Deformable Mirror Survey for Future Exoplanet Direct Imaging Space Missions

Overview and Results

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Survey Goals

1. Survey and document viable DM technologies across the world to inform future exoplanet missions about their capabilities and technology readiness.

2. Make recommendations for DM technologies based on factors such as mission performance requirements, estimated development cost, technology readiness, and how best to advance (directed vs competed).

Survey Team and Scope

We assembled a group of international Subject Matter Experts in deformable mirrors and high-contrast imaging.

- *Tyler Groff (NASA Goddard)*
- *Matt Bolcar (NASA Goddard)*
- *Ruslan Belikov (NASA Ames)*
- *Tim Morris (UK Astronomy technology centre / Durham University)*
- *Stefan Strobele (European Southern Observatory)*
- *Pierre Baudoz (Observatorie de Paris)*
- *Jeremy Kasdin (Princeton Univ. / USFCO)*
- *Olivier Guyon (Univ. of Arizona)*
- *Chris Mendillo (U. Mass Lowell)*
- *John Trauger (JPL)*
- *Pin Chen (JPL)*
- *Camilo Mejia Prada (JPL)*

DM Survey context: Identify a DM for a future exoplanet flagship mission, thus, the evaluation is based on such mission requirements

KT Matrix to organize and evaluate

Evaluation criteria defined in agreement with SMEs

- Establish what are the WFC requirements and how this translates to DM specifications (for a future exoplanet mission)
- Identify programmatic and commercial constraints for those requirements

The KT matrix structure was used to organize the requirements

Descriptors (22)

- Set of technical and business characteristics that define a technology and vendor working on it.

Musts (4)

- Essential characteristics that a given technology must be meet to be considered.
- Binary criterion, yes or no. All criteria must be met.

Wants (23)

- Each one has a weight to define its importance.
- All of them have a score discretized in five levels.

Risks (10)

- Risk are potential problems that a technology might have.
- Severity is discretized in five levels. No weights.

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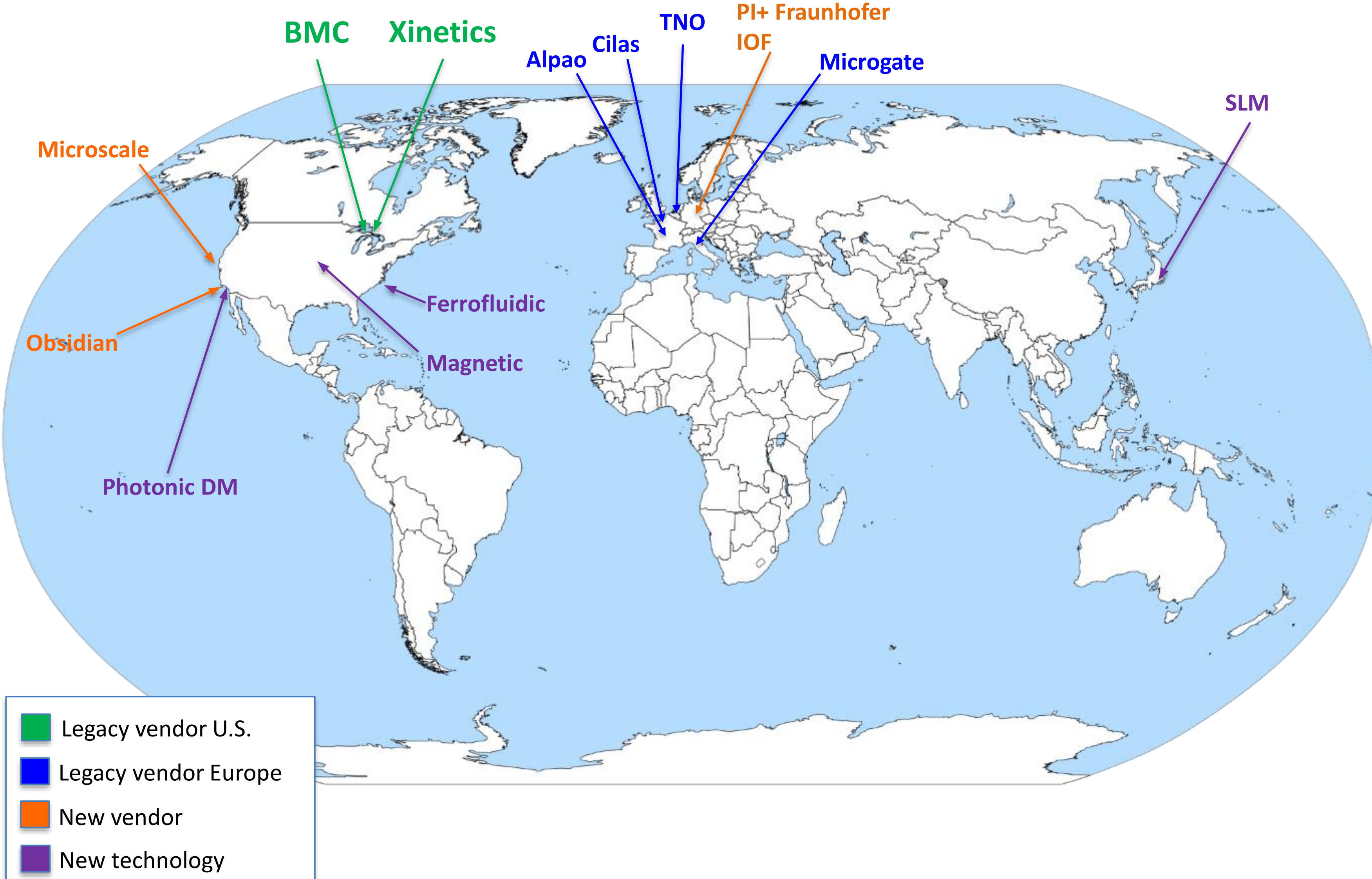
Fact Finding



Fact Finding

Comprehensive search found 13 DM vendors or technologies

1) DM legacy vendors

- Four in Europe:
  - ALPAO (France)
  - Microgate (Italy)
  - Cilas (France)
  - TNO (The Netherland)
- Two in the U.S.:
  - BMC
  - Xinetics

2) New vendor using legacy technologies

- Microscale
- PI Fraunhofer

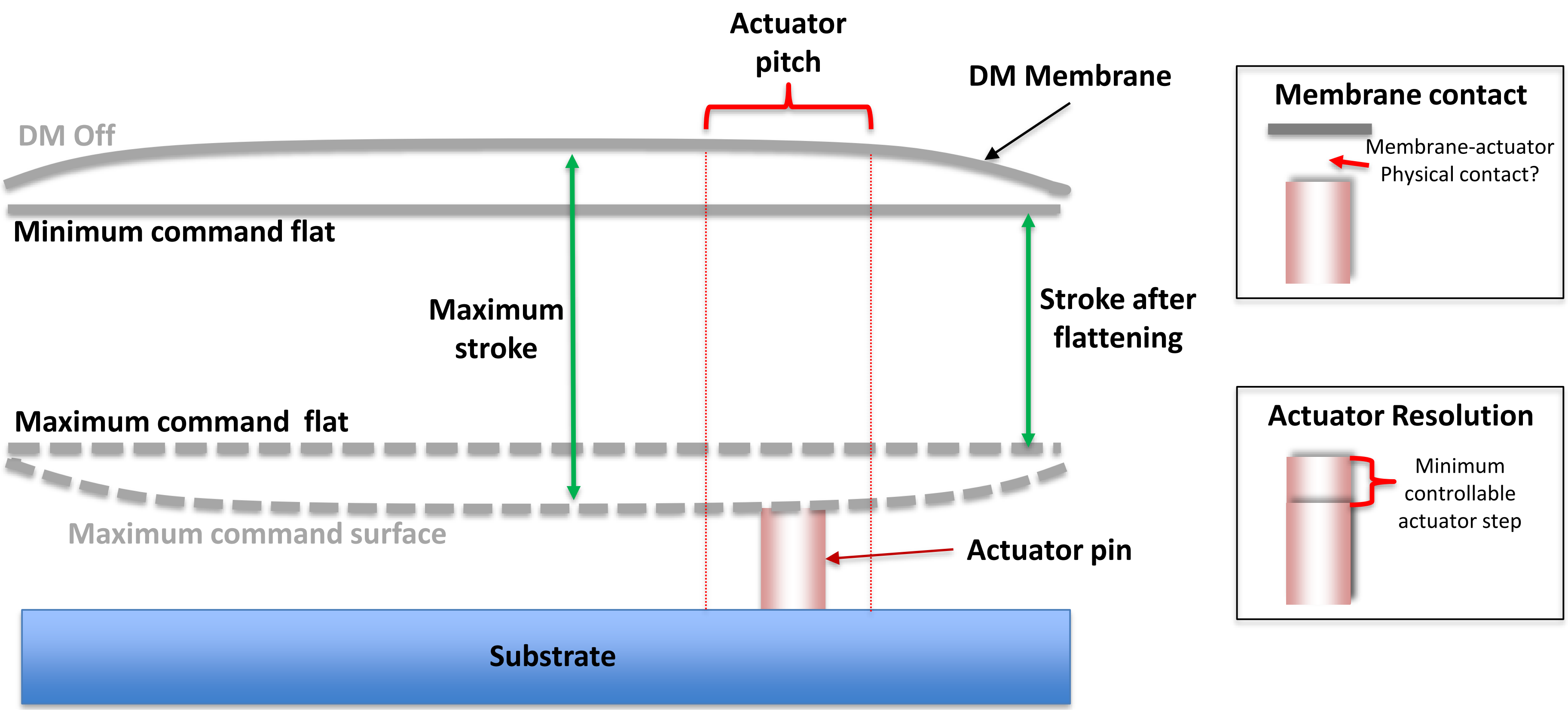
3) New technology developments

- Obsidian
- Spatial Light Modulator (LCoS)
- Ferrofluidic
- Photonic DM
- Magnetic (APERTURE concept)

Fact Finding

DM Technologies overview

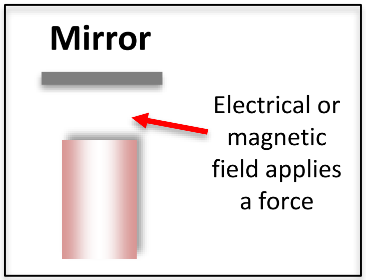
Definitions



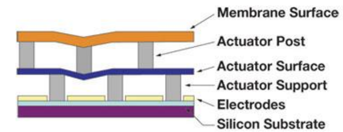
Technologies overview

Actuation type

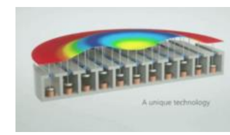
Contactless technologies



Electrostatic
BMC, Obsidian



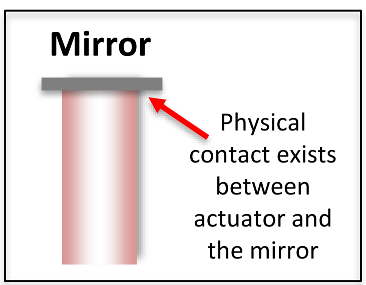
Electromagnetic
ALPAO, Microgate, TNO



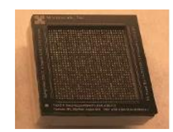
Magnetic
APERTURE

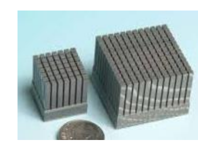
Figure 1 APERTURE concept. For simplicity only one write head is shown. The QR code leads to an animation depicting the concept found here link to video

Contact technologies

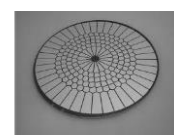


Electrostrictive
Xinetics, Microscale

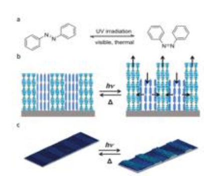




Piezo/monomorph
Cilas, PI+Fraunhofer (PICMA)

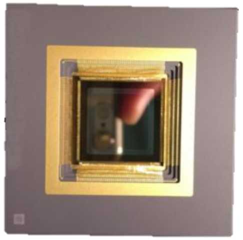


Photonic
Sparse DM



Technologies overview

Small format v/s large format



Small format (Coronagraph level)	Large format (Telescope level)
BMC 15 pm, 0.3 mm	TNO ~500 pm, 5.0 – 50mm
Xinetics 8 pm, 1.0 mm	Microgate ~300 pm, 16 – 39 mm
ALPAO <120 pm, 0.8 – 20.6 mm	Xinetics
Cilas <300 pm, >2.0 mm	Cilas <300 pm, > 2.0 mm
U.S. & European vendors	Mostly European vendors

Legacy technologies

Boston Micro Machines (BMC, U.S.)

Technology: Contactless Electrostatic actuation

Pros:
- Fast and stable actuation
- Large format >3000 actuators demonstrated
- High stability
- High resolution
- Small actuator pitch

Cons:
- Surface quilting
- Reduced stroke for large formats

Legacy technologies

AOX Xinetics (U.S.)

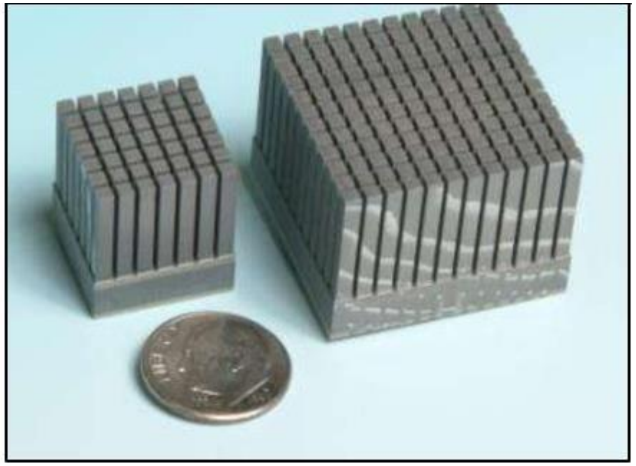
Technology: Contact Electrostrictive PMN technology

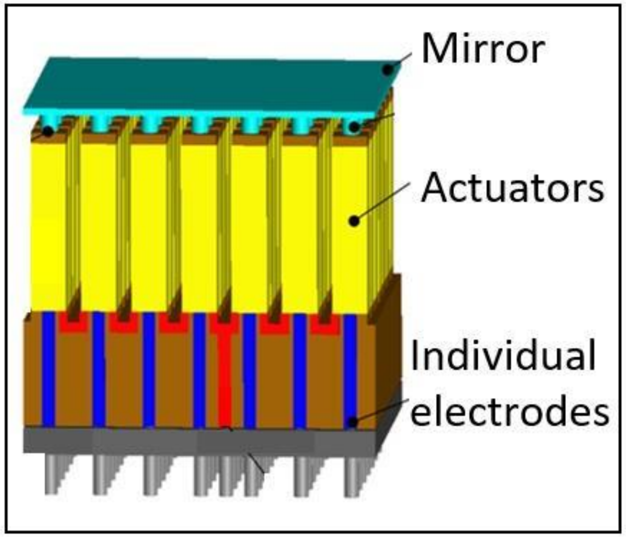
Pros:

- Fast actuation
- Large format >3000 actuators demonstrated
- High resolution
- High surface quality

Cons:

- Stability requires thermal control
- Larger actuators (than BMC) 1 mm pitch
- Small stroke





Legacy technologies

ALPAO (France)

Technology: Indirect Contact Magnetic

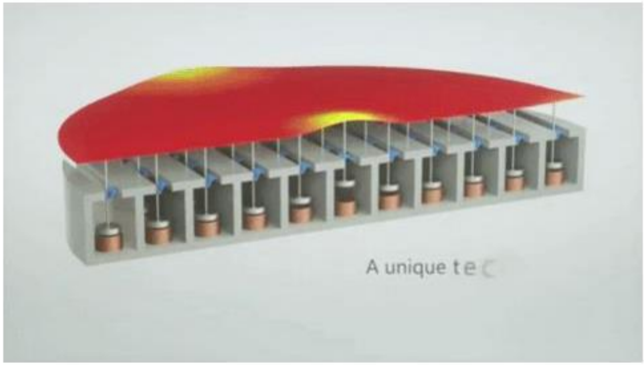
Pros:

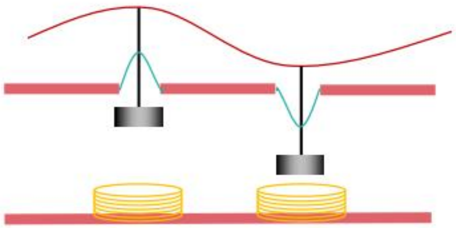
- Fast actuation
- Large format (64x64 and 128x128 for EELT)
- Large stroke
- Embbeded electronics
- Low voltage operation

Cons:

- Residual surface WFE not known at ~1nm level
- Sub nanometer resolution not demonstrated

- Continuous surface motioned with magnetics actuators





Legacy technologies

Microgate (Italy)

Technology: Contacless Magnetic (Voice coils with levitating thin shell mirror)

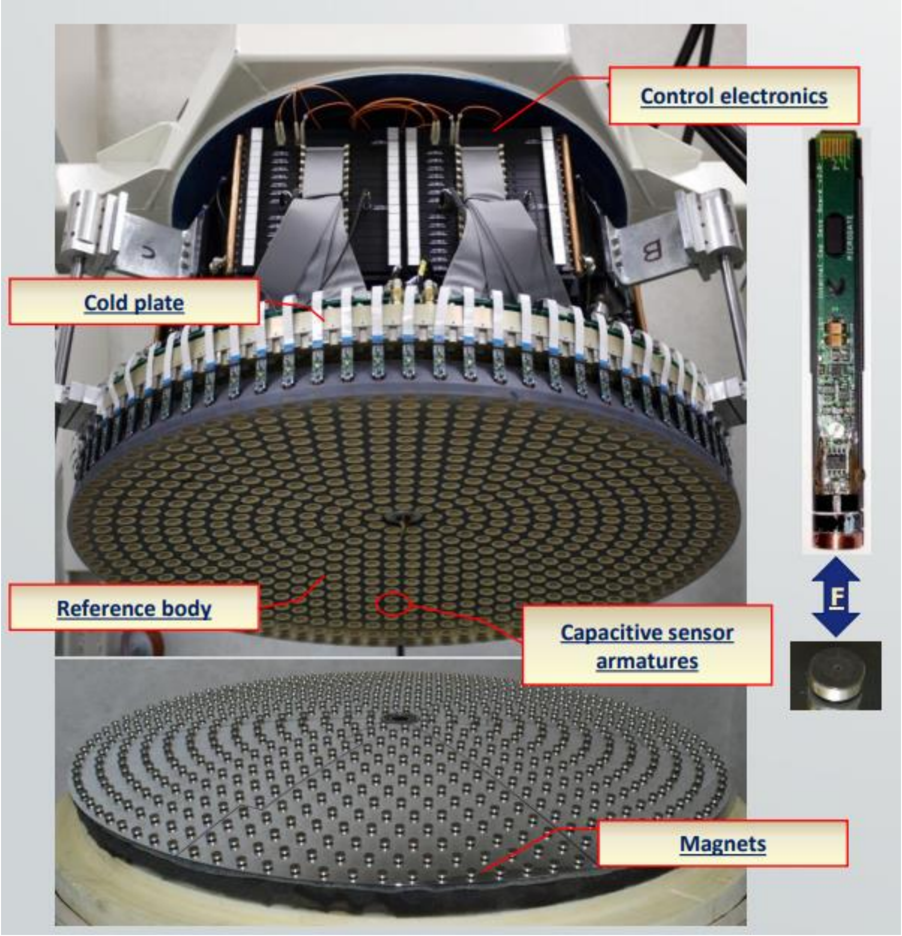
Pros:

- Many ground based secondaries (6.5m MMT, 8.4m LTBx2, 6.5m Magellan, UT4 VLT, GMT and ELT (5316 actuators))
- Fast actuation, levitating thin shell allows fast and pure tip/tilt control
- Large format (64x64 and 128x128 for EELT)
- Large stroke

Cons:

- Sub nanometer resolution not demonstrated
- Large actuators (>18 mm)

=> Potential for a secondary DM mirror in space



Legacy technologies

Cilas (France)

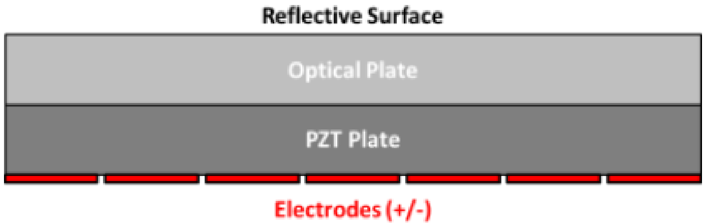
Technologies: Bimorph and Stack

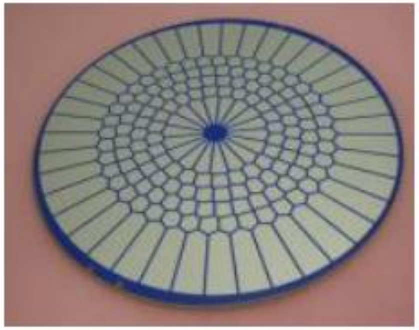
Pros:

- > 20 yr heritage, many ground based system
- Fast actuation
- One piece construction
- Large stroke
- OTOS space DM at high TRL but low number of actuators

Cons:

- Few actuators (Bimorph)
- Thermal drift and hysteresis





Legacy technologies

TNO (Netherlands)

Technology: Electromagnetic hybrid-variable-reluctance actuators

Pros:

- Large force and low consumption
- Large stroke
- High linearity
- Resolution v/s stroke can be traded in the mechanical lever

Cons:

- Few units built
- Few actuators
- Thermal drift and hysteresis
- Large pitch (> 4.3mm)

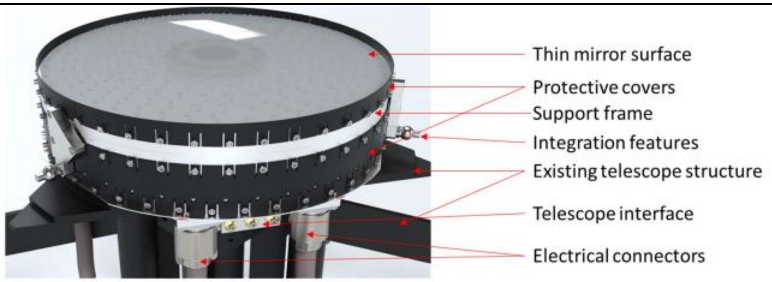


Figure 2-1: CAD-rendering of the ASM for the UH2.2 telescope, containing 210 actuators in a volume of Ø630x135mm. The mass of this ASM is around 55kg.

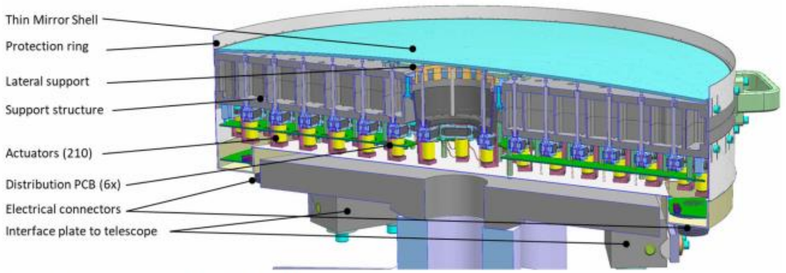
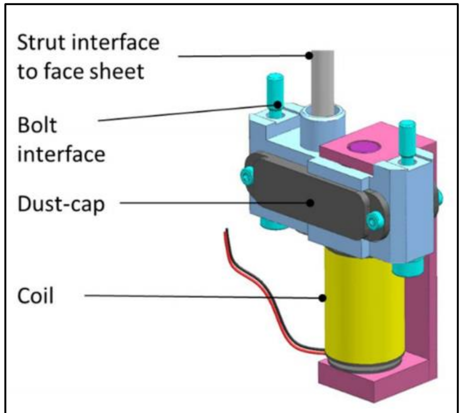
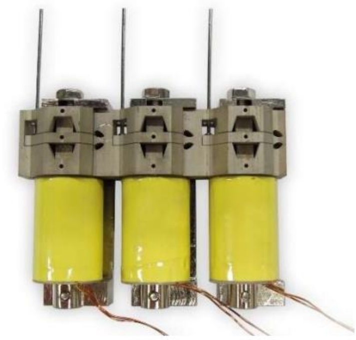


Figure 2-2: Cross-sectional view of the UH2.2 ASM.



18mm pitch actuators



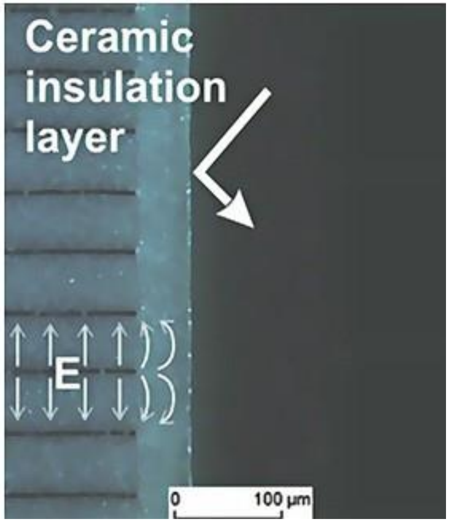
From: White paper: UH2.2 ASM development Q3 2020

New technologies and companies

PI + Fraunhofer (Germany)
Technology: Multilayer PIEZO (PICMA) direct DM Actuation

Pros:
- Scalable to >10,000 actuators
- Similar technology to PMN used by Xinetics
- Reputed vendor and ground based application in development
- Extension to space application can be explored

Cons:
- Weight
- Polishing and print through
- Stability and drift



New technologies and companies

Obsidian (U.S.)

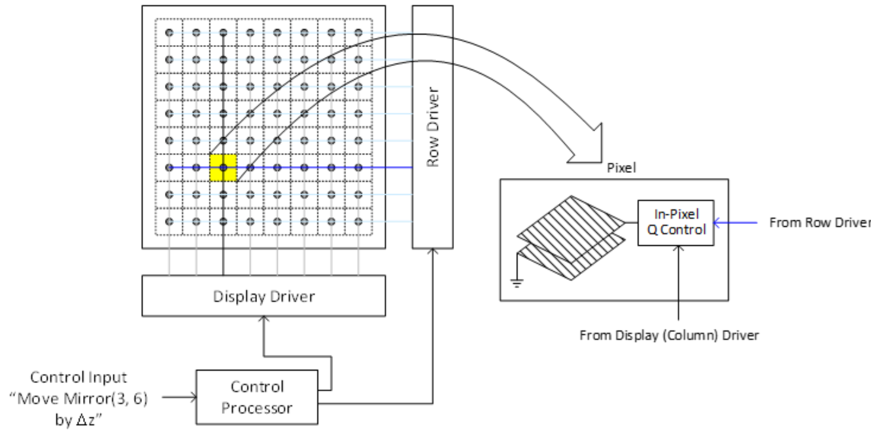
Technology: Active-Matrix Programmable Mirror (AMPM)

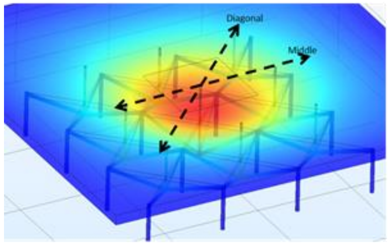
Pros:

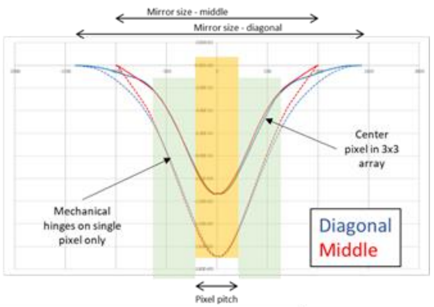
- N channel control, *Not* N^2, for NxN Array
- Charge Drive, *Not* Voltage Drive
- Low voltage drive, < 20V
- High accuracy using available components
    - 17-bit accuracy, using 10-bit driver IC
    - Made possible with Intrapixel Charge DAC
    - 10 pm resolution for 1 um stroke

Cons:

- TRL-3
- 8-bit default dynamic range, can be increased
- Possible surface print through







Technology inherited from displays:

- Use an effect called interferometric absorption in which a thin absorbing metal layer in front of a highly reflective mirror surface selectively absorbs different colors, depending on the gap that separates the two.
- **The gap is controlled by electrostatic actuation** in a relatively simple microelectro-mechanical-system structure.

New technologies and companies

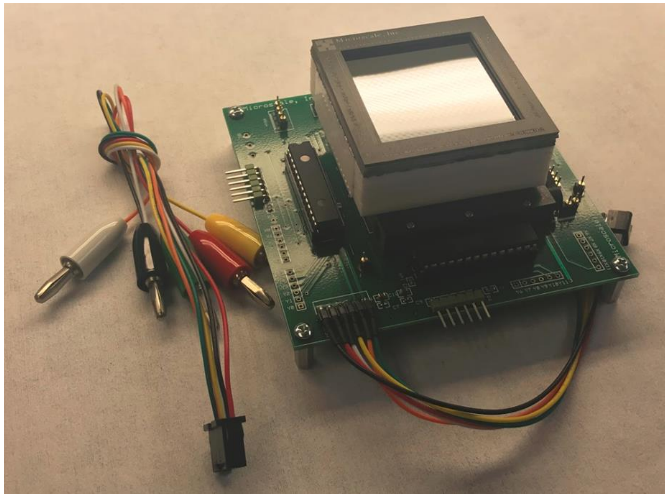
Microscale (U.S.) NASA APRA funded
Technology: ASIC controlled PMN actuator

Pros:

- Electrostrictive PMN technology
- ASIC driver integrated with the DM
- Manufacturing ongoing
- Radiation testing ongoing
- 32x32 actuator device built

Cons:

- Optical performance test pending
- Time multiplexing can be difficult to tune



PMN-PT stack actuator array Integrated 32x32 DM-ASIC System

New technologies

APERTURE (U.S.) NASA NIAC funded

Concept:

- The mirror is made of a foldable and ultra-light metallic membrane
- Magnetic head scans the mirror and correct shape magnetizing the DM surface alloy

Pros:

- DM is ultra-light and foldable
- DM can have power and serve as primary or secondary mirror
- Continuous DM, actuators defined by the scanning resolution
- Simpler electronics and conectorization. Only one cable to magnetic head

Cons:

- TRL-2/3
- Difficult to validate performance on Earth
- Stability is a major challenge

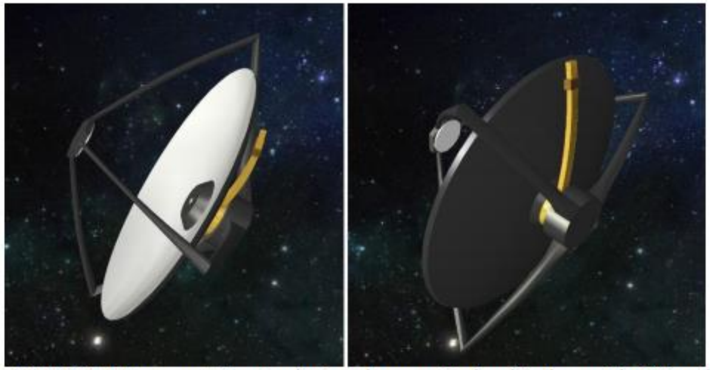


Figure 1 APERTURE concept. For simplicity only one write head is shown. The QR code leads to an animation depicting the concept found here link to video

New technologies

Photonic DM (U.S.)

Concept:

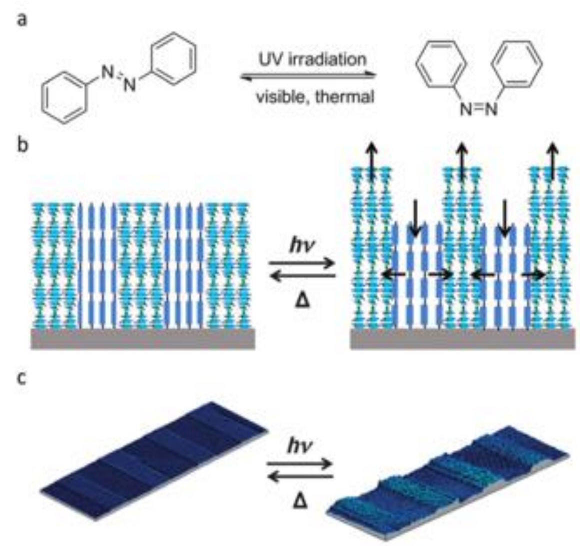
- A photosensitive polymer is applied between the mirror substrate and the reflective coating.
- Mirror actuation is achieved by illuminating the polymer from the back of the mirror causing a reversible isomerization, resulting in a volume change.

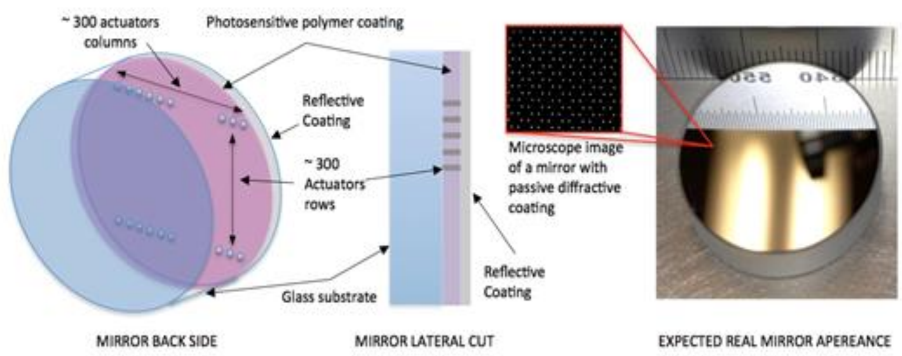
Pros:

- Continuous DM, actuators defined by the scanning resolution
- No cabling or electronics on the DM
- Can be applied on powered surfaces

Cons:

- TRL-2
- Polymer drift
- Small stroke (<1um)





New technologies

Parabolic DM (U.S./France)

Concept:

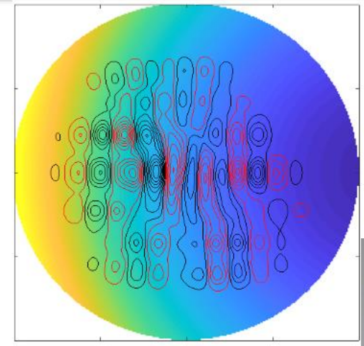
- DM integrated into the off-axis elements of the coronagraph
- Focusing on limited (~324) actuators. Scaling options exist
- Actuation methods
  - Legacy: Ferrofluids/Electromagnetic*
  - Active Development: ALPAO Electromagnetic
  - Identified potential: PMN
- TRL 3-4

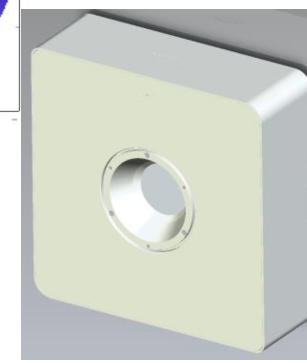
Pros:

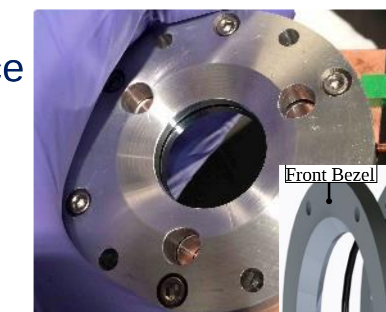
- Continuous DM on coronagraph's powered surfaces
- Eliminates need for a second non-pupil DM
  - Instrument with Pupil DM + Parabolic DMs requires approx. half required actuators for same performance
- Eliminates Talbot effects → Increased bandwidth
- Contributes multiple surfaces which directly compensate low and mid-spatial frequency error

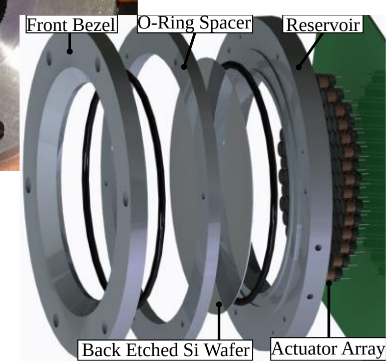
Cons:

- Some active actuation required achieve final shape to reduce prototype complexity. Static design path exists.
- Currently small stroke (<1um). Available stroke increases as required stroke for OAP shape goes down
- Shares stability limitations of actuation method









*Princeton Eric and Wendy Schmidt Transformative Technology Fund + NASA Nancy Grace Roman Technology Fellowship 2014

New technologies

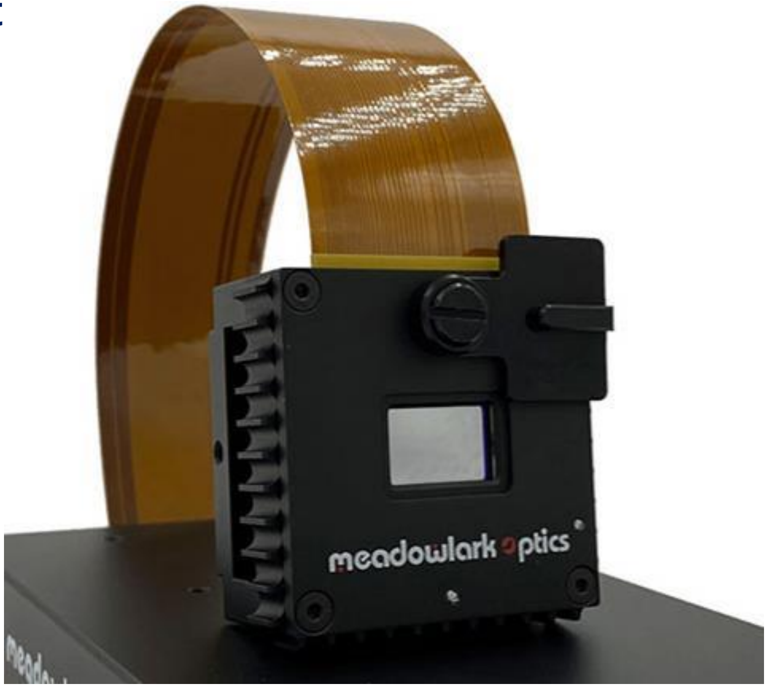
Spatial Light Modulator (SLM)
Technology: Liquid Crystal on Silicon (LCoS) that control the phase delay per pixel

Pros:

- Millions of actuators
- Fast response
- High resolution, 16-bit over 1 wavelength
- Small, no moving parts
- Commercial component, low cost.

Cons:

- Chromatic device
- TRL 3-4
- Not tested in vacuum
- Sensitive to intense light and radiation



New technologies

Free Surface Ferrofluid DM (U. Lavalle, Canada)

Concept:

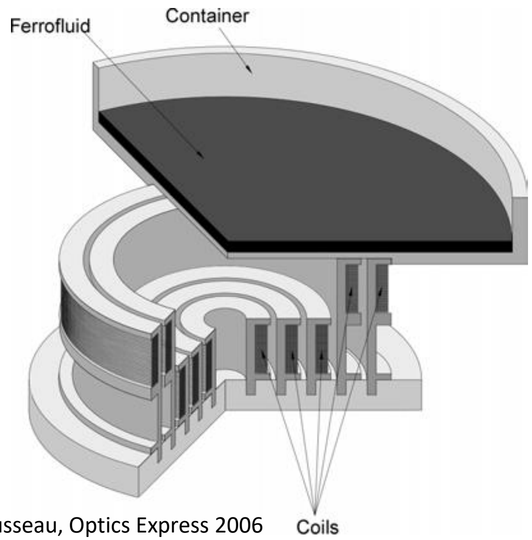
- Silver suspension over Ferrofluid
- Electromagnetic control of free-fluid surface

Pros:

- Continuous DM
- Fast response
- Extremely high stroke

Cons:

- TRL 3-4
- Uncontained fluid not suitable application for space
- Free fluid has potential sensitivity to vibration
- Orientation constrained to be horizontal



Brousseau, Optics Express 2006

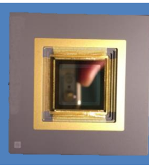
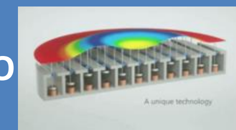
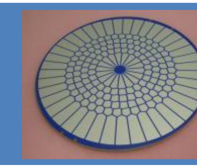
Notes on actuator resolution and stability

- DM actuator resolution and stability (for contactless) is limited by the control electronics, not the actuator itself.
- Trade-off resolution versus stroke is possible for all the technologies.
- The resolution values listed in the following slides have been implemented in at least one of the DM units.
- For most DMs the resolution is interpolated from the actuator response, but not directly measured. Exceptions are Xinetics with VSG (20 pm) and BMC with Zernike WFS.

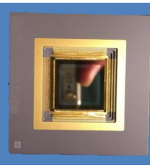
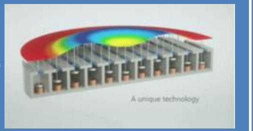
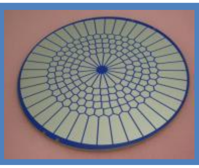
Take away:

1) Custom electronics can improve the resolution of any of the DMs studied if stroke is sacrificed.
2) Stability is the limiting factor if resolution requirement is achieved

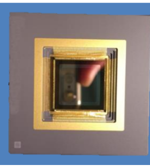
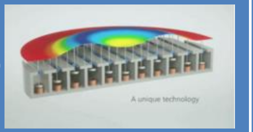
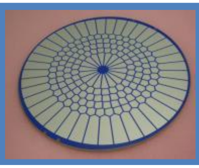
Legacy vendors and technology overview
Small format

	BMC 	Xinetics 	ALPAO 	Cilas 
Technology	Electro static force between pin and membrane	Electrostrictive (PMN) material	Electromagnetic	Bimorph piezoelectric actuation
Control type	Voltage	Voltage	Current	Voltage
Membrane contact	None	Yes	Indirect	Yes

Legacy vendors and technology overview
Small format

	BMC 	Xinetics 	ALPAO 	Cilas 
Technology	Electro static force between pin and membrane	Electrostrictive (PMN) material	Electromagnetic	Bimorph piezoelectric actuation
Control type	Voltage	Voltage	Current	Voltage
Membrane contact	None	Yes	Indirect	Yes
Actuator pitch	0.3 - 0.45 mm	1.0 - 2.5 mm	0.8 – 20.6 mm	≥ 2 mm
Actuator stroke	1 to 2 μm	0.5 μm	8 – 25 μm	20 μm (OTOS)

Legacy vendors and technology overview
Small format

	BMC 	Xinetics 	ALPAO 	Cilas 
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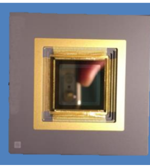
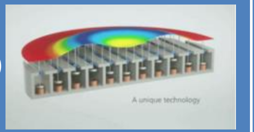
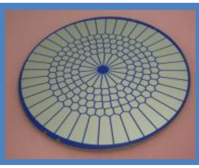
Actuator pitch	0.3 - 0.45 mm	1.0 - 2.5 mm	0.8 – 20.6 mm	≥ 2 mm
Actuator stroke	1 to 2 μm	0.5 μm	8 – 25 μm	20 μm (OTOS)
Actuator count	4096 (64x64)	4356 (66x66)	3228 (64 across)	188(OTOS has 63)
Capability	Up to 9216 (96x96)	Up to 9216 (96x96)	Up to 12912 (128 across)	Few hundreds

Legacy vendors and technology overview
Small format

	BMC 	Xinetics 	ALPAO 	Cilas 
Technology	Electro static force between pin and membrane	Electrostrictive (PMN) material	Electromagnetic	Bimorph piezoelectric actuation
Control type	Voltage	Voltage	Current	Voltage
Membrane contact	None	Yes	Indirect	Yes
Actuator pitch	0.3 - 0.45 mm	1.0 - 2.5 mm	0.8 – 20.6 mm	≥ 2 mm
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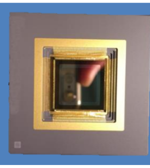
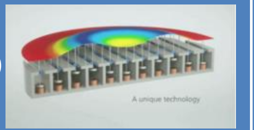
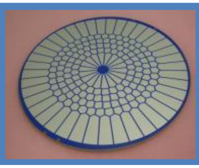
Actuator resolution	15 pm	20 pm measured	120 pm	~300 pm
Capability	15 pm	8 pm	15 pm	50 pm

Legacy vendors and technology overview Small format

	BMC 	Xinetics 	ALPAO 	Cilas 
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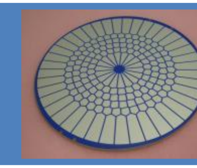
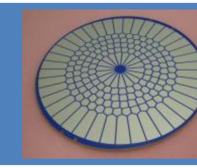
Key limitations for flagship mission	Surface Quilting, actuator **count**	Actuator **pitch**, stability	Actuator **pitch**	Actuator **count, pitch** and resolution
Company information	U.S. Based DMs are the main business Independent company	U.S. Based DMs are the main business Parent: Northrop Grumman, strategic business unit	France DMs 70% of $4M revenue Parent: Eveon	France DM's 10% of revenue Ariane group and AREVA

Legacy vendors and technology overview
Large format

	Microgate 	TNO 	Xinetics	Cilas 
Technology	Electromagnetic	Electromagnetic	Electrostrictive (PMN) material	Bimorph piezoelectric actuation
Control type	Current with feedback	hybrid-variable-reluctance principle.	Voltage	Voltage
Membrane contact	None	Yes	Yes	Yes

Legacy vendors and technology overview Large format

	Microgate 	TNO 	Xinetics	Cilas 
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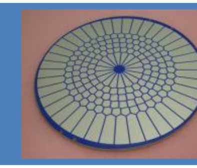
Control type	Current with feedback	hybrid-variable-reluctance principle.	Voltage	Voltage
Membrane contact	None	Yes	Yes	Yes
Actuator pitch	16 - 39 mm	5.0 – 50 mm	NA	≥ 2 mm
Actuator stroke	100 μm	40 μm	NA	20 μm (OTOS)

Legacy vendors and technology overview Large format

	Microgate 	TNO 	Xinetics	Cilas 
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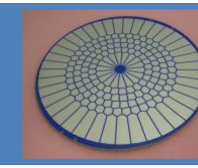
Actuator pitch	16 - 39 mm	5.0 – 50 mm	NA	≥ 2 mm
Actuator stroke	100 μm	40 μm	NA	20 μm (OTOS)
Actuator count	1170 (VLT UT4)	210 (UH 2.2m)	NA	188 (OTOS has 63)
Capability	Up to 5316 (E-ELT)	Up to 3500 (TMT)	NA	Up to 250

Legacy vendors and technology overview
Large format

	Microgate 	TNO 	Xinetics	Cilas 
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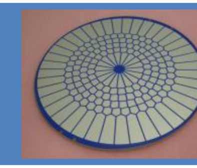
Actuator count	1170 (VLT UT4)	210 (UH 2.2m)	NA	188 (OTOS has 63)
Capability	Up to 5316 (E-ELT)	Up to 3500 (TMT)	NA	Up to 250
Actuator resolution	300 pm (based on accuracy)	500 pm	NA	~300 pm
Capability	TBC	50 pm (TBC)	NA	50 pm

Legacy vendors and technology overview
Large format

	Microgate 	TNO 	Xinetics	Cilas 
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Capability	Up to 5316 (E-ELT)	Up to 3500 (TMT)	NA	Up to 250* (Bimorph)
Actuator resolution	300 pm (based on accuracy)	500 pm	NA	~300 pm
Capability	TBC	50 pm (TBC)	NA	50 pm
Key limitations for flagship mission	Actuator **pitch**	Actuator **pitch**, **count**	NA	Actuator **count, pitch**
Company information	Italy DMs are 30% of revenue Revenue €11M AdOptica (Microgate + ADS)	Netherlands DMs are less 1% Revenue €534M TNO and VDL	U.S. Based DMs are the main business Parent: Northrop Grumman, strategic business unit	France DM's 10% of revenue Ariane group and AREVA

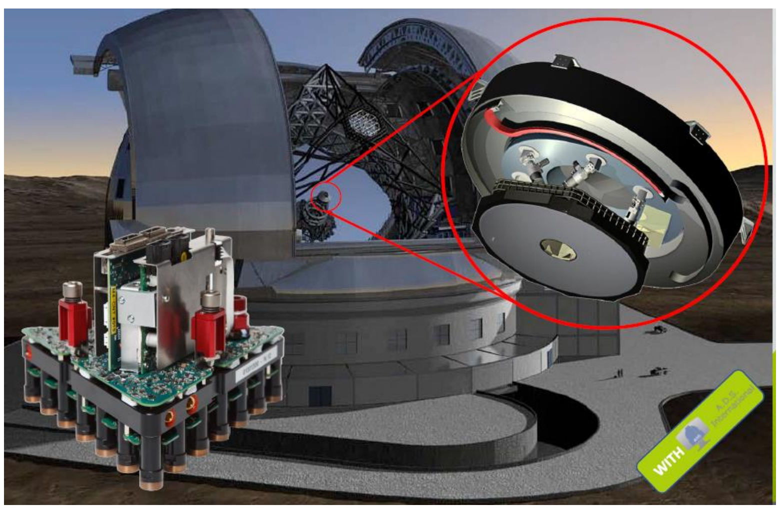
* Cilas for Bimorph, Stack technology can go up to 3000 actuators

Is a large format DM an option for space?

Woofer-tweeter architectures have been implemented in ground based telescopes

- Subaru AO 188 + SCExAO (2K BMC)

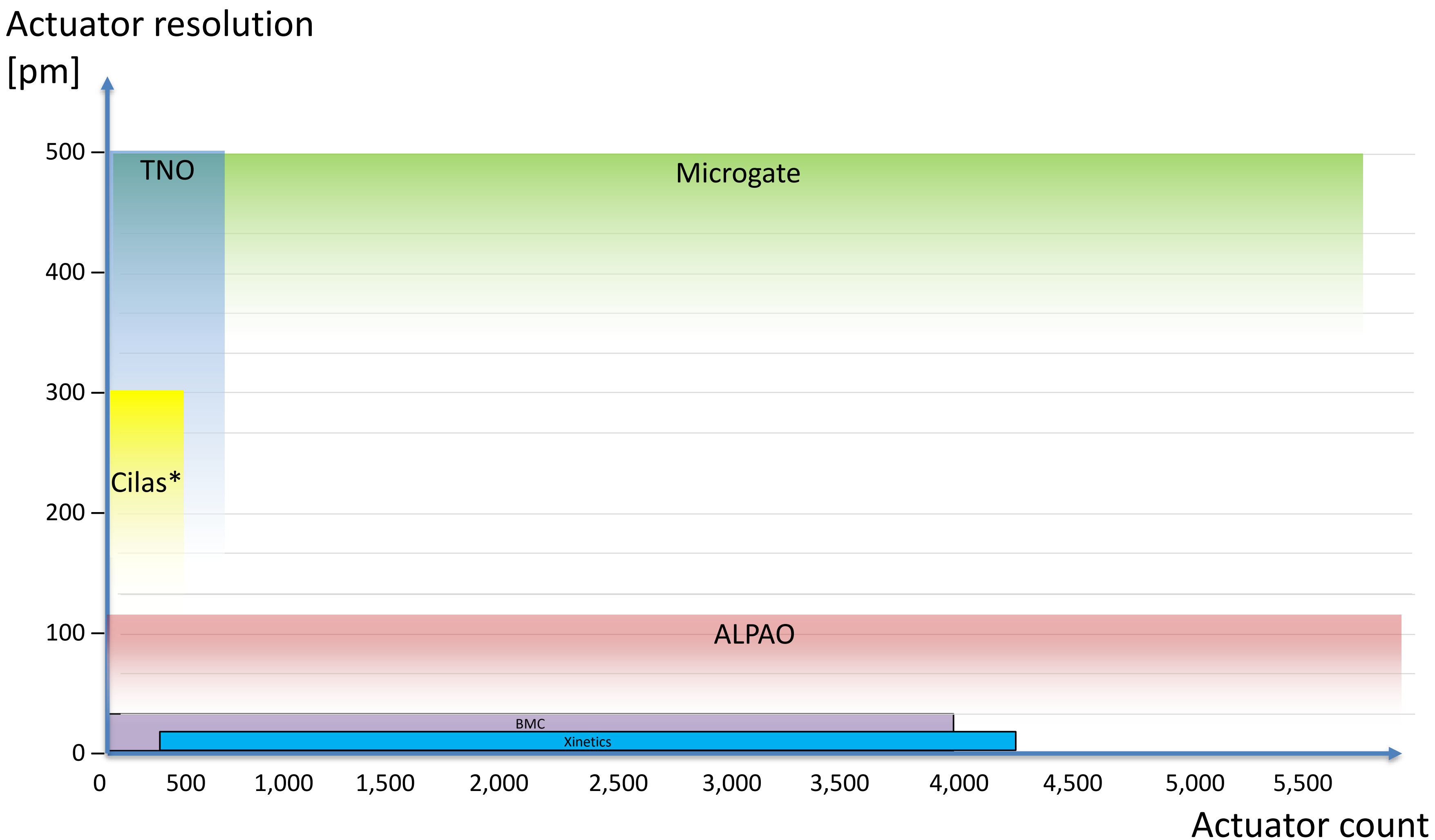
- Baseline for future ELTs
  For example E-ELT uses:
  - M4 (2.5m, 5316 actuators)
  - Extreme AO, 11,000 actuators



Planned M4 deformable mirror at E-ELT with 5315 actuators under development by Microgate

Deformable Secondary Mirror at the VLT UT-4 with 1170 actuators made by Microgate

Resolution vs actuator count



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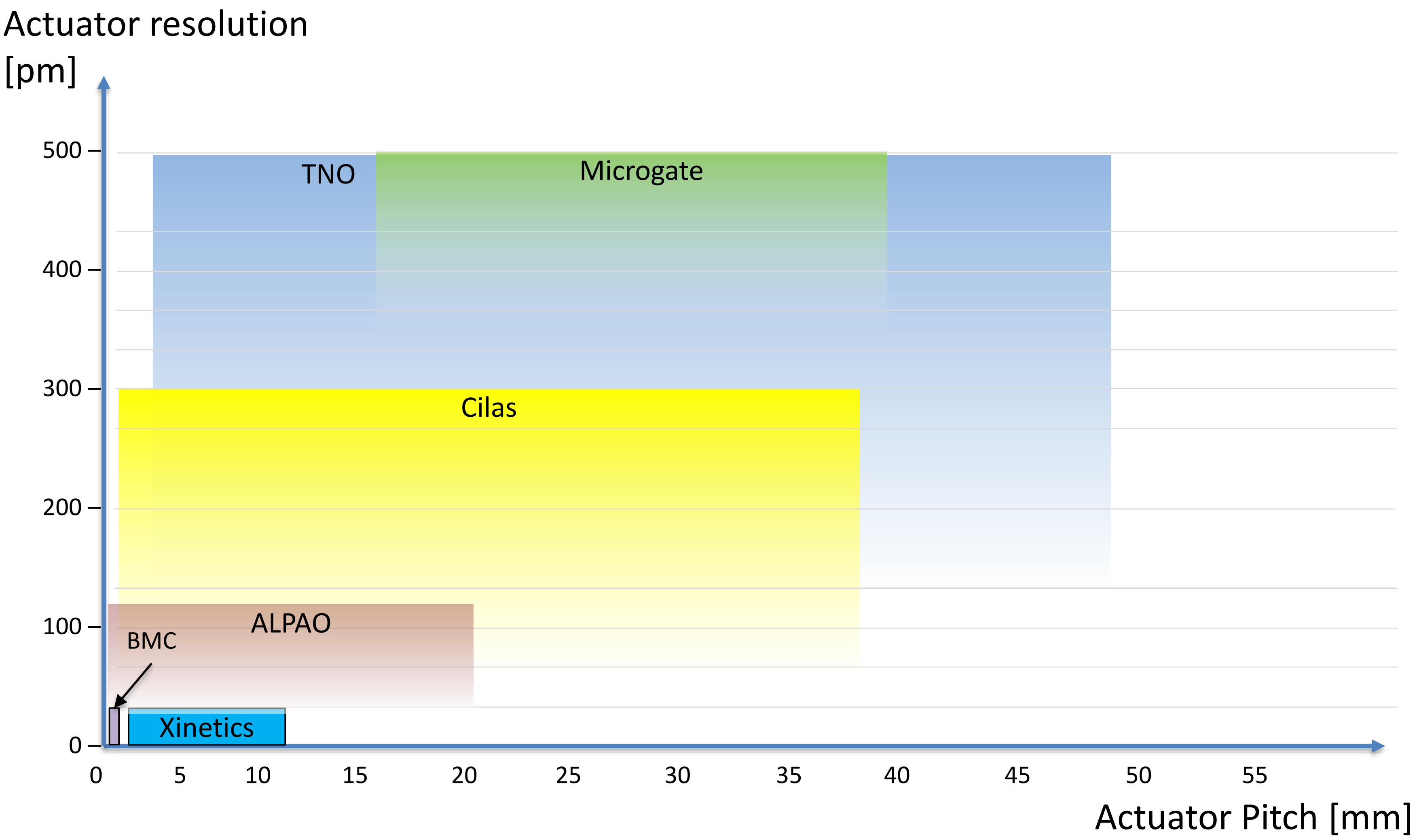
Resolution vs actuator pitch



Space qualification and TRL

	Qualification effort	TRL	Results/Next steps
MEMS BMC 140	DeMi cubesat mission flight	TRL-7	Measurement fidelity no high enough, orbit and mission duration not relevant.
MEMS BMC Kilo	Environmental (TVAC), Shake, vibe and performance	TRL-5	Princeton-BMC TDEM test were inconclusive, flight on Picture-C proved survivability.
MEMS BMC 2K	Ongoing at HCIT	TRL-5	Work in progress, TRL-5 from CGI maturation effort

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Xinetics 2K (CGI)	Environmental, Shake and Vibe, and performance	TRL-6	System being implemented in CGI

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TNO 427, 57	Environmental testing and design	TRL-4/5	427 actuator prototype built. 57 actuator with hybrid-variable-reluctance being built
CILAS (OTOS 63)	Performance demonstrated in relevant environment	TRL-6	Flight demonstration pending (TRL definition may not match)

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TNO 427, 57	Environmental testing and design	TRL-4/5	427 actuator prototype built. 57 actuator with hybrid-variable-reluctance being built
CILAS (OTOS 63)	Performance demonstrated in relevant environment	TRL-6	Flight demonstration pending (TRL definition may not match)
Microgate (LATT 19)	Environmental (TVAC), Shake, vibe and performance	TRL-5	Actuator count, pitch and resolution not relevant to flagship missions. Potential for development exist as levitation is not necessary in space reducing power consumption

Space qualification and TRL

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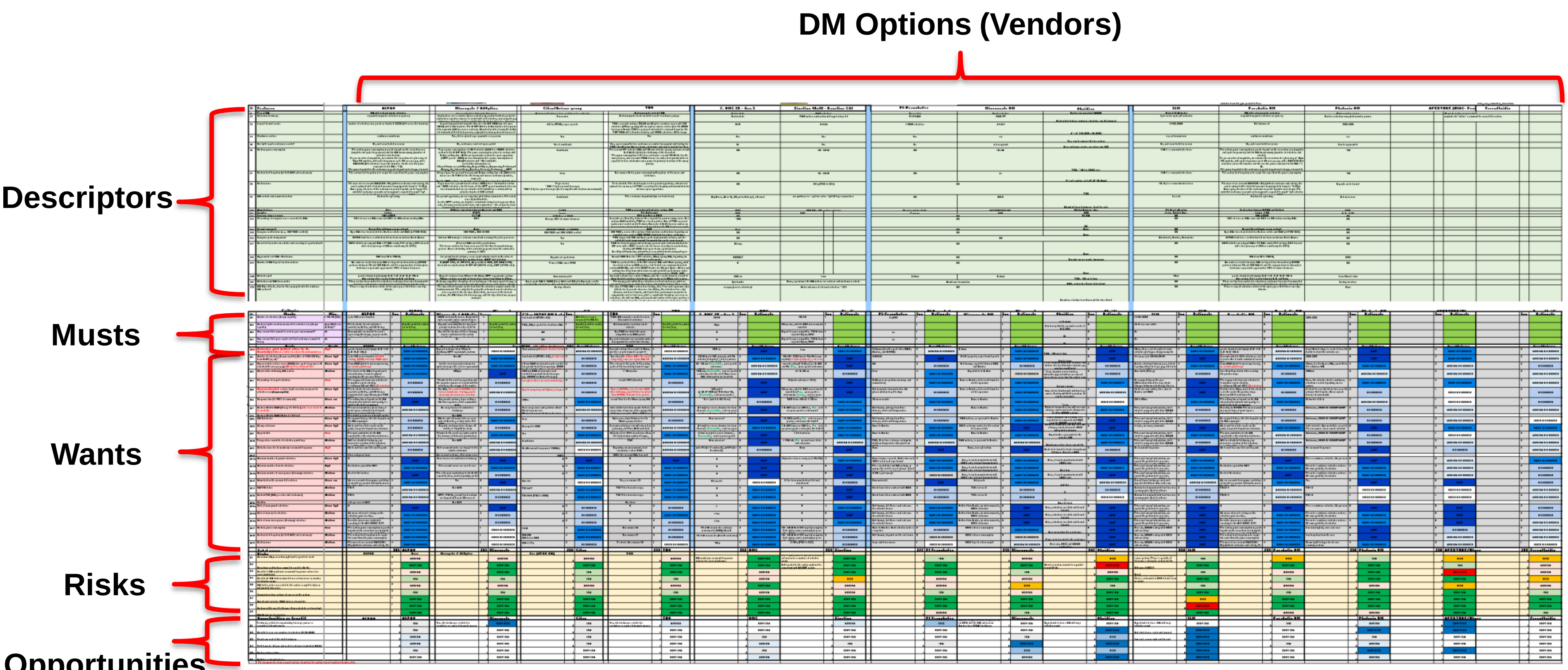
ALPAO	Environmental	TRL-4	The company is interested in developing a space capable version. Potential for coronagraph-level DM in space

Step 3: Scoring and populate KT Matrix

We held multiple working sessions with the SMEs to agree on the weights for each criterion and score give each DM option.

=> The KT matrix result represent the consensus of the team



Results

DM ranking for future flagship exoplanet mission

DM Technology
ALPAO
Microgate
Cilas
TNO
BMC
Xinetics

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Results

DM ranking for future flagship exoplanet mission

DM Technology	Adjusted Final Score
ALPAO	109
Microgate	63
Cilas	84
TNO	62
BMC	158
Xinetics	152

Medium performance (ALPAO)

Top 2(Tied)
Best performance (BMC, Xinetics)

Results

DM ranking for future flagship exoplanet mission

DM Technology	Adjusted Final Score	Maturity Score
ALPAO	109	3.3
Microgate	63	3.3
Cilas	84	3.6
TNO	62	3.6
BMC	158	4.3
Xinetics	152	4.6

Candidate for backup (ALPAO, Microgate)
Medium performance
Medium maturity

Top 2(Tied) (BMC, Xinetics)
Best performance
Highest maturity

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Results

DM ranking for future flagship exoplanet mission

DM Technology	Adjusted Final Score	Maturity Score	Risk Histogram
ALPAO	109	3.3	Very low 6; Low 4; Medium 2; High 0; Very high 0
Microgate	63	3.3	Very low 7; Low 1; Medium 4; High 0; Very high 0
Cilas	84	3.6	Very low 6; Low 3; Medium 3; High 0; Very high 0
TNO	62	3.6	Very low 5; Low 5; Medium 2; High 0; Very high 0
BMC	158	4.3	Very low 6; Low 2; Medium 4; High 1; Very high 0
Xinetics	152	4.6	Very low 5; Low 3; Medium 4; High 1; Very high 0

Candidate for backup (ALPAO)
Medium performance
Medium maturity
Medium risk level

Top 2(Tied) (BMC, Xinetics)
Best performance
Highest maturity
Manageable risk level

Very low	It is very unlikely that the risk will materialize
Low	It is unlikely that the risk will materialize
Medium	The risk can occur but it can be mitigated. Requires attention
High	It is likely that the risk will materialize. Requires investment to mitigate
Very high	Risk has been materialized and mitigation is uncertain even with investment

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Conclusions

Xinetics and BMC are the best options for DMs

- Their scores are in a statistical tie indicating best performance
- Show the highest maturity. TRL estimates between 4 and 5 for HabEx application
- Manageable risks

Three promising new technologies identified

- Microscale, Obsidian, and SLM
- Potential high performance
- Less mature, but higher risk
- Opportunity for investment

Conventional candidate for backup

- ALPAO has demonstrated a medium performance but could meet requirements with some development effort.
- Relatively low risk

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Recommendations

Develop high actuator count DMs

- No off-the-shelf units, meeting requirements requires special projects for every vendor
- Lead times are long > 2 years
- Scalability issues are difficult to predict and time consuming to debug

Advance DM electronics performance and connectorization

- For several key parameters, the DM performance is limited by the electronics and not the DM itself
- Investment in electronics can benefit more than one technology, i.e. electronics for Xinetics and BMC are compatible

Support the development of at least two backup technologies

- Backup technologies allow us to have a timely solution in case scalability of Xinetics and BMC does not progress satisfactorily.

Make the DM survey a living document

- Revise scores, maturity and Risks every year
- Involve vendors and community
- Maybe talk and breakout session at AAS ExoPAG or SPIE.

Additional recommendations and SME comments

Partner with Europe to develop high performance DMs

- ESO also has engaged ALPAO for the development of high resolution and stability DMs in order to perform speckle nulling from ground based telescopes equipped with AO
- NASA's ExEP and Europe could share the DM requirements and explore options to jointly fund the manufacturing of higher performance DMs
- Same for DM electronics including ASICs and HV-DACs
- Create a larger market and demand with more customers (NASA + Europe) – (NASA HQ recommendation)
    - Companies do not have any other market for devices with such format and performance

Risk assessment fidelity is correlated to maturity

- Some less mature DM technologies exhibit less risks than more mature Xinetics and BMC. The reason is that less mature options has unknown risks to be discovered.
- Risk are also used as a way to communicate to vendors the SMEs concerns

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