-gravity drifts, weather and culturing noise with the resulting wave acting as a stochastic gravitational force on the test masses. Since no general filter or shield can be built for gravitational coupling we will investigate the possibility to eliminate this effect from the data stream of the interferometer by using information extracted from a network of geophysical sensors. Moreover, the influence of cavern design (spherical versus elliptical) will be investigated.

It is paramount to identify the criteria for site selection and evaluation at an early stage. These include site availability and acquisition risk, scientific suitability, construction and operations suitability, risks from environmental sources or future development. Furthermore, we will identify issues related to acquisition of land rights, importance of different noise sources, site dependent construction costs due to topographic variation, geological and environmental considerations, flood control, distance to nearby supporting technical facilities, university support, operating costs, surrounding communities providing accommodations for permanent and visiting staff, availability of local skilled work force, accessibility and travel time for visiting staff, environmental dangers

from earthquakes, storms, flooding, etc. Several of these factors impact the (cost of) the main infrastructure design, e.g. groundwater conditions affects the design of buildings and tunnels.
The final result of the above described studies will be a conceptual design report on the requirements for seismic displacement noise and gravity gradient noise. In addition, a conceptual design report for the main infrastructure of the new 3rd generation GW observatory will be delivered.

B1.3.1.2 WP2 strategy description

The suspensions of the optical elements of the interferometer are among the most crucial elements of the detector. They must provide the necessary attenuation from seismic and acoustic noise and must implement the control strategy necessary to keep the interferometer at its working point. The last stage of the suspension plays also another role: all the mechanical elements which are connected to the mirror must be designed not to degrade the intrinsic mechanical losses of the mirror itself. This is necessary because of the well known relation between mechanical dissipations and thermal motion in macroscopic systems. Until now this thermal noise has been reduced by developing sophisticated suspension systems with materials with low mechanical dissipation and low friction mechanical clamps: this is the technology that will be used also for the second generation advanced interferometers. However, at the goal sensitivity of third generation detectors, the only way to have a further reduction of thermal noise will be the use of cryogenics. This choice is quite natural considering also the large amount of power which will be stored in the F-P cavities: it could be found indeed that cryogenics will be the only method available to further reduce the thermal lensing effects at the incident power of third generation interferometers.
The first step of the conceptual design will be a study which will define material, size, optical properties, input power, desired attenuation and desired temperature for the mirror. For instance, the mass of the mirror itself must be decided according to the necessity to limit both thermal noise and the motion noise due to the recoil of the mirror from radiation pressure.
Once the mirror properties will be identified, the design of the suspension chain will continue on two parallel paths: the definition of the upper part and the design of the last stage.
The main parameter driving the design of the upper suspension chain is the required attenuation. A choice will be necessary between an active and a passive systems, which will be guided also by the definition of the best control strategy and by the required sensing and actuation elements, including reading and driving electronics.
To define the lower part of the suspension, a choice between different cryogenic systems will be made, with different options in terms of complexity, infrastructure, absorbed power and injected noise. In all cases, it is most likely that there will be no need to have cryogenic temperatures in the upper part of the suspension, while some care will be needed in the design of the interface between the upper and the lower part. It will be necessary also to have active and passive mechanical filters connecting the refrigeration system to the mirror. The design of these filters will be a trade-off between the necessity to avoid a decrease in sensitivity due to the injected noise and the need to preserve enough refrigeration power to reach the desired temperature on the mirror.
With the experience gained on large ground interferometers, the overall geometry of the last stage suspension will also be chosen in such a way to optimize the control strategy. On the other hand, working at low temperature, the implementation of the last stage control will take advantage of the low noise properties of superconducting technologies.
The final result of the study will be a conceptual design of the suspension including many highlights on the control strategies to be implemented and a consistent model of the overall suspension, with well identified and realistic parameters and a comprehensive noise budget. This result will be a powerful tool for the design of the actual parts during a preparatory phase.

B1.3.1.3 WP3 strategy description

In the following we will distinguish between geometry, topology and configuration of an interferometer. The geometry, defined by the number of detectors and their relative orientation, has a direct impact on the signal extraction techniques. Multiple co-located and co-linear detectors are ideal for extracting stochastic gravitational wave signals while a pair of interferometers out of plane could measure the polarisation of gravitational waves. The topology of a detector, however, is given by the optical system formed by the core optical elements. An interferometer with a given topology can be used differently depending on the configuration which comprises the parameters of the optical elements, the electro-optical control systems.

The main aim of work package 3 (WP3) is to find and define a conceptual design of the core interferometer with regard to geometry, topology and configuration that can surpass the Standard Quantum Limit (SQL) significantly. Several theoretical models exist for the reduction of quantum noise with the respective theories being well understood. At first these techniques should be compared independently from other aspects of system design. In particular the geometry of the detector and the effects of high power can be studied separately from the chosen quantum noise reduction technique. After an initial phase of parallel study we will have compiled quantitative data on the possible options. In addition, the other work packages will provide input on the detector site, the required sensitivity and the suspension performance. A trade-off analysis will use these result in order to create a draft design of the complete interferometer. Subsequently the sensing and control scheme will be modeled, as required to establish the performance and feasibility of the design.

The work package thus consists of three initially independent research threads to provide input to the main task of specifying the interferometer parameters. The three parallel tasks are dedicated to:

- Detector geometry: The boundary conditions for the detector geometry are defined by the possible sites (WP1) and the type of gravitational waves we aim to detect with maximum signal-to-noise ratio (WP4). Thus within the scope of WP3 we will develop analytical models for a detector sensitivity which can be used together with the data from WP1 and WP4 to qualify possible detector sides with respect to specific gravitational wave sources. This work is defined in task 3.

- Reduction of quantum noise : A rich selection of optical technologies have been proposed to reduce the quantum fluctuation below the SQL For conventional Fabry-Perot Michelson interferometers, with or without signal recycling, SQL can already be surpassed in a broad frequency band by making frequency dependent homodyne detections, or injecting squeezed vacuum with frequency dependent squeezing angles, with the help of km-scale optical filters. Performance can be further enhanced if one extra km-scale cavity is inserted into the interferometer dark port, or if the interferometer is built into a zero-area Sagnac topology instead of Michelson topology. In addition, with the help of the optical-spring effect in interferometers with detuned cavities, test mass mechanical resonant frequency can be shifted up into the detection band; sensitivity around the new resonant frequency can be dramatically improved. Furthermore, with the help of a second laser light, one can monitor the motion of cavity front or end mirrors with respect to their local inertial frame, and use these channels in combination with the one from the main carrier, either to cancel radiation pressure noise in the case of free-mass detectors, or to improve low-frequency sensitivity in case of optical-spring detectors. The possible implementation of any of the above noise reduction techniques has to be tested for feasibility within a likely time and cost envelope (task 1). The noise reduction factor has to be parametrised using similar boundary conditions for laser power, detector size, mirror mass and optical losses (task 2). Preliminary results can be achieved analytically. Numeric simulations will then be used to facilitate the search of the full parameter space for an optimised topology. Some of the suggested noise suppression techniques are mutually exclusive; others can be combined. A careful study of the cross-compatibility of the optical techniques shall be performed (task 4).

- Study of high power effects: The techniques for quantum noise reduction require circulating light power comparable to or in several cases much higher than proposed for Advanced VIRGO and Advanced LIGO. Non-linear coupling between the light fields and the mirror suspensions are expected to cause instabilities in the optical cavities. In addition, lock acquisition process becomes more challenging and the coupling of noise into the detector output more complex. These effects are expected to occur in all topologies and we aim to find develop local remedies which can be applied independently of the chosen topology. This work is done in task 5.

Based on the results of the tasks 1-5 a topology for the detector can be identified and requirement for the subsystems (core optics, laser, suspensions) compiled.

A feasibility study for the interferometer control will be performed and a suitable control system designed before the interferometer topology is selected (task 7). The conceptual design of the interferometer does not require a detailed design of an electro-optic control strategy, however, the feasibility of the control system validates the interferometer topology.

B1.3.1.4 WP4 strategy description

The sensitivity of an interferometric detector to astronomical and cosmological sources of gravitational waves crucially depends on several factors. As described in the previous three Sections, this Design Study will consider different options for the location of the interferometers, their topological, seismic and optical configurations. Each of these options will impact the science potential. WP4 will consider in detail the quality and quantity of science afforded by the different choices at our disposal. Our strategy is to begin with a white paper on the science potential of the 'best' possible detector that could be constructed by pushing all technologies to their fundamental limits. The white paper will serve as the basis for comparison of what science would be achievable for different configurations. For each of the relevant options considered by WP1-3, WP4 will produce a detailed document on what can be achieved for a specific set of options. Our activity should result in a summary Table that compares and contrasts the quality and quantity of science that can be achieved for different choices made in the technology.

Science potential: The shape of the detector's noise power spectrum and the various features (due to seismic, thermal and other disturbances) that might be present in the data influence the duration of observation as well as the quality of the signal that can be achieved. Needless to say the interaction between experimentalists and theorists is critical to arrive at optimum choices of the various configurations.

In a suboptimal configuration of the interferometer, necessitated by the trade off between costs and sensitivity, it would not be possible to achieve completeness of the survey for all classes of sources, nor will it will be possible to fully realize the full science potential of such a detector. WP4 will liaise with the experimentalist to work out the different trade-offs and costs benefits. Specifically, we will use metric-based criteria to favour some configurations over others. One of the chief goals of this design study will be to ensure that no compromise is made in weakening certain fundamental scientific pursuits, examples of which include strong field tests of general relativity, resolving the enigma of the origin of gamma ray-bursts, dark energy equation of state, etc. In other words we will set out a hierarchy of science goals for ET, prioritizing a list of *primary science goals*, followed by *secondary science goals*.

Data analysis requirements: Analysis of data from ET will require significant amount of new hardware and human effort. It is perfectly safe to imagine that by the time ET is built our current search software would have reached a high level of maturity that ET can benefit from. However, ET will pose new challenges. Many high-energy transient astronomical sources are very likely to appear in the gravitational window first and only then in other windows. Two important examples are (a) the merger of binary neutron stars and (b) supernovae/hypernovae. Prompt analysis of data and alerts to the relevant astronomy community will be a key requirement in order to benefit from multi-window observations of the transient source. Moreover, depending on the lower cut-off in the sensitivity of ET, the sources that were essentially "static" with respect to current detectors will not remain so in ET. It would be necessary to take into account the detector motion in our searches. It would also be necessary to consider substantially longer data segments for analysis and/or introduce new data analysis methods. Needless to say, it is extremely important to have a clear idea of the data analysis requirements to achieve the science goals that are set out in the foregoing discussion. Therefore, a significant amount of the effort will be spent in defining the various data analysis tasks, what benefit is there of existing search algorithms and software and what new methods will be needed and the corresponding data analysis hardware and software requirements.

B1.3.1.5 WP5 strategy description

The strategy adopted in the WP5 is described in the dedicated section B2.