10th International LISA Symposium (LISAX) IOP Publishing
Journal of Physics: Conference Series **610** (2015) 012022 doi:10.1088/1742-6596/610/1/012022

Summary of the results of the LISA-Pathfinder Test Mass release

C Zanoni[1,2,0] , D Bortoluzzi[1,2], J W Conklin[3], I Köker[4], B Seutchat[1], S Vitale[5,2]

[1] Dept. of Industrial Engineering, University of Trento, Via Sommarive 9, I-38123 Trento, Italy
[2] INFN, Trento associated group, Via Sommarive 6, I-38123 Trento, Italy
[3] Dept. of Mechanical and Aerospace Engineering, University of Florida, FL 32611-6250, USA
[4] Airbus Defence and Space, Claude-Dornier-Strasse, 88090 Immenstaad, Germany
[5] Dept. of Physics, University of Trento, Via Sommarive 6, I-38123 Trento, Italy

E-mail: carlo.zanoni@unitn.it, daniele.bortoluzzi@unitn.it

Abstract. The challenging goal of LISA-Pathfinder in terms of maximum non-gravitational forces applied on the test mass poses tight constraints on the design of the Gravitational Reference Sensor. In particular, large gaps (3-4 mm) must exist between the test mass and its housing and any system there located must be either gold coated or made of a gold-based material. As a consequence, a significant adhesion may arise between the test mass and the mechanism designed to cage it during the spacecraft launch and to release it to free-fall. The criticality of the latter phase is enhanced by the control force authority exerted to the test mass by the surrounding electrodes. Such a force is limited by the large gaps (order of μN). Since the expected adhesion force between the test mass and its holding devices is much larger than the force authority, a dynamic release must be realized. However, following this procedure adhesion converts into test mass velocity, which can be controlled by the capacitive force only if it is smaller than 5 μm/s. At the University of Trento (Italy) the Transferred Momentum Measurement Facility has been designed and developed to measure the impulse produced by metallic adhesion upon quick rupture, in representative conditions of the LISA-Pathfinder test mass release to free-fall. Large sets of data have been collected and a mathematical model of the in-flight release dynamics has been developed, in order to estimate the test mass release velocity. A summary of the results is presented, together with an overview of the recent developments and a prediction of the in-flight performance.

1. Introduction

In the LISA-Pathfinder mission, the main sensor -the Gravitational Reference Sensor (GRS)- measures the position of a 1.96 kg Au/Pt cubic test mass (TM). This object is nominally shielded within the required limits [1] from all forces except gravity and spacecraft actuation. The motion ruled by gravity alone is called Drag-Free and follows a Geodesic trajectory.

In order to survive launch each TM must be carefully constrained during Launch and Early Orbit Phase. Such a constraint is then removed, allowing the beginning of the scientific phase. This release phase is a critical feature of LISA-Pathfinder. In fact, due to the limited available electrostatic actuation (0.5 μN), the initial state of each TM must be within the boundaries of Tab. 1.

The device in charge of holding the TM during launch is called CVM (Caging and Vent Mechanism) [2]. It acts along the z axis of the TM and applies a high load of about 300 N

[0] Current address: EN-MME, CERN, Route de Meyrin 385, 1217 Meyrin, Switzerland

Table 1. TM state requirement

State	Value
offset along x, y and z	$\pm$ 200 μm
linear velocity along x, y and z	$\pm$ 5 μm/s
angle around x, y and z	$\pm$ 2 mrad
angular rate around x, y and z	$\pm$ 100 μrad/s

on each TM corner. Once in space, the CVM hands the TM over to the GPRM (Grabbing, Positioning and Release Mechanism), [3].

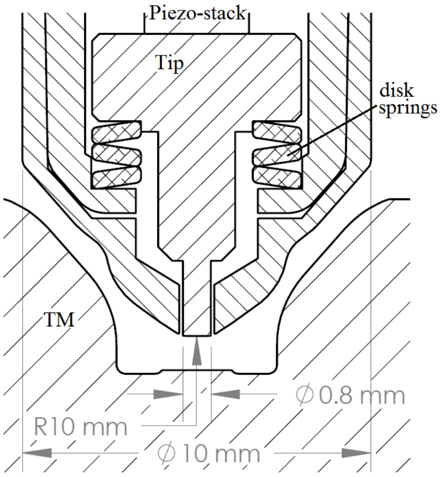

Figure 1. Cut view of the GPRM and TM recess (courtesy of RUAG Schweiz AG, RUAG Space)

The GPRM consists of two subsystems: the plunger (or grabbing finger) and the release tip. See Fig. 1. The first one is in charge of centering and aligning and the second is a small pin moved by a piezo-stack that removes the last mechanical action on the TM by means of a limited contact area and a low contact load (0.3 N). Both GPRM and CVM consist by two symmetrical parts on two TM faces.

The criticality of the release is the result of two effects. First of all, the mechanical action must be really symmetrical on both TM sides. Second, and more important, adhesion acts joining release device and TMand has a limited repeatability. Therefore, the removal of the constraint will transfer a momentum to the TM. More precisely, a pull on the TM is expected along + or - z. Adhesion is enhanced by the fact that both TM and GPRM are Au or Au coated for mitigation of stray forces due to non uniform surface work-functions.

An experimental-analytical on-ground qualification activity has been conceived for assessing the performance and the risk of the release. In the following, we will provide an overview of the main test results and an estimation of the TM release velocity.

2. Testing facility and experimental data

At the University of Trento (Italy), a facility has been designed for studying adhesion in dynamic conditions and in a space-like environment. The Transferred Momentum Measurement Facility (TMMF) is constituted by a 1.15 m pendulum. At its end is suspended a mock-up of the TM. Such a mock-up is a frame in which is included an Au/Pt insert, reproducing the flight TM contact surface. Similarly, a mock-up of the release tip is moved by an ultrasonic piezo stage. This last mock-up is loaded up to 300 mN against the pendulum, which is blocked by a set of 3 needles. The load is then relaxed until a nominal 0 mN value. Such a value is inferred from the commanded motion of the tip and the value of the stiffness of its blades, Fig. 2. At this point the tip is quickly retracted pulling the TM by means of adhesion. An interferometer measures the motion of the pendulum from which the applied force can be derived.

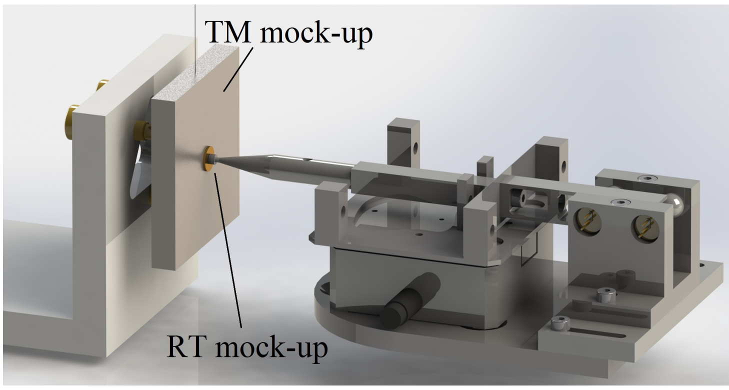

Figure 2. Rendered view of the core of the TMMF.

A more detailed description of the experiment can be found in [4, 5]. Indeed, a large set of actuators are also present for alignment and positioning of TM and release tip mock-ups. Also, the facility is supported by a damping table that mitigates ground vibrations effects.

Three main experimental campaigns have been performed, each one with a different mass attached to the pendulum: 0.0096 kg, 0.089 kg and 0.878 kg. The flight TM is equal to 1.96 kg, but adhesion arises only at the contact patch, whose representativeness is guaranteed on ground. At the same time, budget and organizational reasons make harder the use of a flight TM.. For each of these campaigns the peak force, the time-length of force action and the transferred momentum have been derived from the TM laws of motion. The histograms in Fig. 3 summarize the results in terms of peak force.

Unfortunately, adhesion is only one of the two forces that contribute to the measured motion of the TM. In order to avoid the rupture of the adhesive bond due to microseismic noise and for small positioning errors, a load of a few mN is always left between TM and tip. The effect of such a load is a net impulse on the TM, that can be estimated using:

$$I_{load} = F_{load}\sqrt{\frac{M_{TM}}{k_{nd}}} \tag{1}$$

where F_{load} is the residual load, M_{TM} the mock-up mass and k_{nd} the stiffness of the blocking system (the set of 3 needles).

3. Estimation of in-flight behavior

A first rough estimation of the release velocity is done by observing that the force applied on the TM in the TMMF lasts for about 2 ms. At the same time, the flight release mechanism moves 10 times quicker than the actuator used on-ground. The impulse is roughly equal to the area of the triangle $F_{peak}\delta t/2(=v_{TM}M_{TM})$, the maximum allowed peak force is 100 mN. We conservatively assume that the totality of the force is due to adhesion. The worst case measured peak adhesion value is 48 mN, which still leaves a margin factor of 2. However, this margin factor does not take into account the effect of a possible asymmetry in the mechanisms action.

A finer estimation requires a mathematical model for adhesion, such as [6]:

$$F_{adh} = A_1(\Delta l)e^{-\frac{\Delta l}{\lambda}} \tag{2}$$

where Δl is the elongation. This function, together with a linear model (i.e. spring) for the needles push, can be fitted in the TM measured acceleration in order to estimate adhesion, disentangling the needles effect. The result is a set of force-to-elongation functions.

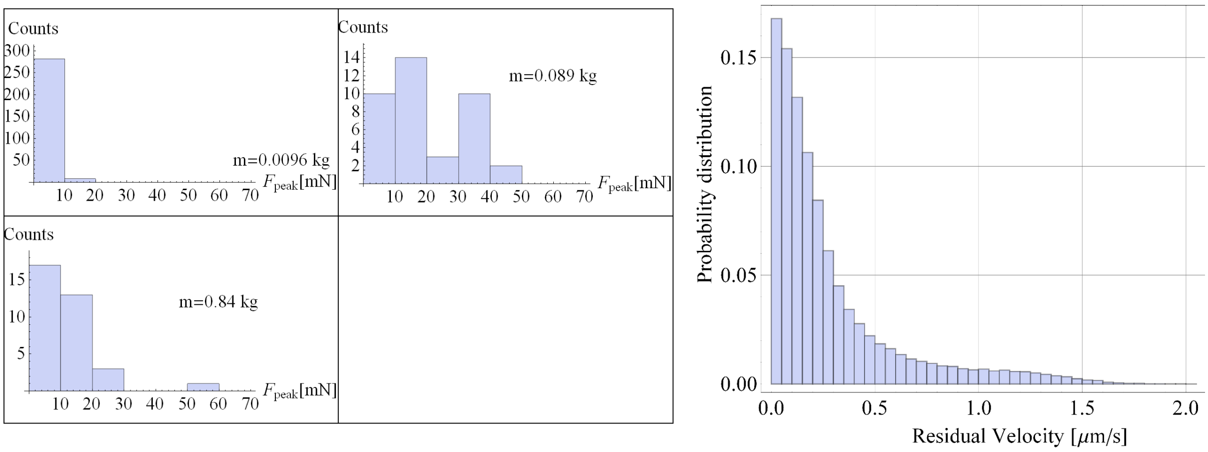

Figure 3. On the left: histograms of the experimental peak forces. On the right: release velocity probability distribution obtained from Montecarlo simulations

A model of the release tip has also been proposed [7] that has a voltage as input and the motion of the tip as output. A mathematical description of the release phase is possible by joining this last model with the adhesion functions and the TM equations of motion.

The output of the simulation is a random variable function of a large set of input random variables:

- Adhesion functions: derived from experimental data, as explained.
- Parameters of the release mechanism model: the model of the release tip is identified on the basis of measurements of its motion. The identification procedure provides both an optimal set of values and their covariance matrix.
- Contact geometry: the uncertainty on the contact radius of the tip is estimated on the basis of the design tolerance.
- Input voltage: the real input is not an ideal step, but has a small drop time whose statistical distribution is extracted from a set of measurements.
- Residual load before release: the nominal value is 300 mN with an uncertainty suggested by Airbus Defence and Space, responsible of all the Caging Assembly.

The release velocity distribution resulting from 100000 simulations is shown in Fig. 3. The 99.73 % upper value is 1.5 μm/sec.

This activity provides key information in the scope of future Drag-Free missions and eLISA especially. One parameter that could improve the performance is the tip's head curvature radius. As a first order approximation, adhesion is proportional to the contact area. In the Hertz model [8], the radius a of the contact area and the force F are:

$$a = \frac{\sqrt[3]{3}\sqrt[3]{\frac{FR}{E_m}}}{2^{2/3}} \qquad F = \frac{4}{3}d^{3/2}E_m\sqrt{R} \tag{3}$$

where R is the radius of the hemisphere in contact, d the indentation and E_m the equivalent elastic modulus. A larger R means a larger a and contact area. At the same time a small R increases the indentation d. The larger the contact area, the larger will be adhesion. Conversely, a larger indentation means a longer contact time and an enhancement of the effects of asymmetrical mechanisms actions. A trade-off value can therefore be found and it can be shown that a radius of about 1 mm would provide much better worst-case performance as shown in Fig. 4. Even in an estimation in which adhesion is low, the current value of 10 mm (Fig. 1) appears large.

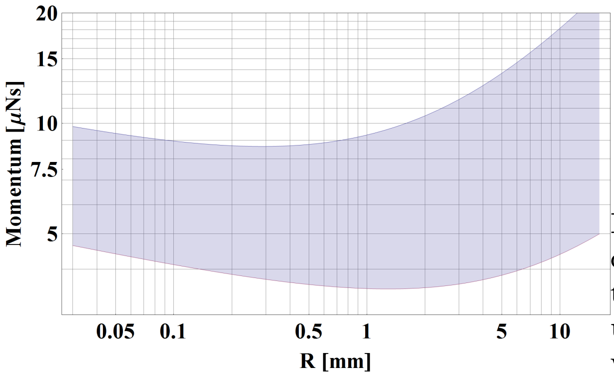

Figure 4. Estimation of the worst case velocity as a function of the tip radius. The two curves are an upper and bottom estimation of the worst-case.

4. Conclusion

The release of the test mass represents a critical phase for the LISA-Pathfinder space mission. In order to declare it successful, it must result in a test mass moving with a velocity below 5 μm/sec. An experimental-analytical procedure has been defined to evaluate the risk of this phase. Most of this risk is due to the presence of adhesion between the Au/Pt test mass and the release mechanism. An experimental facility was built to estimate adhesion effect in dynamic conditions in a space-like environment. The results of on-ground testing activity together with simulations suggest that the worst-case test mass velocity is compliant with the requirement with a margin factor larger than 2.

References

[1] Antonucci F, Armano M, Audley H, Auger G, Benedetti M, Binetruy P, Bogenstahl J, Bortoluzzi D, Bosetti P, Brandt N, Caleno M, Canizares P, Cavalleri A, Cesa M, Chmeissani M, Conchillo A, Congedo G, Cristofolini I, Cruise M, Danzmann K, Marchi F D, Diaz-Aguilo M, Diepholz I, Dixon G, Dolesi R, Dunbar N, Fauste J, Ferraioli L, Ferrone V, Fichter W, Fitzsimons E, Freschi M, Marin A G, Marirrodriga C G, Gerndt R, Gesa L, Gilbert F, Giardini D, Grimani C, Grynagier A, Guillaume B, Guzmn F, Harrison I, Heinzel G, Hernndez V, Hewitson M, Hollington D, Hough J, Hoyland D, Hueller M, Huesler J, Jennrich O, Jetzer P, Johlander B, Karnesis N, Killow C, others, Llamas X, Lloro I, Lobo A, Maarschalkerweerd R, Madden S, Mance D, Mateos I, McNamara P W, Mendes J, Mitchell E, Monsky A, Nicolini D, Nicolodi D, Nofrarias M, Pedersen F, Perreur-Lloyd M, Plagnol E, Prat P, Racca G D, Ramos-Castro J, Reiche J, Perez J A R, Robertson D, Rozemeijer H, Sanjuan J, Schleicher A, Schulte M, Shaul D, Stagnaro L, Strandmoe S, Steier F, Sumner T J, Taylor A, Texier D, Trenkel C, Tu H B, Vitale S, Wanner G, Ward H, Waschke S, Wass P, Weber W J, Ziegler T and Zweifel P 2012 *Classical and Quantum Gravity* **29** 124014
[2] Zahnd B, M Zimmermann M and Spörri R 2013 LISA-Pathfinder cage and vent mechanism - development and qualification *Proceedings 15th European Space Mechanism and Tribology Symposium (ESMATS)*
[3] Neukom A, Romano R and Nellen P M 2009 Testing and lesson learnt of LISA GPRM *Proceedings 13th European Space Mechanism and Tribology Symposium (ESMATS)*
[4] Bortoluzzi D, Benedetti M, Baglivo L, Cecco M D and Vitale S 2011 *Review of Scientific Instruments* **82** 125107 (pages 11)
[5] Bortoluzzi D, Benedetti M, Conklin J W, Baglivo L and Lio M D 2011 Testing the LISA-Pathfinder test mass injection into a geodesic *20th Annual Conference of the Italian Association of Theoretical and Applied Mechanics*
[6] Bortoluzzi D, Benedetti M and Conklin J W 2013 *Mechanical Systems and Signal Processing* **38** 384 – 398 ISSN 0888-3270
[7] Bortoluzzi D, Conklin J W and Zanoni C 2013 *Advances in Space Research* **51** 1145 – 1156 ISSN 0273-1177
[8] Maugis D D 2000 *Contact, adhesion, and rupture of elastic solids* (*Springer series in solid-state sciences* vol XIV) (Berlin, New York: Springer) ISBN 3-540-66113-1