The ESA–L3 Gravitational Wave Mission

Gravitational Observatory Advisory Team

Intermediate Report

15 June 2015

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Executive summary

In 2014, ESA's Science Programme Committee decided that the L3 mission will address the theme 'The Gravitational Universe', responding to the science goals set out in the 2013 report of the Senior Science Committee. Accordingly, a Gravitational Wave Observatory is definitively in ESA's long-term planning, with a current launch date of 2034.

A space mission exploiting laser interferometry has been under consideration, and studied in great detail in various forms, for 30 years. While promising to open a completely new window on the Universe, such a mission presents a set of demanding challenges for the measurement accuracies and associated technologies. The schedule and cost overruns of the precursor technology demonstrator mission LISA Pathfinder, the uncertain status of potential collaborative partners, perceived challenges for the data analysis, and the emergence of potential alternative measurement approaches, have added further cautionary elements to the mission's adoption.

Accordingly, in late 2014, ESA's Director of Science and Robotic Exploration appointed an external committee, the Gravitational Observatory Advisory Team, to advise on the scientific and technical implementation of L3. The Terms of Reference of the committee (Chapter 1) can be paraphrased as follows: (a) is the mission technically feasible? (b) is laser interferometry still the best approach to the measurement of gravitational waves from space? (c) how can the technical development of L3 be organised to minimize cost and schedule overruns? The Committee has been asked to report sometime in early/mid-2016, to allow the preliminary results of LISA Pathfinder (due for launch in October 2015) to be included.

However, certain early findings warrant an intermediate report, with the objective that certain high-priority development activities can be started promptly by ESA, reducing risk, and further facilitating a timely development schedule. Specifically, in its work so far:

- the Committee has undertaken a review of all known measurement approaches to the measurement of gravitational waves (details will be given in the final report). It has reached the preliminary conclusion, contingent on the success of LISA Pathfinder, that *laser interferometry* responds to the science goals set out in the 2013 report of the Senior Science Committee, and is sufficiently well advanced to offer a realistic prospect of implementation according to the 2034 launch schedule;

- the Committee appreciates that a second approach, based on *atom interferometry*, shows interesting potential. The Committee is encouraging the development of a full mission proposal to assess better its challenges, and its prospects for either a more secure, or a less costly, alternative;

- the Committee has re-evaluated the scientific capabilities of a Gravitational Wave Obser-

vatory, quantifying and presenting the expected performance as a function of:
  - the number of interferometric baselines (2 or 3 arms, with 4 or 6 links);
  - the interferometric arm-length (between 1×10^6 km and 5×10^6 km);
  - the mission duration (2 years or 5 years);
  - test mass 'acceleration noise'.

  This is intended to provide ESA and its advisory committees with a menu of scientific performance versus architecture (and, implicitly, cost) at whatever point in time that the financial constraints, national contributions, international partners, and other boundary conditions are known more securely;

- the Committee has undertaken an extensive compilation of all technology developments (and major system trades) required for the laser interferometric approach. The compilation includes details of ongoing technology studies, as well as the item's current 'technology readiness level' (TRL). Only in two cases is the technology development weakly sensitive to the precise mission configuration that could be adopted (specifically, the telescope diameter and laser power are dependent on the interferometric arm-length);

- the technology challenges of L3 are significant, but should not be overstated: laser interferometry has had a very long development and study phase, the techniques are well mastered on ground, and LISA Pathfinder should retire many of the space-specific risks;

- the Committee has identified four high-priority, high mission impact, technology activities, not covered by LISA Pathfinder, which are recommended for immediate start: related to the optical architecture, the telescope, the laser, and the optical bench;

- the Committee is formulating an outline development schedule, given here in preliminary form. It is specifically structured to meet a 2034 launch date (rather than examining an expedited launch schedule). A key (and unusual) element is the introduction of a payload Engineering Model, designed to test critical functionality before mission adoption;

- the Committee's assessment is that there are no fundamental or conceptual issues with the data analysis. At the same time, it represents a challenge, both algorithmically and computationally. The momentum that had built up in the community for LISA/eLISA/NGO has somewhat dissipated, with national funding generally no longer forthcoming due to the distant launch date, and the tasks probably not perceived as a priority. The Committee considers that this is a risk situation, and that it would be advantageous for certain data analysis related activities to be picked up promptly, not least since some will have an impact on, and will guide, the ongoing technical design;

- European studies for L1 suggest a budget requirement of 1.0–1.2 B€. As exemplified by more in-depth US exercises, costs are only rather weakly dependent on system architecture. The Committee identifies some specific considerations relevant to the mission costing, but proposes not to embark on any new or independent cost assessment exercise, for reasons which are given, but would like ESA's guidance on this suggested approach.

In the spirit of the Terms of Reference of the present activity, where a *scientific theme* rather than a *mission architecture* was prescribed, the term 'L3 mission' is used instead of the acronyms LISA, eLISA, or NGO which convey a specific design solution. Literature references have not been included in this intermediate report.

1

Introduction

1.1 Objectives of the Advisory Team

In 2013 the Director of Science & Robotic Exploration (D/SRE) tasked a Senior Science Committee to advise on the goals for the next 'large missions' (L2 and L3, for launch in 2028 and 2034 respectively). The SSC advised that L3 should address the theme 'The Gravitational Universe'.

In November 2013 the Science Programme Committee selected the theme 'The Gravitational Universe' for L3. Subsequently, D/SRE appointed a Gravitational Observatory Advisory Team to advise on the scientific and technological approach for a gravitational wave observatory for launch in 2034. The Committee's boundary conditions were specified as follows:

- L3 will be European-led, with a cost to ESA not to exceed 1 B€ (2014 economic conditions), plus an expected national contribution of order 25% of the ESA cost;
- international participation will be limited to elements not exceeding approximately 20% of the total mission cost;
- the mission must be based on technology that can credibly achieve Technology Readiness Level 6 (TRL 6, on the ISO scale; see p. 24) by the mission's adoption;
- the mission profile must be compatible with a 'Call for Mission' to be issued around the end of the present decade [although the present target of D/SRE is 2016 Q3];
- the mission must address the science goals in the Senior Science Committee report.

The objectives of the committee are:

- to identify promising technologies for the detection of gravitational waves from space and their use as 'astrophysical messengers' in the context of L3;
- to recommend on the technological activities and milestones needed to develop and eventually choose between the most promising technologies;
- to identify possible scientific and technological milestones that should be achieved (either by ESA or independently) and the relevant decisions linked to these milestones;
- to engage with the gravitational wave scientific community to ensure that the most recent information and promising approach are considered.

This intermediate report marks a first milestone of the Committee's work. The Committee has reviewed all proposed approaches to the measurement of gravitational waves from space over the relevant frequency band, and confirms that the most credible approach is indeed based on laser interferometry. Its parallel synthesis of the technologies that must be developed before adoption opens the way to the funding of the necessary preparatory technology activities.

1.2 Development history

The first ideas for detection of gravitational waves by Iong-baseline laser interferometry in space were presented 30 years ago at the Joint Institute for Laboratory Astrophysics (JILA), USA. Over this lengthy interval, various mission concepts have been formulated and studied in detail, marked by the following milestones:

1985 first mission concept (by J. E. Faller, P. L. Bender, D. Hils and M. A. Vincent), named LAGOS (Laser Antenna for Gravitational-radiation Observation in Space): three drag-free spacecraft in a heliocentric orbit, forming a V-shaped interferometer with two arms separated by 120°;

1993 May LISA (Laser Interferometer Space Antenna) proposed to ESA by a European science team coordinated by K. Danzmann, in response to the Call for Mission Proposals for the third 'medium size mission' (M3) within the 'Horizon 2000' programme: four spacecraft in heliocentric orbit, forming an interferometer with a baseline of 5×10^6 km.

Similar objectives were addressed by a second M3 proposal, coordinated by R. W. Hellings. SAGITTARIUS consisted of six spacecraft in a geocentric orbit, to form an interferometer with a baseline of 1×10^6 km. ESA decided to merge the two missions for a common M3 assessment study, initially called LISAG, and later LISA;

1993 Dec with LISA not expected to meet the M3 cost envelope, it was proposed as a cornerstone project for 'Horizon 2000 Plus', and formulated as a mission comprising six spacecraft in heliocentric orbit;

1997 Feb the LISA team and ESA's Fundamental Physics Advisory Group (FPAG) recommended to carry out LISA in collaboration with NASA. Several technical measures were introduced to reduce the overall cost of the mission, including in particular a reduction of the number of spacecraft from six to three, launched by a single Delta II vehicle;

1998 Nov publication of the pre-Phase A Report (2nd edition), summarising the results of the European study for the revised version of LISA with three spacecraft in a heliocentric orbit, in cooperation with NASA. The report took into account an independent Team-X study performed at JPL, basically confirming its feasibility;

1998 proposal for ELITE (European LISA Technology Experiment), a satellite mission to demonstrate dedicated technologies required for LISA;

1999 Jun industrial assessment study of LISA under ESA contract (final report in April 2000): a detailed spacecraft and subsystem design to identify implications of the selected instrument concept and predict the system performance;

2000 Nov the SPC approved SMART–2, a refined version of ELITE. SMART–2 was proposed as a joint LISA and Darwin pathfinder mission, consisting of two spacecraft with a European LISA technology package, a NASA-provided LISA technology package, and a Darwin technology package. After initial industrial study, the mission was descoped to a single spacecraft without the Darwin technology package, and renamed 'LISA Pathfinder';

2005 Jan the industrial LISA mission formulation study detailed all aspects of the LISA mission, trading off and consolidating the payload architecture. The concept of a triangular constellation, formed by laser interferometry over 5×10^6 km between three identical spacecraft, was maintained throughout the entire study. It was concluded in February 2011 with the Mission Consolidation Review;

2007 Oct LISA joined the ESA Cosmic Vision process, in competition with three other L mission candidates (EJSM–LAPLACE, IXO, and TandEM/TSSM), selected by the SPC from 50 mission concept proposals;

2011 Apr in response to US decadal survey rankings of the L missions, as well as projected US budget constraints, ESA investigated the affordability of European-led L missions with only limited international participation, instead of proceeding with the L mission downselection as planned in June 2011. Small industrial assessment studies were awarded to support a corresponding reformulation of all three L missions, and in October 2011 a European only 'reformulation study' was performed by Astrium under ESA contract, with the support of the University of Glasgow for the optical bench. The scaled-down design was initially known as the New Gravitational-wave Observatory (NGO) for the ESA L1 mission selection;

2012 May the SPC selected JUICE as the L1 mission, with a targeted launch date of 2022. The name of the gravitational wave mission was changed to eLISA (Evolved Laser Interferometer Space Antenna);

2013 Nov the SPC selected the science theme 'the hot and energetic Universe' for L2 with a foreseen launch in 2028, and the 'gravitational Universe' as the science theme for L3, with a foreseen launch in 2034;

2015 Oct expected launch of LISA Pathfinder.

1.3 LISA Pathfinder

LISA Pathfinder (formerly SMART–2) is a precursor mission to test the critical technologies needed for a LISA-like gravitational wave observatory, except for those required by the spacecraft-to-spacecraft interferometric laser ranging. Its primary goal is to test the feasibility of measuring geodesic motion to within an order of magnitude of the LISA/eLISA requirements, using specifically-designed hardware, thus representing an improvement of several orders of magnitude relative to any existing or planned mission using free-falling reference bodies.

To achieve its goals, LISA Pathfinder will measure the relative motion of two 2 kg test-masses in near-perfect geodesic motion by means of a picometer-sensitivity laser interferometer. In contrast to LISA with its test masses separated by $\sim 5 \times 10^9$ m, the LISA Pathfinder test masses are 0.38 m apart in a single spacecraft.

LISA Pathfinder will provide an experimentally-anchored physical model for all the spurious effects, including stray forces and optical measurement limits, that may affect the performance of the gravitational wave observatory. The model will only leave out the effect of the laser frequency noise and beam propagation over the million km scale arms, which would require the entire constellation, and which can instead be satisfactorily tested and modeled on ground. In particular, the mission will verify, and advance to TRL > 7:

- drag free control of spacecraft with freely suspended test-masses;
- precision attitude and trajectory control of the spacecraft;
- low noise μN-thrusters to implement drag-free control;
- inertial sensors with large gaps, heavy masses and no mechanical contact to spacecraft (this includes a test-mass launch lock, plus a mechanism for the injection of test-masses into orbit with high positional accuracy and low momentum);
- high stability electrical actuation on orthogonal degrees of freedom;
- non-contact discharging of test-masses by ultraviolet illumination;
- high-stability monolithic optical assemblies;
- relative motion of test-masses and spacecraft from picometer interferometry;
- high spacecraft thermo-mechanical stability (for low self-gravity noise);
- gravitational field control and cancellation;

Inertial sensors, interferometer and associated instrumentation are part of the 'LISA Technology Package', supplied by contributing institutions across Europe, and integrated by Airbus Defence and Space Germany. By using the LISA Technology Package as the reference instrument, LISA Pathfinder will test two drag-free control systems: a European system using cold-gas microNewton thrusters (similar to those used on Gaia) in a dedicated configuration, and a US-built 'Disturbance Reduction System' using the same sensors with colloid-based thrusters.

The spacecraft will be launched by Vega into an elliptical low-Earth orbit, from where successive perigee boosts, using an expendable propulsion module, will raise the apogee closer to the intended halo orbit around the Earth–Sun L1 point. Launch is currently foreseen for October 2015.

2

Scientific objectives

2.1 Introduction

The scientific objectives of LISA/eLISA/NGO have been presented in depth elsewhere. Here, we provide a concise summary, and focus on those aspects that are relevant for an understanding of the implications for mission performance, configuration trade-offs, and data analysis.

The sensitivity curves predicted for a long armlength laser interferometry mission in space (Figure 2.1) are such that many thousands of gravitational wave sources should be detectable at high signal-to-noise, and in many cases (extremely) well characterised in terms of frequency, position on the sky, and luminosity distance.

Detailed simulations of plausible instrument configurations (Chapter 4) shows that there are three main classes of astrophysical sources that should be detected: close compact binaries in our Galaxy [the vast majority are compact white dwarf binaries (CWD), but binaries comprising one or more neutron stars or black holes are of special interest], extreme mass ratio inspirals (EMRI), and massive black hole binaries (MBHB). Stochastic backgrounds of gravitational waves, of primordial or astrophysical origin, can also be detected. From the survey of many individual sources, the scientific themes addressed by the L3 mission will focus on:

- the nature of gravity
- the fundamental nature of black holes
- black holes as sources of energy
- nonlinear structure formation
- dynamics of galactic nuclei
- formation and evolution of stellar binary systems
- the very early universe
- cosmography (specifically, the cosmic distance scale)

Figure 2.2 indicates how these science topics are related to the detection of the various sources. Figure 2.3 shows the detectability of sources as a function of observational frequency and, correspondingly, instrument. It illustrates that a gravitational observatory in space offers the most rewarding bandwith, with an abundance of astrophysical sources.

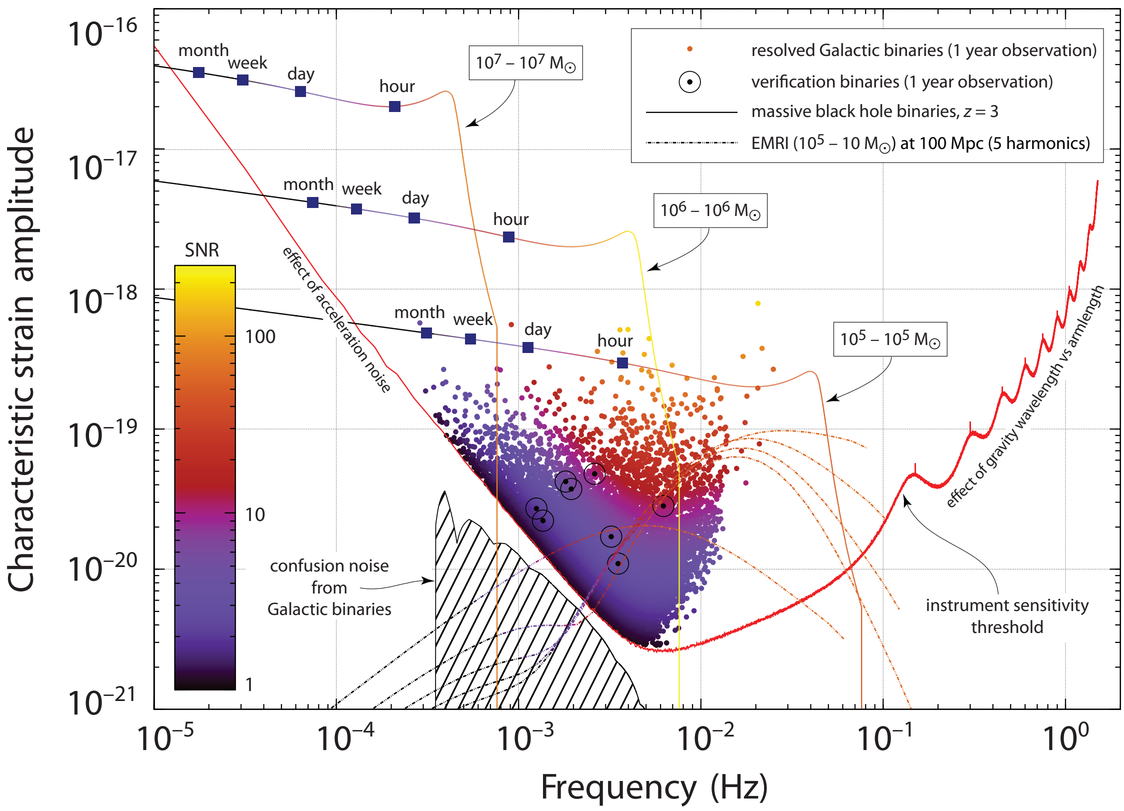

Figure 2.1: Characteristic strain amplitude, $\nu\, h(\nu)$, versus frequency for a space-based laser interferometry mission (armlength = 1×10^6 km, 1-yr observations). Objects expected to be strong gravitational wave sources over this frequency range are indicated. For compact white dwarf binaries, individual simulated sources, known 'verification binaries', and the effect of confusion noise from the ensemble of fainter sources, are shown. Dashed lines give example loci for extreme mass ratio inspirals (EMRIs) for the case of a $10^5 M_\odot - 10 M_\odot$ binary (and showing the 5 strongest harmonics). Solid curves show three example loci of massive black hole binaries of different mass, labelled with the time intervals over which the source remains 'in band'. In all cases, colour coding shows the corresponding (cumulative) S/N, increasing toward higher frequency as each system becomes more compact (this version courtesy Stas Babak, AEI, and Antoine Petiteau, APC).

Figure 2.2: The contribution of the different astrophysical sources detected by the mission to the various scientific topics.The intensity of shading is intended to give some general indication of the relevance of the sources to the topics addressed.

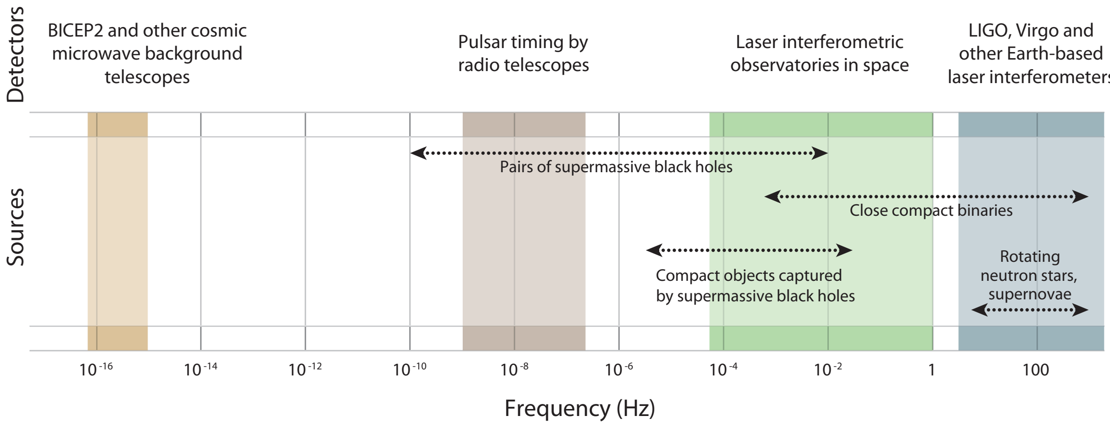

Figure 2.3: Frequency range of gravitational wave sources and bandwidth of corresponding gravitational wave detectors on Earth and in space. A gravitational wave background generated during cosmic inflation should be present over the entire frequency spectrum. From Barke et al. (2015), Classical and Quantum Gravity, Volume 32, article 095004, Fig 1 (courtesy Simon Barke).

2.2 Classes of sources

We first comment briefly on each of the classes of sources which will drive the mission science.

2.2.1 Compact white dwarf binaries (CWDs)

The large population of white dwarf binaries in our Galaxy emits gravitational waves across the whole LISA/eLISA band. There are predicted to be of order 10^7 Galactic binaries, the vast majority of which will not be individually resolvable, and which will therefore create a stochastic gravitational wave foreground below 3–5 mHz. Some Galactic binaries are known from electromagnetic observations (others will be provided by Gaia). Some dozen are guaranteed LISA/eLISA sources, referred to as 'verification binaries'. Depending on the satellite configuration adopted, some 1000–10 000 are expected to be resolved and characterised (Table 4.1). Each signal is long lived, almost monochromatic (with a small frequency drift due to gravitational wave emission and/or mass transfer), with each characterised by 7–8 parameters, depending on whether the frequency drift is measurable. Expected S/N are typically moderate (up to about 100). A sample population is shown as dots in Figure 2.1, among which the known verification binaries are shown as circles.

2.2.2 Massive black hole binaries (MBHBs)

These sources trace the ongoing mergers of massive black holes at the centre of galaxies, when these galaxies are merging. Their numbers and form will establish the cosmological merger history of this important population, and will help to establish what is the role of these central massive black holes in the dynamics of galaxy formation and evolution. These systems are expected to generate some of the strongest signals that low-frequency gravitational waves telescope can detect: they provide what can be considered as the gold-plated events of gravitational astronomy. In many cases, component masses and black hole spins, as well as distance and sky location, can be established from the gravitational wave profiles (Figure 2.4).

2.2.3 Extreme mass ratio inspirals (EMRIs)

These are systems in which an object orbits a much more massive object (factor $\gtrsim 10^4$). The orbit gradually decays through the emission of gravitational waves. Such systems are likely to be found in the centers of galaxies, where stellar mass compact objects, such as stellar black holes and neutron stars, may orbit a supermassive black hole. These systems evolve slowly over many thousands of cycles before eventually plunging, with the gravitational wave signal encoding a precise map of the spacetime geometry of the supermassive black hole (Figure 2.5). Simulations suggest that the most performant (LISA-like) configurations may detect some 5000–10 000 systems. For each, observations will allow accurate determination of the system parameters.

2.2.4 Gravitational wave backgrounds

Backgrounds of gravitational waves will also be searched for by the L3 mission. These backgrounds could be astrophysical (such as the background of unresolved compact white dwarf binaries) or cosmological. One important issue is how to disentangle such backgrounds from the instrumental noise. The symmetry of the 6-link version of the mission provides a mode that suppresses the signals and thus gives access in flight to the instrumental noise. In the case of a 4-link mission, a study is presently conducted to see how one could proceed to achieve the same goal through the knowledge of some of the characteristics of the instrumental noise.

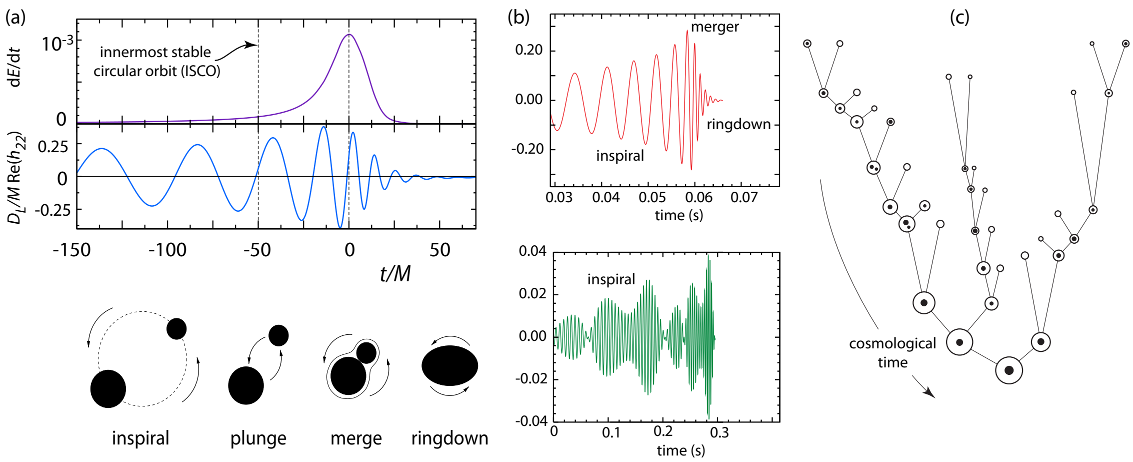

Figure 2.4: Gravitational wave signals from massive black hole binaries (MBHBs): (a) gravitational wave energy (upper) and generic waveform (lower) for a massive black hole binary system illustrating the successive inspiral, plunge, merge, and ringdown phases; (b) two simulated waveforms, illustrating how the waveforms are highly sensitive to the binary system parameters, including the mass and spin of each component, as well as the detailed orbit geometry; (c) in the currently favored cosmological model, galaxies form in a hierarchical fashion, starting from small systems at early times, and then growing via mergers: each galaxy observed today is a consequence of its merger history extending back to high redshifts. If black holes formed at early times, they will have followed the merger hierarchy of their host galaxies. Black hole mergers are therefore expected to be common events.

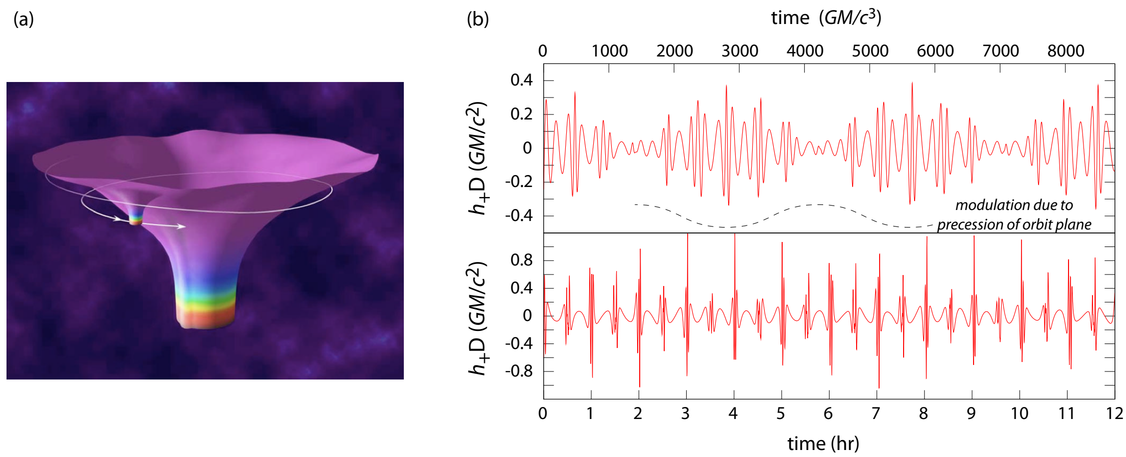

Figure 2.5: Gravitational wave signals from 'extreme mass ratio inspiral' systems (EMRIs): (a) schematic of the associated spacetime; (b) segments of generic waveforms, showing the plus-polarised waves produced by a test mass orbiting a $10^6\,M_\odot$ black hole spinning at 90 per cent of the maximal rate allowed by general relativity, at a distance D from the observer. Top panel: slightly eccentric and inclined retrograde orbit modestly far from the horizon, in which the amplitude modulation is mostly due to Lense–Thirring precession of the orbit plane. Bottom panel: highly eccentric and inclined prograde orbit much closer to the horizon, in which the more eccentric orbit produces sharp spikes at each pericentre passage.

2.3 Science topics

The detection of the various sources and backgrounds allows significant progress in the understanding of the following science themes:

2.3.1 The nature of gravity

Gravity is the least known of the fundamental interactions. The L3 mission would provide key tests of general relativity, the theory of gravity, in the weak regime through the close analysis of the spiraling motion of two black holes, but also in the strong regime. This strong regime, reached in the close vicinity of black hole horizons, remains untested to this date and is uniquely studied with gravitational waves (MBHB and EMRI) because it does not require significant modeling of the black hole environment. The propagation of gravitational waves from distant sources allows to test the masslessness of the graviton, and thus provides bounds on the graviton mass. Likewise, the property of gravitational waves to be realized in only two polarizations is not shared by variants of general relativity: searching for extra polarizations is thus again a key test of the theory of gravity. In summary the mission will probe:

- the nature of gravity in the weak field regime
- the nature of gravity in the strong field regime
- propagation effects, in particular constraining the graviton mass
- the existence of additional polarizations

2.3.2 The fundamental nature of black holes

One good EMRI event should allow to test the existence of a horizon around black holes by identifying the sudden extinction of the signal when the small compact object falls into the horizon. It will also be possible to test the hypothesis, to high accuracy, that the central object is indeed a supermassive black hole, by measuring the quadrupole moment of the gravitational field to an accuracy of a fraction of a percent. More generally, the mapping of the horizon region provided by the many cycles of the compact object around the supermassive black holes should provide key information on the properties of this black hole, especially on its Kerr nature. The final phase (ringdown) of the massive black hole coalescence (MBHB) provides key tests of the 'no-hair theorem', according to which a black hole is defined by three numbers (charge, spin and mass): after coalescence, the system of two black holes sheds its superfluous properties through gravitational wave emission. In summary the mission will probe:

- the existence and nature of the black hole horizon
- tests of the Kerr nature of black holes (black hole mapping)
- ringdown tests of the no-hair theorem (black hole spectroscopy)

2.3.3 Black holes as sources of energy

The (gravitational wave) luminosity of an event such as a massive black hole merger is some 10^{23} orders of magnitude larger than the Sun (electromagnetic) luminosity. If even a very small fraction of this energy is converted into electromagnetic waves, this provides an electromagnetic counterpart to this event. A key issue is however timing: gravitational waves emerge rapidly whereas electromagnetic signals may be delayed by diffusion in the material background of the black hole. In summary the mission will probe:

- the formation of jets, the Blandford–Znajek effect, and the radio loud/quiet dichotomy
- tests of accretion disk models
- transient counterparts (on the time scale of months)

2.3.4 Nonlinear structure formation

In the currently favoured scenario for the formation of cosmic structures in the Universe, present-day galaxies have been built up, via a series of mergers, from small building blocks that formed at earlier cosmic times. Galaxies experience multiple mergers during their lifetime. A single large galaxy, now containing a massive black hole, can be traced back to the stage when it was split up in hundreds of components with masses a million times smaller than today's galaxies. The properties of the black hole population observed are given by the combination of their birth rate, merger rate, and growth rate of each black hole though accession of matter. The mass and the frequency of the seeds, as well as the dynamical evolution of black hole pairs, ultimately dictate the distribution of massive black holes in galaxies. In summary the mission will probe:

- the seed formation (at high redshift),
- the hierarchical assembly (at mid-to-low redshifts),
- models of accretion.

2.3.5 Dynamics of galactic nuclei

It is important to understand the dynamics of the galactic nuclei in order to predict accurate rates for EMRI events. But conversely, the detection of EMRI events will provide key information on the stellar dynamics and content of the inner region of a few 0.01 pc around the galactic nucleus. For example, the distribution of eccentricities of EMRI events might give precious information on the stellar formation in accretion disks and on the tidal disruption of binary systems (two distinct sources of compact remnants in the vicinity of the central black hole). It remains to identify precise figures of merit that would allow to quantify the potential of the various mission configurations.

2.3.6 Formation and evolution of stellar binary systems

A gravitational wave mission will provide scientific insight into the number of ultra-compact binaries in the Galaxy, as well as the merger rate of white dwarfs, neutron stars, and stellar mass black holes in the Galaxy: this will thus better constrain the rate of their associated explosive events. It will allow to study the onset of white dwarf mass exchange events with another white dwarf or neutron star, and the consequences for the explosion mechanism of Type Ia supernovae. Moreover, it will give access to the spatial distribution of ultra-compact binaries, and what this reveals about the structure of our Galaxy as a whole. In summary the mission will probe:

- the formation of compact object binaries
- the nature/physics of white dwarf mergers
- the structure of the Milky Way

2.3.7 The very early Universe

The L3 mission may provide significant information on epochs of the evolution of the Universe which precede the Hydrogen recombination era when the photons of the CMB were produced. Indeed, the frequency window corresponds to the epoch when the energy density in the Universe corresponds to 1 to 10^3 TeV, thus to the electroweak phase transitions and the phase transitions corresponding to physics beyond the Standard Model. There is thus an excellent complementarity with LHC and foreseen higher energy colliders. For the gravitational waves to be detected, the phase transition has to be violent enough (i.e., strongly first order). Other potential cosmological backgrounds are those due to networks of cosmic strings (associated to phase transitions or to fundamental superstrings) or those related with inflation. In the simplest models of inflation, it must be said however that primordial gravitational waves are too low to be detected with the sensitivity of the detector foreseen. In summary the mission will probe:

- Higgs physics and beyond, and multi-TeV physics
- topological defects, in particular cosmic of fundamental strings
- nonstandard inflation and related phenomena (reheating, etc.)

2.3.8 Cosmography

Some of the events identified by the mission (MBHB, EMRI) provide a very different (i.e., gravitational) way of measuring the luminosity distances of far away events, thus leading to new means of identifying cosmic distances. For this method to be successful, one needs to identify the redshift, either with an electromagnetic counterpart or through statistical identification of the host galaxy in the detection window. The advantage of this method is to provide precise determination of cosmological parameters, e.g. the dark energy equation of state parameter, with very different statistical errors (mostly due to gravitational lensing). Similarly, if an EMRI event can be matched with an electromagnetic counterpart, the precise determination of its luminosity distance provides a completely independent way of determining the Hubble parameter at cosmic distances. In summary the mission will probe:

- the Hubble constant to a few percent accuracy
- the equation of state of dark energy to a few percent accuracy

3

Detection technologies

3.1 Survey of available techniques

The Committee has reviewed the various technologies proposed for the detection of gravitational waves using literature searches over the past 50 years, and compared these with the world-wide progress on these approaches where reported. The aim was to identify technologies relevant to the achievement of the science objectives outlined in the Senior Survey Report. That is to say, in broad terms, the ability to achieve a sensitivity in dimensionless amplitude, within one year, of 10^{-23} over the frequency band from 100 micro-Hz to 100 milli-Hz, referred to as the L3 band.

In total, 25 distinct technologies for registering the presence of a gravitational wave were identified (and will be listed in the final report). Identified techniques fell into four categories: many were too insensitive to detect the dimensionless amplitude required; others only operated at frequencies outside the band of interest (either higher or lower); a further group were frequency independent, but lacked published studies quantifying their sensitivity levels over the L3 band.

The final category comprised the only two technologies which the Committee focused on as having the potential to meet the scientific requirements set by the Senior Survey Report: laser interferometry and atom interferometry.

3.2 Laser interferometry

Laser interferometry has been in operational use in gravitational wave detectors on ground since the 1970s. Instruments now in operation such as Advanced LIGO, Advanced Virgo and GEO600 have already demonstrated the ability to read out test mass positions to somewhere below $10^{-19}\,\mathrm{m\,Hz^{-0.5}}$ at frequencies around 100 Hz. Most of the critical subsystem technology required for laser interferometry has also been thoroughly developed for the LISA Pathfinder mission, by institutes in Europe and the US. The benefits from the operational experience gained during the LISA Pathfinder mission will also be available to those designing the L3 mission.

3.3 Atom interferometry

Atom interferometry is currently under development in laboratory and demonstration versions. Ultra-cold neutral atoms provide excellent clocks (optical frequency metrology), and have the potential to be used as gravitational proof masses (through atom interferometry). Combination of these attributes could in principle enable a single baseline *detection* of gravitational waves (with corresponding limitations on sky position and polarisation information). First results date from the 1991 demonstration of an atom interferometer gravimeter. From a system perspective, the most recent concept envisages clouds of $\sim 10^8$ atoms which are extended over several cm, 'fly' for 10–100 s, need to be shielded from solar radiation, and are then retrieved by momentum transfer imposed from the other spacecraft.

Recent publications have given outline descriptions and preliminary noise budgets for a space-based detector capable of achieving the L3 mission objectives, but no detailed studies of implementing such technology on a space platform have been completed.

At this interim stage, the Committee has concluded that laser interferometry indeed offers demonstrated sensitivity on ground, as well as advanced preparation and demonstrated feasibility, for a space mission. No other technology has such an advanced technological status, and we focus on it exclusively in the rest of this intermediate report. Further examination of the prospects for atom interferometry are nevertheless planned.

4

Scientific performance trade-off

4.1 Instrument configurations assessed

To formulate a technology development strategy, an instrument design must be specified. However there will be boundary conditions that may prevail at the time of adoption that are unknown or at least somewhat uncertain today, including national contributions, international partners, cost analysis models, launcher options, and others.

Rather than adopt some configuration *a priori*, we have considered the most important parameters that characterise a laser interferometry mission (Figure 4.1), and obtained the support of the L3 scientific community to assess the associated scientific performances. We adopted the following parameter cases:

- armlength (satellite separation): 1×10^6 km, 2×10^6 km, 5×10^6 km. The sensitivity to long wavelength gravitational waves improves with increasing armlength. However, increasing armlength comes at the expense of a (slightly) larger telescope diameter, higher laser power, and greater complexity in initial acquisition;

- mission duration: 2 years or 5 years. The number of sources increases with...TBC;

- low-frequency acceleration noise, corresponding either to the original LISA requirement (i.e. 10× better than the LISA Pathfinder goal), or to a factor 10 degradation;

- number of laser links: either 6 laser links between the three spacecraft (the original LISA configuration), or 4 links (as in the mother–two daughter design of the descoped NGO).

This gives a total of $3\times2\times2\times2 = 24$ configurations spanning a wide range of possible instrument configurations. For reference, the main attributes of LISA and NGO were as follows:

LISA (ESA–NASA): 3 spacecraft (6 links); orbit: heliocentric, tilted 60°, 20° Earth trailing, $D = 5 \times 10^9$ m; lifetime: 5-yr; test mass: cubes, two per spacecraft; thrusters: Cs FEEPs (ESA), colloidal (NASA), with cold gas (300 kg) as potential backup by ESA; telescope: $d = 0.4$ m (initially on-axis, later Astrium recommended off-axis), pm stability required; laser: 1 W end of life between spacecraft (2 W initial source power); launch: Atlas V (directly into escape orbit).

eLISA/NGO (ESA-led): 3 spacecraft, 4 links (one mother, two daughter); orbit: $D = 10^9$ m in drift away orbit (from 9 to 22°); lifetime: 2 yr; launcher: two Soyuz. Both the reduced nominal lifetime, and the reduced armlength, affected the predicted scientific return.

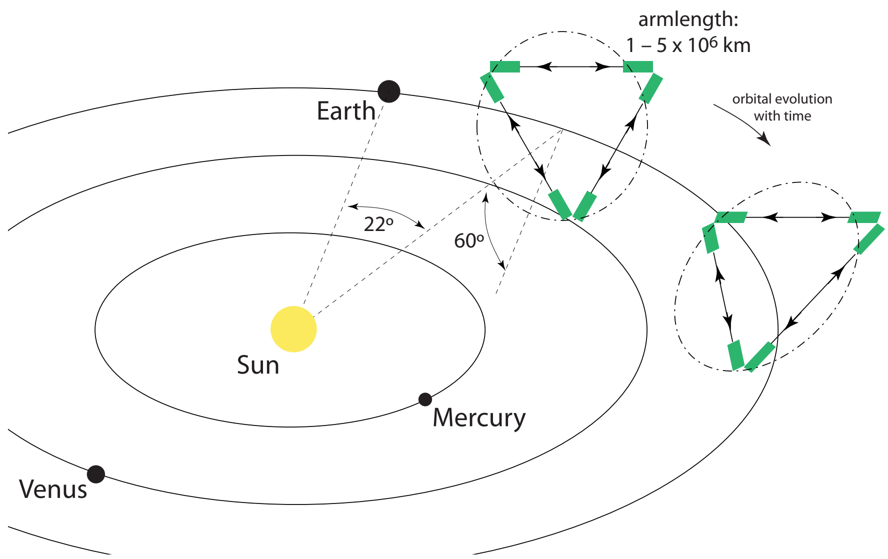

Figure 4.1: Schematic of the satellite and orbit configuration. The three satellites comprising the interferometers are in a heliocentric orbit which trails the Earth by 22°. By a very specific choice of the satellite orbits (in inclination, eccentricity, longitude of ascending node, and argument of pericentre), the three-satellite constellation rotates by 360° per year in inertial space.

4.2 Number of laser links

The number of laser links (4 or 6) has various significant scientific implications, some of which are less easily quantified numerically:

- the 6 link (3 identical satellites) provides significant mission-level redundancy in the case of satellite or laser-link failure.
- the simultaneous presence of 6 links allows the search for stochastic background signals through cross correlation.
- most importantly, the 6 link configuration permits the simultaneous determination of the two polarization states of each individual gravitational wave. There are two source types which must be considered separately:
  - this is less critical in the case of white dwarf–white dwarf binaries and EMRIs, which remain in the detectable frequency band for more than a year, and for which the polarization degeneracy is broken by the orbital motion of the 3-spacecraft constellation. In this case, the improvement brought by 6 links compared with 4 links is basically related to an improvement in signal-to-noise. Accordingly, the detectable number of EMRIs increases by a factor 2.8 ($2^{3/2}$), and their parameter estimation accuracy improves by a factor 1.4 ($2^{1/2}$). The number of resolvable white dwarf–white dwarf binaries increases by a factor 2, and their parameter estimation accuracy improves by a factor 2;

– the gains are of more crucial importance for the strongly time-varying gravitational wave sources, such as massive black hole binaries, where the final merger occurs over weeks or days, and where the time-evolution of the polarization is of substantive diagnostic power. In this case the mass and spin measurements have an improvement consistent with the increase in signal-to-noise going from one to two interferometers, i.e. ~ 1.4. Simulations indicate that mean distance estimates improve by a factor 5.3, while the mean solid angle positional constraints improve by about 30. This in turn implies, for example, that more than 10 times as many sources are constrained to better than 10 $\deg^2$ (from 0.2/yr to 3/yr), a gain of importance for the comparable fields of view of LSST and SKA, with their capability of detecting electromagnetic radiation from a $10^6\,M_\odot$ black hole at $z \sim 2-3$.

4.3 Simulation results

The above parameter cases were passed to an *ad hoc* consortium of scientists from 8 European and US institutes involved in developing the LISA/eLISA simulation and data processing tools[1]. They reported back to the Committee with the detailed results of their performance assessment for the 24 configurations given in Section 4.1.

Tables 4.1, 4.2, and 4.3 summarise the preliminary results in tabular form[2]. They will be used over the coming months as a basis of discussion with the scientific community, and as a framework for more detailed and complete simulations. The goal is to have complete tables available at the time of the Committee's final report (mid-2016).

In particular three directions of study might lead to significant improvements in the scientific capability of some mission configurations:

- Bayesian-based algorithms for massive black hole mergers seem to address some of the shortcomings identified in the more traditional parameter estimation based on the Fischer information matrix;
- the inclusion of the full merger and ringdown part of the signal improves parameter estimation for massive black hole binary mergers, in particular regarding the localisation window;
- a method proposed by Adams & Cornish (2010, Phys. Rev. D82) uses information on the spectral shape and modulation of the astrophysical foreground and instrument noise to improve significantly the detection of stochastic backgrounds.

[1]S. Babak (AEI, Potsdam), E. Barausse (IAP, Paris), E. Berti (University of Mississipi), C. Caprini (IPht, Saclay), R.H. Cole (University of Cambridge), J.R. Gair (University of Cambridge), A. Klein (University of Mississipi), C.J. Moore (University of Cambridge), G. Nelemans (Radboud University, Nijmegen), A. Petiteau (APC, Paris), E. Porter (APC, Paris), A. Sesana (AEI, Potsdam).

[2]in the following tables, '?' indicates ongoing work which is not yet conclusive, while '–' indicates that no estimate exists yet

Table 4.1: Scientific capabilities for the various sources assuming a 2 year mission lifetime (top panel) and a 5 year mission (bottom panel). (acronyms: MBHB = massive black hole binary, EMRI = extreme mass ratio inspiral, CWD = compact white dwarf)

Acceleration noise wrt goal	10×						1×					
Arm length (10^6 km)	1		2		5		1		2		5	
Configuration (arms/links)	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6
Mission lifetime (yr)	2	2	2	2	2	2	2	2	2	2	2	2
total MBHB detected[(a)]	5–36	7–54	15–165	16–197	8–72	11–98	16–197	16–222	13–133	15–165	16–222	16–266
MBHB sky location	✗	✗	✗	✓	✗	✓	✗	✓	✗	✓	✓	✓
MBHB luminosity distance	✗	✗	✗	✗	✗	✓	✗	✓	✓	✓	✓	✓
total EMRIs detected	5–90	12–210	21–385	51–830	88–1205	184–2200	38–640	93–1330	176–2090	332–3270	543–4190	760–5010
EMRI position	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓
EMRI luminosity distance	✗	✗	✗	✗	✗	✓	✗	✗	✓	✓	✓	✓
CWD detected/resolved[(b)]	569	952	1298	2043	3073	4987	5248	8805	9189	14757	13634	21744
CWD position[(c)]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
CWD luminosity distance[(d)]	?	✗	?	✓	?	✓	?	✓	?	✓	?	✓
stochastic background	?	✓	?	✓	?	✓	?	✓	?	✓	?	✓

Acceleration noise wrt goal	10×						1×					
Arm length (10^6 km)	1		2		5		1		2		5	
Configuration (arms/links)	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6
Mission lifetime (yr)	5	5	5	5	5	5	5	5	5	5	5	5
total MBHB detected[(a)]	12–90	16–130	21–180	26–244	33–333	83–406	37–441	39–485	39–493	40–548	40–555	40–590
MBHB sky location	✗	✗	✗	✓	✗	✓	✗	✓	✗	✓	✓	✓
MBHB luminosity distance	✗	✗	✗	✗	✗	✓	✗	✓	✓	✓	✓	✓
total EMRIs detected	12–225	30–525	52–962	127–2075	220–3010	460–5500	95–1600	232–3325	440–5225	830–8175	1360–10475	1900–12525
EMRI position	–	–	–	–	–	–	–	–	–	–	–	–
EMRI luminosity distance	–	–	–	–	–	–	–	–	–	–	–	–
CWD detected/resolved[(b)]	–	–	–	–	–	–	–	–	–	–	–	–
CWD position[(c)]	–	–	–	–	–	–	–	–	–	–	–	–
CWD luminosity distance[(d)]	–	–	–	–	–	–	–	–	–	–	–	–
stochastic background	?	✓	?	✓	?	✓	?	✓	?	✓	?	✓

Notes:
(a) number with SNR > 8
(b) number with SNR > 7
(c) $N > 200$ CWD with SNR > 7 and $\Delta\Omega < \pi\ \mathrm{deg}^2$
(d) $N > 200$ CWD with SNR > 7 and $\Delta\Omega < \pi\ \mathrm{deg}^2$ and $\mathrm{d}f/\mathrm{d}t < 0.1$, $\Delta \log$ amplitude < 0.1

Table 4.2: Scientific returns as a function of instrument configuration, assuming a 2-year mission.

Acceleration noise wrt goal	10×						1×					
Arm length (10^6 km)	1		2		5		1		2		5	
Configuration (arms/links)	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6
The nature of gravity:												
weak field$^{(a)}$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
strong field$^{(a)}$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
propagation effects	–	–	–	–	–	–	–	–	–	–	–	–
polarisation	?	✓	?	✓	?	✓	?	✓	?	✓	?	✓
Fundamental nature of black holes:												
existence of horizon	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
black hole mapping (Kerr)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
black hole spectroscopy$^{(b)}$	–	–	–	–	–	–	–	–	–	–	–	–
Black holes as sources of energy:												
jet formation	–	–	–	–	–	–	–	–	–	–	–	–
accretion disk models	–	–	–	–	–	–	–	–	–	–	–	–
transients	–	–	–	–	–	–	–	–	–	–	–	–
Nonlinear structure formation:												
seed$^{(c)}$	✗	✗	✗	✗	✗	✓	✗	✗	✓	✓	✓	✓
hierarchical assembly	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
accretion	–	–	–	–	–	–	–	–	–	–	–	–
Dynamics of galactic nuclei:												
TBD	–	–	–	–	–	–	–	–	–	–	–	–
Stellar binary systems:												
formation of compact binaries$^{(d)}$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
physics of WD mergers$^{(e)}$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
structure of Milky Way$^{(f)}$	?	✗	?	✓	?	✓	?	✓	?	✓	?	✓
The very early universe:												
Higgs, TeV physics	?	✓	?	✓	?	✓	?	✓	?	✓	?	✓
topological defects	?	✓	?	✓	?	✓	?	✓	?	✓	?	✓
nonstandard inflation	?	✓	?	✓	?	✓	?	✓	?	✓	?	✓
Cosmography:												
Hubble constant$^{(g)}$	✗	°✗	✗	✗	✓	✓	✗	✓	✓	✓	✓	✓
dark matter eqn$^{(h)}$	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗

Notes:
(a) at least one good EMRI detection
(b) 3 MBHBs with SNR > 30
(c) 3 MBHBs at $z > 10$ with $\Delta z/z < 0.3$
(d) $N > 200$ CWD with SNR > 7
(e) $N > 200$ CWD with SNR > 7 and $\Delta\Omega < \pi$ deg^2
(f) $N > 200$ CWD with SNR > 7 and $\Delta\Omega < \pi$ deg^2 and $\mathrm{d}f/\mathrm{d}t < 0.1$, Δlog amplitude < 0.1
(g) 20 EMRIs at $z < 0.5$ with error box < 1deg^2
(h) 20 MBHBs at $z < 3$ with $\Delta\Omega < 10$deg^2, $\Delta d_l/d_l < 0.1$

Table 4.3: Scientific returns as a function of instrument configuration, assuming a 5-year mission.

Acceleration noise wrt goal	10×						1×					
Arm length (10^6 km)	1		2		5		1		2		5	
Configuration (arms/links)	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6
The nature of gravity:												
weak field$^{(a)}$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
strong field$^{(a)}$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
propagation effects	–	–	–	–	–	–	–	–	–	–	–	–
polarisation	?	✓	?	✓	?	✓	?	✓	?	✓	?	✓
Fundamental nature of black holes:												
existence of horizon	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
black hole mapping (Kerr)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
black hole spectroscopy$^{(b)}$	–	–	–	–	–	–	–	–	–	–	–	–
Black holes as sources of energy:												
jet formation	–	–	–	–	–	–	–	–	–	–	–	–
accretion disk models	–	–	–	–	–	–	–	–	–	–	–	–
transients	–	–	–	–	–	–	–	–	–	–	–	–
Nonlinear structure formation:												
seed$^{(c)}$	✗	✗	✗	✗	✗	✓	✗	✗	✗	✓	✓	✓
hierarchical assembly	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
accretion	–	–	–	–	–	–	–	–	–	–	–	–
Dynamics of galactic nuclei:												
TBD	–	–	–	–	–	–	–	–	–	–	–	–
Stellar binary systems:												
formation of compact binaries$^{(d)}$	–	–	–	–	–	–	–	–	–	–	–	–
physics of WD mergers$^{(e)}$	–	–	–	–	–	–	–	–	–	–	–	–
structure of Milky Way$^{(f)}$	–	–	–	–	–	–	–	–	–	–	–	–
The very early universe:												
Higgs, TeV physics	?	✓	?	✓	?	✓	?	✓	?	✓	?	✓
topological defects	?	✓	?	✓	?	✓	?	✓	?	✓	?	✓
nonstandard inflation	?	✓	?	✓	?	✓	?	✓	?	✓	?	✓
Cosmography:												
Hubble constant$^{(g)}$	–	–	–	–	–	–	–	–	–	–	–	–
dark matter eqn$^{(h)}$	✗	✗	✗	✗	✗	✓	✗	✓	✗	✓	✗	✓

Notes:
(a) at least one good EMRI detection
(b) 3 MBHBs with SNR > 30
(c) 3 MBHBs at $z > 10$ with $\Delta z/z < 0.3$
(d) $N > 200$ CWD with SNR > 7
(e) $N > 200$ CWD with SNR > 7 and $\Delta\Omega < \pi$ deg^2
(f) $N > 200$ CWD with SNR > 7 and $\Delta\Omega < \pi$ deg^2 and $\mathrm{d}f/\mathrm{d}t < 0.1$, Δlog amplitude < 0.1
(g) 20 EMRIs at $z < 0.5$ with error box < 1deg^2
(h) 20 MBHBs at $z < 3$ with $\Delta\Omega < 10$deg^2, $\Delta d_l/d_l < 0.1$

5

Technology developments

5.1 Required technologies

A significant part of the Committee's efforts over its first 6 months have been devoted to identifying all of the technology items required for a laser interferometry space mission (both payload and spacecraft elements), and tabulating:

- the relevant system/sub-system, the associated development area, and the required technology item (for example, within the telescope subsystem, developments are required in the area of pico-metre stability, with the required technology item being the access to materials with sufficiently low CTE, combined with appropriate thermal modeling);
- for each of these items, the top-level technology risks, and a tabulation of any ongoing (funded) activity, along with the relevant funding agency, and the relevant contractor;
- again associated with each technology item, an assessment of the current TRL, the current status and expected development timeline;
- an associated recommended action.

In total, more than 40 such development items have been identified and tabulated, and the final report is expected to contain more comprehensive details.

5.2 Risk/schedule criticality

Most importantly for the present exercise, the Technology Developments Activities (TDAs) required for L3 have been divided into three groups:

- high priority: critical for the mission, of projected durations up to 3 years, and with priority for an immediate start;
- medium priority: relevant for a payload EM demonstration (see Section 5.4), but in part awaiting other results before embarking on L3-focused developments (the overlap of these developments with that of the EM shown in Figure 7.1 indicates cross-fertilization);
- low priority: a later start is considered acceptable. These may include technology developments that could reduce cost and/or risk, but which are not on the L3 critical path, and would form part of normal work during Phase B. Other prioritisations may be relevant depending on the EM development requirements.

5.3 Specific technology items identified

Relatively few items have been identified as falling into the first two categories, and they are listed hereafter. Inputs for the corresponding Statements of Work are being prepared.

High priority

- architecture related: in-field guiding versus an optical assembly tracking mechanism, and the consequences for the backlink, the telescope design and fabrication, and an in-field guiding mechanism;
- efficient manufacturing of a highly-populated optical bench (e.g., which components demand high stability, and whether assembly be done robotically);
- telescope: straylight and manufacturability (including a consideration of on-axis versus off-axis configurations);
- laser system: primarily the phase fidelity of the power amplifier and power fluctuations at the laser beat frequencies, but including issues of lifetime and redundancy.

Medium priority

- gravitational reference sensor, including the charge management system (in part awaiting the LISA Pathfinder results);
- micropropulsion: choice of cold gas, colloids, or micro-RITs (in part awaiting Gaia and Euclid developments, amongst others);
- phase measurement system.

5.4 Payload Engineering Model

The present thinking of the ESA D–SRE Future Missions Office is that an Engineering Model of the payload should be developed and validated before mission adoption by the SPC (viz, according to Figure 7.1, before 2025).[1] There are two main objectives of this approach: to provide early performance validation for such a high-criticality payload, as well as to reduce the overall development risk in achieving the necessary TRL.[2]

[1] Concise definitions of the EM, EQM, and QM (adapted from the ECSS guidelines): the EM is flight representative in form and function, without high-reliability parts, used for functional qualification; the EQM combines the EM with flight electronics at MIL standard; the QM is an exact copy of the flight model, but which may be subject to more demanding tests.

[2] ESA adopts the following requirements for a specific TRL on the ISO scale: TRL1: basic principles observed and reported; TRL2: technology concept and/or application formulated; TRL3: analytical and experimental critical function and/or proof-of-concept; TRL4: component and/or breadboard validation in laboratory environment; TRL5: component and/or breadboard validation in relevant environment; TRL6: model or prototype in a relevant environment (ground or space); TRL7: system prototype demonstration in a space environment; TRL8: system 'flight qualified' through test and demonstration (ground or space); TRL9: system 'flight proven' through successful mission operations.

Detailed objectives The Committee is presently considering the goals, functions, advantages and disadvantages of the EM approach in further detail. It may, for example, involve:

- demonstrating the phase measurement accuracy with one arm;
- the EM campaign should make use of EM models for the payload critical units: laser, telescope, optical bench, charge management, onboard data processing, structure, etc;
- the EM campaign should demonstrate the payload system performance (to achieve this, it could be slit into two or more models);
- as a consequence, a payload EM implies the use of flight representatives for (amongst others) the laser head and laser operation, the telescope, and the opto-electronics.

Inputs required Amongst the inputs needed before starting an EM would be:

- a stable mission concept and associated requirements;
- a complete space segment definition, including a detailed design of the payload;
- availability of demonstration models (or better) for critical payload units, including a detailed payload design with specification of the subsystem interfaces;
- a detailed definition of the EM, its development plan, and overall objectives. We suggest that, in advance of the proposed EM phase, ESA should assemble technical experts in gravitational wave instrument development to set priorities for the EM development, tests at subsystem interfaces, and risk reduction testbeds. Beyond the unit-level development, issues will likely include:
  - opto-mechanical and thermal integration challenges of the payload;
  - industrial partnering for implementation and integration of payload elements;
  - interplay among optical elements within a single spacecraft, including stray light;
  - challenges in interspacecraft interferometry;
  - metrology system (laser, laser frequency control, and phase measurement).

Expected benefits The expected benefits of the proposed EM approach should include:

- a payload industrialisation approach which is anticipated through the EM campaign;
- payload development costs and risks should be mastered;
- a successful EM campaign may lead to a shorter development schedule;
- minimising any development gap following the LISA Pathfinder launch, and thereby federating and preserving the LISA and LISA Pathfinder community and expertise.

To conclude, an early payload EM, viz. before SPC adoption, would be unusual in the development cycle of a space mission, but is motivated by certain specific and meritorious objectives. Accordingly, the Committee endorses significant early investments in the development of gravitational wave detector engineering models, risk reduction activities, and testbeds as being in the best interest of a successful mission, although the details remain to be fully assessed.

It must be stressed that the expected financial effort would be substantial, and broadly commensurate with the full payload non-recurring costs. A successful EM development would therefore also require funding, suitable organisation (including appropriate levels of system engineering and management), respective contributions from ESA and partners for the payload, and would presumably require a proto-consortium to be in place.

5.5 Lessons Learnt during LISA Pathfinder development

In addition to the accumulated knowledge and experience of ESA and the Committee members in assessing the L3 schedule, specific consideration has been given to the 'lessons learnt' during the development of LISA Pathfinder. Though an official ESA 'lessons learnt' document is not yet available, the following specific and critical issues were brought to the attention of the committee:

- a lack of space heritage led to a substantial overestimate of the technology readiness;
- the basic concepts turned out to be robust, but the transition to TRL6 was slow;
- the partners initially agreed to go directly to a proto-flight model (PFM), while in the end equipment qualification models (EQMs) had to be implemented for almost all critical items during the development phase;
- the need for strong, top-down, system engineering from Phase 0 through to Phase E was underestimated;
- some tasks originally considered as standard engineering were underestimated, and constituted the main sources of delays, in particular redesigns driven by:
  - the launch lock motor;
  - a poorly qualified brazing procedure for the inertial sensor assembly;
  - the electric μN-thrusters (FEEPs).

In terms of heritage, it should also be stressed that numerous drag-free spacecraft followed the TRIAD demonstration navigational satellite in 1972, with LISA Pathfinder's proof-mass system conceptually derived from the ONERA accelerometers which have flown on Champ, GOCE, GRACE, and others.

6

Data analysis

6.1 Overview of the principles

There are considered to be no conceptual barriers to the principles of the laser-interferometer data analysis. The total satellite data volume is small – operating in the $10^{-4} - 10^{-1}$ Hz band, a sampling rate of order 1 Hz yields a total scientific volume of $\sim 2x10^8$ points per year, assuming 6 links. At the same time, there are substantial computational (and associated organisational) challenges for the numerical processing.

Regarding the proof masses as responding to the superimposed ripples in spacetime as a result of many thousands of gravitational wave sources of unknown form, frequency, and sky location, the data is expected to be signal dominated, and the numerous gravitational wave signals overlap in time and in frequency. The high signal-to-noise ratio of the majority of the signals is expected to guarantee their confident detection. The main data analysis task is then to disentangle them, and accurately determine the source parameters. Data analysis pipelines will aim at a global fit, implementing a procedure which is iterative both in time and in the number of source signals. The potential presence of instrumental artifacts adds significant complexity to the data analysis.

Addressing the organisation and operational aspects of the required ground processing, CNES has recently completed a Phase 0 study of such a ground segment.

6.2 Matched filtering

Matched filtering is presently considered to be the most effective way of estimating and disentangling the gravitational wave signals. This implies that the phase of the gravitational wave must be tracked with an accuracy of less than a fraction of wave cycle. Matched filtering proceeds through a (very large) set of templates (signal models with different parameters) and finding the one that best matches the observed data, by finding the maximum of the likelihood function. This imposes a very stringent requirement on the accuracy for the gravitational wave signal models.

The most successful data analysis methods are stochastic (as compared to the grid-based search adopted for LIGO–VIRGO), and these include parallel tempering Markov Chain Monte Carlo, nested sampling, and multimodal genetic algorithms. The problem is complicated by the multi-modality of the likelihood surface, and the many parameters per source.

Although the strongest gravitational wave from EMRIs may easily be distinguished from the

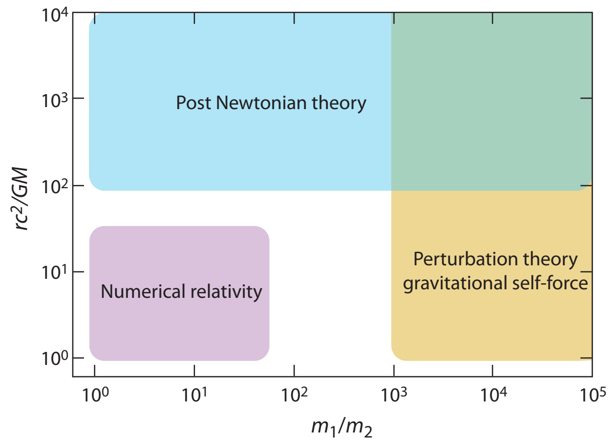

Figure 6.1: The different computational methods that are currently used to model compact object binary systems, and generate their expected waveforms, as a function of $GM/rc^2 \sim v^2/c^2$ and m_2/m_1.

instrumental noise of the gravitational wave detector, most signals will be deeply buried in instrumental noise. However, since an EMRI will go through many gravitational wave cycles before making the plunge into the central supermassive black hole, it should still be possible to extract the signal using matched filtering. In this process, the observed signal is compared with a template of the expected signal, amplifying components that are similar to the theoretical template. This requires accurate theoretical predictions for the wave forms, including accurate modelling of the EMRI trajectory.

6.3 Different computational methods

The equations of motion in general relativity are notoriously hard to solve analytically and, in general, some sort of approximation scheme is required. Two source parameters determine the range of validity of the various computational methods currently available to model compact object binary systems: $GM/rc^2 \sim v^2/c^2$ and m_2/m_1, and the relevant domains are shown schematically in Figure 6.1.

In the case of extreme mass ratio inspirals, for example, the mass of the compact object is much smaller than that of the central supermassive black hole, allowing it to be treated perturbatively, for example through post-Newtonian expansion, or through numerical relativity (by solving the equations of motion numerically). The non-linear nature of the theory makes this very challenging, but significant success has been achieved in numerically modelling the final phase of the inspiral of binaries of comparable mass. The large number of cycles of an EMRI make the purely numerical approach prohibitively expensive in terms of computing time.

6.4 The Mock LISA Data Challenge

Aside from the challenge of computing waveforms for the vast range of systems likely to be encountered, the 'Mock LISA Data Challenge' task force was formulated in 2005 to demonstrate, by simulation, that the scientific requirements of a LISA-like mission could be met, while developing a common framework for comparison of various data analysis methods. The resulting

	MLDC1	MLDC2	MLDC1B	MLDC3	MLDC4
Galactic binaries	• Verification • Unknown isolated • Unknown interfering	• Galaxy: 3 x 10^6	• Verification • Unknown isolated • Unknown interfering	• Galaxy: 6 x 10^7 (chirping)	• Galaxy: 6 x 10^7 (chirping)
Massive black hole binaries	• Isolated	• 4-6 over Galaxy and EMRIs	• Isolated	• 4-6x spinning/ precessing over Galaxy	• 4-6x spinning/ precessing, low mass
EMRIs		• Isolated • 4-6 over Galaxy and MBHs	• Isolated	• 5 together (weaker)	• 3x Poisson (2)
Bursts				• Cosmic string cusp	• Poisson (2) cosmic string cusp
Stochastic background				• Isotropic	• Isotropic

Figure 6.2: Summary of the data sets included within the various Mock LISA Data Challenges. The data release and corresponding analysis for MLDC1–3 was carried out during 2006–2009. The data released for MLDC4 in 2009 have never been fully analysed.

challenges, of increasing complexity, and totaling some 70 participants from 25 institutes, were produced roughly once a year since then: MLDC1 in 2006, MLDC2 in 2007, MLDC3 in 2008–09, and the data challenge for MLDC4 released in 2009 (Figure 6.2).

From these rounds of the mock data challenge, it is considered known (i) how to detect and subtract resolvable white dwarf binaries; (ii) assuming that resolvable white dwarf binaries are subtracted, it is known how to detect (of order) five supermassive black hole binaries with signal-to-noise between 12–1500 on top of the white dwarf stochastic foreground; (iii) how to detect individual EMRIs with signal-to-noise down to ~ 20 in isolated Gaussian data sets. However, as a consequence of the announcement of the L3 launch date in 2034, priorities and national funding for the associated data analysis efforts have been downgraded, and the data released for MLDC4 in 2009 have never been fully analysed.

6.5 Immediate challenges

Improving the waveforms (e.g. by incorporating more physics into the MBHB waveforms, such as spin, higher harmonics, inspiral, merger and eccentricity) promises to enhance the science performance significantly, by improving astrophysical parameter estimation and by breaking degeneracies. There are also practical improvements like improved representation of the detector response function and the speed of Bayesian integrations.

In the context of the present evaluation, the LISA/eLISA teams have identified two rather critical milestones/tasks, which were only partially addressed previously, and which play a key role in the further data analysis development. The first picks up where the previous MLDC left off, viz. disentangling multiple gravitational wave signals (either of the same or of different type) with the simplifying assumption of Gaussian instrumental noise. The second task addresses the question of the presence of instrumental artifacts and their effect on the performance of the data analysis algorithms. Both tasks are considered as somewhat time critical, since the outcome of the study may have a non-negligible impact on the mission design.

7

Schedule

The Committee has worked with the D–SRE Future Missions Office to construct a development schedule for L3 consistent with the target 2034 launch date (Figure 7.1). SPC/IPC decisions have been assigned their 'normal' schedules, while the full ITT process of technology developments (including approval) is assumed to require 9 months. This takes into account the following principles (item numbers correspond to those in the figure):

- (2) no substantive activities start in advance of the first LISA Pathfinder in-orbit results (assumed mid-2016);
- (3) a 'Call for Mission Proposals' is issued in late 2016. The community response must identify a mission satisfying the SSC requirements, as well as potential scientific and payload partners;
- (4–7) early development of the most critical Technology Development Activities (TDAs), as summarised in Section 5, should get underway before the end of 2016;
- (4–8) high- and medium-priority TDAs are concluded before start of the EM definition;
- (10–15) demonstration of the payload concept is completed before mission adoption, through a full payload Engineering Model (EM) with a projected development duration of 4 years. TRL 5–6 is to be achieved before project adoption/approval;
- (17–18) a Phase A study comprising parallel (competitive) industrial studies is undertaken with the support of the payload consortia, ensuring interface definitions and closure of major trade-offs. Industrial competition is maintained until mission adoption;
- (19) a parallel 'technical assistance phase' provides industrial continuity between Phase A and Phase B1;
- (22) while a 1-year schedule margin around 2024 is present in this plan, its availability evidently depends on the successful and timely conclusion of the TDAs and EM;
- (25) the spacecraft schedule assumes 8.5 years for Phases B2/C/D, including margin.

We stress that this is a schedule prepared to match the mandated 2034 launch date, with activities making maximum use of this 18 year period to retire risk and demonstrate timely achievement of the specified TRLs. The Committee was not asked to evaluate an 'expedited' schedule determined only by technology development, and not by financial or other programmatic constraints.

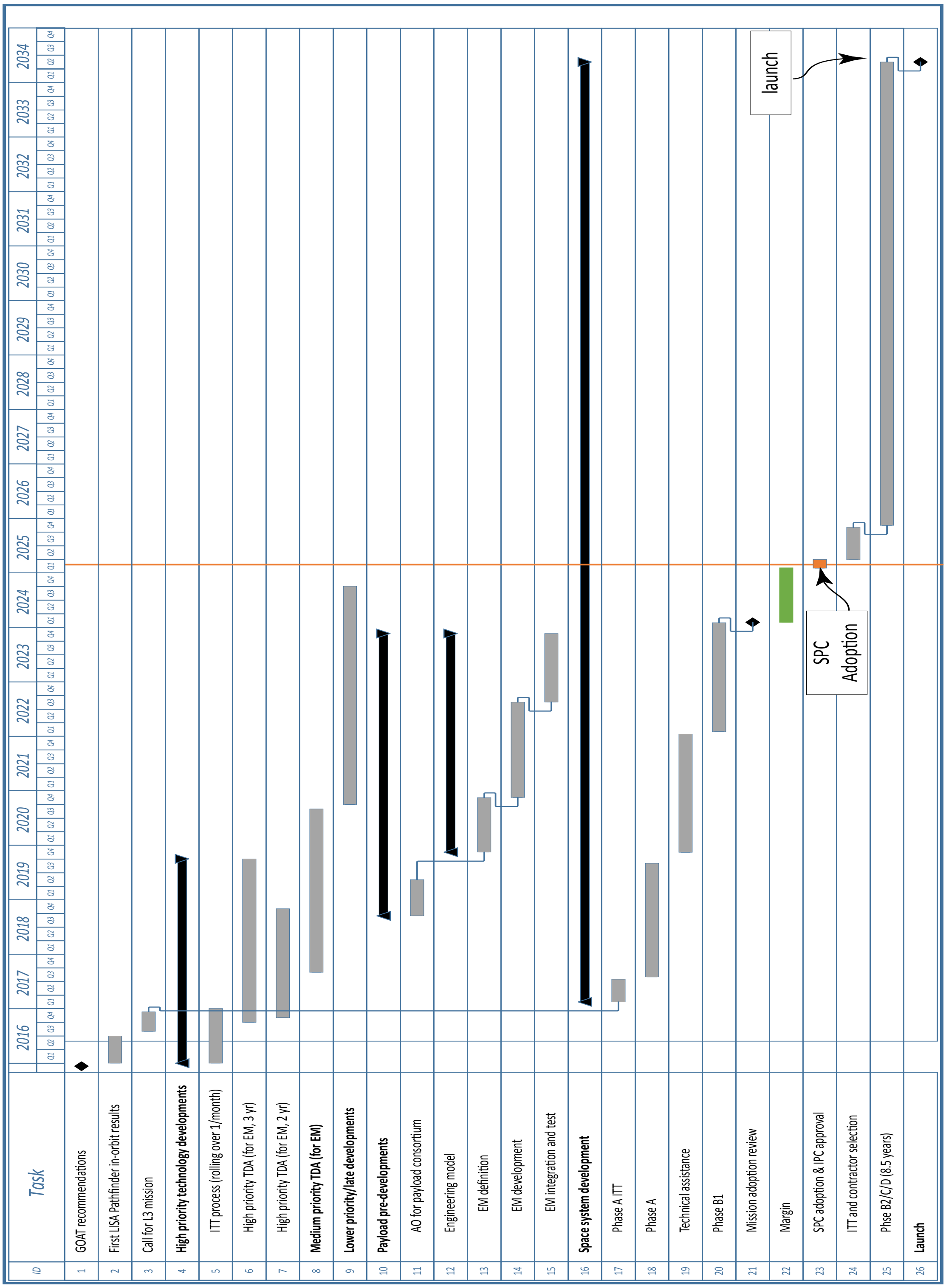

Figure 7.1: Preliminary schedule, showing the technology development timeline, formal decision points, and project phases, consistent with the targeted 2034 launch date. The schedule has been prepared by the D–SRE Future Missions Office (F. Safa and M. Gehler) with inputs from the Committee. Note that this is for preliminary planning purposes, and is not to be construed as an 'approved' schedule.

8 Costs

8.1 Boundary conditions

According to this Committee's mandate, the L3 mission will be European-led, with a cost to ESA not to exceed 1 B€ (2014 economic conditions), plus an expected national contribution of order 25% of the ESA cost. International participation is expected to be limited to elements not exceeding approximately 20% of the total mission cost.

At the start of the Committee's work, it was explicitly stated by the Executive that the Committee was not expected to attempt a revised quantitative estimate of the L3 mission cost. Such a task is notoriously complex for all space missions and, in the case of L3, further complicated by some of the factors which are beyond the Committee's authority, and which will have a strong influence on the final mission cost. Examples are:

- the selected mission configuration, which will be largely dependent on the choice of arm-length, number of links, and mission duration. No attempt has been made to estimate whether any specific configuration would fit into the proposed budget envelope;
- the hardware split between the presently-unknown international partners;
- ESA's role and scope in the payload (for example, whether it will be responsible for the payload management, system engineering, and AIV, or whether it will also pay for items such as the lasers, telescopes and microthrusters);
- the organisational structure, scope, and funding of the payload Engineering Model.

8.2 Specifics of L3

At this stage of the Committee's work, we simply list some of the specifics of the L3 mission that will need to be taken into account in any future rigorous costing exercise. The ESA project Cost at Completion normally includes studies, project oversight (management), the space platform (spacecraft), AIV, launcher and launch operations, operations, and data collection. In the case of L3 there are a number of specific factors which must be taken into account:

- the (substantial) costs of the LISA Pathfinder technology demonstrator are not included in the L3 costing, but the motivation was to retire many of the risks associated with technologies which could not convincingly be demonstrated on-ground. The LISA Pathfinder project has led to the delivery, in fully space qualified form, of many of the main payload subsystems needed for L3. Accordingly, LISA Pathfinder will have reduced the level of project contingency funds required for a number of significant elements of L3;

- working in the sense of risk reduction, it should be stressed that the basic concept of a 3-spacecraft laser interferometry system has been largely unchanged since LAGOS in 1985, thirty years ago. The concept has been the subject of extensive study, including the period between 2005–2011 (Section 1.2) almost corresponding to a 6-year Phase A study;
- the mission will require three space platforms which, in the 6-link configuration, will be of identical design. There should be reductions in platform costs compared to those for three completely different satellite designs, but the reductions are not straightforward to quantify, for example being dependent on manufacturing approach and build sequencing. In a similar way the payload elements will require multiple instances. Cost reductions from quantity production may be available (recurrent versus non-recurrent costs), but there will be further costs arising from the need to manufacture multiple subsystem models, especially if these are carried out sequentially rather than in parallel;
- the mission is not yet fully defined. There has been no final decision on the number or length of the interferometer arms, laser power, telescope entrance diameter or mission lifetime, all of which have an influence on the mission cost, either through platform design or launcher requirements;
- considerable cost differences can result from the selected model philosophy, which will therefore require careful consideration on requirements especially given LISA Pathfinder and the currently-baselined payload Engineering Model;
- if a major contribution to L3 from NASA is assumed (there is no agreement between yet on the division of mission responsibilities), the difference in ESA/NASA costing methodologies complicates total cost estimates, and therefore also a fractional share. For example, NASA characteristically pays for all payload elements under its responsibility, and full staff costs. ESA typically does not pay for the full payload, while different European countries have different approaches to costing work at institutes (e.g., for permanent staff);
- recent trends in decreasing launch costs also have a significant impact on mission costs.

8.3 Reported costs for LISA and eLISA

ESA's latest costing for a laser interferometry mission was conducted in the context of the L1 selection, and in the LISA to eLISA de-scoping exercise. Indicative costs were around 1.0–1.2 B€. NASA has carried out several (extensive) cost estimates of a variety of different LISA-like mission scenarios which, for the reasons outlined above, are usually (substantially) higher than the European estimates (using a generic dollar to Euro conversion rate).

Nevertheless, both ESA and NASA exercises suggest that the mission costs are a relatively weak function of the mission configuration. While mission costs differing by some 100 M€ are of considerable significance, it should also be stressed that, for a given costing model, savings of much more than 10% in going from LISA (6 links, 5 Mkm armlength, 5-year mission) to eLISA (4 links, 1 Mkm armlength, 2-year mission) seem non-trivial to achieve in practice. Stated equivalently, mission complexity and cost change rather weakly with science capability for a given concept, even for rather drastic reductions in science capability. Conclusions of published NASA costings have also suggested that, broadly, giving up more than half the science saves about 10% in cost.

9

Future activities of the Committee

The original Terms of Reference of the Committee anticipated a final report to be prepared around the end of 2016 Q1. The ESA Executive has recently suggested that activities are extended until around the end of 2016 Q2, allowing it to participate in the review of the first LISA Pathfinder results, and to include these within the framework of the final report.

Consequently, the activities foreseen between now and mid-2016 include the following:

- completing an assessment of the scientific performance as a function of mission configuration (as reported in preliminary form in Chapter 4);
- assisting the D–SRE Future Missions Office in formulating detailed Statements of Work for the high-priority and medium-priority Technical Development Activities (Section 5.3);
- formulating some preliminary considerations on the choice of mission configuration, with the aim of balancing technology risk and therefore mission cost, and scientific performance;
- advancing the definition and scope of a payload Engineering Model (Section 5.4);
- formulating considerations for assessing the technical and scientific success of LISA Pathfinder;
- identifying and summarising the detailed technologies and subsystems which are expected to have been validated by LISA Pathfinder;
- detailing any other fundamental risks associated with gravitational wave detection;
- reviewing and concluding on the status and prospects of Atom Interferometry. In this context, a mission concept proposal has been requested from representatives of the AI community, to be submitted to the Committee by 1 September 2015;
- incorporating feedback from delegations interested in possible hardware contributions to L3 (a dedicated meeting is being considered by the ESA Executive for 2015 Q3/4);
- responding to any specific requests on costing coming from the ESA Executive or its advisory committees.

The final report of the Committee should be submitted to ESA before mid-2016.

Acronyms

AIV: Assembly, Integration, and Verification
CMB: Cosmic Microwave Background
CWD: Compact White Dwarf
eLISA: evolved Laser Interferometer Space Antenna
EM: Engineering Model
EMRI: Extreme Mass Ratio Inspiral
EQM: Engineering Qualification Model
FEEP: Field Emission Electric Propulsion
GOAT: Gravitational Observatory Advisory Team (this Committee)
IPC: Industrial Policy Committee (ESA)
LHC: Large Hadron Collider
LIGO: Laser Interferometer Gravitational-Wave Observatory (US)
LISA: Laser Interferometer Space Antenna
LSST: Large Synoptic Survey Telescope
MBHB: Massive Black Hole Binary
MLDC: Mock LISA Data Challenge
NGO: New Gravitational-wave Observatory (scaled-down LISA)
PFM: Proto-Flight Model
SKA: Square Kilometre Array
SPC: Science Programme Committee (ESA)
SNR: signal-to-noise ratio
SSC: Senior Science Committee (ESA)
TDA: Technology Development Activity
TRL: Technology Readiness Level