

From Ground to Orbit: Maturing Bertin Alpao Deformable Mirrors for Spaceborne Adaptive Optics

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ABSTRACT

Deformable mirrors (DMs) are key enabling technologies for future space observatories requiring high-precision wavefront control, including high-contrast imaging, coronagraphy, and primary mirror figure correction. Bertin Alpao has developed a family of continuous-face-sheet deformable mirrors driven by magnetic actuators, benefiting from extensive operational heritage in ground-based astronomy. This paper presents the ongoing maturation of the technology towards space applications. Existing systems demonstrate actuator counts up to 64×64 with excellent optical quality, kilohertz-class dynamic performance, low power consumption, and nanometer-level wavefront control. In parallel, larger 128×128 actuator mirrors are under development for next-generation astronomical instruments. Space adaptation activities include vibration, thermal cycling, and vacuum qualification campaigns performed with CNES and Airbus Defence and Space, as well as collaborations with NASA on future mission concepts. Stability measurements performed under ultra-low-noise conditions demonstrate drift levels in the tens of picometers per hour, approaching requirements envisioned for future flagship missions such as the Habitable Worlds Observatory. These results establish a credible pathway toward flight-qualified deformable mirrors for future space observatories.

Keywords: Deformable Mirror, Space Telescope, High Contrast Imaging

1. INTRODUCTION

Future space telescopes dedicated to exoplanet characterization, astrophysics, Earth observation, and optical communications increasingly require active wavefront control systems capable of delivering unprecedented optical performance. Applications include coronagraphic high-contrast imaging, correction of primary mirror figure errors, laser communication terminals, and adaptive optical payloads [1][2].

Deformable mirrors provide a compact and versatile solution for these functions. Bertin Alpao designs and manufactures a wide range of deformable mirrors (DM) for various applications, from large telescopes through laser or microelectronics to vision science and microscopy. However, space deployment imposes stringent constraints on stability, reliability, volume, power consumption, environmental resistance, and actuator scalability. For instance, future missions such as NASA's Habitable Worlds Observatory (HWO) will require large actuator counts, picometer-scale stability, and extremely low residual wavefront errors [3].

To address these challenges, Bertin Alpao is adapting its mature magnetic-actuator deformable mirror technology, successfully deployed on leading astronomical observatories, for future spaceborne applications.

2. DEFORMABLE MIRROR TECHNOLOGY AND GROUND BASED HERITAGE

Bertin Alpao's deformable mirrors use a continuous optical membrane actuated by an array of electromagnetic actuators (see Figure 1). The architecture combines several characteristics well suited for space deployment: continuous optical surface, low-voltage operation, low power dissipation (typically 1-10 mW per actuator), compatibility with vacuum and cryogenic environments, adjustable stroke-speed trade-off, scalability from a few dozen to several thousand actuators, flat or curved optical surfaces.

The technology currently covers actuator counts ranging from 37 to more than 3000 actuators, with actuator pitches between 0.8 mm and 5 mm and clear apertures extending up to 200 mm.

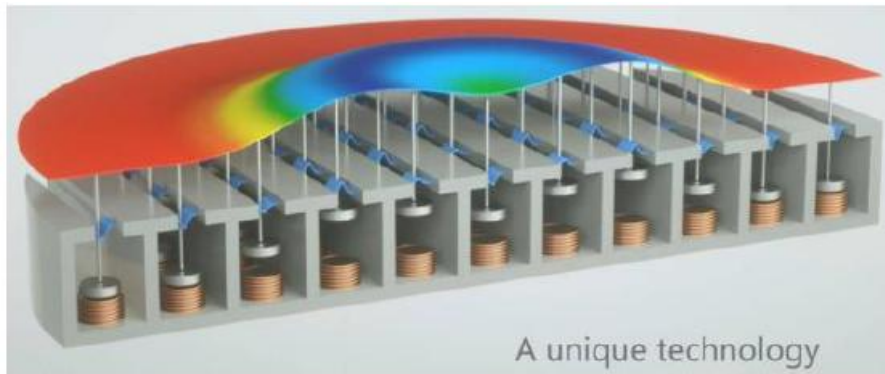


Figure 1. Concept of Bertin Alpao Deformable Mirrors

Table 1 summarizes large deformable mirrors deployed over the past years in major astronomical instruments and observatories. These mirrors demonstrate that high actuator counts can be achieved while maintaining excellent optical quality and dynamic performance. Notably, multiple DM1432 units manufactured for the GRAVITY+ project exhibited highly consistent characteristics, demonstrating manufacturing repeatability (see Figure 2). An important milestone was subsequently achieved with the development of the high-stability DM3228 for the MAVIS adaptive optics instrument at the ESO Very Large Telescope [4]. This mirror features a 64×64 actuator architecture, a best-flat performance of 3.6 nm RMS surface (see Figure 3), and improved long-term stability compared to previous generations. These characteristics are directly aligned with the requirements of future space missions, where stability often becomes a more critical parameter than stroke or bandwidth. Building on these achievements, a new extreme adaptive optics mirror is currently under development for the ESO Planetary Camera and Spectrograph (PCS), featuring a 128×128 actuator architecture with a pupil diameter exceeding 180 mm. This development provides a direct technological stepping stone toward future space systems requiring several thousand degrees of freedom.

Table 1. Examples of high-order deformable mirrors

DM	User	Act grid	Pitch (mm)	Pupil (mm)	Best flat (nm RMS surf)	Stroke (μm PV wft)	Res freq (Hz)
DM1432	VLT/Gravity+ (x6)	43x43	2.62	102	4.4	27	1072
DM2844	Keck/HAKA	60x60	2.50	142.5	8.0	26	1267
DM3228	ELT/MICADO Subaru/SCEXAO	64x64	1.50	94	6.0	19	1400
DM3228 high. stab.	VLT/MAVIS (x2)	64x64	1.50	93	3.6	36	1027
XAO DM (under development)	E-ELT/PCS	128x128	1.50	> 180	5	6	1500

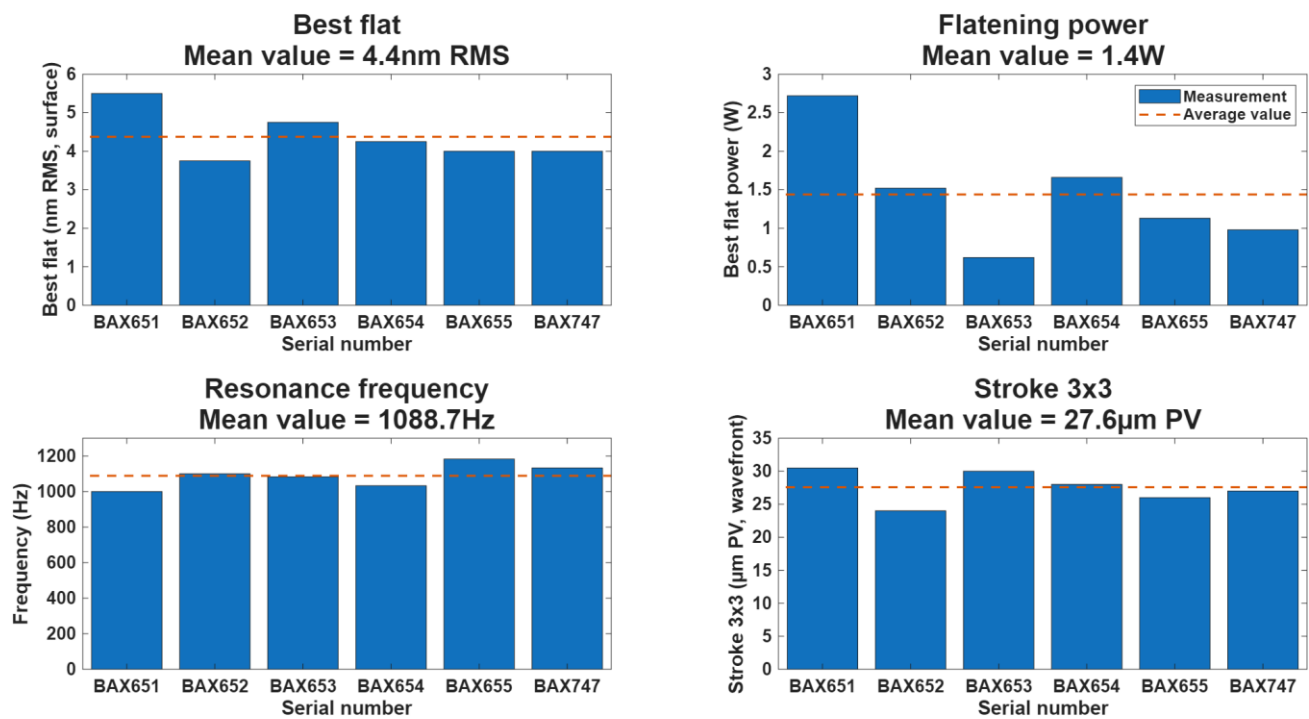


Figure 2. Measured performance on the 6 DMs manufactured for the Gravity+ instrument

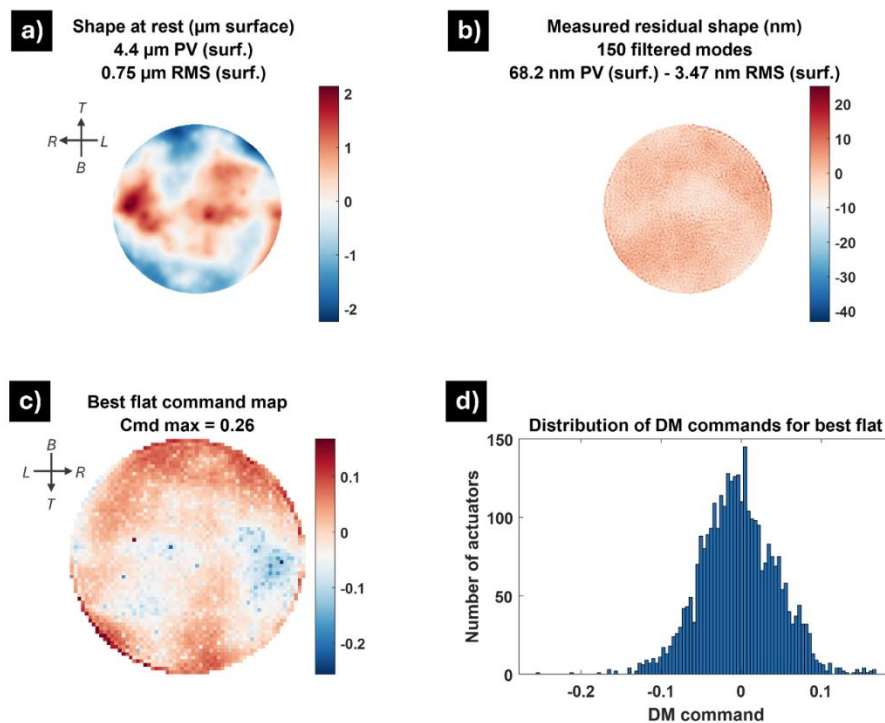


Figure 3. Best flat performance of the DM manufactured for the MAVIS instrument

The same technology is also available in smaller formats suitable for a wide range of applications. Bertin Alpao offers intermediate-size deformable mirrors featuring 192 to 820 actuators and clear apertures of a few centimeters. These devices typically provide resonance frequencies above 1.5 kHz, settling times below 0.5 ms, and wavefront strokes around 10 μm PV, making them attractive for high-bandwidth wavefront correction and beam control applications. Furthermore, the technology offers significant design flexibility, enabling the stroke and response speed to be adjusted according to mission-specific requirements. At the lower end of the range, embedded deformable mirrors with 37 to 97 actuators have been developed with integrated electronics, providing a compact solution with a mass of only 245 g and resonance frequencies around 800 Hz. These mirrors can deliver wavefront strokes of up to 25 μm PV while minimizing volume, power consumption, and system complexity. Such devices are particularly relevant for free-space optical (FSO) communication terminals, where dynamic correction of beam aberrations and pointing errors can improve link efficiency, as well as for compact Earth-observation and remote-sensing instruments. Consequently, the technology portfolio spans applications ranging from compact optical terminals and small satellites to future large space observatories requiring several thousand actuators.

3. SPACE ORIENTED DEVELOPMENT

Several studies have investigated the use of deformable mirrors in future space missions. The targeted applications included high-contrast imaging and coronagraphy, correction of primary mirror figure errors, space optical communication terminals and adaptive Earth observation payloads.

Bertin Alpao has collaborated with Airbus Defence and Space (ADS) on the preliminary design of a space-compatible 70×70 actuator deformable mirror dedicated to primary mirror correction. In this study, we particularly focused on DM performance and actuator reliability, which is a critical consideration for large-format mirrors. Bertin Alpao's magnetic-actuator architecture avoids stuck actuators. Rare actuator failures are floating rather than mechanically blocked, significantly reducing their impact on the optical surface and enabling compensation through calibration procedures. This behavior is particularly important for future systems containing several thousand actuators, where overall system robustness becomes a primary design driver [5].

Additional work with ADS and CNES has focused on environmental qualification activities and the identification of a path toward flight hardware. Environmental testing has been performed to evaluate suitability for space deployment.

The tested mirrors successfully completed:

- Vibration testing up to 50 g;
- Eight thermal cycles between -15°C and $+50^{\circ}\text{C}$;
- Vacuum compatibility assessments.

No measurable degradation of performance was observed following testing. Furthermore, optical characterization performed in vacuum showed influence functions and mirror response equivalent to measurements obtained in air within experimental uncertainty (see Figure 4).

The company is also collaborating with NASA on multiple concepts, including an Off-Axis Parabolic deformable mirror [6] and preliminary studies for a 96×96 actuator mirror relevant to the Habitable Worlds Observatory.

Current developments focus on increasing actuator density, reducing actuator pitch, improving intrinsic optical quality and shape at rest, reducing power consumption and achieving ultra-high stability and resolution.

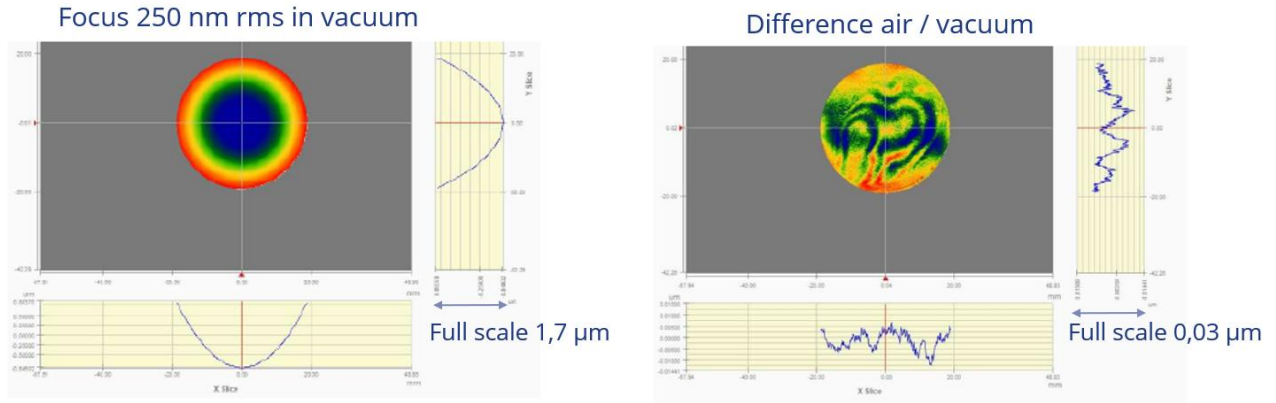


Figure 4. Vacuum characterization of DM

4. STABILITY

High-contrast space missions place extremely demanding requirements on deformable mirror stability, as even picometer-level surface variations can degrade coronagraphic performance and limit exoplanet detection capabilities. To assess the intrinsic stability of the technology, a DM97-15 High Stability deformable mirror was characterized in Bertin's Underground Low Noise Facility (LSBB), a dedicated environment designed to minimize mechanical, acoustic, and thermal disturbances. The experiment was performed under tightly controlled thermal conditions, with the mirror maintained at a temperature stability of approximately 10 mK. The drive electronics was located in a separate room and experienced temperature fluctuations of up to 100 mK, providing a realistic assessment of system-level stability. Interferometric measurements were acquired every 20 s over several hours using a Zygo interferometer.

Several representative wavefront shapes were investigated, including single-actuator commands, focus, and astigmatism modes with varying amplitudes. Figure 5 presents the evolution of a representative focus shape over time. The tested configuration corresponded to a surface deformation of 334 nm RMS (1415 nm PV), representative of the low-amplitude corrections expected in precision wavefront control applications. Surface maps were averaged over multiple time intervals to reduce measurement noise and isolate the contribution of the deformable mirror itself.

The measured drift remained in the range of a few tens of picometers per hour, with approximately 70 pm of cumulative drift observed over 3.75 h, corresponding to about 20 pm/h after the initial transient regime. Residual variations were dominated by measurement noise and local turbulence effects rather than clear actuator-related instabilities. These results are particularly noteworthy because they were obtained with a standard commercial mirror, not specifically optimized for space applications. They therefore highlight the intrinsic stability of the magnetic-actuator architecture and provide confidence that future space-oriented developments, incorporating dedicated electronics, improved thermal control, and optimized materials, can further approach the stringent stability requirements of future missions such as the Habitable Worlds Observatory.

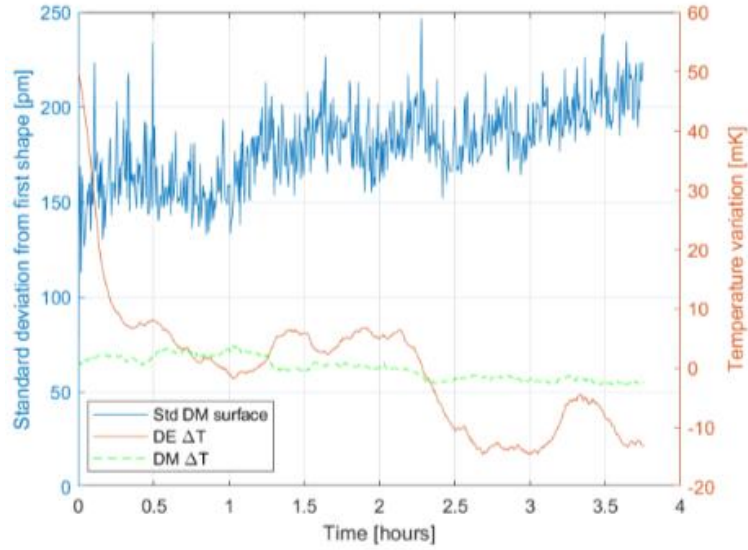
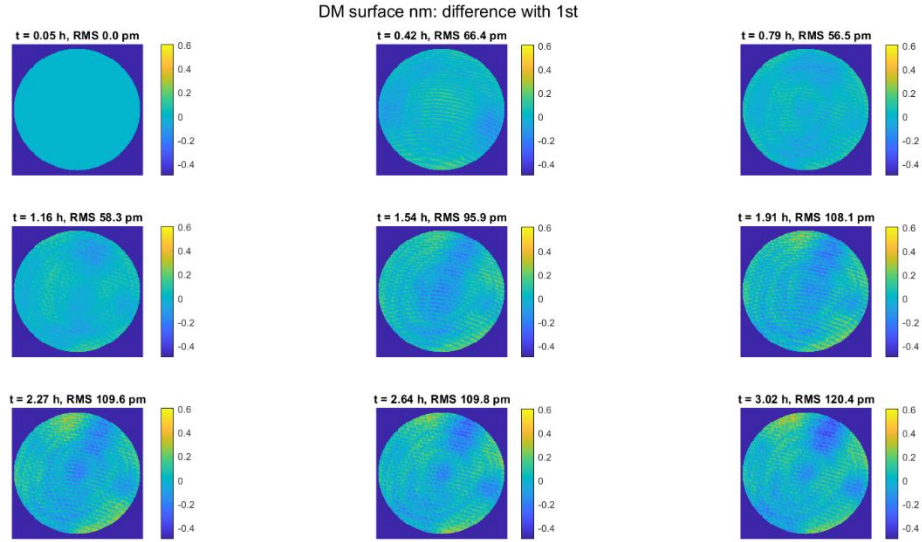


Figure 5. Long-term stability measurements. Top: Surface maps are averaged over 9 equal time intervals across the 3-hour period. Bottom: Standard deviation from first map as a function of time

5. CONCLUSIONS

Bertin Alpao's deformable mirror technology combines high actuator density, low power consumption, excellent optical quality, and demonstrated environmental robustness, making it a strong candidate for future space wavefront control systems. Current devices already provide actuator arrays ranging from compact embedded mirrors with a few dozen actuators to large-aperture systems exceeding 4,000 actuators, while maintaining nanometer-level optical quality, kilohertz-class dynamic performance, and picometer-scale stability under controlled conditions. Successful environmental testing, including vibration, thermal cycling, and vacuum operation, further supports the suitability of the technology for space deployment.

Beyond the demonstrated performances, one of the key strengths of the Bertin Alpao technology lies in its flexibility. The actuator architecture can be tailored to provide different combinations of stroke, bandwidth, actuator density, aperture size, and power consumption, enabling operation across a broad range of mission requirements. As a result, the same technological platform can address applications ranging from compact free-space optical communication terminals and Earth-observation payloads to high-contrast imaging systems and large space observatories requiring thousands of actuators and extreme wavefront stability.

The ongoing development of 128×128 actuator mirrors, together with efforts on space-compatible materials, dedicated electronics, manufacturing processes, and advanced stability characterization, establishes a clear pathway toward flight-qualified deformable mirrors. Through collaborations with various partners, Bertin Alpao is pursuing the maturation of a versatile deformable mirror technology capable of supporting the next generation of space science, Earth observation, and optical communication missions.

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