LISA and LISA Charging

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Abstract. Charging of the isolated proof-masses which form the mirrors defining the path lengths for the LISA and LISAPF interferometers turns out to be one of the limiting sources of spurious noise for both missions. An overview of the charging effects and processes will be given which set the scale of the charge induced noise contributions within the overall LISA sensitivity budget. The current charge control hardware and operations for LISAPF will be described, followed by a forward look to the necessary further developments needed for LISA.

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1. Introduction

The space environment is unfortunately not completely benign for sensitive experiments using isolated proof-masses inside of drag-free satellites. Although the spacecraft does act as a barrier between residual atmospheric drag-free and solar-wind buffeting it can never be dense enough to prevent high-energy particles penetrating through it to the inner regions containing the proof-masses. When this happens a number of effects can be expected. Particles hitting the proof-mass will impart momentum to it. If they stop within the proof-mass, that will cause a temperature rise and cause it to become charged. High-enough energy particles can also interact with surrounding spacecraft materials and generate secondary particles which then reach the proof-mass. This is most significant for charging effects as much of the charge can then result from secondary processes. The seriousness of the consequences caused by penetrating particle fluxes depends both on the mission science and technology, and on the nature of the particle fluxes themselves. For example the cryogenic Satellite Test of the Equivalence Principle (STEP) [1] the proof-masses will experience a directed impulse during passes through the trapped radiation in the South Atlantic Anomaly, a charge build-up producing electrostatic forces causing centre of mass offsets within the proof-mass pairs, and a temperature rise which could change skin-depths mimicking surface displacements. For Gravity-Probe B the steady charge build up from cosmic-rays had to be periodically annulled to avoid electrostatic torques [2]. For the LISA mission the main issue is again charge build-up but it is not just the electrostatic forces which must be constrained but also the acceleration noise which accompanies the forces. It turns out that this noise contribution is one of the major player within the overall LISA noise budget and this added subtlety makes the overall process of charge control a lot more complicated.

In this review the charging effects and process will first be presented. From this will flow the performance requirements for charge control technology and mission operations. Following this the charge control implementation on LISA Pathfinder will be outlined, and finally a forward look to what is required for LISA will be given.

2. Charging

This section will first examine the consequences of charge build-up on the LISA interferometer mirrors (proof-masses). The main critical issues will be identified which drive the need for active charge control. Following this predictions of charging due to cosmic rays and solar energetic particles will be reviewed which then defines the constraints within which the charge control process must operate and also dictates the active control loop requirements.

2.1. Charge induced forces and noise

Free charge, $Q\left(t\right)$, on the LISA proof-masses will give rise to a number of spurious forces [3, 4, 5]. There will be Lorentz forces, $Q\left(t\right)\vec{v}\wedge\vec{B}$ from any motion, $\vec{v}$, of the proof-mass through ambient magnetic fields, $\vec{B}$. These ambient magnetic fields will be partly due to the residual interplanetary field within the spacecraft and partly due to internally generated fields in which cases the proof-mass motion will be either due to the spacecraft velocity or due to local proof-mass motion respectively. Fortunately the effect of the interplanetary magnetic field is compensated by using a metallic enclosure around the proof-mass [6] which then produces an internal electric field (Hall effect) to counterbalance the Lorentz force. It is safe to assume this can reduce the effect by a factor of ~ 100 at which point that force (and noise) becomes insignificant [7, 8]. A stringent magnetic field budget then limits the generation of local fields and gradients at the proof-mass such that those Lorentz forces are also kept well within budget.

Time dependent electrostatic forces on the proof-mass in the k-direction will build up as

$$F\left(t\right)=\frac{Q\left(t\right)^{2}}{2C^{2}}\frac{\partial C}{\partial k}-\frac{Q\left(t\right)}{C}\Sigma_{i=1}^{n}V_{i}\frac{\partial C_{i}}{\partial k} \tag{1}$$

where C is the total capacitance of the proof-mass with respect to its surroundings, C_i is the capacitance with respect to the i-th surrounding surface and V_i is the applied potential on the i-th surface. For simplicity the equation assumes the potential of the proof-mass itself due to the net effect of all the applied potentials is close to zero. The first term in equation (1) depends on the total capacitance gradient, which for a cubic proof-mass inside a symmetrical enclosure would be zero except for imperfections in its positioning or dimensions. For example if the mass is offset, Δd, from the electrostatic centre and there is an area mismatch, ΔA, from one side to the other the first term becomes

$$F\left(t\right)=\frac{2Q\left(t\right)^{2}\epsilon_{o}A}{C^{2}d^{2}}\left(\frac{\Delta d}{d}-\frac{\Delta A}{4A}\right) \tag{2}$$

The right-hand term in equation (1) gives the forces which result from the interaction between Q and any applied potentials on the surrounding surfaces. Common-mode voltages, V_{cm}, give no forces to first order whilst differential-mode voltages, ΔV, are used for charge measurement. These forces give rise to an effective time dependent spring constant, k of

$$k\left(t\right)\approx\frac{2Q\left(t\right)^{2}}{C^{2}}\frac{\epsilon_{o}A}{d^{3}}+\frac{Q\left(t\right)}{C^{2}}\frac{\partial C}{\partial k}\Delta V\frac{\partial C_{r}}{\partial k}+\frac{Q\left(t\right)}{C}V_{cm}\frac{\partial^{2}C_{r}}{\partial k^{2}} \tag{3}$$

where C_r is the one-sided capacitance. In order to keep this negative spring constant below 10% of the nominal intentional spring constant requires that $Q < 2\times10^{7}$ charges. With a total proof-mass capacitance, C, of about 30pF this corresponds to a potential of $\sim 100\,\mathrm{mV}$.

The forces shown in equation (1) will also cause acceleration noise in the proof-masses due to intrinsic noise in d, V and Q. The most critical of the contributions turns out to be from noise in Q interacting with the differential-mode voltage, which, even in science mode can not be guaranteed to be zero. There will inevitably be some uncertainty in ΔV at the level of several mV due to surface properties. The resulting acceleration noise will be

$$a_n^2 \approx \left(\frac{q_n}{mC}\Delta V\frac{\partial C_r}{\partial k}\right)^2 \tag{4}$$

where q_n is the noise associated with the charge build-up. q_n will have a number of contributions. The baseline charging process from cosmic-rays and solar energetic particles (SEPs) is a stochastic process with an intrinsic noise behaviour as will be shown in the next section. In addition to this there will be fluctuations in the cosmic ray arrival rates and in the occurrence of SEPS. Lastly the charge control process will involve discharging the proof-mass which can be viewed as just another contribution to $Q\left(t\right)$ and hence q_n as again this will be a stochastic process.

2.2. Charging Process

On initial un-caging the proof-mass is likely to be left with a residual charge due to a effective 'contact potential'. This in itself must be nullified as it is very likely to exceed the $\sim$ 100 mV limit. However this is a one-off process and the main concern is really charging through the action of penetrating charged particles in the space environment. This process was first studied in detail for cosmic-rays effects in the STEP [9] using GEANT4 [10]. This and the first specific LISA study [4] used simplified spacecraft geometries and modelled the effects of cosmic rays (H^+ and He^{++}) with starting energies between 100 MeV and 10 GeV, following all secondaries down to energies of 10 keV. Shortly after these studies a low-energy extension to GEANT4 was released [11] allowing electromagnetic processes to be tracked down to 250 eV. More extended cosmic-ray simulations for LISA and LISAPF were then undertaken using the most up-to-date geometries available [14, 12, 13]. Protons, ^{3}He and ^{4}He nuclei were studied at solar maximum and minimum conditions. In parallel to these studies, simulations were also carried out using FLUKA [15] with a very simplified spacecraft geometry [16, 17]. These not only provided independent estimates but also included heavier nuclei and electrons. The combined results are shown in table 1. All figures are given in elementary charge units. There is close agreement amongst all of the predictions and this gives high confidence to those predictions. In addition the GEANT4 approach has been used for Gravity Probe B which has allowed comparison with the measured in-flight charging rate with good agreement [19].

From the table it can be seen that both GEANT4 and FLUKA predict average charging rate for each LISA and LISAPF proof-mass from cosmic-rays as $\sim$ +50e/s. However it should be remembered that neither GEANT4 nor FLUKA continue to track particles below 250 eV whereas electron production is possible right down to few-eV levels. A significant effect at these low energies might be surface emission of kinetic electrons [12]. One surprise is that the effective noise levels from the stochastic charging process are higher than expected at first thought. This is because individual cosmic rays, particularly of higher energy, can initiate hadronic and electromagnetic showers which

Table 1. Combined results for charging characteristics for LISA and LISAPF.

Parameter	**LISA**	**LISAPF**
Charging rate at Solar Minimum		
H^+	$+40.5 \pm 0.8$[12],$+37 \pm 1$[16]	$+35.6 \pm 0.7$[13]
$^3He^{++}$	$+1.06 \pm 0.05$[12],+0.9[17]	$+1.11 \pm 0.03$[13]
$^4He^{++}$	$+7.4 \pm 0.3$[12],+5.6[17]	$+7.0 \pm 0.2$[13]
C	$+0.9^{\dagger}$[17]	—
N	$+0.4^{\dagger}$[17]	—
O	$+1.2^{\dagger}$[17]	—
e^-	$-0.5^{\dagger}$[17]	—
Total Rate	$+49.0 \pm 0.9$[12],$+45^{\dagger}$[17]	$+43.7 \pm 0.8$[13]
Effective shot noise rate	293[12],$238^{\dagger\dagger}$[17]	311[13]
Charging rate at Solar Maximum		
H^+	$+18.0 \pm 0.6$[12]	$+17.3 \pm 0.6$[13]
$^3He^{++}$	$+0.45 \pm 0.03$[12],$0.38^{\flat}$[17]	$+0.42 \pm 0.01$[13]
$^4He^{++}$	$+3.5 \pm 0.2$[12],$2.6^{\flat}$[17]	$+3.6 \pm 0.2$[13]
C	$0.8^{\flat}$[17]	—
N	—	—
O	$0.8^{\flat}$[17]	—
e^-	—	—
Total Rate	$+22 \pm 6$[12]	$+21.3 \pm 0.6$[13]
Effective shot noise rate	196[12],$132^{\dagger\dagger\dagger}$[17]	196[13]
Charging rates during SEPs		
Weak	87[12],$\sim +1,073$[16]	100[13]
Average	+10,732[16],4575[18]	—
Strong	$\sim 70,000$[12],$\sim +107,320$[16]	65000[13]

† scaled by the H^+ charging rate given in [16]
†† scaled by the effective charging rate given in [16]
††† scaled by the effective charging rate given in [18]
$^{\flat}$ scaled by the H^+ charging rate given in [12]

give very high charge multiplicities [12]. In addition these high multiplicity events can be of either sign. The effective shot noise rates shown in the table allow the charge noise to be calculated as though the charging were from single charge deposits. Also shown in the table are the charge rate enhancements expected during sporadic solar energetic particle events (SEPs). Although large SEPs occur only very infrequently the peak charging rates expected mean that too much charge will be accumulated in a short time to allow continued science operation. However the small events only produce enhancements comparable to the steady cosmic-ray charging rate. Fortunately the particle energy spectrum of SEPs is softer than of cosmic-rays and the associated instantaneous noise increase is disproportionately smaller, allowing continued good quality science operation through these. However there will be a noise penalty due to these events and, indeed from any real cosmic ray rate variations, if they occur frequently enough. The available information on very low fluence SEPS and low-frequency cosmic ray fluctuations is not sufficient to fully characterise these [19] and LISAPF will carry a radiation monitor partly designed to gather more information. It will be able to detect and identify low fluence SEPS as well as monitor low-frequency cosmic ray variations [19]. The information gathered from this, and the similar monitor(s) on LISA, will be of interest to both the solar phyiscs and the cosmic ray communities [20, 21, 22].

3. Charge Control

3.1. Overview

Effective charge control requires that it be considered at all stages of instrument development as it affects the intrinsic design of the sensor, the overall spacecraft operations and, of course, requires specific hardware and software. During the design phase there has to be a trade-off between the scientific sensitivity and sensitivity to charge. This required a fully featured electrostatic model of the sensor [23]. This model included the full proof-mass volume with all its surrounding electrode and housing structure (a cubic volume $\sim 5\,\mathrm{cm}$ on a side) with $10 - 100\,\mu\mathrm{m}$ sized features in specific places. ANSYS was used, and as it was necessary to derive first and second derivatives of capacitances, the numerical accuracy was assessed very carefully [24]. Output from such a model is also required for spacecraft attitude control algorithms.

Charge control has several components. There is charge measurement using forcing voltages to produce either a translational dither or a rotational oscillation. The amplitude and phase of the proof-mass response is sensed through the capacitive sensor system and these are used to determine the charge level and its sign. UV radiation is used to release photoelectrons differentially from the proof-mass itself and from the surrounding electrons. Applied potentials can assist specific electron transport if needed. Different combinations of measurement and UV exposure are used at different phases.

First use of the charge control system will be during experiment initialisation; uncaging will leave an unknown residual charge on the proof-mass. Dealing with requires a charge measurement followed by a timed exposure of relevant surfaces to UV radiation. The surfaces to be illuminated will depend on the sign of charge left on the proof-mass; if the charge is positive the surrounding surfaces will be illuminated whereas if the charge is negative the proof-mass itself will be illuminated. After the exposure the charge will be remeasured and the process repeated if necessary in iterative adjustments to reduce the charge to the level needed in preparation for science/calibration data taking.

During science mode a simple option would be periodic measurement of charge and when it exceeds a predefined value to use the discharge system to rapidly reduce it back down below some lower level. During the rapid discharge science data would not be usable due to much increased charge noise from the stochastic release of some 30,000 e/s which is $\sim$ 100 times larger than that due to cosmic rays. The charge build up time would be $\sim 4 \times 10^5$ s with a rapid discharge in $\sim$ 700 s. The loss of 0.8% science data would be acceptable but unfortunately the residual fourier components in the science data due to quasi-periodic saw-tooth forces building up as $Q(t)$ and $Q(t)^2$ would be unacceptably large [25, 26]. Continuous UV illumination with a closed loop feedback can reduce the coherent artefacts in the science data and suppress low-frequency $1/f$ acceleration noise caused by long period cosmic-ray fluctuations and SEPs. In principle the radiation monitor data can be used to provide some level of pre-emptive strike.

Occasionally very strong SEPs will charge the proof-mass to the point where it must be discharged immediately to regain low-noise science operations. A rapid discharge will be carried out. In the extreme case that the charge becomes so large that the electrostatic control system looses control of the proof-mass it should be possible to use the caging mechanism to partially discharge the mass sufficiently to regain control.

During data processing removal of residual artefacts due to the charge control process will require a detailed knowledge of the instrument history. The radiation monitor data will be used to provide a cross-correlation with the instrument data to improve the removal and to set data quality flags. Finally it should be possible to use other solar activity data both in-flight and in later data analysis to help mitigate the effect of SEPs.

3.2. Implementation

3.2.1. Hardware The ultra-violet hardware required for charge control includes sources, a fibre optic harness to transport the photons, and an optical coupling interface to direct the photons at specific surfaces. Additional components/capabilities required are actuation and sensing for the proof-masses (provided by the front-end electronics), and controlled surface properties on both the proof-mass and the surrounding housings [27]. In addition a radiation monitor to measure both the cosmic-ray flux and low-fluence SEPs is essential.

3.2.2. On-board software On board software is required to carry out the charge measurement process. This includes applying the appropriate dither/rotation voltages to the control electrodes, acquiring the corresponding sensor response data, and then calculating the charge and its sign. Each measurement will take $\sim$ 2000s and to get the best accuracy it will be necessary to allow/measure also the trend as the charge continues to build-up through the measurement itself. During science mode the charge control system will operate with closed-loop feedback. The charge measurement will be active all the time with a target sensitivity of 10^4 charges. The UV sources will then be operated continuously at very low-intensity to provide a discharge rate as closely balanced to the charging rate as possible. It is important that the level of UV photo-emission is kept low so that the stochastic charge noise is not increased significantly by the discharge process.

3.2.3. Data Processing Data processing and analysis will form an essential component of charge control. It is inevitable that artefacts will be left in the data and their identification and removal will be important for the recovery of the best gravitational wave science data. Once removed from the data stream it will then be necessary to set data quality flags to indicate noise conditions which will vary through the mission. In support of these activities it will be necessary to have fully featured modelling and simulation tools. These will need to include the charging process (including cosmic-rays and SEPs), the UV hardware performance, the microphysics of the discharge process, the sensor response, and the overall spacecraft operations. Part of the input for the simulations will need to be based on laboratory prototype behaviours.

3.3. LISAPF Solution

3.3.1. Hardware The LISAPF ultra-violet light sources are low-pressure Hg discharge lamps [28]. Bare Pen Ray bulbs of the same type as previously used on ROSAT [29] are supplied by UVP LLC [30]. These are then mounted into titanium housings. LISAPF uses six lamps; three for each gravitational reference sensor. The output from the lamps are fed by fibre-optic bundles to the sensor housing. They connect to customised high-vacuum feedthroughs made from titanium which have individual rigid fibre extensions which direct the photons to surfaces within the housing. For each sensor two of the three feedthroughs deliver photons onto electrode surfaces whilst the third points towards the proof-mass. This provides full bipolar discharge capability and some redundancy against failure albeit with the need to aid the electron transport with additional applied voltages. The lamps are driven with a pulse width modulation technique which allows 300:1 dynamic range in the output UV. This provides the low intensity needed for continuous science mode operation and the high intensity required for rapid discharge. The level is programmable over an 8-bit none-linear scale. Radiation tolerance has proven an issue for LISAPF as it requires some tight bend radii to transport the photons from the lamps to the sensors. This has dictated using fibre bundles rather than single fibres and these are much more susceptible to radiation damage [31].

The radiation monitor consists of two large area silicon diodes working as a coincidence telescope. These are mounted inside a thick copper housing to simulate the shielding overburden seen by the proof-mass. The area of the diodes was chosen to ensure a sufficient count rate both for cosmic-ray monitoring and for low-fluence SEP detection. The spectral resolution for protons is sufficiently good that the spectrum from a low-fluence SEP should be differentiable from the cosmic-ray spectrum.

3.3.2. Validation tests A number of tests have been done to validate the charge control concept. This includes measurements with an in-house test-bed at Imperial College, the torsion balance set-up at the University of Trento [32] and the in-flight demonstration by Gravity Probe B (albeit at a somewhat coarser level). These tests have demonstrated rapid discharge, bipolar control, charge measurement, and UV lamp noise compliance. To fully understand the results obtained a discharge model/simulation has been developed. Most results have agreed with expectations. There has also been a successful simulation of closed loop drag-free and attitude control including charge control operations. One recent test in the torsion balance has shown anomalous behaviour with an inability to achieve bipolar control. The most likely issue is the surface properties [27]. The important properties are photo-emission probability and reflectivity at the Hg wavelength, $2537\mathring{A}$. Both of these are uncertain and difficult to measure. Although this has been an isolated test within a batch of other successful tests the consequences of this happening in flight have been mitigated by implementing a wider dynamic range for UV lamps and a surface properties measurement campaign. Finally the radiation monitor has undergone extensive been tests to verify its performance [19].

3.4. LISA

Although the LISAPF mission will fully validate the in-flight charge management technology and processes, there will still be a number of further issues for study for LISA. The specific concern about surface properties clearly needs more work and ideally a controlled surface preparation needs to be established. In addition to this it is clear that the UV wavelength could well benefit from being shorter as it is currently very close to the nominal gold work-function and hence the photo-emission is more determined by other surface species rather than the intrinsic gold. More extended surface studies will also provide better input into the detailed microphysics modelling and understanding. Although the UV lamps being used on LISAPF have previous space heritage through ROSAT and EINSTEIN their use on LISA would be somewhat cumbersome given the extended mission lifetime, which would dictate high-level redundancy. Alternative technologies have become viable with commercial UV light emitting diodes [33] and tripled laser diodes using a BBO crystal demonstrated at Imperial College. A more extended radiation monitor package would allow more detailed and useful information about the ambient particle environment. In principle the radiation monitor output could be incorporated into the on-board control-loop. Charge control mission operations will be much more complicated for LISA as the three separated spacecraft should be treated in a coordinated way. A model needs to be developed including all three spacecraft which can be used to study how best to coordinate activities to avoid additional artefacts in the interferometry data and also how to deal with SEPs which will impact on the three spacecraft with time delays and different spatial properties. Ultimately the science data simulator should include effects induced by both charge and charge control operations. This will allow the development of algorithms for identification and removal of artefacts and data quality indicators. More space weather studies are needed to characterise the low-frequency distributions of SEPs and cosmic rays. At some point the GEANT4 modelling should be repeated with an updated satellite geometry.

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