Report to the IN2P3 Scientific Council – October 2020

The LISA mission in the IN2P3

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Executive Summary

The performance of ground-based gravitational waves detector is limited by seismic and environmental noises, preventing gravitational wave observations below ~1Hz. Detecting gravitational waves between 0.1mHz and 0.1 Hz would however give access to some of the most violent events in the Universe such as the coalescing massive black holes binaries, millions of inspiralling Galactic binaries and, potentially, the relic gravitational waves from the violent processes in the early Universe. In the mHz frequency band, the required environmental ‘quietness’ can be only achieved in space. This idea led to the LISA (Laser Interferometer Space Antenna) mission, presently in Phase A and planned for launch in 2034.

Many of the scientific topics addressed by the LISA mission are relevant to the IN2P3 expertise and fields of interests. In the foreseeable scientific and instrumental context of 2035, LISA shall complement ground based observatories and multi-messengers instruments to give a extensive view on the gravitational waves sky and the history of our Universe.

The French community entered the adventure of GW detection from space with the LISA Pathfinder mission, which admirably paved the way to the LISA mission. Since then, the contributions of the IN2P3 laboratories (both technical and scientific) have been increasing and they now play a major role in the LISA Consortium.

Under the supervision and coordination of the French space agency (CNES), France has proposed to deliver key elements to the LISA mission (the scientific ground segment, the scientific performance model and the integration and tests of the LISA core instruments). These major contributions demonstrate the ambition of the French community and the strong support of the CNES. Design studies and prototyping have already started with major milestones scheduled for end 2021 (end of the Phase A extension) and end 2023 (mission adoption review).

Although ‘real’ signals are not expected before 2036/2037, the LISA scientific community is very active in developing analysis pipelines, designing the instrument and exploring the full scientific potential of LISA data, therefore already producing many published results.

IN2P3 laboratories and platforms currently involved in LISA (APC, CC-IN2P3, CPPM, L2IT, LMA, and LPCC) are participating to all aspects of the LISA mission, from instrumentation to science exploitation, through performance modelling and data analysis techniques. In such a complex system as LISA, this broad view on the full acquisition and processing chain is considered as a major advantage to get the best possible scientific return of the mission’s data.

The launch of LISA is, however, still a long way to go that requires substantial and long-term efforts. The continuing support of the IN2P3 will be crucial until then, either thanks to its scientific and engineering expertise, or through increasing financial and workforce resources.

List of acronyms

AIVT	Assembly, Integration, Verification and Tests
CSGS	Consortium Science Ground Segment
DCC	Data Computing Center
DDPC	Distributed Data Processing Center
FTE	Full Time Equivalent
GB	Galactic Binary
GR	General Relativity
GRS	Gravitational Reference Sensor
GSE	Ground Support Equipment
GW	Gravitational Wave
INREP	Initial Noise REduction Processing
LDC	LISA Data Challenge
LDPG	LISA Data Processing Group
LIG	LISA Instrument Group
LOT	LISA on Table
LSG	LISA Science Group
MBHB	Massive Black Hole Binary
MOSA	Movable Optical Sub-Assembly
MSS	MOSA support structure
OGSE	Optical Ground Support Equipment
RF	Radio frequency
Rx	Received
TDI	Time Delay Interferometry
TM	Test Mass
TTL	Tilt-to-Length
Tx	Transmitted
S/C	Spacecraft
SGS	Scientific Ground Segment

Science Goals and Context

The Science of gravitational waves from space

Beginning with the first detection of a stellar-mass black hole binary in September 2015, the LIGO/Virgo collaboration has issued the first catalogue of gravitational wave (GW) sources identified during the first and second observing runs and 4 noteworthy detections from the third observing run. The identified sources include thirteen merging black hole binaries ranging between 9 and 142 solar masses, and two coalescing binary neutron star mergers. These observations of GWs in the 10–1000 Hz band have inaugurated the era of GW astronomy and opened a new window to the Universe, allowing to infer for the first time the properties of the population of compact binaries and providing new tests of general relativity (GR).

The Laser Interferometer Space Antenna (LISA), scheduled for launch in 2034, will observe GWs in the mHz frequency band and, therefore, complement ground-based detectors. On the ground, the physical size of Michelson interferometers is limited to a few kilometers, and seismic and tectonic gravitational perturbations forbid the access to wave frequencies below about one hertz. Detecting gravitational waves by interferometry requires, at both ends of each interferometric arm, test masses (i.e. mirrors) that are ‘inertial’ along the laser beam, i.e. protected from any other force than gravitation. This inertial direction is achieved on the ground by sophisticated suspensions. In space, free-floating objects represent excellent inertial references, provided that they are shielded from external disturbances such as the solar wind or electromagnetic perturbations. The capability of a satellite to protect and follow an inertial reference is known as ‘drag-free flying’. The LISA Pathfinder (LPF) mission, which flew from December 2015 to July 2017, was specifically designed to address this technology, as well as the demonstration of pm-stable interferometric measurements in space. While designed to achieve a level of ‘inertiality’ relaxed by one order of magnitude compared to LISA requirements, LPF reached a differential residual acceleration (between the two test masses) of (1.74 +/- 0.01) $\mathrm{fm.s^{-2} / Hz^{1/2}}$ above 2 mHz and (6 +/- 1) $\mathrm{fm.s^{-2} / Hz^{1/2}}$ at 0.02 mHz, i.e. 2-3 times better than necessary for LISA.

The strongest anticipated GW sources in the LISA data will be massive black hole binaries (MBHBs), with total mass in the range 10^4 - 10^7 solar masses, and galactic white dwarf binaries (GBs). The latter are so numerous that they will form a stochastic foreground signal dominating over instrumental noise in the frequency range between few 10^{-4} and few 10^{-3} Hz. A smaller fraction of GBs ($\sim 10^4$) could be resolved and characterized by estimating sky position, frequency and its evolution (if present), orbital inclination etc. Merging MBHBs and GBs must be accurately modelled, detected and removed in order to allow for the detection of weaker, but scientifically relevant, signals, and for testing General Relativity.

LISA detection of merging MBHB will allow accurate parameter estimation of the black holes practically throughout the entire Universe. These observations will allow us to infer the channel of formation and evolution of massive black holes through cosmic history — one of the main objectives of the LISA mission. Detecting GBs and characterizing the strength and anisotropy of the stochastic Galactic foreground provide very valuable information about stellar evolution, and about the distribution of the stellar remnants in our Galaxy. Note that some information inferred through GW observation is unique, as it comes from the other side of the Galactic centre, which is completely obscured in electromagnetic astronomy. In addition, LISA will be able to discover exoplanets forming hierarchical triplets in double white-dwarf systems.

Extreme mass ratio inspirals are the result of the capture of a stellar-mass black hole by a massive black hole in the galactic nuclei. The small black hole slowly orbits the massive one, spending a few million orbital cycles in its close vicinity before plunging under the event horizon. The GW signal from such systems could last a few years, it is usually weak (well below the noise) and has to be integrated out utilizing sophisticated data analysis methods. The detection is achieved with fantastic accuracy in estimating the masses of both black holes, and the spin of the primary one. This information (coming from the very heart of galactic nuclei) is truly unique and cannot be obtained by other means. Besides, the GW signal encodes the spacetime structure around the central massive black hole, which can be extracted using data analysis methods — the so-called mapping of spacetime, similar to mapping the gravitational potential of the Earth using probes in geodesic missions. This information could be used to test if the central object is indeed a rotating black hole, as predicted by GR.

The removal of the strong GW sources should facilitate the search and potential discovery of a stochastic GW signal from the early Universe. Several processes following the Big Bang could produce measurable GW signals in the LISA band, providing invaluable tests of new physics. In particular, a strongly first-order electro-weak phase transition could lead to a GW signal in the middle of the frequency band accessible to LISA. This is a fantastic opportunity to test particle physics models beyond the Standard Model (BSM), which in many cases can lead to multiple observables: GW signals in LISA, as well as electroweak baryogenesis and dark matter candidates. In the absence of detection, LISA's observation will put strong constraints on (and maybe eliminate some) fundamental high energy theories. Since a few years, therefore, this subject has gained a lot of attention, as a growing part of the particle physics community has realised the discovery potential of LISA, fully complementary to present and future particle colliders on Earth.

The inspiralling binary black holes with masses similar to those observed by LIGO and Virgo could also be detected by LISA during their early orbital phase, long before entering the frequency band of ground-based detectors and merging. These binaries could be observed at different stages of their evolution, ranging from almost monochromatic sources to chirping sources, which leave the LISA band during the mission lifetime, and reappear in the band of 3rd generation of ground-based GW detectors a few years later, enabling multi-band observations.

Most of these GW sources are shown in the frequency domain in Figure 1. Besides providing scientific insight on the sources themselves, as presented above, the detection of the GW emission from these sources can also be used to perform remarkable science such as testing the foundations of the gravitational interaction and the nature of black holes, probing the accelerated expansion of the universe, investigating the nature of dark matter. The LISA observatory is expected to have an amazing impact not only in astrophysics but also in fundamental physics and cosmology. The Science Objectives of the LISA mission are described in the LISA Science Requirements Document, which is available, together with other documents describing LISA, on the ESA web page: https://www.cosmos.esa.int/web/lisa/lisa-documents.

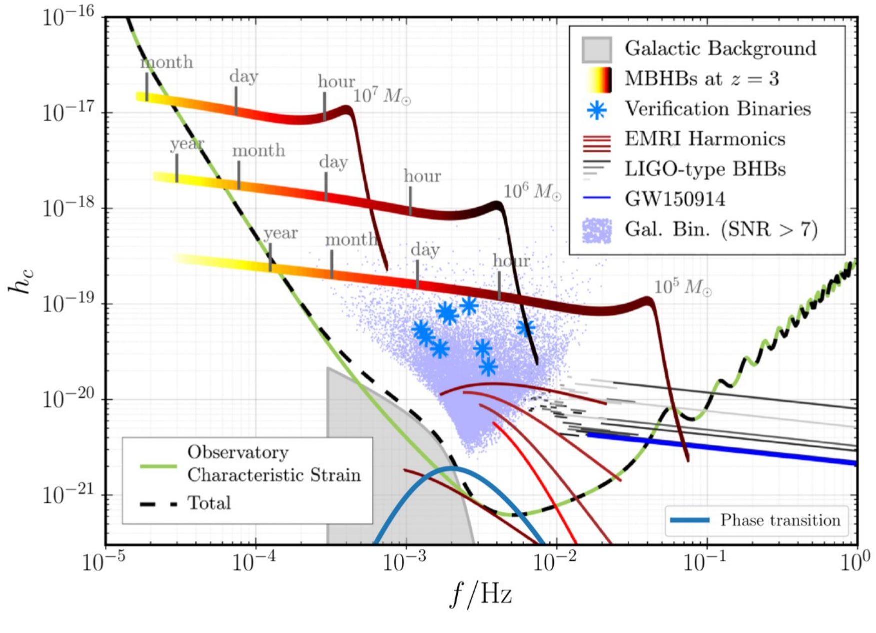


Figure 1 - Expected LISA's sensitivity curve (characteristic strain vs. frequency), and anticipated GW sources. Figure taken from the LISA Science Requirements Document [https://www.cosmos.esa.int/web/lisa/lisa-documents], the phase transition signal is taken from [https://arxiv.org/pdf/2008.09136.pdf]

LISA has also a very rich secondary science: possible detection of the solar g-modes excitation; weather in the solar system (solar wind, flares); estimation of density of small celestial bodies in the near-Earth orbits, etc.

The scientific landscape in the LISA era

The science capabilities of the LISA mission have been described in the previous section. LISA will pioneer gravitational wave observations in the rich frequency band around 1 mHz. Given the predicted state of knowledge in the 2030-2040’s (when LISA is likely to operate), we can ask what unique contributions LISA will make to our understanding of fundamental physics and astronomy at that time.

We could expect the third generation of GW detectors, Cosmic Explorer and Einstein telescope, to be operational in parallel with LISA, allowing us to cover the frequency band from the mHz to the kHz. As mentioned, some binary systems will be first detected by LISA with accurate estimation of their sky position (less than a square degree) and of the time of merger (within a minute), allowing follow up observations not only by the ground-based GW detectors but also by electro-magnetic telescopes. Multi-messenger astronomy will then become an every-day reality. The multi-band observations also give us the possibility to test General Relativity to unprecedented precision. Given the rapid progress in pulsar timing analysis, we expect that GWs will also be observed in the nHz band using the Square Kilometre Array observations of millisecond pulsars. Pulsar Timing Array is sensitive to the GW signal from the wide population of supermassive black hole binaries, and to stochastic GW signals from the early Universe. In particular, the combination of the observations by Pulsar Timing Array, LISA, and Earth-bound detectors will allow to cover the GW spectrum from the nHz to kHz, offering the unprecedented opportunity to detect GW backgrounds by early universe processes taking place at energy scales from the QCD scale to 10^{10} GeV. We will learn about the small-scale behaviour of the GW spectrum from Inflation, about the presence of topological defects and/or of networks of superstrings from string theory, the occurrence and characteristics of phase transitions in the early universe, and other, as yet unforeseen, high energy phenomena.

In parallel to complementary GW observations, we also expect the X-ray space mission ATHENA to be working in synergy with LISA, observing coalescing massive black holes binaries surrounded by a gaseous disk. Telescopes like the LSST and the Square Kilometre Array, with high sensitivity and relatively wide field of view, should be able to follow up the GW mergers and identify the associated transient events. Measuring the luminosity distance using GWs, and the redshift from e/m observations, will allow to constrain the cosmological parameters (the Hubble constant, the dark matter abundance, the presence of a cosmological constant or the dark energy equation of state) alternatively from measurements using CMB and supernovae. In particular, LISA will play a very relevant role in testing the expansion of the universe at high redshift, in the interval $2<z<7$, outside the reach of late-time surveys like supernovae. This will allow to test popular explanations of the accelerated expansion, such as early dark energy models and modified gravity scenarios. The extremely large telescopes (ELT, TMT, GMT) and large space telescopes (JWST) will be observing (proto-)galaxies at unprecedentedly high redshifts, at which LISA will simultaneously observe individual merging black hole systems. “Hearing” the Universe in GWs might allow us also to “see” highly energetic unique events which might have been missed otherwise.

It is unclear how much progress will have been made by 2035 in understanding fundamental particle physics. The LHC reached an energy scale of 13 TeV in 2015; another upgrade resulting in a collision energy of 14 TeV and an increase of a factor 10 in luminosity is expected at the end of 2027. It is difficult to foresee what the LHC will reveal about the nature of the Higgs, of dark matter particles, supersymmetry, extra dimensions. High-sensitivity LISA observations may be crucial in providing clues, since they explore the relevant energy scales in a completely unique way. The information contained in GWs from the early Universe is complementary to (and independent of) the one accessible by particle accelerators. The presence of a first-order phase transition at the TeV scale, the presence of cosmic (super-) strings in the Universe, the properties of the small scale inflationary spectrum, even the nature of the quantum vacuum state before inflation began (which could be different from the standard Quantum Field Theory nature in loop quantum gravity), are some of the fundamental issues that will probably still be open in 2035, and to which LISA might provide some answers.

By 2035 our understanding of the way cosmological structures formed will have been dramatically improved by high-redshift observations of QSOs and protogalaxies from missions like JWST, EUCLID and the Nancy Grace Roman Space Telescope (ex WFIRST), and by the Atacama Large Millimeter/submillimeter Array (ALMA) on the ground. These observations may well have constrained the supermassive black hole mass spectrum from a few times 10^{10} M_{sun}, or even higher, down to around 10^7 M_{sun}, but probably not into the main LISA range of 10^4–10^6 M_{sun}, especially at $z > 2$. LISA observations will fill this gap and also provide a check on selection effects and other systematics of the electromagnetic observations. LISA will allow us to greatly improve models of how supermassive black holes grow and the role of accretion and mergers in their growth.

In the present situation, there is no foreseen competitor to the LISA mission, achieving the same exceptional science goals in the same time frame. LISA will be the first mission of its kind and the science addressed by measuring GWs in the mHz frequency band is broad and unique. LISA, together with the 3rd generation of ground-based detectors (such as the Einstein Telescope), as well as observation of GWs with PTA, will complete the GW spectrum.

Since a few years, the Chinese Academy of Science has started a very ambitious and active program to master the technologies of drag-free flying, precision interferometric metrology and gravitational waves detection. The ultimate goal is the space-borne mission TianQin, announced for launch in the 2030's. The TianQin measurement concept relies on three spacecraft (S/C), about 10^5 km apart, orbiting the Earth. With shorter arm lengths, TianQin exhibits a sensitivity curve shifted to higher frequency (10 mHz - 10 Hz) compared to LISA. A pathfinder mission (TianQin-1) was recently launched to demonstrate inertial sensing and drag-free control. Another mission, TianQin-2, similar to GRACE-FO, is expected to be launched in 2025 for testing inter-satellite laser interferometry. The Chinese program is progressing rapidly but many key technologies still have to be demonstrated before building the TianQin mission. It is therefore difficult to assess the likelihood of a launch of TianQin within the same time frame as LISA.

The organisation of the LISA Consortium and the role of IN2P3

LISA is a major science project, involving many space agencies, research institutes and universities, mostly in Europe and the United States. In France, **19** laboratories and research departments are actively involved in LISA. They gather experts in many different fields such as fundamental physics, astrophysics, metrology, data science, etc. They are supported by different research institutes : IN2P3 (APC, CPPM, L2IT, LPCC, LMA, CC-IN2P3), INSU (LAM, IAP, LPC2E), INSIS (Institut Fresnel), Obs. de Paris (SYRTE, LUTh), Obs. de la Côte d'Azur (ARTEMIS), CEA / Irfu (DEDIP, DIS, DPhN, DPhP, DAP), CEA / IPhT. Closer collaborations (such as 'integrated teams') have been established on research and instrumental projects, e.g. between APC and CEA/Irfu, CPPM and LAM, APC and IAP.

The CNES is deeply involved in the LISA project, providing management, supervision, financial and engineering support for the development of the French contribution to the LISA instrument and ground-segment. The foreseen deliverables of the French community to the LISA mission consist in:

- The Assembly, Integration, Test and Validation of the 'core' of metrology instrument (so-called MOSA, see the description below)
- The supervision of the design, the development and the operating of the Distributed Data Processing Center (DDPC)The management and development of a scientific performance model

These contributions are described in more details in the next sections. In addition to these deliverables, the French scientific community is strongly involved in developing tools and predictions for the scientific exploitation of LISA's observations. In total, **133** researchers, engineers, post-doc and PhD students from French laboratories have registered as 'Full members' to the LISA Consortium (**43** from IN2P3 labs), corresponding to **55.25** FTE, among which **17.7** FTE for members of IN2P3 labs. In addition, **68** have registered as 'Associates' (**7** from IN2P3 labs).

Because of the early and important implication of APC in the LISA Pathfinder and LISA projects, the IN2P3 has a leading role in the community management and LISA working groups (see Figure A-1 in Appendix 1).

Key roles in the LISA Consortium organization by IN2P3 members:

- *Science:* **S. Babak**: LDC co-chair, LSG WP2 co-chair, LDPG WG3 co-chair; **C. Caprini**: Cosmo WG co-chair, LSG Key Science co-chair; **A. Petiteau**: Science study team at ESA
- *CSGS (Consortium Science Ground Segment - DDPC + INREP)*: **M. Lejeune**: technical coordination for the LDPG support; **A. Petiteau**: LDPG lead; **Y. Lemière**: co-lead Initial Noise Reduction Pipeline (INREP)
- *Performance working group:* **J. Martino**: working group chair
- *AIVT Instrument:* **H. Halloin**: LISA Instrument Group core team member, System Engineering Office at ESA.
- Consortium management: **A. Petiteau**: Co-Lead consortium, Board member, Coordination Team

The visibility of IN2P3 teams is also ensured by many active contributions to project deliverables. A more detailed description of the on-going activities, with the contributions of the IN2P3 laboratories is given in section 'Scientific and Technical Achievements' below.

Science coordination in France and links with other communities

LISA France and the beginning of the French involvement in LISA

Prior to 2005, the French involvement in the LISA-like technologies was mainly through the ONERA, a laboratory specialising the "Drag Free" techniques, and the ARTEMIS laboratory in Nice through their work on laser stabilisation. Later, CNES and IN2P3, through Michel Spiro, both supported the decision of APC to participate in LISA/LISAPathfinder activities. In parallel, in order to support the LISA scientific community, an informal organisation, named LISA-France, was set up by P. Binétruy and gathered the different teams and laboratories involved in LISA and/or LISA Pathfinder. The first laboratories to be involved in LISA France were: APC, ARTEMIS, IAP, IPhT, LPC2E, LUTh, ONERA and SYRTE. LISA France was financially supported by the CNES through its APR ("Appel à propositions de Recherche") program. With the proposal of LISA as L1 and then L2 or L3 mission of the ESA Cosmic Vision program, the LISA France community has significantly expanded. Since the adoption of the LISA mission and the beginning of the mission definition phase, the LISA France organisation is superseded by the CNES for the development of the project deliverables and the different science teams can also be supported by CNES funds ('Accompagnement scientifique').

The scientific animation of the LISA community was also reinforced with the creation of the GdR 'Ondes Gravitationnelles'

LISA within the GdR 'Ondes Gravitationnelles'

The GdR "Ondes Gravitationnelles" began its activities in the summer of 2017. After the advent of direct GW detection and the birth of GW astronomy, the amazing potential of GW science became clear, and a wide scientist community, composed of astronomers, experimentalists, theoretical physicists, data analysts, started to become interested in this new branch of observational physics. The GdR was founded to federate, consolidate and structure this newly born community, favouring scientific exchanges and providing the opportunity for discussion and training, with particular attention to the involvement of young researchers. The GdR is structured in eight Working Groups, representing the main branches of GW physics: waveforms, detectors, data analysis, populations of sources, multiband astronomy, cosmology, tests of General Relativity and alternative theories, neutrons stars and heavy elements. French members of the LISA Consortium actively participate in all Working Groups. The GdR assemblies and Working Group meetings offer the opportunity to the French LISA scientists to present the mission, its progress, and its wide scientific potential to a broad community, with a mutual advantage: on one side, motivating a growing number of people to get involved in the mission; on the other side, increasing the knowledge of the French GW community on the prospects of GW science beyond Earth-based detection.

Local Collaborations

Collaborations in PACA region

Created by Aix-Marseille University (AMU) in January 2020, the Institute for the Physics of the Universe (IPhU) brings together and synergizes theoretical, observational and experimental skills from 3 internationally well recognized laboratories (CPPM [IN2P3], CPT [INP] and LAM [INSU]). This synergy represents a unique added value that contributes to the sustainability of the intimate connection that IPhU perpetuates between research, the internationalized and innovative education of its Graduate School, and the socio-economic world. Gravitational Waves, and LISA in particular, are a common scientific and technological interest to the teams of the 3 labs that foster collaborative work of these teams within the institute. Collaboration with ARTEMIS [INSIS] and more generally with OCA is already on-going on the test-bench IR photodiode characterization and is meant to be strengthened to cover common data processing and storage strategies (through the regional computing/data center that AMU and UCA share) as well as scientific interests.

APC-CEA integrated team

The CEA/IRFU has recently joined the LISA collaboration and is bringing its strong experience in different engineering fields, such as mechanics and thermal simulations. The CEA teams are also actively working on the instrumental simulation. At the same time, the APC has acquired experience of interferometric metrology in the mHz range, and in LISA/LISA Pathfinder performance modelling. Beyond the already existing links between the APC and the CEA, a close and fruitful collaboration ('integrated team') has been set up on different aspects such as optical design, performance studies and thermal analysis, optical system integration, etc.

L2IT-CNES collaborations

The L2IT lab, new IN2P3 laboratory in Toulouse, has taken advantage of its geographical proximity with the CNES to collaborate on specific subjects, mostly related to optical design and simulations (e.g. for the future FF-OGSE, far field optical ground support equipment, described below). Moreover, in the beginning of the Phase A, C. Buy, then optical engineer at the APC and later at the L2IT, had been working in the CNES offices in Toulouse to ensure a smooth knowledge transfer and coordination between the CNES and the APC.

APC-IAP collaborations

Scientists of the APC and IAP laboratories collaborate on three main scientific projects, aiming at better characterising the potential of LISA concerning two of its main scientific objectives. The first project concerns testing the expansion of the universe at high redshift with coincident GW and EM detections, with the important by-product of realistically establishing the number and detection properties of possible LISA counterparts. The second project consists in analysing the multi-messenger observational signatures of primordial magnetic fields, of which GW detection at LISA is one of the main observables, together with gamma- and cosmic-rays. The third project concerns modelling the GW signal from coalescing black hole binaries. The accurate modelling is necessary for extracting parameters of binary systems using matched filtering.

LISA technologies beyond gravitational waves

The technology developed for the LISA mission is also relevant in other physics research fields. For LISA and LISA Pathfinder, the APC developed expertise in low-noise interferometric metrology in the mHz to Hz frequency range. On ground, in this frequency range, high precision metrology is usually dominated by environmental noises (which is actually the main reason for developing space-borne instruments). Testing and qualifying the LISA and LISA Pathfinder instruments is, therefore, a technical challenge and requires specific techniques. The same challenge, in an equivalent frequency range, actually appears in planetary seismometry, where extremely precise metrology is required to monitor the movement of a proof mass. The performance of present planetary seismometers (such as the SEIS instrument embarked on the InSight mission and currently running on Mars) has reached the noise limit allowed by capacitive sensing. With the support of the LabEx UnivEarthS, a collaboration has been set up between APC and the IPGP (Institut de Physique du Globe de Paris, PI of the SEIS instrument) with the objective of applying interferometric techniques to the next generation of planetary seismometers.

Mission description

Gravitational waves change the light travel time between purely inertial test masses (TMs). To date, laser interferometry is the most efficient way to detect these tiny fluctuations in the optical pathlength, and this is the main principle used by LISA and by ground-based detectors. The main advantage of going to space is the 'quietness' of perturbations in the mHz band as compared to Earth, due to the absence of seismic noises. Near-infrared laser beams can propagate in space on very long distances with virtually no distortion, allowing building interferometers with Mkm baselines, hence increasing the sensitivity of the instrument. However, building a giant GW detector in space requires to master specific technical challenges such as inertial flying in space, as well as long-distance interferometry.

Mission profile

LISA is a constellation of 3 satellites, about 2.5 Mkm apart, exchanging laser beams and forming a giant interferometer. Each S/C follows a heliocentric orbit, trailing the Earth by 50 to 65 Mkm (see Figure 2 below). Following inertial test masses, the orbit of each satellite is not actively controlled. Therefore, the constellation shape evolves with time, the so-called breathing and flexing effects, and will ultimately be ‘torn apart’ by the gravitational pull of Earth and other planets. However, a careful choice of the initial orbital parameters ensures constellation stability compatible with about 10 years of scientific acquisition.

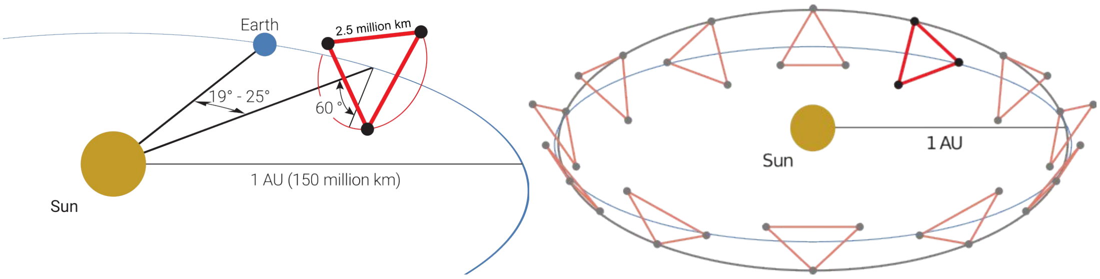


Figure 2 - LISA orbits around the Sun

These optimized orbits lead to breathing angles of +/- 1deg and Doppler shifts of laser beams within +/- 8 MHz. LISA launch is expected in 2034, using Ariane 6.4. After 30 months of transfer and in-orbit commissioning, the scientific mission duration should be at least 6 years, with consumables sized for 10 years. The details of the measurement concept and limiting noises for LISA are given in Appendix 2. In a nutshell, each S/C is floating around two free-falling test masses (TM), whose distances are monitored at the pm/√Hz level using classical interferometry. The optical and mechanical assembly ensuring the interferometric measurements with the TM at each end of each laser arm - is named MOSA (Movable Optical Sub-Assembly). One MOSA contains four main elements (See Figure 3) :

- a telescope for sending and receiving the laser beams
- a Gravitational Reference Sensor hosting the inertial test mass
- an optical bench combining the different laser beams and producing the measured beat notes
- a support structure linking these 3 elements and steerable over +/- 1 deg to accommodate for the constellation breathing.

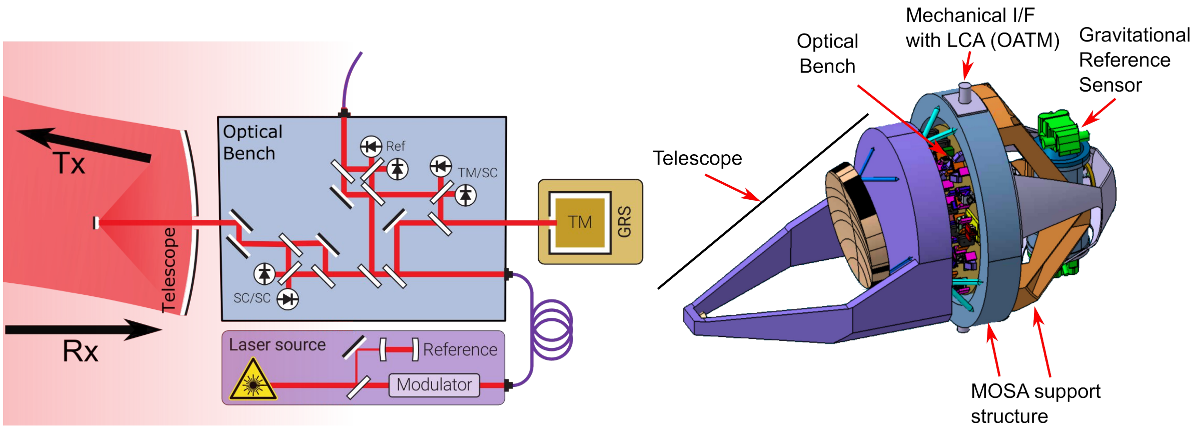


Figure 3 - Scheme of the MOSA onboard LISA

Data analysis workflow

The LISA mission data are special for two main reasons: (i) it will be the first data of its kind and (ii) large astrophysical uncertainties translate in a broad range of expected event rates, which in turn could lead to a large number of overlapping GW signals with highly variable duration and strength. As a result, we need to build a highly flexible data analysis pipeline capable of dealing with a wide range of possible LISA data. The main objective pursued by the mission is to reconstruct the Universe in GWs. Given the LISA observations, we aim at detecting and characterizing GW sources by iteratively building the range of hypotheses best supported by the observed data. A variety of methods to analyse LISA data are being explored and tested on the simulated data within the LISA Data Challenge project. The main technique is based on the guided (but still stochastic) walk in the hypotheses space and in the space of parameters characterizing each model. The stochastic evolution of models is governed by likelihood and assigned prior knowledge. Our intend is to use at least two independent methods to confirm the overall convergence. The first data analysis task is to build a catalogue of GW sources, and the second one is to solve the inverse problem: given LISA observations, we need to infer the most likely channel of formation and evolution of the astrophysical population of GW sources. The secondary objective is testing the consistency of observed data with respect to the predictions of GR.

Data processing will be based on the software/hardware architecture, the Distributed Data Processing Center (DDPC), typically implemented on several generic centres with distributed computing and storage resources. We aim at the scalable solution for use in the mass production (DPC) and for the development/experimentation/submission (micro-DPC).

Description of French deliverables

The development of the mission is under the supervision of ESA, with major contributions of member states, as well as NASA. Figure 4 summarises the main contributions of ESA, ESA member states, and international partners to the development of the LISA instrument.

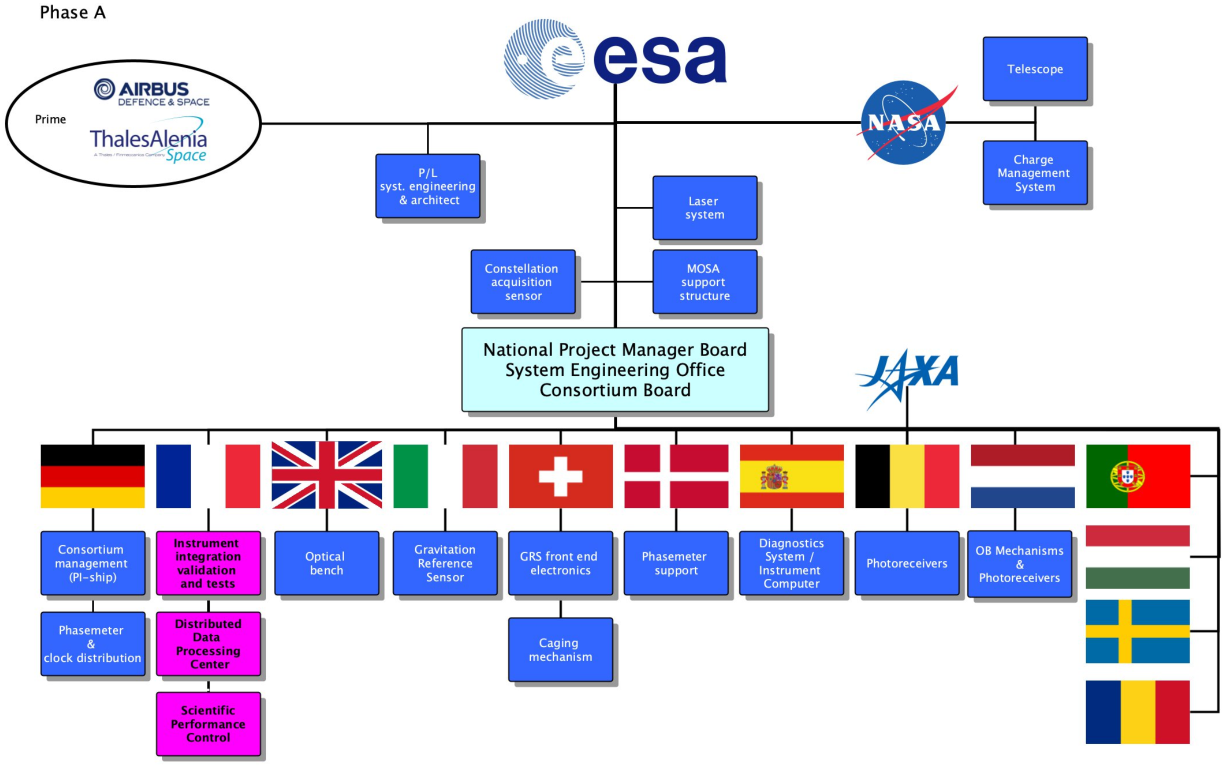


Figure 4 - Contributions to the LISA mission

Based on the current knowledge and skills of the participating institutes, the proposed French contribution to the LISA mission is centred on three topics:

- The supervision and implementation of the Distributed Data Processing Center (DDPC)
- The definition, management and completion of the Assembly, Integration, Verification and Tests (AIVT) of the MOSA
- The coordination of the scientific performance model of the mission

Building facilities for testing the MOSA requires a deep understanding of the whole measurement chain and its critical items. Running these tests will give a very helpful insight into the actual performance of the system 'as-built'.

LISA is a complex system, where the expected scientific performance is entangling most of the S/C subsystems, as well as sophisticated data processing tools. The scientific performance model shall gather all this knowledge, bridging the gap between engineering and science analysis.

The Distributed Data Processing Center is the facility where the 'standard' analysis pipelines shall be designed and the sources' catalogues shall be built. This work requires the understanding of all possible instrumental effects (calibration biases, noise correlations, alignment performance, etc.) and their interplay, as given by the AIVT test campaigns and processed through the performance model.

The Distributed Data Processing Center

Given the novelty of the LISA data: uncertain astrophysical event rates, and instrument performance, we need to cover a broad range of possibilities. The strategy is, therefore, to keep maximum flexibility both on the data analysis pipelines and on the computational resources allowing almost real-time extension if required (e.g. borrowing from shared infrastructure as the cloud). France is leading the Consortium Science Ground Segment (CSGS) with the DDPC being the main element of it. The development activities as well as the computation and storage resources are distributed over international partners and Data Computing Centers (DCC). IN2P3 is at the core of the CSGS activities. APC started prototyping the DDPC in 2014 and is now leading this effort with the LPC-Caen and the CNES. The LISA Data Processing Group (LDPG) led by France is responsible for designing, developing and operating CSGS. During the phase A, the activities of the LDPG are organised in 7 Working Groups: 1) organisation of the SGS, 2) definition and organisation of the DDPC, 3) prototyping, 4) collaborative tools, 5) support, 6) Initial Noise Reduction Pipeline (INREP) and 7) Simulation. IN2P3 members are strongly involved in this activity, leading the LDPG and co-chairing 5 of the 7 working groups.

The MOSA Assembly, Integration, Validation and Tests

As described above, the MOSA is at the core of the interferometric measurements of LISA and consists of four main items that have to be precisely mounted and aligned together :

- The telescope;
- The optical bench;
- The gravitational reference sensor (GRS);
- The MOSA support structure (MSS).

Telescope: With an external diameter of about 300 mm, it receives (Rx path) the laser beam from, and sends it (Tx path) to, the two other distant spacecraft. On Rx, it compresses the beam to achieve a beam diameter of 2.4 mm on the optical bench. On Tx, it expands the beam to reduce its divergence. Its (virtual) entrance pupil should be precisely located (at a level of 10's of µm laterally) on the test mass center of gravity. The telescope shall be provided by NASA (GSFC) and the University of Florida.

The optical bench: It combines the different laser beams to form three heterodyne signals (see the description of the measurement concept above). It holds (among others devices…) beam shifting mechanisms for a fine compensation of alignment errors between the telescope and the optical bench. The integrated optical bench is provided by the UKATC (Edinburgh) and the University of Glasgow.

GRS: It consists of a vacuum enclosure hosting the test mass, surrounded by electrostatic actuators and sensors. The GRS is a direct heritage from the LISA Pathfinder mission. The integrated GRS is delivered by Italy (University of Trento), with contributions of the ETH (Zurich) and the University of Florida.

MSS: this structure holds together the three above items and ensures the pivot interface with the spacecraft. The MSS has very strict requirements in terms of rigidity and deformation (mostly due to thermal and ageing effects). In the present organization, the MSS is under ESA responsibility and delivered to the instrument Consortium.

In this context, the French community has proposed, with the support of the CNES, to be in charge of the integration and tests of the MOSA, prior to delivery to the S/C integrator. More details on the current proposed AIVT flow are given in Appendix 3.

10 MOSA models, including engineering, flight and spare models will have to be manufactured, therefore requiring some kind of serialization in their integration and testing. The current approach is

actually for the research institutes to work out the most demanding performance test benches and procedures during the EQM phase, and then transfer part of this operating knowledge to industrial sub-contractors for the other models. The expertise of the research institutes will however be required at every stage for interpreting and validating the results (or investigating performance discrepancies) for each model. At IN2P3, the APC, CPPM, L2IT and LMA are currently working for prototyping and preparing the required test benches. More details on the ongoing developments and individual lab contributions are given in the 'Technical and Scientific Achievements' section below.

The Scientific Performance Model

A dedicated group in the Consortium was created to develop and maintain a performance model of the LISA instrument. The main goal is to derive what would be the ultimate sensitivity of LISA based on the modelling of every sub-system of the instrument.

The performance model is released periodically and is a snapshot of the consortium's best knowledge of the instrument. Input for building the model comes from the Consortium working groups and from the industrial partners. The main goals of this activity are:

- to support trade-off and design choices by propagating every modification of the LISA instrument or its environment to the sensitivity used to study abilities to achieve LISA's science objectives.
- to propose a set of consistent requirements for each sub-system.

One of the lessons learned from LISA Pathfinder was that understanding the instrument with a system approach was a key element to conduct the science analysis. That is even more true for LISA, because modelling/estimation of the noise is coupled to the GW signals extraction. The French collaboration is heavily involved in this activity through APC and CEA. Some requirements (e.g. alignment precision, temperature stability, etc.) will flow down to the AIVT (see above). Having full control and the understanding of these requirements early in the definition process is also one of the objectives of this project.

The IN2P3 experience within LISA

As members of the LISA France collaboration, the IN2P3 laboratories participate actively in the development of the project's deliverables and prepare for its scientific exploitation.

Although LISA is a space-borne instrument, the contribution foreseen for France is mostly ground-based development. Obviously, a certain knowledge of space engineering is necessary in order to actively take part in the mission progress.. However, the French deliverables do not concern the development of flight hardware; therefore, IN2P3 laboratories will contribute to the improvement and objectives of the mission thanks to their previous expertise in constructing complex scientific instruments. The Appendix 4 summarises the specific technical skills that the IN2P3 labs and platforms currently involved in LISA are bringing to the project.

Development plan

The development of the LISA mission concept is already a long story, the first ideas for a space-borne gravitational wave detectors dating back from the 1970's. Since then, the instrument concept has been constantly improved and regularly evaluated by ESA and NASA. A short story of LISA is summarized in Appendix 5. We focus hereafter on the LISA development plan since its selection as an ESA L3 mission in 2017.

Mission development schedule

As for any space mission, the LISA project is following different development phases (from feasibility studies to operations in flight and ultimately decommissioning), with regular reviews led by the European Space Agency (ESA) at mission level and national agencies (CNES for France) at sub-system level. Table 1 summarizes the main milestones of the LISA development since its selection in 2017.

Event	From	To	Comment
Instrument Phase 0	Jul 2017	Nov 2017	Completed
Mission Definition review (MDR)	27 Nov 2017		Successful
Phase A (mission & instrument)	June 2018	Oct 2020	Completed
Mission Consolidation review (MCR)	22 Oct. 2019		Successful
Extended Phase A (mission & Instrument)	Oct 2020	Dec 2021	Pending
Mission Formulation review (MFR)	End 2021		
Phase B1 (mission & instrument)	Jan 2021	Dec 2023	
Mission adoption	Early 2024		
Prime and providers selection	End 2024		
Phase B2/C/D	Early 2025	2034	
Launch	2034/2035		
Transfer & commissioning	2.5 years		
Operations	6 years		
Extended mission	Up to 4 years		10 years of total science mission

Table 1 - Major milestones in the LISA development schedule

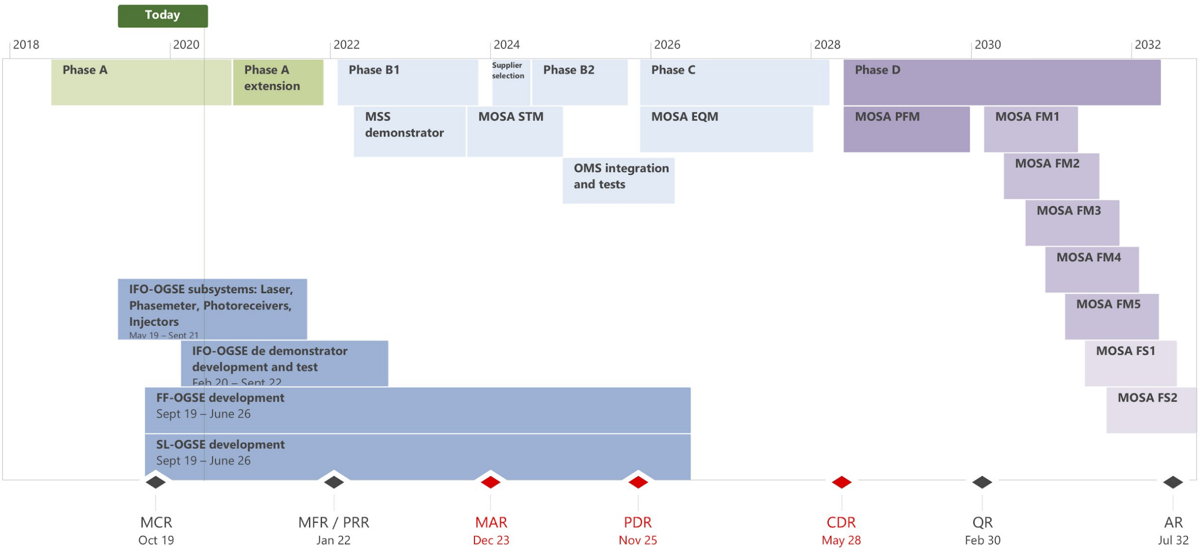


Figure 5 - Instrument development plan, compared with AIVT prototyping sequence.

Figure 5 represents the different development phases of the mission together with the successive instrument models and identified optical ground support equipment (GSE). The development phases of the foreseen French deliverables follow the same calendar, under the supervision and project management of the CNES.

The first CNES phase-0 was conducted on the DPC in 2013 with a final report in February 2014. This study concluded the feasibility of the Data Processing Center and identified possible technical solutions. The second phase-0 led by the CNES evaluated the feasibility of the proposed AIVT contribution. It was conducted between February 2016 and April 2017. No showstoppers were found but the conclusions had to be deferred until the completion of a more mature definition of the mission and instrument designs. Based on the (positive) conclusions of the Mission Definition Review, the CNES started a phase A in 2018, both on the DDPC and the AIVT contributions. The schedule is since then following the development plan at the Consortium level, a phase A extension has been approved (and funded) until end 2021.

Although LISA is scheduled for launch in about 15 years, the integration and tests of the first instrument models start as early as 2026. At that time, the different Ground Support Equipments (GSEs) shall be completed and ready to operate. Consequently, their design and prototyping has already started, with a large contribution of IN2P3 laboratories. During the phase A (and its extension) the contribution perimeter and organization should be consolidated, together with assessment of its feasibility (through system prototyping) and the cost for the CNES and partner institutes. *An important milestone is the mission adoption review, at the end of 2023*. At this time, the contributions of the member states shall be fully consolidated, each agency should commit itself to fund and to provide the instrument's subsystems (incl. the ground segment). Consequently, the French research institutes and laboratories shall precisely define their contribution (especially in terms of human resources) to the deliverables within the next ~2 years. Within the DDPC/LDPG activity, the main deliverables of phase A are the management plan, the development plan, functional tree, product tree, DDPC system requirement, architecture and the demonstration of the feasibility of the main stages of the data processing (data cleaning - INREP, and GW extraction).

During the phase B1 the design will be consolidated for the further distribution of responsibilities with associated costs for adoption (end 2024). During phases B2, C and D instrumental and software (professional) implementation takes place. The implementation goes in close collaboration with continuous research and development within the LISA Science group (scientific research and knowledge do not stop at mission adoption). The distributed infrastructure will be constituted of several interconnected Data Processing Centres, altogether forming the DDPC. Finally, during the operation, the DDPC will produce the scientific products of the mission. The research and development of the algorithms has to continue, to adjust/optimise the analysis to the acquired data. Based on its current strong involvement and its expertise, the IN2P3 can play a major role in the CSGS with an integrated team of scientific/engineers developing and producing simulation and data analysis methods, and with CC-IN2P3 being one of the main DCC of the mission.

Project evaluations

In addition to the regular project evaluations along with its development phases (MDR, MCR, MFR, PDR, etc), the LISA project and the French participation had been reviewed by CNES and local scientific councils. Recently (October 2019), the CNES has conducted prospective exercises for the next 5 years. The first recommendation from the Working Group on Fundamental Physics is the following (see the corresponding report here: https://sps2019.com/rapports/):

> "Un investissement très conséquent du CNES dans la mission LISA, avec une forte implication française (AIVT de l'instrument + DDPC + perfos et simulation). Un soutien du CNES aux laboratoires qui préparent l'exploitation scientifique, y compris pour les aspects multi-messagers, est également indispensable pour assurer d'un retour scientifique à la hauteur de l'investissement."

In the different IN2P3 laboratories, the involvement of the team is regularly presented and evaluated during the EAOM (Entretiens Annuels Objectifs Moyens). The human resources on LISA correspond to priorities of each lab and are agreed/supported by each CNRS unit director. Moreover, the contribution to the LISA mission is evaluated regularly, and always positively, by various scientific councils and committees in laboratories. Some of these recommendations are given in Appendix 6.

Scientific production

Over the last 5 years (2016 to 2020), 44 papers have been published by IN2P3 members on LISA (4 in 2016, 9 in 2017, 7 in 2018, 13 in 2019, 11 in 2020). A complete list is given in Appendix 7. During the same time frame, 5 PhD thesis have been defended on LISA in IN2P3 labs:

- P. Grüning, APC, "Développement et exploitation d'un simulateur électro-optique pour le futur détecteur spatial à ondes gravitationnelles eLISA", December 2015
- M. Pieroni, APC, "Classification of inflationary models and constraints on fundamental physics", November 2016
- Y. Bouffanais, "Bayesian inference for compact binary sources of gravitational waves", 2017
- M. Laporte, APC, "Amélioration et exploitation d'un simulateur électro-optique du détecteur spatial d'ondes gravitationnelles LISA", April 2019
- J-B Bayle, APC, "Simulation and Data Analysis for LISA: Instrumental Modeling, Time-Delay Interferometry, Noise-Reduction Performance Study, and Discrimination of Transient Gravitational Signals", October 2019

Presently 5 PhD students are working on LISA-related projects in IN2P3 labs:

- L. Vidal, APC, "Validation expérimentale des performances interférométriques de LISA"

- N. Quand Dam, APC, “Simulations and associated data analysis for realistic LISA configuration”
- M. Flaxa, APC, “Detecting low-frequency gravitational waves from the astrophysical population of binary systems.”
- P. Auclair, APC, “Cosmology with Gravitational Waves”
- A. Toubiana, APC, “Bayesian population study and testing General Relativity with gravitational waves from coalescing binaries”

Resources

Together with other research institutes and Universities, the IN2P3 supports LISA with human resources, mostly on permanent positions, a few short-term contracts (CDD, post-docs) and co-funding of PhD thesis. Moreover, the LISA project is making use of two technical platforms of the IN2P3: the CC-IN2P3 and the LMA/IP2I.

There is no direct financial support (i.e. excluding human resources and through the technical platforms) of IN2P3 to LISA. CNES is the main supporting agency for missions, hardware development, CDD (engineers) and post-docs.

Contributions of the CC-IN2P3 to the LISA project

The CC-IN2P3 is today the main infrastructure used by the LISA project for computing and storage. The CC-IN2P3 currently provides up to 1,000 concurrent jobs (24 million hours of HS06 pledged computing time for the year 2020) mainly used for the LISA Data Challenge (data generation and analysis). LISA also uses the GPU and HPC infrastructure of the CC-IN2P3. The estimated costs over the past 5 years are 14613 euros for 2019, 9516 euros for 2018, 3381 euros for 2017, 6036 euros for 2016 and 8075 euros for 2015.

The CC-IN2P3 will contribute to LISA's future computations. The data challenges will progressively increase the computing capacity provided. Given the evolution of LISA towards a distributed computing model, the CC-IN2P3 will be involved in discussions and meetings concerning the computing model in order to adapt, if necessary, the envisaged model and the services provided.

In addition, LISA uses shared services provided by CC-IN2P3 such as Gitlab, Atrium for documentation and the cloud for the manufacturing of containers. A consultation will take place concerning the new technologies considered by LISA (kubernetes, singularity, skirt, etc.)

Contributions per laboratory

The mission adoption (end 2023 or early 2024) is a major milestone, also in terms of resources. Once the mission is adopted and the different member states commit to delivering parts of the LISA system, the requirements in terms of financial support and human resources will have to increase significantly to comply with the rising needs in development and implementation. We have attached in the Appendix 8 Table A-1 summarising human resources involved in LISA from 2018. We have extrapolated to 2025 our ***minimal*** requirement/expectation beyond the present date, those are given in the table in red.

The second table in the same appendix gives the financial resources (excl. human resources) acquired by IN2P3 labs from various sources to support LISA activities from 2018 until now. These funds cover mostly travel expenses and equipment for instrumental development.

Technical and scientific achievements

The activities conducted by the IN2P3 labs cover all the aspects of the mission, from instrument development to scientific exploitation, through performance modelling and data analysis techniques. This broad spectrum, closely related to the foreseen deliverables of the French community, is focused on the best possible understanding of the instrument characteristics and analysis algorithms, and, consequently, on an ‘optimal’ scientific return of the LISA data.

Science topics

Extracting the science from LISA's observation requires research across several theoretical subjects integrated with the LISA data analysis. We use parameterized models of GW signals (for characterizing the sources of GWs) which involves accurate modelling of gravitational emission from various coalescing binary systems and from energetic processes in the early Universe. We utilize current astrophysical knowledge of the population of GW sources (expected event rate and distribution in parameter space) to produce the simulated data. The following few paragraphs summarize the main theoretical achievements.

Modelling GW from coalescing black hole binaries: in collaboration with AEI, we have developed a model based on "Effective-one-body" approach for merging black holes. This model involves higher-order modes (neglected previously) and takes into account orbital precession due-to spin-orbital coupling.

Testing GR with LISA requires very accurate modelling of GW signals in GR to start with. Systematic deviations due to mismodelling could be mistaken for violations of GR. We have investigated the possibility of testing GR with stellar-mass black hole binaries, some of those binaries will be first observed by LISA and later on by 3rd generation of GW detectors on ground. We have assumed LISA only and multi-band observations, and have evaluated the upper limit which can be set on the mass of the graviton and on the presence of dipolar radiation.

We have studied the ability of LISA to infer the acceleration of the centre of mass of solar-mass black hole binaries, providing a possible mean to distinguish their formation channel, as high accelerations (detectable by LISA) are expected if the binary is formed within an Active Galactic Nuclei.

Detecting GW from coalescing binaries provides us with luminosity distance and their position. If we can identify the host galaxy from e/m observations, or using statistical techniques (utilizing multiple observations), we can evaluate cosmological parameters in a way complementary to current methods based on EM observations. We use astrophysical catalogues to simulate LISA data and ATHENA/SKA/LSST follow-up observations, and evaluate the ability of LISA to constrain the rate of expansion of the Universe,inferring the Hubble constant, the cosmological constant, the dark energy equation of state. We also performed studies of the capability of LISA to constrain alternative dark energy theories changing the expansion of the universe at relatively high redshift.

Concerning signals from the early universe, we have updated the prediction of stochastic GW backgrounds emitted during a first-order primordial phase transition, and their connection with models beyond the Standard Model of particle physics. We are performing massive simulations of the coupled scalar field and fluid dynamics following a first order phase transition, in order to accurately predict the spectral shape of the stochastic GW signal. We have investigated LISA detection prospects of the stochastic signal emitted by a network of cosmic strings, and the constraints that LISA can establish on the parameters of the string model.

We have developed techniques to infer from the LISA data the presence of a stochastic signal in addition to the instrument noise, and to blindly reconstruct the spectral shape of the signal without fitting to a given model prediction. This reconstruction technique is based on dividing the LISA frequency range of detection into frequency bins and fitting power law spectral shapes or excess noise in the bins.

Participating institutes (***incl. IN2P3***): ***APC***, ***L2IT***, IAP

Performance Modelling

Instrument performance modelling

Two releases of the performance model to ESA were conducted by APC as co-lead of the performance working group over the last two years. The performance model consists of a code capturing all the physical models and their hierarchy to produce the LISA performance but also a technical note summarizing the assumptions and the rationale behind all the sub-systems models and parameters values used.

The following models were developed by the French collaboration and IN2P3 laboratories and included in the LISA performance model:

1. The modelling of straylight and its impact on the measured phase noise, and especially the backscatter of the telescope.

2. The impact of Time Delay Interferometry (TDI) on the propagation of noise sources was included as analytical models. Noise sources that are heavily suppressed like laser noise but also noise sources that are modified or correlated by the TDI algorithm (readout noises, thermal noises etc…)

The LISA Performance model is at a centre of various activities but also communities in the LISA consortium. So developing the software tools is a key contribution to this working group. Most of the work was carried on by the "service informatique" at APC under the DDPC contribution. It was focused on:

- Propagate and trace the physical models and parameters
- Propagate, trace and verify the consistency of the requirements
- Define properly the inputs and outputs of the model and propose a flexible software structure to manage them.
- Develop a web interface that allows the whole consortium to access the LISA performance model, produce plots, graphs and retrieve data.

Participating institutes (***incl. IN2P3***): ***APC***, CEA, ***L2IT***

Scientific performance modelling: figures of merit

LISA is a complex integrated instrument where it is crucial to keep track of the full measurement chain from hardware subsystems to science exploitation. We utilize the noise model produced by "Instrument performance modelling" for a given LISA configuration, we use the "state-of-art" knowledge about the population of GW sources and the best models for GW signal as an input. We simulate the LISA data and perform a simplified analysis. The obtained results (called "figure of merits") indicate the ability of LISA to achieve the science objectives as outlined in the science requirement document. The metric is applied to each figure of merit and translated it into a colour-coded output with the green colour corresponding to "OK", the shift to red implies a loss in science and potential failure to achieve the corresponding scientific objective, the shift to the blue side means a gain in science (or margins in achieving objectives). This project (as an extension of the instrument performance modelling) is the key for decision making during Phase A and B.

Participating institutes (***incl. IN2P3***): ***APC,*** IAP, CEA

Digital resources : DDPC - SGS

IN2P3 labs and CNES members are responsible for building the DDPC components. We are responsible for delivering the key products for the CSGS based on the following activities where IN2P3 is strongly involved.

Instrument Simulation

LISA is highly integrated and complex instrument. In order to understand the details interaction between sub-system and the propagation and correlation of various sources of noises, a detailed end-to-end simulator is required. IN2P3 with APC is working on LISA instrument simulation with the development of two generation of time domain realistic simulator: since 2005 LISACode, and since 2016 LISANode (more flexible than LISACode and suitable for long-term evolution). Thanks to LISACode and LISANode a number of issues in the instrument have been identified and solved. LISANode is today the simulator of the Consortium and is used for the generation of the LDC data. With contribution from experts all over the Consortium, the realism of the simulation is constantly improving. The main goal of LISACode and now LISANode is to be as close as possible to the instrument. It includes simulation of beam propagation, clocks, phasementers measurements, on-board computer processing, etc. It also includes the dynamic of the test masses and spacecrafts thanks to the merging with the LISADyn, a simulator of the dynamic and control loop also develop at APC.

Participating institutes (***incl. IN2P3***): ***APC***, SYRTE/Obs. de Paris

INREP (INitial Noise REduction Processing)

The realization of the GW detection in space, in addition to obvious advantages, also brings challenges. The first challenge (already mentioned above) is a large size of the detector which implies that we need to use the transponding interferometry. The second challenge is related to the laser frequency noise which is orders of magnitude larger than the anticipated GW signal. It is not a problem for the ground-based detectors where we have full control of the detectors armlength. The light travelling along two arms is recombined at the beam splitter, and the differential phase shift is free of the laser noise (the same noise travels exactly the same distance in both directions and, therefore, is cancelled in the differential measurement). The LISA's S/C are in free-fall and the orbits are chosen to maintain the equal distance between S/C to a high degree, but not exactly. So that we have two main constraints (i) the laser frequency noise is not cancelled and is by far the dominant one (and several orders larger than GW signals) (ii) the use of several independent laser sources on distant satellites. The analysis of LISA interferometer data is thus conditioned on the suppression of the main sources of noise and the construction of a TDI (Time delay Interferometry) signal (digital interferometry). TDI is a way to recombine the individual measurements in the post-processing which cancels a large portion of the laser frequency noise bringing it to an acceptable level.

The first ground data processing (called INREP for Initial Noise REduction Processing) is summarized in these steps:

- Signal calibration: from gain correction to time synchronization of signals.
- Improvement of absolute armlength measurement using, for example, Kalman filtering
- Removal of part of the optical path noise as well as half of the laser noise.
- Construction of the second generation digital interferometry signal taking into account the evolution of each LISA's arm in time.
- Correction of additional clock jitter noise

The resulting data (known as level-1 data, L1) will be ready for the further analysis searching for gravitational wave signals.

Participating institutes (***incl. IN2P3***): ***APC, LPCC***, CEA, SYRTE/Obs. de Paris,

LDC (LISA Data Challenges)

As we have already mentioned that we are using LISA Data Challenge (LDC) project to prototype LISA data analysis. LDC serves a dual purpose (i) from the project side, we try different data formats to be used in the LISA pipeline, we set standards for the simulated data (unified constants, orbits, GW models, etc). We also develop a strategy for evaluating the performance of various algorithms both on the level of robustness and on computational efficiency; (ii) from the side of the scientific community, we aim at introducing LISA data and LISA data analysis to the new groups and open a door to new ideas.

We issue simulated LISA data with different levels of complexity (realism) aiming at solving a particular set of questions. The data is publicly available, participants are expected to submit their results by a given date. The suggested algorithms will form the basis for LISA data analysis pipeline and the results will be used to assess computational and storage requirements of the LISA mission. APC produces the data challenges as well as taking part as participants.

LDC-1 (*Radler*). The first data challenge (nick-named *Radler*) contains several data sets, each data set contained idealized (Gaussian stationary) instrumental noise and GW sources of the same type. The main objective was to develop robust data analysis tools capable of reliably detect individual sources. The most sophisticated data contained 30 millions Galactic ultra-compact binaries. The results of this challenge will be used to prototype building catalogues of GW sources

LDC-2a (*Sangria*) is ready and will be announced (official release) on 12 October. This (blind) data challenge is addressing the problem of confusion of multiple sources (about 30 millions Galactic binaries and 10-30 merging black hole binaries).

We have developed data analysis methods for detecting GW signals from stochastic GW background, merging BH binaries and Galactic white dwarf binaries. We are currently working on developing and implementing the metric for assessment of submitted results.

Participating institutes (***incl. IN2P3***): ***APC***, SYRTE/Obs. de Paris, ARTEMIS/OCA, CEA

DDPC Architecture

During the Phase A/B1, the DDPC should be specified and designed, and a share of responsibilities should be made. One of the key inputs to this is the DDPC Architecture. We are currently investigating different approaches. One of the main ones is from LPCC and uses concept inspired by genetic algorithms and a combination of one main DPC and multiple micro-DPCs for addressing the challenge of the infrastructure for LISA data analysis while keeping flexibility. There are also other approaches from APC and NASA. With CNES and various members of the LDPG and LSG, we are studying the way of merging all these approaches to define a coherent and efficient DDPC architecture for the mission.

Participating institutes (***incl. IN2P3***): ***LPCC***, ***APC***, CNES

Collaborative tools

Besides the computing means associated with the data analysis, the ground segment is equipped with a set of on-line common tools, provided for sharing information at large within the consortium. Those web services constitute a key element of the DDPC, such that it has been necessary to provide some of them even for phase 0. In order to answer to this need, some collaborative tools have been made available to the consortium since 2015, based upon the existing resources at CCIN2P3:

- a document management system through Atrium
- a software project management system through GitLab
- a wiki hosted at CCIN2P3
- docker and singularity containers for the common development environment

Some others, dedicated to specific working groups have been developed by APC members:

- the LISA Data Challenge web portal
- the performance tree visualization tool
- the LISAPathfinder legacy database

A complete list of the LISA consortium member toolbox can be seen from here: (https://lisa.pages.in2p3.fr/consortium-userguide/). In addition to the proper service offered by each of those tools, the provision of consortium wide web services has changed the way the LISA community was working, bringing a more coherent and structured effort. It has also permitted the French community to ensure his leading role in the DDPC design.

Regarding human resources, those services rely on a best effort basis, both for the CCIN2P3 which is hosting them and for the APC laboratory in terms of supporting and interfacing work. This strategy has made a significant impact on the work efficiency of the consortium in those early phases, at a very low cost. As those services are built on top of free software solutions, supported by a large community, they constitute an opportunity to contribute with very high visibility and low investment, even in the longer term.

The LISA Consortium is conducting a feedback study on those tools, both in terms of quality and functionalities, in preparation of the coming phases, where proper financial support and dedicated solution (if necessary) will be possible. However, the preferred scenario at this stage regarding the services provided by the CCIN2P3 is:

- to get a consolidated cost in order to set an agreement between IN2P3 and space agencies (CNES, ESA) for a long term financial support;
- to closely interact with the CCIN2P3 in order to align the future LISA requirements with the development plan envisaged by the CCIN2P3. The provision of a Kubernetes cluster at CCIN2P3 is one good example of topics where CCIN2P3 and LISA can collaborate.

Participating institutes (***incl. IN2P3***): ***CCIN2P3***, ***APC***, CNES

Instrument development

Molecular laser frequency stabilization

The APC started R&T activities on laser frequency stabilization using molecular iodine, following pioneering work by A. Brillet at ARTEMIS/OCA. Because of the uncertainty on the arm-length knowledge, the laser frequency noise couples with the measured phase noise of the interferometer. The relative frequency stability requirement is at about $10^{-13}/\sqrt{\text{Hz}}$ above 3 mHz. This stability can be achieved by using an ultra-stable Fabry-Perot cavity but then requires a very strict control of its thermal and vibration environment. An alternative solution is to use a molecular reference (namely here a hyperfine transition of molecular iodine) as a frequency reference. This approach is much less sensitive to environmental conditions and offers additionally the advantage of an 'absolute' knowledge of the laser frequency but at the expense of slightly increased complexity and lower technology maturity level.

The experimental work conducted at the APC, supported by the R&T program of the CNES, demonstrated that iodine laser stabilization could reach the required performance, using a detection scheme that could be more easily adapted to space qualification requirements. This work was further developed by the SYRTE/Obs. de Paris, with a focus on the 'compactification' of the experiment and the use of an even more stable transition of iodine (and also well adapted in the context of telecom lasers). The laser source developed by the SYRTE for the Optical Ground Support Equipment (OGSE) prototypes (see the description below) is the last sequel to date of this R&D activity.

Participating institutes (***incl. IN2P3***): ***APC***, SYRTE/Obs. de Paris, ARTEMIS/OCA

LISA on Table

LISA on Table (LOT) is a table-top electro/optical experiment aiming at producing realistic LISA interferometric signals, taking into account propagation delays and Doppler effects. This experiment is based on the possibility to add, thanks to acousto-optic modulators, pre-computed phase noise on different arms of a Mach-Zehnder interferometer. The beat signals, recorded on photodiodes are then processed using TDI-like algorithms and the noise reduction factor is compared to numerical predictions. The LOT can also generate the electrical beat signals directly by mixing the simulated radio frequency carriers. The comparison between optical and RF signals give insights into the origin of the noises and their relevance for LISA.

The LOT experiment shall demonstrate a reduction in the noise by a factor 10^8 through TDI using realistic photodiode signals. This is a very important experimental proof of the concept which exists in theory.

Participating institutes (***incl. IN2P3***): ***APC***

Telescope design studies for ESA

In April 2016, the ESA issued an ITT (Invitation To Tender) for the design study of a Telescope for LISA. The goal was to ensure the disponibility of a suitable design in Europe, in case of failure of the NASA contribution. The LISA telescope design should meet stringent requirements in terms of field-of-view, compactness, wavefront quality and straylight contribution (and its sensitivity to contamination).

A consortium gathering Thales Alenia Space Italy, INRIM, ARTEMIS/OCA, LAM and APC answered to this ITT. In this collaboration, the APC (C. Buy, C. Nguyen) was responsible for system-level studies of the diffused back-scattered straylight, due to components micro-roughness and dust contamination. The LMA (L. Pinard) brought its expertise in components characterization, straylight modelling and coating design (decision to use a polarized beam for LISA).

Straylight is any undesired light present in the design of an optical system. In the LISA context, the straylight is produced by back-scattering of photons by mirrors from the telescopes and can be a significant source of the phase noise: the received beam can interfere with the back-scattered light of the transmitted beam instead of interfering with the local laser, at the detector position. The amplitude of the back-scattered light from the transmitted beam can be a significant fraction (i.e. more than 10^{-6}) of the local laser amplitude.

This work lasted until the end of 2017 and demonstrated that the requirements could be met. This study has also identified the most critical optics in the design and the cleanness level needed for the telescope during the integration and in flight. Moreover, the methodology devised in this work will be applied to the NASA design to assess the straylight contribution from the particle contamination.

<u>Participating institutes (***incl. IN2P3***)</u>: ***APC***, ***LMA***, ARTEMIS/OCA

Optical bench prototypes for MOSA AIVT

The future Assembly, Integration, Test and Validation of the LISA instrument requires dedicated Optical Ground Support Equipment for the performance assessment in terms of the phase noise. It involves the development of two demonstrators of the interferometric bench. The functional scheme is shown on Figure 6 . This optical demonstrator includes the following subsystems:

- A 1064 nm laser system producing two phase-locked laser beams (resp: Ouali Acef, SYRTE/Obs. de Paris)
- An injection system collimating the beams on the optical bench (resp.: R. Granelli, CEA/IRFU)
- An optical bench including optical components forming one equal-arm length interferometer and two unequal armlength interferometers. Two versions of the optical bench are being developped, in Invar (resp.: C. buy until 01/2020, T. Zerguerras afterwards, ***APC***) and in Zerodur (resp: Winlight Systems)
- A thermal shield for improving the stability of the bench in vacuum (resp. : J-L Gimenez, LAM)
- Phasemeters to collect the beatnote signals and measure their phases (joint development: P. Prat, ***APC*** & S. Sube, CEA-IRFU)
- Photoreceivers recording the laser beatnotes (architect: N. Dinu-Jaeger, ARTEMIS/OCA, photodiodes characterization : A. Secroun, ***CPPM***)
- The monitoring, control and acquisition system (resp.: A. Secroun, ***CPPM***)

This experiment is first being manufactured with an invar baseplate and commercial opto-mechanics for extensive functional tests. This setup will be tested at the ***APC*** (by end of 2021). In a second step, optical components will be optically contacted on a zerodur baseplate for an optimal performance. The performance evaluation will be conducted in a representative test environment, namely the ERIOS facility at the LAM (Laboratoire d'Astrophysique de Marseille) in mid-2022.

The optical design of these benches is coordinated by the ***L2IT*** (C. Buy) with an important contribution of the ***APC***. The system engineering (incl. the performance model) is led by the ***APC***, with a significant contribution of all partners.

The characterization tests of these optical benches will be performed in vacuum. The ultimate goal is to achieve a pathlength stability of about 10 pm/√Hz in the [10 mHz; 1 Hz] frequency range, representative of the required stability for testing the LISA instrument. A crucial result will be to understand all the sources of experimental perturbations and assess the lowest noise level that can be reached on-ground. This project creates the opportunity for the French Gravitational Waves community to gather and deepen the skills necessary to design such equipment and identify the required test infrastructures.

The development of these prototypes is entirely funded by the CNES (equipment and short term contracts).

<u>Participating institutes (***incl. IN2P3***)</u>: ***APC***, ARTEMIS/OCA, CEA/IRFU, CNES, ***CPPM***, ***L2IT***, LAM, SYRTE/Obs. de Paris

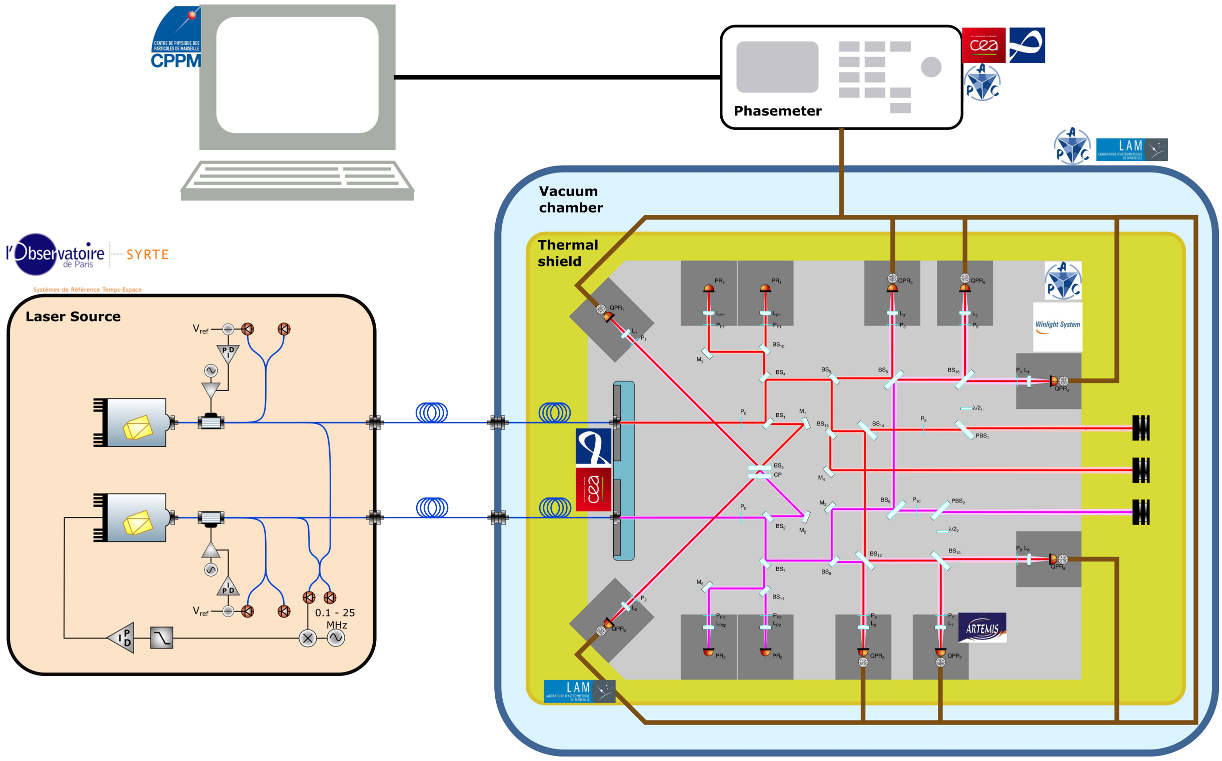


Figure 6 - Functional scheme of the AIVT prototype bench, with mention of the main contributors to the hardware

Building AIVT GSEs

The study of the AIVT plan for the MOSA and associated Ground Support Equipment is under the responsibility of the CNES. However, the French laboratories have major contributions to the definition of the required performance tests and preliminary design of the test benches.

First study has identified 5 main ground support equipment required to perform dedicated optical performance tests:

- *Beam wavefront measurement*: the imperfections of the transmitted beam wavefront is an important contributor to the so-called 'tilt-to-length' (TTL) effect on the Tx beam, coupling the rotation of the S/C around the TM to longitudinal phase noise. The quality of the Tx beam shall therefore be accurately checked and any biases, if present, included in the performance model.
- *Beam centring measurement*: this test is dedicated to the measurement of the alignment offset of the Tx beam w.r.t the position of the TM (known w.r.t fiducial points on the GRS). A lateral accuracy of less than ~35 µm is required to comply with the present TTL Tx alignment budget.
- *Direct TTL measurement*: a dedicated Far-Field Optical Ground Support Equipment (FF-OGSE) should be designed to produce a tiltable Rx beam. This beam will then be used to calibrate (and reduce using beam steering mechanisms on the optical bench) the TTL coupling coefficient on the Rx beam. This facility is presently identified as the most complex optical GSE for the MOSA test campaign.
- *Differential and global interferometric tests*: these tests are meant to characterize the phase stability of the interferometric measurements once the MOSA have been integrated. Due to unavoidable (mostly thermal) perturbations of ground measurements, pm-stable measurements at 1 mHz are probably beyond our reach in a fully representative LISA configuration. However, the differential and reciprocity measurements with three interferometers on the LISA optical bench (and dedicated optical test benches) can be used to constrain most of the possible noise and bias sources.

Various studies on the design of these test benches are currently on-going, especially the FF-OGSE. We also analyse the test sequence, expected performance and relevance for the characterization of the MOSA in flight. The exact contribution of the French laboratories to the hardware development of these optical benches is yet to be defined. Their construction will start in ~2022/2023 to be compliant with the MOSA EQM test campaign scheduled for late 2026.

Participating institutes (***incl. IN2P3***): ***APC***, ARTEMIS/OCA, CEA/IRFU, CNES, ***CPPM***, Institut Fresnel, ***L2IT***, LAM, ***LMA***, SYRTE/Obs. de Paris

SWOT (Strengths, Weaknesses, Opportunities, Threats)

We summarize the SWOT analysis on the LISA collaboration in France in the following table.

Strengths	**Weaknesses**
- ***High-level technical skills in IN2P3 laboratories: data analysis softwares, computing infrastructure,*** *optics, interferometry measurement, RF electronics, mechanics CAD & machining, control & command, sensor characterization, QA/PA, large scale projects.* - ***Leading role of IN2P3 labs in the LISA Consortium.*** - ***Skills in space project management*** - ***National and international recognition and visibility*** *: CNES, LISA Consortium, ESA …* - *Skills / knowledge on the instrumentation, data processing, software architecture building, scientific interpretation of LISA data.*	- ***Risk of losing strategic skills*** *(fixed-term contracts, mobility, retirement …)* - ***Some of the permanent staff members have unique skills*** *(ex: optics, AIT/AIV, electronics PA, mechanics workshop technician), their loss will create void leading to delays* - ***High turn-over (ex: fixed-term contract) in some laboratories.*** - ***Limited number of permanent regarding the level of responsibilities*** - ***Necessity to reinforce the link with the astrophysics and cosmology communities, in order to meet the challenge of strategic science objectives such as multi-messenger detection***
Opportunities	**Threats**
- ***The unique and promising science of GW in the mHz regime*** - ***Collaboration and partnerships with other Research institutes (CEA, INSU, INSIS, Obs. de Paris, OCA), CNES and private companies (Winlight System)*** - ***Strong financial and engineering support from the CNES*** - ***The LISA mission brings a long-term, motivating perspective*** - ***Multi-messenger astronomy through GW, radio, X-Ray, etc.*** - ***GW detection is a priority topic for the IN2P3. The LISA mission covers detecting GW in mHz band: complementary to the ground-based detectors and PTA.*** - ***Securing the future by training students (PhD, Post-Docs, Engineering students …)***	- ***Delayed mission casued by technical or programmatic problems, or by performance discrepancies*** - ***Delays induced by external events (ex: COVID-19 pandemic)*** - ***Insufficient technical and financial support from agencies and partners*** - ***Difficulty to recruit specific skills*** - ***No support from research agencies for permanent position hiring: loss of expertise on the long term.***

Conclusion

The LISA mission has been selected by the European Space Agency in 2017 and is scheduled for launch in 2034/2035. The French laboratories are very active and contributing significantly to LISA, either on the scientific exploitation of the future LISA data, or on the mission deliverables (Instrument AIVT, scientific performance monitoring and DDPC). The expertise of the IN2P3 in LISA technologies and science is based on the experience gained in the related projects such as LIGO/VIRGO, computing infrastructures, contributions to previous space missions and, obviously, the very successful results of LISA Pathfinder. The LISA activities are also fully integrated into the gravitational waves community, particularly thanks to the GdR 'Ondes Gravitationnelles'. The unique scientific objectives of the LISA mission make it perfectly complementary to the present and future ground based GW detectors (such as the Einstein Telescope) and give a great opportunity to conduct multi-band and multi-messenger observations.

LISA is a long term project, but crucial decisions have to be taken within the next few years. A major milestone is the mission adoption, scheduled in December 2023, when the exact perimeter of the French contributions (hence also the contribution of the IN2P3) shall be identified with the corresponding commitment. We are actively working toward that deadline by prototyping models of the instrumental sub-systems and their performance, and of data analysis workflow and its robustness/efficiency: these are the critical elements of the overall simulation of the LISA instrument, and of its ability to achieve its science objectives. This work is conducted by IN2P3 laboratories in close collaboration with CNES and other research institutes: CEA, INSU, INSIS, OCA, Obs. de Paris, IAP, SYRTE.

The CNES is strongly supporting LISA, through equipment, travel funds, engineering expertise and short term contracts. The continuing support of the IN2P3 is also very crucial, e.g. by securing the permanent positions with the expertise brought by young engineers and researchers.

Important development milestones are scheduled in the near future. Consequently, regular reviews and discussion of the LISA project status at the IN2P3 (especially its scientific council) seem necessary in the next years.

Appendix 1 - Consortium-level organigram of LISA

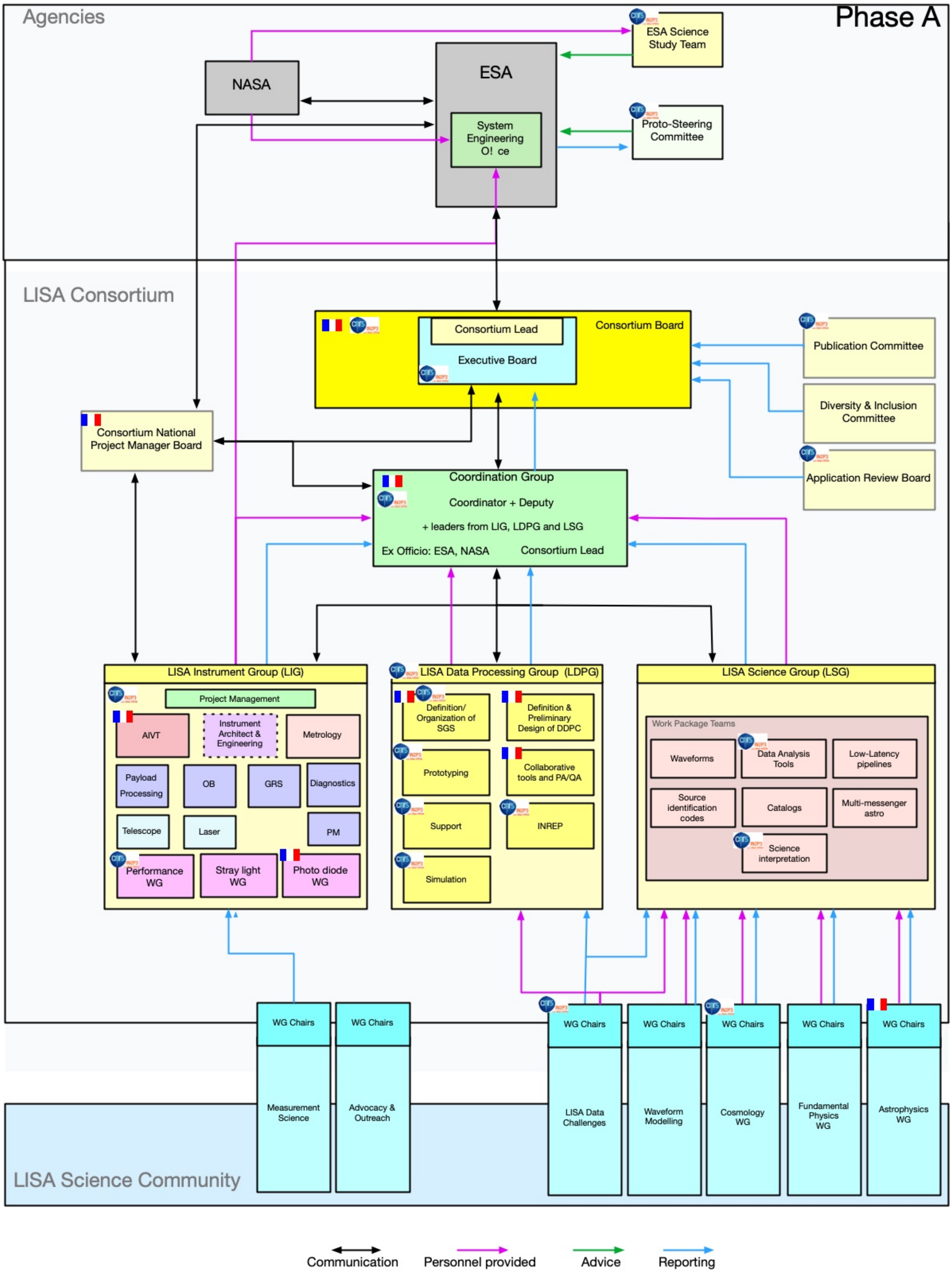


Figure A-1 - Organigram of the LISA Consortium, with the indication of responsibilities with French flag or CNRS-IN2P3 logo when French institute or IN2P3 has responsibilities (lead, chair, co-chair) or part of the core team.

Appendix 2 - LISA measurement concept

Each LISA S/C hosts two free-falling test masses, one at both ends of each laser link. The optical pathlength variation or, equivalently, time-varying Doppler shift of the light frequency, due to the pass of a GW is detected by laser interferometry, with optical phase measurements performed in each of the three S/C. The sensitivity of the observatory is limited by the noise in the measurement of the optical pathlength variation between the TMs, also by any noise in the orbits of the TM and by stray accelerations from spurious forces. The S/C serve as shields for the geodesic reference TMs as well as platforms for the metrology hardware. The S/C are “drag-free” as they are steered by µN thrusters to stay centred on the TMs. The TMs are left force-free along the critical interferometry axes.

The distance changes between the test masses caused by the gravitational waves are small (pm to nm), equivalent to relative accelerations of femto-m/s^2. These are small compared to the variations caused by solar system celestial dynamics (±35 000 km armlength changes with µm/s^2 relative accelerations). However the later variations are happening on a different timescale (minutes to hours for GWs compared to months to a year variations) and, therefore, falling at very low frequency. This translates into the following engineering requirements:

- The optical metrology must allow TM-TM measurements with an equivalent single link noise of 10 pm/√Hz (with a relaxation below 2 mHz
- The residual acceleration noise of the TM should be less than 2.4 fm.s^{-2}/√Hz (with a relaxation below 0.4 mHz)

The optical pathlength measurement uses continuously operating heterodyne lasers at 1064 nm in both directions along each arm with a few Watts of power transmitted at each end. All lasers within the constellation are offset frequency phase-locked with one laser acting as the reference laser. Planned laser frequency design allows to keep the resulting interferometric beat notes within the optimal photoreceiver frequency range (6 to 25 MHz) for 10 year of extended mission lifetime.

The beam divergence over several million km limits the received laser light power to 500 pW and rules out passive reflection for the return path. Each S/C acts as an active transponder, transmitting a fresh high-power beam that is phase-locked to the incoming weak beam. The constellation is fully symmetric, with similar measurements taking place in both directions along each of the three arms.

The total TM- TM measurement along each arm is separated into three parts (see Figure A-2):

- TM 2 to optical bench in S/C 2 (local);
- optical bench in S/C 2 to optical bench in S/C 3 (long arm); and
- optical bench in S/C 3 to TM 3 (local).

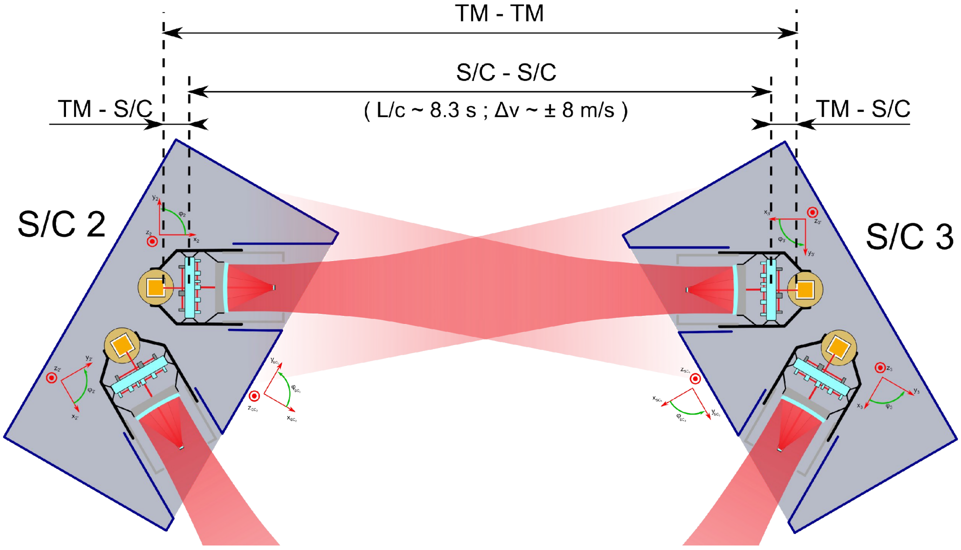


Figure A-2 - Principle of the split interferometry for retrieving the TM-TM distance between two S/C.

Combining these three measurements along the 6 links in post-processing on the ground yields the desired TM to TM separation measurement, cancelling out the much noisier S/C motion present in the single phase measurements. Synthesising virtual equal-armlength interferometers using the time-delay interferometry algorithm will suppress the otherwise dominating laser frequency noise. A third post-processing correction is required to suppress the coupling of S/C angular and lateral jitter to the TM to TM separation.

All phase measurements could be combined in two TDI corresponding to “Michelson-like” interferometers plus a third stream with a suppressed sensitivity to GWs. The absolute inter-spacecraft distances (required by TDI) are determined using an auxiliary modulation on the laser beams.

Appendix 3 - MOSA AIVT flow

The AIVT of a MOSA can be split into two stages: a first assembly phase, followed by a test phase. While the assembly phase should be mostly sub-contracted to dedicated industries, the research institutes will play a major role in the MOSA performance characterization during the test phase. The details of the MOSA AIVT are still under active study, but Figure A-3 gives a plausible test flow for the engineering and qualification model (of all the models, the EQM will undergo the most complete set of tests).

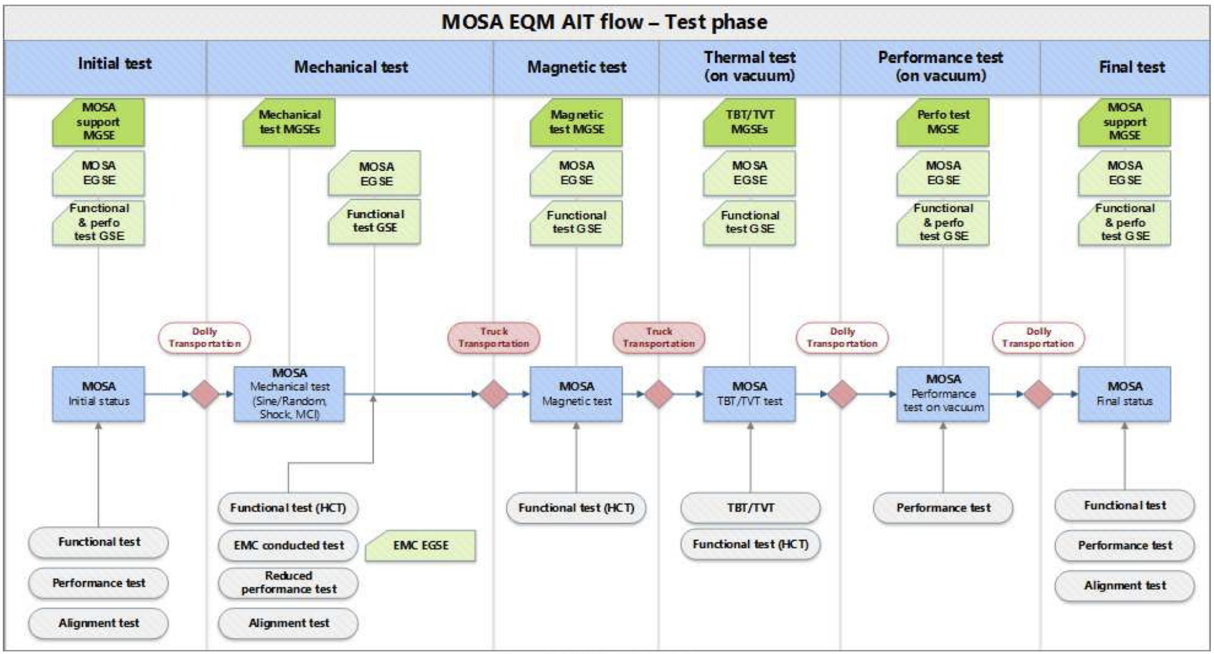


Figure 6: MOSA EQM test phase

Figure A-3 - Proposed testing steps for the Engineering and Qualification Model of the LISA instrument.

Unlike most of the scientific space-borne instruments, the AIVT process should be somehow ‘serialized’ since the model philosophy chosen for LISA implies the integration of 10 MOSAs, including 1 engineering model, 6 (proto)flight models and 2 flight spares. The GSEs (including the ones used for performance testing) shall therefore be robust, reliable and sufficiently ‘easy to operate’, so that they can be used in a semi-automated way for the (proto)flight and spare models.

Appendix 4 - Technical expertise of IN2P3 labs

The three deliverables (DDPC, performance model, MOSA AIVT) have as a common requirement a deep understanding of the system, from the instrument's secrets to the subtleties of data analysis. For successful completion of these tasks it is necessary to combine various engineering and scientific skills (mechanics, electronics, optics, data process science, metrology, etc.).

The IN2P3 has a long history of building and exploiting large and complex instruments, from particle accelerators to ground based GW detectors. More recently, the IN2P3 has also been involved in the development of space-based instruments (e.g. with Planck, Euclid, SVOM, TARANIS, etc.). From these experiences, the IN2P3 has developed renown skills in managing large projects and system engineering. These competences will be especially important when developing the ground support equipment for the MOSA AIVT, as well as the data analysis pipelines and computing infrastructures required by the DDPC.

The following IN2P3 laboratories and platforms involved in LISA are bringing their expertise and experience to LISA:

- CC-IN2P3:
  The CC-IN2P3 ("Centre de Calcul de l'IN2P3") is the National Computing Centre of IN2P3. It is a CNRS Service and Research Unit with a staff of 80 people, including 60 high level computing engineers. CC-IN2P3 operates the largest computing center in France dedicated to data processing. It provides computing and storage services for scientific research needs, mainly in the field of High Energy Physics. More than 4000 users working within 70 international experiments use its services. As a Tier1 for LHC experiments, it has contributed to many of the major EGEE and WLCG projects. It plays a central role in the operation of the GRID and Clouds at national (France-Grilles) and international levels (via the EGI-Engage and INDIGO-DataCloud projects). Its expertise is very valuable in the development of the French deliverables to the LISA mission and scientific exploitation of its data.

- LMA/IP2I: :
  The LMA has a long expertise in optical coatings and straylight analysis. The LMA is already a major contributor to the VIRGO/LIGO project and, e.g., the coating of the massive input and end mirrors. The LMA is involved in LISA France since 2016 as an IN2P3 research lab, and since 2019 as an IN2P3 National Platform of IP2I.
  The coating and straylight expertise of LMA was first used in 2017 during the studies following an ITT (Invitation to Tender) of ESA (about the Metrology Telescope Design) with Thales Alenia Space (TAS) Italy, ARTEMIS, APC. Then LMA has continued to be involved in several working groups on Straylight (SLWG) in LISA France with ARTEMIS and APC or at the European level in the SLWG with AEI Hannover, ARTEMIS, APC...

- APC:
  The very reason for the creation of the 'AstroParticule & Cosmologie' in 2005 was to gather the various expertise involved in the study of particle and fundamental physics (incl. GW) using astrophysical phenomena. The science groups 'Gravitation' and 'Theory' are particularly involved in LISA, with also connexions with the 'High Energy' group. Instrumental development can also be efficiently supported by its technical departments (mechanics, electronics, informatics, instrument science). In LISA, the APC contributes with a very broad range of expertise in different specific fields, such as fundamental physics, astrophysics, system engineering, optics instrumentation, space engineering, AIVT, data science, quality and product assurance. …
  Over the years, the APC has contributed to different space missions, in data analysis as well as hardware development: Planck, TARANIS, SVOM, Integral, Euclid, Athena, … and of course LISA Pathfinder. This experience is extremely valuable and crucial for the implication of the APC within LISA.

- CPPM:
    - *Strong experience in ESA/CNES space projects and associated activities*
      CPPM has been involved in space projects since the start of the years 2000 through cosmology with the SNAP project, a DOE-NASA funded project which eventually got abandoned. Thereafter, as early as 2008, CPPM got involved in the Euclid project, a class M ESA mission. CPPM has provided a very strong contribution to Euclid with some 15 FTE over several years. Activities cover various aspects:
        - Characterization of the IR detectors of the NISP spectrophotometer
        - Development of the control-command of the test benches in collaboration with IP2I (characterization test bench at CPPM and AIVT instrument test bench at LAM)
        - AIVT of the NI-DS (Detector System) sub-system as well as the NISP instrument
        - Instrument model of the NISP
        - Pipeline (SGS) including simulation of the NISP response

      More recently, CPPM has committed to the SVOM project with a smaller contribution which covers IR detector characterization activities as well as pipeline development for the ground follow-up telescope Colibri, being built in San Pedro Martir, Mexico, in the framework of the OCEVU LabEx.

    - *Science expertise*
      CPPM researchers involved in LISA are also strongly involved in space projects with a launch in the near future: Euclid for cosmology and SVOM for detection of gamma ray bursts in an overall multi-messenger analysis. This multi-messenger approach is enriched by other experiments to which CPPM directly contributes, namely: HESS and CTA for gamma astronomy; ANTARES and KM3NeT for neutrino astronomy. Leading roles played in many particle physics experiments at the energy and intensity frontiers quite naturally connect CPPM with the fundamental physics aspects that LISA will be able to explore.

- LPCC:

  Our group participates to the LDPG focusing on the design and construction of the LISA Distributed Data Processing Centre (DDPC) and some of its components. Based on our experience from particles physics group, we are workin on setting up the common software tools that will be used by the LISA Consortium: software development framework, continuous integration, coding templates and standards, design of the data processing pipeline(s).

  We have a long experience in large scale computing, simulation and data processing management, both at system and science levels. We utilize the LISA Data Challenge tools, set up and results to prototype the environment and architecture.

- L2IT:

  The L2IT (Laboratoire des deux infinis de Toulouse) is a newborn laboratory, created in 2019. Its implication into LISA started in september 2019 with the recruitment of C. Buy, optical engineer, previously working at the APC. The L2IT is officially member of the LISA Consortium since early 2020. Its contribution is therefore centered on the coordination of optical simulations, for the future test benches for the MOSA characterization, as well as their prototypes and on straylight simulations within the Consortium straylight working group. Because of its geographical proximity, dedicated collaborations on LISA have been set up with the CNES. With the recent recruitment of a research director, the L2IT will get actively involved in the LDPG (LISA Data Processing Group) and LSG (LISA Science Group) in the near future.

Appendix 5 - A short story of LISA

LISA was selected in April 2017 as the third large mission of the European Space Agency, with a foreseen launch in 2034/2035. The history of LISA however started much earlier. The first mission concepts proposed for detecting GW from space were studied at NASA as early as 1974. The instrument was based on the deployment, in orbit, of a rigid structure with 1 km long armlength. This concept was soon replaced (in 1980) by 3 distant satellites exchanging lasers to form a Michelson interferometer with 1 Mkm armlengths, i.e. already close to the present design of LISA.

Since then, LISA underwent many feasibility studies, raising progressively its technology readiness level. In early 1990, LISA was first proposed (with this name) to ESA as a M3 mission, and later on selected as the third 'cornerstone' mission of the Horizon 2000 Plus program (together with Gaia). In 1997, LISA became a joint mission with NASA, with a launch foreseen in the first decade of 2000 to benefit from simultaneous observations with ground-based detectors.

In 2000, LISA was proposed as the first Large mission (L1) of the new 'Cosmic Vision (2015-2025)' program of ESA. In the same timeframe, a technology demonstrator (SMART-2) for drag-free and formation flying was proposed and selected. The formation flying demonstration was later cancelled and SMART-2 became LISA Pathfinder.

Because of budget limitations (partly due to the re-estimated cost of the JWST), NASA cancelled its participation in the three large missions of ESA. The ESA decided to continue on its own budget but this required to reduce the cost of the LISA mission and led to the *evolving LISA* concept (eLISA) with only two, shorter interferometric arms. The scientific theme 'the Gravitational Universe' was then selected in October 2013 by ESA for the L3 slot with eLISA as a strawman mission. In the following years, NASA expressed its interest to participate in the mission as a junior partner. Its contribution 'brought back' the third interferometric arm and LISA was selected by ESA in April 2017 under its original name and present configuration as the third large mission of the Cosmic Vision program.

Appendix 6 - Project evaluation in the IN2P3 laboratories

We give hereafter the recommendations given to the LISA activities in IN2P3 laboratories by various evaluation committees. The full reports are available for download here: https://mycore.core-cloud.net/index.php/s/50TGDX2w8WP4o4D. We give hereafter some excerpts concerning LISA.

- at APC :
  APC Scientific council recommendations, March 2020:
  “

  APC is traditionally involved in gravity and in gravitational wave (GW) research with Earth-based and Space detectors and should keep its leading role now that GW has become a truly new messenger.

  In the 2017 report the committee said that ‘in gravity and gravitational waves the opportunity of expansion is obvious considering the key role occupied by APC in LISA and the synergy with VIRGO, theory and with SVOM and ATHENA projects for the MM aspect. In the future the resources of the gravity group have to be expanded more than the other groups.

  The committee maintains the priority of expanding this sector.

  The committee recommends high priority for the activity in the new phase of Advanced VIRGO+. APC is committed to LISA and the position of this group is well in line with their strong know-how and should not be reduced. There are synergies with the HEA projects but the positioning of APC in LISA should have priority, considering that HEA is more distributed among French laboratories. The involvement of APC in the Einstein Telescope (ET), the European third generation Earth-based detector, has also to be considered of the highest interest but the development of ET should be harmonised with the commitment on LISA, especially in terms of the relative expansion with respect to the other science groups.
  ”

HCERES report on the Gravitation group at APC, April 2018:
“

Assessment of scientific outputs, reputation and appeal:

As the leading French Lab for LISA, and one of the major contributors to VIRGO analyses, the overall contributions by APC are excellent.

[...]

Assessment of the scientific strategy and projects:

The choice of the projects is strategically excellent. The plans for their implementation carry significant risk.

[...]

Recommendations on scientific strategy and projects:

The long-term effect of the loss of the LISA co-PI should be monitored, and the group should be supported to maintain its reputation.

[...]

The role in LISA hardware is still poorly defined and should be monitored. The lack of a solid leadership role on some critical aspect of the mission hardware may weaken the position of the team within the collaboration.
”

Rapport sur la visite ‘tourniquet’, novembre 2017:
“

Ainsi, le groupe gravitation de l’APC est impliqué dans deux projets majeurs d’astronomie des ondes gravitationnelles. Il couvre les développements instrumentaux (l’APC est équipé d'une vaste salle blanche accueillant des projets de R&D d'instrumentation optique associés à Virgo et LISA), la construction hardware, le développement de logiciels et d'infrastructures de calcul, l'analyse des données et les aspects théoriques. Les membres de l'équipe sont également actifs dans la dissémination des résultats en conférences, workshops, et auprès du grand public. Le groupe a acquis une visibilité dans le domaine, son expertise est reconnue, et les perspectives de développement de ces programmes sont évidentes. Le groupe regrette que la communauté en France s'intéressant aux ondes gravitationnelles reste encore limitée. À l'IN2P3 seuls deux laboratoires (l'APC et le LMA) participent à LISA, même si d'autres laboratoires ont exprimé récemment un intérêt. Les physiciens de l'équipe LISA, qui travaillent au quotidien avec des informaticiens de l'APC dans les locaux de la plateforme FACe, s'inquiètent des conséquences de son déménagement et de sa réorganisation, le lien fort avec l'équipe informatique pourrait en particulier être compromis.

”

APC Scientific council report, November 2017:

“

In gravity and gravitational waves the opportunity of expansion is obvious considering the key role occupied by APC in LISA and the synergy with VIRGO, theory and with the SVOM and ATHENA projects for the multi messenger aspect. In the future the resources of the gravity group have to be expanded more than in other groups.

[...]

The level of technical resources has been stable, but not sufficient to support the ambitions of the scientific program. It should be noted that APC has the lowest ratio of engineers to researchers in IN2P3. It is partly alleviated by the recruitment of non-permanent technical staff, but this introduces continuity problems and the danger of loss of expertise. Complementary contributions between the CNES CST and the laboratory technical departments on space projects could also alleviate the burden (eg. in ATHENA and LISA). Recruitment of instrumentalists in permanent positions would tighten the link between the researchers and technical departments.

“

- at LMA/IP2I:
  The implication of some LMA engineers in LISA was mentioned and discussed since 2017 in the IN2P3 EAOM (Entretien Annuel Objectif Moyen) and IN2P3 direction has always seen and supported this involvement as a positive point.

- at CPPM:
  The current activity of CPPM members in LISA is considered so far by CPPM management as an R&D effort in preparation of a future full commitment. The activity is reviewed regularly at CPPM through the internal Project Advancement Review process and, as far as photodiode characterization is concerned, it has also been reviewed by the CPPM Scientific Council in the context of CPPM's IR platform, resulting in very positive recommendations. As such it is officially supported (access to technical staff power) by CPPM management. It is planned to have a full fledge review at the CPPM Scientific Council before committing for the phase B2 of LISA.

Appendix 7 - List of publications 2016 - 2020

We list hereafter the LISA publications between 2016 and 2020, with at least one member of an IN2P3 lab as co-author.

1. Contaldi, C. R. *et al.* Maximum likelihood map making with the Laser Interferometer Space Antenna. *Phys. Rev. D* **102**, 043502 (2020).
2. Barausse, E. *et al.* Prospects for fundamental physics with LISA. *General Relativity and Gravitation* **52**, 81 (2020).
3. Katz, M. L., Marsat, S., Chua, A. J. K., Babak, S. & Larson, S. L. GPU-accelerated massive black hole binary parameter estimation with LISA. *Phys. Rev. D* **102**, 023033 (2020).
4. Toubiana, A., Marsat, S., Babak, S., Barausse, E. & Baker, J. Tests of general relativity with stellar-mass black hole binaries observed by LISA. *Phys. Rev. D* **101**, 104038 (2020).
5. Caputo, A. *et al.* Gravitational-wave Detection and Parameter Estimation for Accreting Black-hole Binaries and Their Electromagnetic Counterpart. *ApJ* **892**, 90 (2020).
6. Armano, M. *et al.* Spacecraft and interplanetary contributions to the magnetic environment on-board LISA Pathfinder. *MNRAS* **494**, 3014–3027 (2020).
7. Abramowicz, M., Bejger, M., Gourgoulhon, É. & Straub, O. A Galactic centre gravitational-wave Messenger. *Scientific Reports* **10**, 7054 (2020).
8. Tamanini, N., Klein, A., Bonvin, C., Barausse, E. & Caprini, C. Peculiar acceleration of stellar-origin black hole binaries: Measurement and biases with LISA. *Phys. Rev. D* **101**, 063002 (2020).
9. Sesana, A., Lamberts, A. & Petiteau, A. Finding binary black holes in the Milky Way with LISA. *MNRAS* **494**, L75–L80 (2020).
10. Caprini, C. *et al.* Detecting gravitational waves from cosmological phase transitions with LISA: an update. *JCAP* **2020**, 024 (2020).
11. Chua, A. J. K., Korsakova, N., Moore, C. J., Gair, J. R. & Babak, S. Gaussian processes for the interpolation and marginalization of waveform error in extreme-mass-ratio-inspiral parameter estimation. *Phys. Rev. D* **101**, 044027 (2020).
12. Caprini, C. *et al.* Reconstructing the spectral shape of a stochastic gravitational wave background with LISA. *JCAP* **2019**, 017 (2019).
13. Calcagni, G. *et al.* Gravitational-wave luminosity distance in quantum gravity. *Physics Letters B* **798**, 135000 (2019).
14. Lacour, S. *et al.* SAGE: finding IMBH in the black hole desert. *Classical and Quantum Gravity* **36**, 195005 (2019).
15. Calcagni, G. *et al.* Quantum gravity and gravitational-wave astronomy. *JCAP* **2019**, 012 (2019).
16. Thorpe, J. I. *et al.* Micrometeoroid Events in LISA Pathfinder. *ApJ* **883**, 53 (2019).
17. Armano, M. *et al.* Novel methods to measure the gravitational constant in space. *Phys. Rev. D* **100**, 062003 (2019).
18. Armano, M. *et al.* LISA Pathfinder Performance Confirmed in an Open-Loop Configuration: Results from the Free-Fall Actuation Mode. *Phys. Review Letters***123**, 111101 (2019).
19. Armano, M. *et al.* Temperature stability in the sub-milliHertz band with LISA Pathfinder. *MNRAS* **486**, 3368–3379 (2019).
20. Armano, M. *et al.* LISA Pathfinder micronewton cold gas thrusters: In-flight characterization. *Phys. Rev. D* **99**, 122003 (2019).
21. Bayle, J.-B., Lilley, M., Petiteau, A. & Halloin, H. Effect of filters on the time-delay interferometry residual laser noise for LISA. *Phys. Rev. D* **99**, 084023 (2019).
22. Armano, M. *et al.* LISA Pathfinder platform stability and drag-free performance. *Phys. Rev. D* **99**, 082001 (2019).
23. Armano, M. *et al.* Forbush Decreases and <2 Day GCR Flux Non-recurrent Variations Studied with LISA Pathfinder. *ApJ* **874**, 167 (2019).
24. Baghi, Q. S., Thorpe, J. I., Slutsky, J., Korsakova, N. & Karnesis, N. Extracting gravitational-wave sources from incomplete listening sessions with LISA. in *American Astronomical Society Meeting Abstracts #233* vol. 233 141.08 (2019).
25. Fitz Axen, M., Banagiri, S., Matas, A., Caprini, C. & Mandic, V. Multiwavelength observations of cosmological phase transitions using LISA and Cosmic Explorer. *Phys. Rev. D* **98**, 103508 (2018).
26. Armano, M. *et al.* Precision charge control for isolated free-falling test masses: LISA pathfinder

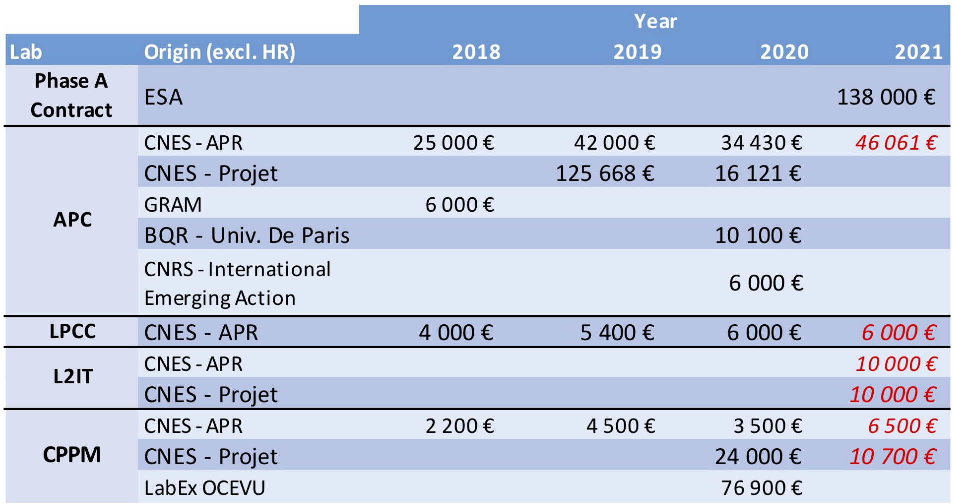
results. *Phys. Rev. D* **98**, 062001 (2018).

27. de Angelis, A. *et al.* Science with e-ASTROGAM. A space mission for MeV-GeV gamma-ray astrophysics. *Journal of High Energy Astrophysics* **19**, 1–106 (2018).
28. Caprini, C. & Figueroa, D. G. Cosmological backgrounds of gravitational waves. *Classical and Quantum Gravity* **35**, 163001 (2018).
29. Armano, M. *et al.* Measuring the Galactic Cosmic Ray flux with the LISA Pathfinder radiation monitor. *Astroparticle Physics* **98**, 28–37 (2018).
30. Armano, M. *et al.* Characteristics and Energy Dependence of Recurrent Galactic Cosmic-Ray Flux Depressions and of a Forbush Decrease with LISA Pathfinder. *ApJ* **854**, 113 (2018).
31. Armano, M. *et al.* Beyond the Required LISA Free-Fall Performance: New LISA Pathfinder Results down to 20 μHz. *Phys. Review Letters***120**, 061101 (2018).
32. Halloin, H. *et al.* LISA on Table: an optical simulator for LISA. in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* vol. 10565 105652Y (2017).
33. Grüning, P. *et al.* An electro-optical simulator of the space based gravitational wave detector Elisa. in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* vol. 10563 105635L (2017).
34. Armano, M. *et al.* Capacitive sensing of test mass motion with nanometer precision over millimeter-wide sensing gaps for space-borne gravitational reference sensors. *Phys. Rev. D* **96**, 062004 (2017).
35. Pieroni, M. Primordial GWs from universality classes of pseudo-scalar inflation. in *Journal of Physics Conference Series* vol. 840 012033 (2017).
36. Laporte, M. *et al.* Status of the LISA On Table experiment: a electro-optical simulator for LISA. in *Journal of Physics Conference Series* vol. 840 012014 (2017).
37. Halloin, H. Optimizing orbits for (e)LISA. in *Journal of Physics Conference Series* vol. 840 012048 (2017).
38. Cavet, C. *et al.* A proto-Data Processing Center for LISA. in *Journal of Physics Conference Series* vol. 840 012045 (2017).
39. Bonvin, C., Caprini, C., Sturani, R. & Tamanini, N. Effect of matter structure on the gravitational waveform. *Phys. Rev. D* **95**, 044029 (2017).
40. Bartolo, N. *et al.* Science with the space-based interferometer LISA. IV: probing inflation with gravitational waves. *JCAP* **2016**, 026 (2016).
41. Armano, M. *et al.* Constraints on LISA Pathfinder's self-gravity: design requirements, estimates and testing procedures. *Classical and Quantum Gravity* **33**, 235015 (2016).
42. Armano, M. *et al.* Sub-Femto-g Free Fall for Space-Based Gravitational Wave Observatories: LISA Pathfinder Results. *Phys. Review Letters***116**, 231101 (2016).
43. Nofrarias, M. *et al.* Optimal design of calibration signals in space-borne gravitational wave detectors. *Phys. Rev. D* **93**, 102004 (2016).
44. Inayoshi, K *et al* , Probing stellar binary black hole formation in galactic nuclei via the imprint of their center of mass acceleration on their gravitational wave signal, *Phys. Rev. D* **96**, 063014 (2017)

Appendix 8 - Human and financial resources on LISA

Laboratory	Name	Field / function	Qualif	Funding institute	Year							
					2018	2019	2020	2021	2022	2023	2024	2025
Researchers (permanent positions)												
APC	Stas Babak	Science, DDPC	DR	IN2P3	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5
	Chiara Caprini	Science	DR	IN2P3	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7
	Antoine Petiteau	coord. Consortium, science, DDPC,	MdC	Univ. Paris	0,6	0,6	0,8	0,6	0,6	0,6	0,6	0,6
	Eric Plagnol	Science	DR Emeritus	IN2P3	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5
	Danièle Steer	Science	Prof	Univ. Paris	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
	Hubert Halloin	Instrument, AIVT	MdC	Univ. Paris	0,4	0,4	0,5	0,5	0,5	0,6	0,6	0,6
	Eleonora Capocasa	Instrument, AIVT	MdC	Univ. Paris				0,2	0,2	0,2	0,2	0,2
L2IT	Nicola Tamanini	Science / DDPC	DR	IN2P3				0,7	0,7	0,7	0,7	0,7
LPCC	François Mauger	DDPC	Prof	Univ. Caen	0,2	0,2	0,25	0,3	0,3	0,3	0,3	0,3
	Yves Lemière	DDPC	MdC	Univ. Caen	0,2	0,15	0,15	0,4	0,4	0,4	0,4	0,4
LMA	Anne Ealet	Science	DR	IN2P3					0,1	0,1	0,1	0,1
CPPM	Eric Kajfasz	Science	DR	IN2P3		0,3	0,3	0,3	0,3	0,5	0,5	0,5
	Yannick Boursier	DDPC	MCF	AMU		0,1	0,1	0,1	0,1	0,1	0,1	0,1
	Damien Dornic	Science	CR	IN2P3		0,1	0,1	0,1	0,1	0,1	0,1	0,1
	Stéphanie Escoffier	Science	DR	IN2P3		0,1	0,1	0,1	0,1	0,1	0,1	0,1
				Sum researchers	3,2	3,75	4,1	5,1	5,2	5,5	5,5	5,5
				Incl. IN2P3	**1,7**	**2,2**	**2,2**	**2,9**	**3**	**3,2**	**3,2**	**3,2**
PhD and post-docs												
APC	Nikos Karnesis	DDPC/Science	Postdoc	CNES	1	1	0,7					
	Henri Inchauspe	DDPC/Science/perfo	Postdoc	CNES		0,1	1	1				
	Sylvain Marsat	DDPC/Science	Postdoc	IN2P3	0,15	0,6	0,45					
	Francis Fortin	Science	ATER	Univ. Paris		0,1	0,4					
	Etienne Savelle	Science	Postdoc	CNES			0,15	1	0,85			
	A. Mangiali	Science	Postdoc	IN2P3			0,25	1	0,75			
	Postdoc science/DA 1	Science/DA	Postdoc	CNES / IN2P3						1	1	1
	Jean-Baptiste Bayle	DDPC/Science/perfo	PhD	Univ. Paris	1	0,85						
	Matthieu Laporte	Instrument	PhD	CNES + Univ Paris	1	0,3						
	Alexandre Toubiana	Science	PhD	IN2P3	0,1	0,5	0,5	0,4				
	Pierre Auclair	Science	PhD	Ecole Polytechnique	0,15	0,7	0,7	0,55				
	Nam Quand Dam	DDPC/Science/perfo	PhD	IN2P3		0,15	1	1	0,85			
	Mikel Flaxa	Science	PhD	ANR			0,2	0,2	0,15			
	Léon Vidal	Instrument	PhD	CNES + Univ Paris		0,15	1	1	0,85			
	PhD Instrum 1	Instrument	PhD	CNES / Univ. Paris / IN2P3					0,15	1	1	0,85
	PhD Instrum 2	Instrument	PhD	CNES / Univ. Paris / IN2P3								0,15
	PhD science/DA 1	Science/DA	PhD	CNES / Univ. Paris / IN2P3				0,15	1	1	0,85	
	PhD science/DA 2	Science/DA	PhD	CNES / Univ. Paris / IN2P3					0,15	1	1	0,85
L2IT	Postdoc science 1	Science	Postdoc	IN2P3				0,25	0,75			
	PhD science 1	Science	PhD	Univ. Paul Sabatier				0,25	1	1	0,75	
CPPM	Adam Hawken	Science	Postdoc	ANR / AMU		0,2						
	PhD science	Science	PhD	CNES					1	1	2	1
	PhD science	Science	PhD	IN2P3					1	1	2	1
	Postdoc science	Science	Postdoc	CNES				1	1	**1**	1	1
				Sum PhD + Postdocs	3,4	4,65	6,35	7,8	9,5	8	9,6	5,85
				Incl. IN2P3	**0,25**	**1,25**	**2,2**	**2,65**	**3,35**	**1**	**2**	**1**
				Totlal researchers	6,6	8,4	10,45	12,9	14,7	13,5	15,1	11,35
				Incl. IN2P3	**1,95**	**3,45**	**4,4**	**5,55**	**6,35**	**4,2**	**5,2**	**4,2**
ITA (Permanent positions)												
APC	Maude Lejeune	Chef de projet DDPC	IR	IN2P3	0,4	0,5	0,9	0,5	0,5	0,5	0,5	0,5
	Cécile Cavet	Développement DDPC	IR	IN2P3	0,3	0,2	0,3	0,3	0,3	0,3	0,3	0,3
	Martin Souchal	Infrastructure informatique	IE	Univ. Paris	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
	BOUCAUD Alexandre	Développement DDPC	IR	IN2P3		0,05	0,05	0,2	0,2	0,2	0,2	0,2
	IR LISA DDPC - recrut en cours	Développement DDPC	IR	IN2P3			0,05	0,8	0,8	0,8	0,8	0,8
	MARTINO Joseph	Modèle Performance - Simulations	IR	IN2P3	1	1	1	1	1	1	1	1
	ZERGUERRAS Thomas	Chef de projet ZIFO	IR	IN2P3		0,6	1	1	1	0,8	0,7	0,7
	BARONICK Jean Pierre	Ingénieur mécanique	IE	IN2P3		0,5	0,1					
	BERTOLI Walter	Ingénieur mécanique	IR	IN2P3			0,2	0,2				
	DHELLY Stéphane	Mecanicien	T	IN2P3			0,2	0,1	0,1	0,1	0,1	0,1
	JUFFROY Corinne	Ingénieur qualité	IR	IN2P3			0,3	0,3	0,3	0,3	0,3	0,3
	PRAT Pierre	Ingénieur électronique analogique	IR	IN2P3	0,3	0,2	0,5	0,7	0,7	0,5	0,5	0,5
	MONIER Guy	Cableur	T	IN2P3	0	0,1	0,3	0,3	0,2		0,2	0,2
	BREELE Eric	AIVT	IR	IN2P3	0,6	0,5	0,3	0,3	0,3	0,3	0,3	0,3
	BUY Christelle	Chef de projet / Ingénieur Optique	IR	IN2P3	0,7	0,7						
	IR CNRS (demande recrutement)	Ingénieur optique	IR	IN2P3					0,4	0,5	0,5	0,5
	IR CNRS	Ingénieur Mécanique	IR	IN2P3				0,2	0,5	0,5	0,5	0,5
	AI CNRS	Assistant Ingénieur CAO Mécanique	AI	IN2P3				0,2	0,2	0,2	0,2	0,2
	IR CNRS	Développement DDPC	IR	IN2P3								0,8
L2IT	BUY Christelle	Ingénieur optique	IR	IN2P3			0,65	0,65	0,65	0,65	0,65	0,65
	CLEDASSOUS Rodolphe	Ingénieur	IR	IN2P3			0,05	0,05	0,05	0,05	0,05	0,05
	IR CNRS (demande recrutement)	Développement DDPC	IR	IN2P3				0,1	1	1	1	1
LPCC	HOMMET Jean	DDPC	IR	IN2P3	0,2	0,2	0,25	0,3	0,3	0,3	0,3	0,3
LMA	Laurent Pinard	Ingénieur optique / couches minces	IR	IN2P3	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
CPPM	Aurélia Secroun	Chef de projet / Instrumentation	IR	IN2P3		0,3	0,3	0,3	0,5	0,5	0,5	0,5
	Jérôme Royon	Ingénieur Électronique	IE	IN2P3		0,2	0,8	0,8	0,8	0,8	0,8	0,8
	Stéphan Beurthey	Ingénieur Mécanique	IR	IN2P3		0,1	0,1	0,1	0,1	0,1	0,1	0,1
	Fabrice Gallo	Assistant Ingénieur Mécanique	AI	IN2P3		0,1	0,1	0,1	0,1	0,1	0,1	0,1
	Luz Guevara	Ingénieur Informatique Instrumentale	IR	IN2P3			0,2	0,8	0,8	0,8	0,8	0,8
	Julien Zoubian	Ingénieur Informatique	IR	IN2P3			0,1	0,1	0,1	0,1	0,1	0,1
	IR CNRS (demande recrutement)	Ingénieur Instrumentation	IR	IN2P3					0,2	0,2	0,2	0,2
				Sum ITA	3,7	5,45	7,95	9,6	11,3	10,8	10,9	11,7
				Incl. IN2P3	**3,6**	**5,35**	**7,85**	**9,5**	**11,2**	**10,7**	**10,8**	**11,6**
ITA (short term contracts)												
APC	LILEY Marc	Développement DDPC	CDD IR	CNES	1	0,5	-	-	-	-	-	
	BATMANABANE Mylène	Développement DDPC	Apprentice	IN2P3+CNES	0,25	0,25	0	0	0	0	0	0
	LAUPIN VINATIER Alain	Développement DDPC	CDD IE	CNES		0,7	0,3 -	-	-	-	-	
	VAN DE WALLE Aymeric	Ingénieur Optique	CDD IR	CNES		0,2	1	0	0	0	0	0
	CDD IR CNES (recrutement en cours)	Ingénieur Optique & AIVT	CDD IR	CNES				1	0	0	0	0
	CDD IR CNES	Ingénieur Instrumentaliste	CDD IR	CNES					1	1	1	1
	CDD CNES LISA	Développement DDPC	CDD IR	CNES			0,2	1	0,8			
	CDD CNES LISA	Développement DDPC	CDD IR	CNES					0,2	1	1	1
	CORTAVARRIA Fabio	Projeteur mécanique	CDD AI	APC (RP)	0	0	0,4	0	0	0	0	0
CPPM	Mohamed Zayed	Ingénieur Instrumentation	CDD IE	AMU/OCEVU		0,1	1					
	CDD IR	Ingénieur Instrumentation	CDD IR	IPhU				0,2				
	CDD IR (besoin)	Ingénieur Instrumentation	CDD IR	??					1	1	1	1
	CDD IR (besoin)	Ingénieur Informatique Instrumentale	CDD IR	CNES					1	1	1	1
				Sum CDD ITA	1,25	1,75	2,9	2,2	4	4	4	4
				Incl. IN2P3	**0,25**	**0,25**	**0**	**0**	**0**	**0**	**0**	**0**
				Total ITA	4,95	7,2	10,85	11,8	15,3	14,8	14,9	15,7
				Incl. IN2P3	**3,85**	**5,6**	**7,85**	**9,5**	**11,2**	**10,7**	**10,8**	**11,6**
				Ratio CDD/Total ITA	25%	24%	27%	19%	26%	27%	27%	25%
				GRAND TOTAL	**11,55**	**15,6**	**21,3**	**24,7**	**30**	**28,3**	**30**	**27,05**
				Incl IN2P3	5,8	9,05	12,25	15,05	17,55	14,9	16	15,8

Table A-1 - Human resources on the LISA project in IN2P3 labs from 2018 to 2025. The foreseen/expected FTEs are given in red.



		Year			
Lab	**Origin (excl. HR)**	**2018**	**2019**	**2020**	**2021**
Phase A Contract	ESA				138 000 €
APC	CNES - APR	25 000 €	42 000 €	34 430 €	*46 061 €*
	CNES - Projet		125 668 €	16 121 €	
	GRAM	6 000 €			
	BQR - Univ. De Paris			10 100 €	
	CNRS - International Emerging Action			6 000 €	
LPCC	CNES - APR	4 000 €	5 400 €	6 000 €	*6 000 €*
L2IT	CNES - APR				*10 000 €*
	CNES - Projet				*10 000 €*
CPPM	CNES - APR	2 200 €	4 500 €	3 500 €	*6 500 €*
	CNES - Projet			24 000 €	*10 700 €*
	LabEx OCEVU			76 900 €	

Table A-2 - Financial resources on LISA since 2018. The red figures are the proposed amounts requested at CNES (APR and project funds) but not yet approved. Effectively, the allocated funds are expected to be much lower, due to surplus amount from 2020 foreseen travel expenses. The 'Phase A Contract' corresponds to the funds allocated by ESA to Consortium members states to support the Phase A activity.