KICKSTARTING HYBRID VARIABLE-RELUCTANCE ACTUATOR TECHNOLOGY ON-SKY

Astronomers use deformable mirrors to improve the image of a telescope by correcting for the optical distortions caused by atmospheric turbulence. Together with academic and industrial partners, TNO is working on technology to enable larger, more robust and more affordable systems. A sudden opportunity presented itself to demonstrate the technology in a real-life setting on a NASA telescope in Hawai'i. With smart re-use of existing hardware and building on existing design concepts, the team managed to get from project kick-off to system shipment in only one year. First light is planned for late April 2024.

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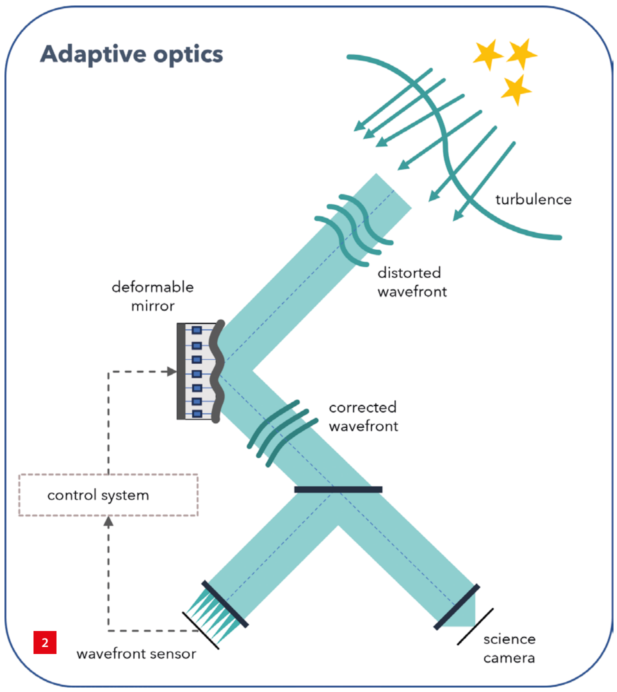
Introduction

The summit of Mauna Kea, an inactive volcano on the big island of Hawai'i, is one of the premier sites in the world for astronomers (Figure 1). Located far away from population centres and at an altitude of 4,200 meters, the night sky is as dark, clear and tranquil as it gets. One of the observatories on the mountain is NASA's 3-meter Infrared Telescope, originally built to support the Voyager missions and now the US national facility for infrared astronomy. It is about to get an upgrade: an adaptive deformable secondary mirror, to create even sharper views of the Universe.

In ground-based astronomy, adaptive deformable mirrors (DMs) are used to correct the telescope image in real-time for the blurring effects of atmospheric turbulence. The principle of adaptive optics (AO) is shown in Figure 2. Turbulence distorts the optical wavefront of the incoming starlight. This distortion can be characterised with a wavefront sensor. Based on the sensor data, the control system commands the actuators of the DM to push and pull on a thin mirror shell to adjust its shape to counter the distortion.

Traditionally, DMs are small subsystems of the science detectors, but there is a trend to incorporate larger systems as part of the main optical layout of the telescope. Such



Schematic layout of an adaptive optics system.

High above the clouds on Mauna Kea: the NASA Infrared Telescope (right) next to the twin Keck telescopes (centre) and the Subaru Telescope (left).

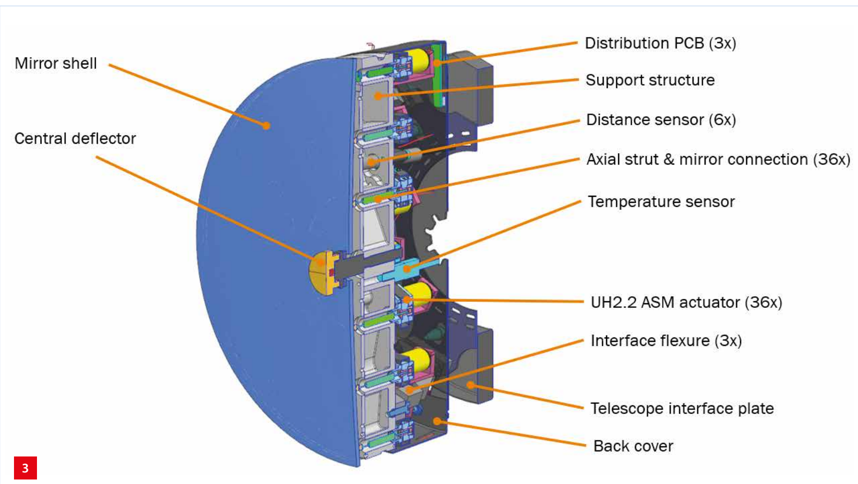
Adaptive Secondary Mirrors (ASMs) allow for better correction across a wider field of view, particularly for the turbulence in the atmospheric ground layer where most of the distortion happens.

A consortium of TNO, VDL ETG Precision, AAC Hyperion and NOVA (the Netherlands Research School for Astronomy) is working on the assembly, integration and testing of a 62-cm diameter ASM for the University of Hawai'i's 2.2-meter UH2.2 telescope. The goal of the development is to demonstrate the underlaying hybrid variable-reluctance actuator technology on-sky [1].

In early 2023, an unexpected opportunity presented itself to also build an ASM for the NASA Infrared Telescope Facility (IRTF). The limited size of the IRTF mirror would allow this development to actually leapfrog the UH2.2 ASM project, and provide an on-sky demonstration sooner. To achieve this, the IRTF ASM would have to be available by February 2024 in order to be installed on the telescope during a scheduled maintenance window in April. This required to go from design kick-off to hardware shipment in less than a year!

Conceptual design

To be able to meet the very ambitious timeline, the IRTF ASM design had to be based on existing concepts and even on existing hardware as much as possible. A cross-sectional view of the IRTF ASM is depicted in Figure 3. The concept design for the IRTF adaptive M2 follows the mechanical layout of previous designs: a set of actuators is mounted in a circular grid pattern on a high-stiffness support structure. Thin struts mechanically connect the actuators, through holes in the support structure, with epoxy bonds to the mirror shell on the other side. The connection between the struts and the shell is designed to minimise stresses and print-through from CTE (coefficient of thermal expansion) mismatches and from shrinkage of the epoxy bonds.



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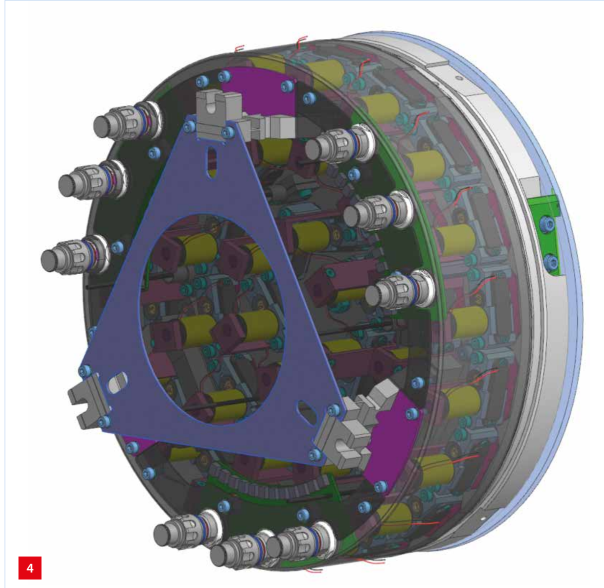
Cross-sectional view of the adaptive mirror design.



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Backside of the IRTF ASM. The three interface flexures and connectors are clearly visible. The yellow cylinders are the coils of the actuators.

Three in-plane struts along the circumference of the support structure constrain the lateral (X, Y) and clocking (Rz) degrees of freedom of the mirror shell. This location provides both good accessibility for integration and a high eigenfrequency around Rz. The kinematic interface is based on three flexures that connect to a sheet-metal plate that is CTE-matched to the interface on the telescope side. The backside view of the ASM is shown in Figure 4.

To achieve a DM control bandwidth of 100 Hz or higher, the requirement on the first bandwidth-limiting eigenfrequency was set at > 500 Hz. Finite-element method (FEM) analysis showed that the first bandwidth-limiting eigenfrequency is a piston eigenmode (Z-translation) that can be found around 700 Hz. The first flexible mode of the support structure, also bandwidth-limiting, is over 1,400 Hz. Finally, the design includes a central deflector – a small extra mirror in the centre placed at a slight angle, so that the infrared science camera does not see the reflection of the relatively warm M2 itself but only the cold sky.

Manufacturing, integration and testing

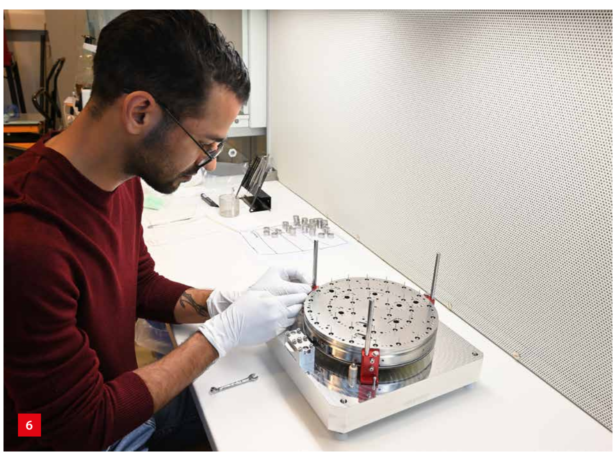
It was decided to recycle the linear current amplifiers and control electronics from a previous laboratory-DM. A set of 36 actuators was assembled from spare parts left over from the UH2.2 actuator set, and from parts obtained by the dismantling of another DM prototype.

The thin mirror shell was created in a three-step process that was pioneered for UH2.2. As a first step, a 3.3-mm-thick borosilicate glass blank was formed to an intermediate spec by the University of Santa Cruz with a process called 'slumping'. In this process, the blank was placed in an oven, supported at the edges on a metal ring and with concentric

Visual inspection of the mirror shell prior to MRF finishing.

weights at specific diameters. The blank was then heated through a precisely tuned $T(t)$ process to around 600 °C, causing it to 'slump' to within 100 μm of the final shape. The shell was then made to a best-fit sphere of the required high-spatial surface form error and required roughness through classical polishing by Huygens Optics. As a last step, the shell was brought to its final aspheric shape by magneto-rheological finishing (MRF) at TNO (Figure 5).

The fact that the shell is used for a deformable mirror opens up design freedoms. Low-spatial shape errors are not important since the actuators can correct most errors – which allows the use of slumping. The slumping process with weights and temperatures is sufficiently tuneable, and the flat glass blanks are cheap, which allows a lot of iterations at low cost to achieve the best intermediate shape for further processing. And finally, MRF works relative to the surface and not to an absolute position, which relaxes requirements on the mounting of the glass during manufacturing. Residual errors from the gravity vector and thermal deformations were modelled extensively during the design phase, and were also found to be well correctable with the actuators.



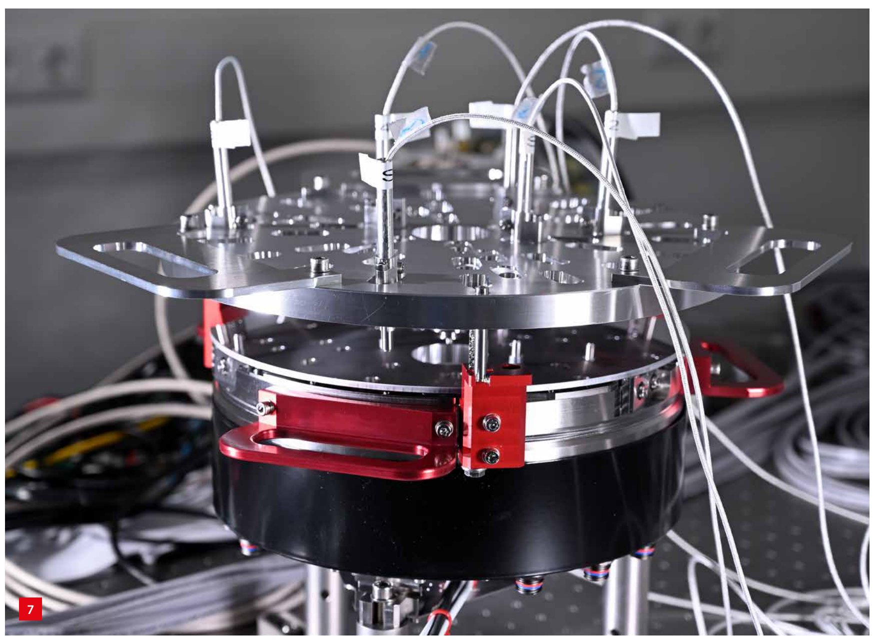
Preparing for the integration of the actuators on the support structure in the integration jig. The thin struts, which are bonded to the mirror shell, can be seen protruding from the top.

The support structure material was changed from the original low-cost aluminium to titanium for a better CTE match with the borosilicate mirror shell. The support structure is made in two parts: a lightweighted main body and a 3-mm thick top plate that is mounted with fasteners. Figure 6 shows the support structure in the integration jig, in preparation for the mounting of the actuators. The stresses on the epoxy bonds were extensively modelled for both gravity and thermal loads to ensure proper safety margins, and a dedicated breadboard set-up was built to verify bond strength under pull tests, bending moments and thermal cycling.

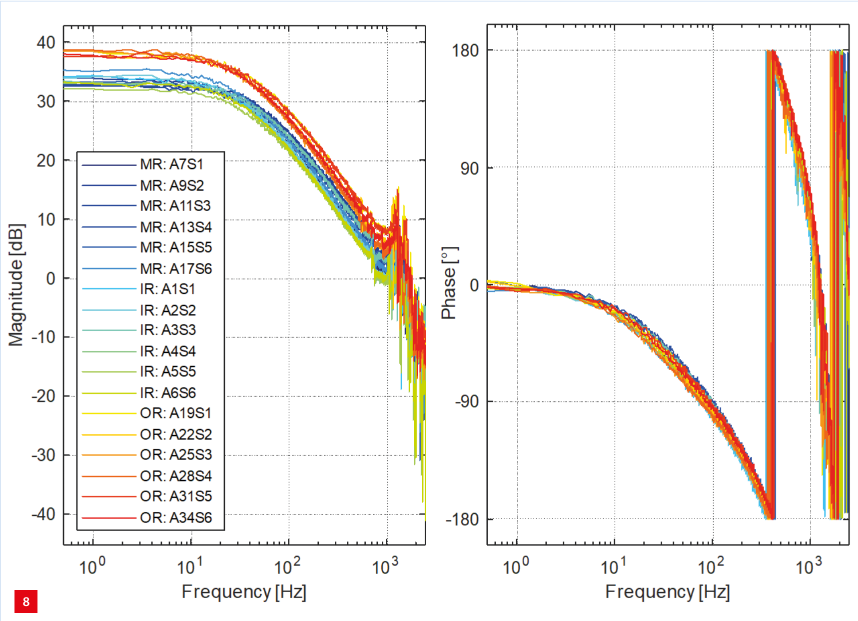
To test the functionality, and assess the dynamic performance of the adaptive mirror, a sensor mount was used designed such that capacitive sensors could be placed in front of each actuator. A set of six Lion Precision capacitive sensors were rotated such that all actuators have been measured. Figure 7 shows the ASM fitted with these sensors.

On each actuator, one by one, a sine-wave current was applied, smoothly going through the complete range of the actuator while recording the movement of the mirror shell on all six capacitive sensors. The co-located actuator and sensor measurements were used to determine the stroke, linearity and hysteresis for each actuator. The measured results were on average 13 μm stroke on the inner ring actuators and 20 μm on the outer ring. The linearity was on average 2.2% and the hysteresis 3%.

The dynamic response of the system was measured by injecting noise on each actuator while recording the movement of the mirror shell with the capacitive sensors; see Figure 8. Analysis of these measurements confirmed



The adaptive mirror fitted with capacitive sensors for functional and dynamic testing.

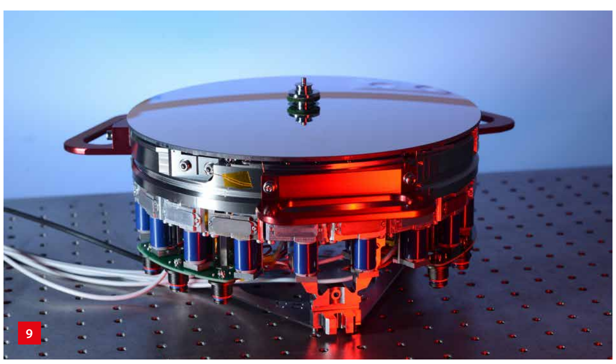


Frequency response (magnitude on the left, phase on the right) of a subset of actuators: six actuators in the inner ring (IR, green); six in the middle ring (MR, blue); and six in the outer ring (OR, yellow/red).

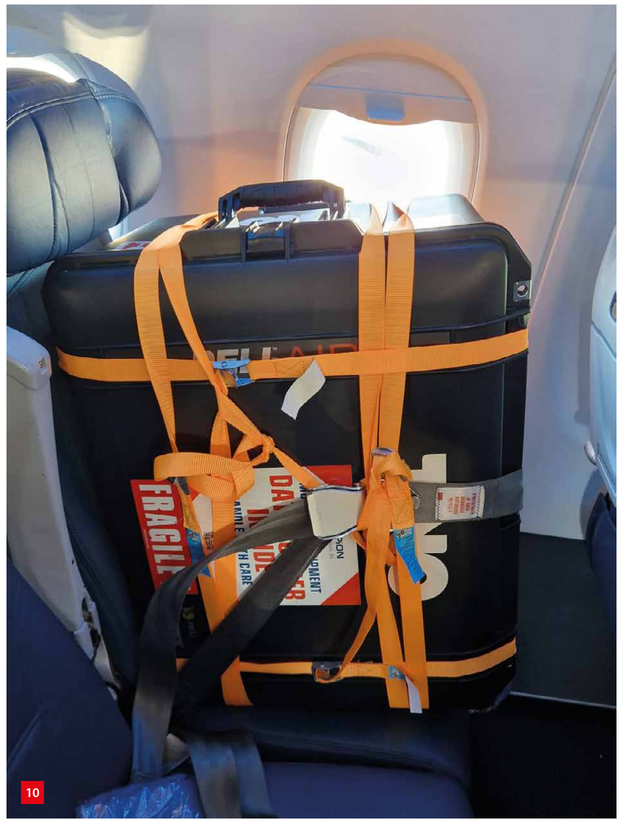
the FEM results, showing that no modes occur with resonance frequencies lower than 500 Hz. Actuators in the outer ring 'feel' a lower stiffness of the mirror shell, since they are not 'surrounded' by other actuators like the inner ones are. This results in a higher magnitude of the response for actuators in the outer ring across the entire frequency range.

The ASM itself is also equipped with six internal capacitive sensors, which will be used to monitor the position of the mirror shell relative to the structure. These capacitive sensors are not used for feedback control of the actuators, since this can be done with the optical wavefront sensors in the AO system of the telescope. The internal sensors are only used for global shape monitoring and to verify the output of the wavefront sensor. Verification is done by placing an external sensor directly opposite to an internal one and comparing signals.

One of the benefits of the deformable mirrors based on the TNO hybrid variable-reluctance actuator is that these actuators can be replaced. Actuator replacement has been



The fully tested adaptive mirror; ready for delivery.



An expensive and sensitive piece of high-tech equipment, safely tied to its own airplane seat.

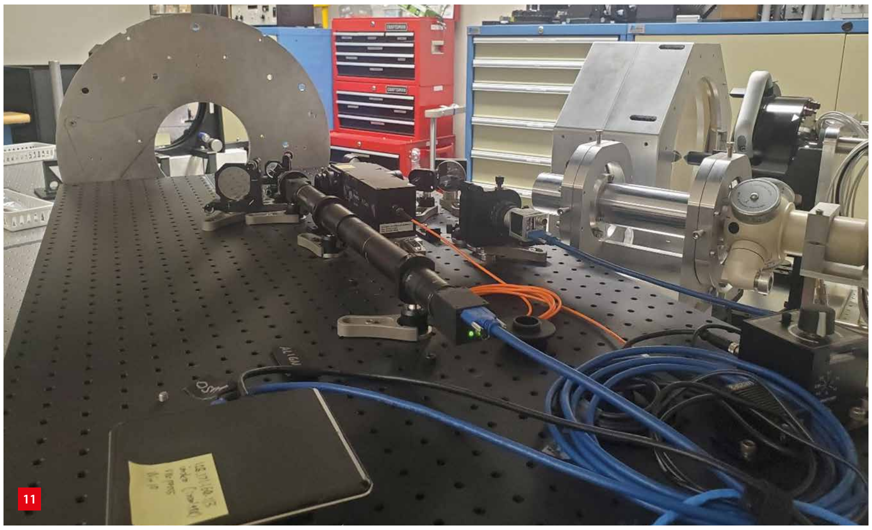
tested on the IRTF ASM. Three actuators were replaced after functional testing. The functional testing was repeated and no significant changes were observed in any of the non-replaced actuators. With this, the adaptive mirror was ready for delivery to the end user (Figure 9).

Shipment

To ship the ASM in a fast and safe way, the standard solution for smaller adaptive mirrors had been to hand-carry them on an airplane. Bringing the mirror on a commercial flight to Hawai'i allowed to avoid high acceleration and shock loads that can occur during commercial cargo transport. The IRTF mirror was too large to completely hand-carry it, and so a custom transport case was designed, with the ASM mounted on a separate platform suspended on wire-rope isolators to dampen high acceleration loads. The case was equipped with shock sensors for shock tests and logging during the transport. The container was tested with a standard series of vertical and rotational drops. As the height of the ASM plus the suspended platform was too big for hand-luggage requirements and the risk of shock loads for checked luggage was to be avoided, the airline was found to agree to accept it on a separately booked chair; see Figure 10.

Performance testing on-site

After delivery of the ASM to the Institute for Astronomy at the University of Hawai'i in Hilo, the AO team responsible



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The adaptive mirror on the optical test bench in Hawai'i; in front, the black breadboard contains the wavefront sensors. The small tube is an alignment telescope. The light goes through the circular metal plate on a flat mirror to the Hindle-sphere lens in the hexagonal mount (top right). Next to this, the ASM can be seen with its black housing and the white triangular alignment marker.

for integrating the ASM with the wavefront sensor hooked up the ASM to their real-time controller to verify the functionality of each actuator (Figure 11). Following the successful verification, the ASM was mounted on the optical table in a set-up with a Hindle-sphere lens designed to capture the diverging light to the wavefront sensor breadboard to be mounted on the telescope. In this way, the AO team could close the loop with the wavefront sensor within a few days after receiving the ASM. With some tuning, a wavefront error of 20 nm rms was achieved, which is well within specification for the infrared telescope. Next steps are to use the internal capacitive sensors and a second, high-order wavefront sensor to verify the AO correction performance of the ASM.

Outlook

At the time of writing this article (March 2024), the IRTF ASM was undergoing the final tests in the lab of the Institute for Astronomy. In early April, the ASM including all control systems and wavefront sensors was to be transported up the mountain to the IRTF telescope (Figure 12). 'First light', the main goal with this development, was planned for April 23rd. This would mark the start of on-sky testing, which consists of three campaigns of three consecutive nights each.

While the IRTF mirror awaits its first light on sky, the integration of the 210-actuator adaptive mirror for UH2.2 has continued. All hardware is in and the critical assembly procedures have been prepared and rehearsed. With vital assistance from NOVA, one 62-cm mirror shell is now fully in spec, and a second has been nearly finished. The functional testing is scheduled for June with delivery expected by September of this year.

The IRTF adaptive mirror will provide the first on-sky demonstration of this ASM technology, with the UH2.2 ASM following up as the pathfinder for larger-format ASMs for world-leading observatories such as Keck, Gemini North and the Large Binocular Telescope. Success with these projects will allow astronomers to get even sharper views of the Universe, made possible with Dutch technology.

REFERENCE

[1] S. Kuiper, W. Jonker, and M. Chun. "Towards larger deformable mirrors – Adaptive Secondary Mirror development for the UH2.2 telescope", *Mikroniek*, vol. 61 (5), pp. 28-33, 2021.

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The NASA Infrared Telescope in its dome. The 3-meter primary mirror is just left of the centre, covered with the orange protective covers for the day. A truss structure connects to the large orange ring, the 'top end'. Mounted in the centre of that ring is a long grey tube. The current passive M2, which will be replaced by the ASM, is just visible on the left side of it.