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SISSI Project: A Feasibility Study for a Super Resolved Compressive Sensing Multispectral Imager in the Medium Infrared †

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Abstract: This paper describes the activities related to a feasibility study for an Earth observation optical payload, operating in the medium infrared, based on super-resolution and compressive sensing techniques. The presented activities are running in the framework of the ASI project SISSI, aiming to improve ground spatial resolution and mitigate saturation/blooming effects. The core of the payload is a spatial light modulator (SLM): a bidimensional array of micromirrors electronically actuated. Thanks to compressive sensing approach, the proposed payload eliminates the compression board, saving mass, memory and energy consumption.

Keywords: compressive sensing; earth observation; super-resolution; spatial resolution; medium infrared payload; hotspots; spatial light modulator

1. Introduction

The Mid Infrared (MIR) spectral region is important for different applications, ranging from agriculture to meteorological studies. Multispectral observations in the MIR are relevant for monitoring natural and anthropogenic hazards, in particular they gain relevance when performed at high spatial resolution [1]. One example is the characterization of high temperature events, such as volcanic events, that are improved when high spatial resolution is reached [2–4]. In the framework of the Italian Space Agency call "ASI 2018—Payloads", a feasibility study for a multispectral imager, operating in the medium infrared and based on super-resolution and compressive sensing (CS), was funded (SISSI—super resolved imaging spectrometer in the medium Infrared—project). The use of CS and super resolution aims to improve the performance of MIR optical payloads in terms of ground spatial sampling (Ground Sampling Distance—GSD) and to mitigate effects, such as saturation, that can affect the monitoring of high-temperature events (HTE). With the term 'super-resolution', we define a method for increasing the number of pixels of the final reconstructed radiance image with respect to the number of pixels of the detector used for its acquisition. The proposed approach is based on the use of a spatial light modulator (SLM), an array of electronically actuated micro-mirrors (MMA—micromirror Array). The CS approach foresees a compressed acquisition, in this way the compression board can be discarded, saving memory and energy consumption. CS also provides a data encryption feature, intrinsically protecting the acquired information. It is worth noting that the simplification on the on-board payload is moved to the ground segment, where the calculation constraints are less. The super-resolved image reconstruction is totally demanded to the ground station, allowing the transmission of a lighter data packet. Unlike other prototypes working at shorter wavelengths [5], the novelty of the SISSI payload lies in the MIR spectrally resolved acquisition, also investigating the use of an SLM as a spatial encoder in such spectral range. The study performed during the SISSI project is of great interest for the scientific community, both from an application and a technological point of view. The SISSI study could bring significant contributions to different scientific challenges [6].

2. Materials and Method

The schematics of SISSI instrument operation mode are depicted in Figure 1. The operating principle is the one of a single pixel [7] camera and CS architecture [8]: it uses a light modulation element SLM and a single pixel detector on which the modulated light is concentrated through a lens (condenser). Each acquisition (measurement) is given by the product between each element of the encoding binary pattern applied to the modulator and the corresponding element of the image focused on it. The condenser performs the subsequent integration on the single-pixel detector. On the basis of the sparseness of the acquired data, the initial image can be reconstructed with sufficient quality by making a number of measurements equal to or less than half of the pixels of the image to be reconstructed. In this way, CS acquisition merges acquisition and compression processes into a single step. Following the single pixel camera concept, the SISSI instrument performs a parallel acquisition of the images. Each detector pixel as a whole subtends an area of the scene on the ground corresponding to a macropixel on the SLM. Each SLM macropixel is made up of $N \times N$ micropixels, each of which corresponds to a micromirror of the SLM (Figure 1). Each group (macro-pixel) consists of $N \times N$ micro pixel (micromirrors) encoded by a binary mask, different for each frame. Each of the $M \times M$ elements of the detector acquires the signal coming from one of the $M \times M$ groups of $N \times N$ micromirrors. The $N \times N$ factor represents the super-resolution factor of the instrument. Each micropixel subtends to the ground a portion of the scene corresponding to the super-resolute GSD (Figure 1). The acquisition of the same scene in several spectral bands (data cube) is obtained thanks to the presence of spectral filters on the detector, arranged along the across-track dimension of the scene on several contiguous lines of the detector, and to the apparent movement of the scene in the direction along-track through the field of view (slitless push-broom acquisition). The SISSI instrument aims to achieve a super-resolution factor equal to 4×4.

The main characteristic of SISSI instruments are listed in Table 1. The SISSI payload is composed as follows: the optical module composed of collection optics, SLM, focusing optics, and a detector (2D detector array); and the electronic section made by HPU module (Head Power Unit), HPE module (Head Proximity Electronic), HDP module (Head Data Processing), and HCC module (Head Communication and Control). Concerning the CS algorithm, two different categories of reconstruction algorithms have been analyzed: traditional and based on deep learning. For this project, as the representative of the traditional algorithm the total variation (TV) pseudo-norm was chosen, while for the deep learning approach the convolutional neural network called ISTA-Net (ISTA-Net + in its improved version) was selected.

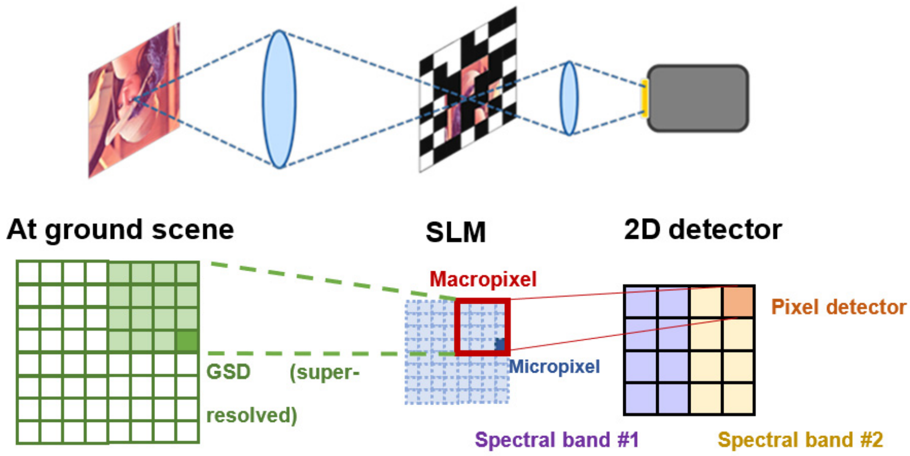


Figure 1. Schematic of SISSI operation mode.

Table 1. SISSI payload main characteristics.

Parameter	Value
Acquisition mode	Slitless push-broom
Operational working spectral range µm	3–5 (MWIR)
Nr. 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	4×4
Detector	MARS by Sofradir/Lynred
SLM	DMD® Texas Instruments Inc.

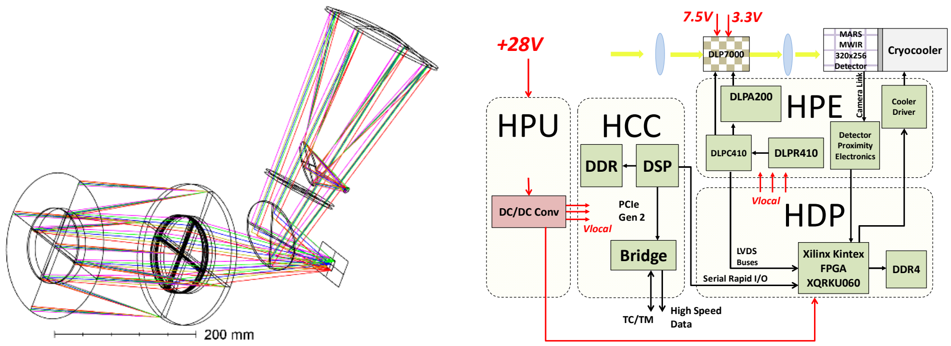
3. Results

With respect to future applications, the SISSI payload could give significant contributions to the applications listed in Table 2, all are relevant for ESA Living Planet Program.

Table 2. SISSI spectral bands and related applications.

Central Wavelength (µm)	Temperature Range (K)	Applications
3.3	300–1000	Detection CH_4
3.5	300–400	Background temperature
3.7	300–400	Background temperature
3.9	400–1000	(Detection N_2O), HTE
4.8	400–1000	Detection CO_2

The detailed design of the SISSI optical module is shown in Figure 2a, while the schematics of the electronic design are shown in Figure 2b.



(**a**) (**b**)

Figure 2. (**a**) Optical payload design and (**b**) electronic design.

In Figure 3 an example of image reconstruction is reported where reconstruction algorithms were tested using an image acquired by ASI-PRISMA hyperspectral instrument acquired over Trasimeno Lake (PG—Italy).

(**a**) (**b**) (**c**)

Figure 3. Image reconstruction: (**a**) image original, (**b**) macropixel 4 × 4, (**c**) macropixel 32 × 32.

4. Discussion

The proposal of the SISSI payload, with its characteristics, was principally motivated by the possibility to develop a payload in the MIR spectral range with high spatial resolution, especially tailored to the application reported in Table 2. The optical design was challenging due to the CS architecture and the considered spectral range; however, it has been completed meeting the project's requirements. Concerning the reconstruction algorithm for CS, innovative techniques were tested, such as deep learning, showing better results than traditional methods. A possible drawback of deep learning techniques is the training phase, that possibly needs a dataset with similar characteristics to the images that will be acquired by the SISSI. A reconstruction test carried out on PRISMA images shows a good quality, especially with macropixel of 4 × 4 micropixels.

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Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. ASI Workshop for MWIR-LWIR Mission Study. 2019. Available online: https://www.asi.it/event/mwir-lwir-mission-study/ (accessed on 8 September 2021).
2. Romaniello, V.; Spinetti, C.; Silvestri, M.; Buongiorno, M.F. A Sensitivity Study of the 4.8 µm Carbon Dioxide Absorption Band in the MWIR Spectral Range. *Remote Sens.* **2020**, *12*, 172. [CrossRef]

3. Wooster, M.J.; Roberts, G.; Perry, G.L.W. Retrieval of biomass combustion rate and totals from fire radiative power observations: FRP derivation and calibration relationships between biomass consumption and fire radiative energy release. *J. Geophys. Res.* **2005**, *110*, D24311. [CrossRef]
4. Lombardo, V.; Musacchio, M.; Buongiorno, M.F. Error Analysis of Subpixel Lava Temperature Measurements Using Infrared Remotely Sensed Data. *Geophys. J. Int.* **2012**, *191*, 112–125. [CrossRef]
5. Zhang, X.; Li, C.; Meng, Q.; Liu, S.; Zhang, Y.; Wang, J. Infrared Image Super Resolution by Combining Compressive Sensing and Deep Learning. *Sensors* **2018**, *18*, 2587. [CrossRef] [PubMed]
6. O'Neill, A.; Barber, D.; Bauer, P.; Dahlin, H.; Diament, M.; Hauglustaine, D.; Traon, P.-Y.; Mattia, F.; Mauser, W.; Merchant, C.; et al. *ESA's Living Planet Programme: Scientific Achievements and Future Challenges—Scientific Context of the Earth Observation Science Strategy for ESA*; ESA SP-1329/2; European Space Agency: Noordwijk, The Netherlands, 2015.
7. Digital Signal Processing (DSP) at Rice University. Available online: http://dsp.rice.edu/publications/ (accessed on 8 September 2021).
8. Candes, E.J.; Wakin, M. An introduction to compressive sampling. *IEEE Signal Process. Mag.* **2008**, *25*, 21–30. [CrossRef]