ATLAS Probe Instrument Concept

Enabling Massively Multiplexed Spectroscopy in Space

M. Robberto

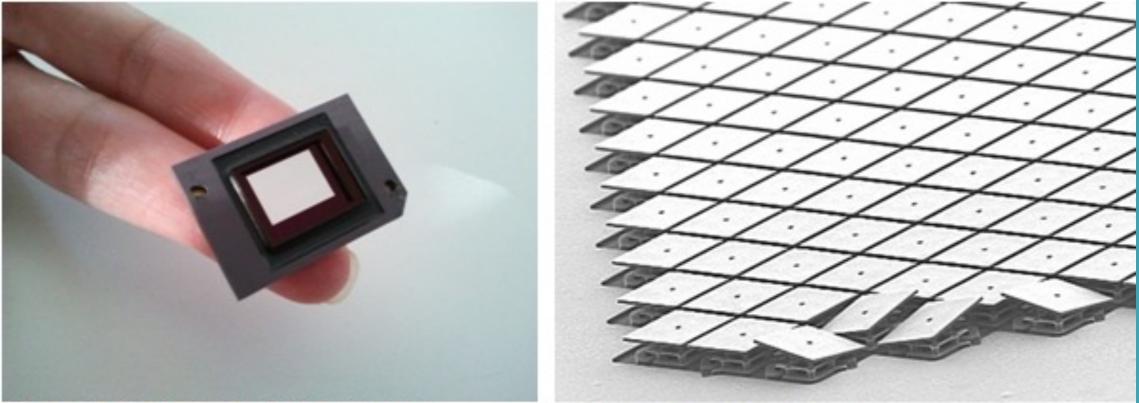
Space Telescope Science Institute

and

Johns Hopkins Universtity

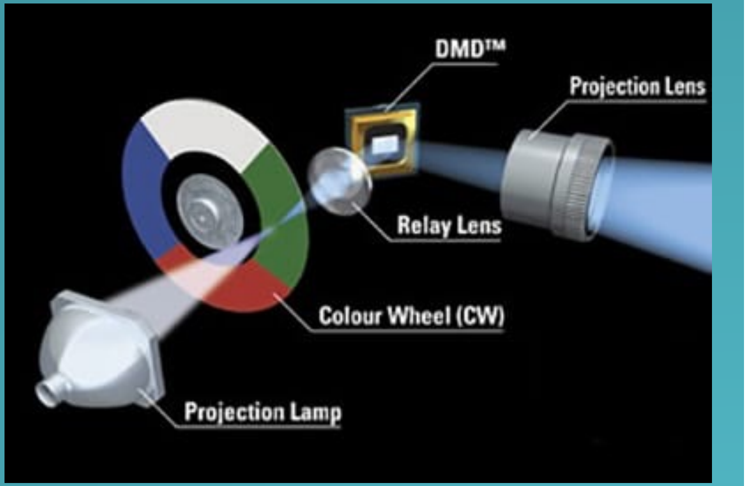
What is a Digital Micromirror Device?

- A DMD is a MEM's device comprising of an array of thousands of mirrors, each of which can be biased electrostatically to one of two fixed angular positions – typically +/- 12° from nominal



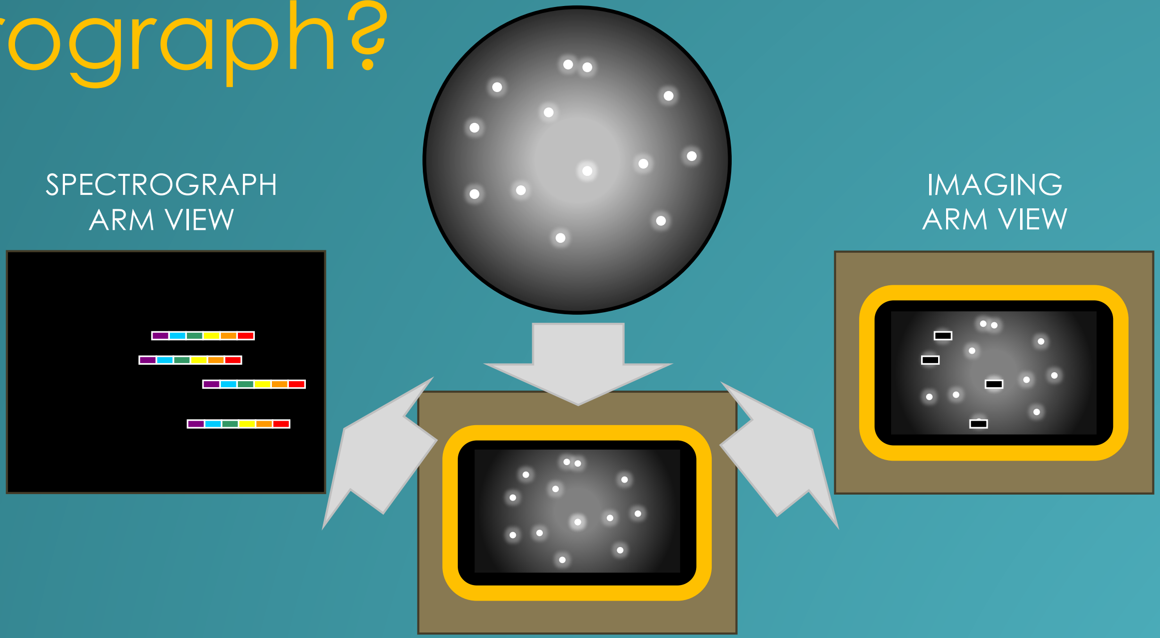
DIGITAL MICRO MIRROR DEVICE **(DMD)**
(**SLM** - Spatial Light Modulator)

MICRO MIRRORS CLOSE UP

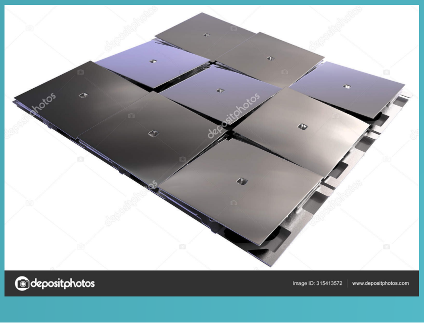


Basic DLP projector

How is a DMD used in a spectrograph?



- An image of interest is projected onto the DMD
- DMD mirrors are configured to form a slit mask
- Light from objects of interest is directed toward a spectral arm
- The remaining image is directed toward an imaging arm



1996: after ~15 years of research TI makes DMD commercially available

1981

(Hornbeck, TI Technical Journal, Jul-Sep. 1998, p.31)

LARGE FORMAT!
SVGA (800x600)
SXGA (1280x1024)

... but LOW CONTRAST

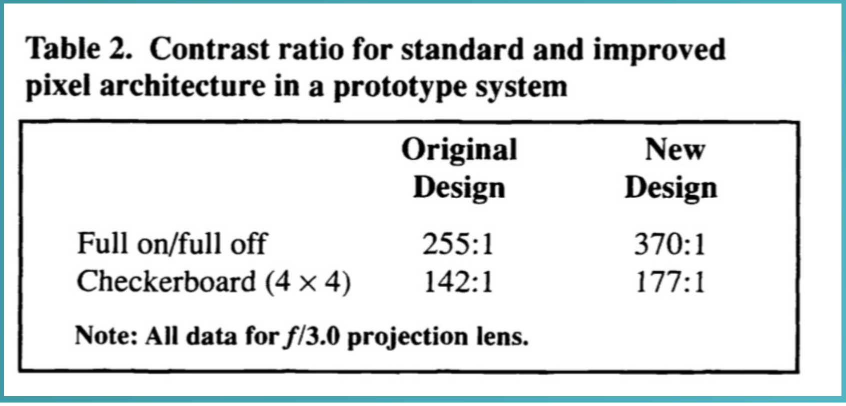


Table 2. Contrast ratio for standard and improved pixel architecture in a prototype system

	Original Design	New Design
Full on/full off	255:1	370:1
Checkerboard (4 × 4)	142:1	177:1

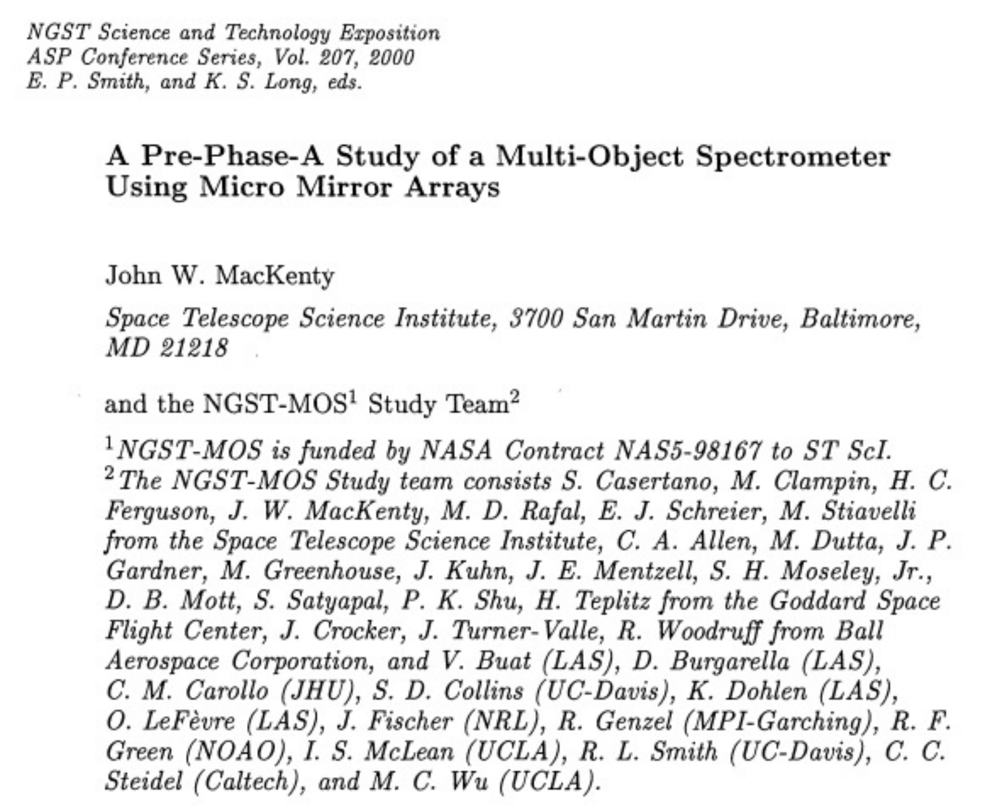
Note: All data for *f*/3.0 projection lens.

1996: astronomers take notice

(John Mackenty at STScI)

- 1996: NGST yardstick concept
- 1997: MIROS - next gen. HST instrument proposal
- ~1998: NASA funds pre-phase-A study
  - IR Multi-object spectrograph for NGST
  - Development of Micro-Mirrors for space applications
- 1998: concept of IRMOS ground-based near-IR spectrograph based on Texas Instrument DMD
  - Funded by GSFC, STScI, KPNO - PI J. MacKenty

Goddard develops Micro Mirror Arrays for NGST



NGST Science and Technology Exposition
ASP Conference Series, Vol. 207, 2000
E. P. Smith, and K. S. Long, eds.

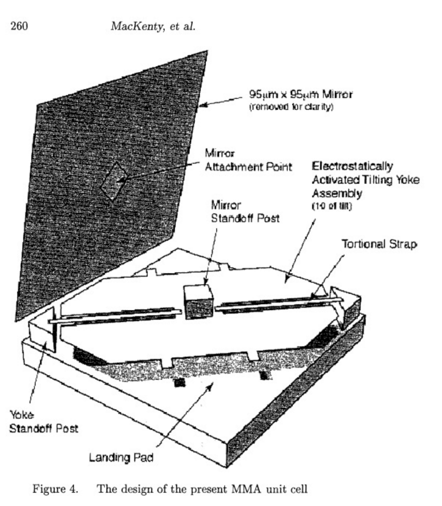
A Pre-Phase-A Study of a Multi-Object Spectrometer Using Micro Mirror Arrays

John W. MacKenty

Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218

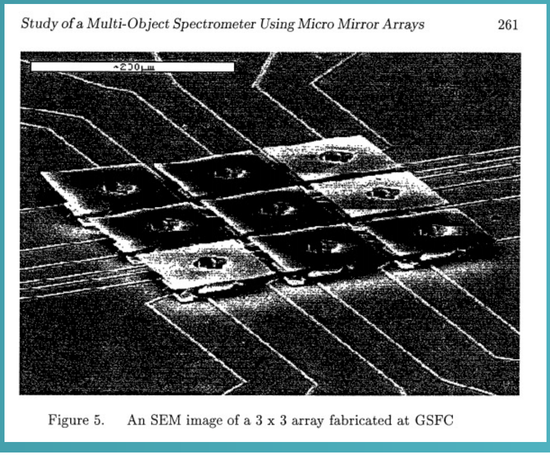
and the NGST-MOS[1] Study Team[2]

[1] *NGST-MOS is funded by NASA Contract NAS5-98167 to ST ScI.*
[2] *The NGST-MOS Study team consists S. Casertano, M. Clampin, H. C. Ferguson, J. W. MacKenty, M. D. Rafal, E. J. Schreier, M. Stiavelli from the Space Telescope Science Institute, C. A. Allen, M. Dutta, J. P. Gardner, M. Greenhouse, J. Kuhn, J. E. Mentzell, S. H. Moseley, Jr., D. B. Mott, S. Satyapal, P. K. Shu, H. Teplitz from the Goddard Space Flight Center, J. Crocker, J. Turner-Valle, R. Woodruff from Ball Aerospace Corporation, and V. Buat (LAS), D. Burgarella (LAS), C. M. Carollo (JHU), S. D. Collins (UC-Davis), K. Dohlen (LAS), O. LeFèvre (LAS), J. Fischer (NRL), R. Genzel (MPI-Garching), R. F. Green (NOAO), I. S. McLean (UCLA), R. L. Smith (UC-Davis), C. C. Steidel (Caltech), and M. C. Wu (UCLA).*



260 *MacKenty, et al.*

Figure 4. The design of the present MMA unit cell



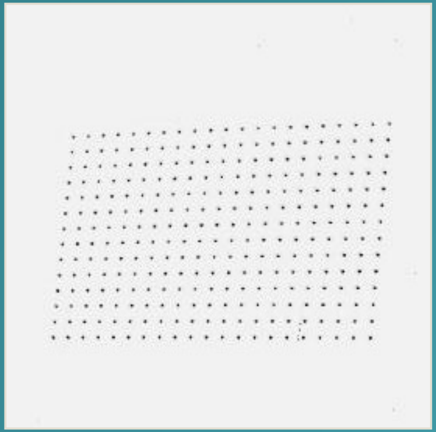
Study of a Multi-Object Spectrometer Using Micro Mirror Arrays 261

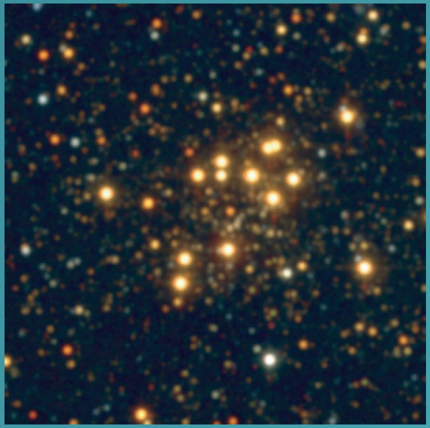
Figure 5. An SEM image of a 3 x 3 array fabricated at GSFC

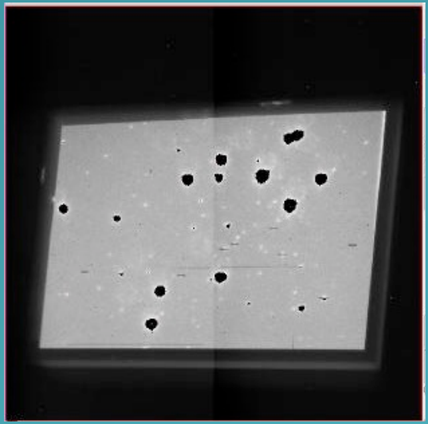
100 micron size
Contrast a concern
(1:2000 requirement)

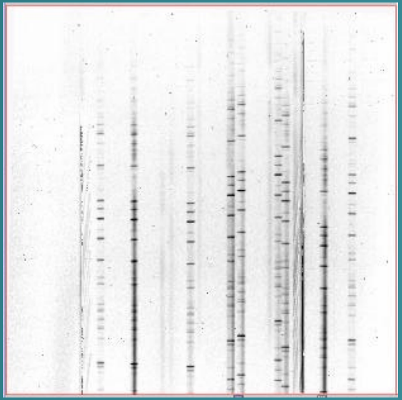
2004: IRMOS at KPNO demonstrates the potential of DMD based instruments

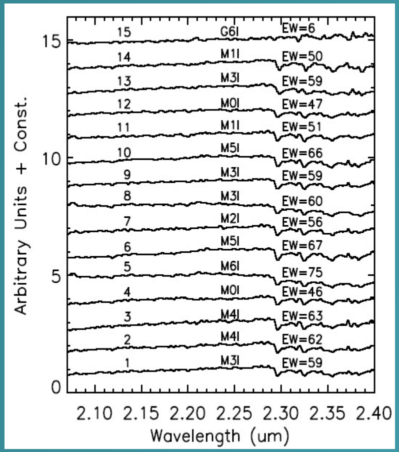
Figure 8: Texas Instruments DMD in test dewar operating at -50C in IRMOS custom socket (without baffle). Note Lakeshore thermal diode mounted at top.

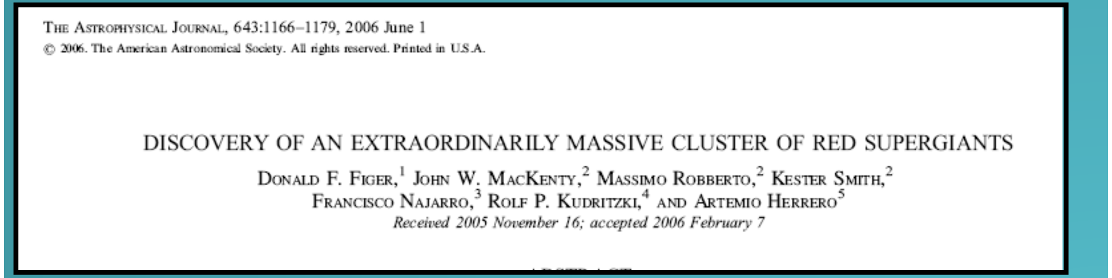












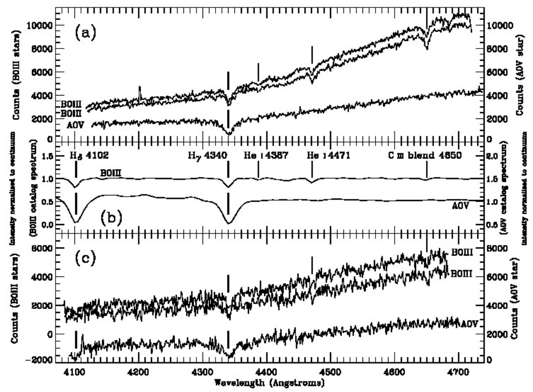
The Astrophysical Journal, 643:1166–1179, 2006 June 1

DISCOVERY OF AN EXTRAORDINARILY MASSIVE CLUSTER OF RED SUPERGIANTS

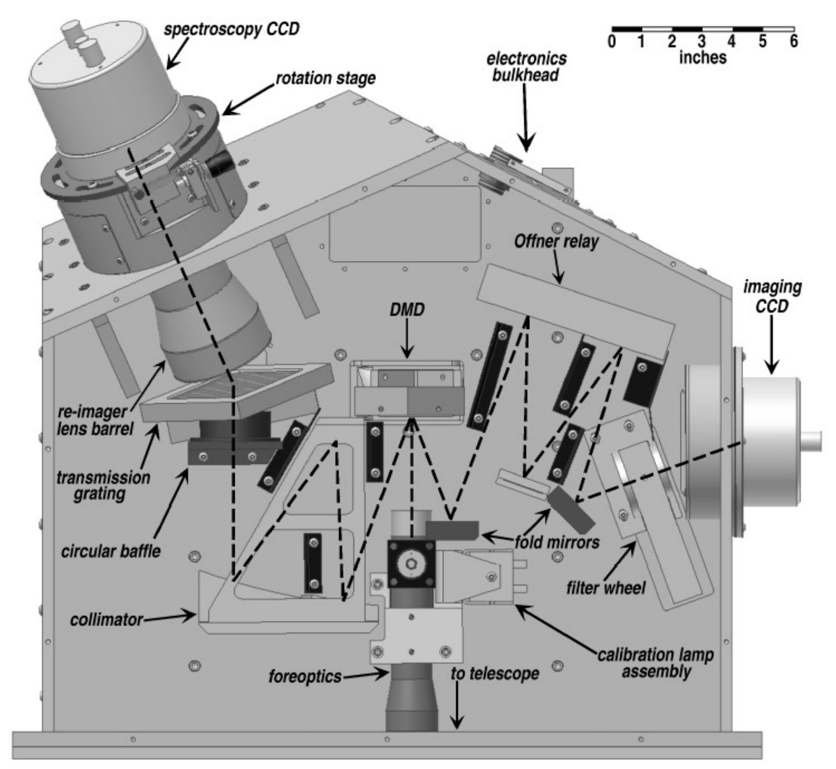
Donald F. Figer,[1] John W. MacKenty,[2] Massimo Robberto,[2] Kester Smith,[2]
Francisco Najarro,[3] Rolf P. Kudritzki,[4] and Artemio Herrero[5]

Received 2005 November 16; accepted 2006 February 7

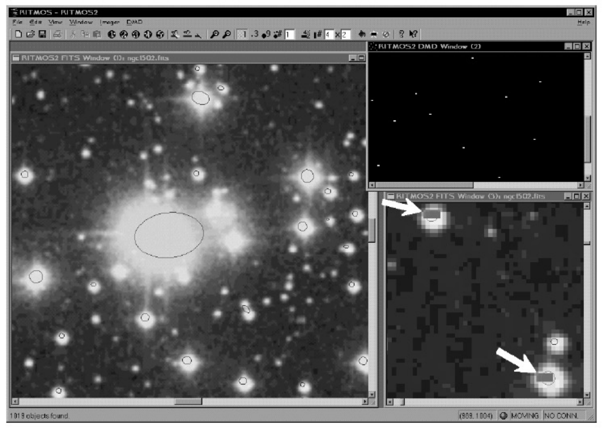
2003: RITMOS
demonstrates the “dual mode” of DMDs



Spectroscopic Channel



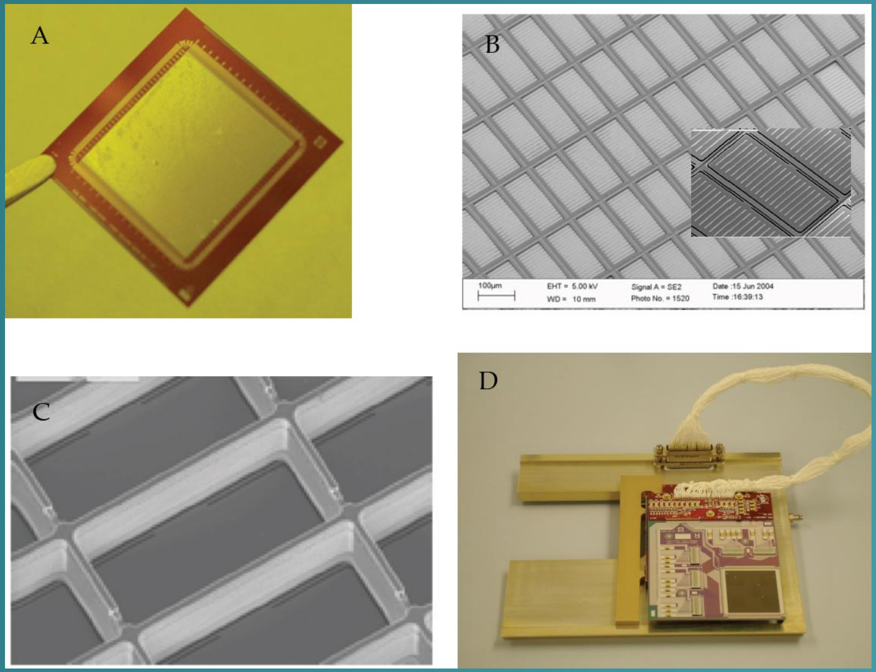
Imaging Channel



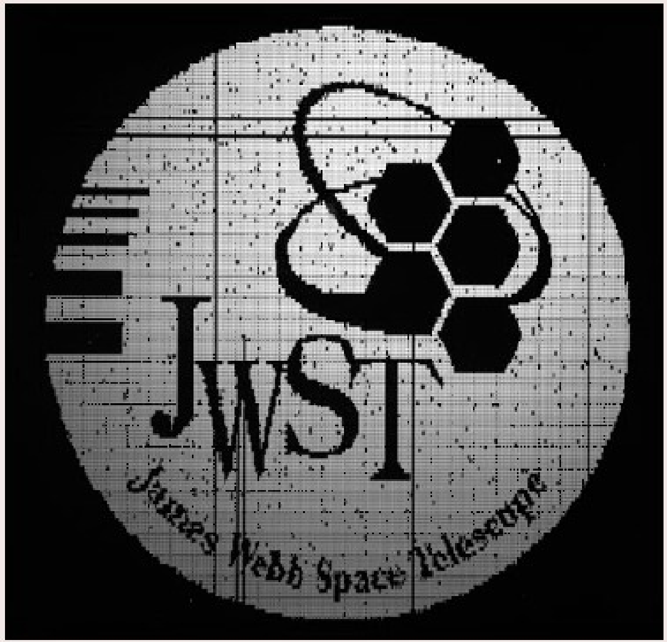
based on a TI DMD
of 848×600 elements

Meyer et al., Proc. SPIE 492 (2004)

January 23, 2002: NASA selects micro-shutter technology (MSA) for NGST NIRSpec



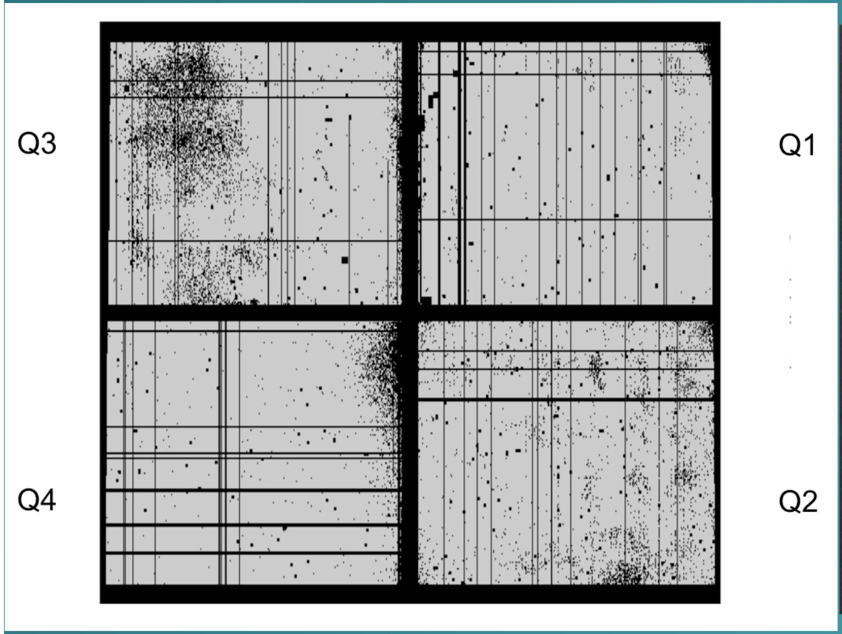
171x365 elements
100 x 200 micron



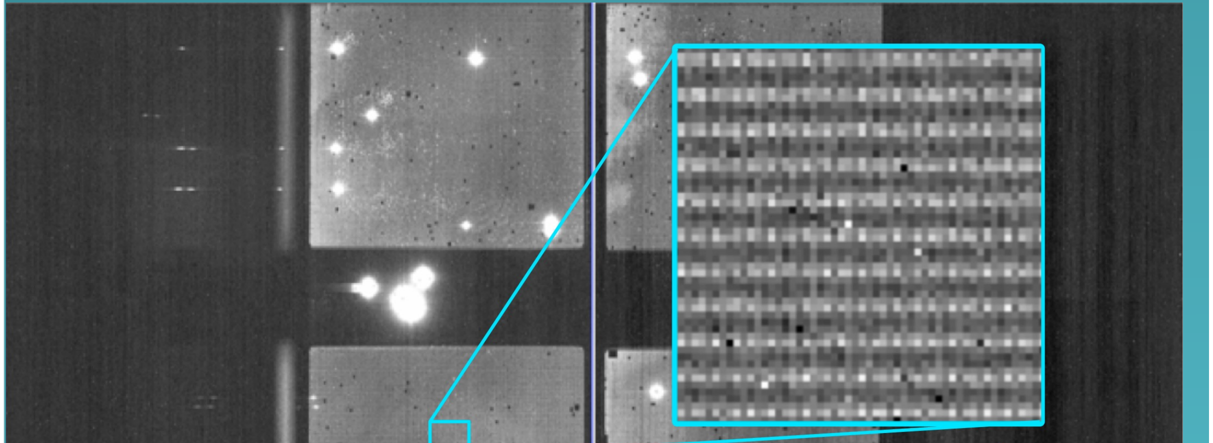
Actual MSA performance for JWST/NIRSpec

Open Area Fill Factor: 62.1%

15% failed closed



<20 failed open



Detector NRS1

Next Generation 840x420 elements

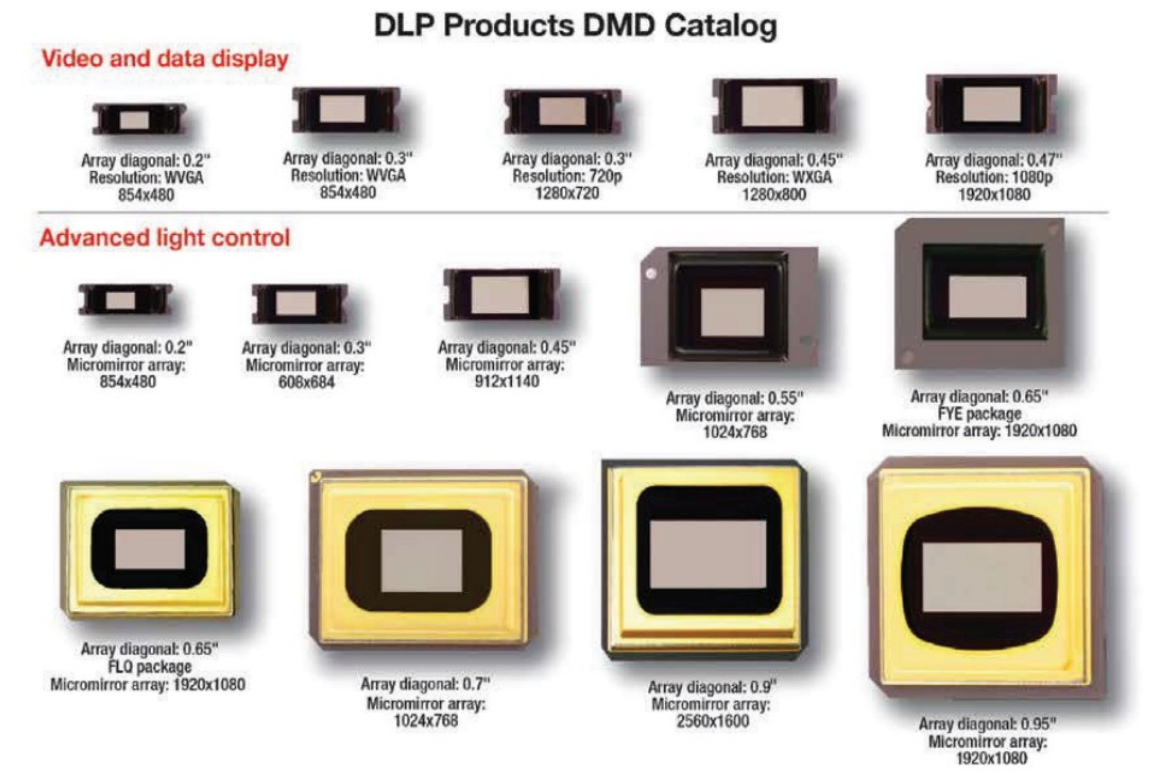
“MSA flux leakage can accumulate to a level that is closer t

https://jwst-docs.stsci.edu/near-infrared-spectrograph/nirspec-instrument

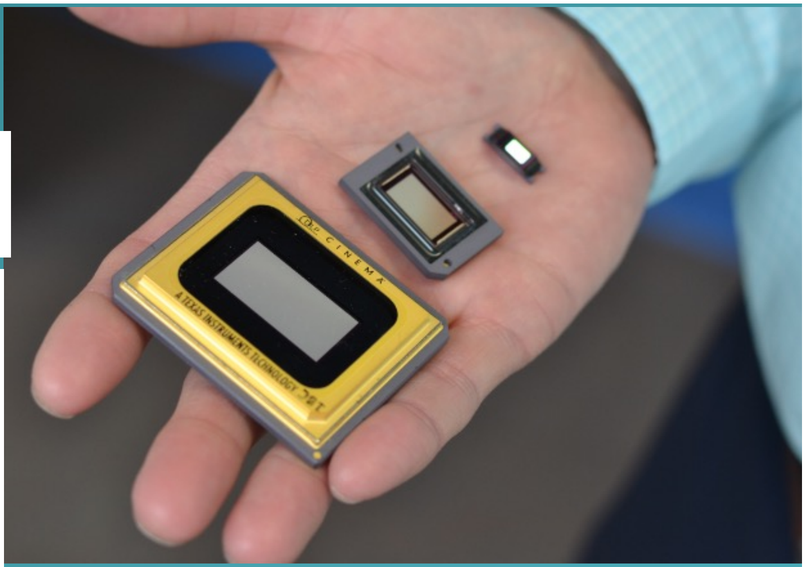
TI development of DMDs

DMD reliability: a MEMS success story

Michael R. Douglass SPIE 4980 (2003)



~40 millions produced by 2016

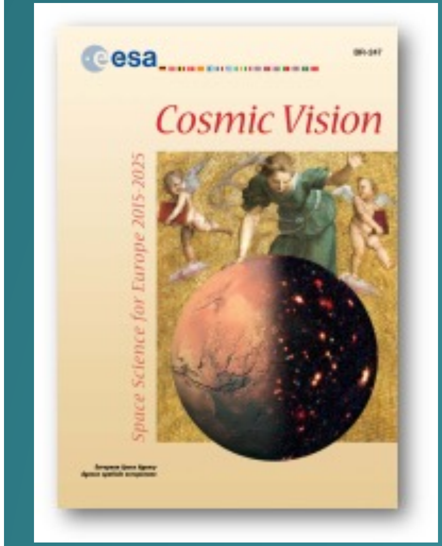


2003: Digital Cinema DC2K DMD

2048 x 1080 mirrors
13.7 micron
12° tilt

JOHNS HOPKINS
UNIVERSITY

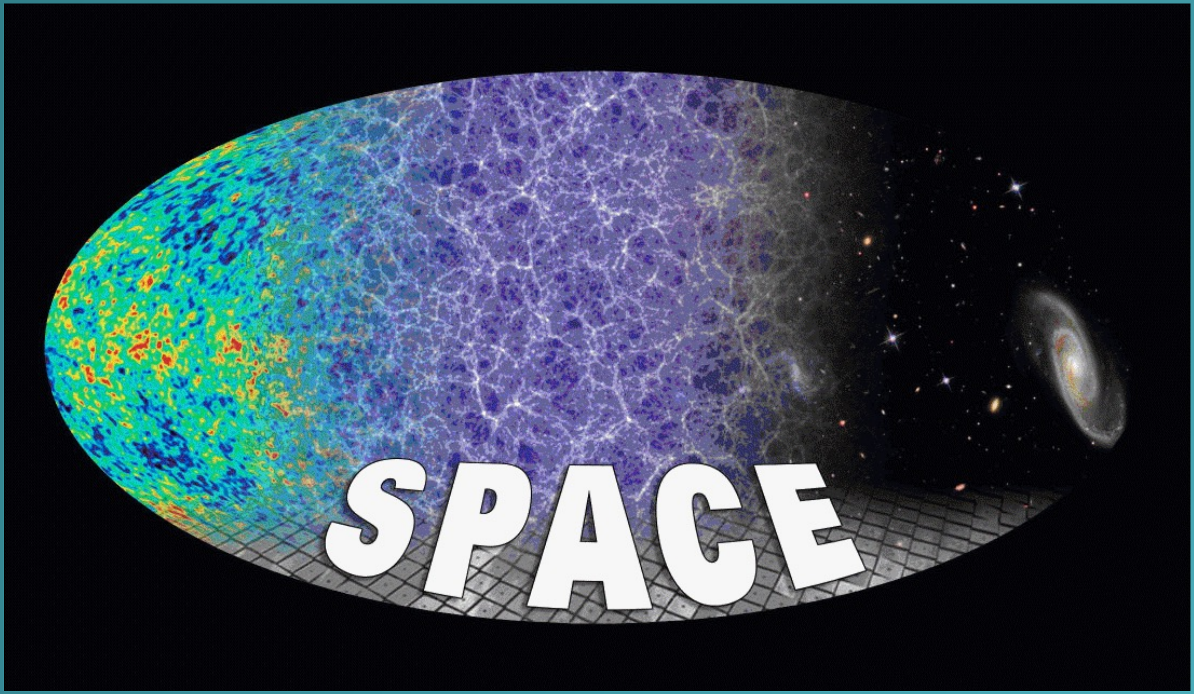
2006-2008



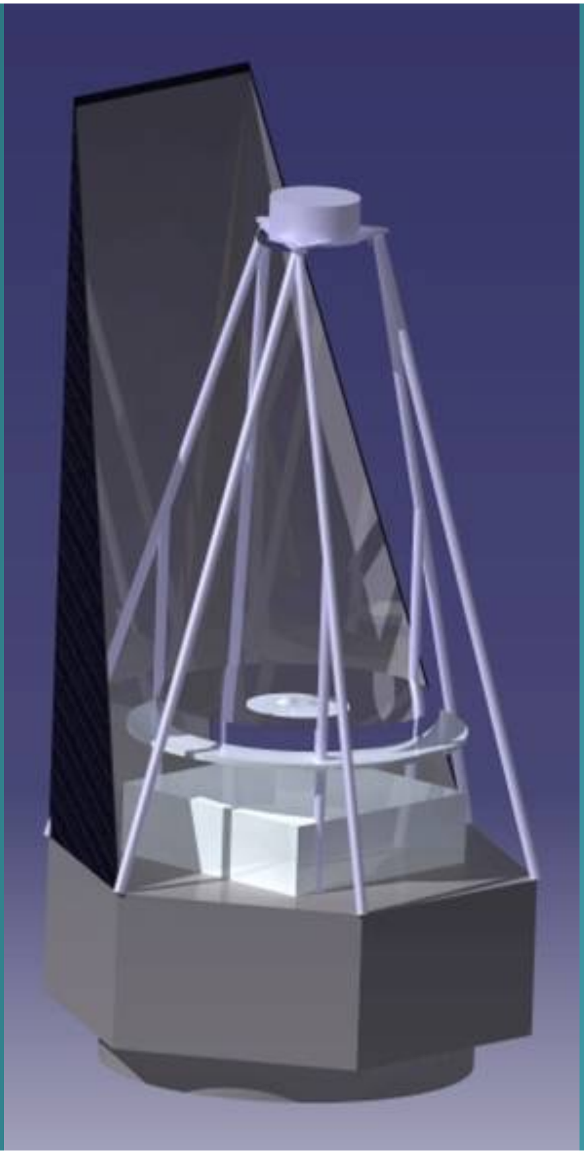
esa

Cosmic Vision

Space Science for Europe 2015-2025



SPectroscopic **A**ll-sky **C**osmic **E**xplorer



SPACE MISSION SUMMARY

Telescope diameter	***1.5m***
Optical configuration	*Ritchey-Chrétien*
Wavelength range	***0.6 - 1.8 μm***
Optical quality	*Diffraction limited $\lambda > 0.65 \mu m$*
Pointing stability	*0.1" rms/ 30min*
Overall mass	*1486 kg*
Data rate	*1.5Mbit/s*
Orbit/Launcher	*L2/Soyuz*
Launch date	*Mid 2017*
Mission Duration	*5 years*
Partners	*ESA-NASA-* *European Agencies*

SPACE INSTRUMENT PERFORMANCE

Total field of view	***51' x 27' (0.4 sq. degrees)***
Nr. and type of DMDs	*4 CINEMA chip (2048x1080)*
Total nr. of mirrors	***8.8 million***
Mirror field of view	*0.75" x 0.75"*
Number of spectra	*~* ***6,000 simultaneous***
Detector Pixel size	*0.375" x 0.375"*
Dispersing element	*Prism* ***R~400; 0.8-1.8μm***
Imaging filters	***z, J, H, narrow band***
Detector	*HgCdTe 0.4-1.8μm, 2k x 2k*
Nr. of detectors	*16 (4 mosaics of 2x2 chips)*
Detector Temperature	*~145 K*
QE	*>75% average*
Readout noise	*$5e^-$/multiple read*
Observing modes	***Broad- and narrow-band imaging, multi-slit, slitless spectroscopy***

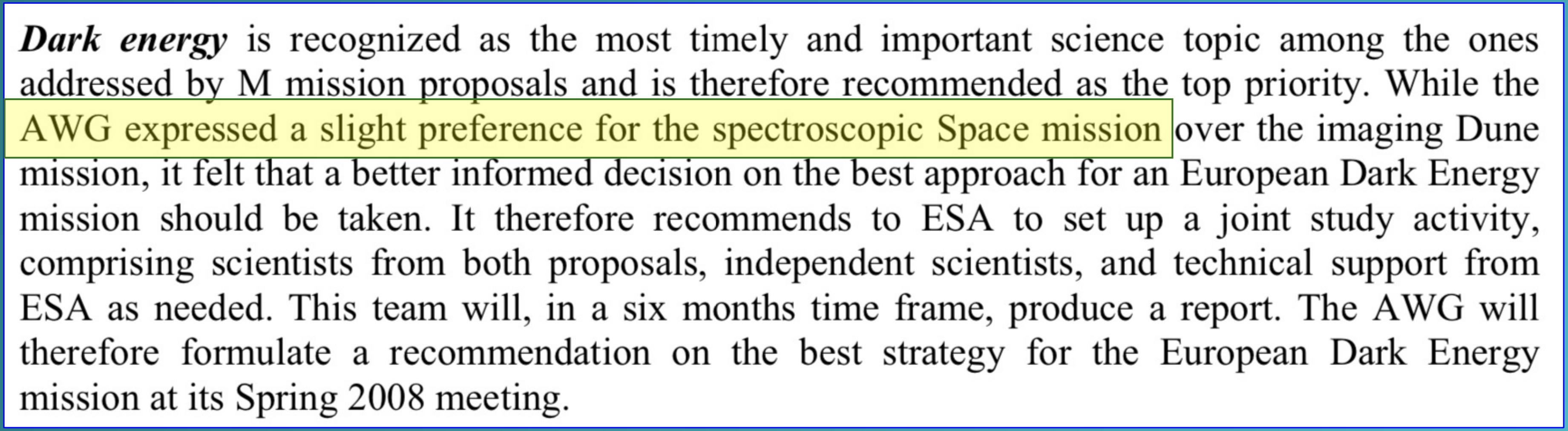
Astronomers liked it…

Paris, 29 October 2007
(Original : English)

EUROPEAN SPACE AGENCY

SCIENCE PROGRAMME COMMITTEE

Cosmic Vision Call cycle1: Selection of mission proposals for assessment/technology studies



Dark energy is recognized as the most timely and important science topic among the ones addressed by M mission proposals and is therefore recommended as the top priority. While the AWG expressed a slight preference for the spectroscopic Space mission over the imaging Dune mission, it felt that a better informed decision on the best approach for an European Dark Energy mission should be taken. It therefore recommends to ESA to set up a joint study activity, comprising scientists from both proposals, independent scientists, and technical support from ESA as needed. This team will, in a six months time frame, produce a report. The AWG will therefore formulate a recommendation on the best strategy for the European Dark Energy mission at its Spring 2008 meeting.

…but it was too early

2010: ESA supports evaluation tests on DMDs

Space evaluation of 2048x1080 mirrors DMD chip for ESA EUCLID mission

Frederic Zamkotsian[1], Patrick Lanzoni[1], Emmanuel Grassi[1], Rudy Barette[1], Christophe Fabron[1],
Kyrre Tangen[2], Luca Valenziano[3], Laurent Marchand[4], Ludovic Duvet[4]

Proc. of SPIE Vol. 7731 773130-1

See F. Zamkotsian talk tomorrow

Tested

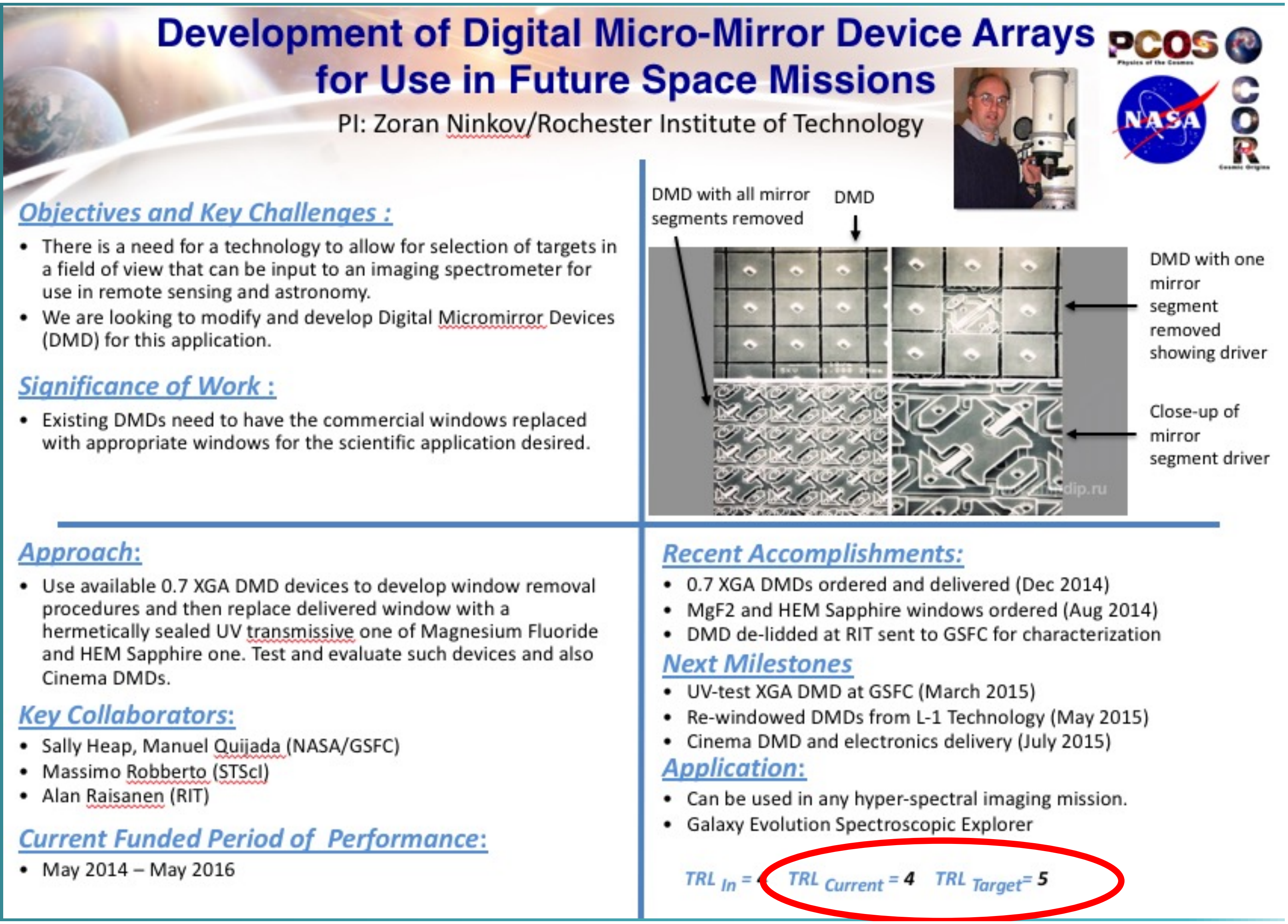
- Thermal: operational at -40C
- Total ionizing dose: operational up to 10-15Krads
- Single Proton: no failures observed (short test)
- Vibration and shock: no degradation following stress tests
- Contrast: 2,250:1 at f/3

Conclusion

"[…] These results do not reveal any show-stopper concerning the ability of the DMD to meet environmental space requirements. […]"

2013:

NASA SAT (Strategic Astrophysics Technology) program begins support of DMD space qualification tests



Development of Digital Micro-Mirror Device Arrays for Use in Future Space Missions

PI: Zoran Ninkov/Rochester Institute of Technology

Objectives and Key Challenges :

- There is a need for a technology to allow for selection of targets in a field of view that can be input to an imaging spectrometer for use in remote sensing and astronomy.
- We are looking to modify and develop Digital Micromirror Devices (DMD) for this application.

Significance of Work :

- Existing DMDs need to have the commercial windows replaced with appropriate windows for the scientific application desired.

DMD with all mirror segments removed

DMD

DMD with one mirror segment removed showing driver

Close-up of mirror segment driver

Approach:

- Use available 0.7 XGA DMD devices to develop window removal procedures and then replace delivered window with a hermetically sealed UV transmissive one of Magnesium Fluoride and HEM Sapphire one. Test and evaluate such devices and also Cinema DMDs.

Key Collaborators:

- Sally Heap, Manuel Quijada (NASA/GSFC)
- Massimo Robberto (STScI)
- Alan Raisanen (RIT)

Current Funded Period of Performance:

- May 2014 – May 2016

Recent Accomplishments:

- 0.7 XGA DMDs ordered and delivered (Dec 2014)
- MgF2 and HEM Sapphire windows ordered (Aug 2014)
- DMD de-lidded at RIT sent to GSFC for characterization

Next Milestones

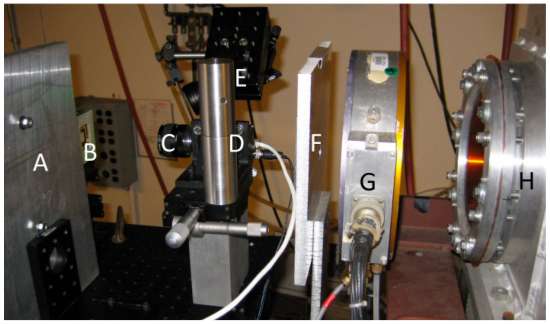
- UV-test XGA DMD at GSFC (March 2015)
- Re-windowed DMDs from L-1 Technology (May 2015)
- Cinema DMD and electronics delivery (July 2015)

Application:

- Can be used in any hyper-spectral imaging mission.
- Galaxy Evolution Spectroscopic Explorer

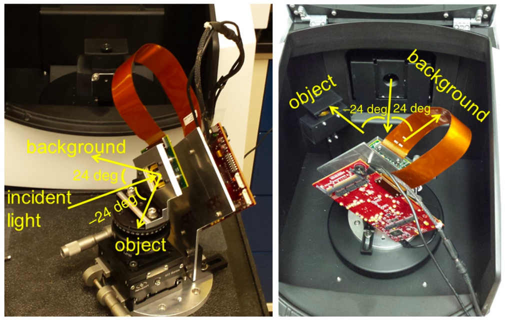
$TRL_{In} = 4$ $TRL_{Current} = 4$ $TRL_{Target} = 5$

Snapshots from the test facilities

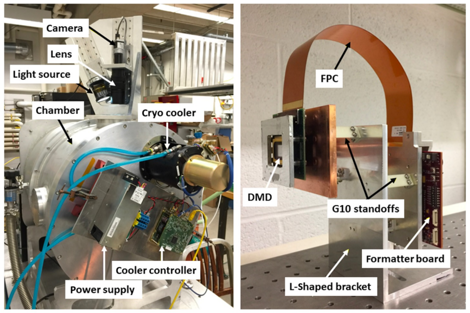


Radiation (LBNL, Texas A&M,NASA/GSFC)

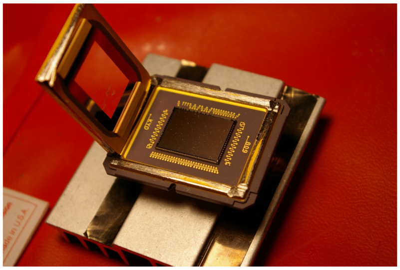
Vibration (RIT)



Scattering (GSFC)



Cryogenics (JHU)

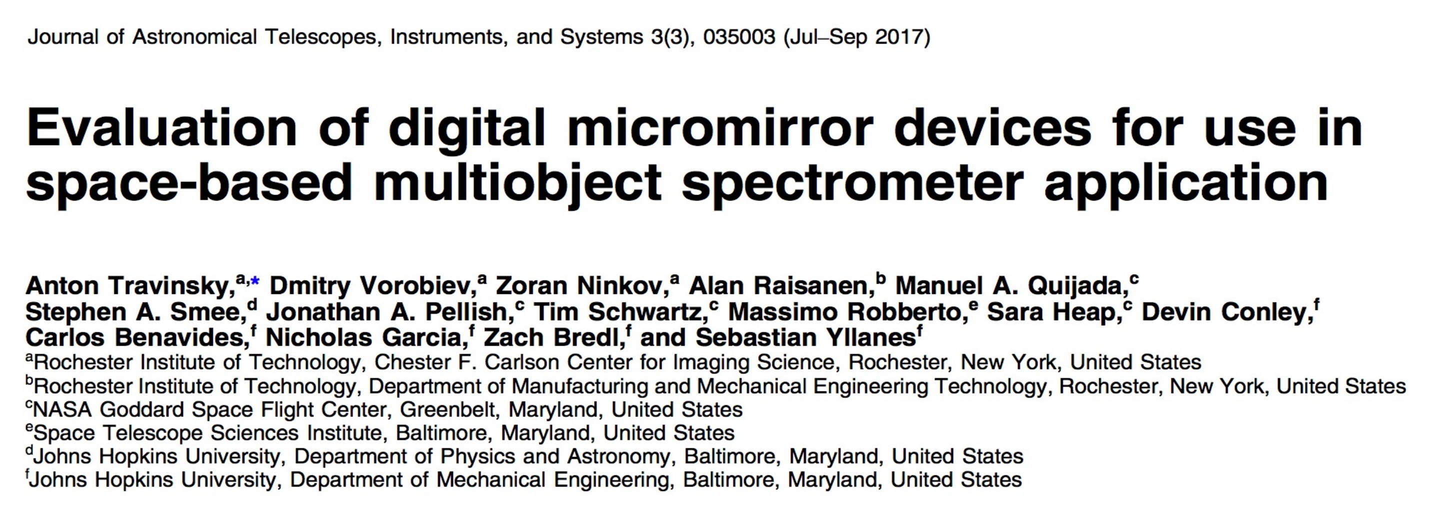


window replacement (RIT)

XGA DMDs (768 x 1024) space-qualification program led by RIT

- ***Proton Radiation*** *Testing of Digital Micromirror Devices for Space Applications*, Fourspring et al., Opt.Eng. 52,9 (2013)
- *The effects of **gamma radiatio**n on digital micromirror devices*, Oram et al. SPIE 10932, (2019)
- ***Total ionizing dose*** *effects on digital micromirror devices*, Oram et al. JATIS, 6 045006 (2020)
- ***Shock and vibration testing*** *of digital micromirror devices (DMDs) for space-based applications*, Vorobiev et al. SPIE 9912, 2016
- *Measurements of the **reflectance, contrast ratio, and scatterin**g properties of digital micromirror devices (DMDs)*, Vorobiev et al. SPIE 9912, 2016
- *Optical evaluation of digital micromirror devices (DMDs) with **UV-grade fused silica, sapphire, and magnesium fluoride windows and long-term reflectance of bare device**s*, Quijada et al., SPIE 9912, 2016
-

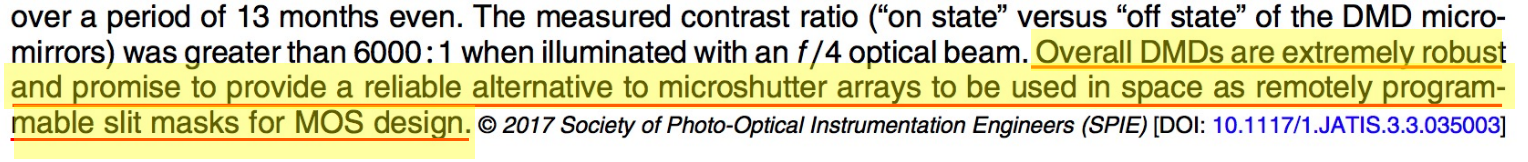
DMD Testing confirm TRL 5



Journal of Astronomical Telescopes, Instruments, and Systems 3(3), 035003 (Jul–Sep 2017)

Evaluation of digital micromirror devices for use in space-based multiobject spectrometer application

Anton Travinsky,[a,*] Dmitry Vorobiev,[a] Zoran Ninkov,[a] Alan Raisanen,[b] Manuel A. Quijada,[c]
Stephen A. Smee,[d] Jonathan A. Pellish,[c] Tim Schwartz,[c] Massimo Robberto,[e] Sara Heap,[c] Devin Conley,[f]
Carlos Benavides,[f] Nicholas Garcia,[f] Zach Bredl,[f] and Sebastian Yllanes[f]
[a]Rochester Institute of Technology, Chester F. Carlson Center for Imaging Science, Rochester, New York, United States
[b]Rochester Institute of Technology, Department of Manufacturing and Mechanical Engineering Technology, Rochester, New York, United States
[c]NASA Goddard Space Flight Center, Greenbelt, Maryland, United States
[e]Space Telescope Sciences Institute, Baltimore, Maryland, United States
[d]Johns Hopkins University, Department of Physics and Astronomy, Baltimore, Maryland, United States
[f]Johns Hopkins University, Department of Mechanical Engineering, Baltimore, Maryland, United States



over a period of 13 months even. The measured contrast ratio (“on state” versus “off state” of the DMD micromirrors) was greater than 6000 : 1 when illuminated with an $f/4$ optical beam. Overall DMDs are extremely robust and promise to provide a reliable alternative to microshutter arrays to be used in space as remotely programmable slit masks for MOS design. [DOI: 10.1117/1.JATIS.3.3.035003]

Current TRL for DMDs

We expect COTS XGA DMDs (768 x 1024 mirrors), will be certified at TRL 6.

ATLAS requires DC2K (Cinema) arrays (1024 x 2048 mirrors),

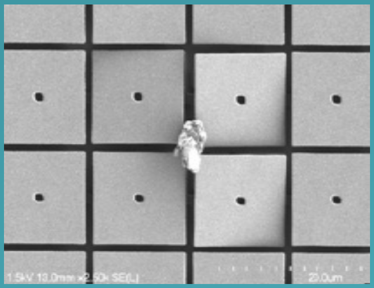
\+ Identical architecture as XGA DMDs

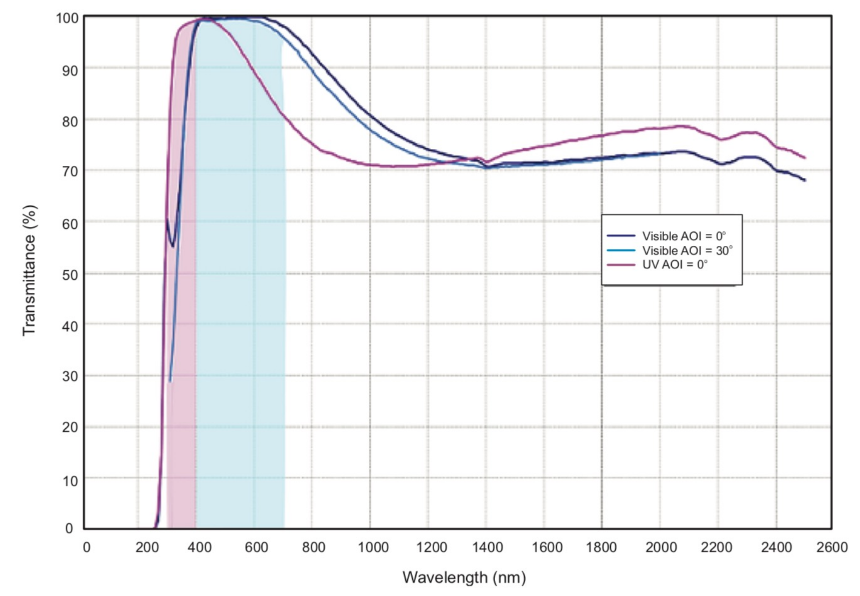
However

- DC2K have not passed the same level of testing
- Non-VIS applications require window replacement

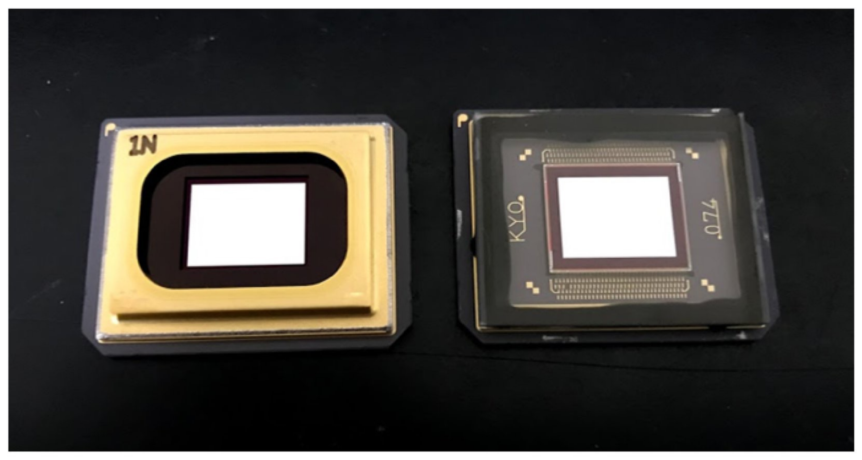
Window replacement

- DMD are packaged with a Borosilicate window with A/R thin film coating.
- DC2K DMDs are optimized for visible light 400-700nm
- Transmission drops significantly in the near-IR
- TI does not customize window coating of DC2K DMDs.





We have developed the capability of replacing the DMD window.

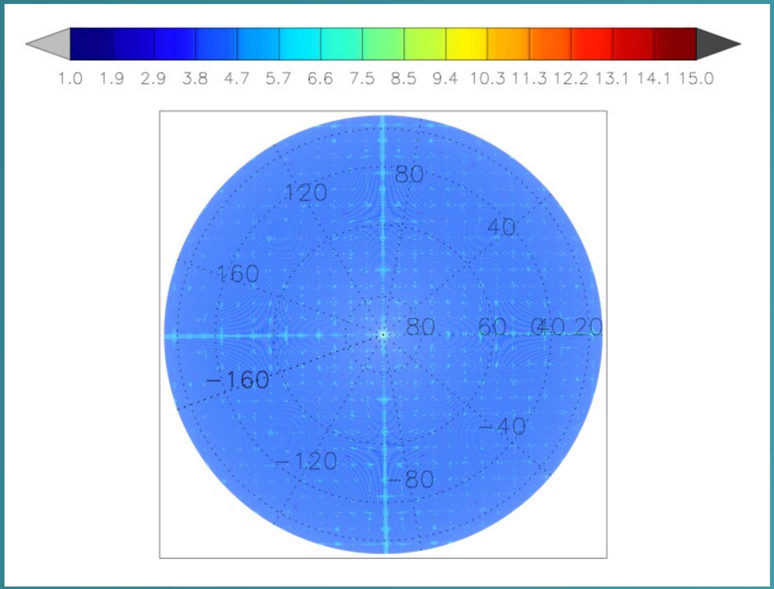


COTS XGA DMD (left) and a re-windowed DMD (right) that has had its original borosilicate window replaced with a sapphire window.

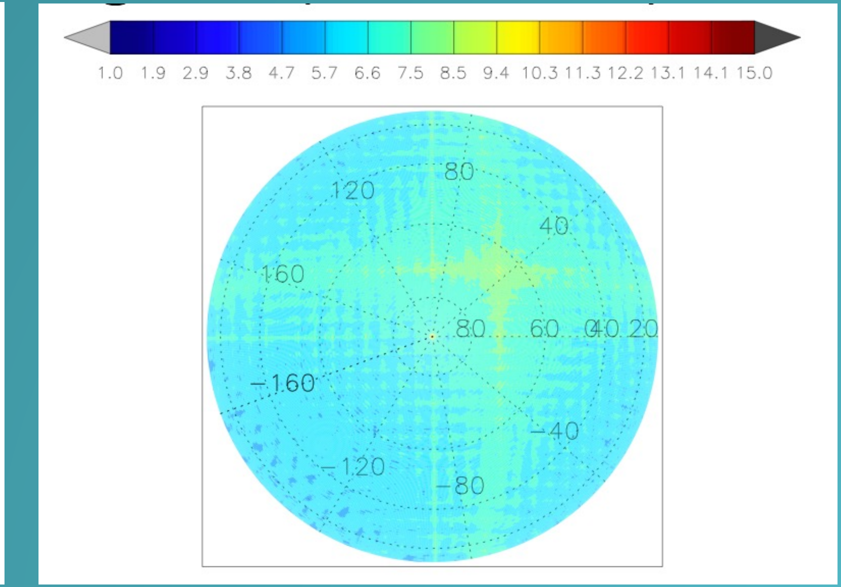
Contrast: Diffraction and Scattering

DMDs can modeled as a double-ruled diffraction grating with 12° blazing at 45° tilt

Diffraction in case of Normal illumination



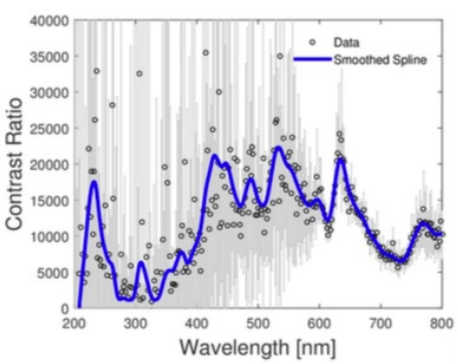
Orthogonal grid
(DMD in flat state)



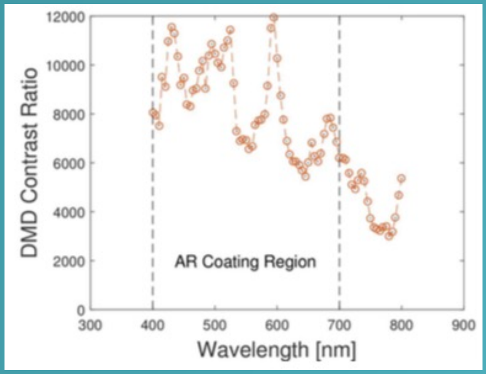
Blazed orthogonal grid
(DMDs at 24deg tilt)

Scattering

- Hard to measure: Generally compounded with diffraction in standard "flat illumination" measures: historic DMD "contrast" issue.



f/10 beam, no window

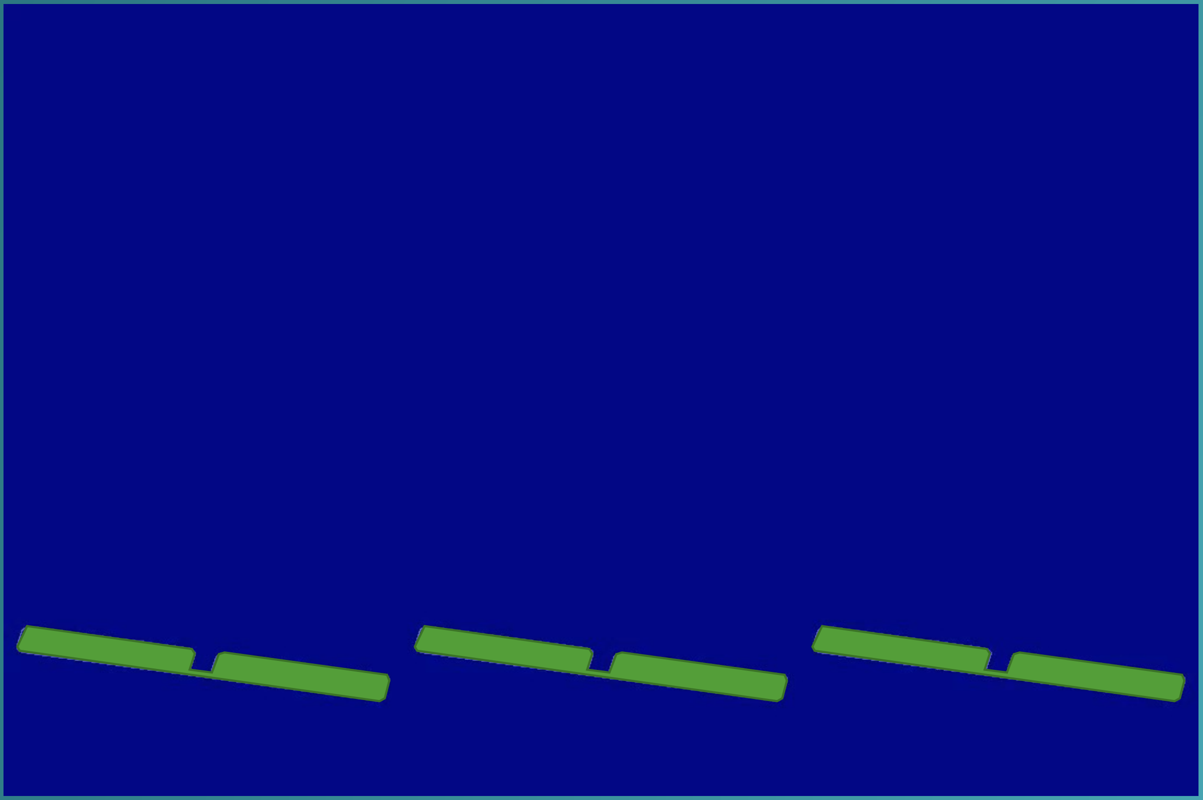


f/3.5 beam, BK7 window

(original NGST requirement >2500)

Vorobiev et al. 2016, SPIE 9912, 99125U

Lumerical modeling: electric field from a wavepacket incident an array of DMDs titled 12deg



Model Parameters

Pitch (mirror): 13.68 µm

Width (mirror): 13.143 µm

Width (via): 0.75 µm

Depth (via): 1.75 um

Radius (edge): 0.4 µm

Fill factor: 92%

Simulation Parameters

Width (X): 58.04 µm

Width (Y): 58.04 µm

Height (Z): 100 µm

Wavelength: 4.0 µm

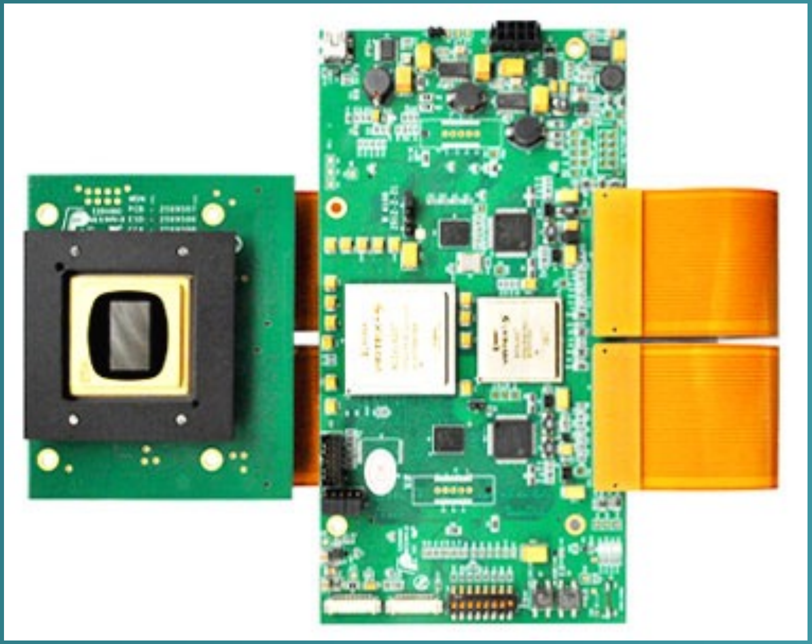
f-number: 4

Width (PSF): 39.04 µm

J. Piotrowski, JHU

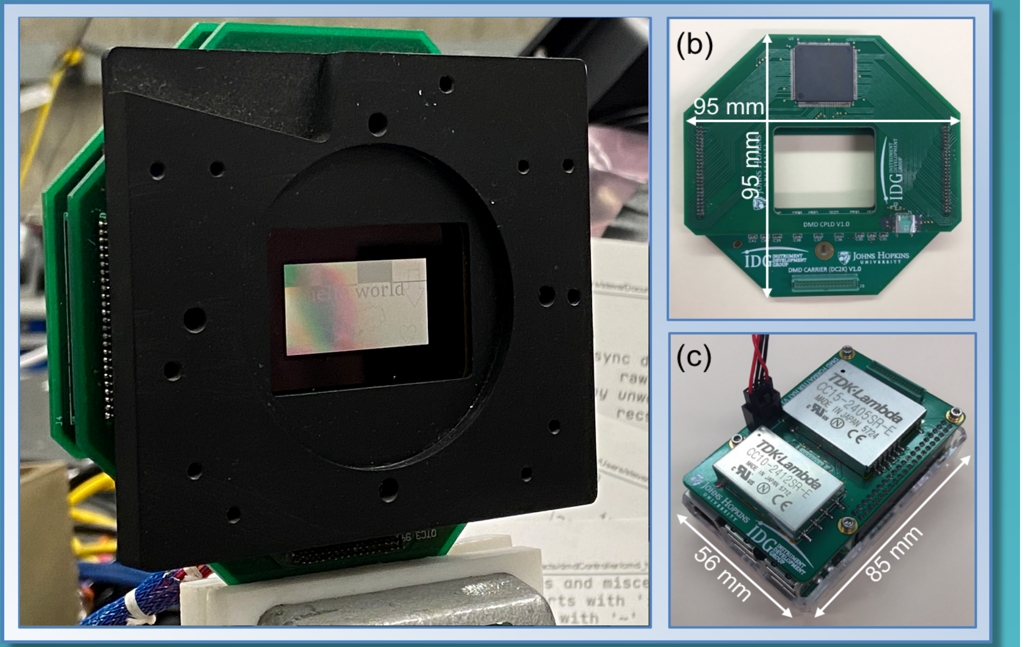
Electronics and control

- The typical DMD driving board



Wintech DLP W4100

- New JHU control board



Performance Metrics

- Hear dissipation in the full DC2K DMD has been reduced to <3% of a standard controller
- Conductive heat load from wiring has been reduced to <4% of a standard controller, based on reduced wire count and increased wire length

Parameter	**IDGs full HD DMD Controller**	**Third Party Controller using TI's full HD Chipset**
DMD Power Dissipation:	< 50 mW (Includes both the DMD and the CPLD. Measured while idle)	1.8 W (DMD only per TI specifications)
Number of wires between the DMD controller and the DMD carrier assembly:	36 Note: The current controller uses 36 conductors, however, this could potentially be reduced to 20	300 (Comprised of 3, 100 conductor ribbon cables)
Length of wiring:	1000 mm	300 mm

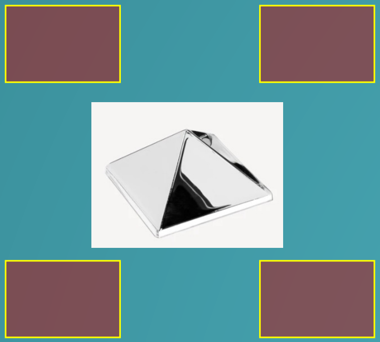
Enables IR spectrographs
⇒ Extreme AO
  - SAMOS @ SOAR (GLAO)
  - GMOX @ Gemini (MCAO)

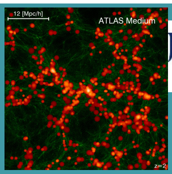
Know-how in hand to build radiation-hard version

Last constraint: DMDs cannot be physically butted together

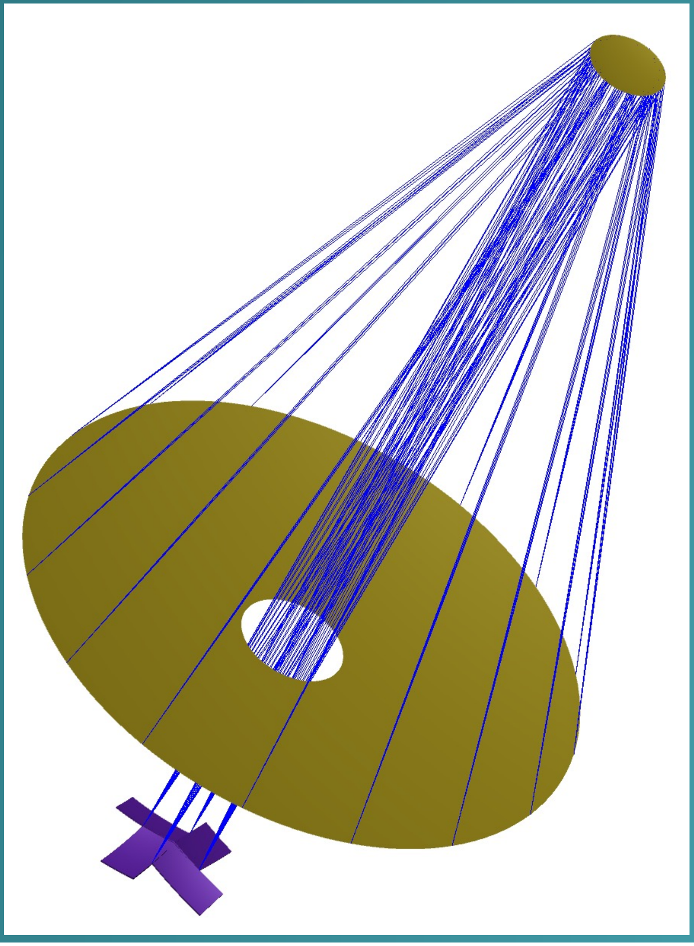
Last constraint: DMDs cannot be physically butted together

~20% filling factor of a focal plane

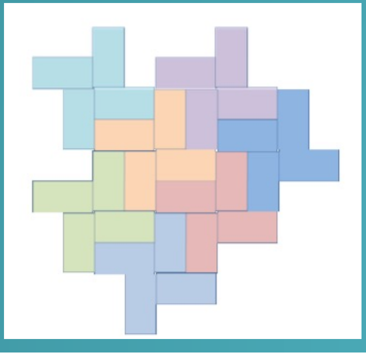




Telescope and pyramid mirror

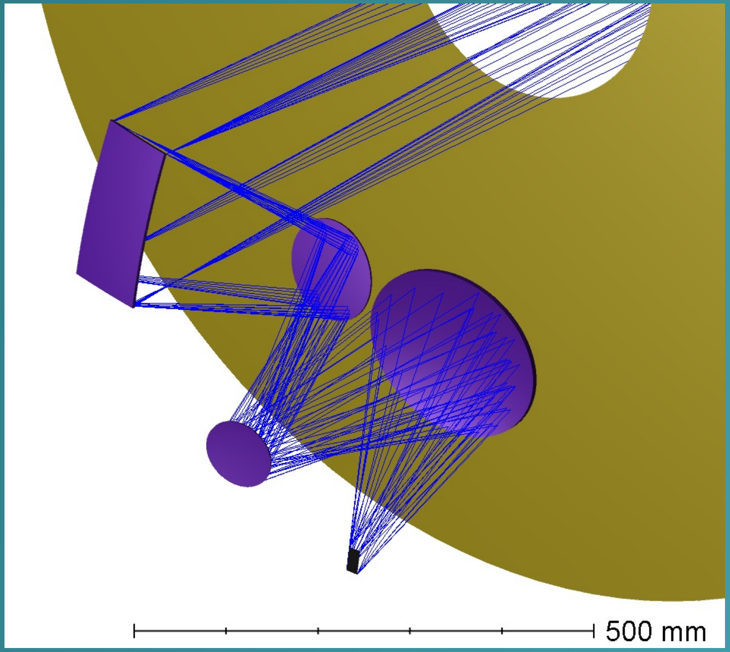


- Diameter: 1.5-m
- Focal Ratio f/15.3
- Ffl = 23 m, scale = 8.968 arcsec/mm
- Design: modified Ritchey-Chrétien.
- Small aspheric secondary 274 mm dia
- Hole in M1 is 340 mm
- Areal fill factor: 94.8%



tiling pattern
DMD Aspect Ratio
1.896:1
1 dither move needed
for 100% field coverage

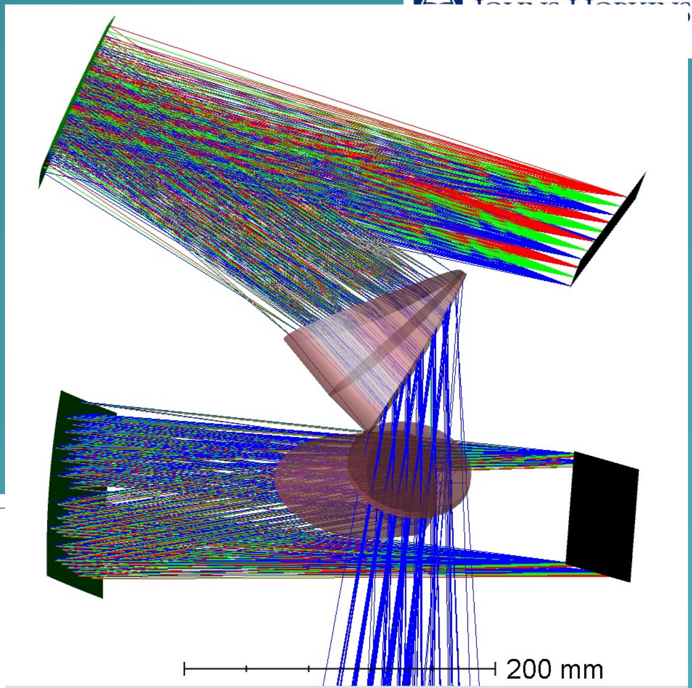
Reimaging Optics

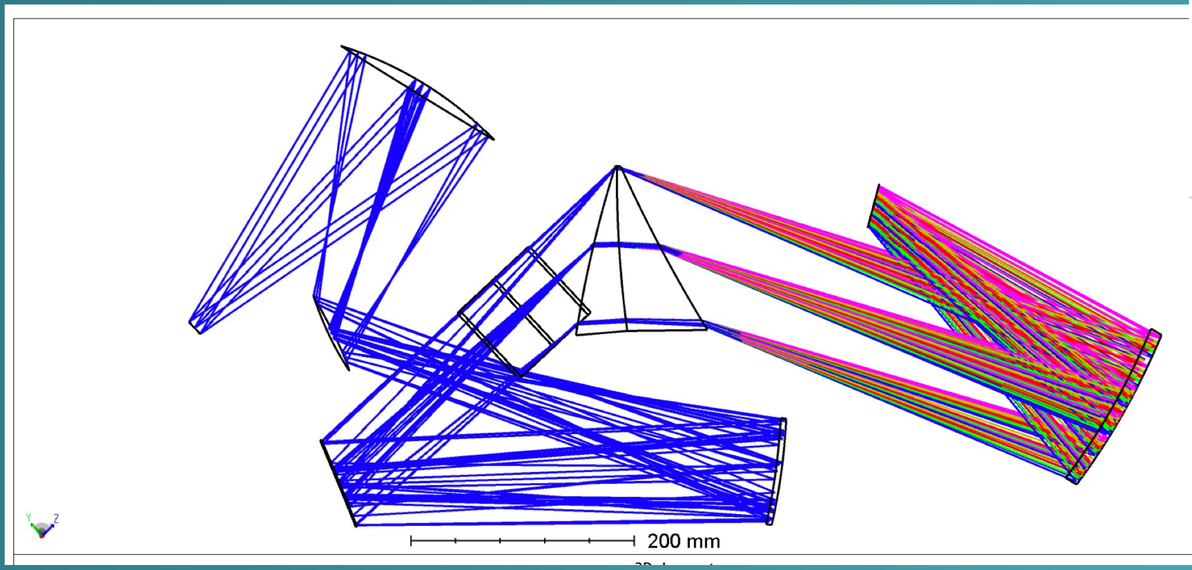


- 3 Mirror system (aspheres)
- Receive the f/15 telescope beam and release a f/2.4xf/2.2 beam on the 2048x1080 DMD
- Scale: 0.75”x0.75”/mirror
- Field of view : 0.1 sq.deg./DMD
- ±12 deg beam is directed to spectrograph (+) or light dump (-)

Dual channel spectrograph

- 3 mirror collimator
- beam splitter at 2micron
- 2 prisms (or gratings)
- 1 mirror camera



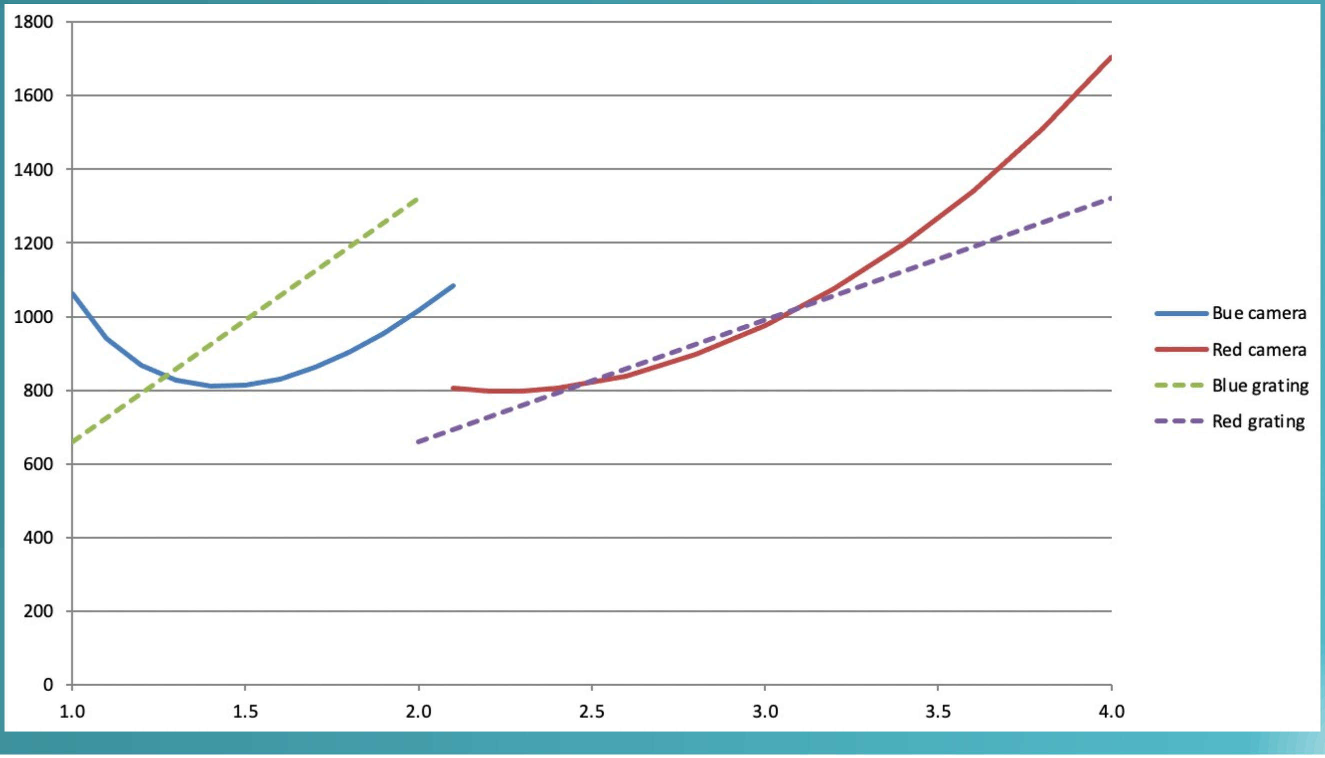


See Talk by R. Content

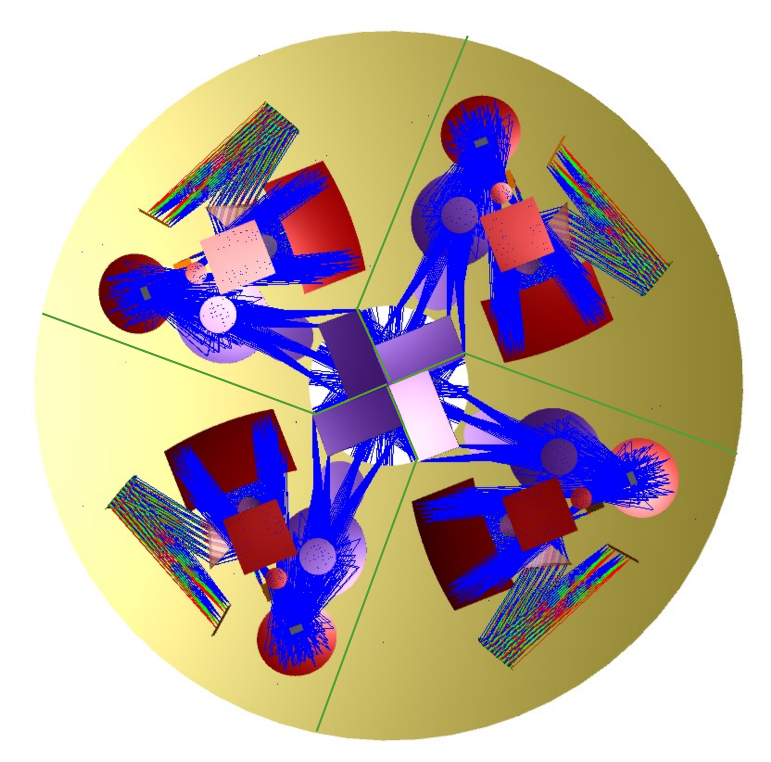
Prisms or grating?

- Dispersion
- Throughput
- Mass

Dispersion prism vs. grating

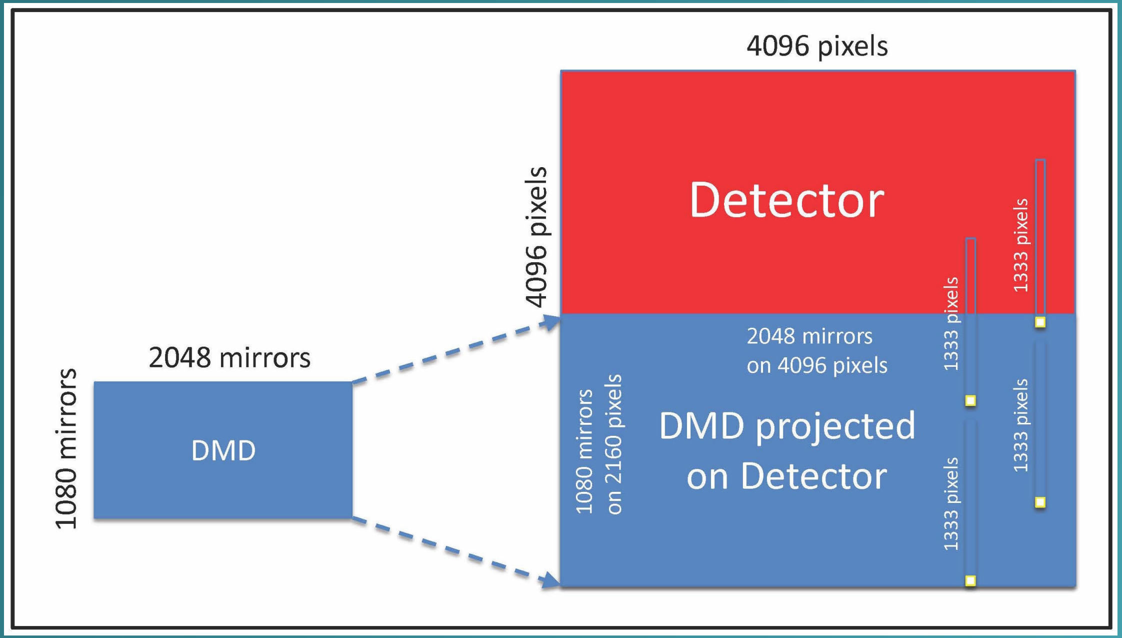


A Modular Design



Detectors

- 2 x 4 H4RG-10 pixels (same as NGRoman ST)
- 32 channels, 200Khz, 2.5s frame



4096 pixels

4096 pixels

Detector

1333 pixels

1333 pixels

2048 mirrors

1080 mirrors

DMD

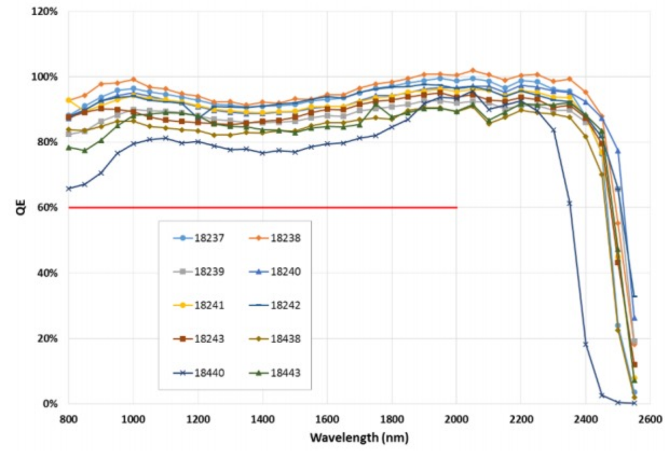
2048 mirrors
on 4096 pixels

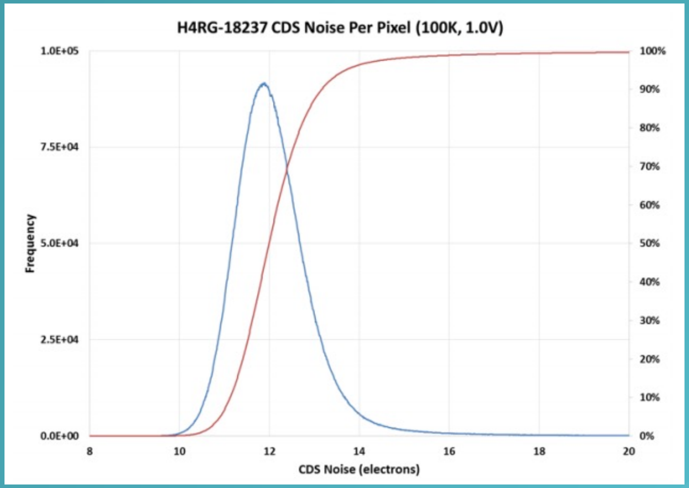
1080 mirrors
on 2160 pixels

DMD projected
on Detector

1333 pixels

1333 pixels





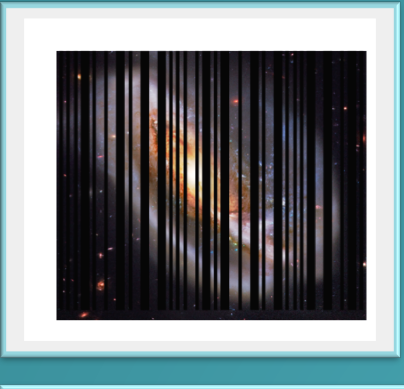
H4RG-18237 CDS Noise Per Pixel (100K, 1.0V)

Mosby et al. (2020) https://arxiv.org/pdf/2005.00505.pdf

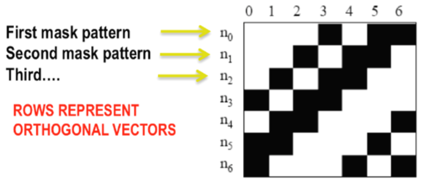
IFU capabilities through HTS

The Hadamard transform

- ❑ The focal plane is projected onto N long slits
- ❑ For each of N exposures only N/2 slits are open, according to the eigenvectors of an orthogonal base
- ❑ Pixels receive superimposed light from a series of spaxels, each at different λ
- ❑ The superposition matrix is inverted to obtain the spectrum for each spaxel
- ❑ Exposure time is the same as long-slit scanning, but on-source time is N/2 longer



$$\begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 & 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \\ 1 & 1 & 1 & 1 & -1 & -1 & -1 & -1 \\ 1 & -1 & 1 & -1 & -1 & 1 & -1 & 1 \\ 1 & 1 & -1 & -1 & -1 & -1 & 1 & 1 \\ 1 & -1 & -1 & 1 & -1 & 1 & 1 & -1 \end{pmatrix}$$



ROWS REPRESENT ORTHOGONAL VECTORS

$$\begin{aligned} n_0 &= \psi_0 + \psi_1 + \psi_2 + \psi_4 + \varepsilon_0 \\ n_1 &= \psi_0 + \psi_1 + \psi_3 + \psi_6 + \varepsilon_1 \\ n_2 &= \psi_0 + \psi_2 + \psi_5 + \psi_6 + \varepsilon_2 \\ n_3 &= \psi_1 + \psi_4 + \psi_5 + \psi_6 + \varepsilon_3 \\ n_4 &= \psi_0 + \psi_3 + \psi_4 + \psi_5 + \varepsilon_4 \\ n_5 &= \psi_2 + \psi_3 + \psi_4 + \psi_6 + \varepsilon_5 \\ n_6 &= \psi_1 + \psi_2 + \psi_3 + \psi_5 + \varepsilon_6 \end{aligned}$$

On the left is the code for the 7 binary masks, providing $n_0 \ldots n_6$ read values; The masks select 4 out of 7 element of the (x,l) cube, indicated by $y_0 \ldots y_6$

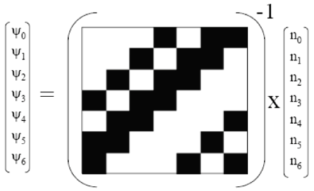
Let' s do the inversion

ORTHOGONAL MATRIX:

$Q^T Q = Q Q^T = 1$

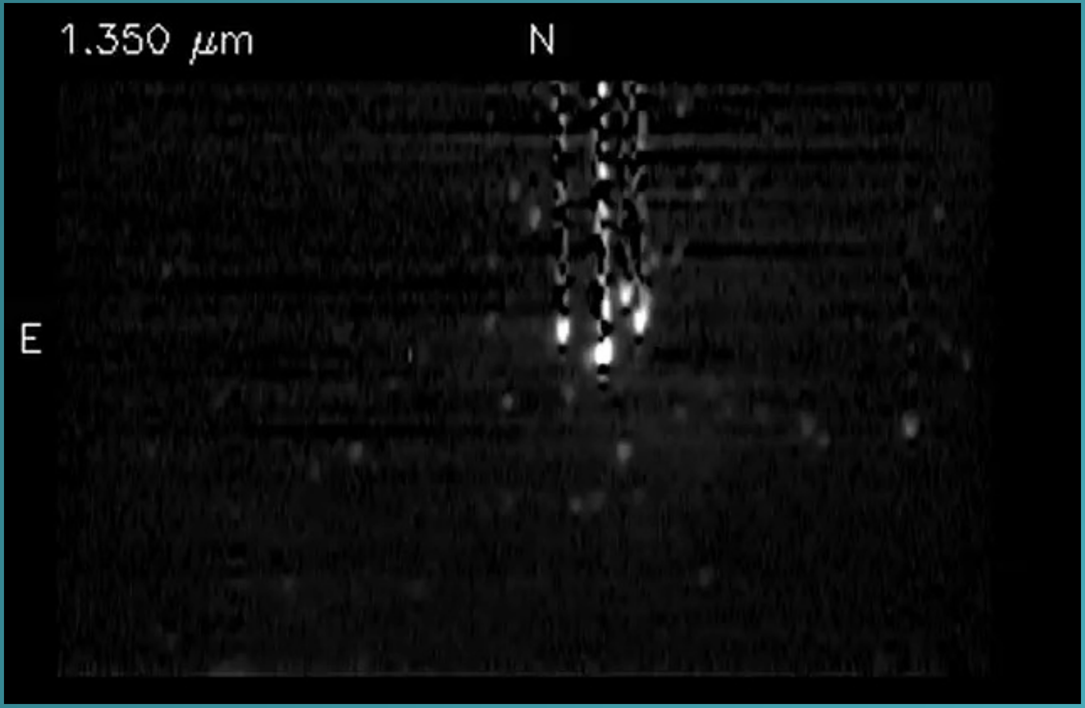
and

$Q^T = Q^{-1}$



Hadamard: the inverted matrix is equal to the direct one!

IRMOS IFU scan through the Orion Trapezium (Row images, J-band, KPNO 2.2m)



Courtesy J. MacKenty

Summary

- DMD is a 40yr old technology
- COTS DMDs are TRL 5-6
- ATLAS-Probe uses a traditional spectrograph concept, fully modular, ingenious design
- H4RG-10 detectors being developed for Roman ST show excellent performance

Ancillary slides

From 17 to 100 micron slit size?

Matching a diffraction limited PSF to a narrow slit requires FAST optics

$$\frac{\lambda}{D} \times F = \lambda \times f/\#$$

i.e. at $\lambda = 5\ \mu m$:

$$\begin{aligned} \lambda \times f/\# &= 15\ \mu m \ \text{ requires } f/3 \\ &= 100 \mu m \ \text{ requires } f/20 \end{aligned}$$

Commercial DMDs are [17.0], 13.6, 10.8, 7.6, 5.4 micron

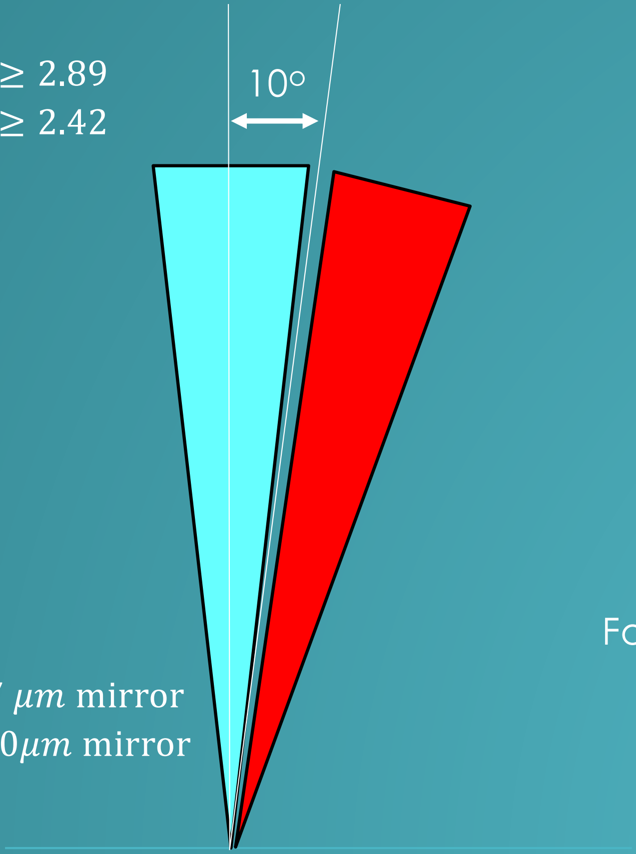
For reference at $\lambda = 5\ \mu m$

D = 8m, $\frac{\lambda}{D} = 0.125''$ (D=1m, $\frac{\lambda}{D} = 1.0''$)

Fast f/# can be a problem with DMDs:

Mirror tilt angle limits the f/# (in order to split the in/out beam)

$$f/\# = \frac{1}{2 \times \mathrm{atan}(\vartheta)} \text{ implies } \begin{cases} \vartheta = 10° \rightarrow f/\# \geq 2.89 \\ \vartheta = 12° \rightarrow f/\# \geq 2.42 \end{cases}$$



A limit on f/# is a limit on the pixel scale

$$A\Omega = const. \Longrightarrow d_{tel}\vartheta_{pix} \cong d_{pix} \ \tan^{-1}\frac{1}{f/\#}$$

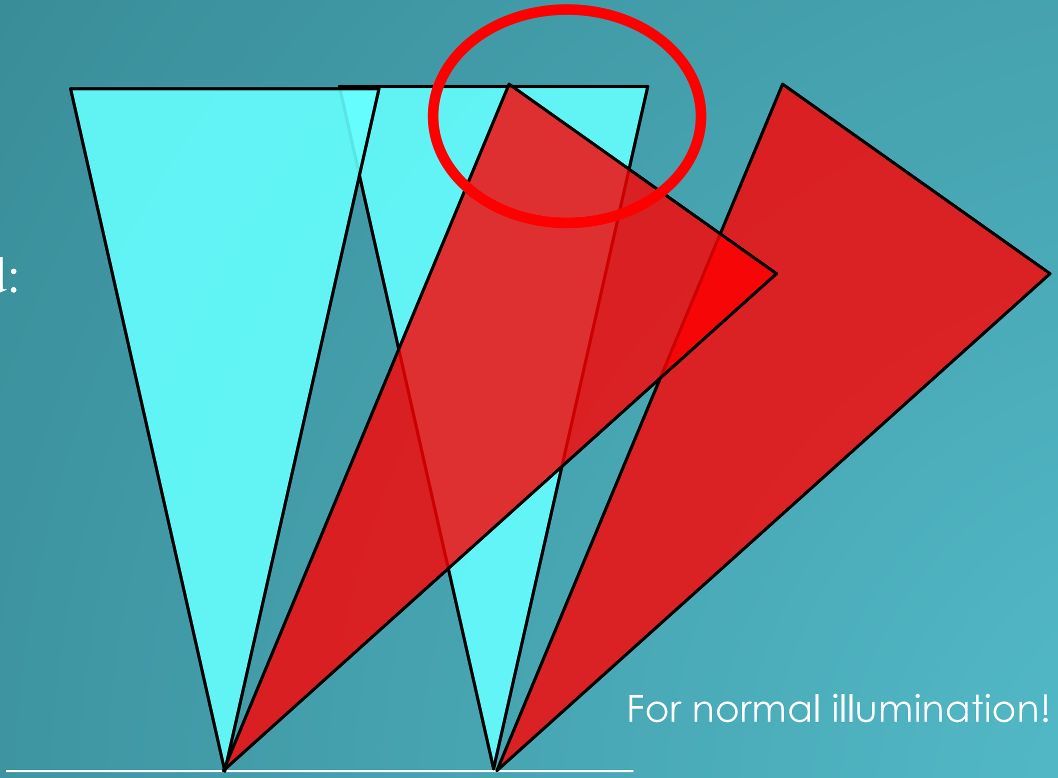
Therefore…

$$\vartheta_{pix} \geq 0.125'' \text{ requires} \begin{cases} f/\# \leq 3.4 \text{ with } 17\ \mu m \text{ mirror} \\ f/\# \leq 20 \text{ with } 100\mu m \text{ mirror} \end{cases}$$

For normal illumination!

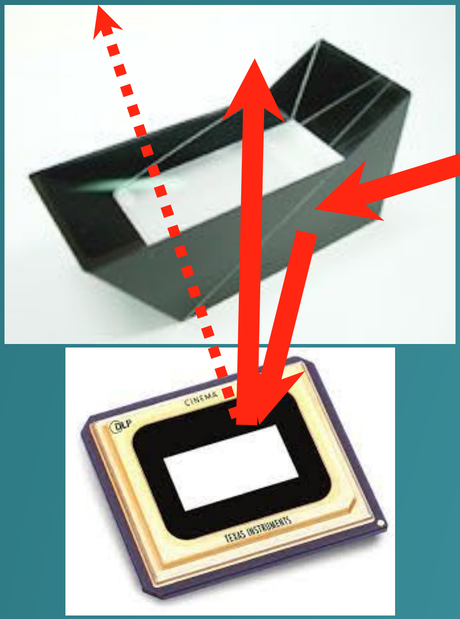
2) The full field must be split: instrument size increases with the f/#

Fast beams need space to be splitted:
=> Large optics
=> Large instruments

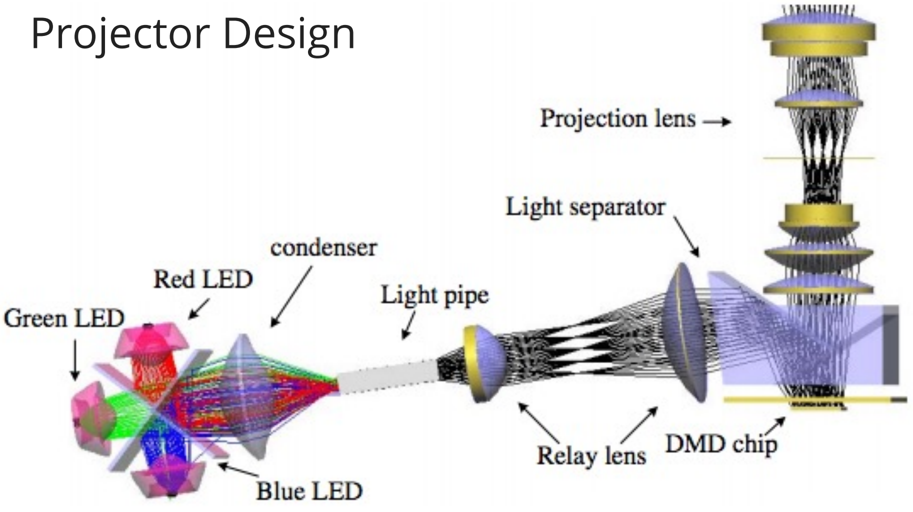


For normal illumination!

Projectors use Total Internal Reflection prisms

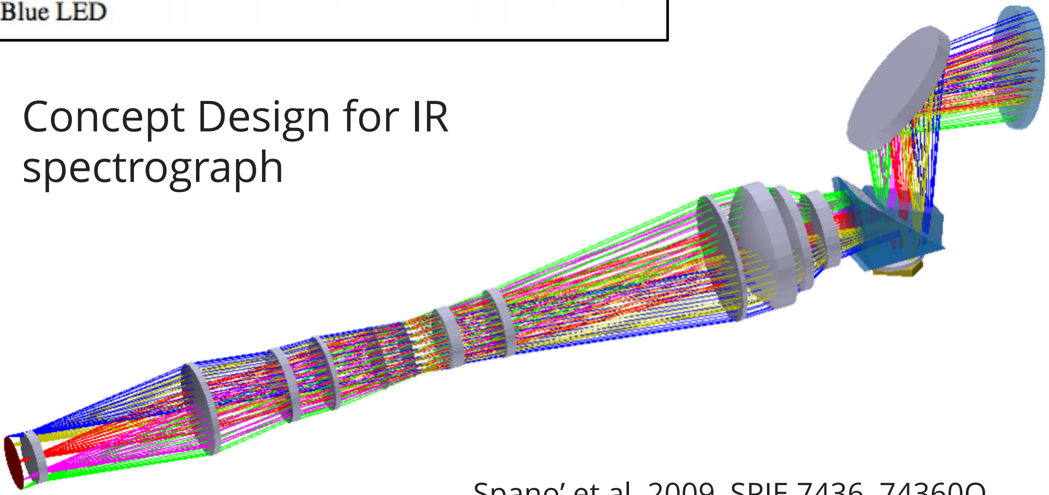


Projector Design



Pan & Wang 2013, Applied Optics 52, 8347

Concept Design for IR spectrograph



Spano' et al. 2009, SPIE 7436, 74360O