Laser Interferometer Space Antenna (LISA) Measurement Requirements Flowdown Guide

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1 Purpose

The purpose of this document is to outline the process by which the measurement system requirements are flowed down from the science requirements and to summarize the noise budget that has been developed to support them.

It is intended to outline at a high level the thought process and sketch out how the flowdown to measurement requirements works. It is not intended to replace the original references or to introduce new material.

2 Science Requirements

The LISA science requirements are set forth by the LISA International Science Team (LIST) in the LISA Science Requirements Document[1] (ScRD). The ScRD contains a set of science objectives in the form of Observation Requirements. The Observation Requirements are statements about specific astrophysical sources and their parameters that can be quantified sufficiently to predict the required sensitivity needed to make the observation. This required astrophysical sensitivity can then be compared against an instrument sensitivity model to determine if the requirement can be met. The instrument sensitivity model represents the top-level science requirements for LISA.

The sensitivity model is stated in terms of a strain amplitude spectral density $\sqrt{S_h}(f)$ as a function of frequency. Table 1 contains a summary of the model.

Table 1: Top Level LISA Science Requirements Summary

Quantity	Requirement
Strain amplitude spectral density	$\sqrt{S_h}(f) = (\sqrt{5}) \times (\frac{2}{\sqrt{3}}) \times T(f) \times \frac{\sqrt{S_{\delta x\_IMS}(f) + S_{\delta x\_DRS}(f)}}{L}$ where T(f) is a transfer function representing the LISA instrument response to a differential length change, usually calculated for the Michelson configuration
Single link IMS displacement noise amplitude spectral density	$\sqrt{S_{\delta x\_IMS}}(f) = \Delta X_0 \times 10^{-12} \frac{m}{\sqrt{Hz}} \times \sqrt{1 + \left(\frac{f_0}{f}\right)^4}$ $\Delta X_0 = 18$, $f_0 = 2$ mHz
DRS displacement noise amplitude spectral density	$\sqrt{S_{\delta x\_DRS}}(f) = 2 \frac{\sqrt{S_{\delta a\_DRS}(f)}}{(2\pi f)^2}$
Single proof mass DRS acceleration noise amplitude spectral density	$\sqrt{S_{\delta a\_DRS}}(f) = \Delta A_0 \times 10^{-16} \frac{m}{s^2\sqrt{Hz}} \sqrt{1 + \left(\frac{f}{f_H}\right)^4} \sqrt{1 + \left(\frac{f_L}{f}\right)}$ $\Delta A_0 = 30$, $f_H = 8$ mHz, $f_L = 0.1$ mHz
Measurement Band	0.03-100 mHz
Operational lifetime	5 yr
Operating interferometers	LISA shall be designed for 3 spacecraft with 6 working links (2 independent interferometers). A link is a one-way optical measurement between proof masses. Two links in opposite directions

Quantity	Requirement
	between a pair of spacecraft constitute a single arm. The design shall ensure 2 operating arms for the full mission duration.
Advanced notice of merger	Identify and announce the time of a massive black hole merger at least two weeks prior to the merger
Instrument noise monitoring	Distinguish between instrumental noise and gravitational wave signals above the sensitivity threshold when all three arms are available.
Observing interruptions	4 days uninterrupted data acquisition around merger time with 2 weeks advanced notice.

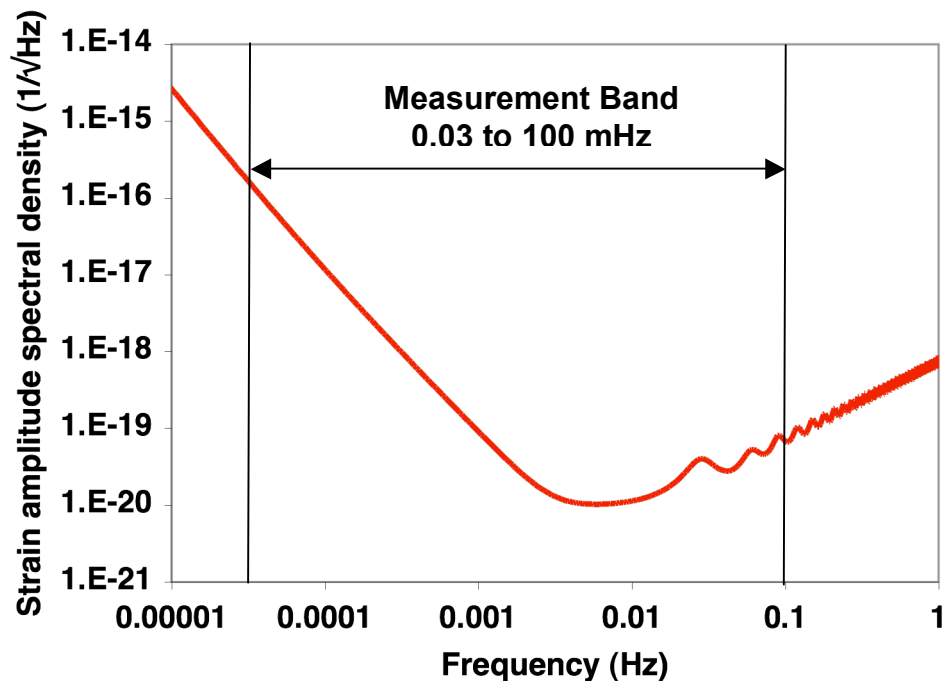The sensitivity curve defined by the model is shown in Figure 1.

Figure 1: LISA Sensitivity Curve. The strain amplitude spectral density of the Instrument Sensitivity Model is plotted. The measurement bandwidth extends from 0.03 mHz to 100 mHz.

3   Mission Requirements

The high level mission requirements are detailed in the Mission Requirements Document (MRD)[2]. They specify architectural choices and design constraints specific to the mission,

such as the number of spacecraft, the number and orientation of the arms, and the choice of laser interferometry as a measurement technique. These choices must be specified before the measurement system requirements can be fully defined. The focus in this document is on the measurement system requirements, including interferometry and drag-free control.

4 Measurement System Requirements

The measurement system requirements specify the detailed operation of the LISA mission from an engineering measurement system point of view with the specific architecture as defined in the MRD as a given. The measurement requirements are developed from the ScRD and the MRD together, and are contained in the MRD.

4.1 General measurement concept overview

The basic measurement is a determination of in-band changes to the separation between proof masses inside 3 drag free spacecraft in a triangular configuration. The drag free condition relies on sensing two of these free-flying cubical proof masses on each spacecraft and actuation of micro-Newton thrusters for precision control. There are three measurement arms and six links, where a link represents a one-way transit of an arm. The strain sensitivity of LISA is achieved by measuring picometer level changes out of the 5×10^9 meter separation between spacecraft.

A laser beam is sent from one spacecraft to a distant spacecraft where it is interfered with a small amount of light from the local laser. The picometer level of precision is realized by measuring the phase of the RF beatnote as recorded by a digital phasemeter with microcycle accuracy. Changes in separation are recorded as changes in the phase of the beatnote. The ability to reach the required sensitivity for the strain depends mainly on three factors:

- arm length
- accurate measurement of the relative displacement between two opposite PMs
- the ability to shield the proof masses from all substantial disturbances

The design of the LISA sciencecraft is driven by the need to keep the proof masses as undisturbed as possible. 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 local 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 shields, magnetic controls and self-gravitational force balancing, that are implemented to keep disturbances from reaching the proof mass (PM).

The heart of the DRS is the Gravitational Reference Sensor (GRS), which houses the PM. It provides sensing and forcing of the relative PM-spacecraft position and orientation along with other functions. Micronewton thrusters provide the actuation for controlling the position and orientation of the spacecraft (S/C) for drag-free operation as well as pointing the outgoing beams toward the distant S/C.

The Interferometry Measurement System (IMS) is the part of the measurement system that uses optical interferometry to measure the distance between proof masses. Because the interferometer arm lengths are neither equal nor constant, the raw data measurements taken on board the SC must be re-combined by post-processing using the Time-Delay Interferometry (TDI) algorithm [3,4]. One TDI algorithm is equivalent to synthesizing a particular equal length Michelson

interferometer as an output, called the X variable. This variable then enters the data analysis chain where it is used to extract the gravitational wave signals [5].

4.2 Measurement System Requirements

The measurement system requirements are derived from the strain sensitivity in a straightforward way [6] as outlined in Figure 2.
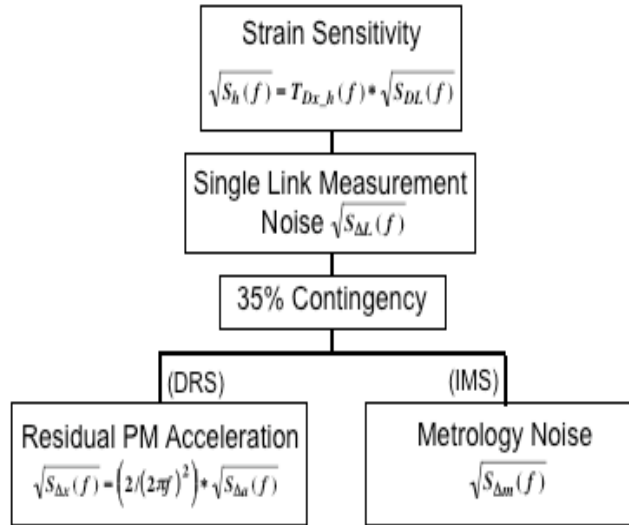

Figure 2: Summary of the requirements flowdown process from strain sensitivity requirements as specified in the ScRD to the acceleration and metrology noise requirements for the instrument. $\sqrt{S_h}(f)$ is the strain amplitude spectral density, $T_{\Delta x\_h}(f)$ is the transfer function for the LISA instrument response from a strain input to an equivalent Michelson interferometer, $\sqrt{S_{\Delta L}}(f)$ is the amplitude spectral density for total displacement noise from the instrument, and has two components - $\sqrt{S_{\Delta x_m}}(f)$ which is the displacement uncertainty from the interferometric measurement system, and $\sqrt{S_{\Delta x_a}}(f)$, which is the equivalent displacement sensitivity from the residual acceleration noise spectrum $\sqrt{S_{\Delta a}}(f)$.

Each measurement requirement is described by an amplitude spectral density, which is defined as the square root of the power spectral density for that quantity, indicated by a subscript. For example, $\sqrt{S_h}(f)$ is the amplitude spectral density for the gravitational wave strain, h. Amplitude spectral densities are convenient because the LISA instrument measures them directly. The strain sensitivity requirements are specified in the ScRD, and the transfer functions are defined by the instrument architecture and data processing algorithms (TDI). The following sections briefly describe each step indicated in the diagram.

4.2.1 The Single Link sensitivity

The measurement system requirements are determined from the ScRD strain sensitivity requirements by first determining the required equivalent "single link measurement noise". This determination requires knowledge of the system response to a gravitational wave. The response

to a gravitational wave is calculated with the TDI variables [3,4], which are sums and differences of the phases measured in each of the six links of the instrument combined in post-processing with suitable delays. If we take the noises in each of the links to be statistically independent, a transfer function can be defined with an equivalent single link noise as input.

The first step is to require that the system response to a gravitational wave is the same as the response to displacement noise. This is equivalent to saying that the signal to noise ratio (SNR) is one. We use the Michelson response function $T_{\Delta x\_h}(f)$ because it is the most sensitive and therefore provides the most stringent constraint. The response to a gravitational wave depends on the angle of incidence of the wave relative to the antenna orientation as specified by the angles ϕ,θ, and the orientation of the polarization, specified by the angle ψ. For simplicity, we average the response over all sky angles and polarization. The measurement requirements as an equivalent displacement noise are then given by

$$\sqrt{S_{h_{ScRD}}}(f) = \left\langle T_{\Delta x\_h}(f,\phi,\theta,\psi) \right\rangle \bullet \sqrt{S_{\Delta L_{noise}}}(f) = T_{\Delta x\_h}(f) \bullet \sqrt{S_{\Delta L_{noise}}}(f)$$

where $\sqrt{S_{h_{ScRD}}}(f)$ is the required strain sensitivity as a function of frequency as specified in the ScRD, $\sqrt{S_{\Delta L_{noise}}}(f)$ is the single link displacement measurement noise, and the angle brackets indicate an average over sky angle and polarization.
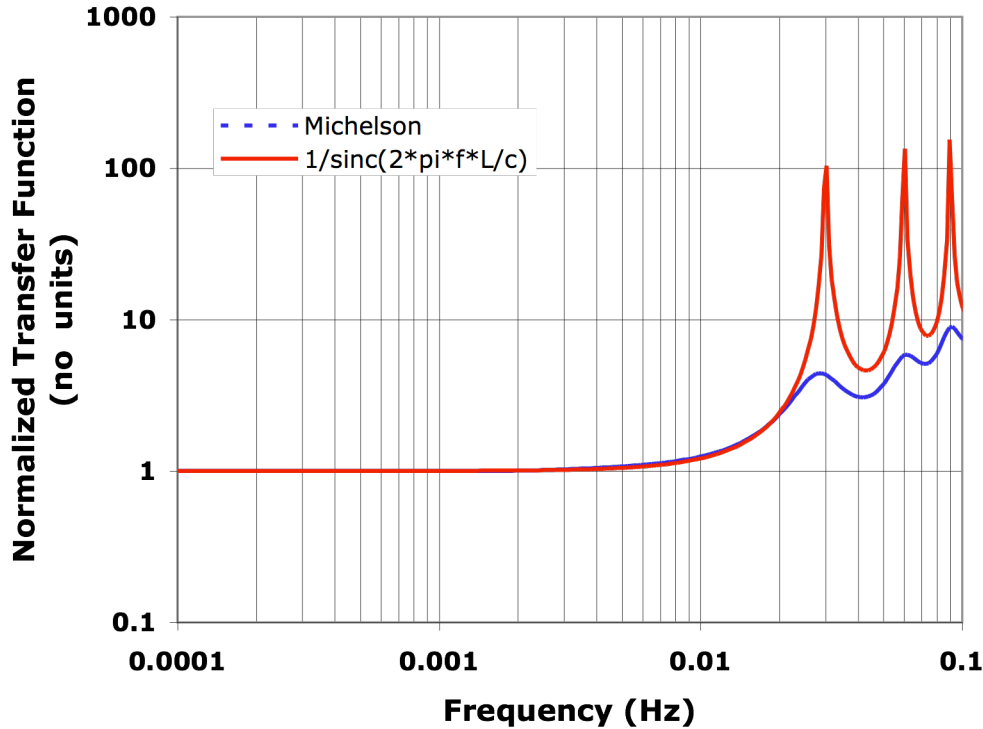

Figure 3: The simplified normalized transfer function (solid red curve) provides a conservative estimate for the full Michelson response (dotted blue curve) at high frequencies and agrees at low frequencies (after [7]) averaged over all sky positions and polarizations.

The full response function $T_{\Delta x\_h}(f)$ for strain from displacement is complicated because there are four different links involved. It has a response of zero for gravitational waves with frequencies that are multiples of the inverse round trip light travel time between sciencecraft. The actual Michelson response has a smooth response because we use an averaged form. Figure 3 shows the simplified form compared with the full Michelson response over the LISA bandwidth showing that the two agree at low frequencies and at high frequencies the simple response overestimates the sensitivity to instrumental noise and therefore provides a conservative estimate.
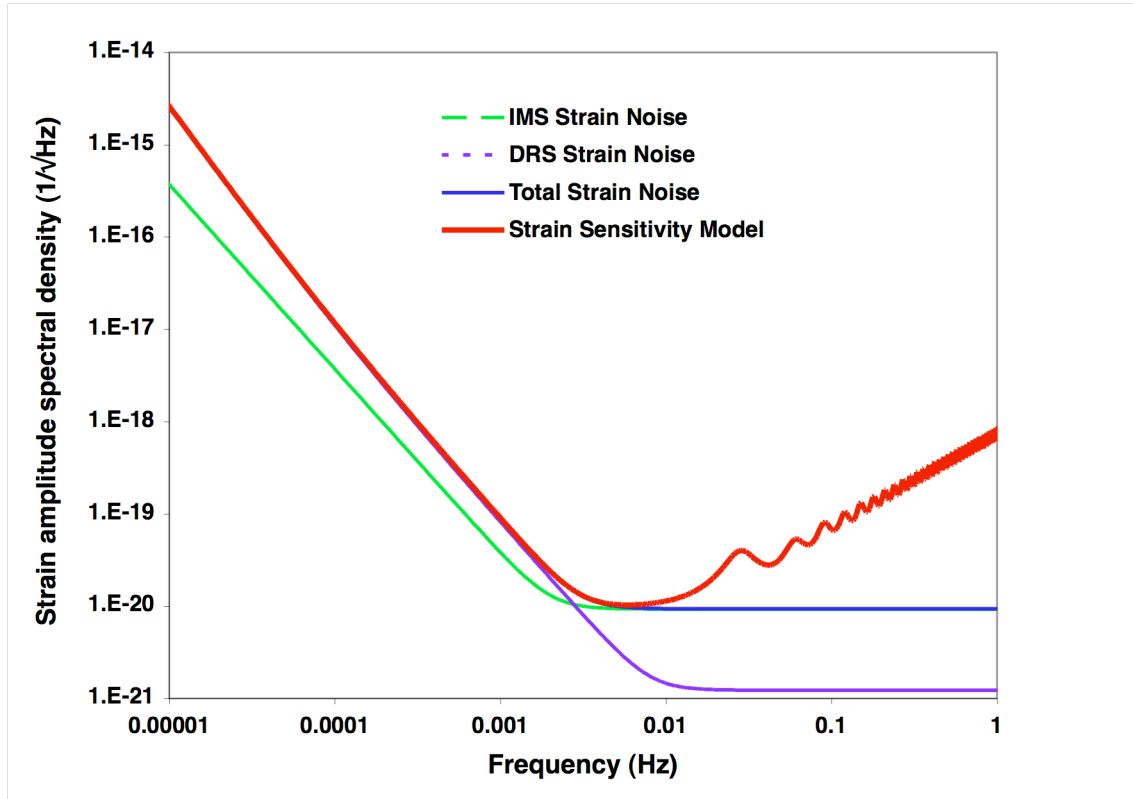

Figure 4: LISA Sensitivity model showing the total strain noise allocation as well as the separate allocations for the IMS and DRS. The strain sensitivity is the strain noise multiplied by the normalized transfer function from Figure 3. The engineering performance requirements are 35% lower than the allocations shown.

Figure 4 shows how the separate pieces combine to produce the strain sensitivity curve. The allocations for the strain noise for the IMS and DRS are shown separately, as well as the total strain noise. The strain sensitivity is calculated from the displacement noise by dividing by the arm length and multiplying by the normalized transfer function shown in Figure 3.

4.2.2 Performance Requirements

The measurement performance requirements are derived directly from the single link strain sensitivity requirements and are characterized as the square root of the power spectral density of relative displacement, in picometers per square root of hertz. The equivalent displacement measurement noise has two contributions, interferometry measurement system (IMS) or sensing

noise, and residual acceleration noise from forces acting on the proof masses, resulting from noise and errors in the disturbance reduction system (DRS). These contributions add incoherently to give the total equivalent displacement noise:

$$S_{\Delta L_{noise}}(f) = S_{\Delta x_{IMS}}(f) + S_{\Delta x_{DRS}}(f)$$

$$= S_{\Delta x_{IMS}}(f) + S_{\Delta a_{DRS}}(f)\left(\frac{2}{(2\pi f)^2}\right)^2$$

where the residual acceleration noise on a single proof mass $\sqrt{S_{\Delta x_{DRS}}}(f)$ has been converted to an equivalent displacement noise $\sqrt{S_{\Delta a_{DRS}}}(f)$ by integrating twice (which corresponds to dividing by $(2\pi f)^2$)), and multiplying by 2. There are 4 proof masses in a Michelson configuration, so if all are uncorrelated the total noise should be $\sqrt{4} = 2$ times the motion of a single mass.

For engineering design purposes, a 35% contingency is currently held by Mission Systems Engineering at the system level. This means that the instrument designs for the IMS and the DRS must be capable of meeting a requirement which is 65% of the total allowable error. This decomposition is not unique and is guided by current capabilities and best estimates.

5 Interferometer Measurement System (IMS) Requirements

The noise budget allocates a requirement on the IMS for a displacement uncertainty amplitude spectral density of:

$$\sqrt{S_{\Delta x_{IMS}}}(f) \leq 12 \times 10^{-12} \frac{m}{\sqrt{Hz}} \sqrt{1 + \left(\frac{2\,mHz}{f}\right)^4}$$

A detailed budget has been developed to allocate the total to three classes of contributions: shot noise, optical path length changes, and measurement noise. Table 2 below summarizes the values for each of the allocations, and a brief description of some of the effects contributing to each of the classes follows.

5.1 IMS Subsystem Allocations

Subsystem allocations for the IMS displacement noise are:

1) Shot noise represents slightly more than half of the total allocation and is a fundamental noise source. Requirements derived from this allocation include:
   - Received power, which depends primarily on the transmit laser power, the telescope diameter and beam quality, and the distance between spacecraft.
   - Fringe Contrast (visibility) at the detector. This factor accounts for wavefront error, simple tilt misalignment, and the systematic phase mismatch due to the overlap of a Gaussian beam from the local oscillator with a "top-hat" beam from the receiving telescope.
   - Detector Quantum efficiency, which measures how well photons are converted to electrons.

Table 2: Summary of IMS subsystem noise allocations.

Effect	$\times 10^{-12}\,\dfrac{m}{\sqrt{Hz}}\sqrt{1+\left(\dfrac{2\,mHz}{f}\right)^{4}}$ Total per group (pm/√Hz)	Sub-Allocation	Comments
Total IMS Error/Noise Budget	**12.0**		
Total of subsystem allocations	**11.7**		RSS of subsystems
Subsystem Allocations			
Shot noise	**7.7**		100 pW received power
Pathlength noise	**7.0**		root sum of squares
Pointing Errors		5.3	
Telescope pathlength stability		1	
Optical bench pathlength stability		4.5	
Measurement noise	**5.4**		root sum of squares
Photoreceiver errors		3	
Residual laser frequency noise		2	
Residual clock frequency noise		3	
Phasemeter noise		1	
Intensity noise		1	
Phase reconstruction		1	
Stray light		2	

2) Pathlength noise is generally either motions that change the apparent distance between spacecraft or alignment errors that cross-couple other effects into apparent distance changes. Requirements derived from this allocation include:
- Pointing Errors that arise from the coupling between angle and pathlength from the input pupil of the telescope on the optical bench to the input pupil of the telescope at the far spacecraft due to wavefront non-uniformity and alignment errors
- Changes in the separation between the primary and secondary mirrors in the telescope
- Optical bench pathlength stability, which includes
  - geometrical pathlength changes on the optical bench from the first beamsplitter to the input pupil of the telescope.
  - dimensional changes (e.g. through coefficients of temperature expansion (CTE's)) and optical effects such as index of refraction changes with temperature. The two major sources for these fluctuations are variations in the solar output (typically of order 1%) and changes in the power dissipation of the spacecraft avionics.

3) The measurement noise allocation is for noise and errors in the representation of the true phase of the LISA heterodyne signals. Requirements derived from this allocation include:

- Photoreceiver errors comprised of errors from all three pairs of photoreceivers involved in a single-link measurement: the main science quadrant receivers, the proof mass metrology, and the reference interferometer. This noise equivalent

displacement from front-end analog electronics noise is for a noise equivalent power over the main RF heterodyne frequency band of 4-18 MHz. A local oscillator power of 3 mW per quadrant on the science receivers is used to amplify the small received signal over electronic noise of the amplifier [8].

- Residual laser frequency noise is limited to a level that can be corrected by the TDI filtering with knowledge of the interspacecraft range and relative signal timing of 30 meters and 80 nanoseconds respectively [9]. Prestabilization of each laser to 9 Hz/√Hz is taken as the input noise.

- Residual clock frequency noise is due to timing errors in sampling the laser heterodyne phase and is indistinguishable from laser frequency noise or length changes. The ultra-stable oscillator (USO) has only modest stability requirements, allowing for an error of 100 nanoseconds over 160 s (the duration of data streams used to form TDI variables), but relative jitter in clocks on the separated spacecraft must be measured to 3 microcycles/√Hz. A reference signal derived from the clock is modulated onto an 8 GHz sideband and transferred to the other sciencecraft so that the clocks may be compared with each other in a manner analogous to the comparison done for laser phase noise.

- Phasemeter noise is introduced errors in the measurement due to the stringent but imperfect anti-aliasing filters, tracking errors, and finite quantization noise. It has been demonstrated that these errors are at the requirements level in the measurement bandwidth [10].

- Intensity noise in the laser, corresponding to 1 pm/√Hz. May be reduced by balanced detection.

- Phase reconstruction errors. The main science data comes from the phasemeter at a rate of 3 Hz. These data are sent to ground and interpolation is performed to provide appropriately sampled date for the formation of TDI variables. Each of these steps creates some finite error [11,12,13].

- Stray light contributions are not errors in the phase measurement, per se, but rather the measurement of an unintended phase change caused by stray light. This allocation amounts to a sum of scattering sources weighted by their stability in the measurement bandwidth. Measurement strategies in the interferometer mitigate the direct contributions of these parasitic signals.

6   Disturbance Reduction System (DRS) Requirements

The top-level acceleration noise requirement allocated to the DRS is given as an amplitude spectral density for a single proof mass:

$$\sqrt{S_{\Delta a_{DRS}}} \leq 30 \times 10^{-16} \frac{m}{s^2 \sqrt{Hz}} \sqrt{1 + \left(\frac{f}{8\,mHz}\right)^4} \sqrt{1 + \left(\frac{0.1\,mHz}{f}\right)}$$

The equivalent displacement noise is then given by:

$$\sqrt{S_{\Delta x_{DRS}}}(f) = 2\frac{\sqrt{S_{\Delta a_{DRS}}}(f)}{(2\pi f)^2} \leq 60 \times 10^{-16} \frac{m}{\sqrt{Hz}} \frac{1}{(2\pi f)^2} \sqrt{1 + \left(\frac{f}{8\,mHz}\right)^4} \sqrt{1 + \left(\frac{0.1\,mHz}{f}\right)}$$

A detailed acceleration noise budget was developed that sets the required level of all known disturbance effects [14]. For convenience in flowing down requirements from the noise budget, the effects are grouped into categories that cover the common parameters associated with the effects. The disturbance groups and the allocated disturbance levels are listed in Table 3. The full frequency dependence of all the disturbance effects can be found in the detailed noise budget document [14].

Table 3: Summary of DRS Subsystem allocations

	$\times 10^{-16} \dfrac{m}{s^2\sqrt{Hz}}\sqrt{1+\left(\dfrac{f}{8\,mHz}\right)^4}\sqrt{1+\left(\dfrac{0.1\,mHz}{f}\right)}$		
Effect	**Total per group**	**Per group**	**Comments**
Total Acceleration Noise Budget	30.0		
Total of subsystem allocations	19.5		RSS of sub-allocations
Disturbance Groups			
Electrostatics		12.0	
Brownian		9.1	
Spacecraft magnetic		7.0	
Spacecraft coupling		6.0	
Spacecraft cross coupling		4.5	
Thermal		4.0	
Interplanetary Magnetic		4.0	
Misc small effects		4.0	

6.1 DRS Disturbance Groups

Sub-allocations for the residual acceleration noise are:

1) The first group of disturbance effects is electrostatics, often referred to as charge and voltage effects. The PM acts as the central electrode to a bank of capacitors formed by the surrounding electrodes of the GRS. Stray DC fields and charges on the PM will lead to fluctuating forces through Lorentz and Coulomb interactions. Cosmic ray impacts will cause the total charge on the proof mass to fluctuate and increase over time. To balance this, the charge management system will measure the total charge of the PM and shine UV light on the PM and electrode housing (EH) surfaces to bring the total charge to an acceptable level. The current capacitive PM sensing and actuation does not apply any DC bias to the electrodes, however, residual stray DC potential will be present from patch fields arising from spatially varying DC surface potentials on the PM and electrode housing. However, this field can be partially compensated for by carefully applying electrode voltages [15]. Requirements derived from this group's allocation include:

   - Stray DC electrode potential (surface quality),
   - In-band voltage fluctuations from voltage references,
   - Maximum PM charge maintained by charge management.

2) A number of effects are grouped together as Brownian noise as they are characterized by a dissipation mechanism. Eddy current and residual gas damping are the dominant effects in this group along with losses in the dielectric layers on the PM and electrode surfaces. Requirements derived from this group's allocation include:

- Sensing capacity loss angle,
- Pressure in electrode housing,
- Stray DC electrode potential (surface quality).

3) The magnetic properties of the PM and characteristics of the magnetic field contribute to 10 effects throughout the DRS error budget. The leading effects are: the interaction between the fluctuating interplanetary magnetic field with the magnetic field gradient and a fluctuating magnetic field gradient. Requirements derived from this group's allocation include:

- S/C magnetic field magnitude,
- S/C magnetic field gradient,
- S/C magnetic field fluctuations,
- Proof mass magnetic susceptibility,
- Proof mass permanent magnetic moment.

4) Residual S/C motion will couple to the PM through the parasitic stiffness between the PM and S/C. This includes S/C motion in all degrees of freedom as the stiffness matrix has non-zero off diagonal terms. The motion of the S/C is controlled relative to the PM by the DRS control system. This system uses the capacitive and optical measurements of the PM displacement to determine the amount of force to exert on the S/C using the micronewton thrusters and how much electrostatic force to apply to each PM using the electrodes. Typically, sensor noise dominates the control performance at low frequency, while thruster noise dominates at the higher end (above about 1 mHz). Requirements derived from this group's allocation include:

- Self-gravity field gradient,
- Relative S/C-PM displacement jitter,
- PM displacement readout sensitivity,
- Micronewton thruster thrust noise.

5) A number of unrelated small effects are captured in the miscellaneous group. Included here are laser power fluctuations (photon pressure) from the optical readout, self-gravity fluctuations from the spacecraft distortions, and back-action from the capacitive readout. Requirements derived from this group's allocation include:

- PM optical readout laser power stability,
- Spacecraft self-gravity field stability.

6) Temperature fluctuations in the material near the PM will contribute to a number of disturbing effects. A fluctuating temperature gradient of residual gas will disturb the PM though the radiometer effect. Likewise, temperature gradients of the housing walls will cause pressure fluctuations due to asymmetric outgassing. These same temperature fluctuations will cause the blackbody radiation to disturb the PM through a fluctuating photon pressure. Finally, the thermal distortion of the housing will couple to the PM through self-gravity and capacitance changes. Since all these disturbances are driven by the same source they are coherent and will add linearly. Requirements derived from this group's allocation include:

- Pressure in electrode housing,

- Temperature gradient fluctuations of electrode housing.

The noise model is described in detail in the "LISA DRS Acceleration Noise Current Best Estimate" document [14]. This document is updated periodically to reflect the current status of the technology and system design.

7 Requirements Management Process

The LISA requirements management process is consistent with the guidelines established for all NASA projects in Phase A of the mission lifecycle as defined in the NASA Systems Engineering Handbook [16], GPR 7120.A [17], and the Golden Rules [18]. The requirements identification and management function is the responsibility of Mission Systems Engineering (MSE) per GPR 7120.A. Science requirements and measurement concepts are led by the LISA Science Team and coordinated with MSE.

The NASA Systems Engineering Handbook states that the major activity with respect to requirements during Phase A is the development of top-level requirements. The top-level requirements documents generated by the LISA Project to date include: the Science Requirements Document (ScRD) the source of the science requirements, a Mission Requirements Document (MRD), a System-level Noise budget spreadsheet that provides error allocations, and a large number of supporting technical notes and presentations written by NASA, ESA, and their support contractors. These documents are maintained in an internal Project document management archive/database. Configuration Management (CM) is informal, consistent with GPR 7120.A, but the database access is restricted. The mission architecture is a product of these requirements.

As the mission design is matured during Phase A, modifications to the requirements are proposed and resolved during quarterly Technical Interchange Meetings (TIMs) between the NASA and ESA technical teams. After discussion, a decision is made to adopt the change, conduct further study or initiate a trade study, or reject the change to the baseline. These decisions are recorded in the minutes of the meeting, and appropriate revisions are made to the requirements documents to reflect the new baseline. Upon completion of Phase A, a single mission design based on a final set of top-level requirements will go forward to Phase B for further system definition.

As the mission progresses to more advanced stages of its lifecycle, a more formal Requirements Management Process will be developed that is in agreement with the NASA system engineering processes as well as applicable ESA standards. Details of the process will be contained in the System Engineering Management Plan (SEMP). All requirement documents will be under formal CM.

8 Summary

The measurement performance requirements for the LISA instrument are derived in a systematic way from the science requirements as specified in the ScRD. The current instrument design is capable of meeting these performance requirements with a 35% contingency that may be used as needed against noise sources that are not included or underestimated, or else as an off-ramp to provide relief against an unexpected development.

9 References

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