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Front-window replacement and performance characterization of a commercial digital micro-mirror device for use in the infrared spectrum

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ABSTRACT

In this paper, a validated procedure to replace the protective front-window of a commercial digital micro-mirror device (DMD) from Texas Instruments (TI) to allow its use over a large spectral range is presented. This reworking process was required since the original window employed for encapsulation is made from glass with an anti-reflection coating designed for a specific spectral range, incompatible with the required large spectral range of the demonstrator under development. In addition, a characterisation of the DMD performance in terms of spectral transmission, as well as switching time and pointing stability is presented.

The motivation behind this study lies within the development of a novel instrument in the frame of the EU H2020 funded SURPRISE project. The project aims at developing a super-resolved compressive imager operating in the visible-near infrared (VNIR) and mid-wave infrared (MWIR) spectral ranges for space applications, especially targeting Earth Observation. The instrument concept is based on the use of a spatial light modulator (SLM), in this case a digital micro-mirror device (DMD), as a core element of its architecture to enable data acquisition and compression in single step based on the compressive sensing principle. Even though one of the long-term objectives is to develop a European-based SLM solution, a commercial SLM component has been selected for the demonstrator This allows reducing the development cost and initiating the development of the demonstrator in parallel to the development of a European-based solution.

Keywords: Spatial Light Modulator, digital micro-mirror device, MEMS, space, Earth Observation, environmental tests, compressive sensing.

1. INTRODUCTION

The availability of fast and reliable spatial light modulators (SLM) for space would allow targeting new types of applications. As an example, the aim of the EU H2020 funded SURPRISE project consists in developing a super-resolved compressive imager operating in the visible-near infrared (VNIR) and mid-wave infrared (MWIR) spectral ranges. The instrument concept is based on the use of a digital micro-mirror device (DMD) as a core element of its architecture to enable data acquisition and compression in single step based on the compressive sensing principle. In this context, the availability of a space compatible SLM active over a large spectral range will be crucial for the success of future missions possibly relying on this technology.

Today, Texas Instruments benefits from a monopolistic position on the market of commercial DMDs. These devices are integrated in most of commercial video projection systems (i.e. beamers). One aim of the SURPRISE project lies in the development of a European-based solution. Nevertheless, for the SURPRISE demonstrator, a commercial component from TI has been selected. This enables reducing the development cost and initiate the development of the demonstrator prior finalizing the custom European design.

Each DMD model from TI is encapsulated with a protective window made from glass with an anti-reflection coating designed for a specific spectral range. However, none of the DMD models was compatible with the required large spectral range for the SURPRISE demonstrator (VIS-NIR and MWIR). Nevertheless, without protective window, the micro-mirrors made of aluminum present an intrinsic reflectivity compatible with such a large spectral range.

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In this paper, we first present investigations performed to rework the selected DMD by replacing the original borosilicate window with an uncoated window presenting a high transmittance over the VIS-NIR and MWIR spectrum. The reworking process must be carried out safely to protect the sensitive micro-mirrors from dust and water vapor all along the process, and over the whole lifetime of the reworked DMD. Second, we present an assessment of the micro-mirror reflectivity in VNIR and MWIR spectral ranges, with and without the replacement protective window. Finally, the micro-mirror switching time and pointing stability were measured since these are key parameters in view of the future demonstration with the SURPRISE prototype.

1.1 Selected commercial digital micro-mirror device

Considering the targeted specifications for the SURPRISE demonstrator, the model DLP7000 from TI was selected in its evaluation kit version (DLPLCR70EVM) together with a controller (DLPLCRC410EVM) to facilitate performance tests. The main optical specifications of this DMD are summarized in Table .

Table 1-1. DLP7000 optical specifications.

Tilting type	Tilt angle	Pitch	Array size	Spectral range	Reflectivity	Diffraction efficiency	Fill factor
diagonal	±12°	13.68 µm	1024x768 pixels	400-700 nm	88%	86%	92%

Each micro-mirror of this DMD can be actuated independently along binary positions, either deflected at +12° or -12° with respect to the horizontal plane.

2. FRONT-WINDOW REPLACEMENT PROCEDURE

As explained above, the main challenge for integrating a commercial off-the-shelf (COTS) DMD in the SURPRISE demonstrator lies in the limited spectral transmittance range of protective windows. We thus investigated ways to remove the original window and replace it with a better-suited glass interface, without damaging the micro-mirrors.

Similar reworking processes have already been reported in the literature [1][2][3]. Based on these studies, we investigated two solutions for sealing the replacing protective window: indium wire and epoxy resin.

2.1 Selection of materials

Sapphire was selected for replacing the protective window since this glass presents a high transmittance over a wavelength range from 400 nm to 5 µm, is characterized by a high hardness and its coefficient of thermal expansion (CTE) almost matches the metallic housing frame. The window was procured from Crystran (UK) with a diameter of 25 mm and 1 mm thickness. The aperture covers the full DMD size, and a 1 mm thickness offers a sufficient mechanical resistance to the shear stress resulting from the assembly process. The frame was manufactured in Kovar, with a CTE that matches both the sapphire window and DMD frame.

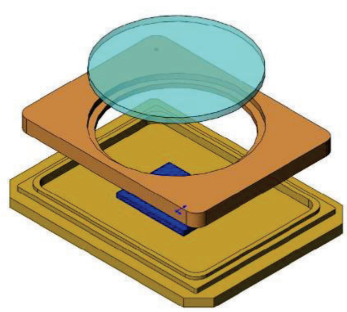

Figure 1: Exploded view showing (bottom-up): unwindowed DMD, window frame in Kovar, and sapphire window.

2.2 Indium wire sealing

A CAD model of the DMD, replacing window and frame was designed, as shown in Figure 2.

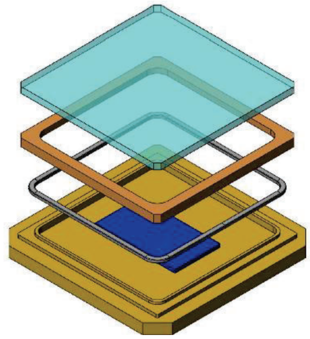

Figure 2: Exploded view showing (bottom-up): unwindowed DMD, indium wire (crushed shape), window frame, and window.

Prior finalizing the designed reworking procedure, we realized a preliminary validation test of indium sealing. This test was conducted onto an existing DMD that was sealed with its package into a mechanical housing. The resulting assembly was then tested with a helium leak detector. This test proved a lack of hermiticity of the assembly. After the leak detection test, the DMD was disassembled for further inspection and confirmed a poor adhesion of the frame onto the housing. Figure 3 shows pictures of the different parts after disassembly.

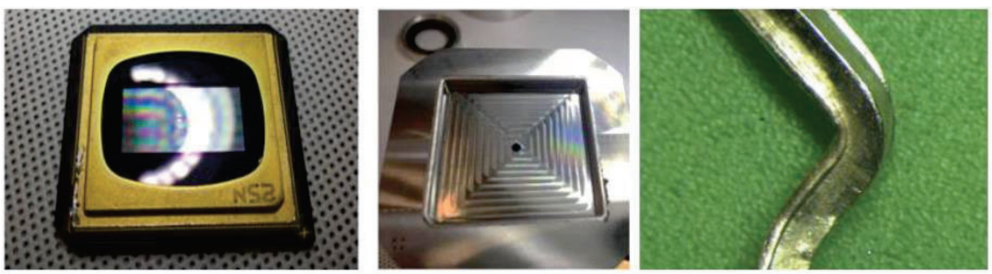

Figure 3: Disassembled DMD and housing, together with the indium wire. It is noteworthy that the indium wire remains intact into the groove of the mechanical housing.

This first realization led to the conclusion that indium sealing was inappropriate for the following reasons:

- A lack of purity in the indium wire led to a poor adhesion.
- The process required applying an importance force to shape the joint.
- The process is time-consuming, and its complexity hindered the development of a reliable process.

2.3 Epoxy resin sealing

Considering the results obtained with the indium wire sealing implementation, we investigated a second approach based on epoxy resin sealing. The final reworking procedure consists of the following steps:

1. The original DMD frame is milled at ambient conditions, as shown in Figure 4.
    - Experimental tests showed that no deterioration of the micro-mirrors is present at normal atmosphere if the DMD is not activated.
    - The milled surface of the DMD is properly cleaned to remove residual metal burrs and guarantee good epoxy adhesion.
2. The sapphire window is glued to the Kovar frame.
    - The process is performed inside a clean environment (ISO-5) to avoid dust and contaminant depositions.

- The gluing is performed using an Epo-Tek H72 epoxy resin and following the recommended curing conditions of 150°C during 1h.
- To guarantee a good adhesion and hermicity between the two parts, the resin is properly outgassed before application and a constant pressure over the window is applied during the whole curing process.

3. The frame is glued to the decapsulated DMD.
    - The process is undertaken inside an inert atmosphere. A glovebox with argon is employed, allowing for sufficient dexterity to apply the required epoxy resin and guarantee that the DMD is encapsulated with inert gas inside.
    - All parts to be employed in the encapsulation process, such as DMD, frame, window and tools, are first outgassed at 80°C during 4h.
    - As the glovebox does not feature a sufficient cleanliness level for the procedure, special care needs to be taken, such as using dust protection for the inner surface of the window or applying the resin on the DMD with a cover.
    - The curing process of the Epo-Tek H72 epoxy resin is performed using a heating plate at 80°C during 2h to avoid damage of the electronic components.
    - As the heating process will increase the gas pressure inside the encapsulation, a constant force over the Kovar frame needs to be applied. The same holder used for milling and shown in Figure 4 is employed to hold the DMD and frame together.
    - Once the curing is complete, the encapsulated unit is sealed inside an argon atmosphere package to minimise contaminations before the parylene deposition.
4. A parylene layer deposed to guarantee good hermicity of the reworked DMD.
    - Experimental tests proved that the epoxy alone was not sufficient to guarantee long-term hermicity of the package.
    - After protecting window and electric pads, plasma activation is performed on the outer surface of the joints between frame and window and frame and DMD, followed by silanisation using silane A-174. This guarantees improved adhesion of the parylene layer over the metallic and glass surfaces.
    - Apply a 3 µm parylene layer deposition and remove window and electric pad protections.

Initial tests followed a procedure in which steps 2 and 3 were combined and performed in a clean environment but at a normal atmosphere. These units were initially functional, but were progressively deteriorated, featuring more and more non-functional pixels. Further investigation showed that the presence of oxidants such as oxygen and water vapour inside the encapsulation were the main cause of damage of the micro-mirrors flexing structures.

The procedure had to be adapted to perform the encapsulation inside an inert or oxidant-free atmosphere such as nitrogen or any inert gas. Due to equipment availability, the aforementioned solution using a glovebox and argon was selected showing good results. Unfortunately, the stability of the solution was not sufficient, as eight days after encapsulation the micro-mirrors started showing the same problems. The final modification in the procedure to guarantee a longer-term hermicity of the encapsulation, the parylene deposition, proved to be sufficient, as at the time of writing, the reworked units are fully functional after 10 months.

This method allows obtaining a highly hermetic package and facilitates the development of a reliable and repeatable process that fulfils the application requirements.

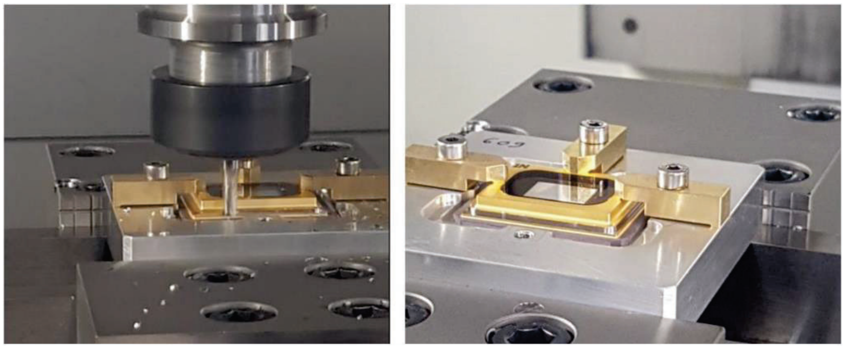

Figure 4: DMD on the milling machine, removal of the edges of the original DMD package.

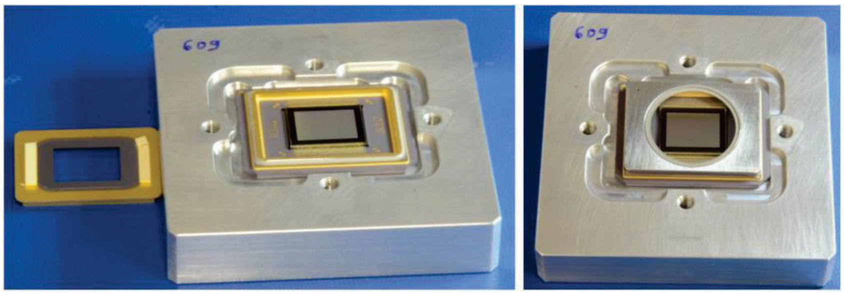

Figure 5: Left: DMD without its cover and epoxy resin sealing (grey ribbon along the edges). Right: DMD with the replacing window frame and sapphire window in place.

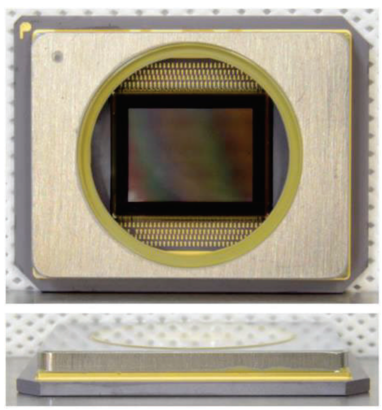

Figure 6: Final assembly of the reworked DMD with Kovar frame and sapphire window before parylene deposition.

3. PERFORMANCES CHARACTERIZATION

Once the reworking procedure validated, we could prepare reworked DMDs fulfilling the requirements in terms of spectral range and reliability. The reflectivity of micro-mirrors was characterized both with the replacement front window and without, to ensure its compatibility with the SURPRISE demonstrator. In parallel, operation verification tests were performed before and after the replacement of the front window to ensure a nominal functionality after rework. In addition, the micro-mirror switching time and pointing direction stability were evaluated on an original DMD. These characteristics are key for a successful demonstration of the SURPRISE concept.

3.1 Visible spectrum transmission

The aim was to measure the spectral reflectivity of micro-mirrors in the wavelength range 400-2000 nm both with the new sapphire front window and without. The test was carried out using Agilent Technologies' Cary 7000 UV-Vis-NIR Spectrophotometer, including Cary Universal Measurement Accessory (UMA) for reflectivity measurement. The characterization was performed with micro-mirrors in off-state. The resulting reflectivity in VNIR range of all both samples is depicted in Figure 7.

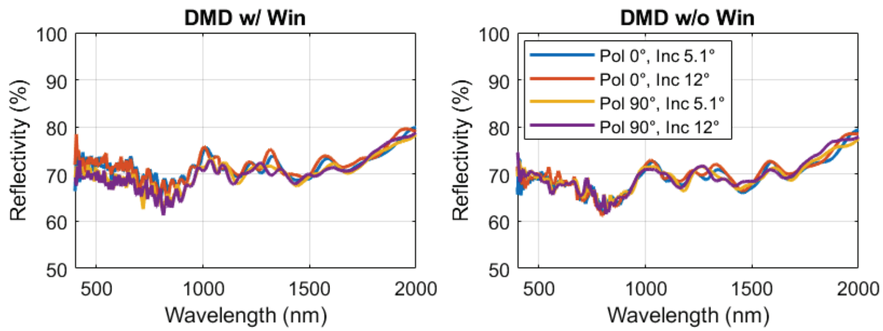

Figure 7: VNIR reflectivity test results with (left) and without (right) sapphire window.

Interestingly, different incidence angles and polarization states do not greatly affect the reflectivity of both samples. No considerable impact in the reflectivity is seen between the samples with and without sapphire window.

3.2 Mid-infrared spectrum transmission

The aim was to measure the spectral reflectivity of micro-mirrors in the wavelength range 2-5 µm both with the new sapphire front window and without. The reflectivity assessment was performed using Bruker's Vertex 70 FT-IR Spectrometer with Bruker's HYPERION FT-IR Microscope. Measurements are performed against a reference sample made from an uncoated gold mirror. Results are presented in Figure 8.

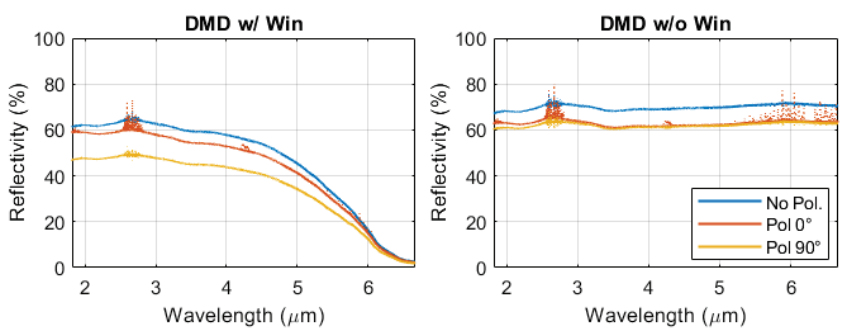

Figure 8: MWIR reflectivity test results with (left) and without (right) sapphire window.

Firstly, it is worth noting that it was not possible to avoid the absorption of H_2O and CO_2 at certain wavelengths, due to the necessity of transmitting the light beam in the open atmosphere. For this reason, raw measurements were post-process to minimise this impact, by down sampling the signal at those specific ranges. As reference, the reflectivity using the raw signals is included as dashed lines.

The reflectivity of the reworked DMD features a considerable drop above 4 µm and is considerably influenced by the polarization state. This drop matches very well the expected transmission curve of sapphire. On the other hand, micro-mirrors without window show a constant reflectivity in the studied spectral range, as expected for aluminium.

3.3 Switching time

The objective of this test was to measure the switching time of a small set of micro-mirror pixels from ON to OFF positions and vice versa. Then, perform a statistical analysis over several random regions of the DMD. This test aimed at verifying the maximal achievable frame rate. Figure 9 presents the assembled test setup.

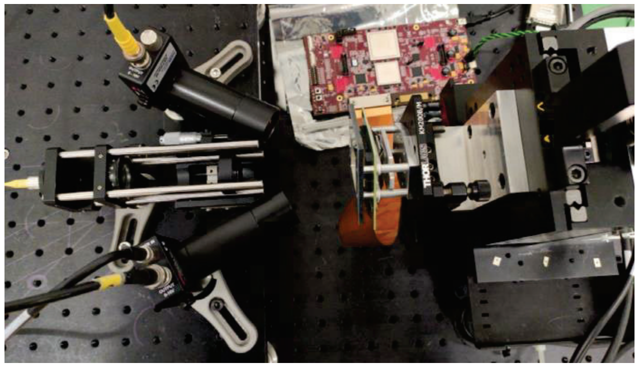

Figure 9: Switching time test setup including light source in the middle, photodiodes in top and bottom and DMD on the right.

A focused light source illuminates a small area of the DMD where all pixels are switched from ON to OFF states and vice versa. Two optical lenses collect the reflected light onto two different photodiodes (PD), either when in ON state (PD1) or in OFF state (PD2). An oscilloscope records the signals arising from both photodiodes. Repeated several times, a statistical analysis of the switching time is performed. Since the DMD is mounted on a x-y translation stage, statistical analysis over several areas can be performed.

Results were obtained for 6 random positions on the active part of the DMD. For each position, 10 measurements were recorded during the switch from one state to the other. Figure 10 plots the results for a single position showing the mean and standard deviation of the switching time for all repetitions.

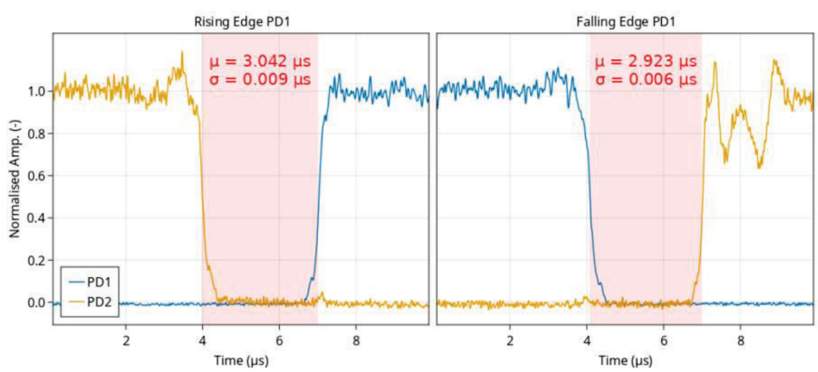

Figure 10: Switching time test results for a single position.

It is first worth noting that as the photodiodes are not the same model, some differences are appreciable in the output data from each one. Mainly, PD2 features a lower output gain leading to a smaller signal-to-noise ratio. Nevertheless, this difference does play any role on the analysis. The signal from both PDs is simultaneously sampled at 0.5 GHz and triggered by either rising edge of PD1 or PD2. The logged data is then normalised to force low and high states at 0 and 1, respectively. The transition from one state to the other is defined at 0.5 threshold. Due to lower magnitude of PD2 signal, greater sensitivity to small misalignments is experienced, generating over and undershoots of the signal. As the shape and length of such characteristics are fully determined by the alignment, they are assumed to happen at high level, and not during transition.

To summarise, considering all measurements, the mean and standard deviation values of the switching time were measured as 2.99 and 0.05 µs. This short switching time ensures achieving the maximum frame rate of 32’552 Hz (30.72 µs) stated in the DLP7000 datasheet and presents a high stability.

3.4 Pointing stability

The objective of this test was to measure the pointing direction repeatability and deviation for a single micro-mirror pixel. Then, perform a statistical analysis over several random pixels of the DMD. This test aimed at assessing the necessary alignment precision and compatibility with the SURPRISE demonstrator design. Figure 11 presents the assembled test setup.

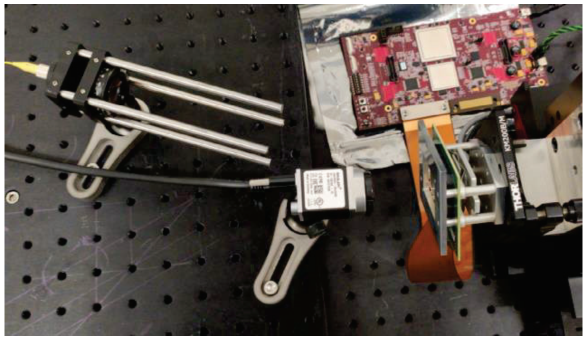

Figure 11: Pointing direction stability test setup consisting of light source on the left, high-resolution CMOS camera in the middle and DMD on the right.

A collimated light source illuminates the DMD where all pixels are in OFF state. A single mirror on the optical axis of the detection system is then turned ON and OFF and one image is recorded to measure the reflection position on a camera, each time the mirror is turned ON, after stabilisation. By placing a camera (detector only, no lens) at a certain distance, computing the centroid of the recorded pattern enables resolving micro-mirror angle variations below 0.1°. The angular resolution will be given by the distance from the mirror to the camera, the pixel size and the precision in computing the centroid. The camera is located at approximately 45 mm from the DMD, considering a camera pixel size of 2.74 µm, an angular resolution of 0.0035° is achieved. Since the DMD is mounted on a XYZ translation stage, statistical analysis over several pixels can be performed.

Results were obtained for 6 random single micro-mirror on the active part of the DMD. For each pixel, 6 repetitions were recorded. For each image, as shown for a single pixel and two repetitions in Figure 12, a gaussian distribution is fitted for both X and Y positions, giving the centre (mean µ) and width (standard deviation σ) of the light intensity.

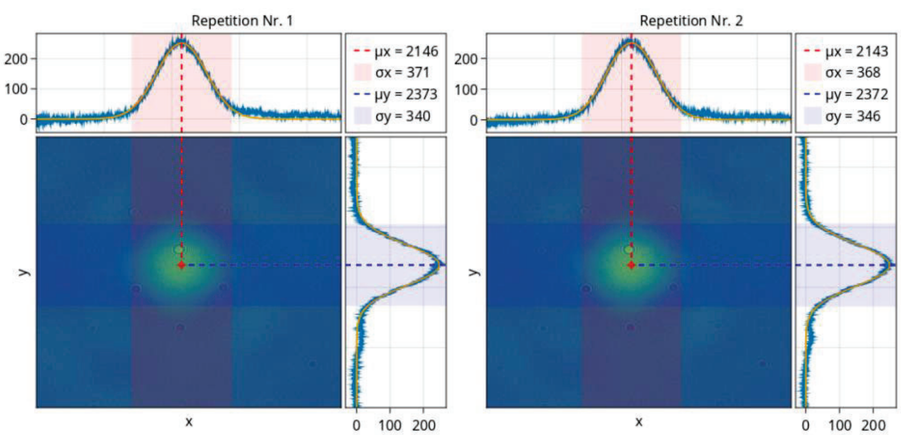

Figure 12: Pointing direction stability test results for a single pixel and two repetitions showing the normal distribution fit for X and Y pixels, as well as their mean and standard deviations.

To summarise, considering all measurements, the standard deviation of the angle was measured to be inferior to 0.025°.

4. CONCLUSION

In this report, we first investigated two ways to replace the front window of the DMD in a safe and reliable manner. The aim of this reworking process was to produce a modified DMD that fulfils the requirements in terms of spectral transmittance range for the SURPRIRSE demonstrator. The main challenge was to encapsulate the micro-mirrors in an inert atmosphere and ensure long-term hermeticity. The established procedure was then detailed and followed to assemble two SLM demonstrators. One of these demonstrators is currently being integrated into the SURPRISE demonstrator in the next steps of the project.

Thanks to the characterization of micro-mirrors reflectivity with the replacement protective window and without, we could prove the compatibility of the reworked DMD with the large spectral range aimed by the SURPRISE demonstrator. Also, these spectral reflectance measurements confirmed the need for the reworking procedure and replacement of the front window with sapphire. In addition, tests on switching time and pointing stability allowed verifying the adequacy of key performances with the datasheet, which is promising in view of the future integration into the demonstrator.

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