DMD Spectroscopy

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(with DMD slides from Massimo Robberto)

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Outline

• Scientific Advantages of Multi-slit Spectroscopy
• A status report on DMDs
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1. What is the difference between DMDs and Microshutters?
2. What information is available on the reliability of the DMDs?
3. Why have they not been selected for Euclid?
4. How complex is a DMD-based spectrograph?
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Micro-shutter arrays (MSA)

Developed by NASA/GSFC for NIRSPEC on JWST

- 100x200 micron
- operate at ~35K
- 171x365 element
- limited production for JWST
Digital Micromirror Devices

- Built by Texas Instr.
- Square mirrors, 14µm side
- $2048 \times 1080$ elements
- Tilt angle ±12°

DMDs come in different format; Together, more than 20 million pieces have been produced (2010)
<table>
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<th><strong>MSA</strong> vs. <strong>DMD</strong></th>
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<td>works in transmission (easier optical design)</td>
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<td>cryogenic (T~35K) (up to 5micron)</td>
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<td>large slits, 100x200micron (good for ~8m-class telescopes)</td>
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<td>contrast ~1/10,000 ? (limited by cosmetic defects)</td>
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<td>radiation hard (NASA test at 60Krad)</td>
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<td>small format: 171x365</td>
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<td><strong>limited NASA production</strong></td>
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For standard applications, extensive literature is available both from TI (white papers, SPIE papers,...) and academic work.

**DMDs are generally considered the most successful example of MEMS technology.**
Hinge Fatigue

* Virtual absence of 3-d structure (no crystal lattice) means that mechanical stresses are relieved at the hinge surface.

A batch of DMDs has been operated per year in parallel at full speed: total 1.4E19 cycles without a single breaking.

DMDs are probably the most reliable mechanical system ever built (and tested)
Stiction

* Electrostatic forces hold the mirrors ON/OFF
* Surface effects (capillarity and Van der Waals forces) could cause the mirrors to stick
* TI are designed with:
  - anti-stick coating
  - mirror landing tips
  - hermetic packaging

stiction virtually eliminated
Acoustic Vibrations

• The lowest frequency mode of a DMD is ~100KH, with resonant modes measured in MHz

• Completely decoupled from the acoustic environment of rockets

No vibration coupling with the launch environment
Contamination
(this is a real risk factor!)

Class 1 manufacturing allows for 100% defect free parts
Thermal Operations

* Overheating is generally the main concern of the industry
* TI SPECS are typical of microelectronic industry:
  
  • Operation temperature: 10 – 65°C
  • Storage temperature: -40 – 80°C
  • IRMOS is now operated at -40 ºC

IRMOS@KPNO-4m operates routinely at -40C
RECENT Update!!
ESA tests on DMDs for Euclid have been released

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

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Experimental Set-Up at LAM Marseille

Fig. 3: Cold temperature test set-up
Results: Thermal

- The cold temperature step stress test has been done from room temperature down to -60°C. This test shows that permanent failure, i.e. stuck mirrors, is appearing on some mirrors when the device is taken down to -55°C. Based on these results, the nominal temperature condition for EUCLID has been set to -40°C.

- 562 thermal cycles have been applied. No anomaly was observed... In particular no cracks, no flakes were observed. The results for the measurement at -40°C after a series of 313 cycles show 0 stuck mirrors, 6 lossy (throughput loss >20%), and 30 weak mirrors (throughput loss <20%) due to misalignment (out of 2,211,840 mirrors).
Results: Radiation
Total Ionizing Dose

“Total Ionizing Dose (TID) radiation tests established a tolerance level of 10 - 15 Krads for the DMD; at mission level, this limitation could likely be overcome by shielding the device.”

No blocked mirrors have been observed before and after TID radiations; the 36 lossy/weak mirrors remained at the same location, with no increase after the radiation test. We can then conclude that these results show that space conditions did not degrade the device performance, within this TID radiations test conditions.
Results: Radiation
Proton Single Event

The proton radiation testing was unfortunately ended prematurely because of a break down in the accelerator. The lack of observed single event upsets is promising, but considering the length of the test, no conclusions can be made on the tolerance of the test vehicle in regards to single event upsets.
Results: Vibrations and Shocks

Standard MIL-STD-883F, methods 2005 (vibration fatigue) and 2007 (vibration at variable frequency) condition A were followed: 20g during 32 hours on each axis for vibration fatigue, and 20g at 20-2000Hz, 4 times on each axis for vibration at variable frequency... This shows that space conditions did not degrade the device performances, within this vibration test conditions.

Shock test condition B of the MIL-STD-883f Method 2002 was applied on one DMD during shock testing. It consists of a shock with a peak acceleration of 1500g and pulse duration equal to 0.5ms, 5 times on each axis. No blocked mirror and three lossy mirrors have been observed before and after shocks (at -40°C after shocks), at the same locations. Other affected mirrors are weak mirrors and their number is very low, with no increase after the test. This shows that space conditions did not degrade the device performances, within this shock test conditions.
Results: Imaging and Contrast

Complementary pattern have been generated; camera images 9x9 CCD pixel per micromirror for high precision photometry; illumination at f/3; neutral density filter to maximize dynamic range, etc...

**Measured contrast is 2,250:1**

(MSA were selected for JWST mostly because the could reach 2,500:1)
“... These results do not reveal any show-stopper concerning the ability of the DMD to meet environmental space requirements. Insertion of such devices into final flight hardware would still require additional efforts such as development of space compatible electronics, and original opto-mechanical design of the instrument. From an ESA perspective, the micromirror arrays have therefore achieved a reasonable TRL (Technology Readiness Level). Insertion of such devices into final flight hardware would still require additional efforts (estimation is approximately 2 years) in terms of change of the window coating, re-development of space compatible electronics as well as a different package interface compatible with spacecraft launch conditions.”
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A BIT OF HISTORY...

SPACE (with DMDs) ”won” the competition being “slightly preferred” to DUNE as the top Medium-class mission.

However, ESA did not believe that DMDs could have reached TRL6 before the next down-selection (later this year): schedule problem.

ESA also decided to merge SPACE with DUNE into Euclid, which calls for a more expensive satellite: cost problem.

As a result, DMDs were first descoped to an “option”; ESA also directed the industry to ignore them for their pre-phase A study (“yellow book”).

Euclid has been eventually configured with a slitless “spectroscopic mode” (i.e. grism has been added to the IR imaging channel).
... and about NASA

- For JWST/NIRSPEC, NASA funded two micromirror teams (GSFC and Sandia) and a MSA team (GSFC)
- Each team started an independent development program. The micromirror team at GSFC worked to create DMD-like devices of larger size (~100 micron) that could operate at 35K.
- NASA eventually selected MSA against micromirrors for NIRSPEC mostly because of expected higher contrast.
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Optical Design: DMDs Allow for Unique Solutions

Probably the most important lesson we have learned is that MEMS-based instruments can be made very compact. Of course, this is ideal for space.

Consider that you can buy (not in the USA) a DMD-based projector inserted into a cellular phone. How can they do it?
Industry Commonly Uses
Total Internal Reflection Prism

A TIR prism splits the reflected beams ("ON Spectrograph" and "OFF") just in front of the DMD, exploiting the fact that the ON beam hits with TIR angle a thin diagonal gap between the two prism faces.
CAN YOU SEE THE TIR PRISM?
An example: HIREX

- TIR prism + DMD feeding a compact grating spectrograph
- All refractive, shoebox size spectrograph at R=1,000
An Example: HIREX

- 4 central Hi2RG SCAs for direct imaging
- 4 TIR+DMD fed spectrographs at the field corners
- 1/6 of a square degree covered in parallel @2m space telescope (smaller telescope would give larger field);
- >2,000 deep IR spectra R=1000 taken simultaneously

Proposed to ESA as post-Euclid mission