Principles, operations, and expected performance of the LISA Pathfinder charge management system

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Abstract. The test masses of LISA Pathfinder are free flying and therefore not grounded to the spacecraft by a wire. Because of galactic cosmic rays, solar energetic particles, and unknown microscopic surface effects during initial test mass release, an unacceptable level of absolute charge might be present on the test masses. A charged test mass can endanger transition to high accuracy control modes which are required for science experiments. Furthermore, charged test masses introduce unwanted disturbance accelerations for example due to Coulomb interactions with surrounding conducting surfaces. The charge management system is designed to discharge the test masses up to a tolerable level of absolute charge such that the mission goal can be achieved. It is therefore an essential part of the experiments to be performed with the LISA Technology Package. The paper describes charge management tasks to be performed on board the spacecraft and summarizes the principles of charge measurement and discharge control. An overview of the experiment operations is given where the interconnection of operational charge management system modes and operational modes of the drag-free, suspension and attitude control system is considered. Simulated performance results are presented.

1. Introduction
LISA Pathfinder aims at the verification of differential free fall between the two test masses along one axis, with a required level of $3 \times 10^{-14} \text{m/s}^2/\sqrt{\text{Hz}}$ in the measurement bandwidth between 1 mHz and 30 mHz [1]. This is accomplished by measuring the distance between the test masses along this sensitive axis with a precise optical metrology system. From this data, the acceleration can be obtained on ground. A drag-free control system [2] controls the spacecraft inertial attitude and stabilizes the test mass dynamics in such a way, that the non-gravitational acceleration along the sensitive axis is minimized. The primary science task is to measure and characterize all non-gravitational forces along the sensitive axis in a series of runs, each run consisting of one or more experiments.

2. Motivation for on-board charge management
The test masses within the gravitational reference sensors are free-floating. They are electrically isolated from the spacecraft and may therefore accumulate an unacceptable level of absolute charge. The test mass charging is due to galactic cosmic rays, solar energetic particle events and unknown microscopic surface effects which might occur during initial test mass release from
the caging mechanism assembly. Even though the test mass net charging rate from energetic
radiation is predicted to be positive [3], the test mass can also be negatively charged due to the
unknown charge separation phenomenons during release. High absolute test mass charge levels
impose functional and performance limitations on the experiment:

(i) functional limitations
• mode transitions from *DFACS accelerometer mode* (a control system control mode to
capture test masses after release) to high accuracy control modes with less actuation
authority (used to perform science experiments) might be endangered

(ii) performance limitations
• charged test masses introduce differential disturbance acceleration noise due to coupling
with stray DC voltages, magnetic fields, and electrostatic actuation noise [4],
• DC forces due to errors in electrostatic actuation algorithm which assumes that test
mass charge is zero, and
• increase actuation stiffness (in science modes a constant stiffness is assumed).

In order to keep this limitations sufficiently small, the test mass charge must be actively
controlled on board the spacecraft. This is accomplished by means of the charge management
system (CMS) software application and specific hardware equipment.

3. Provided functionality and required performance
The CMS provides the functionality to perform on board

(i) charge measurement without any discharge actuation,
(ii) fast discharge control to ensure the transition from accelerometer mode to high performance
science control modes and to discharge a test mass in preparation of specific science runs,
(iii) continuous discharge control during the main science test run is carried out (the reason for
this experiment is that in LISA continuous measurement and discharging is planned to be
part of the baseline science control mode).

Fast discharge and continuous discharge are closed-loop control algorithms. However, their
purpose and therefore their principle of operation is different. The goal of fast discharge is to
quickly discharge a test mass up to a desired level; disregarding the cause of any disturbance
noise. Robustness of the control algorithm is driving the design since it should work directly
after test mass de-caging before the discharge performance can be calibrated in-flight. Fast
discharge is terminated as soon as a user defined threshold value is reached. The main
purpose of continuous discharge is to keep the test mass charge below a certain threshold
without introducing considerable disturbance noise on the differential test mass acceleration.
The performance requirements of the CMS functionalities are summarized in table 1. The

| Functionality                                      | Requirement |
|---------------------------------------------------|-------------|
| Fast discharge in DFACS accelerometer mode        | 7.23 $\cdot 10^7$ e |
| Fast discharge in DFACS science mode              | 1.36 $\cdot 10^6$ e |
| Continuous discharge in DFACS science mode        | 1.00 $\cdot 10^5$ e |
| Only charge measurement in DFACS science mode     | 1.00 $\cdot 10^4$ e |

requirement on fast discharge in DFACS science mode ensures the test mass charge level to be
below $10^7$ unit charges for the duration of a 24 h science run. Notice that a charge level of $10^7$ unit charges is allocated in the experiment performance budget. However, for the preparation of an individual test run, the desired discharge performance might be less stringent and fast discharge can be terminated earlier. The derivation of fast discharge requirements is reported in [5]. Charge measurement without discharge actuation does not necessarily impose a requirement on the on-board application. The test mass charge can also be obtained by means of ground based estimation algorithms. This implies that the required data for ground based estimation algorithms must be visible in telemetry.

4. Experiment operation scenarios

The attainable closed-loop discharge control performance is limited by the charge estimation performance which in turn depends on the currently active DFACS mode of operation. The mode link table depicted in figure 1 shows possible CMS-DFACS mode combinations. It becomes clear that fast discharge control can be done in any DFACS mode where the test mass is free-flying. Continuous discharge is only possible in DFACS science modes.

The CMS has been designed such that the required functionalities can be realized by means of a flexible on-board software structure. The CMS implementation is a set of functional units (rather than a set of operational modes) which can be configured/parameterized according to the required functionalities. A certain configuration/parameterization defines an CMS operational mode. Configuration means the setting of configuration parameters (e.g. used test mass coordinate for charge measurement or UV lamps to be activated), whereas parameterization means the setting of any other parameter that influences the performance of an operational mode (e.g. frequency of dither voltage for charge measurement, controller gains, DC bias voltages on actuation electrodes, etc). The bold entries (P1-P3) indicate dedicated configurations/parameterizations of the functional units for baseline CMS-DFACS mode combinations. The entries P4-P9 are mode combinations which are in principle possible but not investigated as a baseline.

In principle all experiments (like the test of continuous discharge or the execution of fast discharge in the preparatory phase of other experiments) will be packed into the mission time. The complete definition of runs forms the Experiment Master Plan (EMP) of the mission. An example of a possible discharging operational scenario is illustrated in figure 2: Firstly, the test masses are discharged in accelerometer mode such that the transfer to DFACS science modes via the transition modes (normal modes) works smoothly. As soon as the DFACS science mode is in steady state, fast discharge of test mass 2 is performed such that the test mass charge is well below $10^7$ e. This can be considered as a preparation of the following science run; which is
the test of continuous discharge in this example.

The fundamental elements of closed-loop discharge control are charge estimation and discharge actuation. Their basic principles are summarized in the following.

5. Principle of discharge actuation
The test masses are discharged by using ultra-violet (UV) light via the photoelectric effect. Depending on the polarity of the test mass charge, the surface of the test mass itself or those of the electrodes and the electrode housing will be illuminated with UV light in order to release photoelectrons. The charge management device (CMD) hardware unit [6] generates the UV light and directs it to the gravitational reference sensors using feedthroughs that enter the shielding vacuum enclosures. In order to discharge a positively charged test mass, one of the feedthroughs pointed towards the electrode housing will be used; a negatively charged test mass will be discharged by using the feedthrough directed towards the test mass (see figure 3).

![Figure 3. Principle of discharge actuation.](image)

![Figure 4. Dependency of discharge rate on voltage difference.](image)

Primary illumination of the test mass should cause a dominant electron flow $N_{TM}$ from the test mass (TM) to the electrode/housing surfaces (EH). As illustrated in figure 3, a significant amount of light is reflected off the primary surface, hitting opposing surfaces which causes an undesired electron flow $N_{EH}$ from the EH to the TM (moreover, a powered lamp which is not actively used to support discharge actuation emits some light). A positive test mass discharge rate ($\frac{dQ_{TM}}{dt} > 0$) is obtained if $N_{TM} - N_{EH} > 0$. Thus, the dominant electron flow determines the sign of $\dot{Q}_{TM}$. The efficiency of photoelectron emission depends on the workfunction of the gold coated surfaces, their reflectivity, the quantum yield, and the amount of illumination. These parameters influence the effectiveness of the discharge, and need to be measured accurately in order to ensure a working design. A measurement campaign [7] to improve the knowledge of the flight test masses and electrode housing surface properties is currently carried out. The discharge performance depends not only on the emitted photoelectrons but also on the voltage difference between the test mass and the electrode/housing surfaces. The dependency is schematically illustrated in figure 4 and can be used to enhance/suppress the discharge. DC bias voltages are applied during fast discharge actuation.

The relation between UV lamp and voltage commands and the finally obtained discharge rate is non-linear, complex, and uncertain. For the design of the controllers and the actuation algorithms, a static actuation model has been derived which is a function of surface properties, CMD hardware parameters, and applied voltages.
Sinusoidal dither voltages are applied to a set of four actuation electrodes (see figure 5). If a charge is present on the test mass, a force or torque along the considered test mass DoF is generated [8]. Assuming equal electrodes and no DC bias voltages, the force/torque signal is proportional to the charge and has same frequency as the dither voltage. Such forces/torques can either be compensated with the suspension controllers (test mass charge information would be part of the controller signal) or it produces a test mass displacement. In the latter case, the resulting test mass motion along the corresponding degree of freedom can be measured using electrostatic or optical sensors. A recursive time-variant Kalman filter based on a model of the test mass dynamics and certain stochastic disturbances is used for on board charge estimation.

Figure 5. Test mass and $x/\varphi$-actuation electrodes.

Figure 6. Standard deviation of expected charge error vs. test signal frequency and amplitude after estimation time of 3600 s.

The achievable estimation performance depends on factors like estimation time, stochastic force and torque disturbances acting on the test mass, measurement noise from electrostatic or optical displacement sensors, charging noise, etc. A detailed breakdown of all considered disturbances is given in [5]. The ideal sinusoidal dither voltages for charge estimation are determined by means of an optimal error covariance analysis. Figure 6 shows the obtained standard deviation of the charge estimation error as a function of dither frequency and amplitude. For an estimation time of 3600 s, the ideal dither voltage frequency is 0.88 mHz.

7. Performance Results
All baseline CMS-DFACS mode combinations have been tested with an end-to-end simulator. This simulator features (among others) a detailed inertial sensor model on voltage level for electrostatic actuation and sensing, an optical metrology model, models for environmental test mass charging and discharging using UV light, various disturbances models as well as an 18 DoF non-linear dynamics of the spacecraft and test masses. It also includes the on board computer software, including a top-level logic for experiment control, the DFACS and the CMS implementation.

Figure 7 shows the nominal performance of the continuous discharge control loop as well as the commanded UV lamp currents. In the performed test run, the transition to DFACS science mode (M3) is initiated after 10000 s; steady state is reached after 15000 s. At this time, the continuous discharge mode for test mass 2 is enabled via mission timeline. After a specified estimator
settling time, the reference signal $Q_{TM} = 0$ is linearly faded in to avoid overshoots. The initial test mass charge at the start of the continuous discharge control mode is approximately $10^7$ unit charges. As soon as the 8000 s reference signal fade-in is over, the test mass charge is kept below the requirement. The configuration/parameter settings are according to the derived baseline for continuous discharge control (CMS parameterization P3). The spectra of the differential test mass acceleration for two scenarios (with and without continuous discharge) have been computed in order to assess the impact on the main science data. The only apparent difference in the measurement bandwidth occurs at double dither voltage frequency; the influence is uncritical.

![Figure 7. Nominal performance of continuous discharge control mode of operation.](image)

![Figure 8. Nominal performance of fast discharge in DFACS science mode (M3).](image)

Figure 8 shows the closed-loop performance of fast discharge performed in science mode (M3). Fast discharge is initiated after 15000 s via the experiment control logic. The initial test mass charge corresponds to approx. $10^8$ unit charges. Fast discharge can be considered as discrete-time closed-loop control with variable stepsize. The estimation intervals are constant and set to 500 s; the actuation cycles are variable depending on the absolute level of test mass charge. After 15500 s the first discharge actuation cycle is performed. The discharge actuation is done with the maximum possible negative discharge rate which is obtained by applying appropriate DC bias voltages. After the second discharge actuation, the test mass charge has been controlled below the requirement which is verified by the third estimation interval. This is reported to the higher level experiment controller logic and fast discharge is automatically terminated. The fast discharge control algorithm can adapt the controller gains in order to cope with uncertainties in the discharge chain.

References
[1] Anza et al 2005 The LTP experiment on the LISA Pathfinder mission Class. Quantum Grav. 22 125–38
[2] Fichter W, Schleicher A and Vitale S 2007 Drag-Free Control Design with Cubic Test Masses (Lasers, Clocks, and Drag-Free) ed H Dittus, C Lämmerzahl and S G Turyshhev (Berlin: Springer Verlag) pp 365–80
[3] Wass P J et al 2005 Class. Quantum Grav. 22 311-17
[4] Brandt N et al 2008 Experiment performance budget S2-ASD-RP-3036, LPF project documentation
[5] Ziegler T and Bergner P 2008 CMS design and analysis S2-ASD-TN-2044, LPF project documentation
[6] Schulte M and Shaul D et al 2007 CMD design synthesis report S2-ICL-DDD-3001, LPF project documentation
[7] Schulte M et al 2008 Inertial sensor surface properties for LPF Pathfinder and their effect on test mass discharging Class. Quantum Grav. (submitted)
[8] Vitale S 2007 Continuous charge measurement S2-UTN-TN-3033, LPF project documentation