LISA Ground Segment

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in collaboration with L. Chaoul (CNES), M. Le Jeune (APC)
and with the inputs/feedbacks from LISA Consortium and ESA

SciOps 2017 - ESAC
20 October 2017
Gravitational waves (GWs)
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- General relativity: GW are created by non-spherical acceleration of one or several massive objects (asymmetric collapse, bodies in orbits or coalescing)
Gravitational waves (GWs)

- General relativity: GW are created by non-spherical acceleration of one or several massive objects (asymmetric collapse, bodies in orbits or coalescing)

- Modification of distance between 2 objects:
  - Elastic deformation proportional to the distance between the 2 obj.,
  - Transverse deformation: perpendicular to the direction of propagation (different from ripples on water!),
  - Two components of polarisation: $h_+$ and $h_\times$
THE GRAVITATIONAL WAVE SPECTRUM

Sources:
- Quantum fluctuations in the very early Universe
- Binary supermassive black holes in galactic nuclei
- Phase transitions in the early universe
- Black holes, compact stars captured by supermassive holes in galactic nuclei
- Binary stars in the galaxy and beyond
- Merging binary neutron stars and stellar black holes in distant galaxies; fast pulsars with mountains

Wave Period:
- Age of the Universe
- Years
- Hours
- Seconds
- Msec

Frequency (Hz):
- $10^{-16}$
- $10^{-14}$
- $10^{-12}$
- $10^{-10}$
- $10^{-8}$
- $10^{-6}$
- $10^{-4}$
- $10^{-2}$
- 1
- $10^2$

Detectors:
- Inflation Probe
- Polarization map of cosmic microwave background
- Precision timing of millisecond pulsars
- LISA
- Big Bang Obs
- GEO, LIGO, VIRGO, TAMA
Figures summarized in relation of the detectors at the time of GW170817 is also operating at the time, but its sensitivity was insufficient.

Livingston and LIGO-Hanford detectors could detect a tors and the Advanced Virgo detector were in observing.

was composed of two neutron stars.

Moreover, although a neutron star components between 1.17 and 2

BNS systems are between 2.57 and 3

gravitational-wave signal, as the total masses of known uncertainties. This suggests a BNS as the source of the

ranges of 0.86 to 1

1

From the gravitational-wave signal, the best measured

1

for details), the total mass of the system is between 3

26

M

004

002

M

29

M

2

2.

The combination of data from

– 45

The individual masses are in the broad general have precisely measured masses as large as

sure the masses of the two objects and set a lower limit on

consistent with the localization and distance inferred from

In addition, a

sensitive band, the inspiral signal ended at 12

s

Time-frequency representation of the strain data around the time of GW170814.

20 Hz

removal, increasing the BNS horizon of that detector

broad peaks in the 150

subtraction removed calibration lines and 60 Hz ac power

selection, several independently measured terrestrial contributions to the detector noise were subtracted from the LIGO

detectors. Times are shown relative to August 17, 2017 12

UTC. The amplitude scale in each detector is normalized to that

FIG. 1: The GW event GW170814 observed by LIGO Hanford, LIGO Livingston and Virgo. Times are shown from August 14, 2017,

GW170814

Hanford

Livingston

Virgo

Hanover, Germany

Advanced LIGO detectors have

been operational since 2015

LIGO stopped observing in 2010 for the Advanced

upgrade, during which many parts of the detector were re-

been operational since 2015

They underwent a se-

2011. LIGO stopped observing in 2010 for the Advanced

During the LIGO upgrade

larged, as described in

of data containing

of scattered light. The test mass mirrors

last-stage pendulum and the accommodation of baffles to

cryogenic traps have

suspended and put under vacuum to reduce impact

of scattered light and acoustic noise. Cryogenic traps have

been suspended and put under vacuum to reduce impact

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GWs detected

Binary Neutron Star - GW170817
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Polarization map of cosmic microwave background
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Polarization map of cosmic microwave background
History of LISA

- 1978: first study based on a rigid structure (NASA)
- 1980s: studies with 3 free-falling spacecrafts (US)
- 1993: proposal ESA/NASA: 4 spacecrafts
- 1996-2000: pre-phase A report
- 2000-2010: LISA and LISAPathfinder: ESA/NASA mission
- 2011: NASA stops => ESA continue: reduce mission
- 2012: selection of JUICE L1 ESA
- 2013: selection of ESA L3 : « The gravitational Universe »
- 2015-2016: success of LISAPathfinder + detection GWs
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Call for mission at ESA
The LISA Proposal

LISA
Laser Interferometer Space Antenna

A proposal in response to the ESA call for L3 mission concepts

Lead Proposer
Prof. Dr. Karsten Danzmann

https://www.lisamission.org/proposal/LISA.pdf
LISA science objectives

- SO1: Study the formation and evolution of compact binary stars in the Milky Way Galaxy.
- SO2: Trace the origin, growth and merger history of massive black holes across cosmic ages.
- SO3: Probe the dynamics of dense nuclear clusters using EMRIs.
- SO4: Understand the astrophysics of stellar origin black holes.
- SO5: Explore the fundamental nature of gravity and black holes.
- SO6: Probe the rate of expansion of the Universe.
- SO8: Search for GW bursts and unforeseen sources.
LISA at ESA

- 25/10/2016 : Call for mission
- 13/01/2017 : submission of «LISA proposal» (LISA consortium)
- 8/3/2017 : Phase 0 mission (CDF 8/3/17 → 5/5/17)
- 20/06/2017 : LISA mission approved by SPC
- 8/3/2017 : Phase 0 payload (CDF June → November 2017)
- 2018→2020 : competitive phase A : 2 companies compete
- 2020→2022 : B1: start industrial implementation
- 2022-2024 : mission adoption
- During about 8.5 years : construction
- 2030-2034 : launch Ariane 6.4
- 1.5 years for transfert
- 4 years of nominal mission
- Possible extension to 10 years

GW observations !
LISA

- Laser Interferometer Space Antenna
- 3 spacecrafts on heliocentric orbits and distant from 2.5 millions kilometers
- Goal: detect relative distance changes of $10^{-21}$: few picometers

Diagram showing orbit parameters:
- Initial displacement angle (IDA) 20°
- Distance to Earth 50-65 million km
- Arm length of constellation 2.5 million km
- Inclination of constellation wrt ecliptic 60°
- Corner angles 60°
- Round trip time for communications 433 s
- Earth azimuth and elevation during science Az=360°; El=-9.35±3°
- Arm length variation ±35000 km
- Arm length variation rate <10 m/s
- Breathing angle ±0.9°
- Breathing angle rate 5 nrad/s

- Three SC required in free flight forming an equilateral triangle, no actuation during science mode (except drag free control)
- Low perturbations environment required to achieve performances and limit the constellation deformation and fuel
- No need to keep rigid geometry, though range rate (Doppler) and breathing angle (optics/mechanisms) shall be limited
- Long mission duration, minimum of 4 years of science operations
- High data volume generated, remain in the vicinity of the Earth
Spacecraft (SC) should only be sensible to gravity:

- the spacecraft protects test-masses (TMs) from external forces and always adjusts itself on it using micro-thrusters

Readout:
- interferometric (sensitive axis)
- capacitive sensing
LISA

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  - the spacecraft protects test-masses (TMs) from external forces and always adjusts itself on it using micro-thrusters
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    - interferometric (sensitive axis)
    - capacitive sensing
LISAPathfinder

- Basic idea: Reduce one LISA arm in one SC.
- LISAPathfinder is testing:
  - Inertial sensor,
  - Drag-free and attitude control system
  - Interferometric measurement between 2 free-falling test-masses,
  - Micro-thrusters
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  - Micro-thrusters
LISAPathfinder first results

- Results after 45 days of operations ... and after 1.5 years, better than LISA requirements
Exchange of laser beam to form several interferometers

Phasemeter measurements on each of the 6 Optical Benches:
- Distant OB vs local OB
- Test-mass vs OB
- Reference using adjacent OB
- Transmission using sidebands
- Distance between spacecrafts

Noises sources:
- Laser noise: $10^{-13}$ (vs $10^{-21}$)
- Clock noise (3 clocks)
- Acceleration noise (see LPF)
- Read-out noises
Photon flight time measurement between free-floating objects:
LISA

- Photon flight time measurement between free-floating objects:
  - Reference masses in each spacecraft only sensitive to gravity along measurement axis (follow geodesics)
LISA

- Photon flight time measurement between free-floating objects:
  - Reference masses in each spacecraft only sensitive to gravity along measurement axis (follow geodesics)
  - Exchange of laser beam between spacecraft
  - Interferometry at the picometer precision

Figure 2.3: Interferometric measurement on one LISA satellite, exemplarily explained for the horizontal OB. Light of a local laser (red) is used for transmission to the distant S/C and to sense the space-time variation between for GW interaction. Simultaneously, the light interferes on the local optical bench with the received weak light (wine red) to form the science interferometer beatnote. The test mass motion is read out in the TM interferometer using light (orange) from the adjacent optical bench transmitted through a back-link fibre. The reference IFO directly compares local laser and adjacent local laser. Moreover, the spacecraft is controlled by DFACS including TM position readout and thruster actuation such that the S/C follows the test masses.
Photon flight time measurement between free-floating objects:

- Reference masses in each spacecraft only sensitive to gravity along measurement axis (follow geodesics)
- Exchange of laser beam between spacecraft
- Interferometry at the picometer precision
- Extracting GW signals in the data
LISA data

- Data Analysis of GWs
- Catalogs of GWs sources with their waveform

- Phasemeters (carrier, sidebands, distance)
- Gravitational Reference Sensor
- Auxiliary channels

- Calibrations corrections
- Resynchronisation (clock)
- Time-Delay Interferometry reduction of laser noise

- 2 data channels TDI non-correlated

- 16

Gravitational wave sources emitting between 0.02 mHz and 100 mHz
Gravitational wave sources emitting between 0.02 mHz and 100 mHz

Data

- Phasemeters (carrier, sidebands, distance)
- Gravitational Reference Sensor
- Auxiliary channels

Survey type observatory

<table>
<thead>
<tr>
<th>Source</th>
<th>Measurement</th>
<th>Channel Count</th>
<th>Sample Rate [Hz]</th>
<th>Bits per Channel</th>
<th>Rate [bits/s]</th>
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<tr>
<td>IFO Longitudinal</td>
<td>Inter-S/C IFO</td>
<td>2</td>
<td>3.0</td>
<td>64</td>
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<td>3.0</td>
<td>64</td>
<td>0.0</td>
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<td>3.0</td>
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<td>0</td>
<td>3.0</td>
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<td></td>
<td>2 lasers, 2 frequencies, 2 quadratures</td>
<td>8</td>
<td>3.0</td>
<td>32</td>
</tr>
</tbody>
</table>

Total Payload: 7984

Housekeeping [Based on LPF]

Total Platform: 4000

Raw Rate per SC

Packetisation Overhead [10%]

Packaged Rate per SC

Packaged Rate for Constellation

Totals

11984

1198

13182

39546
LISA data

Phasemeters (carrier, sidebands, distance)

+ Gravitational Reference Sensor

+ Auxiliary channels

Calibrations and corrections

Resynchronisation (clock)

Time-Delay Interferometry

reduction of laser noise

2 data channels TDI non-correlated

Data Analysis of GWs

Catalogs of GWs sources with their waveform

‘Survey’ type observatory

Gravitational wave sources emitting between 0.02 mHz and 100 mHz
Galactic binaries

GW sources
- $6 \times 10^7$ galactic binaries
Super Massive Black Hole Binaries

GW sources

- $6 \times 10^7$ galactic binaries
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- 10-100/year SMBHBs
- 10-1000/year EMRIs
- large number of Stellar Origin BH binaries (LIGO/Virgo)
- Cosmological backgrounds
- Unknown sources
GW sources
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LISA data level

- **Level L0 data**: raw science telemetry and housekeeping data.

- **Level L1 data**: TDI variables, all calibrated science data streams and auxiliary data.

- **Level L2**: intermediate waveform products such as partially regressed observable series (i.e., dataset obtained by progressively deeper subtraction of identified signals).

- **Level L3**: catalogs of identified sources, with faithful representations of posterior parameter distributions.
LISA data volume

- Data volume to be stored:
  - Level L0: about 300 Mo per day
  - Level L1: about 600 Mo per day
  - Sub-product of the analysis: fews Go per day
  - Level L2 and L3: about 6 Go per day

⇒ Storages and archives are not problematic

- But simulations will require some storage to be properly sized

- Complexity for the DPC is mainly in data analysis because the goal is to extract the parameters for a maximum number of sources.
LISA Data Challenges

- Mock LDC: 2005 → 2011
- 2017: start of the LDC
  - Develop data analysis
  - Design the pipelines of the mission
- Example of the potential data for LDC1
Particularities LISA data

- **First** data of this kind
  - Discovery mission; no previous expertise on this kind of data

- Event rate is **uncertain**
  - Depending on the type of sources but typically from few tens to few thousands per year

- Potential **unknown** sources

- **Transient** sources + continuous sources

\[\Rightarrow\] Constrains on data processing:
- **Large fluctuation** of computation needs
- **Continuous evolution** of the pipelines
Activities of scientific operations, data processing, dissemination and archives share between:

- The **Science Operation Center (SOC): ESA + Consortium**
- The **unique Consortium DPC:**
  - « Direct and supervise data analysis and processing activities »
  - Organise **Data Computing Centers** (DCCs): member states, ESA and/or NASA

**SOC:**
- Operations: science planning (update config., calibrations, …)
- Pre-processing: ingestion of L0 data from MOC, calibration, monitoring, quicklook and production of L1 data
DPC activities:

- Receive L1 data from the SOC;
- Identify and extract waveforms;
- Build the catalogs of sources;
- Create L2 et L3 science products;
- Analyse the quality of science data products;
- Distribute data to SOC & to the scientific community of the Consortium
- Produce periodic releases of science data products
- Generate alerts for upcoming transients, such as mergers
Transient events processing:

- Quick notifications by the SOC to the astronomer community
- DPC should *quickly* establish the quality of the events:
  - Produce and assess preliminary *events notices*
  - Provide detailed transient parameters (time span) to the science planning team => protected period
- Powerful events: latency of about one day requires at the SOC.
- Other events: longer latency at SOC+DPC
Current vision of the DPC

- DPC: unique entity responsible for the data processing
- DPC in charge of delivering L2 & L3 products + what's necessary to reproduce/refine the analysis (i.e. input data + software + its running environment + some CPU to run it).

Distributed DPC:
- Data Computing Centres (DCC): hardware, computer rooms (computing and storage) taking part to the data processing activities.
- The DPC software «suite» can run on any DCC.
  Software: codes (DA & Simu.) + services (LDAP, wiki, database) + OS

First solutions:
- Separation of hardware and software: light virtualization, ...
- Collaborative development: continuous integration, ...
- Fluctuations of computing load: hybrids cluster/cloud
DPC: history & status

- Previous studies:
  - Before 2011, LISA yellow books
  - eLISA/NGO yellow book
  - 2014: CNES Phase 0 for eLISA/NGO

- 2015: Start of the proto-DPC

- 2017: Proposal LISA

- 2017: DPC kickoff meeting

- In progress:
  - DPC Definition Document
  - Definition of the LISA Ground Segment with ESA

- Next: detailed definition in phase A
DPC: history & status

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- In progress:
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- Next: detailed definition in phase A

- Support LISA developments (simulation, data analysis - LISA Data Challenge)

- Prototyping future DPC
-The DPC is a set of tools provided to ease the challenging data analysis tasks of LISA:

- Hardware (CPU and disk) usage not a major concern
- Data Analysis itself is challenging: lot of unknowns, complex noises and pre-processing

=> Keep a simple and easy to use DPC infrastructure.

- How IT will look like in 10 years? Will virtualization be the next standard?

- Our guideline: The DPC has to be easy-to-use, simple, flexible and easily upgradeable until the end of the mission.
Development environment: in production

- **Goals**
  - Ease the **collaborative work**: reason why it’s already started
  - During the operation: guarantee **reproducibility** of a **rapidly evolving** and composite DA pipeline
  - In fine: **keep control** of performance, precision, readability, etc

- **Use existing standard tool**
  - **Control version system** to keep track of code revision history, manage teams and workflows.
  - **Continuous integration** (like in Euclid, LSST): suite of non-regression tests automatically run after each commit
  - **Docker image**: a way to encapsulate source code + its execution
LISA proto-DPC

- Development environment: in production
  - Done:
    - Simple install of open and standard tools: Jenkins, SonarQube, gitlab CI
    - Worked on moving from 'simple' to 'automatic' using Docker
    - More projects, more users to come.

More images and details are shown on the screen, including a screenshot of a Jenkins dashboard and a webpage for LISA CI.
LISA proto-DPC

- **Data basis & data model: in R&D**
  - **Motivations**
    - Data sharing among people and computing centers
    - Mainly processed, temporary or intermediate data: need meta data management to use them
    - A lot of information: a web 2.0 (intuitive) interface is mandatory (search engine, DB request, tree view to show data dependancies, etc)
  - **Context**
    - Not big LISA data volume
    - But still implies some specific developments even if using standard data format. One has to define LISA data model first ...
      - LDC, simulations, LPF data
      - Django website + its sqlite DB: first version ready
LISA proto-DPC

Execution environment: in R&D

Objectives: a composite computer center

- Pooling of CPU resources with a single scheduler for all DCCs
  - the user-friendly way to go
  - a dynamic CPU pool to adapt the resources to the actual needs (the economic way)
  - transferring data if needed

- Assumptions
  - it’s easy to plug new hardware
  - it’s easy to transfer data

same principles than grid computing with a shorter learning phase.

R&D activities

- Docker orchestrator R&T study performed by CNES
- APC involved in the French cloud network
- Doing some actual testing of cloud platform and containers orchestration (singularity).
Conclusion

- LISA in phase 0/A: Ground Segment in definition

- First mission of this kind $\Rightarrow$ some uncertainties (number of sources, data quality, unknown sources ...) $\Rightarrow$ flexibility + continuous evolution + computation load fluctuations

- Distributed Ground Segment: MOC + SOC + DPC running on DCCs
  - SOC: L0 $\rightarrow$ L1: calibration, pre-processing reducing noises
  - DPC: L1 $\rightarrow$ L2, L3: extract GW sources from TDI data (L1) to produce catalogs and science products (L2 & L3)
    $\Rightarrow$ Same shared software running on distributed infrastructure

- Existing LISA proto-DPC to:
  - Support LISA developments: simulations, data analysis (LISA Data Challenge)
  - Prototype for the future DPC
Thank you