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SISSI instrument: challenges in the optical design of a super resolved compressive sensing multispectral imager in the medium infrared

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ABSTRACT

The paper describes the challenges faced during the optical design of a multispectral imager in the Mid Wave InfraRed (MWIR) based on super-resolution and compressive sensing, performed in the framework of the SISSI project funded by the Italian Space Agency. The project aimed to improve ground sampling distance and to mitigate possible saturation/blooming effects. The operating principle is the one of the single pixel camera. The use of CS architecture allows the scene reconstruction without loss of significant information by using a reduced number of acquisitions. A Digital Micromirror Device (DMD) was used to modulate the observed image by using a binary ON-OFF pattern. A sequence of such spatially-coded acquisitions is integrated by a condenser lens and focused on the 2D detector array, each element of which acting, in parallel, as the single element detector of a single pixel camera. Multispectral acquisition is obtained by deposition of different band pass filters on the 2D detector. The optical design has posed strict constraints on the optics involved. The collection optics, focusing on the DMD plane, must match with the condensing optics. An additional issue is due to the DMD working in reflection mode. A further requirement is given by the Airy disk size. Such constraints lead to an upper limit for the optics f-number. Chromatic aberration introduces further difficulties in glasses selection with high transmissivity in the MWIR. The final optical design of the system involves both reflective and dielectric optical elements, making use of aspheric and free-form surfaces.

Keywords: Super resolution, Compressive sensing, optical design, medium infrared, pushbroom, Earth observation.

1. INTRODUCTION

The importance of observations in the Mid Wave InfraRed (MWIR) spectral region, from agriculture to meteorological and climatic studies or for monitoring environmental risks such as fires and volcanic eruptions, has been highlighted by the scientific community. In particular, multispectral observations gain relevant importance when done at high spatial resolution [1]. For example, high temperature events like volcanic eruptions or wild fires are better characterized when observed at high spatial resolution [2 - 4]. The possibility to obtain multispectral, high spatial resolution observation in the MWIR range was investigated in the frame work of SISSI project funded by the Italian Space Agency. During the SISSI project, an innovative concept of optical payload, operating in the MWIR, based on two emerging technological approaches - super-resolution and Compressive Sensing (CS) - was studied to obtain particularly interesting performances in terms of spatial resolution on the ground and mitigation of some effects, such as saturation and blooming. Both approaches are based on the use of a Spatial Light Modulator (SLM), an optoelectronic device consisting of an array of electronically actuated micro-mirrors (MMA - MicroMirror Array).

The concept of super-resolution is based on the possibility of obtaining an image - with a larger number of pixels than the nominal ones provided by the chosen detector - thanks to the use of an SLM with a number of elements N times greater than the elements of the detector. The Compressive Sensing (CS) theory, on the other hand, exploits *a priori* knowledge on the sparsity characteristics of the image to acquire. Using CS approach fewer samples than those predicted by the Nyquist-Shannon theorem [5] are acquired and the image is (lossy) reconstructed. In general, it is always possible to find a domain in which the data to be acquired is sparse.

The operating principle of SISSI instrument is the one of the single pixel camera [6], in which a single element detector acquires, by multiple acquisitions, different modulations of the scene of interest, allowing the reconstruction of the original scene. Such modulation is usually performed via binary spatial masking. The use of CS architecture [7, 8] allows the scene reconstruction without loss of significant information by using a reduced number of acquisitions.

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For SISSI, a bidimensional electronically actuated array of micro-mirrors (namely a Digital Micromirror Device (DMD)) was used to modulate the observed image using a binary on-off pattern. A sequence of such spatially-coded acquisitions is then integrated by a condenser lens and focused on the detector, each element of which acting, in parallel, as the single element detector of a single pixel camera. A contiguous ensemble of micromirrors subtends a so-called macropixel on the DMD plane, each macropixel corresponding to one detector element. Each micropixel subtends a portion of the scene corresponding, at ground, to the super-resolute ground sampling distance. Multispectral acquisition is obtained by applying a linear variable filter on the 2D detector, allowing the multiple coded acquisition of a generic group of across-track lines of macropixels through different spectral filters. The optical design of such imager required strict constraints on the optics involved. The collection optics, focusing on the DMD plane, must match with the condensing optics, coupling each macropixel on the DMD plane to the corresponding detector element. A major difficulty is added by the DMD working in reflection mode, making the optical design more complex due to the need of the impinging and reflected ray beams being separated and being collected by the condensing optics. A further requirement is given by the Airy disk size being comparable to the DMD micropixel. Such constraints lead to an upper limit for the optics f-number. A small f-number increases the collected number of photons but also the geometric aberrations of the optics.
In the following after a brief description of SISSI instrument operation mode, the optical design will be presented and the challenges faced during the design will be discussed.

2. SISSI INSTRUMENT CONCEPT

The schematic of SISSI instrument operation mode is depicted in Figure 1. It is based on the CS architecture [7]: a single pixel detector collect the light modulated by a spatial light modulator (SLM) by mean of a lens acting as light condenser. Each acquisition is the product between the encoding binary pattern applied to the modulator and the corresponding element of the image focused on it and the condenser acts the integration on the single-pixel detector. The quality and the number of acquisitions needed for the reconstruction of the image depends on the sparsity of the observed image. CS merges acquisition and compression phases into a single step. It is worth to note that SISSI instrument performs a parallel acquisition of the images. Each detector pixel subtends an area of the scene on the ground corresponding to a macropixel on the DMD. Each DMD macropixel is made up of NxN micropixels, each of which corresponds to a micromirror of the DMD (Figure 1). Each DMD macropixel is made up of NxN micropixels – that corresponds to NxN micromirrors- and is encoded by a binary mask different for each frame. The final sampling of the reconstructed scene is increased by a NxN factor with respect to the native detector resolution, NxN being the super-resolution factor of the instrument.

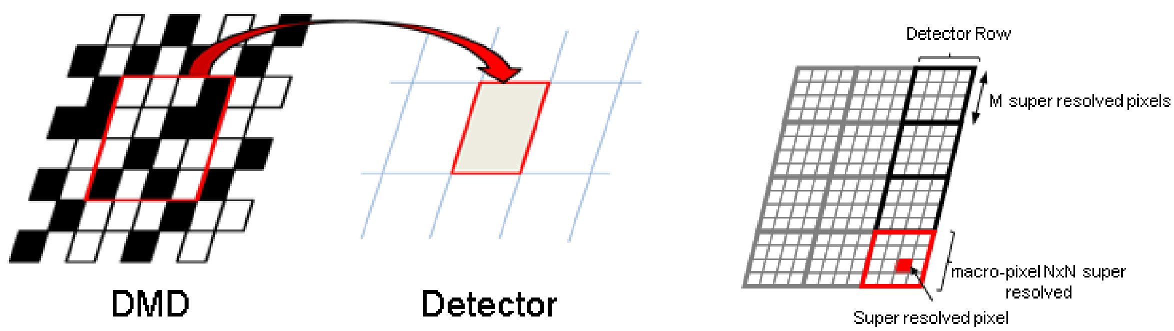

Figure 1. Super resolution for SISSI instrument: macro-pixel, and micro-pixel

Multispectral acquisition of the same scene is performed due to the application of spectral filters on several contiguous lines of the detector, arranged along the across-track dimension of the scene, and to the apparent movement of the scene in the direction along-track through the field of view (Figure 2). SISSI instrument will achieve a super-resolution factor equal to 4x4.

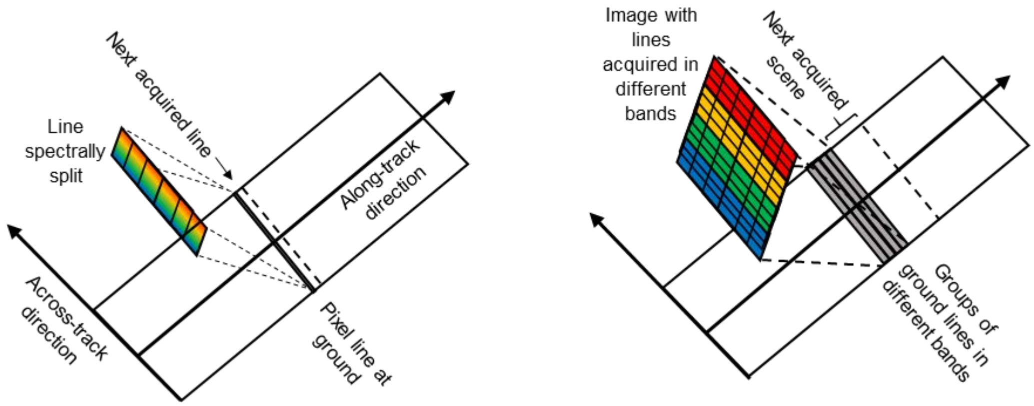

Figure 2. Schematic of SISSI operation mode

The main characteristic of SISSI instruments are listed in Table 1.

Table 1. SISSI payload main characteristics

PARAMETER	VALUE
Operational working spectral range µm	3 – 5 (MWIR)
Number of spectral bands	5
Spectral band central wavelengths µm	3.3, 3.5, 3.7, 3.9, 4.8
FWHM (nm)	100 @ 3.5, 3.7, 3.9 µm, 150 @ 4.8 µm, 200 @ 3.3 µm
Nominal GSD (m)	15.0
Nominal altitude (km)	700
Number of micropixels (across track)	1024
Swath across track (km)	15.36
Super-resolution factor	4x4
Detector	MARS by Sofradir/Lynred
DMD®	DLP 7000 Texas Instruments Inc.

SISSI payload was conceived as formed by an optical module (collection optics, DMD, condensing optics and detector) and the electronic section. For what concern CS algorithm [9], two different categories of reconstruction algorithms were taken into consideration: traditional and based [10] on deep learning [11]. In the following the activities related to the design of the optical module are described and the obtained results discussed.

3. OPTICAL DESIGN

The design of the optical module took into account four key elements:

- collection optics, i.e. the telescope that focuses the observed scene on DMD (the coding element);
- DMD that acts as spatial light modulator;
- condensing optics (condenser), that images on a single pixel of a bi-dimensional detector the corresponding macropixel on the DMD, where each macropixel is formed by 4x4 micro pixels (micro-mirrors);
- bi-dimensional detector.

In Figure 3 the schematic of the main functional block of the optical section are shown.

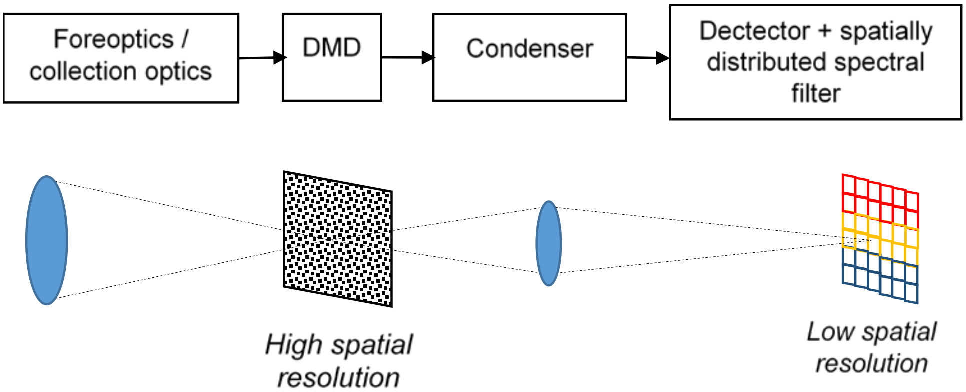

Figure 3. Functional blocks of SISSI instrument optical section

In the following the optical design of SISSI instrument is presented paying particular attention to the design of collection optics and condensing optics.

3.1 DMD selection

One of the key elements during the design of SISSI payload was the choice of DMD, since its characteristics such as micromirrors dimension, or tilt angle (δ) influence the optical layout and the dimensioning of the other optical elements. For example, tilt angle δ determines the direction where the focusing optic is placed. If the optical system is designed so that collection and condensing optics have the same f-number, in order to avoid the superimposition of impinging and outgoing beams the minimum, f-number is equal to:

$$f/\#_{\min} = (2 + \tan(\delta))^{-1} \quad (1)$$

Due to the dimension of micromirrors, the choice of DMD have to take into consideration the effects of light diffraction on the performance of the optical system. On the basis of simulations (not reported here), the optimal choice for the SISSI instrument was the DMD produced by Texas Instrument DLP 7000 was selected because it gives the better performance in terms of diffraction efficiency.

3.2 Detector selection

The bidimensional array MARS MW produced by Lynred/SOFRADIR was the detector selected for SISSI Payload.
The choice was driven by the following characteristics: the working spectral interval, the small NEDT (about 13 mK) and the bidimensional array dimensions. The high TRL level for such detector was also another relevant reason for its selection. The main characteristics of MARS MW are listed in the following table.

Table 2: MARS MW main features

Parameter	Value
Array dimension	320 pixels x 256 pixels
Pixel dimension	30 µm x 30 µm
Spectral range	3.7 – 4.8 µm
Focal Plane Array working temperature	< 90 K
Readout noise	1000 e-
NETD	8.5 mK (f/2, 36 106 e-, 300 K, 50% well fill, 90 Hz) 13 mK (f/4, 12 106 e-, 300 K, 50% well fill, 80 Hz)
Non uniformity	2.5% RMS

The dimension of 30 µm x 30 µm for each pixel allows a good match between the detector and the optical system. On the basis of SISSI operational mode depicted in Figure 2, band pass spectral filter will be deposed on detector window.

3.3 Collection optics

The collection optics focuses the image of the observed ground on the DMD plane. The resolution in MWIR bands is limited by the dimensions of the spot radius. The upper limit of the spot radius is given by the DMD micromirror size (i.e. the micropixel). On the other hand, diffraction provides an upper limit to the optics' f-number and wavelength, due to the fact that the minimum spot radius size is given by the Airy disk size (i.e. the diffraction limit), and Airy disk increases with both wavelength and f-number, as shown in Table 4.

Table 3. Airy disk size for different values of wavelengths and f-number.

F-number	FOV(degrees)	Airy disk radius (µm) at		
		λ = 3000 nm	λ = 3500 nm	λ = 4000 nm
2	28.1	7.32	8.54	9.76
3	18.9	11.0	12.8	14.6
4	14.3	14.6	17.1	19.5

Another constraint is given by the DMD mirrors tilt of ±12°. The tilt causes the reflected bean to be partially overlapped with the incident beam focusing the image on the DMD. The need for avoiding the overlap of reflected and incident beams fixes a lower limit for both the f-number and the back focal length of the instrument. With such constraints, the aperture angle of the incident cone fixes a lower limit to the distance needed to the reflected rays to be deflected out of the cone of the incident ones (namely, the back focal length).
Chromatic aberration introduces further difficulties in glasses selection, due to the reduced number of materials having high transmissivity in the MWIR. The optical system involves both reflective and dielectric optical elements, making use of aspheric and free-form surfaces
On the basis of these considerations, keeping into account the requirements about the instrument's Field Of View (FOV) and considering an input pupil diameter of 200 mm, the collection optics focal was fixed to 638.4 mm, with an f-number of 3.192. The following modified Schmidt–Cassegrain configuration is used:

- parabolic primary mirror;
- oblate elliptic secondary mirror;
- image corrector, having:
    - three aspheric lenses in CaF_2,
    - one aspheric lens in ZnSe (for chromatic correction).

The Cassegrain-type configuration grants a low-distortion image plane (on the DMD), allowing the focused image to be as flat as possible. Tables 5 to 7 summarize the nominal parameters taken into account for the optical design of SISSI instrument.

Table 4. Nominal parameters used for SISSI optical design.

Parameter	Value
Ground micropixel side (m)	15
Nominal altitude (km)	700
Super-resolved across-track spatial resolution (micromirrors)	1024
Across track swath (km)	15.36
Super-resolution factor (micropixels x micropixels)	4 x 4

Table 5. SLM parameters.

Parameter	Value
DMD	Texas Instruments DLP7000
Across-track DMD resolution (micromirrors)	1024
Along-track DMD resolution (micromirrors)	768
Pitch micromirror (µm)	13.68
Micromirror tilt mode	Diagonal
Micromirror tilt (degrees)	12°

Table 6. Collection optics optical parameters

Parameter	**Value**
Entrance pupil diameter (mm)	200.0
Nominal focal length (mm)	638.4
F-number	3.192
Back focal length (mm)	280.2

3.4 Condensing optics

The condensing optics (or condenser) collects the (binary coded) signal reflected by each group of 4 by 4 micromirrors (i.e. the micropixel) allowing its spatially integrated acquisition by each corresponding element on the detector. In such way, the image reflected by the DMD becomes the object plane for the condensing optics. The magnification ratio is consequently fixed by the side of a group of four mirrors and the side of a single element of the detector. Such parameter, together with the DMD to condensing optics distance, fixes both the pupil and the focal of the condensing optics.
The condensing optics has critical spatial constraints due to the DMD reflection. To avoid the condensing optics to collide with the primary mirror, firstly a plane mirror is used to fold the rays. A second folding mirror allows the image plane to be outside the reflection cone of the condensing optics.
The focusing element of the condensing optics consists of an aspheric mirror. A further free-form correction plate in CaF2 is used to reduce aberrations.

3.5 SISSI optical CAD

The optical cad of SISSI instrument is depicted in Figure 7. The use of a folding mirror avoids the collision of the reflected rays on the mechanical support of the primary mirror. A second folding mirrors is used for extracting the detector from the focusing cone of the aspheric mirror. It is worth to note the non-planarity due to the presence of DMD which reflects the light along a direction that does not lie in the plane of the incident optical axis. The use of folding mirrors avoids, respectively, the collision of the rays reflected by DMD with the primary mirror of the collection optics and (for the condensing-optics-focused rays) with the CaF2 corrector plate.

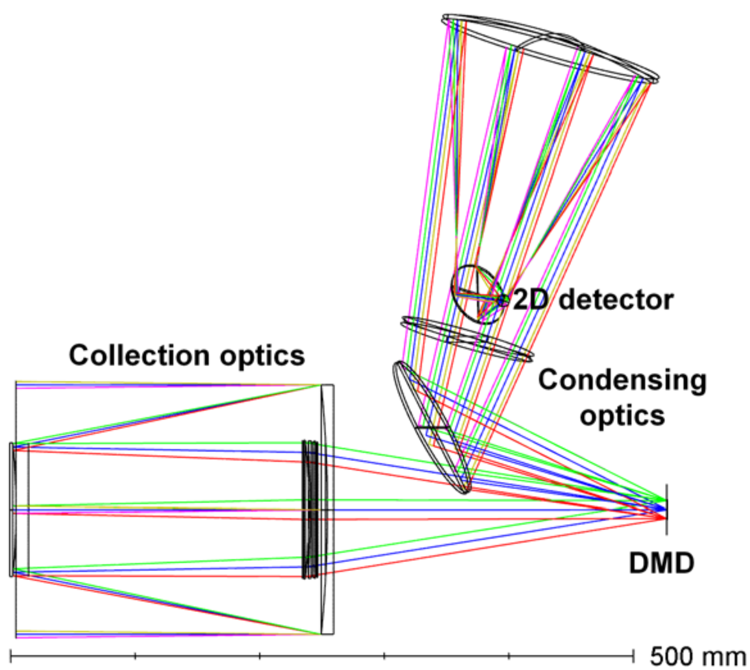

Figure 4. SISSI instrument 3D optical CAD.

The use of mirrors minimizes the chromatic aberration and maximize the overall transmittance of the optical system. For the lenses CaF2 was preferred, when possible, for maximizing the transmittance.

3.6 Performance evaluation

Part of the energy from the rays entering into the collection optics is spread on neighbouring micropixels, due to the extent of the spot radius being larger than a single micromirrors. The 95% of the total ensquared energy falls in the macropixel area (4 x 4 micromirrors). For the condensing optics, approximately the 85% of the energy falls into each single element of the detector.
Total transmissivity of SISSI instrument (Table 8) is less than 30% (without considering the loss due to DMD).
The transmissivity of the system is strongly influenced both by the glasses absorption (excluded the CaF_2), and by the collection optics vignetting. It is worth to note that the use of a non-vignetting, off-axis optics is strongly limited by the low value of the f-number of the system.
The technical feasibility of such a system is limited by the difficulties in manufacturing of collection optics lenses, having large diameter with respect to their thickness. Such design aimed at minimizing the absorption and maximizing the light throughput.
Also, the assembly of such prototype would require an accurate design of its mechanical mountings, together with a precise sensitivity analysis of the tolerance to vibrations of each single optical component of the system.

Table 7. Transmissivity of both collection and condensing optics of SISSI instrument. For the purpose of this simulation, only the optics transmission has been considered, as a consequence the DMD reflectivity is set to 1. Vignetting and glass absorption effects are included.

Wavelength (μm)	Transmissivity entrance pupil to DMD	Transmissivity DMD to detector	Total transmissivity (excluded DMD)
3.0	0.357	0.748	0.267
4.0	0.360	0.749	0.270
4.8	0.363	0.751	0.272
5.0	0.363	0.751	0.273
Average	0.361	0.750	0.271

4. CONCLUSIONS

The optical design of SISSI instrument satisfies the nominal requirements requested by its compressive sensing architecture, representing an example of a multispectral imager MWIR implementing super-resolution thanks to the use of a DMD.

The system can be ideally divided into a collection optics that focuses the scene on the DMD plane, and a condensing optics performing the spatial coding and integration on the detector.

During the design of SISSI instrument, the use of free-form optics was necessary for reducing the number of optical surfaces involved, thus maximizing the instrument transmissivity.

The optical elements envisaged during the design are in large part easy to manufacture, mount and align, with the exception of the collection optics lenses, having large diameter with respect to their thickness. Aspheric surfaces could lead to further difficulties in both feasibility and alignment.

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