ALIGNMENT AND TESTING OF THE GPRM AS PART OF THE LTP CAGING MECHANISM

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Background

The GPRM (Grabbing, Position and Release Mechanism) is part of the Caging Mechanism (CM) and its electrical control unit (CCU) of the LISA Technology Package (LTP) on board ESA's LISA Pathfinder Spacecraft (LPF). The GPRM was only tested at sub-assembly level (one half on the mechanism) but never in assembled configuration on system level with the flight electronics (CCU). The developing company (RUAG Space, CH) was contracted with these limited activities.

The GPRM EQM was successfully tested in 2008 and the two flight models were delivered in 2009. Due to design evolution of the CM, the flight GPRMs could not be tested in assembled configuration directly after their delivery. These GPRM system tests needed to be implemented in the upgraded CM design. In addition an alternative integration and alignment approach was developed taking advantage of the experience to date, which also resulted in an optimised schedule.

As a consequence of the above mentioned starting point and the evolution of Caging Mechanism, the interface to the CM, an alternative alignment concept and verification approach of the GPRM needed to be developed and implemented by MAGNA Steyr Aerospace in close cooperation with all involved parties. The TV and functional test set-up was refurbished and pre-tests were performed such that the requirements could be verified.
Vibration testing of the GPRM in its assembled and aligned configuration was different due to the new test and verification approach. New FEM models for the GPRM vibration test needed to be established and verified.
Handling and operating the flight hardware, establishment of new alignment approaches and upgrade of test equipment for the new approach were the major challenges in this verification programme.

This paper presents the alignment and testing activities of the GPRM together with its control electronics – the CCU.

1. INTRODUCTION

1.1. GPRM function

The GPRM is located in the centre of the Caging Mechanism. The GPRM consists of one upper and one lower half which are identical except the interface to the Test Mass (TM, 46x46x46 mm). One half is built of 2 main sub-assemblies - the actuator unit and the grabbing finger unit.

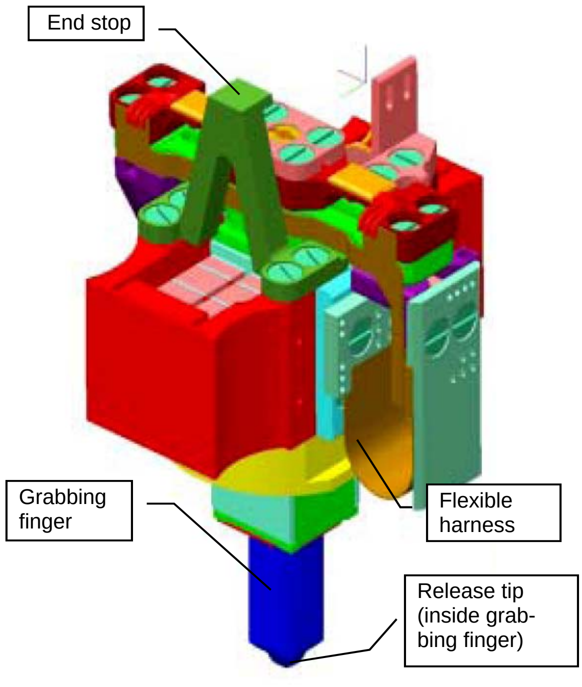

Figure 1-1: one half of the GPRM

The main functions of the GRPM are:
- Grabbing the free falling TM
- Centering and positioning of the TM
- Release of TM into free-fall

The grabbing function ensures that the TM can be grabbed from each position and attitude within the Electrode Housing (EH) cavity. This is performed with two

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plungers (grabbing fingers) interfacing the Test Mass at a special designed area, one on each z surface.
The centring and positioning function provides the task of moving the TM into the centre of the EH. The TM shall be positioned in the centre with accuracy smaller than ±100 µm in all axes. The rotational accuracy is defined with ±1600 µrad about all axes for release in-orbit.

Once the test mass is properly positioned the release into free-fall will be performed by accelerating the release tip and retracting the plungers away from the TM leaving the TM with a residual speed of smaller than 5 µm/sec and 100 µrad/sec.
After release the grabbing finger will wait in the vicinity of the TM until the command to move into retracted position where the tips of the plunger are about 5 mm behind the surface of the electrodes' plates of the EH. In science mode the GPRM is completely switched off.

In case of a S/C safe mode the GRPM grabs the TM and stores it with a low force between the grabbing fingers. Furthermore the TM can be discharged while held by the completely isolated grabbing fingers.
Further details can be found in reference 1.

1.2. Start of Project

The single GPRM halves were developed, tested and delivered by its supplier. In order to verify all functions and performances of the GPRM, it needs to be assembled and aligned on its interfacing structure called IIS (Internal Interface Structure). In this configuration it can be tested in full with its Control Electronics, the CCU. The functional test, thermal vacuum test and magnetic test were not performed on the single GPRM halves. The tests had to be performed in assembled configuration for the FMs with the GPRM only.
For all these activities the test equipment was shipped to MAGNA Steyr Aerospace who had to develop a new alignment concept, update the test equipment and become familiar with the hard- and software.

2. ALIGNMENT AND MEASUREMENT

2.1. Alignment

The evolution of the CM and the new GPRM integration and alignment concept involved all parties dealing with the Caging Mechanism. The integration procedure defined the alignment of the GPRM halves onto the Vacuum Enclosure (VE) flanges and afterwards the alignment of the flanges w.r.t. each other on the IIS dummy such that the GPRM system tests in assembled configuration could be performed.
New references needed to be defined on the VE flange and the GPRM. These references were the precise holes

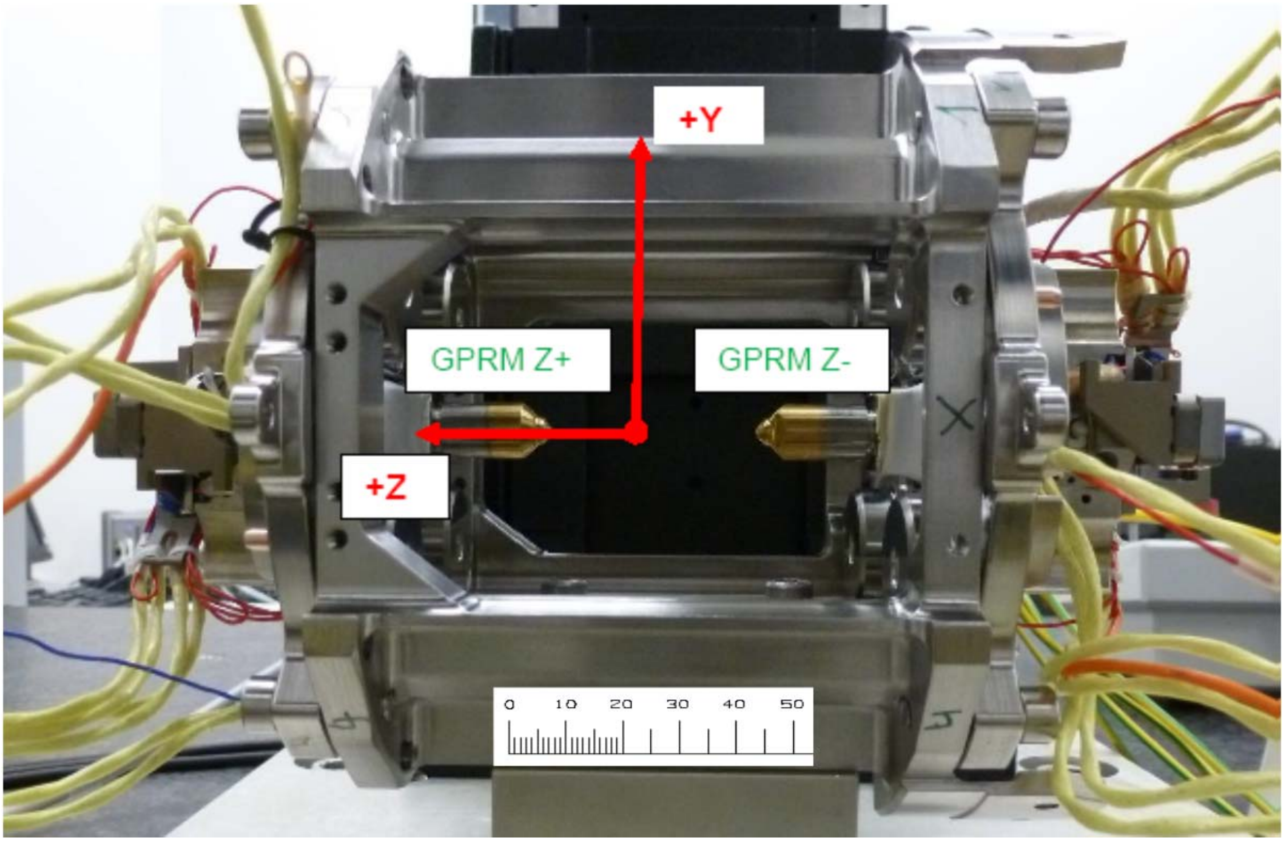

Figure 2-1: GPRM aligned on IIS

for the launch lock fingers of the Caging Mechanism in the VE flange and dedicated measurable surface points. All these references must be accessible when the GPRM halves with the flange are mou nted in the ISH as the TM as main reference is no more accessible.

During the integration of the GPRM halves onto the VE flanges the TM was sitting on one plunger of the GPRM. The position and attitude of the TM coordinate system could now be projected to dedicated surfaces of the GPRM avoiding the usage of the TM during the whole alignment process. Now the GPRM was aligned against the flange and in a second step the alignment flange against flange was performed. The obtained alignment data form the basis for the alignment on ISH (Inertial Sensor Housing) level later on.

The following alignment accuracies have been achieved w.r.t. to the defined requirements are:

Requirement	RQMT	upper	lower
GPRM against flange			
- In x direction [µm]	±5	-5	-5
- In y direction [µm]	±5	-2	-2
- In z direction [µm]	±5	-3	-3
- About x [µrad]	±130	-34	58
- About y [µrad]	±130	65	-11
- About z [µrad] (Z- only)	±370	-	136
Flange against flange			
- In x direction [µm]	±5	1	
- In y direction [µm]	±5	3	
- In z direction [µm]	±5	-2	
- Tilt ξ [µrad]	±30	28	
- About z [µrad]	±43	-57	

Table 2-1: Measured Alignment values of the GPRM

2.2. Verification measurement

The verification measurement was performed in order to determine the absolute position and attitude of the grabbed TM. The aligned GPRM on the flanges was mounted with the z-axis in vertical position. The plunger of the lower GPRM (with the pyramidal tip) was moved in grabbing position. The flight test mass made out of AuPt was placed on the lower plunger and grabbed with 5 N by the upper plunger. Due to the mass of the TM (2 kg) and the 5 N grabbing load the lower plunger moved slightly downwards. The reference system is located on the lower flange (Z-). A defined offset represents the EH centre which should coincide with the TM centre.

The TM centre position and orientation was measured against the EH centre. The first five measurements determined a mean position. The next five measurements showed the repeatability w.r.t. the mean position. This verification measurement was performed before and after the environmental test campaign. Table 2-2 shows the absolute values of the grabbed TM.

	RQMT	Abs. value before	Abs. value after
Linear accuracy			
- x direction [µm]	±100	-4 ÷ -1	-5 ÷ -2
- y direction [µm]	±100	-17 ÷ -1	-2 ÷ 5
- z direction [µm]	±100	-45 ÷ -34	-5 ÷ 14
Rotation accuracy			
- About x [µrad]	±1600	462 ÷ 831	23 ÷ 381
- About y [µrad]	±1600	1061 ÷1152	737 ÷ 958
- About z [µrad]	±1600	-689 ÷ -334	-383 ÷ -199

Table 2-2: absolute TM centre w.r.t. EH centre

In Figure 2-2 the LDTM is held by the upper and lower GPRM during the verification measurement

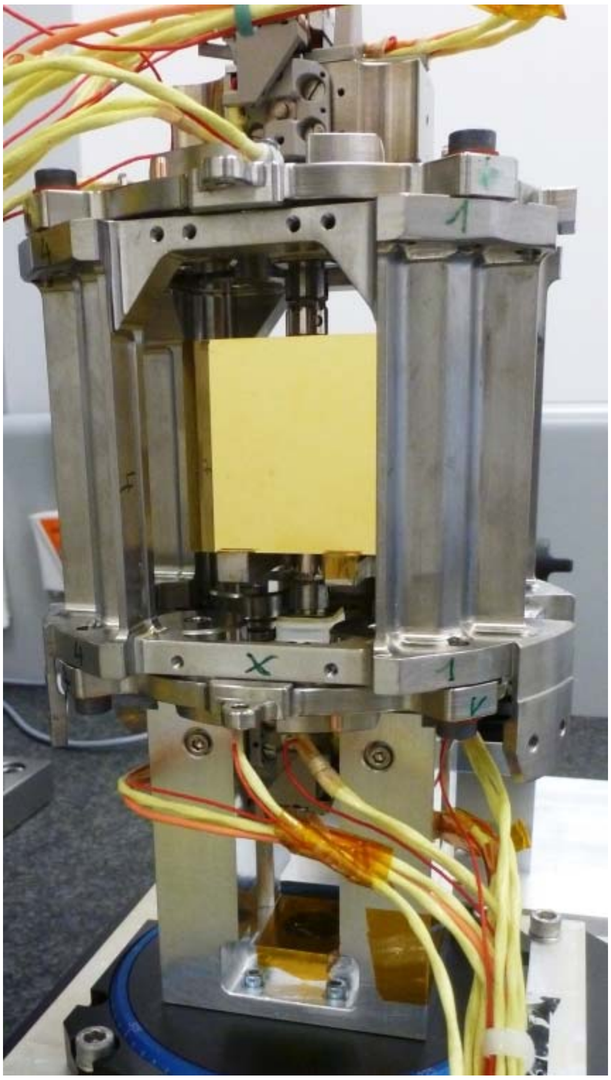

Figure 2-2: Verification measurement

3. TEST PREPARATION

3.1. Calibration of sensors

During the test preparation phase the sensors used on the GPRM had to be calibrated with the flight electronics. The initial calibration was performed on the single GPRM halves in vertical configuration. The calibration measurements were performed against a load cell up to 30 N. To eliminate the gravity effect of the spring supported element the zero load position was calibrated with the plunger pointing upwards and the second time downwards.

When the GPRM was prepared for functional testing in horizontal position the unloaded sensor monitored a load different from zero. A re-calibration was required in order to get the GPRM working with the CCU.

3.2. Release Tip adjustment

For the release of the TM into free-fall the release tip inside the plunger, with a diameter of 0,8mm, had to be adjusted. The release tip holds the TM before release and is retracted very quickly releasing the TM into free fall without a very low residual velocity. The adjustment had to be very accurate as the maximum extension of the release tip is about 15 µm. The flight TM was available for the GPRM adjustment at begin of the alignment campaign and then shipped back to the ISH contractor to be gold coated. During all functional tests a Light Density TM (LDTM) was used which used a movable floor where the release tips contacts. This floor was required as the GPRM could not be adjusted to the LDTM floor without destroying the adjustment w.r.t. the flight TM. The floor provides the possibility to use a non-conductive material which helped to indicate the successful separation of TM and GPRM.

3.3. Patching with CCU

One important step is to update the configuration tables and macros within the CCU. The CCU supplier was invited to the test site to perform the electrical integration of the GPRM with the CCU. The parameter within the configuration table were defined and patched. The GPRM was activated by direct CCU commands to check the function and performance. Small changes to the predefined values of position and load tolerances required a further patch of the parameter. The macro (sequence of direct commands) “Grab_TM” and “Release_TM” were executed to verify their functionality successfully.

4. VERIFICATION TESTING

4.1. Magnetic testing

During the EQM test campaign no magnetic test was performed on the GPRM. Due to the stringent magnetic requirement in the Lisa Pathfinder project such a test was mandatory. The magnetic requirements for a retracted and switched off GPRM are:

- Magnetic field < 0,1 µT at position of TM
- Magnetic gradient < 0,5 µT/m at position of TM

The measurements were done on 2 corresponding FM GPRM halves in the magnetic lab at the Institut für Weltraumforschung (IWF) in Graz. This institute was perfect from logistic point of view and was in the past also involved in the magnetic measurement campaign for the Cluster mission.

In the set up each GPRM half was measured individually. The unit under test was placed together with a high sensitive tri-axial fluxgate magnetic sensor in a cylindrical mu metal chamber. Magnetic measurements were done by rotating the GPRM around its plunger axis 360º in steps of 90º. The accuracy of the set up was better than +/- 0.5nT.

Analysis of the results showed that for a single dipole approximation both GPRM were well within the requirements. The predicted field at the TM centre was < 2.5nT and the gradient < 40 nT/m.

4.2. Functional Performance Testing

4.2.1. <u>Test Set-up</u>

The aim of the GPRM functional test is to verify the

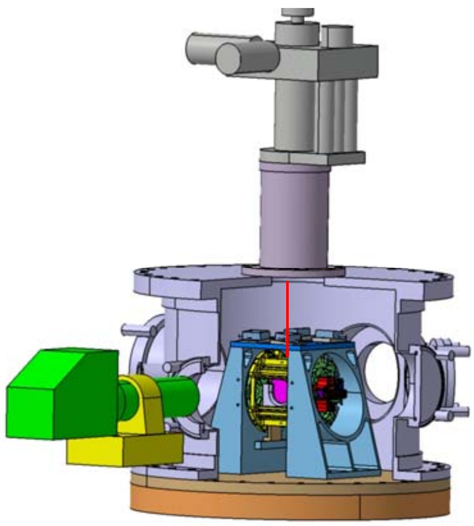

Figure 4-1: GPRM Test set-up

function and performance of the mechanism. Mainly the macros stored within the CCU needed to be verified but also the direct commands had to be tested. The GPRM was mounted in horizontal position within a special designed vacuum chamber. On top of the chamber a tower was mounted to which the LDTM was attached using a soft spring to compensate small misalignments.
The LDTM could be adjusted along all lateral directions and about the vertical y-axis. The TM itself had to be balanced using small mass elements for rotation about x and y. The chamber itself could also be rotated about these 2 axes.
To identify the release of the TM from the plungers an electrical circuit was used. The plunger and the release tip were insulated from their support in order to bias the TM in-orbit. This line could now be used to identify the TM release. The bottom of the LDTM was insulated. While one wire was connected to the TM the other one was connected to the bias line of the GPRM. When the plunger was in contact with the TM the circuit was closed. During and after extension of the release tip the circuit was open. Shortly after the release which lasts only a few msec a re-contact was established between TM and plunger - enough to demonstrate a successful release.

4.2.2. Start of test

Due to the new configuration of the complete Caging Mechanism system the in-orbit de-caging sequence needed to be adopted. To performed the hand-over from the CVM to the GPRM the test was started using the STEPWISE command (executing single steps controlled by a counter) to move the GPRM from retracted position towards the centre. The command was executed with 9000 steps (step size ~1.6 µm) sufficient to reach the sensor measurement range in extracted position. After execution of the command the mechanism stopped in the dark zone (no sensor signal). The probable reason for this early stop was that the NEXLINE® step size depends on position, temperature and load. A new start sequence needed to be established as further uncontrolled movement could have damaged the TM as this command is not load controlled.
The next command verification was the STEP_LOOP command with 3 steps per NEXLINE actuator and a final grabbing load of 1 N. The command was correctly executed with the suspended LDTM and a command STEPWISE BACK with 60 steps ended in the correct position.
The next command sent addressed the macro GRAB_TM. The command was executed but did not finish in the expected position. This macro contains the STEP_LOOP command to grab the TM and the POSITIONING command to move the grabbed TM into the centre. The TM was grabbed but the GPRM moved into its internal end stop.
The solution to this issue was to send an additional POSITIONING command to move the TM back in the centre position. The direct command ended with a grabbed TM successfully in the centre.
The RELEASE_TM macro command was sent and executed successfully. Within this RELEASE_TM macro the pass-over of the TM from the plungers to the release tips on both GPRM halves is performed. The TM is held with a small load of about 300 mN. The release is initiated by retracting the release tips and retraction of the plungers by 250 steps.
The grabbing and release was performed 2 more times and the sequence ended with the retraction of the GPRM. The redundant side was connected and the test repeated. The final test was performed again on the main side. During all tests the unsuccessful grabbing occurred randomly but the root cause could not yet be identified.

4.2.3. Test results

Table 4-1 shows the test results of the grabbed position which was measured using eddy current sensor for the position and an autocollimator for 2 angles.
Despite the repeatability of the position accuracy the execution of the release macro was of high interest as this also defines the performance of the system.

Requirement	RQMT	repeatability
Linear position accuracy		
- In x direction [µm]	±100	-7 ÷ -5
- In y direction [µm]	±100	0 ÷ +12
- In z direction [µm]	±100	-8 ÷ 119
Rotational position accuracy		
- In x direction [µm]	±1600	-710 ÷ -235
- In y direction [µm]	±1600	-181 ÷ -120
- In z direction [µm]	±1600	-208 ÷ +84

Table 4-1: repeatability of TM centre

In Figure 4-1 the pass-over and release sequence is shown. The black and red line shows the force on the plunger and release tip. The load drops from a grabbing load of 2 N to a release tip load of about 300 mN. This low load is required to minimize the adhesion force on the release tip during release in orbit. The lowest load during the pass-over was about 100 mN – just enough not to loose the TM and to keep its orientation. At the release (retraction of release tips) the load drops to zero.

The light green and light blue curves show the position of the plunger. During the pass-over (TM is handed-over from plunger to release tip) the plungers move about 12 microns back. After the release has been initiated the plunger retracts with 250 step (~0.5 mm).

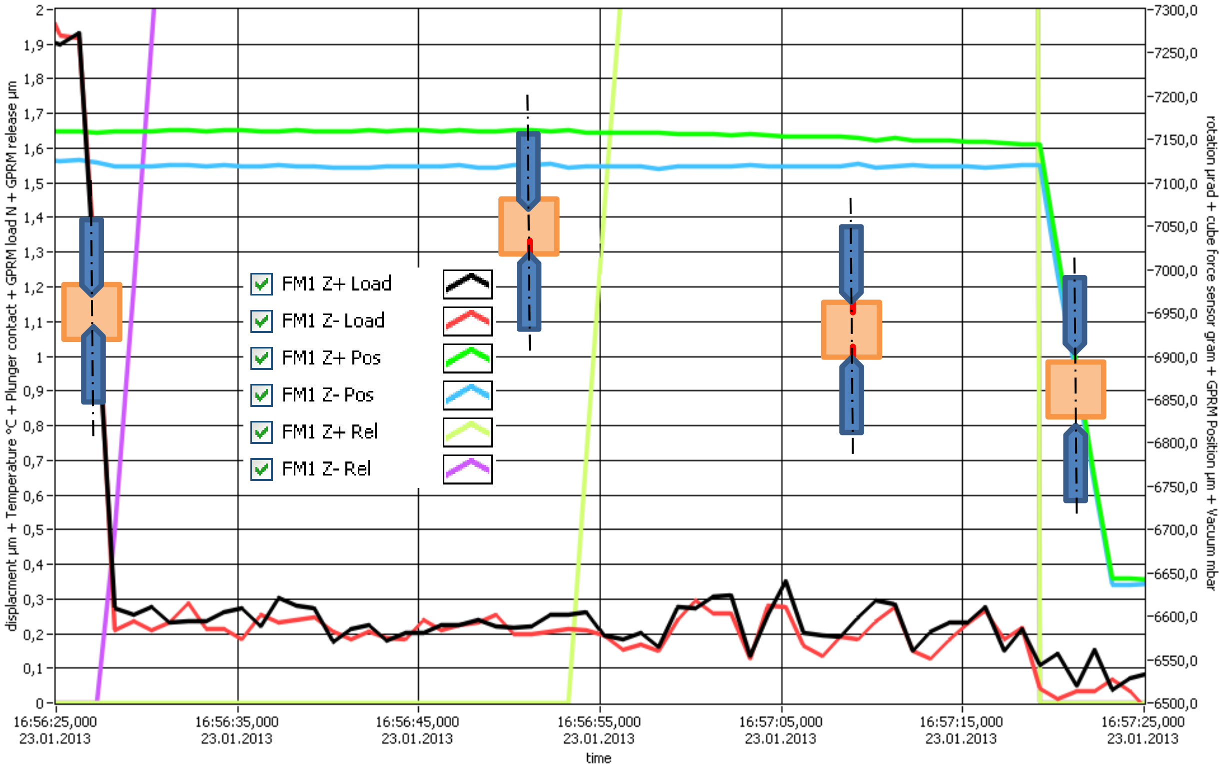

Figure 4-1: typical pass-over and release cycle (force, plunger position, release tip)

The mint green and violet curves show the extension and retraction (release) of the release tip. The first pass-over takes place with the Z+ GPRM (increase of violet line) and then the Z- Pass-over starts (mint green line). At release both lines form a vertical line just before the plunger retraction starts.

4.3. Vibration Testing

The EQM GPRM was already vibration tested within the EQM of the Caging Mechanism. The FM GPRMs however were not yet tested at acceptance level. In order to test these mechanisms at GPRM level a new load profile had to be established. Based on already performed breadboard test done for the Caging Mechanism integrated in the ISH new loads were derived. A new vibration FEM model was established reflecting the latest modifications including the adapted test set-up. Thanks to an excellent model and preparation the vibration test of the 2 GPRM flight models were successfully executed. Both mechanisms were tested up to levels of 72 g within a short time frame without any discrepancies.

4.4. TV Performance

For the TV test a PFM approach was followed for one of the models (0ºC/40ºC and 4 cycles) and the other model was subjected to the acceptance levels (5ºC/35ºC and 4 cycles). During the thermal vacuum functional tests at temperature extremes the GPRM also showed an excellent behaviour.

4.4.1. Test results

During the TV functional test the performance of the GPRM has been tested and verified.

Requirement	RQMT	repeatability
Linear position accuracy		
- In x direction [µm]	±100	-29 ÷ +29
- In y direction [µm]	±100	-5 ÷ +23
- In z direction [µm]	±100	-31 ÷ -117
Rotational position accuracy		
- In x direction [µm]	±1600	-764 ÷ +365
- In y direction [µm]	±1600	-968 ÷ +101
- In z direction [µm]	±1600	-349 ÷ +425

Table 4-2: repeatability of TM centre

4.4.2. Release velocity performance

The very small TM release velocities (i.e. 5µm/sec) of the GPRM could not directly be tested and verified with the GPRM itself. The verification of the TM release velocity was performed in a combined approach as several effects would have influenced the final verification of the release velocity i.e. seismic noise. The University of Trento (UTN), Italy measured the release velocity using their dedicated pendulum facility. These measurement results, the retraction measurements of the GPRM, the preload during pass-over and the time delay measured with the CCU were fed into the TM release model, which calculated the TM release velocity in-orbit using the Monte-Carlo method. This verification is described in detail within another paper (see reference 2) and the latest version as poster session on this ESMATS symposium (reference 3).

During verification and testing of the GPRM halves the retraction of the release tips were measured. An interferometer measured the retraction distance over time and its derivatives were calculated.
During the functional tests of the GPRM in assembled configuration the maximum force between the release tip and the TM during the pass-over was measured.
The functional test with the CCU provided the information about the time delay between upper and lower release tip retraction start.
The Figure 4-1 shows the estimated release velocity depending on the applied preload and the time delay of the retraction.

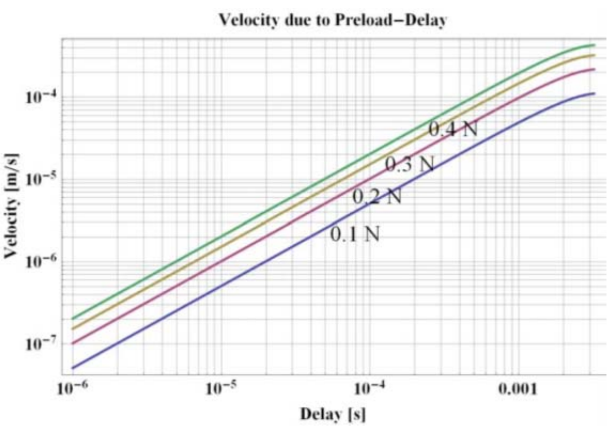

Figure 4-2: Release velocity dependence from preload and delay

Using the data of the tests performed on the GPRM and the pendulum tests in Trento the TM release model provides a release velocity of 1.8 µm/s, which is well within specification.

5. Conclusions

The GPRM FM1 was successfully function tested in its flight configuration. The verification of the release velocity was successfully performed at of the University of Trento, Italy.
The GPRM FM1 is ready to be built into the Inertial Senor which will then be integrated into the LTP and later on into the spacecraft.
At present the GPRM FM2 is undergoing the test sequence. The verification measurements showed good results and it will be ready to be integrated by end of October2013.

For the future eLISA mission the GPRM will be one of the key components.

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