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Optical MEMS for Earth Observation payloads

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Abstract: An ESA study has been taken by Lusospace Ltd and Surrey Satellite Techonoly Ltd (SSTL) into the use of optical Micro Eletro-Mechanical Systems (MEMS) for earth Observation.

A review and analysis was undertaken of the Micro-Optical Electro-Mechanical Systems (MOEMS) available in the market with potential application in systems for Earth Observation. A summary of this review will be presented.

Following the review two space-instrument design concepts were selected for more detailed analysis. The first was the use of a MEMS device to remove cloud from Earth images. The concept is potentially of interest for any mission using imaging spectrometers. A spectrometer concept was selected and detailed design aspects and benefits evaluated. The second concept developed uses MEMS devices to control the width of entrance slits of spectrometers, to provide variable spectral resolution.

This paper will present a summary of the results of the study.

Keywords: MEMS, MOEMS, Earth Observation, Electrostatic, Micro-Slit, Micro-Shutter

1. Introduction

MOEMS (Micro Electro Mechanical Systems) devices are products ranging from a micron to a centimetre in size that combine mechanical, electrical, and optical components. Numerous types of optical MEMS devices have been successfully used with a wide range of applications, including optical communications, display systems, biomedical instrumentation, and adaptive optics. Because optical MEMS devices have the advantages of small size, high robustness, and low power consumption, they have recently attracted particular attention for space optical systems, such as the James Webb Space Telescope. When discussing the applicability of MEMS in space optical instruments of existing or potential new kinds, it will be essential to consider the basic constraints imposed by the need to gather photons and cover useful ground area. This means that large apertures and image areas present obvious limitations to the use of MEMS and to miniaturization benefits of any optical function, implemented in this kind of devices. The use of MEMS in instruments that could contain several miniaturized components performing active, light-modulating functions or passive elements such as miniaturized optics, need much larger optics to provide the interface to the external world. The performance of such systems is nevertheless limited by the smaller components. The design of miniaturized optics is therefore driven by the design of the miniaturized components, not the interface optics, simply because the systems become limited by the brightness that the miniaturized components can ultimately handle.

Below is presented the functional analysis of available MOEMS devices and technologies in Earth-observation instruments.

1.1 Single tiltable mirror applications

Tiltable mirrors on a MEMs scale can in principle be included in any instrument with low values for the Helmholtz invariants H_{act} and H_{alt} (in across-track and along-track sections with respect to satellite coordinates, or other orthogonal sections). This includes systems with single-point or small fields, including: LIDARs, some FTIR systems, and instruments for tropospheric chemistry. Tiltable mirrors up to 10mm diameter may be considered for:

- Correction of pointing direction over small angles. Particularly (a) for LIDARs on output or receive path, and (b) for limb scan in limb-sounding FTIR systems. Not obviously both needed and feasible (at MEMs scale), in other applications identified so far.
- Introducing light from calibration sources – typically replacing other rotating mirror mechanisms – typically tilting through moderate angles, e.g. >10°. Particularly for tropospheric chemistry and FTIR systems (introducing light from diffuser and black-body sources respectively).
- Converting continuous scan over Earth into micro-step-and-stare scan by saw-tooth oscillation. (This will generally improve along-track spatial resolution of pushbroom imaging systems. Note: not useful for TDI imagers.) Applicable to tropospheric chemistry pushbroom imagers, and possibly to other push broom imagers.

1.2 Micro-shutters in linear and area arrays

Micro-shutters may be located in planes of small intermediate images, including entrance slits of spectrometers. In these locations, they may be used for:

- Selection between alternate entrances slits of imaging spectrometers, for example for selection between orthogonal polarisations, different spectral resolutions of shifted spectral bands. Linear shutter array to be considered for any hyperspectral push-broom imaging spectrometer.
- Control of stray light and diffraction in sensitive radiometers, by removal of bright scene areas (cloud, Earth limb…) from an intermediate image, e.g. at a

spectrometer entrance slit. May be extended to selection of dark areas of special interest.
- Comb-filter application: variable selection of spectral bands in a hyperspectral focal plane. May be followed by a dispersive stage recombining selected wavelengths to a linear array detector.

1.3 Micro-mirror arrays

Micro-shutter and micro-mirror arrays will probably be located only at (or very near) image planes, since in other locations they will generally introduce unacceptable diffraction effects. In the planes of relatively small images they may be considered for:

- Introducing light from calibration sources, by re-direction of view-direction – may be limited to spectral and white-light lamp sources. Particularly for hyperspectral systems requiring wavelength and relative spectral response calibration.
- Controlling diffuser speckle in tropospheric chemistry calibration sub-systems.
- Control of stray light, including diffraction effects, by removal of bright scene areas (cloud, Earth limb…) from an intermediate image. As for micro-shutters.
- Comb filter application: as for micro-shutter array.

1.4 Micro-bolometer arrays

Micro-bolometer arrays, if accepted as MEMs devices, may be considered for:

- 2-3 band thermal imagers in TDI configurations, for example as potential improvements on scanning sea-surface temperature systems.
- FTIR spectrometer of low spectral resolution, using the SHIS (spatial heterodyne imaging spectrometer) approach. The science return is uncertain, but the approach makes optimum use of the properties of micro-bolometers.

2. MOEMS concepts for Earth observation instruments

The proposed Si-based MOEMS concepts targeted two important applications in optical instruments:

- de-clouding of Earth images and
- adjustment of spectral range and resolution of spectrometers.

De-clouding has been suggested initially as a method to reduce effects of stray light on data produced by Earth-observing instruments. Particularly in the visible spectral region, clouds, snow, ice and sun-glint are much brighter than the darkest Earth areas that are imaged within the same scenes. Light from bright image areas, scattered by instrument optics, can generate significant errors in the measured spectral radiances of darker scene areas. Removal of cloud from Earth images can therefore improve control of stray light.

On more detailed review of real potential application, gains in terms of reduced stray light are not dramatic. However, users of multi-spectral and hyperspectral data generally require cloud-free data to monitor land surfaces and tropospheric chemistry, since cloud radiance corrupts the analysis of partially-cloudy pixels. Scientists have demanded the best feasible spatial resolution, particularly in atmosphere-chemistry instruments – in trade-offs against other requirements including signal-to-noise ratios and swath widths – essentially to provide some useful data over partially-cloudy scenes. Using MEMS, de-clouding can in principle be performed at a sub-pixel level. This offers the possibility of providing cloud-free images in systems that have limited spatial resolution, due for example to limitations of detectors.

MEMS devices can in principle be used to define the entrance slits of dispersive imaging spectrometers, and may be used either: (a) to select between slits, by shuttering, or (b) to vary the width of a single entrance slit. Selection between different slit locations can be used to control the spectral band imaged on a fixed detector. Selection between slits of different widths, or MEMS control of slit width, can control spectral resolution in a trade-off between resolution and signal levels. Loss of performance relates to time-sharing between different spectral bands or spectral resolutions. The switching capability could be treated simply as an opportunity to experiment with different performance profiles – perhaps using different slit widths on successive days. This would of course allow a very slow movement to be used. Alternatively, the system might be used to switch between high SNR and fine spectral resolution, with some loss of spatial sampling.

2.1 MEMS Micro Shutter

In spectrometer systems, a MEMS de-clouding component will be located at (or very near) a spectrometer entrance slit, or at a slit-shaped field image that is then relayed onto the entrance slit. In general, it is desirable to limit use of relay optics, so that integration of the slit with the de-clouding component will be preferred when this is feasible. It will be desirable for the MEMS elements to be smaller than the sample-spacing of the Earth image determined by the detectors element size, so that the MEMS can perform de-clouding at sub-pixel resolution. A future atmosphere-chemistry spectrometer provides a potential candidate for de-clouding. MEMS requirements that would be appropriate for the main payload of the ESA Sentinel 5 mission are listed in Figure 3.

Similar in structure to that of the CSFG device [1][2][3],[4], the device operates independent shutters allowing control of the transmitted light in the area covered by the shutters array. The shutter cell is formed by a static structure, and a shutter that covers most of the area defined by the surrounding structure. The shutter is connected to the structure by a torsion bar responsible for the shutter movement and correct positioning. In the rest position, 0º, the shutter reaches the lowest transmission level. The virtual complete block of the incoming light is limited by the gaps between the shutter/surrounding structure and gaps inherent to the torsion bar mechanism. In the 90º position, the shutter rotates downwards releasing the optical path to the incoming light, thereby reaching the maximum transmission level. In this position, only the surrounding structure and the area, proportional to the shutter thickness and length, blocks the passage of light. Compared to similar micro-shutter devices, this concept features a rotating blades in opposite direction and no separation structure every two consecutive blades -see Figure 1. The ultimate goal with this architecture is the maximization of transmitted light through the device.

The proposed concept operation relies solely on the electrostatic force. Once the electrostatic force surpasses the mechanical resistance of the torsion bar-hinge system, the plate rotates to the vertical position staying in the open state. Once the voltage is driven down, the electrostatic force fades and the shutter is released to the natural position, as result of the torsion bar restoring force. On the structure of the shutter and frame are two sets of strip electrodes used for addressing the array. One set of electrodes cover the bottom surface of the shutter are connected together via leads on the torsion hinge and array frame in columns (when the array is oriented so that the torsion hinge is at the top of each cell) and connected to bonding pads on the bottom of the outer frame of the array. The second set of electrodes cover the inside wall of the shutter cell aperture on the hinge's nearest side. These vertical electrodes are connected via leads on the top of the frame in rows to another set of bonding pads on the top of the outer frame.

Based on the application requirements, the proposed arrangement – 3x1 MSAs – features an array of 1230 pixels in length and 315 in width and a pixel size of 100µm x 100µm. Thus, the overall MSA length is 12,30cm x 3,15cm. The individual MSA's dimensions are 410 pixels in length and 315 in width, for an overall size of 4,1cm x 3,15cm. Through a physical and electrical bond between the arrays, it is possible to use a single controller to manage the entire shutter array. The overall array thickness is defined by the SI substrate.

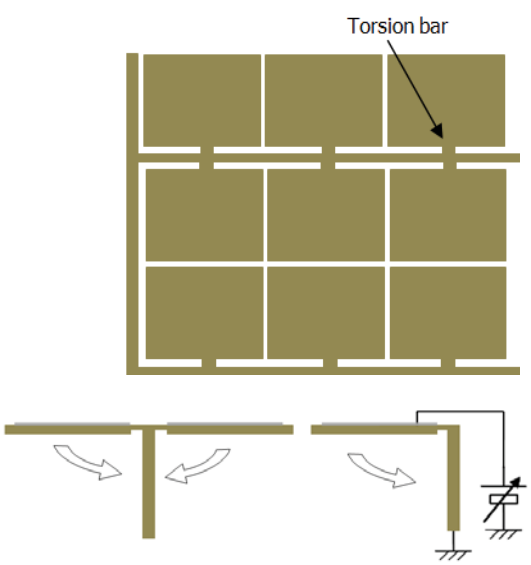

Figure 1 – MSA top view (top) and side view (bottom) of a section of the micro shutter array.

Parameter	Requirement	
	Threshold	Goal
Total dimension across-track (1)	120mm	
Total dimension along-track (2)	3mm	
Clearance to slit plane	<3mm	<0.75 mm
Element spacing across-track	<0.2mm	0.1mm
Element spacing along-track	<0.1mm	0.05mm
Fill factor (3)	>95%	90%
Response	<0.2s	<0.1s
Life in flight (4)	3 years	10 years

Figure 2 – Summary of typical parameters for a de-clouding MEMS device.
(1) May use several MSAs or MMAs
(2) Allows in-field separation for 3 channels +margins for alignment
(3) Transmitting area /element area
(4) At average 0.1operations/s

2.2 MEMS Variable Slit

The proposed Si MEMS device is based on an electrostatic actuator to guarantee compliance to requirements derived for a spectrometer concept forming part of the paload for the FLEX (Fluorescence Explorer) mission payload. The requirement list is outlined in Figure 3.

The MEMS concept simplicity is compatible with bulk micromachining or LIGA fabrication processes. The proposed design features a slit with 30mm length and variable width between 10µm to 100µm. The varying slit width is achieved by one movable edge slit and a fixed one. The movable edge is connected to the device structure by two springs placed at the extremities of the movable edge. A comb drive connected length wise to the movable edge controls the position and movement. The option for a comb drive length matching the movable edge and identical poles, positioned in symmetric locations with regards to the edge physical mass centre, assures parallelism between edges in the actuated and non-actuated positions. From the operation point of view, a rise in the driving voltage exerts an attractive force between the opposite finger banks on the comb drive. Once the electrostatic force surpasses the elastic resistance of the connection springs, the movable edge starts to retract widening the free space between the edges and changing the slit width. Should the applied voltage decrease from a certain value, set by the elastic force of the connecting springs, the movable edge returns to the original position, redressing the mechanical equilibrium of the device.

The actuator is the critical element of the proposed concept: not only comprises the movable elements but also limits the performance of the device. The proposed actuator configuration – a comb drive – comprises one stationary set of fingers (stator) and a movable set of fingers (rotor). A ground plane is located under the comb drive structure and kepts the rotor at the same potential in order to prevent pull down forces and potential device breakdown.

Parameter	Value
Type of MEMS	Shutter
Effective slit length	30mm
Slit width range	0.1mm to 0.01mm
Width uniformity	0.5 microns
Width repeatability	0.5 microns
Duty cycle (5)	One change per second
Switching period	<0.1s
Life	>3 years

Figure 3 – Variable single slit device requirement's list.
(5) Sampling 7km ground-tracks

The comb drive design also influences the device's performance and reliability, e.g. the comb drive displacement varies with the number of comb drive fingers and the square of the applied voltage and an increase in the number of fingers will considerable decrease the required actuation voltage.[6]

$$y = \frac{n \epsilon_0 b}{k_y d} V^2$$

Where:

y – displacement in the y-direction
n – number of comb fingers
ε0 – dielectric constant
b – comb fingers width
d – gap between comb fingers
V – applied voltage

For displacements higher than a few micrometers the design should address undesired behaviours caused by displacements in directions other than that set by the electrostatic forces in the y-direction. Different spring design options lead to dissimilar performance in terms of displacement, actuation voltage and movement instability in the x-direction [5][6].The preferred beam structure solution is the folded-flexure design comprising a set of beams to assure higher displacement potential without loss in the overall stiffness. [6]

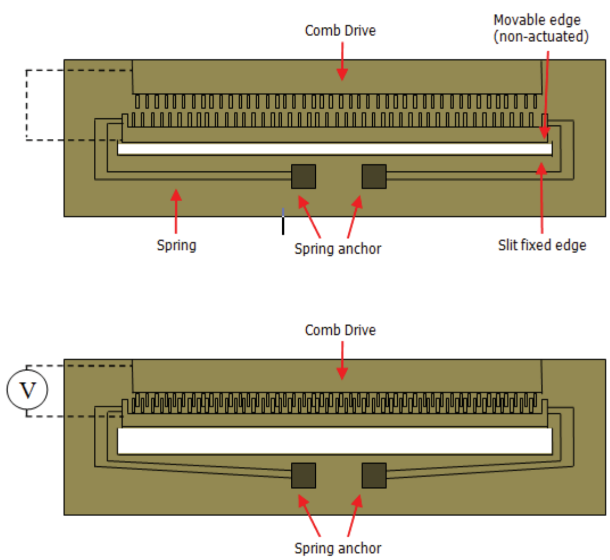

Figure 4 – Top view of the MEMS variable slit. Non-actuated position (top) and actuated position (bottom).

Conclusions

A list of MEMS of potential interest for Earth Observation missions has been presented and potential applications discussed. Additionally, a new device, a MEMS variable slit, has been presented and briefly discussed. Finally, an electrostatic actuated Micro Shutter Array with an improved design over the known concepts has been disclosed. Detailed analysis will be required to validate the concepts feasibility and adequacy to the space environment.

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