LISA-OPS-RP-0001

Laser Interferometer Space Antenna (LISA)

Operations Concept

March 24, 2009

Submitted by: ______________________________ ________

Roger Diehl –- JPL/Caltech
JPL Mission System Engineer

Date

Approved by: ______________________________ ________

Moshe Pniel – JPL/Caltech
NASA Deputy Project Manager

Date

______________________________ ________

Mansoor Ahmed - GSFC
NASA Project Manager

Date

______________________________ ________

Alberto Gianolio - ESTEC
ESA Project Manager

Date

Table of Contents

List of Tables

List of Figures

1 Mission Overview

1.1 Mission Description

LISA is a space mission designed to measure gravitational radiation over a broad band at low frequencies from about 0.03 mHz to 0.1 Hz. The LISA Observatory will continuously monitor the entire sky for all sources across this band where the Universe is richly populated in strong sources of gravitational waves. The sensitivity of the instrument is such that many sources can be detected at distances right out to the edge of the observable Universe.

The LISA mission consists of the deployment and operation of three spacecraft in order to measure the strain in space-time caused by gravitational waves. The strain occurs in a plane transverse to the direction of propagation of the wave, and has a specific signature defined by the expected properties of gravitational waves – namely it stretches space in one direction and simultaneously shrinks it in the other, orthogonal direction. The science measurement is made by placing test, or proof, masses that are freely falling in inertial space (responding only to gravitational forces) to mark locations in space-time, and using laser interferometry to measure changes in their relative separation.

LISA measures time-varying strains in space-time by interferometrically monitoring changes in 5 million kilometer baselines. The three baselines extend between three spacecraft orbiting the Sun in a formation 20° from the Earth as shown in Figure 1. The orbits are chosen to keep the three baselines as close to equal as possible over the mission lifetime. The spacecraft at the corners house two proof masses and interferometry equipment.

The three baselines form a nearly equilateral triangle that appears to cartwheel around the Sun once per year. The measured baselines extend from a proof mass in one spacecraft to another proof mass in a distant spacecraft. Hence the proof masses are the measurement fiducials defining the endpoints of the monitored distance. The orbits of the three spacecraft are nearly identical except for the phasing of their inclinations. The plane of the triangle is inclined 60° to the Earth's ecliptic plane. This geometry has the added benefit of a very benign environment, and a constant solar illumination angle on the spacecraft, thereby reducing unwanted disturbances.

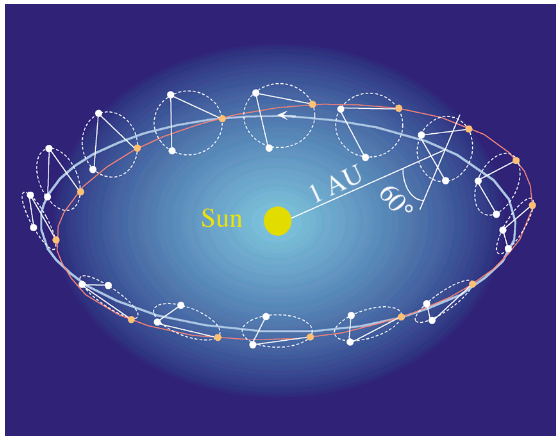


Figure 1. LISA Orbits do not Require any Regular Adjustments

The LISA orbits do not require any regular adjustments to maintain the formation throughout the life of the mission. The spacecraft are represented by 3 dots in the snapshots of the formation's annual motion around the Sun. The orbit of one spacecraft is traced by the inclined circle running through the same dot in each snapshot.

The proof masses are protected from disturbances by careful design and "drag-free" operation. In drag-free operation, the mass is free-falling, but a housing around the proof mass senses the relative position of proof mass and spacecraft, and a control system commands the spacecraft's thrusters to follow the free-falling mass. This can be done with two proof masses, following each in only its sensitive direction. Drag-free operation keeps force gradients arising in the spacecraft from applying time-varying disturbances to the proof masses.

The distance measuring system is essentially a continuous interferometric laser ranging scheme. Lasers at each end of each arm operate in a "transponder" mode. A beam is sent out from one spacecraft to a distant one. The laser in the distant spacecraft is phase-locked to the incoming beam and returns a high power phase replica. When that beam returns to the original spacecraft, it is beat against the local laser. Variants of this basic scheme are repeated for all long baselines, and the lasers illuminating different baselines are also compared. Optical path difference changes, laser frequency noise, and clock noise are determined.

The disturbance spectrum and the noise floor of the ranging system conspire to give a useful measurement bandwidth from 3×10^{-5} to 0.1 Hz. The three arms can simultaneously measure both polarizations of quadrupolar waves. The source direction is decoded from amplitude, frequency, and phase modulation caused by annual orbital motion.

The LISA measurement concept is presented in greater detail in the *LISA Mission Concept Document*.[1]

1.2 Operations Concept

The LISA operations concept has been developed to provide simplicity that reduces operations risk and costs. LISA mission attributes that contribute to simplicity are

- **Single instrument mode:** The three spacecraft together form the LISA instrument. Once the three spacecraft have achieved their proper heliocentric orbits and the laser links have been established between all three spacecraft, the mission takes on a single monitoring mode.
- **No targeted observations:** LISA is a single instrument that will see all of the galactic sources simultaneously. Unlike other missions with multiple instruments there is no competition between instruments for observation time or spacecraft resources.
- **No formation maintenance maneuvers:** The heliocentric orbits of the three spacecraft are designed so that the Doppler rates between spacecraft stay within bounds to allow proper interferometric operation during the entire period of science operations. No maneuvers are required to maintain the formation between the three spacecraft. After delivery into the final science orbits the propulsion modules used to execute maneuvers are jettisoned.
- **Low DSN contact:** Interferometric data is collected and stored on board each spacecraft for 6 days and then downlinked to Earth. Every other day contact is made with one of the spacecraft to download telemetry from the previous 6 days and to upload any instrument or spacecraft commands needed to maintain the proper generation of the science data. If the instrument and spacecraft are working properly there may be no need to uplink any commands
- **Low telemetry data rates:** Telemetry will be generated onboard each spacecraft at a rate between 4 and 5Kbps. On a daily basis the 3 spacecraft together will generate a total of about 1.3 Gbit/day. This is lower than the daily data volume for other observatory missions such as HST (18 Gbit/day) and Spitzer (5.6 Gbit/day).
- **Reduced mission planning:** No instrument operations scheduling, no targeted observations requiring instrument slews, and no maneuvers during science operations means less mission planning.

A summary of key LISA characteristics is given in Table 1.

Table 1. LISA Characteristics

Metric	
Number of Modes	Launch Phase = 1 Cruise Phase = 4 Commissioning Phase = 2 Science Phase = 3
Number of spacecraft	3
DSN pass frequency	1 every other day
Onboard data storage per spacecraft	5GB
Recorded data per day per spacecraft	432Mb (5Kbps for 24 hrs)
Total mission data for 3 spacecraft	2.4 Tb
Time required to downlink 6 days data	8 hours @ 90kbps
Frequency of required commanding	Once every six days
Number of Ops shifts per day	1
High gain antenna slews	2 slews per spacecraft every 12 days
Ephemeris loads	Once every six days
Number of Maneuvers	Deterministic Mnvrs = 3 per spacecraft Traj Correction Mnvrs =5 per spacecraft

The operations concept for the flow of data (see Figure 2) is that spacecraft telemetry and science data after downlink to the Deep Space Network (DSN) are routed to a Mission Operations Center (MOC). Routine spacecraft operations are conducted at the MOC as well as instrument monitoring for health assessment. The science data receives initial processing at the MOC and then is sent to the Science Center where detailed analysis is performed to extract the gravity wave information from the data.

The various operations teams at the MOC and Science Center are shown in Figure 2. Section 2 of this document describes the activities that each of the operations teams performs. The role that each of the teams play during the various mission phases (launch, cruise, commissioning, and science operations) is discussed in Section 3. Rationale for team staffing during the various mission phases is also given.

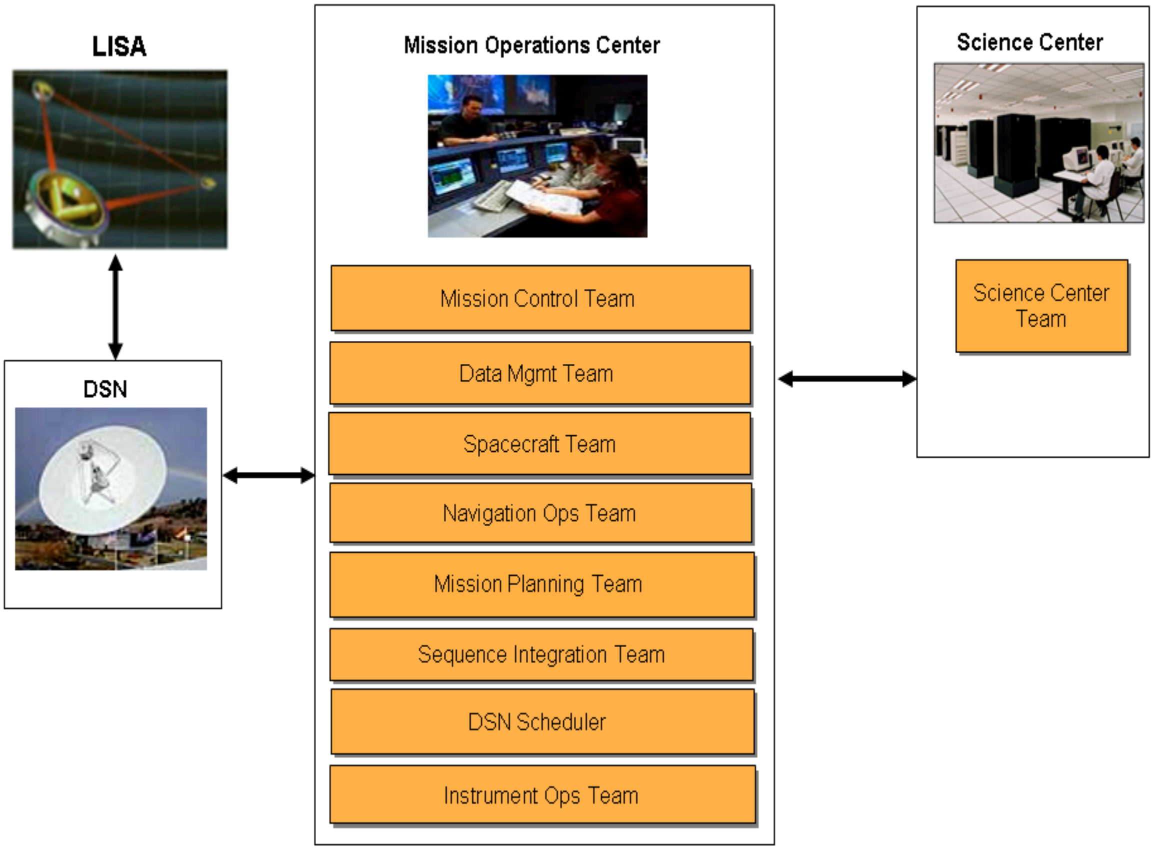


Figure 2. Mission Operations

2 Mission Operations Elements

2.1 Deep Space Network

The Deep Space Network (DSN) will provide command radiation, telemetry reception, and navigation services to the LISA Project. Specific services that are provided are

- Prior to launch, supports the design and development of the spacecraft telecommunications hardware, the mission operations system, and the operations concept.
- Provides a simulator for verifying compatibility of the flight hardware during integration and test.
- Receives requests for contacts, files and command sequences from the Mission Operations Center.
- Transmits commands and files to the three spacecraft.
- Schedules passes with the network of 34-meter antennae, reconciling competing demands from other users.
- Delivers tracking and navigation data, de-commutated telemetry, and event logs back to the Mission Operations Center

2.2 Flight Operations

Spacecraft and instrument operations will be conducted at the Mission Operations Center (MOC). The key operations functions are described next.

2.2.1 Mission Control Team

The Mission Control Team has the basic responsibility of monitoring and controlling the spacecraft. Specific activities include

- Radiate commands to all three spacecraft
- Monitor spacecraft engineering telemetry
- Perform real time analysis and characterizations of performance parameters
- Contribute to definition and correction of spacecraft anomalies

2.2.2 Data Management Team

The Data Management Team is responsible for the processing, storage and distribution of spacecraft and instrument data. Specific duties include

- Create channelized engineering telemetry for real time monitoring
- Remove spacecraft headers from raw telemetry received from DSN to create Level 0 products
- Deliver Level 0 products to Spacecraft Team and Instrument Operations Team
- Locally archive raw telemetry and Level 0 products

2.2.3 Spacecraft Team

The analysis of spacecraft performance and health and the planning of future spacecraft activities are performed by the spacecraft team. Detailed activities include

- Monitor, analyze and characterize spacecraft health including thermal, telecom, consumables such as propellant, and flight software
- Identify anomalous conditions and work their resolution
- Participate in command generation
- Coordinate with Navigation Team on spacecraft maneuvers
- Operate flight testbeds

2.2.4 Navigation Operations Team

The Navigation Operations Team is responsible for those functions required to deliver the three spacecraft from launch into their final operations orbit. After the operations orbit is achieved the propulsion module is dropped off since additional maneuvers are not required. Activities include

- Perform trajectory analysis
- Perform orbit determination
- Design cruise phase maneuvers
- Create maneuver commands for incorporation into command sequences

2.2.5 Mission Planning Team

The Mission Planning Team plays a lead coordination role in the planning and organizing of mission activities. Specific activities include

- Provide high level integration of mission resources required for activity execution
- Plan use scenarios with other teams
- Design operational procedures
- Support development of flight operations plan
- Develop contingency plans
- Interface with Science Center to coordinate observation strategies
- Work telemetry return priority schemes

2.2.6 Sequence Integration Team

The Sequence Integration Team develops and integrates the sequence of commands to control spacecraft and instrument activities. Specific activities include

- Receive and integrate commands from Spacecraft Operations Team and Instrument Operations team into command sequences
- Test command sequences in project testbed prior to radiation
- Prepare predictions of spacecraft state after command execution for comparison against real time telemetry results

2.2.7 DSN Scheduler

It is necessary that that mission operations, represented by the DSN scheduler, participate in the DSN allocation process to ensure that critical DSN resources are available to the Project. The DSN scheduler does the following.

- Schedule DSN antenna resources to meet project needs
- Resolve conflicts in antenna coverage requirements between LISA and other projects
- Maintain accurate allocation files of scheduled resources and distribute to other operations teams

2.2.8 Instrument Operations Team

The Instrument Operations Team handles the instrument activities performed at the Mission Operations Center. These activities include

- Monitor sciencecraft instrument health
- Analyze, characterize, and calibrate instrument
- Provide instrument commands to Sequence Integration Team
- Interface with Science Center concerning instrument performance issues
- Remove LIMAS headers from Level 0 data products and correct for readout errors to create Level 1 science products
- Make Level 1 science products available to Science Center

2.3 Science Operations

The Science Center is where instrument performance and data quality is assessed. The time-series of phase measurements is processed here to identify and match strong signals, and build up a catalog of known sources. The signal from these sources can be subtracted from the raw data to reveal underlying weaker signals, and maintain the search for a diffuse background. The world-wide distributed team of Guest Investigators accesses the data through public networks, and performs focused investigations of specific sources and phenomena. More details of Science Center operations are given in the *LISA Data Analysis Document*[2] and *LISA Science Data Products Document.*[3]

2.3.1 Science Center Team

Data quality assessment and science product generation are performed by the Science Center Team. A list of activities performed by the Science Center Team is given below.

- Serve as primary repository for all mission data and science products. Level 1 products delivered to the Science Center will be archived.
- Create Levels 2,3, and 4 science products
  - Level 2: TDI observables
  - Level 3: Preliminary source lists, event alerts, and instrument noise information
  - Level 4: Lists of resolved sources, instrument noise model, diffuse source model, combined data model
- Produce periodic releases of final science data products and provide access to publicly released data products
- Perform data quality analysis of instrument telemetry and science products
- Perform trending and characterization of instrument telemetry for science team
- Provide instrument command inputs to Instrument Operations Team
- Perform data analysis required to generate event alerts for upcoming supermassive black hole mergers, and disseminate alerts to the science community
- Provide interface with Guest Investigators

3 Mission Phases

The LISA mission may be broken up into 4 distinct phases

- **Launch Phase**: This phase covers the first 30 days after launch. The activities include all the launch related activities leading to the separation of the three spacecraft on their trajectories.
- **Cruise Phase**: This phase covers the 14-month period during which the three spacecraft move away from the Earth to their respective operational orbits. The major cruise activities are the spacecraft maneuvers that are required to change the spacecraft trajectory.
- **Commissioning Phase**: This phase covers the 4-month period to achieve the science mode configuration required for science operations. Key activities include acquisition, drag-free testing, and instrument calibration.
- **Science Operations Phase**: This phase covers the 5-year period during which science data is collected. Activities for this phase include the generation of science data products, health monitoring of the spacecraft and instrument, and the planning and execution of downlinks every other day with one spacecraft.

A mission timeline is given in Figure 3 showing placement of the spacecraft maneuvers for each of the three spacecraft.

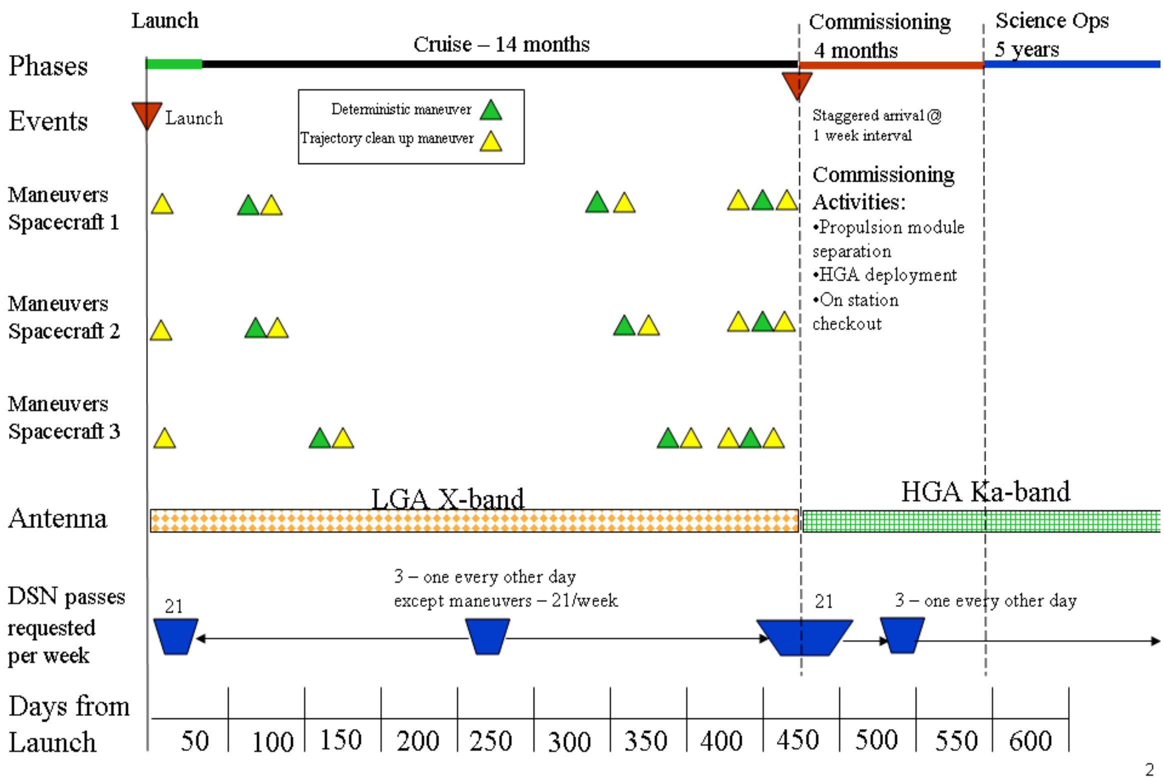


Figure 3. Mission Timeline

The total workforce profile for all the operations teams is given in Figure 4. The workforce ramps up to its maximum size during the late cruise, commissioning, and early portions of the science operations phase. Once the spacecraft and instrument are working properly staffing is reduced. Staffing profiles and rationale for each of the mission phases are given in the following subsections.

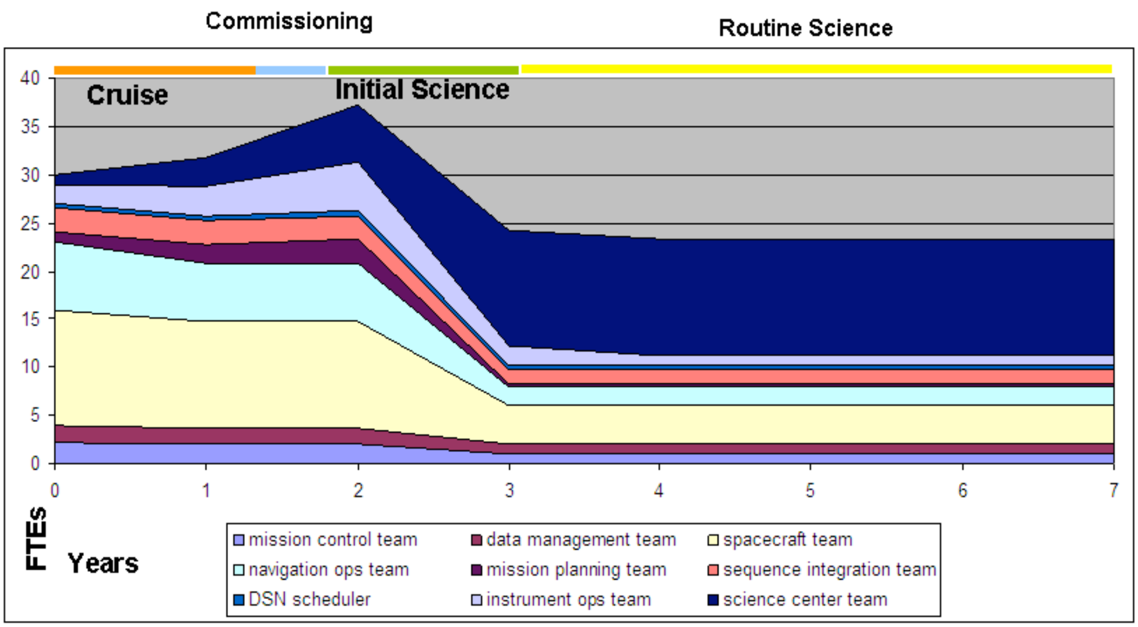


Figure 4. Mission Operations FTEs

3.1 Launch Phase

The launch phase contains the following critical activities.

- **Launch:** An Expendable Launch Vehicle (ELV) will launch the entire stack (the three integrated spacecraft) from Kennedy Space Center (KSC) into a heliocentric orbit with a period of a few weeks longer than a year, so that after one orbit the Earth will be 20 degrees away from the spacecraft constellation.
- **Spacecraft separation:** Separation of the stack from the second stage of the ELV will occur approximately five minutes after the injection burn. Ten minutes after separation of the stack the spacecraft will separate from each other with 1 m/s ΔV. After an appropriate interval, allowing for sufficient separation between spacecraft, each spacecraft will use thrusters located on the propulsion module to orient its solar cells to the Sun. The spacecraft battery is sized to allow for approximately three hours of operation prior to sun acquisition, although nominal acquisition will occur as early as one hour.
- **DSN acquisition:** After separation from the launch vehicle or alternatively after a ground station comes into view approximately an hour after launch, each spacecraft will maintain continuous communications with the ground using omni antennas to allow initial orbit determination and to downlink engineering status

data. After the spacecraft power levels are sufficient, each spacecraft will perform an initial functional checkout. Continuous communications will be maintained until the end of the Launch Phase to allow daily orbit determination updates.

- **Near-Earth trajectory correction maneuvers:** Five, eight, and eleven days after launch respectively, trajectory correction maneuvers (TCM) will be performed by one of the spacecraft to correct launch errors. Because liquid rocket injection errors are expected to be small these TCMs should be less than 10 m/s. These TCMs will also allow calibration of the spacecraft thrusters that will be used for the deterministic transfer maneuvers.

Operations Workforce Considerations: The operations teams staffing for the launch phase is shown in Figure 5. Launch Phase FTEs. The spacecraft team is at maximum staffing at launch and for the first several months of cruise to provide health monitoring and characterization of each spacecraft. There will be a dedicated system engineer for each spacecraft and shared subsystem engineers. During times of high critical activity such as launch there will be dedicated engineers for some subsystems such as attitude control.

During the first month after launch the Mission Control Team provides around the clock command and telemetry support for the daily DSN passes with each spacecraft. These passes provide the tracking data for the Navigation Team to design the first series of TCMs for each spacecraft.

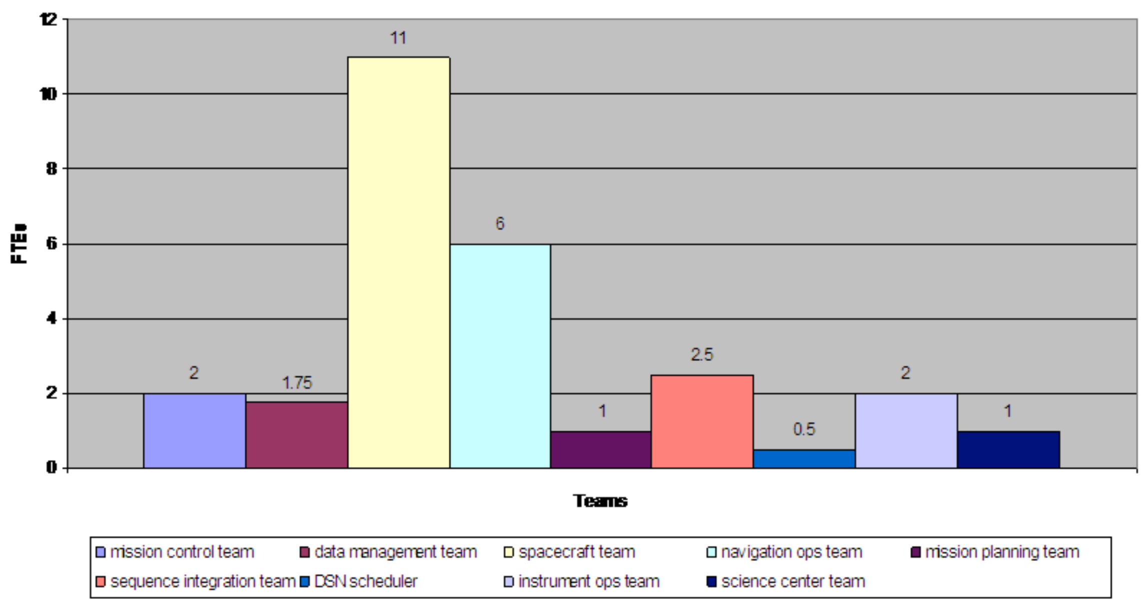


Figure 5. Launch Phase FTEs

3.2 Cruise Phase

During the cruise phase the following activities take place.

- **Spacecraft health monitoring**: During the majority of the cruise phase the spacecraft are in a sun-pointing attitude with minimal active operations. Engineering telemetry is collected during this time and formulated into packets for storage and transmission to the ground at the next communication window. The spacecraft health monitoring telemetry will include spacecraft attitude, propulsion module thruster usage, solar array output, and temperature monitoring. It is unlikely that much payload commissioning can be performed during the cruise phase. However there is plenty of time if useful functional checks can be done that are compatible with the cruise configuration.
- **Maneuver design and execution**: The major cruise activities for the spacecraft are the planning and execution of 8 maneuvers per spacecraft over a 14-month time period. Each of the spacecraft will require three large deterministic transfer maneuvers (DTMs) to transfer from launch to its respective operations orbit that establishes the triangular configuration. Fortunately these maneuvers may be designed to occur at different times to smooth out the operations team workload. Each of these DTM maneuvers will require a correction maneuver one week afterward to compensate for execution errors.
- **Operations orbit delivery**: At the end of the cruise phase each spacecraft performs the final DTM which establishes the operational orbit for the next 5 years. The cruise trajectories are designed to provide staggered arrivals with a two week separation. This final DTM for each spacecraft will be preceded by a correction maneuver 7 days earlier to correct any position delivery error. An additional final cleanup maneuver will be scheduled for two weeks after the DTM. This final cleanup maneuver will adjust the spacecraft velocity so that period of the achieved orbit will preserve the stability of the triangular configuration for the next 5 years. Final delivery of each spacecraft is accomplished by separation of the propulsion module using a spring mechanism to impart a 3 cm/s separation velocity. The delivery target for each spacecraft is rendezvous with a point on its respective operations orbit within 500 km in position and 0.1 m/s in velocity and with an achieved heliocentric period within 38 s of nominal.
- **DSN passes**: Communications during most of the interplanetary transfer will be a pass weekly for each spacecraft with Doppler and range data being taken for orbit determination. This will be increased to daily passes starting one week before the first two DTMs and two weeks before the final DTM for each spacecraft; the daily passes will continue for each spacecraft until one week after the last TCM for each DTM.

Operations Workforce Considerations: The operations teams staffing for the cruise phase is given in Figure 6. During the cruise phase there will be off-loading of some of the spacecraft subsystem engineers (i.e. thermal and power) as the spacecraft becomes better characterized and spacecraft analysis tools are recalibrated and refined. After the jettisoning of all the propulsion modules the propulsion subsystem engineer is no longer needed. In the event of any spacecraft problem subsystem engineers will be brought back onboard as needed to resolve the problem.

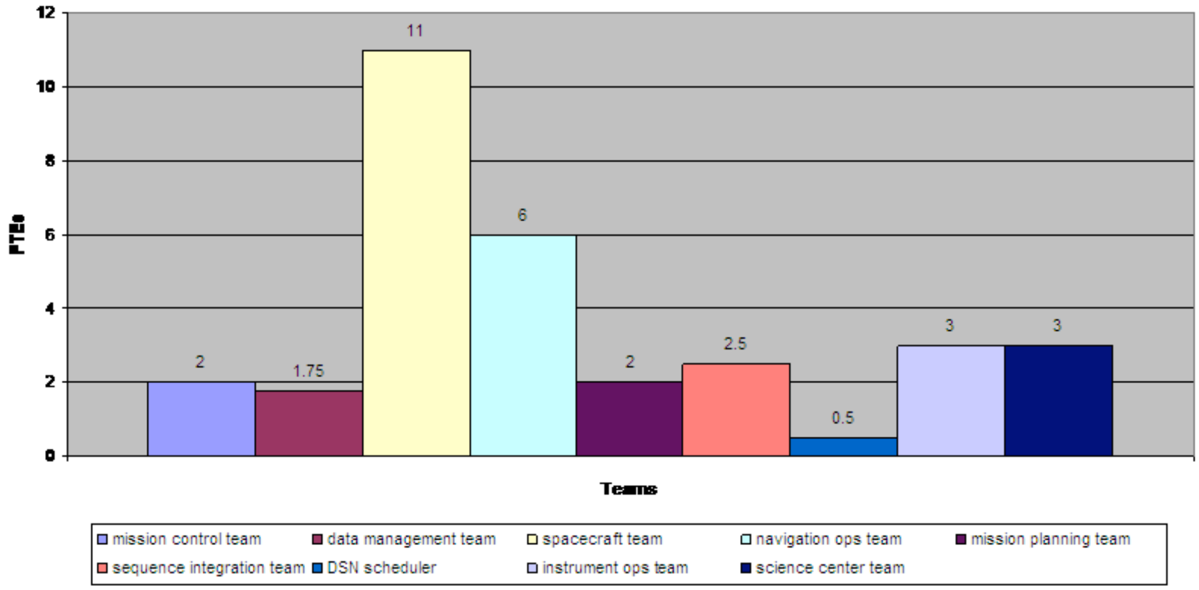


Figure 6. Cruise Phase FTEs

3.3 Commissioning Phase

During the commissioning phase the following activities take place.

- **Drag- free control testing**: The commissioning phase begins with spacecraft functionality testing that could not be accomplished during the cruise phase. This includes micro-propulsion calibration, and thermal system performance when the payload is fully operational to check the full capability of the power subsystem. On the payload side the complete instrument must be checked out. This involves GRS test and calibration, telescope pointing mechanisms, point-ahead mechanisms, lasers, and phasemeters. The main goal of the early commissioning phase is to achieve a complete drag-free control of the spacecraft and to bring all systems to a state from which the acquisition phase can be started. Continuous communication is required from one day prior to the beginning of drag-free testing through successful testing of one-week duration.
- **Acquisition**: The goal of acquisition is to bring the three spacecraft together to a science mode configuration that is only lacking some of the calibrations. All laser links between the three spacecraft need to be established. The main task of ground operations during the acquisition phase is to provide relative position and velocity information of all spacecraft to each of the three spacecraft.

  There are currently two strategies under consideration to establish the laser links. Both strategies are sequential, in that they establish one laser-link at a time.

The first acquisition strategy, referred to as the **defocus strategy**, defocuses the outgoing laser beam to an extent that it covers the uncertainty cone about the location of the receiving spacecraft. The process then utilizes a number of pointing sensors, each with increasing resolution but diminishing field of view, to align the laser beam and establish heterodyned measurements.

The second strategy, referred to as the **scan strategy**, relies on scanning the outgoing laser beam to cover the uncertainty cone. One spacecraft would shine its laser at various discrete points within the cone of uncertainty. Once the incoming laser beam is detected, the receiving spacecraft points in the direction of the incoming light and turns on its local laser.

- **Instrument calibration**: Once all laser links have been established, the final instrument check-outs and calibrations can be performed. This includes:
    - laser beam far-field characterization
    - telescope phase-center characterization
    - inter-spacecraft communications
    - frequency switching coordination
    - determination of instrument noise levels
    - instrument performance evaluation

  This phase is complete when all spacecraft and payload functions have been checked in the operational mode and reviewed.

Operations Workforce Considerations: The operations teams staffing for the commissioning phase is given in Figure 7. A four-month period is planned for the individual and joint commissioning activities for all three spacecraft. The spacecraft subsystem engineers who were off-loaded for the cruise phase will return. There will be extensive interaction between the spacecraft and instrument teams. The Mission Control Team will have occasional heavy periods of activity building and testing of sequences required for commissioning. The Instrument Operations Team will be involved in instrument health monitoring and calibration, instrument commanding, and initial instrument data processing.

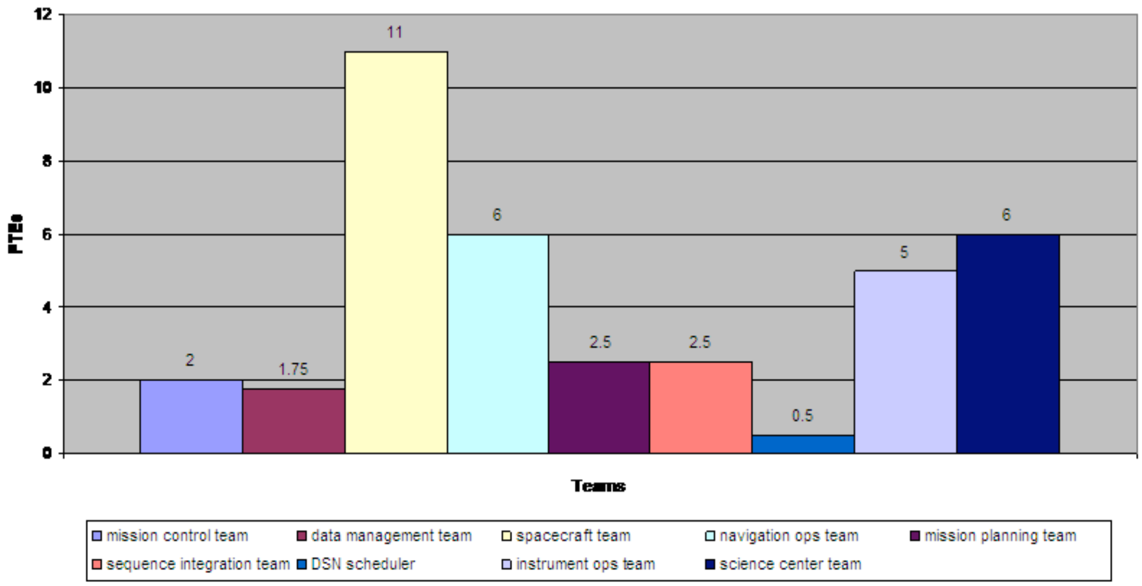


Figure 7. Commissioning Phase FTEs

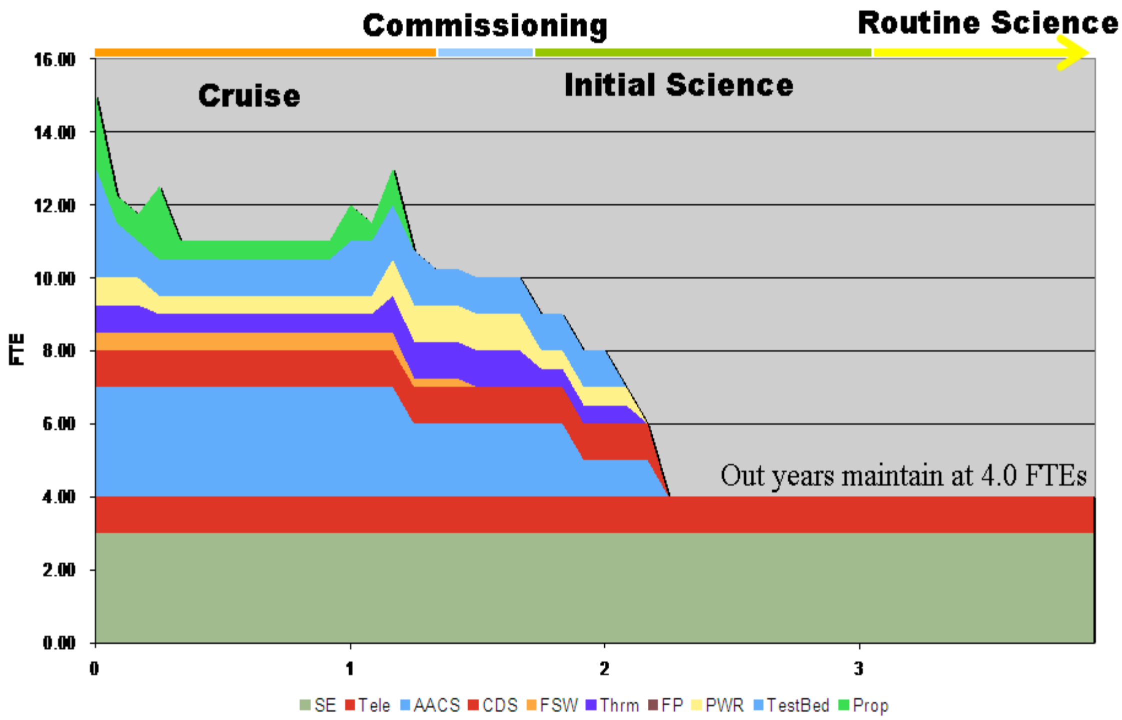
3.4 Science Operations Phase

During the science operations phase the following activities take place.

- **Data Collection**: Science data collection will continue for 5 years until end of mission. Science operations are particularly simple as there is a single operating mode wherein data is collected. The major activities in support of data collection are the planning and execution of the downlinks every other day with one spacecraft and the health monitoring of the spacecraft and instrument.
- **Science Product Generation**: The science products, as described in Section 2.3.1 are generated at the Science Center.
- **Decommissioning**: At the end of the science operations phase decommissioning activities whereby the spacecraft is placed in a known passive state are performed. The remaining fuel contained in the micro-propulsion system will be expended to a safe level. All systems will be powered off.

Operations Workforce Considerations:

A summary of the spacecraft operations team workforce profile is given in Figure 8. During early science operations the subsystem engineers characterize the spacecraft-payload interactions, and recalibrate analysis tools and procedures. After several months of science operations the subsystem engineers handover tools and procedures to the System Engineers and move to on-call status. The System Engineers then perform the routine spacecraft health monitoring and analysis. In the event of anomalies the on-call subsystem engineers return to assist in the anomaly resolution. For most of the science operations phase the spacecraft engineering team consists of the 3 dedicated system engineers and a single telecommunications engineer.



SE = System Engineering, **Tele** = Telecom, **CDS** = Command and Data System, **FSW** = Flight Software, **Thrm** = Thermal, **PWR** = Power, **Prop** = Propulsion

Figure 8. Spacecraft Team FTEs

The various operations teams such as Mission Control, Sequence Integration, and Data Management will be reduced during the first six months of operations as activities become routine, predictable and repetitious. The Navigation Team is significantly reduced from 6 persons to 2 persons as the jettisoning of the propulsion modules eliminates the need for any maneuver design. The Instrument Operations Team will also be reduced once instrument behavior has been characterized and calibrated, and processing has become routine.

Several times a year, maybe once a quarter, special galactic events such as the merger of two binaries will require daily downlinks with telemetry from all three spacecraft for a week or so in advance of the event. This may require some additional support from the Mission Control Team to support increased tracking and from the Data Management Team to handle increased data return volume and frequency. The Instrument Operations Team may be briefly increased to handle any special instrument commanding (e.g., increase sample rate during observation) and additional data processing.

The operations teams staffing for the science operations phase is given in Figure 9. Science Team staffing accounts for most of the workforce in this phase.

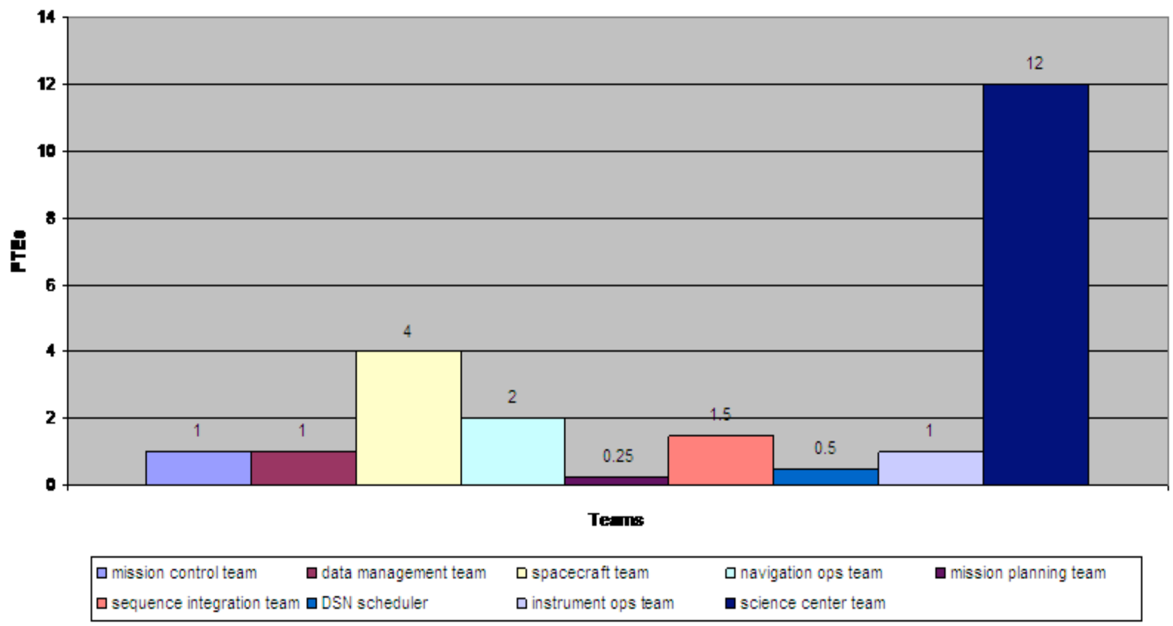


Figure 9. Science Operations Phase FTEs

All references are available at http://lisa.gsfc.nasa.gov/documentation.html.

[1]Laser Interferometer Space Antenna (LISA) Mission Concept, LISA-PRJ-RP0001 (2009).
[2]LISA Data Analysis Status, LISA-MSO-TN-1001 (2009).
[3]LISA Science Data Products, LISA-MSO-RP-001 (2009).