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Donatella Guzzi

Giulio Coluccia

Demetrio Labate

Cinzia Lastri

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Optical compressive sensing technologies for space applications: instrumental concepts and performance analysis

Donatella Guzzi[1], Giulio Coluccia[2], Demetrio Labate[3], Cinzia Lastri[1], Enrico Magli[2], Vanni Nardino[1], Lorenzo Palombi[1], Ivan Pippi[1], Daniela Coltuc[4], Alessandro Barducci[5], Alessandro Zuccaro Marchi[6], Valentina Raimondi[1*]

[1]*Consiglio Nazionale delle Ricerche – Istituto di Fisica Applicata "Nello Carrara" (CNR-IFAC), Via Madonna del Piano, 10 - 50019 Sesto Fiorentino (Firenze, Italy). e-mail: v.raimondi@ifac.cnr.it,*
[2]*Politecnico di Torino, DET, Corso Duca degli Abruzzi 24, 10129 Torino, Italy*
[3]*Leonardo-Company S.p.A.,Via Officine Galileo 1, 50013 Campi Bisenzio (FI), Italy*
[4]*University Politehnica of Bucharest, Research Centre for Spatial Information Splaiul Independentei 313, 060032 Bucharest, Romania*
[5]*SOFASI srl, Viale Alessandro Guidoni 139, 50127 Firenze (FI), Italy*
[6]*ESA-ESTEC, Keplerlaan 1, NL-2200AG Noordwijk, The Netherlands*

ABSTRACT

This paper presents the results of a study aimed at investigating the potential of Compressive Sensing (CS) technologies for optical space instruments. Besides assessing the pros and cons for a wide set of proposed instrumental concepts for space applications, the study analyzed in further detail two CS-based instrument concepts, each targeting a specific application: an UV-VIS hyperspectral imager on orbiter for stellar spectro-photometry and a MIR camera for sky observation and real-time detection of Near Earth Objects (NEO). The proposed UV-VIS hyperspectral imager relies on a classical CS approach and addresses the CS reconstruction of the full image in order to implement slitless spectro-photometry of stars. The CS-based MIR camera for NEO detection instead explores a novel approach aiming at information extraction without a prior full reconstruction of the image. Besides outlining the optical design of the instruments, its key elements and a pros and cons analysis of the architecture, this paper presents the performance assessment of these instruments for typical application scenarios by means of simulated data. The results showed that, from the point of view of data reconstruction quality, a good performance can be achieved by the designed instruments in terms of compression ratio (CR) and image reconstruction. In terms of system budgets, the CS architecture offered only some marginal benefits with respect to their traditional counterparts, mainly due to the lack of a compression board. Most advantages are instead provided in terms of downlink requirements and memory buffer.

Keywords: Compressive sensing, hyperspectral imaging, MIR camera, stellar spectrophotometry, NEO, DMD.

1. INTRODUCTION

CS theory, leveraging the concept of sparsity, affirms that a sparse signal can be efficiently reconstructed by the acquisition of a number of samples far below the minimal one dictated by Nyquist theorem, thus providing a new approach to data acquisition. CS, in fact, permits the design of efficient sensing or sampling protocols that capture the useful information content embedded in a sparse signal and compact it into a small amount of data.

Besides the inherent compression of data, CS approach enables the development of novel instrumental concepts, such as the single-pixel camera that can acquire an image using a single photodetector element instead of an array of detectors.

The CS approach becomes particularly appealing in those spectral regions where the availability of detector matrices is limited. On the whole, several space applications and related instruments could benefit from the CS approach, with a positive impact on system architecture, detector throughput and downlink bandwidth.

This paper presents the results of a study that investigated the potential of CS technologies for optical space instruments in different application domains: Space Science (SS), Planetary Exploration (PE) and Earth Observation (EO). The study was carried out under Optical Compressive Sensing Technologies for Space Applications (OCS-TECH) project funded by European Space Agency (ESA).

After a first stage focused on a review of optical CS technology and space applications, the project analyzed in detail two CS-based instrument concepts, each targeting a specific space application: an UV-VIS hyperspectral imager on orbiter for stellar spectrophotometry and a MIR camera for sky observation and real-time detection of NEO. The first instrument relies on a classical CS approach and addresses the reconstruction of the full image; the second instrumental concept explores a novel approach aiming at information extraction without a prior full reconstruction of the image. In this paper, the optical design of the instruments and their critical evaluation is presented. The performance assessment for both instruments is discussed for typical application scenarios by means of simulated data. From the point of view of data reconstruction quality, the results showed a good performance. With reference to system budgets, CS instruments offer some marginal benefits with respect to their traditional counterparts. Most advantages are instead provided in terms of downlink requirements and memory buffer. The knowledge gained during the project also suggested that CS technology can express its best potential when the instrument retrieves information on the acquired data through the use of specific CS signal processing techniques applied directly on-board.

2. STATE OF THE ART

2.1 State of the art of CS instruments

CS-based instruments essentially rely on the use of a 2-D Spatial Light Modulator (SLM) - which physically performs a element-by-element product between a random pattern and the incoming light - and of an optical assembly that concentrates the radiation on a single-element detector. In the last few years, several CS-based prototypal instruments have been developed, although the majority of them did not target space applications. The best known CS-prototype is the single-pixel camera developed at Rice University[1]. The intensive and well-funded research performed at Rice University has fostered the creation of a commercial company, the InView Technology Corporation (http://inviewcorp.com/), that presently produces and commercializes a SWIR camera based on CS technology. The company is also the owner of 23 patents and patent applications inherent to CS instruments development. Another project involving CS technology is the Compressive Optical MONTAGE Photography Initiative (COMP-I) funded under DARPA's MONTAGE program. The COMP-I project goals are to produce a miniaturized visible and LWIR camera[2]. The Georgia Institute of Technology has developed an original CS architecture that employs a standard 256x256 CMOS. The sensor and its interface circuitry have been combined with a complex computational circuitry that performs the domain transformation intrinsic in a CS-system[3]. High spatial and temporal resolutions are obtained in Chen *et al.*[4] by using an array of single pixel cameras that sense in parallel to increase the measurement rate. A proof-of-concept prototype using a sensor with 64× 64 pixels has been developed on this idea. Each sensor pixel is the detector for a single pixel camera, the light modulator being a larger Digital Micromirror Device (DMD), unique for the entire system. A different solution consisting in a lensless compressive imaging is proposed in Huang *et al.*[5] for VIS or IR spectral ranges. At present, there are not commercial CS-based imaging systems for the THz range: nonetheless, a series of prototypal cameras have been developed in the last decade. The major problem is represented by the SLM: DMD and Liquid Crystal Plate (LCP), which have shown great potential from the UV to the NIR, do not operate at longer wavelengths like those of THz domain. Recently, Si- and Ge-based modulators have been used in single pixel camera laboratory prototypes. They are optically controlled through a DMD or electrically driven. An interesting solution that overcomes the problem of low depth modulation is a modulator made up of metamaterials. Single pixel camera prototypes using metamaterials to implement the modulator are reported in Watts *et al.*[6] and Shrekenhamer *et al.*[7]. Images of 8x8 pixels have been obtained by CS.

Different studies have faced the problem of the application of CS to spectroscopic measurements and in particular to hyperspectral imaging[8-12]. Results coming from these studies have shown some advantages, but also several problems related to the use of CS in this field, such as the availability of large-size, high speed modulators. Some developments have led to patent registration, like the Tel-Aviv Digital Snapshot Spectral Imager[13]. Research in developing hyperspectral imaging system with CS technology is driven by the opportunity of reducing the data throughput of sensors, which can be challenging especially for satellite missions. Presently, CS-based instrumentation tailored to space applications has not yet been constructed, except for an ESA-funded study for the development of a laboratory demonstrator of a CS-based hyperspectral imager for Earth Observation[11].

2.2 State of the art of CS technology

The key components of a CS-based system are the SLM and the single-element detector. Such components are critical because the performance of the entire system depends on their characteristics. Both the switching speed of SLM and the detector frame rate are key parameters to obtain a good data quality, together with the sensitivity and noise figure of the detector.

The SLM is the component that physically implements the random pattern modulations foreseen by CS theory. Since CS paradigm requires the acquisition of a large number of measurements during a given integration time, the SLM must be fast enough to meet such requirement. The number of elements of the SLM is also a crucial parameter that affects the dimensions of the retrieved image. On the other hand, the computational burden for reconstruction algorithms depends on the number of pixels N to be reconstructed for each image. In general, a maximum number of pixels of 512x512 can be considered as a good tradeoff to obtain a good image quality, yet with an acceptable computational burden. Moreover, SLM cryogenic capabilities would be beneficial, especially for infrared spectral range applications.

Presently on the market there are three types of programmable SLMs:

- DMD characterized by speed up to 32 kHz, large format, up to 2048x1080 pixels; small elements of maximum 14x14 μm^2. They work only in reflection. Recently, this device was also tested for cryogenic operation (T~78°K)[14],

- Micro-Shutter Arrays (MSA) characterized by speed of few frames/s, small format (171x365), cryogenic capabilities (T~35°K), large elements of 100x200 μm^2. They work only in transmission.

- LCP characterized by speed up to 400 Hz, large format up to 4k pixels, non-cryogenic capabilities (T~230°K). They work in reflection or transmission.

The other key element of a CS-based system is the single pixel detector that physically performs the integration. The detector is less critical than the SLM, although high speed, large photosensitive area and low noise are requested for a good performance. Another key feature is the rise time of the detector response, the shorter the rise time the shorter is the time effectively available for a single measurement. In the following, a selection of single pixel detectors suitable for CS applications is listed:

- Silicon Photodiodes (from X-ray to NIR) are characterized by medium to fast rise times. Several studies have been carried out concerning their use for space applications.

- Photomultipliers (from VIS to NIR) are low noise detectors characterized by fast rise time. They are able to detect low-intensity signals. Several photomultipliers operating in the visible-near infrared range have been tested for space applications.

- Silicon Photomultipliers (from X-ray to NIR) are characterized by fast rise time and low light detection. They are able to detect low light signals down to the single-photon level.

- Avalanche Photo Detectors (Visible to MIR) are very low noise detectors characterized by fast rise time. They are able to detect low-light signals. In addition, a few of them are also space qualified.

- InGaA, InSb, PbS, PbSe Photodiodes (SWIR to MIR) are characterized by medium to fast rise time. They show high sensitivity and low dark current, but they need a cooling system to optimize their performances.

- Mercury Cadmium Telluride Photodiodes (from VIS to TIR) are low noise detectors characterized by medium to fast rise time. They are widely used for space applications, but they need to be cooled to optimize their performances.
- Bolometers (from MIR to TIR) are characterized by slow rise time. They are noisy sensors, but they do not need cooling.
- THz receivers can be divided into two broad classes: (1) incoherent detection systems, that permit only detection of amplitude and, as a rule, are broadband systems; and (2) coherent detection systems, that permit to detect both the amplitude and phase of the signal. In case of CS architecture, the most suitable sensors are pyroelectric, bolometer or semiconductor detectors. In general, the bolometer has to be preferred due to its highest sensitivity.

2.3 State of the art of CS reconstruction algorithms

Several image recovery algorithms from compressive measurements have been proposed in the literature, also for astronomical remote sensing[15]. They exploit the fact that the image is sparse in a given domain (wavelet, Discrete Cosine Transform (DCT), gradient domain, and so on) and attempt to perform the reconstruction via convex optimization using a l_1-norm penalty term[16]. Although interior point methods can be used to solve this convex optimization problem, they have high computational complexity and run in a time that is asymptotically polynomial ($O(N^3)$) in the number N of image pixels.

The most popular method in image reconstruction is to find the image consistent to the acquired data that minimizes the Total Variation (TV) pseudo norm. In Lustig *et al*.[17] the TV minimization is combined with the l_1-norm minimization of a sparsifying transform. This approach can be interpreted as requiring the image to be sparse by both the finite differences and the sparsifying transform.

To speed up the computation, iterative and greedy algorithms have been proposed to perform the optimization. Greedy algorithms, generally, build up an approximation to the solution one step at a time by making locally optimal choices at each step. One of the most popular greedy algorithms is Orthogonal Matching Pursuit (OMP)[18]. However, although greedy algorithms are extremely fast, they generally require a larger number of measurements, thereby worsening the CR.

3. INSTRUMENT CONCEPTS FOR SPACE APPLICATIONS

A set of CS instrumental concepts showing an expected significant advantage compared to a traditional counterpart system were identified on the basis of the results coming from the review of current space applications and the state of the art for the core component of a CS-based system.

The instrumental concepts listed in Table 1 were analyzed, with the aim of identifying the most promising ones. The following parameters were taken into account: available technologies, modulation methods and strategies, instrumental mass and power consumption, number and/or typology of components constituting the system. Data compression expected performance was also preliminarily assessed in terms of expected CR, reconstruction quality and processing time with respect to standard compression procedures.

Table 1. List of proposed Instrument Concepts

Instrument	Application domain	Spectral Range
UV-SWIR hyperspectral imager with tunable filters or dispersive elements on rover	PE	UV - SWIR
UV-MIR hyperspectral imager with tunable filters or dispersive elements on orbiter	PE	UV-MIR
UV-VIS optical camera with extended sensitivity on rover	PE	UV-VIS
EUV camera on orbiter	SS	EUV
UV-VIS hyperspectral imager with dispersive elements on orbiter	SS	UV-VIS
TIR Hyperspectral/Multispectral imager on rover	PE	TIR
TIR Hyperspectral/Multispectral imager on orbiter	PE	TIR

TIR Multispectral imager on nano/micro/minisatellite	EO	TIR
Punctual/whiskbroom spectrometer on rover for detecting the presence of pre-selected substances	PE	VIS - SWIR
Punctual/whiskbroom spectrometer on orbiter for detecting the presence of pre-selected substances	PE	UV-NIR
Camera operating in the MIR-TIR for sky observation and real-time detection of Near Earth Objects (NEO)	SS	MIR-TIR
Star-Tracker, with dual use for asteroids detection	SS	VIS
Pushbroom imager for thematic maps generation	EO	VIS - NIR
THz single-pixel imaging with a Si wafer based optical modulator and IR single-pixel imaging with a DMD based modulator	SS	THz, IR
CS-based atmospheric sounder for sub-millimeter wave band	EO	THz

Amongst these concepts, all the rover-based instruments offer the possibility to increase the total measurement time, and consequently the integration time for a single measure, which is a crucial parameter to obtain a good data quality after CS reconstruction. A CS approach is beneficial for instruments working in spectral regions such as IR e EUV/UV where large matrix detectors are not always available and, in any case, single pixel detectors are definitely cheaper. Several proposed applications are based on a novel approach to CS, relying on the information extraction rather than on a full reconstruction of image/signal.

Two out of the fifteen proposed concepts were selected for a preliminary optical design of the CS-based payload. In particular, this paper reports an overview of the preliminary design of a UV-VIS hyperspectral imager on orbiter for stellar spectrophotometry and of a CS-based camera working in the MIR for the on-board detection of NEO.

4. UV-VIS HYPERSPECTRAL IMAGER ON ORBITER FOR STELLAR SPECTROPHOTOMETRY

The proposed CS based instrument is an UV to VIS hyperspectral imager targeting space science applications. The instrument was conceived as an imaging spectrometer/photometer - working in the UV – VIS spectral range - implemented for slitless spectroscopic/photometric astronomy and operating from geostationary or sun-synchronous platform, with characteristics similar to the ones of STIS on Hubble Space Telescope (HST). The acquisition domain for this kind of instruments is highly sparse, thus allowing a good data quality even with high CRs, assuring a significant downlink bandwidth reduction. Moreover, a CS system does not need a compression board with a consequent reduction of system power consumption and mass. A schematic diagram of the instrument is shown in Figure 1. The payload is made up of the following main elements: the telescope, the prism imaging spectrometer, the SLM device, the condenser lens, and the single pixel detector. A Texas Instrument DMD was used as SLM. This device is characterized by micromirrors with a tilt angle of ±12°.

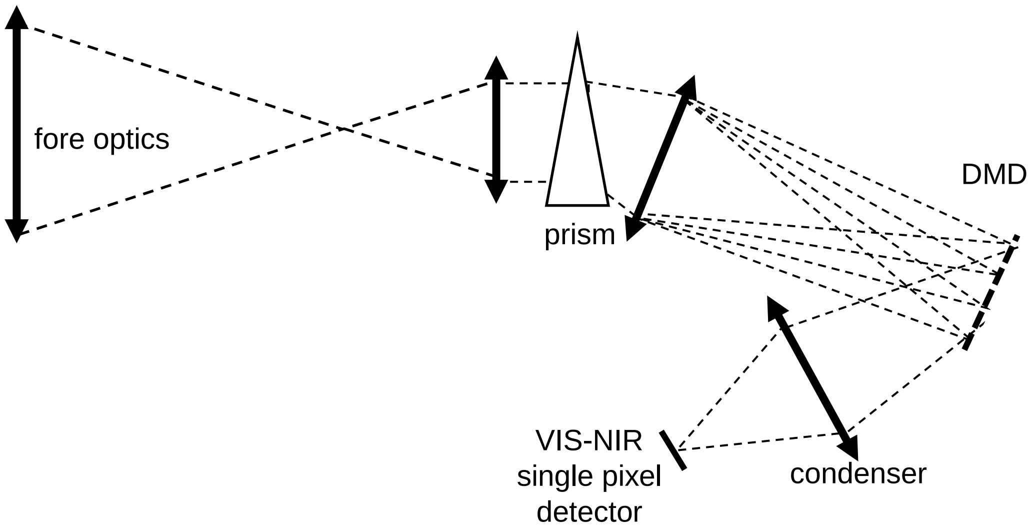
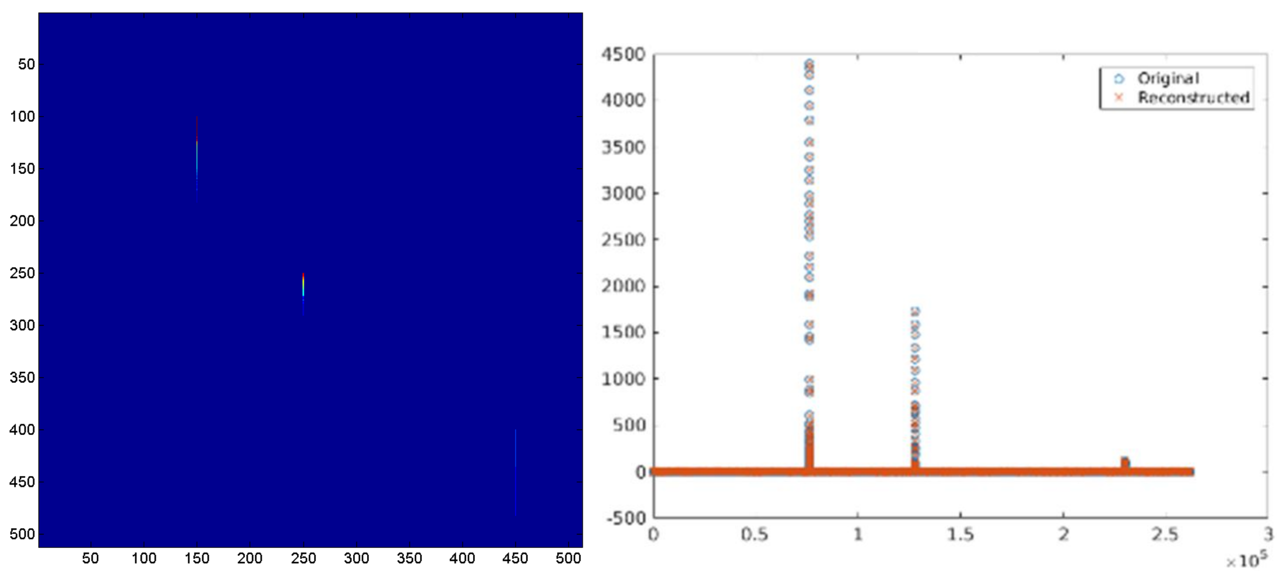


Figure 1. Schematic layout of the UV-VIS hyperspectral imager.



. (a) (b)

Figure 2: UV-VIS hyperspectral imager: (a) Original synthetic image, and (b) Reconstruction vs. original with CR =10.

Data simulation was carried out to evaluate the system performance and data quality after image reconstruction from a set of measurements using OMP[18]. In Figure 2, the original simulated image with three star spectra and reconstruction results for CR=10 (i.e. a number of measurements equal to 1/10 of the number of pixels of the original image) are reported; Figure 2b shows the original and reconstructed value of each pixel in Figure 2a in raster order. Figure 2b shows a good agreement between original and reconstructed data. This instrument relies on a classical implementation of the CS-techniques, addressing the full reconstruction of the image.

5. MIR CAMERA FOR THE DETECTION OF NEAR EARTH OBJECTS

The proposed instrument is a CS-based camera for sky observations performing on-board detection of moving objects (NEO). This instrument was conceived as a CS-counterpart of the WISE instrument[19]. This instrument relies on a novel concept that aims at joining a sky survey with image acquisition to the on-board detection of NEO. This approach is different from the classical data-mining and processing of the images at ground. The main advantages offered by this CS architecture consist in the use of a single pixel detector and in the possibility to apply techniques - derived from CS theory - directly on board. The last characteristic permits to obtain information on the NEO presence directly in the measurements domain, without reconstructing the images. The very sparse acquisition domain represented by star fields would permit to achieve high CRs, yet maintaining a good quality of the retrieved information and consequently a considerable downlink bandwidth reduction. Also in this case, the compression board is not needed. The schematic diagram of the proposed optical payload is reported in Figure 3.

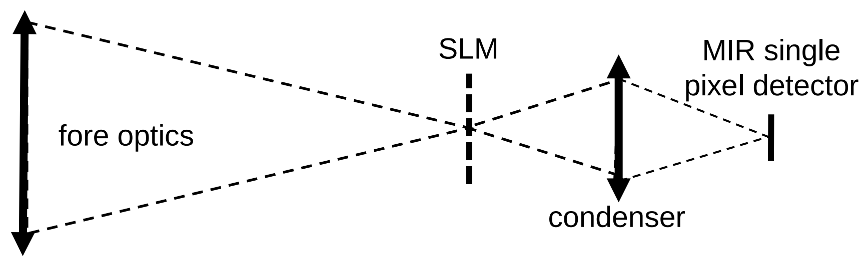
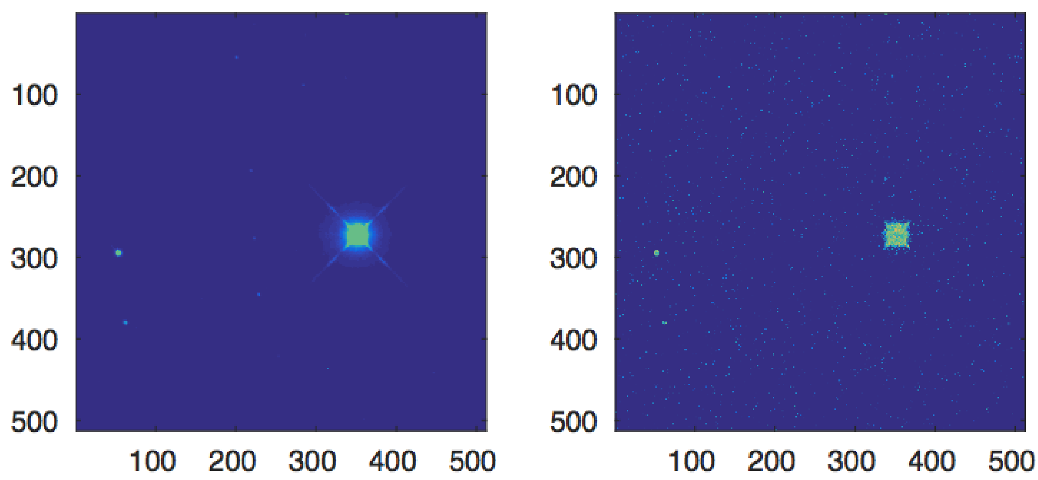


Figure 3. Schematic layout of the camera operating in the MIR-TIR for sky observations and real time detection of NEO.

The payload consists of the following main elements: a 50-cm telescope, a 512x512 pixel SLM, a condenser lens, a single pixel detector, a proximity electronic board, a temperature controller and coolers. The main drawbacks are the limitations posed by the working temperature of the SLM, which must be higher than 233°K for commercial DMD[20]. The background emission at such temperature is strong enough to affect the signal of interest, which can be very low. The system should be cooled to cryogenic temperatures in order to reduce the unwanted background contribution. MSA are cryogenic SLM devices, but their frame rate (3-4 Hz) is slow and would require accurate pointing stability of the platform for long time periods to fulfil the requirements of this application. A cryogenic DMD is under development at LAM-CNRS and EPFL[20,21], but its size of 32x64 micromirrors is actually too small for this applications. Recent studies have demonstrated that Texas Instrument commercial DMDs can tolerate cryogenic temperature without damage[14].



(a) (b)

Figure 4. MIR camera (a) Simulated image at the SLM: (a) image with a very large star and few small objects, and (b) Reconstruction from 10% samples using BCCB sensing matrix and OMP.

The acquisition process was tested using simulated images at the SLM with an operational temperature of 233° K and a procedure that mimics the CS acquisition. Starting from simulated acquisition employing Block Circulant sensing matrices with Circulant Blocks (BCCB), the images are reconstructed by OMP[17] by keeping only 10% of samples and exhibit a satisfying quality (Figure 4), although the reconstructed image shows some "noise" due to the presence of background emission. Further tests were made using *ad hoc* algorithms to detect the NEO without a full reconstruction of the image.

6. CONCLUSIONS

The performance assessment for two instruments based on CS approach has been presented. From the point of view of data reconstruction quality, the results showed a good performance of the designed instruments. With respect to their traditional counterparts however, CS instruments offer only some marginal benefits in terms of mass and power consumption, mainly due to the lack of a compression board. Major advantages are instead provided in terms of downlink requirements and memory buffer. The slitless spectrometer for stellar spectrophotometry adopts a more conservative approach and the technologies needed for its construction are all commercially available, enabling a possible prototype development. The MIR camera for NEO detection instead, although able to exploit the CS potential at its best for its capacity to retrieve information without a full reconstruction of the scene, is expected to operate at cryogenic temperatures to avoid background emission and this requires further development and test activity for key components like the DMD.

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