Report to the IN2P3 Scientific Council – July 2023

The LISA mission in the IN2P3

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List of acronyms

AIVT	Assembly, Integration, Verification and Tests
BSim	Beams Simulator
CSGS	Consortium Science Ground Segment
DCC	Data Computing Center
DDPC	Distributed Data Processing Center
FFOGSE	Far Field Optical Ground Support Equipmentt
FTE	Full Time Equivalent
GB	Galactic Binary
GR	General Relativity
GRS	Gravitational Reference Sensor
GSE	Ground Support Equipment
GW	Gravitational Wave
IDS	Interferometric Detection System
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
OTS	Optical Tests System
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

The Science 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) fm.s^{-2} / Hz$^{1/2}$ above 2 mHz and (6 +/- 1) 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 inspiraling 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.

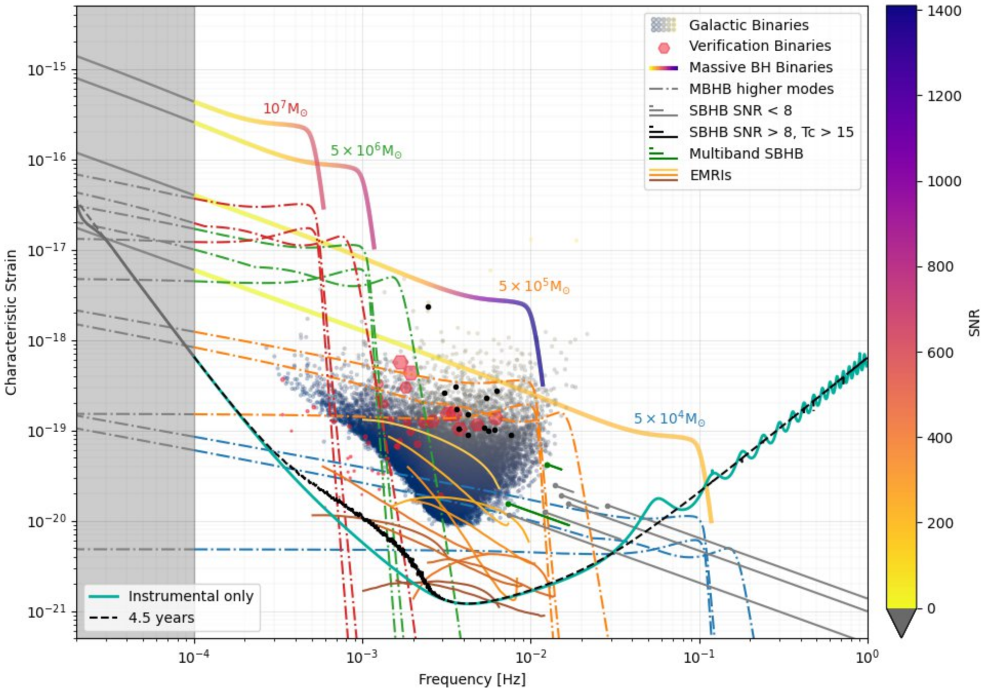


Figure 1 - Expected LISA's sensitivity curve (characteristic strain vs. frequency), and anticipated GW sources. Figure built as part of the Figure of Merit pipeline and used in the RedBook (LISA Definition Study Report)

Overview of the mission

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 million kilometers 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 (or heading) 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 12 years of constellation stability.

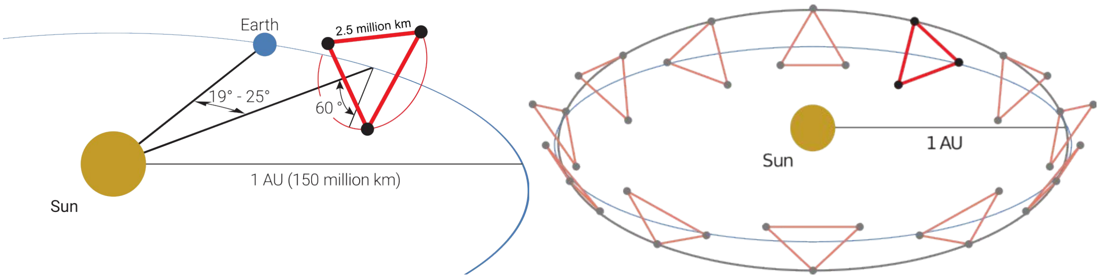


Figure 2 - LISA orbits around the Sun

Each S/C is floating around two free-falling test masses (TM), whose distances are monitored at the pm/√Hz level using classical laser 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.

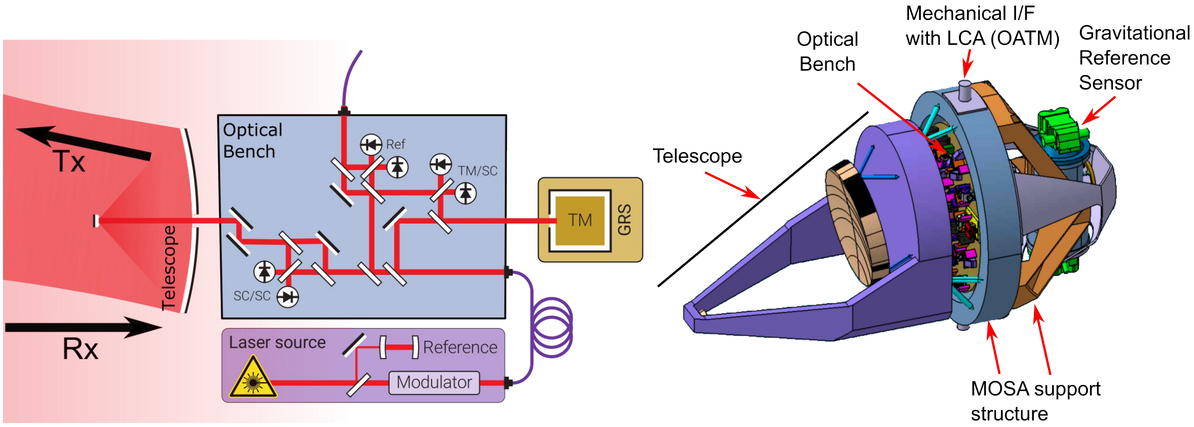


Figure 3 - Scheme of the MOSA onboard LISA

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).

General organisation of the LISA Project

The LISA mission is part of the ESA Cosmic Vision Program, involving many institutional and private partners. In addition to the ESA funded activities, the completion of LISA relies on the contributions from NASA and voluntary contributions from ESA member states.

ESA is more specifically in charge of :

- the project management of the whole mission and its in-orbit exploitation
- the design and manufacturing of the satellite's platform
- the design, manufacturing and integration of the payload (2 MOSAs per satellite), using the deliverables from NASA and ESA member states
- the development of the MOC (Mission Operation Center) and SOC (Science Operation Center), producing data at level L0 (fully reconstructed but unprocessed data) and L1 (fully calibrated, including TDI processing, data)

After the mission adoption, a Prime contractor will be chosen by ESA for on board developments (platform and payload integration). Meanwhile, two Prime candidates (Airbus Defence and Space and Thales Alenia Space) are working independently and concurrently to define a preliminary mission design and development plan.

NASA is a 'junior partner' to ESA in the development of LISA. It is in charge of :

- The telescope (emitting and receiving the laser beam)
- The UV discharge system for the test masses
- The frequency and power stabilised laser sources (the stabilisation cavity is an heritage from GRACE-FO)
- A scientific data processing center, complementary to the European DDPC, and producing L1 and L2 processed data.

The ESA member states are in charge of the following items :

- the **IDS** (Interferometric Detection System) which corresponds to the metrological core of the instrument. It consists of the fully integrated LISA Optical Bench (including mechanisms, photoreceivers, etc.), the acquisition phasemeter and representative laser sources and connecting harness (optical and electrical). The IDS is crucial to the LISA performance and should be validated as early as possible. France is in charge of testing the IDS at EM (engineering model) and first FM (Flight Model).
- the **OTS** (Optical Test System) which is a specific set of Optical Ground Support Equipment (OGSE) that shall be used by the Prime Contractor to characterize and tune the Qualification and Flight models at MOSA level. France in in charge of delivering the two 'complex' OGSEs : the Far Field OGSE (FFOGSE) and the Straylight OGSE (SLOGSE)
- the **GRS** (Gravitational Reference System), which consists of a vacuum tank enclosing the free floating tests mass and its associated monitoring and control electronics.

- the **SDS** (Science Diagnostics Subsystem), which consists of the different probes (temperature, magnetic field, radiations), required to correlate the scientific results with environmental conditions.
- the **DDPC** (Distributed Data Processing Center), which is the European scientific infrastructure producing L2 and L3 data. The development of the DDPC is under the responsibility of France, with contributions of other members states (e.g. by providing additional computing facilities).

This share of responsibilities is described on Figure 1, where the flags indicate the coordinating country on each item.

Figure 1 - Share of responsibilities between LISA partners.

On this figure, the French contributions are included in the LISA Consortium activities. The LISA Consortium is divided in different projects corresponding to the deliverables described above (GRS, IDS, OTS, SDS and DDPC), in addition to the P&O (Performance and operations) project, whose two main goals are to maintain a full instrumental model for the scientific performance evaluation and prepare flight operations (especially the instrument commissioning). Each of these project have a dedicated development and management plan. The necessary coordination between projects is performed at ESA and Consortium level (through the Formulation Management Team).

France, under CNES supervision, is directly in charge of two projects : the OTS and the DDPC. It is also a major contributor to the IDS (in charge of the integrated tests) and P&O. The share of responsibilities on the flight segment, resp. DDPC, is given on Figure 2, resp. Figure 3.

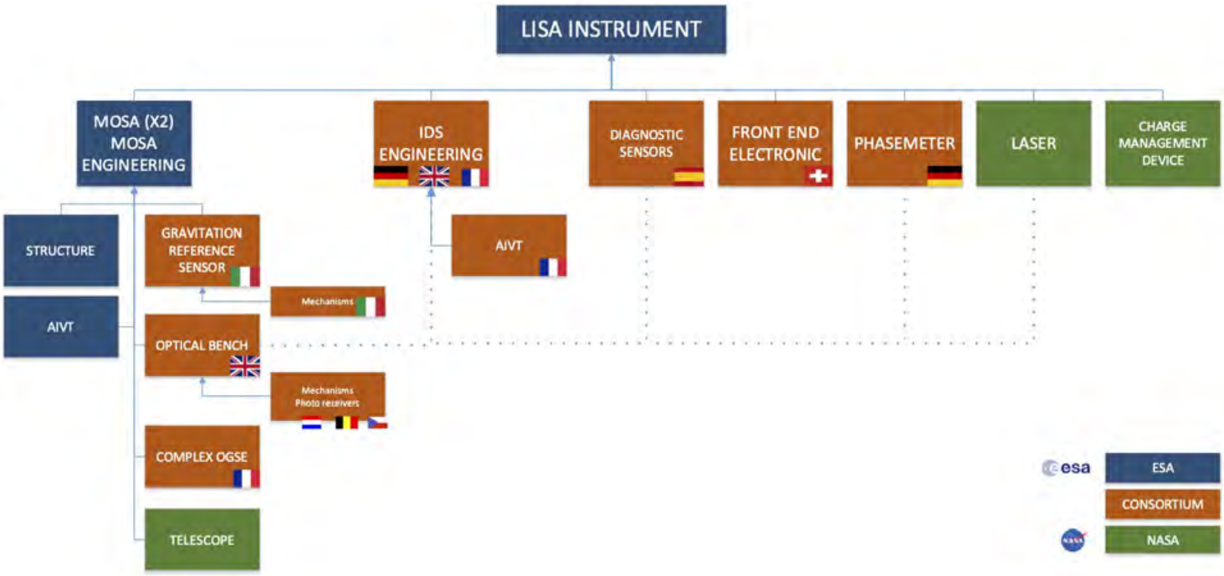


Figure 2 - Scheme of the contributions to the flight instrument. The dashed lines connects the elements of the IDS

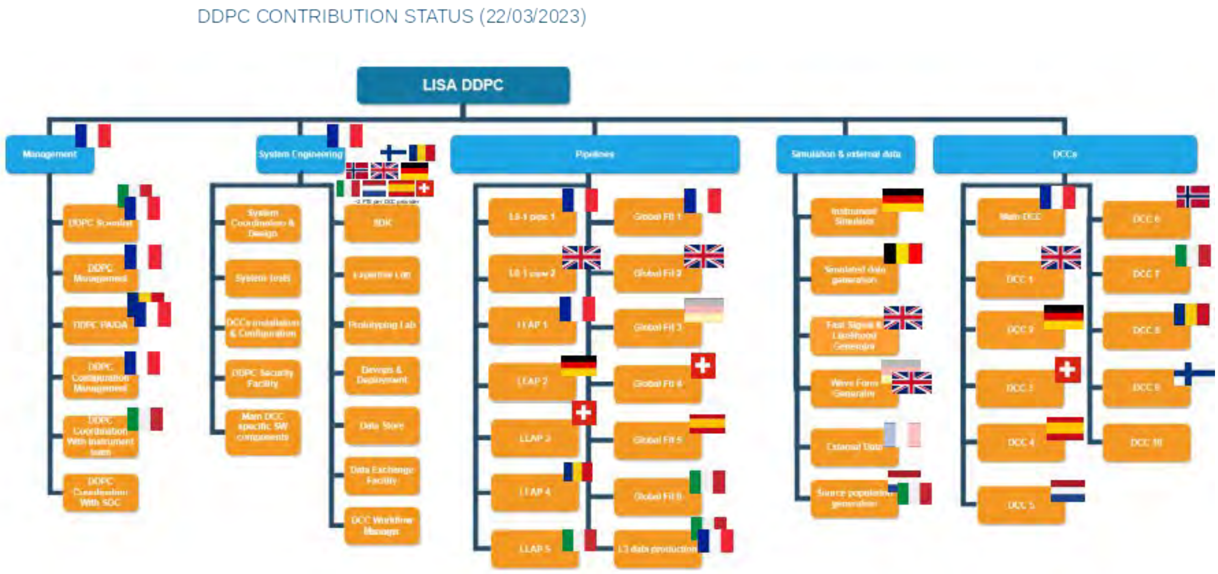


Figure 3 - Scheme of the contributions to the DDPC

Description of French deliverables and IN2P3 contributions

The French contributions to the LISA mission have been originally proposed by the scientific community. They have been approved and are now developed under the CNES supervision. Beyond the management tasks focused on the three main French deliverables (IDS, OTS and DDPC, as described above), CNES is also bringing expertise and supporting engineering activities either with internal human resources or by funding short term contracts in the laboratories.

CNES is also funding postdocs and PhD students to work on the preparation of the scientific exploitation of the mission.

Many French scientific institutes are interested and actively prepare the scientific exploitation of the LISA data. They also have major contributions to the completion of the deliverables. The following table summarizes the tasks addressed by the different French institutes contributing to LISA.

	Technology development	IDS	OTS	Performance and simulations	DDPC	Science
APC (CNRS-IN2P3)	X	X	X	X	X	X
ARTEMIS (OCA / CNRS-INSIS)	X	X	X		X	X
IRFU (CEA)	X	X	X	X	X	X
SYRTE (Obs. Paris-CNRS)	X	X	X	X	X	X
L2IT (CNRS-IN2P3)	X	X	X		X	X
CPPM (CNRS-IN2P3)	X	(X)				X
LAM (CNRS-INSU)	X					X
LMA/IP2I (CNRS-IN2P3)		(X)				
Institut Fresnel (CNRS-INSIS)	X					
Lagrange (OCA / CNRS-INSIS)					X	X
LPC Caen (CNRS-IN2P3)		(X)		X	X	X
IRAP (CNRS-INSU)					X	X
IAP (CNRS-INSU)						X
LPC2E (CNRS-INSU)						X
LUTH (Obs. Paris-CNRS)						X
IPhT (CEA / CNRS)						X

Table 1 - Contributions of French institutes to LISA

Beyond their contribution to LISA science, the IN2P3 laboratories contribute to :

- **Technology developments** : The design and manufacturing of complex optical ground support equipments (for the IDS, then for the OTS projects) require specific methods and technics of high stability interferometric metrology, which must be experimentally validated and mastered. The APC is more specifically in charge of the technology demonstrators MIFO (Metallic Interferometer) and ZIFO (Zerodur Interferometer) with important contributions from the CPPM and L2IT.
- **IDS (Interferometric Detection System)** : As already mentionned, the engineering and first flight model of the IDS shall be submitted to extensive functional and performance tests, starting end 2026. These tests require high performance (high stability) optical benches to simulate (and stimulate) the optical interfaces of the LISA optical bench. In this context and based on the experience form MIFO and ZIFO, the APC is in charge the 'Beams Simulator' (BSim), with contributions from the L2IT (optical modelling), and potentially the CPPM (lab control/command unit) and the LPCCaen (BSim handling devices and contribution to the control/command software). The LMA/IP2I is also foreseen as the provider of the critical optical coatings for the Beams Simulator (discussions are on-going with the industrial in charge of the Beams Simulator pre-design)
- **OTS (Optical Tests System)** : The APC and L2IT laboratories are presently working with the CNES to define the technical specifications of the FFOGSE (Far Field Optical Ground

Support Equipment), which will be used to characterize and tune the 6 MOSA Flight Models and the Qualification Model. The exact perimeter of this contribution shall be revised once the Prime Contractor is chosen (at mission adoption) and its verification strategy is known.

- **Performance and Simulations** : The APC and LPCCaen will contribute to the instrumental modelling, performance monitoring and scientific validation of the analysis pipelines. Their expertise in this field is based on their current design activities, especially through the development of the Figures of Merit pipeline (used to assess the scientific return of LISA based on current mission design and technical trade-offs) and their leading role in the development and management of the constellation performance model of LISA.
- **DDPC** : The APC and the L2IT have proposed to collaborate in developing a 'global fit' pipeline, i.e producing L3 data (source catalogues) from L2 (fully calibrated, corrected and 'cleaned' data streams). The APC is in charge of this deliverable, while the L2IT is bringing its expertise in the fast waveform modelling. The L2IT is also in charge, together with the IRAP laboratory, of the Work Package 'External Data'. In addition, the LPCCaen will contribute to the low latency pipeline, lead by the CEA/IRFU, as well as to the global fit for the characterization of the noise model and stochastic background.

The CNRS/IN2P3 (thanks to the CC-IN2P3) may also contribute to the data analysis challenge by providing computation resources (as main data processing centre) and/or by providing collaborative tools. An alternative scenario is presently under study where the main data processing centre would be provided by the CNES.

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. We focus hereafter on the LISA development plan since its selection as an ESA L3 mission in 2017 and main milestones and reviews foreseen until launch and operations.

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 2 summarizes the main milestones, as known today, of the LISA development at mission level.

Event	From	To	Comment
Phase 0 (Concept study)	Jul 2017	Nov 2017	Completed
Mission Definition review (MDR)	27 Nov 2017		Successful
Phase A (Feasibility study)	June 2018	Oct 2020	Completed
Mission Consolidation review (MCR)	22 Oct. 2019		Successful
Extended Phase A	Oct 2020	Dec 2021	Completed
Mission Formulation review (MFR)	End 2021		Successful
Phase B1 (Preliminary Definition with concurrent Prime Contractors)	Jan 2021	Dec 2023	On-going
Mission adoption review (MAR)	Nov. 2023		
Mission adoption (by ESA SPC)	Q1 2024		
Phase B2 (Preliminary Definition with a single Prime Contractor)	Q1 2024	April 2027	
Prime Contractor Kick-Off	Q4 2024		
Mission System Requirement Review	April 2025		
Mission Preliminary Design review	April 2027		
Phase C (Detailed Definition)	Q3 2027	Q4 2030	
Mission Critical Design review (CDR)	Jan. 2031		

Phase D (production and Verification)	Q1 2031	2035	
Flight Acceptance Review (FAR) and Launch	2034/2035		
Transfer & commissioning	2.5 years		
Operations	6 years		
Extended mission	Up to 4 years		10 years of total science mission

Table 2 - Major milestones in the LISA development schedule (at mission level)

A very important milestone is the mission adoption, with a review planned in December 2023 and a formal adoption by the Science Program Committee of ESA early 2024. Therefore, within the next months, the contributions of the member states shall be fully consolidated, each agency committing to fund and to provide instrument's subsystems (incl. the ground segment).

IDS and OTS development Plan

The development of the LISA Instrument (and associated projects, such as the IDS as described above) follow the same development logic but with early due date, so that the deliverables can be provided to the Prime Contractor in time to complete the satellite integration :

- Instrument System Requirement review (I-SRR) : June 2023
- Instrument Preliminary Design Review (I-PDR) : Q3 2025
- Instrument Critical Design Review (I-CDR) : Q1 2028

This instrument schedule applies in particular to the IDS project and sets the main milestones for the French contributions :

- IN2P2 Key Development Point 2 : 27th June 2023
- Interagency Committee : 13th July 2023
- Contribution review by the CNES board of directors : March 2024
- IDS GSEs milestones :
    - System Requirement Review (SRR) : June 2023
    - Preliminary Design Review (PDR) : Q4 2023
    - Interface Definition Keypoint : Q1 2024
    - Critical Design Review (CDR) : Q2 2025
    - Delivery of the final item to CNES : Q4 2025
    - IDS EM test campaign : Q1 2026 – Q1 2028
    - IDS FM1 test campaign : Q2 2028 – Q4 2029
- OTS / FFOGSE milestones :
    - Preliminary Requirements : December 2023
    - Specification & Interface Definition Update : Q2 2025
    - Preliminary Design Review (PDR) : Q4 2026
    - Critical Design Review (CDR) : Q2 2027
    - Delivery to Prime Contractor : Q2 2029

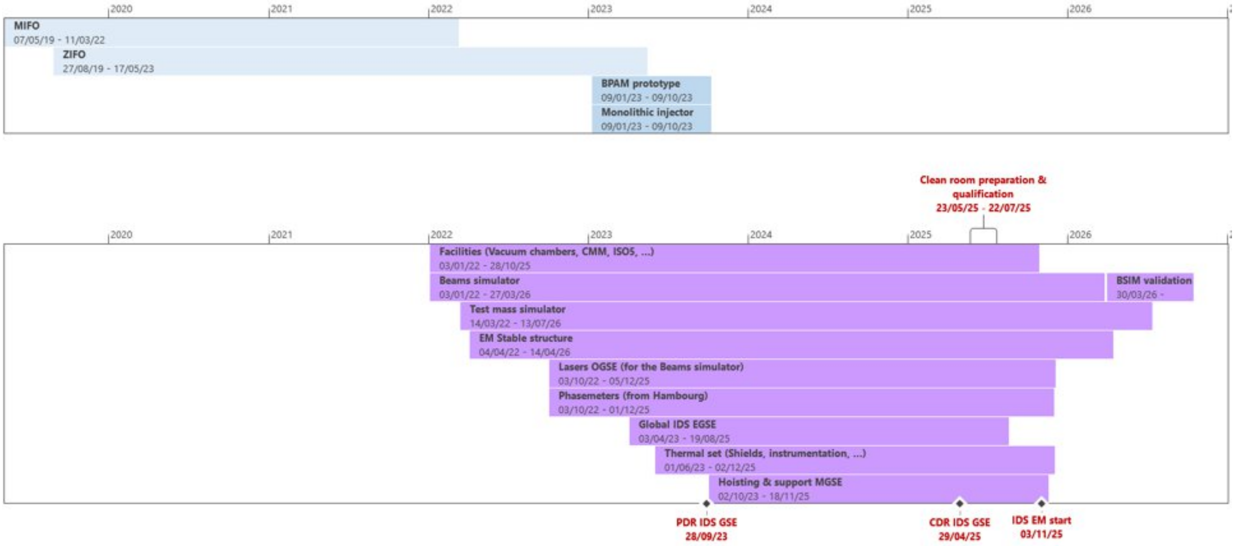


Figure 4 - Development schedule of the IDS GSEs. Top : Experimental demonstrators and prototypes. Bottom : IDS GSE development.

Figure 4 shows a more detailed view of the development schedule for the IDS Ground Support Equipment, with the different subsystems to be delivered. The IN2P3 laboratories (APC, L2IT, CPPM, LMA/IP2I and LPCCaen) are mostly involved in the development of the 'Beams Simulator' and Phasemeters.

DDPC Development Plan

Within the DDPC/LDPG activity, the main deliverables of phase A have been 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 has been consolidated and multi lateral agreement discussions have taken place to distribute the responsibilities with associated costs for adoption (end 2023). The demonstration of the feasibility of the data analysis have been made thanks to the organisation of dedicated LISA Data Challenges, for which conclusions are drawn in the redbook (LISA study report). During phases B2, C and D instrumental and software implementation and periodical releases 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 Computing Centres (DCC), 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.

Performance Model Development Plan

During phase B1, mission performance modelling activities supported ESA in establishing and justifying requirements for the various instrument systems delivered by the collaboration, the Prime and ground pre-processing pipelines. This involved several releases of the performance model containing the latest collaboration studies, as well as a tracing of each input to the ESA and CFI (Custome Furnished Items) specification documents.

This was backed up by risk analysis of constellation-level performance with regard to potential specification violations.

The same model development and performance monitoring activities for different instrument configurations (beginning of life, end of live, best estimate, etc.) will continue in phases C and D.

In addition, we will be carrying out extensive verification work using the time domain simulator, and monitor the results of ground test campaigns. This work will involve integrating the various existing software frameworks (simulation, performance constellation, ESA database, etc.) within the project as part of a common approach.

Phase D will focus mainly on operations and commissioning activities. Here is a list of planned activities during this phase:

- Support the development of the in-orbit commissioning plans
- Support the development of early science phase characterisation and optimisation experiments
- Support the development of routine maintenance operations
- Develop and operate constellation monitoring tools
- Develop data analysis tools for use in operations
- Perform simulations to support operational decisions and validate operational procedures

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. In the following sections, we emp~~a~~ha~~i~~size on the achievements since the last IN2P3 Scientific Council in October 2020.

Science topics

Extracting the science from LISA's observation requires research across several theoretical subjects integrated with the LISA data analysis. We use parametrized 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 accurate and fast-to-generate models of GW signals are essential part of LISA data analysis. 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. In addition, we are also working on a different branch of models, called phenomenological models, which are designed as a phenomenological ansatz which fits well numerical models and very fast to produce. In particular, we are extending the existing models by including orbital eccentricity.

Global fit will require a set of LISA data challenges to validate the performance and efficiency of the global fit pipeline as we progress. We utilize current astrophysical knowledge of the population of GW sources (expected event rate and distribution in parameter space) to produce the simulated data.

LISA will observe coalescing binaries which could still interact with gaseous environment. We evaluate the effect of the environment on the detectability and parameter estimation. We have considered extreme mass ratio inspirals embedded in the circumnuclear gaseous disk and found no loss in detection but significant biases in the parameter estimation. Embedding the stellar-mass binary in the accreting disk might lead to loss of these sources if environmental effects are not taken into account. Similarly, a possible presence of axion (ultra-light boson) clouds around black holes might need to be considered in modelling GW signals. While the main aim of the global fit is estimation of parameters assuming the vacuum GR solutions, we need to understand the limitations which it brings (the Universe is full of matter and GR is not the final stop) and design the analysis pipeline accordingly.

Even though our main activity will be connected to production of catalogues of GW sources, we always need to keep in mind that this is only the first step. We should continue developing methods (and incorporating into the data analysis infrastructure, e.g. observational selection biases) which allow us to infer astrophysical model of formation and evolution of various astrophysical populations, to infer cosmological parameters of the expanding Universe etc.

Detection of the stochastic GWs requires accurate subtraction of the resolvable deterministic signals. Any residuals due to mismodelling of GW signals could conspire as a stochastic signal leading to erroneous interpretation. In addition, detection of the stochastic GWs requires a good understanding of the instrumental noise. We parametrize and infer the noise model as a part of the global fit.

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 soon Euclid and DESI survey catalogs), 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.

In conclusion, scientific R&D is a necessary part of understanding the LISA data and has a significant impact on the design of LISA data processing pipeline.

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

Performance Modelling

Instrument performance modelling

Management of the performance model and releases to ESA were conducted by APC as co-lead of this activity over the phase A and B1 of the project. The performance model consists of a code capturing physical models of the interferometric measurement system, the residual test mass acceleration and the contribution of Time Delay Interferometry (TDI) and post-processing algorithms used by the ground segment to process data from L0 to L1. These models are combined to estimate the performance of LISA instrument at constellation level. The model is supported by a justification note summarizing the assumptions and the rationale behind all the sub-systems models and parameters values used. Moreover it provides a full traceability to the various requirements documents issued by ESA and the member states.

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…)
3. The propagation of Tilt-To-Length noise at constellation level accounting correlations between links due to Spacecraft Jitters.

During the phase B1, the main goal of performance model was to ensure that the Interface Requirements Documents issued to the various sub-systems (IDS, GRS, Telescope, Laser) were consistent in terms of performance at constellation level and that all inputs to our models were covered by a requirement. The release 2.3 of the constellation performance model delivered for the I-SRR is an assessment of constellation performance where all the inputs used in the model are linked to sub-system parameters at their requirements level. We also provide a framework to track and report performance risk by a systematic evaluation of any requirements violation on constellation performance. We have supported ESA in the flow-down of requirements from mission performance to requirements on the space segment and ground segment.

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

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. The operation and performance are in fact based on the scientific requirements aiming to achieve the main LISA's objectives. Figures of merit (FoM) are the link connecting mission duration, duty cycle and the noise model produced by "Instrument performance modelling" for a given LISA configuration as an input to evaluate the scientific performance of LISA and inform on whether we can achieve the main objectives. We use the "state-of-art" knowledge about the population of GW sources and the best models for GW signal in the analysis. We simulate the LISA data and assess detectability of sources (based on the signal-to-noise ratio) and parameter estimation of various sources (assuming the data analysis methods are efficient to identify those sources).

The metric is applied to each figure of merit and translates 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).

The set of tools developed for FoMs was essential in preparing the red book. All numerical evaluations were performed using FoM framework. We will continue to maintain these tools and extend/update as necessary. Together with Instrument performance modelling, these tools will be essential guide to what LISA can do up until we acquire actual measurements.

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

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.

Construction of a full data analysis pipeline is in progress but its completion will take several years. In the mean time, the proof of principal end-to-end data flow was suggested and tested, starting with simulation of a short segment of data that incorporates all currently modelled components of instrumental noise and a single GW signal. The data is passed through INREP and simplified version of the source detection algorithm. The complexity and realism of the simulated data will be gradually increasing and used in testing the DDPC.

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 has been used to prototype building catalogues of GW sources.

LDC-2a (Sangria) has been released in 2021, and closed on the 1st of December 2022. 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 altogether, and we have submitted complete set of results of the analysis (catalogs with posterior distributions) in due time. A preliminary assessment of the submitted results of all teams has been conducted and reported in the redbook for adoption.

LDC-2b (Spritz), released in 2021 too, is addressing the problem induced by the presence of instrumental artifacts like gaps, glitches and non-stationary noise in the data and their impact on the noise model. APC has produced this data set gathering contribution from the artifact working group, but has not been involved in the analysis.

LDC-1a (Yorsh) aims at completing Radler with up-to-date waveforms for 2 GW source types: EMRIs and stellar mass black holes and is in its final validation stage.

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

DDPC Architecture

During the Phase A/B1, the DDPC has been the subject of more and more complete studies feeding design and conceptual documents released for the Mission Formulation Review and Adoption Review. Technical architectural choices have been studied, along with scientific investigation linked to the LISA Data Challenges to get a first estimate of the computing power needed to tackle all stages of the data analysis. Following on design studies, a preliminary version of the WBS and PBS have been made to support multi-lateral agreement discussions, with the objective of getting a mapping of responsibilities and costing at the time of adoption. The contribution of APC and LPCCaen into this work has been significant, with a strong support provided by those labs to the CNES team, to ease their understanding of the science case, and data analysis ingredients.

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

DDPC Pipelines

The APC and the L2IT will collaborate in developing a 'global fit' pipeline (with APC lead), i.e producing the L2 data from the fully calibrate and pre-processed L1 data. L2 data contains all intermediate steps of the data analysis and several plausible solutions (recall that the number of sources and their parameters will be delivered in probabilistic manner). The second global fit pipeline will be designed by NASA. APC will be the main developer of the infrastructure and the data flows as well as participant in designing and testing analysis methods for each type of sources. L2IT is bringing its expertise in the fast waveform modelling and in detection of merging massive black hole binaries. Elements of the global fit designed jointly by APC, L2IT and LPCCaen will be propagated to the low-latency pipeline (lead by the CEA/IRFU). LPCCaen will contribute to the global fit in characterization of the noise model and stochastic GW background. Finally, validation of L2 results is in a very close connection with production of L3 data (catalogues of GW sources). L3 production is under responsibility of ARTEMIS/OCA with a very strong contribution from APC and L2IT.

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

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 coming phases should bring proper financial support and dedicated solutions, although not clearly defined yet. A consolidated cost has been requested to CCIN2P3 in order to evaluate the possibility of extending them. CNES might also play a bigger role in that respect,again with cost evaluation ongoing.

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

Instrument development

Since October 2020, the perimeter of the French contribution to the Instrument AIVT has evolved, to match the development strategy and schedule of the mission. The main evolution concerns the 2-steps approach to the verification of the instrument performance. The first step consists of the extensive testing of the IDS subsystem (as described above), at Engineering (EM) and first Flight Model (FM1) level. France is responsible for these tests, which shall be conducted in the CNES premises in Toulouse. The second testing step shall focus on acceptance characterization and instrument tuning at the MOSA level, in the Prime Contractor premises. France is responsible for the delivery of 2 complex OGSEs required for these tests (FFOGSE and SLOGSE, parts of the OTS project described above).

The development strategy of the IDS and OTS test benches can be summarized with the following steps :

- Technology demonstrator and prototypes : the MIFO and ZIFO benches enter this category, aiming at demonstrating the possibility to reach the desired performance on ground
- Design, manufacturing, tuning and exploitation of the IDS GSEs subsystems : the IN2P3 laboratories are mostly involved in the development of the Beams Simulator (BSim) and Phasemeter
- Detailed specifications and critical design choices for the OTS/FFOGSE : it is currently foreseen that the FFOGSE will be fully manufactured under the responsibility of an industrial architect, following the specifications and critical design choices given by the LISA team and based on the return of experience from the demonstrators and BSim.

Metallic and Zerodur Interferometers (MIFO/ZIFO)

The Metallic and Zerodur Interferometers (MIFO & ZIFO) are two interferometric optical benches sharing the same optical design (and some components). The MIFO is making use, as much as possible, of ‘on the shelf’ optical components and optics holders, mounted on a custom-made Invar baseplate. For the ZIFO, the optical components have been optically contacted on a Zerodur baseplate. In addition, the ZIFO comes with a iodine stabilized laser source, whereas the master laser source of the MIFO is free-running. The ZIFO is therefore expected to reach the ‘optimal’ stability which can be achieve on ground, whereas the MIFO validates the performance of some key elements (injectors, photoreceivers, phasemeters, command/control unit, etc.) and the full functional chain (including the analysis pipelines). Figure 5 gives a functional scheme of the MIFO/ZIFO design. The optical design was coordinated by the L2IT with a strong support of the APC. The overall system engineering tasks (including performance models and budgets, test plans, etc.) is led by the APC with significant contributions from all partners.

The design includes an equal arm interferometer ending on two quadrant photoreceivers. This interferometer serves as phase reference, rejecting initial relative phase noise between laser beams injected on the bench. The optical bench also hosts two symmetrical, unequal arm interferometers.These interferometers are used to distinguish common noise sources (e.g. laser frequency noise, homogeneous thermal expansion, etc.) from individual contributions. The two 1064 nm laser beams are generated and phase locked (with a frequency offset from 1 to 25 MHz) by a dedicated laser system. For the ZIFO, the master laser is phase locked on a frequency stabilized source (using an iodine cell). Four single element photoreceivers (2 in-loop, 2 out-of-loop) are used to monitor and lock the laser power.

The different subsusystems of the MIFO/ZIFO are under different responsibilities :

- The laser system : SYRTE/Obs. de Paris
- Fiber injectors : CEA/IRFU
- Populated optical baseplate : ***APC (for the MIFO***) and Winlight Systems (for the ZIFO)
- Thermal shield : LAM
- Phasemeters : ***APC*** (hardware) & CEA-IRFU (firmware)
- Photoreceivers : ARTEMIS/OCA (design, manufacturing and integration) & ***CPPM (Photodiode characterization)***
- Command & Control system : ***CPPM***

The MIFO has been designed,manufactured and integrated under the responsibility of the APC with an invar baseplate,commercial opto-mechanical components and subsystems provided by partners laboratories. . The MIFO has been tested in vacuum in the ***APC*** premises beginning 2022 (see Figure 6). As expected, the noise performance (defined as the residual phase noise between the unequal and the equal armlength interferometers) is limited by the laser frequency noise (unstabilized for the MIFO). The objectives of the MIFO were all fulfilled :

- Validation of the performance of the phasemeter (updated design from an original AEI design) [**APC** + CEA/IRFU]
- Successful development of ultra-stable fiber collimators [CEA/IRFU]

- Successful development of high-performance quadrant (and single element) photoreceivers [OCA/ARTEMIS]
- Full functional measurement and command/control chain [**CPPM**]
- Validation of the CMM-assisted integration procedure, with the required level of positioning accuracy [**APC**]
- Demonstration of a thermally stable environment better than 40 µK/√Hz (limited by the measurement system) above 1 mHz [**APC**].

The second step of the experimental demonstration is using the ZIFO, a zerodur bench with optically contacted components and following the same optical design. This bench was developped and integrated by a private company : Bertin/Winlight. The fully integrated bench was delivered to the LAM end 2022, where it was installed in the ERIOS vacuum chamber to achieve an environment representative of MOSA AIVT (see Figure 7). The test campaign has to be delayed because of anomalies detected on the laser sources and straylight issues. The tests are still on-going and shall be completed by end september 2023.

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.

This project is the opportunity for the French Gravitational Waves community to gather and deepen the skills necessary to design and operate ultra-stable interferometric benches 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

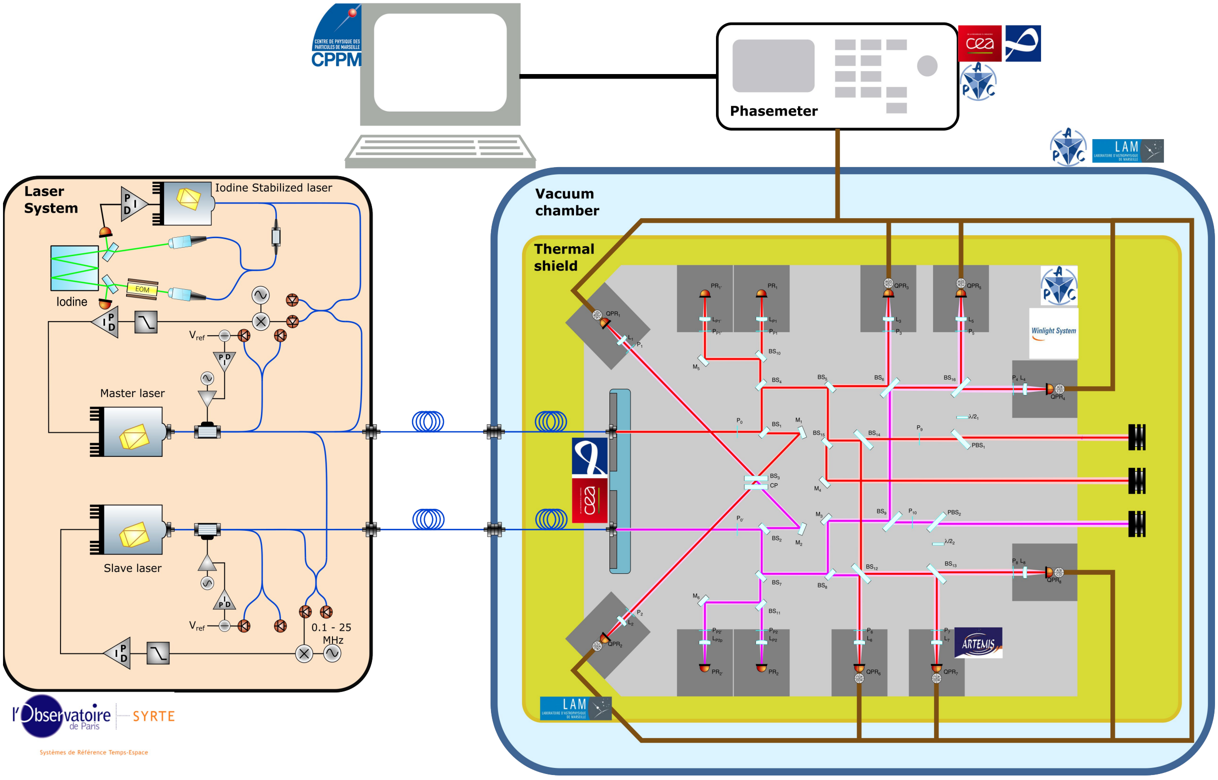


Figure 5 - Functional scheme of the MIFO/ZIFO demonstrator. Note : the iodine stabilisation is not present in the MIFO system.

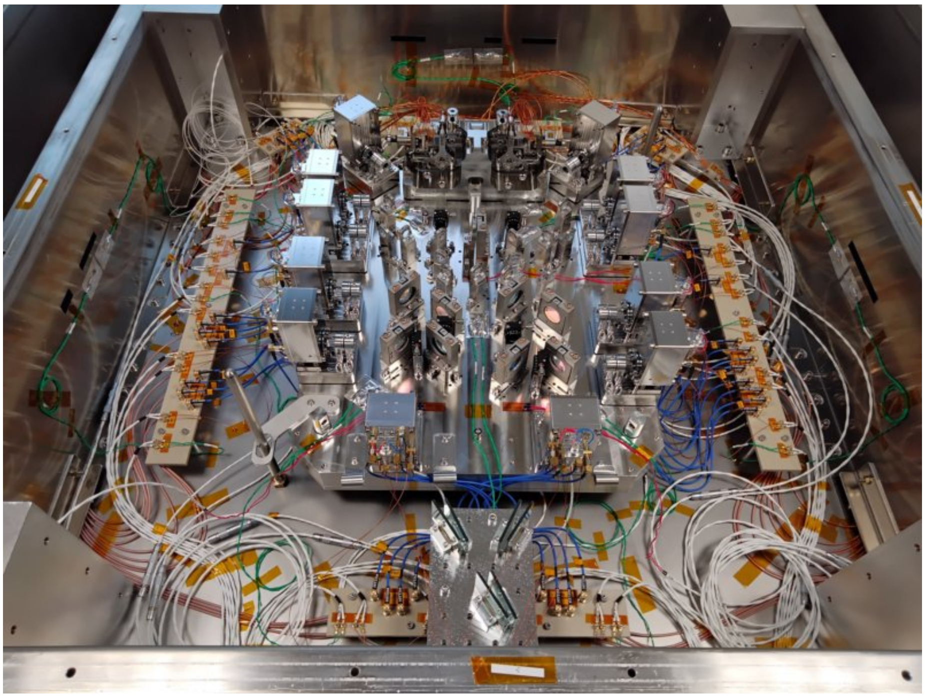


Figure 6 - MIFO bench in the vacuum tank during performance tests at the APC

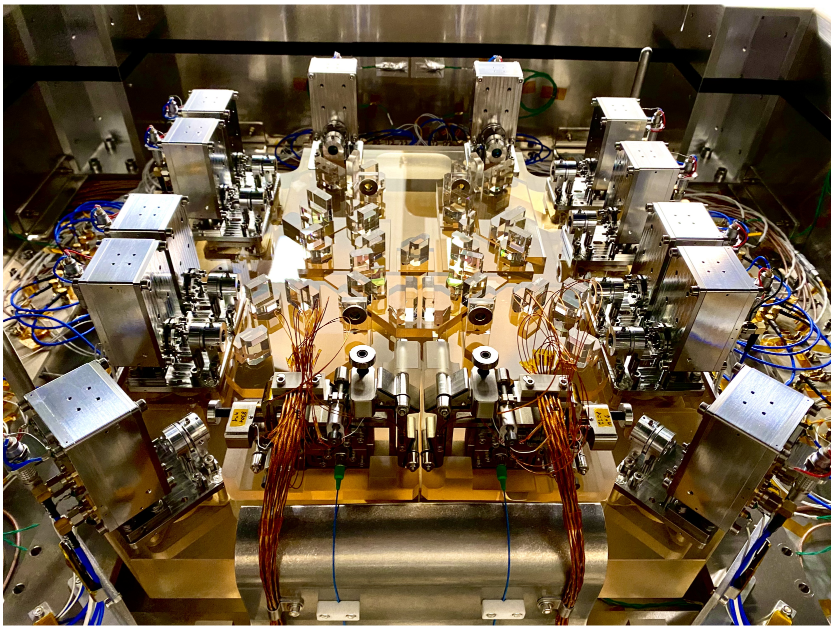


Figure 7 - ZIFO bench installed in the ERIOS vacuum chamber at the LAM

Development of the Beams Simulator for the IDS tests

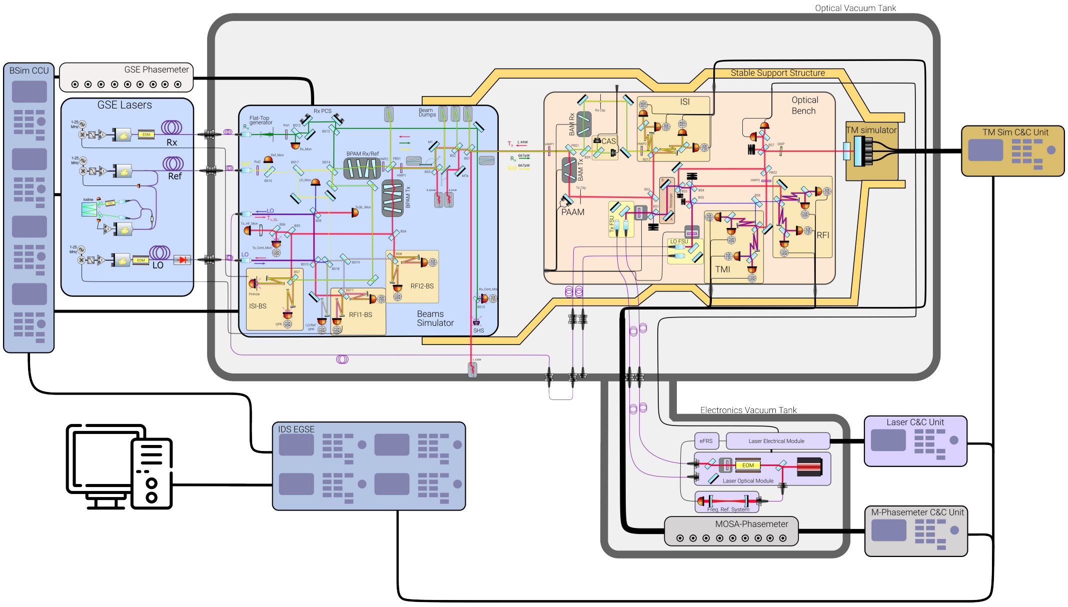


Figure 8 - Sketch of the IDS under tests

The Figure 8 represents a sketch of the IDS subsystem under test. One of the main required optical ground support equipment is the ‘Beams Simulator’, which aims at simulating the optical interfaces with the LISA optical bench (both free space and fibred interfaces). The main objectives of the Beams Simulator are to characterize the optical path length noise and residual tilt-to-length coefficients of the inter-satellite interferometer on the LISA optical bench.

The design of the Beams Simulator is inspired from the results of the ZIFO, on-going prototyping activities conducted at ARTEMIS/OCA and previous similar experiments in the LISA collaboration. The Beams Simulator is made of a Zerodur baseplate with optically contacted components (same technique as for the ZIFO) and subsystems (photoreceivers, pointing mechanisms) provided by laboratories. A co-engineering phase focused on the Beams Simulator feasibility is already on-going (finishing in June 2023) with Bertin/Winlight.

The Beams Simulator shall be developed under the responsibility of the **APC** (with an industrial contract for the provision of the baseplate and contacted optics). The **APC** is also in charge of providing two kinds of beams pointing mechanisms, and, together with CEA/IRFU, of adapting the generic ‘LISA’ phasemeter developed by the University of Hamburg to the specific needs of the Beams Simulator. A contribution of the **LMA/IP2I** is foreseen for the coatings of the optical components. A collaboration between the **CPPM** and **LPCCaen** is proposed to develop the control/command software suite which is required for the Beams Simulator tuning and commissioning phase at the **APC**. This work shall be based on the existing software developed for the MIFO/ZIFO and low-level interfacing drivers could be reused in the command/control operating system developed by the CNES for the IDS test campaign. Morevoer, the LPCCaen proposed to design and manufacture the delicate hoisting and transportation equipment required to safely and ‘gently’ move the Beams Simulator assembly to the integration and test tables (in the **APC** and **CNES** premises).

The Beams Simulator (with all its associated equipment and software) shall be available (for tuning and commisionning) at the APC end 2025 and delivered to the CNES premises in fall 2026.

Following the OGSEs deliveries, the teams will also participate to the tests campaign of the IDS Engineering and First Flight Models from 2026 to 2029.

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

Contributions to the tests at MOSA level

Beyond the functional and performance tests of the IDS, France has also proposed to deliver two 'complex' Optical Ground Support Equipment for measuring and optimizing key optical performance of the LISA instrument (grouped under the project OTS, 'Optical Tests System'). These two OGSEs are named SLOGSE and FFOGSE :

- The SLOGSE (Straylight OGSE) aims at quantifying the amount of straylight (from spurious optical paths and scatering) coupling into the main beams, and identify the offending components.
- The FFOGSE (Far Field OGSE) aims at measuring the coupling between the angular movement of the incident beam on the instrument telescope and the measured optical pathlength. This spurious coupling is mostly due to misalignments during the instrument integration and shall be reduced (with a dedicated realignment mechanism on the LISA optical bench) to achieve the expected in-pathlength noise performance.

These two test benches shall be operated by the Prime Contractor during the MOSA AIVT. In addition to deliver the OGSEs, France is also responsible for validating and supervising associated tests plans, as well as reviewing the test results for the qualification and every flight and spares models (i.e. 8 or 9 instruments in total).

Up to now the scientific teams (incl. the **APC** and the **L2IT** from IN2P3) have participated to the specifications and first feasibility studies of the FFOGSE, in coordination with the LISA Consortium, ESA and the two Prime candidates. These OGSEs must be compatible with the infrastructure and test philosophy of the Prime (which is currently only conceptual). The detailed design of the FFOGSE and SLOGSE shall be consolidated once the Prime contractor will be chosen and fully operational (end 2024). Therefore, the preliminary design review for the OTS is currently planned end 2026 and the critical design review mid 2027. The scientific laboratories will contribute to the technical definition and requirements of the FFOGSE/SLOGSE, but not to their actual manufacturing which shall be delegated to a private system architect. The test benches shall be delivered to the Prime in 2029, so that the instrument characterization can be achieved between 2029 to 2033.

Participating institutes (***incl. IN2P3***): ***APC***, ARTEMIS/OCA, CNES, ***L2IT***

Conclusion

After being selected in 2017, a successful Mission Formulation Review in 2021 and an on-going Instrument System Specification Review LISA is now on good tracks for adoption end 2023/beginning 2024 and a 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 (Optical GSEs, scientific performance models, DDPC). Over the last few years, the development of prototypes (both software and hardware) has allowed to define with more details the perimeter of the French contributions and the implication of the IN2P3 laboratories. Although the launch shall append in a more than a decade, the schedule of the LISA development is tight, with different validation levels (units, IDS, MOSA, spacecraft) and 6 flight models (+ spares) to produce. For example, the manufacturing of some optical GSEs required to validate the IDS shall start in 2024, right after adoption, with anticipated long lead items procurement starting in 2023.

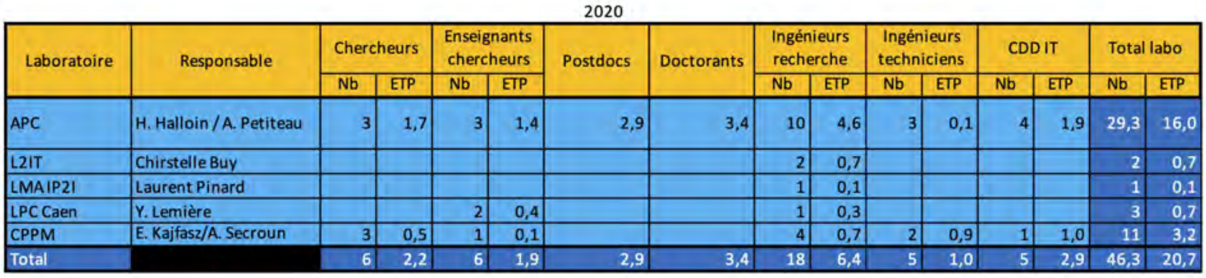
With the strong (financial and technical) support of the CNES, the French scientific community has gained a privileged position in the LISA development, with a focus on the best understanding and exploitation of the instrument, from ground tests and instrument modelling to data processing pipelines and science analysis. The IN2P3 has a leading role in many critical aspects of the French contribution (DDPC, Performance models, Beams Simulator) and is working in close collaboration with the CNES and other research institutes : ARTEMIS, Institut Fresnel, IPhT, IRAP, IRFU, Lagrange, LAM, LPC2E, LUTh, SYRTE.

The next few years are crucial for demonstrating the ability of IN2P3 laboratories to deliver complex and sophisticated hardware and software for LISA and fulfil its commitments.

The continuing support of the IN2P3 is therefore very crucial, e.g. by securing the permanent positions with the expertise brought by young engineers and researchers.

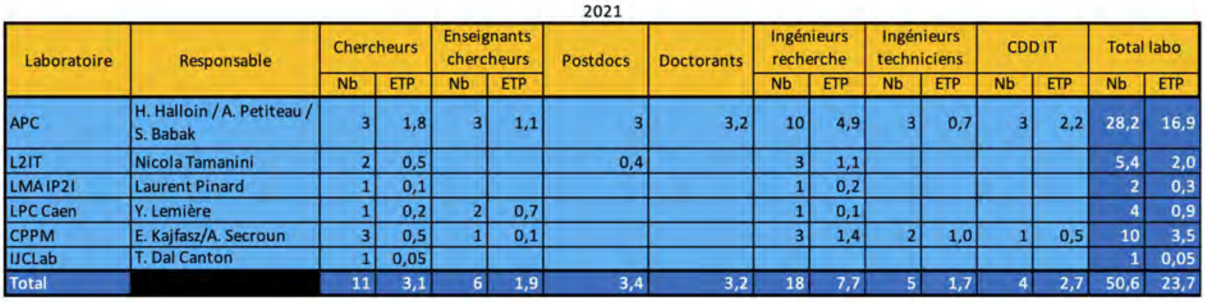
Appendix 1 - Evolution of IN2P3 human resources since 2020

Detailed data per year



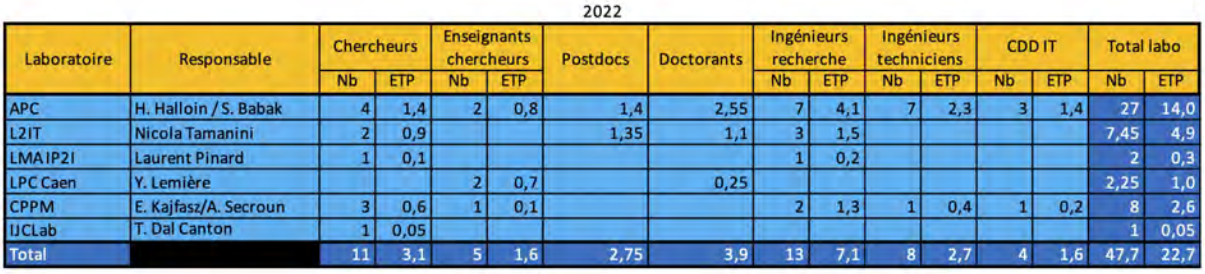
2020

Laboratoire	Responsable	Chercheurs		Enseignants chercheurs		Postdocs	Doctorants	Ingénieurs recherche		Ingénieurs techniciens		CDD IT		Total labo	
		Nb	ETP	Nb	ETP			Nb	ETP	Nb	ETP	Nb	ETP	Nb	ETP
APC	H. Halloin / A. Petiteau	3	1,7	3	1,4	2,9	3,4	10	4,6	3	0,1	4	1,9	29,3	16,0
L2IT	Chirstelle Buy							2	0,7					2	0,7
LMA IP2I	Laurent Pinard							1	0,1					1	0,1
LPC Caen	Y. Lemière			2	0,4			1	0,3					3	0,7
CPPM	E. Kajfasz/A. Secroun	3	0,5	1	0,1			4	0,7	2	0,9	1	1,0	11	3,2
Total		6	2,2	6	1,9	2,9	3,4	18	6,4	5	1,0	5	2,9	46,3	20,7



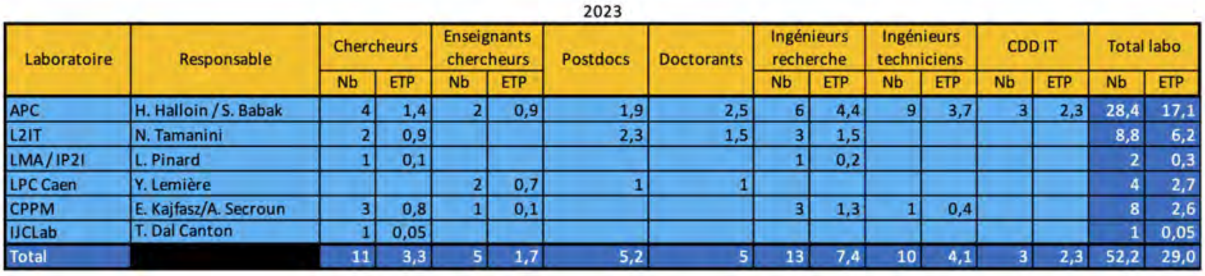
2021

Laboratoire	Responsable	Chercheurs		Enseignants chercheurs		Postdocs	Doctorants	Ingénieurs recherche		Ingénieurs techniciens		CDD IT		Total labo	
		Nb	ETP	Nb	ETP			Nb	ETP	Nb	ETP	Nb	ETP	Nb	ETP
APC	H. Halloin / A. Petiteau / S. Babak	3	1,8	3	1,1	3	3,2	10	4,9	3	0,7	3	2,2	28,2	16,9
L2IT	Nicola Tamanini	2	0,5			0,4		3	1,1					5,4	2,0
LMA IP2I	Laurent Pinard	1	0,1					1	0,2					2	0,3
LPC Caen	Y. Lemière	1	0,2	2	0,7			1	0,1					4	0,9
CPPM	E. Kajfasz/A. Secroun	3	0,5	1	0,1			3	1,4	2	1,0	1	0,5	10	3,5
IJCLab	T. Dal Canton	1	0,05											1	0,05
Total		11	3,1	6	1,9	3,4	3,2	18	7,7	5	1,7	4	2,7	50,6	23,7



2022

Laboratoire	Responsable	Chercheurs		Enseignants chercheurs		Postdocs	Doctorants	Ingénieurs recherche		Ingénieurs techniciens		CDD IT		Total labo	
		Nb	ETP	Nb	ETP			Nb	ETP	Nb	ETP	Nb	ETP	Nb	ETP
APC	H. Halloin / S. Babak	4	1,4	2	0,8	1,4	2,55	7	4,1	7	2,3	3	1,4	27	14,0
L2IT	Nicola Tamanini	2	0,9			1,35	1,1	3	1,5					7,45	4,9
LMA IP2I	Laurent Pinard	1	0,1					1	0,2					2	0,3
LPC Caen	Y. Lemière			2	0,7		0,25							2,25	1,0
CPPM	E. Kajfasz/A. Secroun	3	0,6	1	0,1			2	1,3	1	0,4	1	0,2	8	2,6
IJCLab	T. Dal Canton	1	0,05											1	0,05
Total		11	3,1	5	1,6	2,75	3,9	13	7,1	8	2,7	4	1,6	47,7	22,7

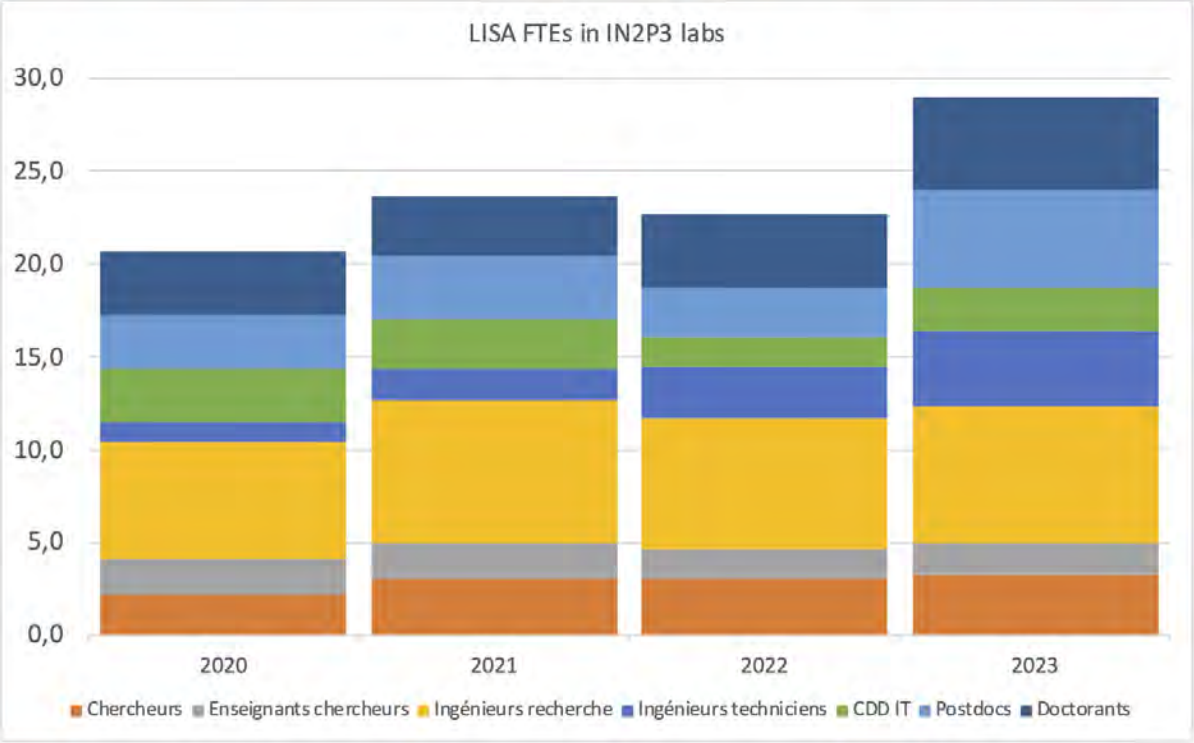


2023

Laboratoire	Responsable	Chercheurs		Enseignants chercheurs		Postdocs	Doctorants	Ingénieurs recherche		Ingénieurs techniciens		CDD IT		Total labo	
		Nb	ETP	Nb	ETP			Nb	ETP	Nb	ETP	Nb	ETP	Nb	ETP
APC	H. Halloin / S. Babak	4	1,4	2	0,9	1,9	2,5	6	4,4	9	3,7	3	2,3	28,4	17,1
L2IT	N. Tamanini	2	0,9			2,3	1,5	3	1,5					8,8	6,2
LMA / IP2I	L. Pinard	1	0,1					1	0,2					2	0,3
LPC Caen	Y. Lemière			2	0,7	1	1							4	2,7
CPPM	E. Kajfasz/A. Secroun	3	0,8	1	0,1			3	1,3	1	0,4			8	2,6
IJCLab	T. Dal Canton	1	0,05											1	0,05
Total		11	3,3	5	1,7	5,2	5	13	7,4	10	4,1	3	2,3	52,2	29,0

Summary and evolution

Year	Chercheurs		Enseignants		Postdocs	Doctorants	Ingénieurs		Ingénieurs		CDD IT		Total labo	
	Nb	ETP	Nb	ETP			Nb	ETP	Nb	ETP	Nb	ETP	Nb	ETP
2020	6	2,2	6	1,9	2,9	3,4	18	6,4	5	1,0	5	2,9	46,3	20,7
2021	11	3,1	6	1,9	3,4	3,2	18	7,7	5	1,7	4	2,7	50,6	23,7
2022	11	3,1	5	1,6	2,75	3,9	13	7,1	8	2,7	4	1,6	47,7	22,7
2023	11	3,3	5	1,7	5,2	5	13	7,4	10	4,1	3	2,3	52,2	29,0



Appendix 2 - List of publications 2020 - 2022

We list hereafter the LISA publications between 2020 and 2022, with at least one member of an IN2P3 lab as co-author.

1. A. Sesana, A. Lamberts, **A. Petiteau**, "*Finding binary black holes in the Milky Way with LISA*", Mon.Not.Roy.Astron.Soc. 494 (2020) 1, L75-L80
2. **A. Toubiana, S. Marsat, S. Babak**, E. Barausse, J. Baker, "*Tests of general relativity with stellar-mass black hole binaries observed by LISA*", Phys.Rev.D 101 (2020) 10, 104038
3. A. Caputo, L. Sberna, **A. Toubiana, S. Babak**, E. Barausse, **S. Marsat**, P. Pani, "*Gravitational-wave Detection and Parameter Estimation for Accreting Black-hole Binaries and Their Electromagnetic Counterpart*", Astrophys. J. (2020) 892,
4. **N. Tamanini**, A. Klein, C. Bonvin, E. Barausse, **Ch. Caprini**, "*Peculiar acceleration of stellar-origin black hole binaries: Measurement and biases with LISA*", Phys.Rev.D 101 (2020) 6, 063002
5. **Ch. Caprini**, M. Chala, G. Dorsch, M. Hindmarsh, S. Huber et al. "*Detecting gravitational waves from cosmological phase transitions with LISA: an update*", JCAP 03 (2020) 024
6. A. Chua, N. Korsakova, C. Moore, J. Gair, **S. Babak**, "*Gaussian processes for the interpolation and marginalization of waveform error in extreme-mass-ratio-inspiral parameter estimation*", Phys.Rev.D 101 (2020) 4, 044027
7. **P. Auclair**, J.J. Blanco-Pillado, D.G. Figueroa, A.C. Jenkins, Marek Lewicki et al, "*Probing the gravitational wave background from cosmic strings with LISA*", JCAP 04 (2020) 034
8. M. Katz, **S. Marsat, S. Babak**, A. Chua, Sh. Larson, "*GPU-accelerated massive black hole binary parameter estimation with LISA*", Phys.Rev.D 102 (2020) 2, 023033
9. S. Ossokine, A. Buonanno, **S. Marsat**, R. Cotesta, **S. Babak** et. al. "*Multipolar Effective-One-Body Waveforms for Precessing Binary Black Holes: Construction and Validation"*, Phys.Rev.D 102 (2020) 4, 044055
10. **A. Toubiana, S. Marsat, S. Babak**, J. Baker, T. Del Canton "*Parameter estimation of stellar-mass black hole binaries with LISA*", Phys.Rev.D 102 (2020) 12, 124037
11. E. Barausse, … **A. Toubiana**,… "*Prospects for Fundamental Physics with LISA*", Gen.Rel.Grav. 52 (2020) 8, 81.
12. M. Vallisneri, J-B Bayle, **S. Babak, A. Petiteau** "*TDI-infinity : time-delay interferometry without delays*", e-Print 2008.12343 (submitted to PRD)
13. T. Marchand, Q. Henry, F. Larrouturou, **S. Marsat**, G. Faye et al. "*The mass quadrupole moment of compact binary systems at the fourth post-Newtonian order"*, Class.Quant.Grav. 37 (2020) 21, 215006
14. R. Cotesta, **S. Marsat**, M. Pürrer, "*Frequency domain reduced order model of aligned-spin effective-one-body waveforms with higher-order modes"*, Phys.Rev.D 101 (2020) 12, 124040
15. **N. Karnesis, A. Petiteau, M. Lilley, "***A template-free approach for detecting a gravitational wave stochastic background with LISA*", Class.Quant.Grav. 37 (2020) 21, 215017
16. C. Contaldi, M. Pieroni, A. Renzini, G. Cusin, **N. Karnesis**, "*Maximum likelihood map-making with the Laser Interferometer Space Antenna"*, e-Print: 2006.03313
17. **H. Inchauspé**, T. Olatunde, S. Apple, S. Parry, B. Letson, N. Turetta, G. Mueller, P. J. Wass, and J. W. Conklin, *Numerical Modeling and Experimental Demonstration of Pulsed Charge Control for the Space Inertial Sensor Used in LISA*, Phys. Rev. D **102**, 042002 (2020).
18. **N. Tamanini**, A. Klein, C. Bonvin, E. Barausse and C. Caprini, *Peculiar acceleration of stellar-origin black hole binaries: Measurement and biases with LISA*, Phys. Rev. D 101 (2020) no.6, 063002
19. M. Nardello, M. Lintz, **C. Buy** , *Scattering paths in test optical bench for LISA mission,* in Frontiers in Optics / Laser Science, B. Lee, C. Mazzali, K. Corwin, and R. Jason Jones, eds., OSA Technical Digest (Optical Society of America, 2020), paper JTu1A.6
20. C. Danielski and N. Tamanini, *Will Gravitational Waves Discover the First Extra-Galactic Planetary System?*, Int. J. Mod. Phys. D 29 (2020) 2043007

21. Mangiagli A., Klein A., Bonetti M., Katz M., Sesana A., Volonteri M., Colpi, **M., Marsat S., Babak S.**, *Observing the inspiral of coalescing massive black hole binaries with LISA in the era of multimessenger astrophysics*, PRD, Vol. 102, N◦ 8, pp. 084056 (2020)

22. L. Sberna, **A. Toubiana**, C. Miller, "*Golden galactic binaries for LISA: mass-transferring white dwarf black hole binaries*", ApJ **908,** 1 (2021)
23. **A. Toubiana,** K. Wong, **S. Babak**, E. Barausse, E. Berti, J. Gair, **S. Marsat**, S. Taylor, "Discriminating between different scenarios for the formation and evolution of massive black holes with LISA" Phys. Rev. D 104, 083027 (2021)
24. N. Karnesis, **S. Babak**, M. Pieroni, N. Cornish, T. Littenberg, "Characterization of the stochastic signal originating from compact binary populations as measured by LISA", Phys.Rev.D 104 (2021) 4, 043019
25. D. Laghi, **N. Tamanini**, W. Del Pozzo, A. Sesana, J. Gair, **S. Babak**, D. Izquierdo-Villalba, "Gravitational wave cosmology with extreme mass-ratio inspirals", M. N. R. A. S., Volume 508, Issue 3, (2021)
26. **A. Toubiana, S. Babak**, E. Barausse, L. Lehner, "Modeling gravitational waves from exotic compact objects", Phys.Rev.D 103 (2021) 6, 064042
27. M. Vallisneri, J-B. Bayle, **S. Babak, A. Petiteau**, "Time-delay interferometry without delays", Phys.Rev.D 103 (2021) 8, 082001
28. **S. Marsat**, J. Baker, **T. Dal Canton**, "Exploring the Bayesian parameter estimation of binary black holes with LISA", Phys.Rev.D 103 (2021) 8, 083011
29. M. Armano, …, **H. Inchauspe, J. Martino, A. Petiteau, E. Plagnol,** … "Sensor Noise in LISA Pathfinder : In-Flight Performance of the Optical Test Mass Readout", Phys.Rev.Lett. 126 (2021) 13, 131103
30. D. Bortoluzzi,... **H. Inchauspe, J. Martino, A. Petiteau, E. Plagnol**, … ‘’In-flight testing of the injection of the LISA Pathfinder test mass into a geodesic", Adv.Space Res. 67 (2021) 1, 504-520
31. P. Amaro-Seoane, M. Arca-Sedda, **S. Babak, Ch. Caprini**, … "The Effect of Mission Duration on LISA Science Objectives", e-Print: 2107.09665, Accepted in GRG (2021)
32. **A. Toubiana**, L. Sberna, A. Caputo, G. Cusin, **S. Marsat**, K. Jani, **S. Babak**, E. Barausse, **Ch. Caprini**, P. Pani, A. Sesana, **N. Tamanini**, "Detectable environmental effects in GW190521-like black-hole binaries with LISA", Phys.Rev.Lett. 126 (2021) 10, 101105
33. M. Arca-Sedda,... **Ch. Caprini**, …, "The missing link in gravitational-wave astronomy: A summary of discoveries waiting in the decihertz range", Exper.Astron. 51 (2021) 3, 1427-1440
34. A. Sesana, N. Korsakova, … **Ch. Caprini**,... "Unveiling the gravitational universe at μ-Hz frequencies", Exper.Astron. 51 (2021) 3, 1333-1383
35. G. Cusin and **N. Tamanini**, *Characterisation of lensing selection effects for LISA massive black hole binary mergers*, Mon. Not. Roy. Astron. Soc. 504 (2021) no.3, 3610-3618
36. L. Speri, **N. Tamanini**, R. R. Caldwell, J. R. Gair and B. Wang, *Testing the Quasar Hubble Diagram with LISA Standard Sirens*, Phys. Rev. D 103 (2021) no.8, 083526
37. M. A. Sedda et al., *The missing link in gravitational-wave astronomy: A summary of discoveries waiting in the decihertz range*, Exper. Astron. 51 (2021) no.3, 1427-1440
38. **Marsat S.**, Baker J. G., **Dal Canton T**., *Exploring Bayesian parameter estimation of binary black holes with LISA*, PRD, Vol. 103, N◦ 8, pp. 083011 (2021)

39. P. Amaro-Seoane, M. Arca-Sedda, **S. Babak, Ch. Caprini, A. Mangiagli**, … "The effect of mission duration on LISA science objectives", Gen.Rel.Grav. 54 (2022) 1, 3
40. **E. Savalle**, J. Gair, L. Speri, **S. Babak**, "Assessing the impact of instrumental calibration uncertainty on LISA science", Phys.Rev.D 106 (2022) 2, 022003
41. L. Sberna, **S. Babak, Ch. Caprini**,.. "Observing GW190521-like binary black holes and their environment with LISA", Phys.Rev.D 106 (2022) 6, 064056
42. **P. Auclair, Ch. Caprini, …, D. Steer**, "Generation of gravitational waves from freely decaying turbulence", JCAP 09 (2022) 029

43. N. Muttoni, **A. Mangiagli**, …, “Multiband gravitational wave cosmology with stellar origin black hole binaries”, Phys.Rev.D 105 (2022) 4, 043509
44. H. Estelles, … **C. Garcia-Quiros**, “New twists in compact binary waveform modeling: A fast time-domain model for precession” , Phys.Rev.D 105 (2022) 8, 084040
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47. Q. Baghi, **N. Korsakova**, .., “Detection and characterization of instrumental transients in LISA Pathfinder and their projection to LISA”, Phys.Rev.D 105 (2022) 4, 042002
48. Xue-Ting Zhang, … **N. Korsakova**, …, “Detecting gravitational waves from extreme mass ratio inspirals using convolutional neural networks”, Phys.Rev.D 105 (2022) 12, 123027
49. M. Corman, A. Ghosh, C. Escamilla-Rivera, M. Hendry, **S. Marsat** et al, “Constraining cosmological extra dimensions with gravitational wave standard sirens: from theory to current and future multi-messenger observations”, Phys.Rev.D 105 (2022) 6, 064061
50. **A. Mangiagli, Ch. Caprini**, M. Volonteri,... “Massive black hole binaries in LISA: multimessenger prospects and electromagnetic counterparts”, Phys.Rev.D 106 (2022) 10, 103017
51. LISA Fundamental Physics WG (incl. **N. Tamanini**), *New Horizons for Fundamental Physics with LISA*, Living Rev. Rel. 25 (2022) no.1, 4
52. P. Amaro Seoane et al. (incl **N. Tamanini**), *The Effect of Mission Duration on LISA Science Objectives*, Gen. Rel. Grav. 54 (2022) no.1, 3
53. **N. Muttoni**, A. Mangiagli, A. Sesana, **D. Laghi**, W. Del Pozzo, D. Izquierdo-Villalba, M*ulti-band gravitational wave cosmology with stellar origin black hole binaries*, Phys. Rev. D 105, 043509 (2022)
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55. J. Bayle, **N. Tamanini,** et al., *Workshop on Gravitational-Wave Astrophysics for Early Career Scientists*, Nature Astron. 6 (2022), 304
56. Q. Henry, **S. Marsat**, M. Khalil, *Spin contributions to the gravitational-waveform modes for spin-aligned binaries at the 3.5PN order,* Phys. Rev. D 106 (2022) no.12, 124018
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59. A. Toubiana, **S. Babak, S. Marsat**, S. Ossokine, Detectability and parameter estimation of GWTC-3 events with LISA, Phys. Rev. D 106 (2022)
60. M. L. Katz, C. Danielski, N. Karnesis, V. Korol, **N. Tamanin**i, N. J. Cornish and T. B. Littenberg, *Bayesian Characterisation of Circumbinary Exoplanets with LISA*, Mon. Not. Roy. Astron. Soc. 517 (2022) no.1, 697-711