

High-Performance Fast Steering Mirrors for Space Optical Communication and Defense Applications

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ABSTRACT

Fast steering mirrors (FSMs) close the fine-pointing loop in free-space optical communication and directed-energy systems, where the beam must be aimed far more finely than its own divergence. We report two FSM configurations with 1-inch mirrors, one voice-coil and one piezoelectric. The voice-coil configuration gives a measured optical steering range of ± 35.4 and ± 35.2 mrad; its compliant flexure places the fundamental resonance near 116 Hz, so the loop is closed above it using lead-compensated PID control. The piezoelectric configuration gives ± 5.0 mrad optical range with a closed-loop bandwidth of 1165 and 1091 Hz, a servo error of 0.021–0.023 %FS RMS, and a 10–90 % rise time of 0.28–0.40 ms; its first mode lies near 1.7 kHz, so the loop is closed below resonance with PID control and a notch at the resonance. Both have completed environmental qualification: the voice-coil assembly survived random vibration 3 dB above the ECSS qualification level in three axes, and the piezoelectric unit completed 14.1 G_{rms} random vibration within the 5 % resonance-shift criterion, together with eight thermal cycles of functional verification. Results for a larger-aperture implementation are also reported. The 1-inch piezoelectric FSM is scheduled for in-orbit validation on the fifth launch of the Nuri (KSLV-II) space launch vehicle in October 2026, which is expected to provide data on its on-orbit performance and reliability.

Keywords: Fast steering mirror, Piezoelectric actuator, Voice coil actuator, Beam steering, Closed-loop bandwidth, Space optical communication, Environmental qualification

1. INTRODUCTION

Free-space optical communication between satellites, and between satellites and ground stations, requires the transmitted laser beam to be aimed with an accuracy far finer than the divergence of the beam itself. At an inter-satellite separation of several hundred kilometres, a pointing error of a few microradians already translates into a link margin penalty of several decibels. The same requirement appears, for different reasons, in directed-energy applications, where the beam must be held on a moving aim point for the duration of engagement. In both cases the fast steering mirror (FSM) is the element that closes the fine-pointing loop: it must combine a usable angular stroke, a control bandwidth high enough to reject platform disturbance, and sub-microradian resolution, while surviving launch loads and orbital thermal cycling.

No single suspension meets the stroke and bandwidth demands together: the compliance that provides a large stroke also places the structural resonances low, while a stiff structure pushes them clear of the control band at the cost of stroke.¹ We therefore build two configurations around the same mirror size — a voice-coil FSM for wide steering range and a piezoelectric FSM for high bandwidth and fine resolution — whose actuators differ not only in stroke but in the kind of resonance they present to the loop, leading to opposite compensation strategies described in Section 2. Implementations of other apertures exist for both actuator types, and the characterization methods and qualification criteria reported here transfer directly to them.

This paper reports the 1-inch configurations. Section 2 describes the two configurations, their control architecture and the measurement methods; Section 3 presents the voice-coil configuration and Section 4 the piezoelectric configuration, each covering characterization followed by environmental qualification, with a larger-aperture piezoelectric implementation in Section 4.8; Section 5 outlines the on-orbit validation plan.

2. FSM CONFIGURATIONS, CONTROL ARCHITECTURE AND METHODS

2.1 Specifications

The two implementations reported here use a 1-inch (25 mm diameter, 5 mm thick) mirror on a monolithic flexure suspension, and share the same control board hardware, RS422 command interface and 20 kHz digital control loop. They differ in actuator type, and consequently in flexure stiffness, in the power driver stage — current-mode for the voice coil, high-voltage mode for the piezoelectric stack — and in the control firmware. The two models are designated InceraFSM-V25-COTS (voice-coil) and InceraFSM-P25-COTS (piezoelectric). Both driver stages incorporate heatsinking and over-temperature shutdown. Table 1 summarizes the two configurations.

Table 1. Summary of the two 1-inch configurations. Angles are given in the mechanical convention unless noted; optical angles are twice the mechanical value.

Parameter	InceraFSM-V25-COTS	InceraFSM-P25-COTS
Actuator	Voice coil (force)	PZT stack (displacement)
Mirror	1 inch, $\varnothing 25 \times t5$	1 inch, $\varnothing 25 \times t5$
Mechanical range	± 17.7 mrad (X) / ± 17.6 mrad (Y)	± 2.5 mrad
Fundamental resonance	≈ 116 Hz	≈ 1.7 kHz
Drive mode	Current	Voltage (high-voltage)
Feedback sensor	Eddy-current (Lion Precision)	Collocated strain gauge
Compensation	Lead+PID	Notch+PID

2.2 Actuator physics and its consequence for loop shaping

The distinction between the two configurations is not merely one of stroke. A voice coil is a force actuator: below the suspension resonance the plant is stiffness-dominated and flat, above it the plant is mass-dominated and rolls off as $1/s^2$ with an asymptotic phase of -180° . A piezoelectric stack is a displacement actuator working against a stiff flexure, giving a flat plant response up to a much higher first mode.

This leads to opposite control strategies, and the difference extends to the nature of the fundamental resonance itself. In the voice-coil configuration the mode lies along the magnet's drive axis, so the actuator has direct authority over it and the loop can cross above it: lead compensation supplies the phase margin consumed by the mass line.^{2,3} In the piezoelectric configuration the mode shape is not aligned with the drive axis and the loop has little authority over it, so the design instead places it near 1.7 kHz, above the intended control band, and suppresses it with a notch; PID control then provides a crossover at a substantial fraction of the resonance frequency. The voice-coil loop thus crosses over between the suspension mode and the first structural mode, whereas the piezoelectric loop crosses over below its only significant mode.

2.3 Measurement methods

Angular displacement was referenced to a SmarAct PicoScale interferometer, which resolves linear displacement at the picometre level. Two points on the mirror surface, separated by a 16 mm baseline, were measured simultaneously and the differential displacement converted to mechanical tilt angle. A 1 pm displacement resolution over this baseline corresponds to 62.5 prad of tilt, more than four orders of magnitude below the microradian-scale quantities reported here, so the measurement resolution is not a limiting factor; in practice the achievable angular noise floor is set by environmental disturbance and by the accuracy of the baseline dimension rather than by the interferometer specification. Signals were acquired through an NI USB-6341. Records were sampled at 5 kHz unless stated otherwise, with a sentinel value of -32768 marking dropped samples. All tests were performed at ambient temperature with the mirror installed, on a single unit of each configuration.

Frequency response functions were obtained from swept-sine (chirp) excitation using the H_1 estimator, P_{xy}/P_{xx} , with Welch averaging at $n_{\text{perseg}} = 2048$.⁴ For the piezoelectric FSM, open-loop measurements used the drive voltage as input and the interferometric angle as output, giving units of $\mu\text{rad}/\text{V}$, and closed-loop measurements used the commanded angle as input, giving a dimensionless transfer function; coherence remained above 0.95 up to approximately 1.5 kHz, and the region near the chirp end frequency is not considered reliable. For the voice-coil plant measurement of Section 3.2 the eddy-current output serves as the response, giving a sensor-referred, dimensionless gain.

Reflecting the two structures — a compliant moving assembly of magnet, flexure and mirror in the voice-coil configuration, and a near-rigid body in the piezoelectric one — the voice-coil unit is characterized through calibration, its open-loop plant, and modal properties, and the piezoelectric unit through closed-loop performance.

3. VOICE-COIL-TYPE FSM

Figure 1 shows the voice-coil FSM and its cross-section. The mirror is carried on the main flexure and guided by two sub-flexures and a maraging-steel axial pin; voice-coil actuators drive the moving assembly directly, and eddy-current sensors provide the position feedback. The hardware is fully developed and has completed the environmental qualification reported in Section 3.3; its closed-loop characterization campaign is still in progress, so the performance results below are open-loop quantities.

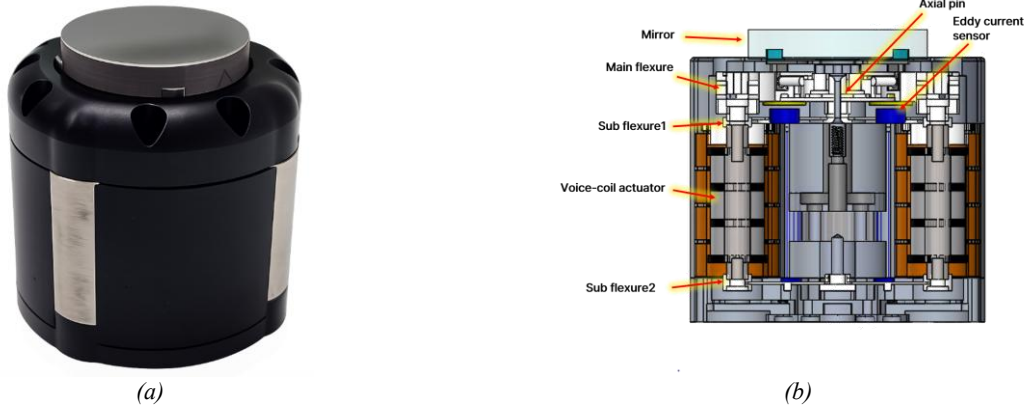


Figure 1. Voice-coil FSM (InceraFSM-V25-COTS): (a) assembled unit; (b) cross-section showing the mirror, main and sub flexures, voice-coil actuators, axial pin, and eddy-current sensors.

3.1 Calibration and sensor verification

The calibration factors of the two eddy-current sensor channels are 0.165551 and 0.156820 deg/V, with the axis angles formed as $X = ch0 + ch1$ and $Y = ch0 - ch1$; the mechanical range measured under a ± 0.7 A current command is listed in Table 1. The eddy-current readout was further checked against the interferometric reference under a 1 Hz sinusoidal drive spanning approximately ± 14 % of full stroke; the harmonic distortion of the eddy signal exceeded that of the reference motion by 2–3 percentage points, bounding the sensor-chain nonlinearity at the few-percent level over that range.

Figure 2 shows the quasi-static open-loop response over the full stroke: a 1 Hz sinusoidal current command spanning the full ± 0.7 A range, recorded at the calibrated tilt output. The loop width at mid-stroke is approximately 0.5 mrad, or 1.5 % of full stroke, and includes the drive and readout phase lag at 1 Hz, so it constitutes an upper bound on any rate-independent hysteresis of the magnet–flexure drive, which contains no ferroelectric element. The wide ferroelectric loop reported in Section 4.3 is by contrast intrinsic to the piezoelectric actuator rather than to any mirror suspension, and it is the property that the collocated feedback of that configuration exists to remove.

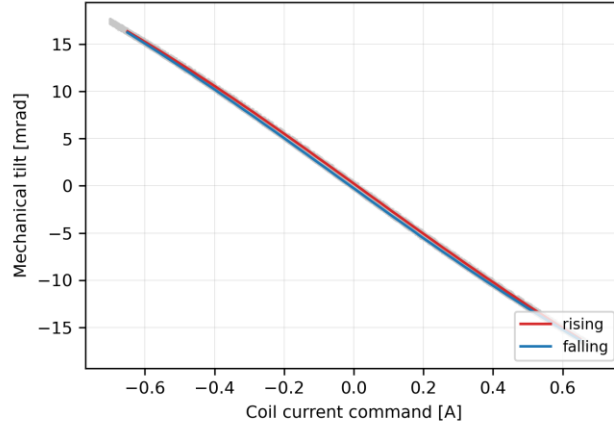


Figure 2. Quasi-static open-loop response of the voice-coil FSM: calibrated tilt versus a 1 Hz sinusoidal coil-current command spanning the full ± 0.7 A range (one axis shown; the orthogonal axis behaves similarly). Rising and falling branches are cycle-averaged; the loop width at mid-stroke is approximately 1.5 % of full stroke and is an upper bound on rate-independent hysteresis (see text).

3.2 Open-loop plant response

The open-loop plant was measured on the X axis with a ± 50 mV chirp in the mirror-installed configuration; Figure 3 shows the result. The response is flat below resonance with a sensor-referred DC gain of 20.3 mV/mV at the eddy-current output, and the fundamental suspension mode appears at 116 Hz with a +17 dB peak, the phase crossing -90° at 112 Hz. Coherence remains near unity through the resonance, and above it the response rolls off along the mass line, consistent with the force-actuator plant of Section 2.2. Higher-order structural modes of the vibration test article were identified during the vibration campaign of Section 3.3 at approximately 680 Hz, 1.31–1.37 kHz, 1.54 kHz and 1.64 kHz, with quality factors between 17 and 66; the lowest of these bounds the achievable crossover frequency.

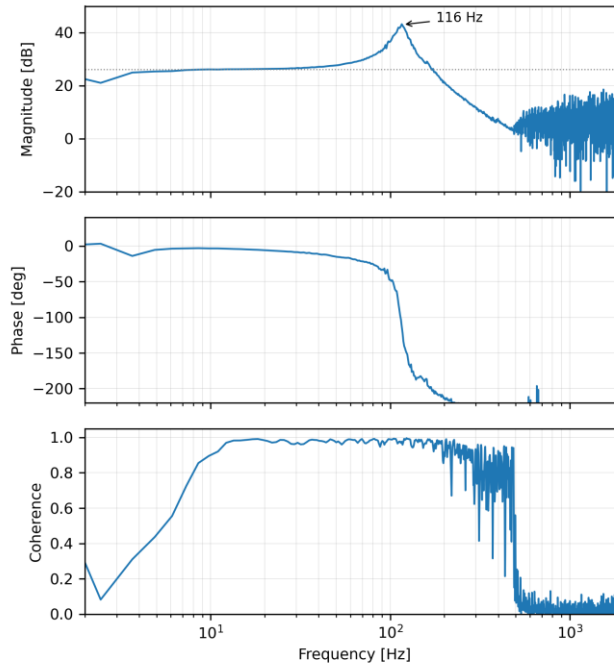


Figure 3. Open-loop plant response of the voice-coil configuration (X axis), measured with a ± 50 mV chirp and referenced to the eddy-current sensor output: magnitude, phase, and coherence. The fundamental suspension mode appears at 116 Hz.

3.3 Random vibration qualification

The voice-coil assembly was tested against the random vibration profile of ECSS-E-HB-10-03A, Figure A-26,⁵ for which the acceptance level is 8.0 G_{rms} for 1 min and the qualification level is 11.30 G_{rms} for 2 min. Rather than demonstrate compliance at the qualification level alone, the campaign was run as a margin search, stepping the level upward in 3 dB increments until failure. The random excitation was applied for 3 min per axis at each level, and each level was bracketed by 10-minute low-level sine sweeps, with a resonance shift below 5 % taken as the criterion for structural integrity.

The assembly survived qualification level +3 dB (15.96 G_{rms}) in all three axes, with resonance shifts of 0.30 % (x), 0.90 % (y), and 2.37 % (–z). First failure occurred at qualification level +6 dB (22.55 G_{rms}) in the –z axis, where the post-test sweep showed the disappearance of a resonance peak rather than a shift. Failure was localized to the maraging-steel axial pin, which is the designed weakest link of the assembly. At qualification level +9 dB (31.85 G_{rms}) the x axis also failed, with a resonance shift of 29.79 % — an unambiguous signature well outside the 5 % criterion, which supports the adequacy of that threshold. Table 2 summarizes the campaign.

Table 2. Voice-coil FSM random vibration margin search. Q.L. denotes the qualification level of 11.30 G_{rms} per ECSS-E-HB-10-03A Fig. A-26.

Level	G_{rms}	x	y	–z	Max $\Delta f/f_0$
Q.L. + 3 dB	15.96	Survived	Survived	Survived	2.37 %
Q.L. + 6 dB	22.55	Survived	—	Failed	—
Q.L. + 9 dB	31.85	Failed	—	—	29.79 %

4. PIEZOELECTRIC-TYPE FSM

4.1 Design and payload integration

Figure 4 shows the piezoelectric FSM and its cross-section. The mirror is carried on the main flexure and guided by a sub-flexure; amplified piezoelectric actuators drive the assembly through the flexure, with the collocated strain gauge integrated in the amplified actuator providing the feedback.

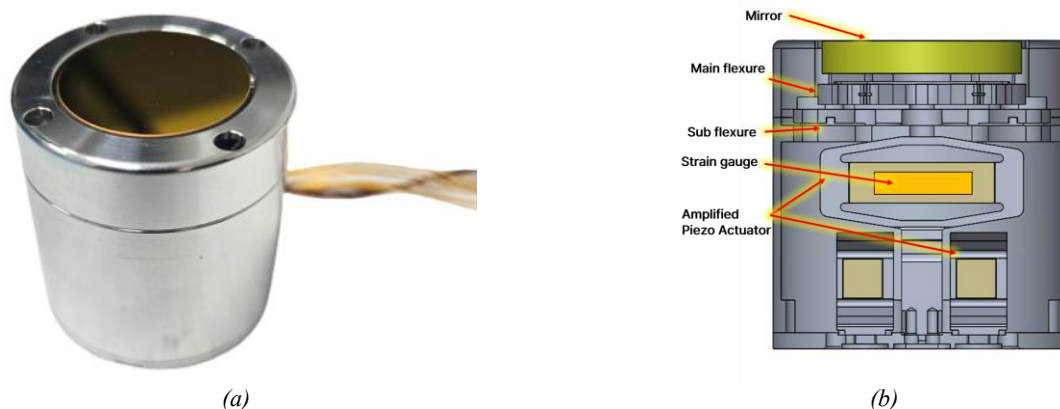


Figure 4. Piezoelectric FSM (InceraFSM-P25-COTS): (a) assembled unit; (b) cross-section showing the mirror, main and sub flexures, amplified piezoelectric actuators, and the integrated strain gauge.

For the space-qualification programme the piezoelectric FSM is integrated into a $10 \times 10 \times 10$ cm payload housing machined from Al6061-T6 with anodizing and chromate conversion coating. The FSM assembly itself is 40 mm in diameter and 40 mm high, with a mass of 72 g, and combines Al7075-T6 structural parts, PZT actuators, and a Zerodur mirror substrate. Three FR-4 high-Tg boards — power, driver, and control — are conformally coated and populated with MIL- or automotive-grade components. External interfaces are Harwin Gecko connectors carrying a 5 V supply and a CAN bus. Steady-state consumption is 5 W with a 1.5 A inrush.

4.2 Calibration and linearity

Calibration of the piezoelectric FSM was performed with a 200 mHz open-loop sine at 60 V drive. A 1 Hz zero-phase low-pass filter was applied to the reference channel and one second of data was trimmed from each end to remove edge transients. Table 3 gives the resulting calibration factors and the residual nonlinearity of the linear fit. Without filtering, the apparent nonlinearity was approximately 6 %FS on both axes; this was dominated by high-frequency noise on the reference channel and converged to 0.6–0.8 %FS after filtering, while the calibration gain was essentially unchanged.

Table 3. Piezoelectric FSM calibration factor and residual nonlinearity of the linear fit.

Axis	Calibration factor [$\mu\text{rad}/\text{V}$]	R^2	Max deviation [%FS]	RMS deviation [%FS]
X	931.46	0.999954	0.755	0.246
Y	916.17	0.999982	0.616	0.150

4.3 Open-loop hysteresis

Figure 5 shows the open-loop hysteresis loop of the piezoelectric FSM, plotted as drive voltage against displacement. The maximum loop width at mid-stroke is approximately 597 μrad , corresponding to 11.9 %FS over the 5000 μrad command span. The figure title quotes 11.2 %FS, which is normalized to the open-loop stroke of that particular record. This is the actuator nonlinearity that the closed loop must compensate, and it motivates the collocated-sensor feedback architecture: with the loop closed, the residual servo error is reduced by more than two orders of magnitude, as shown in Section 4.4.

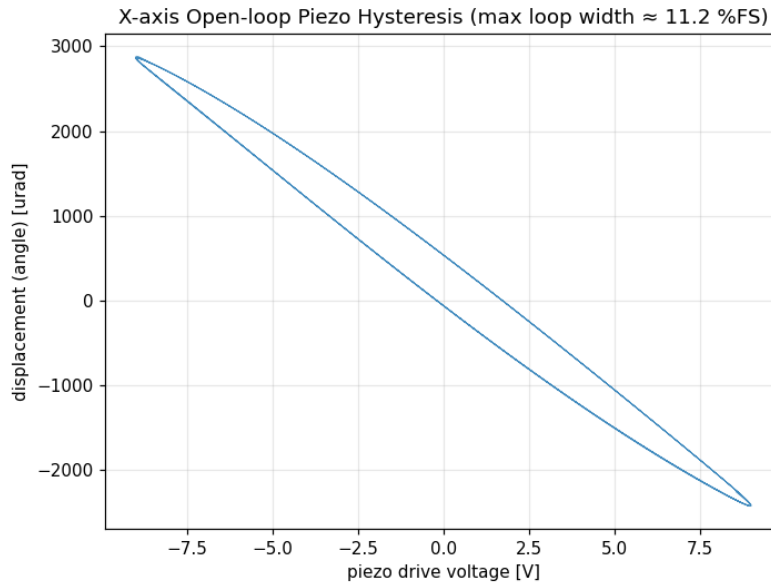


Figure 5. Open-loop hysteresis of the piezoelectric FSM, X axis (drive voltage vs. displacement). Maximum loop width at mid-stroke is approximately 597 μrad .

4.4 Closed-loop servo error

For the piezoelectric FSM the servo error is evaluated against the collocated strain-gauge feedback, which is the quantity regulated by the controller. Because the gauge senses actuator elongation rather than mirror angle directly, this metric characterizes closed-loop servo regulation performance rather than absolute pointing accuracy. The sensor-to-reference deviation is bounded by the linearity measurement reported in Section 4.2.

Closed-loop regulation was measured with a 200 mHz sine of 2500 μrad amplitude, giving a 5000 μrad full stroke. Table 4 lists the resulting servo error together with the 10–90 % rise time obtained from a $-250 \rightarrow +250$ μrad square command. The rise time values are discretization-limited by the 5 kHz record rate (0.2 ms resolution) and are consistent with the measured closed-loop bandwidth through the approximation $t_r \approx 0.35/f_{\text{BW}}$.

Table 4. Piezoelectric FSM closed-loop servo error and step response. Servo error is referenced to the collocated strain-gauge feedback (see text).

Axis	Full stroke [μrad]	Servo error max [%FS]	Servo error RMS [%FS]	Rise time 10–90 % [ms]
X	5000	0.080	0.021	0.40
Y	5000	0.100	0.023	0.28 ± 0.10

4.5 Frequency response

The open-loop plant response of the piezoelectric FSM is flat to approximately 1 kHz with a DC gain of 29.6–29.7 dB (about 30.5 $\mu\text{rad}/\text{V}$) and a first resonance near 1.7 kHz on both axes. With the notch-plus-PID controller the closed-loop –3 dB bandwidth reaches 1165 Hz on X and 1091 Hz on Y, that is, approximately 0.65 of the resonance frequency. Table 5 summarizes the result and Figure 6 shows the corresponding Bode plots.

Table 5. Piezoelectric FSM frequency response summary (H_1 estimator, chirp 1–2000 Hz, 10 s).

Axis	CL –3 dB bandwidth [Hz]	OL DC gain [dB]	First resonance [kHz]	Coherence (≤ 1.5 kHz)
X	1165	29.70	≈ 1.7	≈ 1.0
Y	1091	29.57	≈ 1.7	≈ 1.0

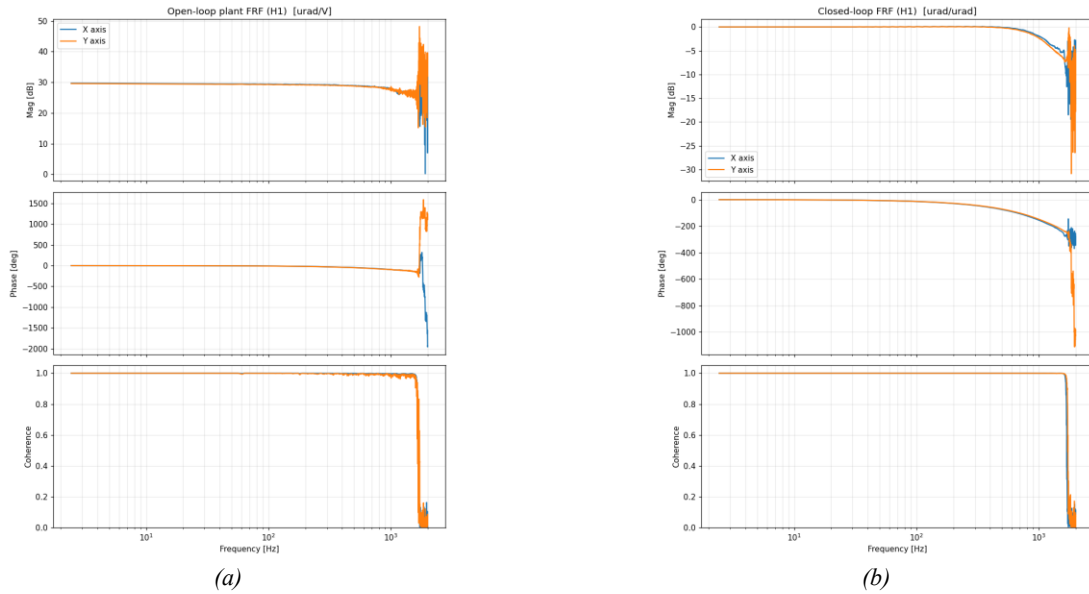


Figure 6. Piezoelectric FSM frequency response, H_1 estimator. (a) Open-loop plant: magnitude [$\mu\text{rad}/\text{V}$], phase, and coherence. (b) Closed-loop: magnitude [$\mu\text{rad}/\mu\text{rad}$], phase, and coherence. Coherence remains near unity to approximately 1.5 kHz on both axes.

4.6 Vibration qualification

The piezoelectric FSM was qualified in two campaigns. The first, on the FSM engineering model, verified the FSM structural design; the second, on the integrated payload, verified the payload structural design under identical conditions. Each campaign comprised a low-level sine sweep (0.5 G, 5–2000 Hz, 2 octave/min, 10 min), a sine burst as a quasi-static equivalent (10 G, 100 Hz, 10 cycles), and random vibration at 14.1 G_{rms} over 20–2000 Hz for 3 min, each applied along three orthogonal axes. A low-level sine sweep was repeated before and after every excitation, so that the sine burst and the random run were each bracketed by sweeps. Figure 7 shows the shaker demand and the measured control acceleration for the three excitation types. Pre- and post-test sine sweeps showed resonance frequency shifts below 5 % in both campaigns, indicating no structural degradation.

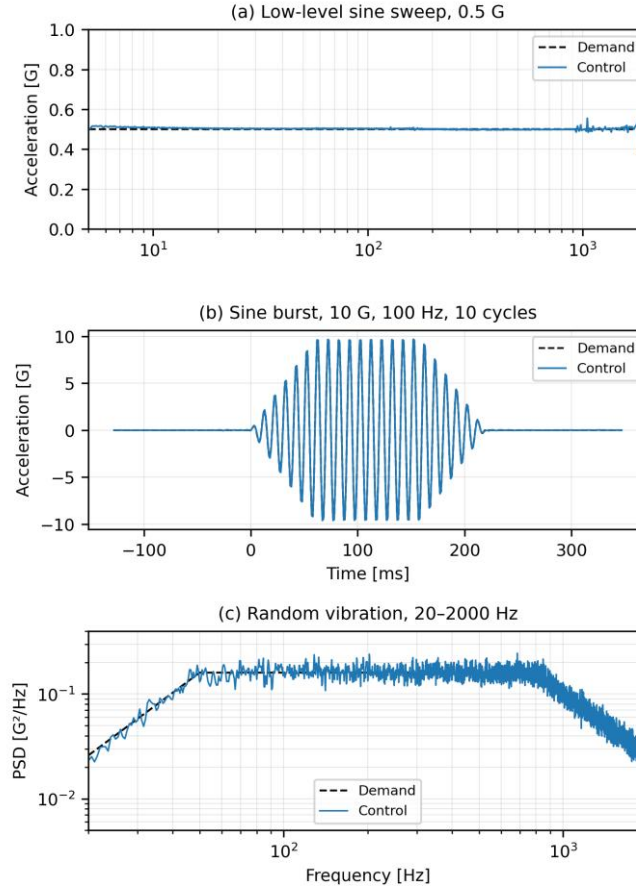


Figure 7. Vibration excitations applied to the piezoelectric FSM and the integrated payload, shown as shaker demand (dashed) and control accelerometer (solid): (a) low-level sine sweep used to bracket every excitation, (b) sine burst, and (c) random vibration. Identical profiles were applied along all three orthogonal axes.

4.7 Thermal cycling

The objective of the thermal cycling campaign was functional verification: to confirm that the integrated payload operates without failure across the temperature range, rather than to track performance parameters. The payload was subjected to 8 cycles between -25 and $+55$ °C setpoint. The payload-mounted sensor, offset-referenced to the $+55$ °C dwell, recorded -28.8 to $+57.8$ °C over a total duration of 32.7 hours, with approximately one hour of dwell at each extreme. Figure 8 shows the recorded profile.

The flight command protocol was exercised throughout cycling as the functional pass criterion. The test sequences completed nominally at every temperature, the FSM remained under closed-loop control for the duration of the campaign, and no functional anomaly of the payload was observed. Of the twenty-two data transmissions to the ground station, two failed in the external ground-support communication board — equipment outside the payload — while the payload-internal communication system operated nominally throughout.

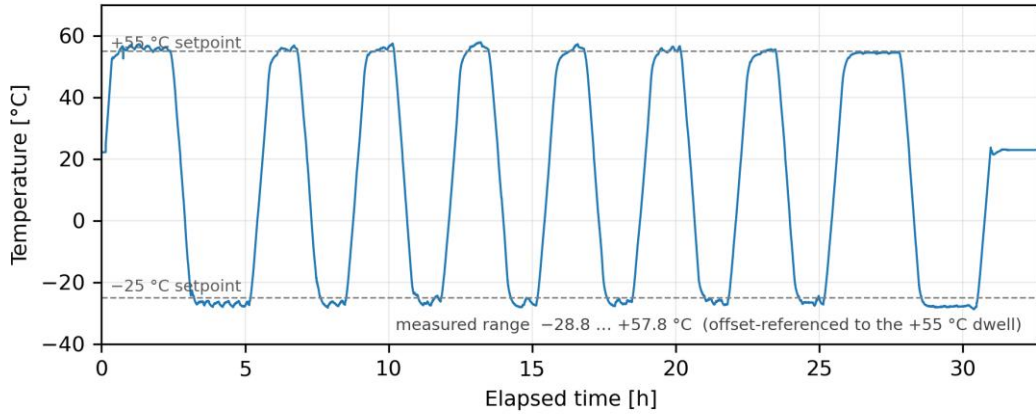


Figure 8. Thermal cycling profile at the payload-mounted sensor, offset-referenced to the +55 °C dwell: 8 cycles between -28.8 and +57.8 °C over 32.7 hours.

4.8 Structural integrity of a larger-aperture implementation

A larger-aperture implementation of the same piezoelectric technology — sharing the actuator type, the driver stage topology and the control board, and differing in mirror aperture, flexure geometry and stroke — was subjected to random vibration and to a shock transient. Closed-loop frequency response was measured before and after the sequence under identical controller settings. Detailed specifications of this implementation are withheld.

Because this implementation is stiffness-dominated and structurally rigid, closed-loop response was adopted as the integrity metric in place of modal tracking. Across the common control band the pre- and post-test responses agreed to within 0.12 dB (X) and 0.23 dB (Y) peak deviation, with an RMS deviation of 0.05–0.07 dB; the -3 dB bandwidth changed by +1.9 % and -3.5 % respectively, well within the 5 % criterion applied to the modal measurements above. During excitation the unit maintained closed-loop lock throughout, with the residual pointing jitter increasing from its quiescent value by less than a factor of three. Figure 9 shows the pre- and post-test overlay.

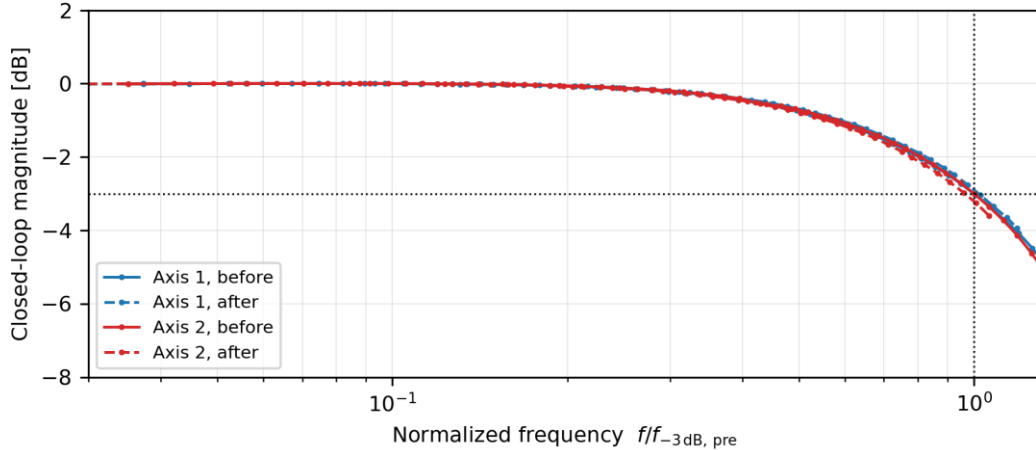


Figure 9. Closed-loop frequency response of the larger-aperture implementation before and after the vibration and shock sequence. The frequency axis is normalized to the pre-test -3 dB bandwidth of each axis, so the post-test curves display the measured bandwidth change (+1.9 % on axis 1, -3.5 % on axis 2) directly; across the control band the responses agree to within 0.23 dB.

5. IN-ORBIT VALIDATION

The piezoelectric FSM is manifested on the fifth launch of the Nuri (KSLV-II) space launch vehicle of the Republic of Korea, planned for October 2026, as a payload on a technology demonstration platform. The objective is to verify that the qualified ground performance is retained through launch and sustained across the orbital environment.

The on-orbit test sequence is executed once per day and lasts approximately 35 minutes excluding housekeeping communication. It comprises mirror calibration, in which driver offset and travel range are measured and reset; a drive-bandwidth measurement using a chirp excitation; a scanning process combining a spiral and a raster scan over the full ± 2.5 mrad mechanical field; a pointing process in which a randomly assigned angle is acquired and held under closed-loop control; and a tracking process in which the mirror follows a linear trajectory for 30 minutes at 15 mrad/s, representative of an inter-satellite link at a relative velocity of 7.5 km/s and a minimum separation of 500 km. A second bandwidth measurement closes the sequence, so that any change over the run is directly observable. Peak power consumption across the sequence is 4.6 W during scanning. Each run generates 3.5 Mbytes, which is downlinked in full for ground analysis.

Success is assessed in three stages: satisfaction of the space-suitability performance criteria at the first commissioning run after orbit insertion; retention of those criteria 30 days later; and retention after two years of operation, which addresses aging of the piezoelectric actuator and of the flexure under thermal cycling.

6. LIMITATIONS

Several limitations bound the results reported above. Rise time was measured at a 5 kHz record rate, giving a time resolution of 0.2 ms, so the values in Table 3 rest on one to two samples and should be read as discretized approximations consistent with the measured bandwidth rather than as independent measurements. Closed-loop characterization of the voice-coil configuration is still in progress, so no closed-loop bandwidth is claimed for it here; the open-loop plant measurement covers one axis, and the eddy-current verification spans ± 14 % of stroke at a single frequency. The thermal cycling campaign was a functional verification, and quantified closed-loop performance across temperature was outside its scope; the pre- and post-test closed-loop comparison reported in Section 4.8 pertains to the vibration and shock sequence. Closed-loop servo error is referenced to the collocated strain gauge and does not include the sensor-to-mirror deviation, which is bounded separately by the linearity result of Section 4.2. All results are from a single unit of each configuration, so no unit-to-unit repeatability statistics are available. Finally, absolute specifications of the larger-aperture implementation are withheld, so only relative changes are reported for it.

7. CONCLUSIONS

Two fast steering mirror configurations with 1-inch mirrors have been characterized and qualified. The voice-coil design provides a measured optical steering range of ± 35.4 mrad (X) and ± 35.2 mrad (Y) on a compliant suspension whose fundamental resonance near 116 Hz is crossed rather than avoided, and survived random vibration at 3 dB above the ECSS qualification level in all three axes with resonance shifts below 2.4 %. The piezoelectric design provides ± 5.0 mrad optical range with a measured closed-loop bandwidth of 1165 Hz and 1091 Hz on the two axes, a servo error of 0.021–0.023 %FS RMS, and a 10–90 % rise time of 0.28–0.40 ms; it has completed vibration and thermal cycling qualification and is manifested for in-orbit validation in October 2026.

The choice of actuator determines how the mirror is driven and where the loop crossover can be placed relative to the first structural mode, which in turn fixes the compensation strategy and the measurement that most sensitively reveals structural degradation. Because the control board and command interface are common to both configurations, with the current- versus voltage-mode difference confined to the driver stage and the firmware, either actuation type can be applied at a given aperture without redeveloping the digital control system.

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