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Current LISA Spacecraft Design

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Abstract. The Laser Interferometer Space Antenna (LISA) mission, a space based gravitational wave detector, uses laser metrology to measure distance fluctuations between proof masses aboard three spacecraft. LISA is unique from a mission design perspective in that the three spacecraft and their associated operations form one distributed science instrument, unlike more conventional missions where an instrument is a component of an individual spacecraft. The design of the LISA spacecraft is also tightly coupled to the design and requirements of the scientific payload; for this reason it is often referred to as a "sciencecraft." Here we describe some of the unique features of the LISA spacecraft design that help create the quiet environment necessary for gravitational wave observations.

1. Introduction

The Laser Interferometer Space Antenna (LISA) mission will be sensitive to gravitational waves from astrophysical sources such as black hole, white dwarf, and neutron star binaries. LISA is comprised of three identical spacecraft separated by 5 million kilometers nominally forming an equilateral triangle. Each spacecraft (S/C) encompasses two freely floating proof masses that are the references for the gravitational wave measurement. Each leg of the triangle acts as a single arm of an interferometer that is used to measure any change in the distance between the distant proof masses.

The current design of LISA requires that all spurious accelerations of the proof masses be reduced to a level below $3\times10^{-15}(1+(f/8\text{mHz})^4+(0.1\text{mHz}/f)^2)^{1/2}$ m/s^2/$\sqrt{\text{Hz}}$ within the measurement bandwidth. A detailed noise budget was developed that set the required level of all known disturbance effects [1,2]. There are two types of contributors to this noise: effects that act directly on a proof mass (such as magnetic field fluctuations, voltage and charge effects, and thermally driven gas and radiation effects), and effects that couple S/C motion (caused by fluctuations in the forces acting on the spacecraft, such as thruster noise and variations in the solar photon pressure) to a proof mass through spatial gradients of the static force fields (gravitational, electric, etc.).

The design of the LISA S/C is driven by the need to keep the proof masses as undisturbed as possible by providing a quiet and stable environment. All the elements used for this purpose are grouped together into what is called the Disturbance Reduction System (DRS). The DRS consists of a set of sensors, actuators, and the control laws that bind them together to meet the disturbance and pointing requirements during LISA science operations. It also includes design features, such as thermal and magnetic shields, that are implemented to keep disturbances from reaching the proof masses. In this paper, we discuss how the current design of the LISA S/C supports the requirements of the DRS by creating the necessary environment for the gravitational wave observations.

2. Mechanical Design

The primary S/C structure consists of honeycomb panel upper and lower decks with aluminum alloy exterior sidewalls and a thermally isolated honeycomb panel solar array deck. Each of the three S/C will be nested inside of a propulsion module with the three propulsion modules stacked into a column inside the launch vehicle payload fairing. The stack design was chosen to carry the launch loads through the propulsion modules' outer shells, thereby isolating the S/C from the direct launch loads. A separation system, located on the bottom deck will serve to jettison the S/C from the propulsion module once the S/C has reached its operational orbit.

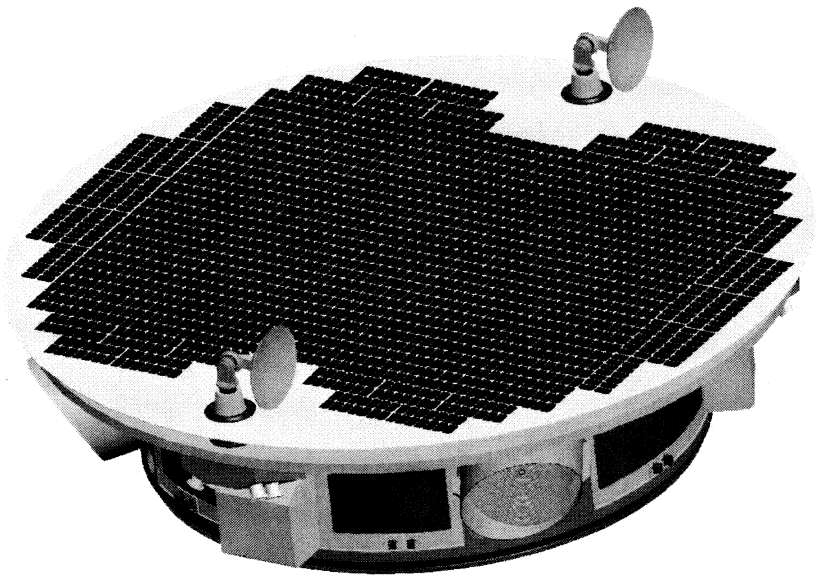

Figure 1. Top view of the LISA Spacecraft.

The S/C bus structure is designed seamlessly with the scientific payload. The optical assemblies are contained within thermal shrouds and incorporate the use of flex-pivots for rotational motion. The electronic boxes are mounted directly onto the bottom deck panel and the exterior wall. The current design philosophy to isolate the payload and bus electronics from solar heat input and to reject extraneous electrical waste heat into space means that mounting of any electronic components to the top deck panel is avoided.

In addition to housing the payload, the S/C bus structure must also provide mounting accommodations for the high gain and omni antennas, sun sensors, star trackers, and micronewton thrusters on the outside of the main structure as seen in figures 1 and 2.

All initial integration activities will occur with the solar array and top deck components removed, including the panels themselves. The solar array and top deck components will be installed in the last steps of assembly. In order to accommodate removal and replacement of components, maintenance or repairs after the S/C is completely assembled, access panels are provided at six locations around the circumference of the bus structure.

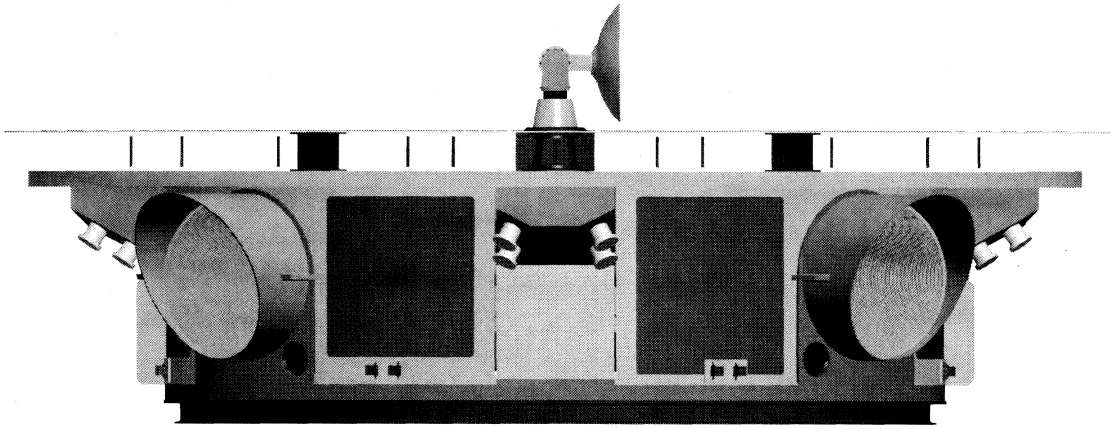

Figure 2. Side view of the LISA Spacecraft.

3. Thermal Design

The LISA thermal design benefits greatly from the stable thermal environment provided by the operational orbits, as the S/C operate far from the earth where eclipse, albedo, and planetary heating effects are negligible. The orientations of the S/C are held at a constant 30° angle between the S/C normal and the solar vector, providing for a stable solar heat input. All electrical components are power stabilized to provide constant power dissipations, with switching operations minimized, particularly within the LISA measurement bandwidth. The shape and design of the S/C also provides for further thermal stability [3].

The LISA S/C thermal design has two primary functions: protect the payload and mission critical components from the harsh thermal environment of space throughout the mission, and maintain thermal stability within the LISA measurement bandwidth during the science phase of the mission. Survival of the instrumentation during the cruise phase is achieved through the use of heaters and multi-layer-insulation on the S/C and propulsion module. Active thermal control is applied using thermostats and thermistors located inside the electronics boxes during the cruise phase. During the science phase, the survival heaters are turned off, being supplemented by electronics box waste heat. Current thermal analysis indicates that the required thermal stability during the science phase can be achieved without the use of active temperature control through the use of successive thermal shields [4].

The first layer of thermal isolation is provided by the solar array deck. The deck will be made of aluminum or composite honeycomb. The sun facing facesheet of the deck contains either gold or vapor deposited aluminum coated optical surface reflectors and solar cells. The solar array deck is isolated from the bus structure using low conductivity flexures. The top surface of the top deck panel is gold coated to minimize absorption of any radiation from the bottom surface of the solar array deck. A high emissivity coating around the bottom outer edge of the solar array will facilitate heat rejection to space. This isolation results in less than 1% of incident solar energy being transferred to the structure.

A second layer of isolation is provided by the payload shield, which is gold coated on the inside and outside surfaces in order to minimize the absorption of any radiated energy (e.g. electronic box radiated heat). Low conductivity standoffs are also placed between the payload shield and the bottom plate to reduce the conduction path.

The last layer of payload thermal isolation is provided by an internal shield, which is also gold coated on both sides and includes low conductivity mounts. This helps to shield the optical bench from any disturbances or gradients in the payload shield.

Finally, the cylindrical exterior wall and bottom deck of the S/C function as radiators to reject electronics waste heat. The area and coatings of these surfaces are optimized to keep the temperature inside the S/C within the operating range of the electronics without the need for additional heaters.

4. Self-Gravity

The gravitational field at the proof masses must be kept as small, flat, and as stable as possible. The static gravitational field at the proof masses must be kept below $5x10^{-10}$ m/s^2 along the measurement axes. In meeting this requirement, the amount of static force that must be compensated for by the gravitational reference sensor electrodes will be minimized. This is important for two reasons: first, the force fluctuations generated by the applied compensating electric field are proportional to the total force applied by that field. Fields in both the measurement axes and the other degrees of freedom are important as some of the force fluctuations from other directions will leak into the measurement axis through cross-couplings. Second, the compensating electric field creates a virtual spring between the S/C and the proof mass. The residual motion of the S/C will couple through this stiffness causing an acceleration disturbance to the proof mass [2].

The gradient of the gravitational field at the proof mass locations must be kept below $3x10^{-8}$ s^{-2}. The gravity gradient creates a virtual spring between the S/C and the proof mass. The residual motion of the S/C will couple through this stiffness causing an acceleration disturbance to the proof mass. Finally, fluctuating distortions of the S/C will change the gravitational field. These distortions must be minimized such that their acceleration disturbance to the proof masses is kept below $5x10^{-16}$ m/s^2/$\sqrt{Hz}$.

These self-gravity requirements are met through careful mass balancing of the spacecraft components and the minimization of moving parts. The use of items such as deployed solar arrays are ruled out due to both their uncertain positioning and the gravitational field fluctuations due to thermal distortions. The S/C structure is also designed to minimize thermal distortions and excitable vibrational modes.

The self-gravity requirements flow down to set requirements on the knowledge of the mass properties and placement of all hardware in the LISA S/C. The S/C can be divided into zones where all items within a zone have the same knowledge requirements. This does not set the accuracy needed in producing each part; rather it sets the accuracy needed in measuring and identifying the part after it is manufactured. In other words, it defines how well the part must be weighed, measured, and placed within the S/C. A detailed discussion of self-gravity analysis and balancing can be found in references [5-7].

5. Magnetic Environment

The magnetic properties of the proof mass and characteristics of the magnetic field contribute to several effects throughout the DRS error budget. The leading effects are: the interaction between the fluctuating interplanetary magnetic field with the S/C magnetic gradient, fluctuations from the magnetic gradient induced current dissipations (Eddy current damping), and a fluctuating S/C magnetic gradient [2]. The current budget value for the magnetic gradient at the proof mass is $5x10^{-6}$ T/m. Magnetic gradient fluctuations must be kept below $2.5x10^{-8}$ T/m/$\sqrt{Hz}$ at 0.1 mHz at the proof mass locations.

The magnetic field inside the spacecraft is driven by the magnetically hot components. Magnetic parts are generally avoided in the LISA design, however it is not cost effective to completely eliminate them all. All magnetic items are tracked so that a magnetic budget can be maintained. The budget magnetic field should be easily met by placing all the magnetic components far from the proof masses and including a modest amount of magnetic shielding and compensation.

A number of design rules are available to minimize magnetic fields. The obvious solution is to minimize the use of magnetic material. Unavoidable permanent magnets can be compensated for with oppositely oriented duplicates such as a cold spare. The remaining permanent magnets can be shielded using high permeability foil magnetic materials such as METGLAS or VITROVAC. Twisted

pair is used for all wiring. Current loops in the power system is eliminated by using a star or single point grounding. No primary supply currents are allowed to flow through the S/C structure.

The solar array can be a very significant source of stray magnetic fields due to the large currents, however, its linear geometry makes it straightforward to cancel out by correct placement of forward and return interconnections using a technique called "backwiring." In backwiring the return wire from each string of solar cell modules is returned directly underneath the modules in that particular string and carefully routed along a line just behind the centerline of the modules. Each string and module of the string is self-canceling and does not depend on the magnetic field of an adjacent module or string for cancellation. If a module fails in flight the current in both the string and the return drop to zero simultaneously leaving no uncompensated currents in the array.

6. Attitude and Drag Free Control

The LISA attitude and drag-free control system is responsible for ensuring that the residual acceleration of the two proof masses fall below the LISA sensitivity requirements by providing tight pointing and translational control of the LISA spacecraft and its proof masses. Stringent requirements are placed on the rotational (8 nrad/$\sqrt{\text{Hz}}$) and translational dynamics ($1.5\times(1+(f/8\text{mHz})^4)^{1/2}$ nm/$\sqrt{\text{Hz}}$) of each spacecraft to ensure that the proper sensitivity for science measurements can be achieved. This is implemented by performing a number of control functions [8,9].

Along the two sensitive axes (telescopes' lines of sight), the S/C is controlled around the proof-masses such that all residual accelerations in the sensitive axes are minimized. In addition, the S/C follows the average out-of-plane motion of the proof masses in order to compensate for the solar radiation pressure. The control error signals are obtained from the optical and electrostatic readouts of the proof masses. The very sensitive optical proof mass metrology is used on the two sensitive axes in order to reduce the sensor noise in the generated force signals to the micronewton propulsion system. The drag-free control covers all 3 translational degrees of freedom of the S/C.

During science mode, the S/C attitude control is performed by feeding back the information from inertial wavefront sensing of the incoming laser light to the micronewton propulsion system. Since two telescopes are on-board and mounted at an angle of nominally 60 deg with respect to each other, inertial wavefront sensing provides a total of 4 tip and tilt error angles. By applying the corresponding geometric relations, these angles can be used to determine the complete S/C attitude error to align the telescopes with respect to the incoming laser beams as well as the angular error between the two telescopes.

Due to orbital mechanics, the angle between the two interferometer arms is constantly changing, therefore, this angle must be controlled as well. The information from the inertial wavefront sensing is used again to determine the angular error between the two telescopes. The measured angular error is used to generate a feedback signal for the optical assembly actuators. Note that one of the two optical assemblies will remain in a fixed position while the second one will be constantly actuated at 10 Hz (either assembly can be actuated, providing redundancy).

The constellation of three S/C rotates about the constellation center on a once per year period. Consequently, the three S/C are always moving relative to each other. Because of this motion and the 5 million km separation between S/C, the outgoing beam must be pointed ahead of the incoming beam in order to be directed towards where the distant S/C will be when the light arrives. This is accomplished by a point-ahead mirror that can be actuated. The mirror is actuated out-of-plane only, since that component of the point-ahead angle exhibits large variations throughout the year. The in-plane component shows a small variation about a fixed bias, which may be accommodated by a pre-fixed tilt of the mirror. The mirror pointing can be performed by a simple lookup table as the angles are slowly varying and are sufficiently predictable.

LISA requires micronewton thrusters to provide the fine spacecraft attitude and position control for drag free flight and beam pointing to the distant spacecrafts. The thrusters are operated continuously during science operations with their thrust levels set by the disturbance reduction system control loops. Three different thruster technologies are nearing flight readiness for LISA Pathfinder and have

demonstrated the LISA thrust and thrust noise requirements: the colloid micronewton thruster (CMNT) made by Busek Co. in Boston [10], the indium needle field emission electric propulsion (In-FEEP) thruster made by ARC Seibersdorf in Austria [11], and cesium slit FEEP (Cs-FEEP) made by ALTA S.p.A. in Italy [12].

At least six micronewton thrusters on each spacecraft must be operating continually during science operations for the entire LISA mission. Enough consumables are carried for the entire extended mission. With sunlight photon pressure as the largest external force acting on the spacecraft, the micronewton thrusters must produce on the order of 10 μN of thrust with better than a 0.1 μN resolution during science measurements. Furthermore, over the LISA science measurement bandwidth, thrust and thrust noise must be stable and within the error limitations of the DRS over the entire mission, < 0.1 $\mu N/\sqrt{Hz}$ (open loop) at the high end of the measurement band. Brief periods of higher thrust, >30 μN, may be required during tip-off recovery, constellation acquisition, and safe-mode operations.

7. Summary

The LISA S/C and scientific payload are tightly coupled into one seamless design in order to optimize the sensitivity to gravitational waves. While some of the LISA requirements are unique among spacecraft design (such as self gravity), the design principles and methodologies are familiar. Modeling and analysis of the current LISA S/C design indicates that these requirements can be met through standard engineering practices without the need for new technologies. For example, the self-gravity requirements can be met through careful tracking of the mass of all components. The level of precision may be more than a traditional space mission, but not beyond standard metrological techniques. With careful design and strong systems engineering, the LISA S/C will be ready to support the exciting astrophysical measurements from the first space based gravitational wave observations.

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