Spatial Light Modulator-Based Architecture to Implement a Super-Resolved Compressive Instrument for Earth Observation

SPATIAL LIGHT MODULATOR-BASED ARCHITECTURE TO IMPLEMENT A SUPER-RESOLVED COMPRESSIVE INSTRUMENT FOR EARTH OBSERVATION

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ABSTRACT

Due to a growing interest for imagery with high spatial and spectral resolution, Earth Observation sensors are producing increasing amounts of data. This poses a severe challenge in terms of computational, memory and transmission requirements. In order to overcome these limitations, a fascinating approach is the implementation of a compressive sensing architecture. In this paper, we present an instrumental concept based on the use of a spatial light modulator to implement a super-resolved, compressive demonstrator of an instrument aimed at Earth Observation in the visible and medium infrared spectral regions from geostationary platform.

Index Terms **—** Compressive sensing, Earth Observation, infrared spectrometer, super-resolution

1. INTRODUCTION

Earth Observation (EO) sensors are producing increasing amounts of data, due to a growing need for high spatial and spectral resolution dataset aimed at providing improved scientific and commercial products. The increase in amount of data implies demanding requirements in terms of computational and memory resources available on the onboard processing units, yet with limited power consumption budgets. In addition to this, the transmission system can become a bottleneck, preventing full exploitation of the acquired information [1].

In this context, signal processing techniques can play a role by providing information extraction from the acquired data and images directly onboard satellites. Among these techniques, Compressive Sensing (CS) can be regarded as one of the most interesting to address these issues [2].

In this paper, we present an instrumental concept based on the use of a spatial light modulator to implement a super-resolved, compressive demonstrator of an instrument aimed at EO in the visible (VIS), near-infrared (NIR), and medium infrared (MWIR) spectral regions from geostationary (GEO) platform. The demonstrator is under development in the frame of the SURPRISE project, recently funded under the H2020 programme. The project relies on the expertise from eight partners across Europe to implement a demonstrator of a super-spectral payload with enhanced performance in terms of at-ground spatial resolution, and featuring innovative on-board data processing and encryption functionalities.

2. COMPRESSIVE SENSING AND SPATIAL LIGHT MODULATORS

CS is a signal processing technique that, leveraging on the feature of many natural signals being highly correlated, can represent a signal (or image) through a small set of linear measurements:

$$y = \Phi x \tag{1}$$

where x is the signal of interest, Φ is a sensing matrix, and y is a vector of measurements having much fewer entries than x. Since Φ is typically chosen as a random matrix with independent and identically distributed entries (i.i.d.), y is also called a vector of random projections.

The sensing process relies on the assumption that the signal x is "sparse" in some domain, so that most coefficients are close to zero and only few can be retained to recover x exactly or with high fidelity by means of nonlinear reconstruction algorithms.

CS idea essentially relies on *a priori* knowledge about the signal's sparsity so that the signal can be reconstructed using fewer samples. In order to reduce final data volume, in a traditional signal compression approach, data is first sampled and then compressed. CS instead merges these two steps into a single step, thus reducing the volume of acquired signal samples.

CS relies on the acquisition of a set of spatially integrated measurements of the target, each corresponding to an integrated value of the image modulated by a suitable spatial coding mask. From an instrumental point of view, this is obtained by using a Spatial Light Modulator (SLM), typically implemented by means of an array of digitally driven micromirrors. This device physically implements the scalar product between a random pattern (coding mask) and the incoming light. The coded image is then integrated by an optical system and focused on a single element detector that acquires it. Signal reconstruction is performed by determining the sparsest signal that matches the measurements acquired. This last step can be performed by using linear programming techniques. A classical example of a CS instrument is the single-pixel camera, in which the CS paradigm is used for efficient computational imaging, e.g. reducing the number of detectors [3-5].

Another fascinating aspect of CS is the feasibility of information extraction directly from the acquired random projections [6]. This opens the possibility to on board data processing, without performing computationally heavy reconstruction at the ground segment.

Finally, CS can also be used as a cryptosystem, as shown in [7]. In this case, the sensing matrix acts as an encryption key. Native encryption is very interesting for space applications, since CS technology paves the way to the design of a class of innovative computational imaging instruments perfectly suited to "big data from space". Actually, CS paradigm natively offers the advantage of compression and encryption, enabling onboard data analysis, yet decreasing the computational burden on the onboard processing system.

In the literature, several CS-based instruments based on the CS paradigm were presented mainly addressing spectroscopic applications [3-5], while only few were specifically focused on space applications [8-11].

3. THE SURPRISE DEMONSTRATOR

The SURPRISE demonstrator aims at investigating the potential of a super-resolved, compressive architecture to enhance the performance of EO super-spectral payloads in the VIS-MWIR, with specific focus on their spatial resolution, on-board data processing and encryption capabilities.

The overall idea at the basis of the demonstrator's development relies on two pillars: 1) CS paradigm, used to optimise the data acquisition process and related processing and analysis steps; 2) SLM technology, used to implement the CS paradigm and achieve a super-resolution architecture.

Figure 1 shows a simplified diagram of the optical section of the demonstrator. The demonstrator is based on whiskbroom architecture. The observed scene is scanned along two axes. The fore optics provides the image of an area (target) of the observed scene on the SLM located at the fore optics image plane. The image captured in the instrument's instantaneous field of view (IFOV) and focused on the SLM surface will be named 'macro-pixel'. Each macro-pixel is made of several micro-pixels, each of which corresponds to one micromirror (or a set of binned micromirrors). The macro-pixel is modulated by a series of coding masks applied to the SLM. Depending on the number of SLM's micromirrors, the macro-pixel will be modulated at a higher spatial resolution.

In Figure 1 - for the sake of diagram's clarity - the SLM is supposed to work in transmission. The modulated image of the target (corresponding typically to 50% of the light) is collimated and filtered by a dichroic filter in order to separate the VIS-NIR from the MWIR light along two different optical paths. Both optical paths will be further split spectrally to implement the two channels in the MWIR spectral region. Different optical components will be used for the VIS-NIR channels and the MWIR channels:

- VIS-NIR channels are implemented by means of a spectrometer coupled to an array detector;
- MWIR channels are implemented according to a typical single-pixel camera architecture by using a beam splitter and spectral filters coupled to single pixel detectors.

An additional optical path is implemented by means of a removable mirror in order to redirect the image acquired by the fore-optics directly to a high-resolution camera. The latter is used to provide an alternative optical configuration and allow for a comparison between the image acquired by the high-resolution camera and the image reconstructed by using the super-resolution compressive architecture.

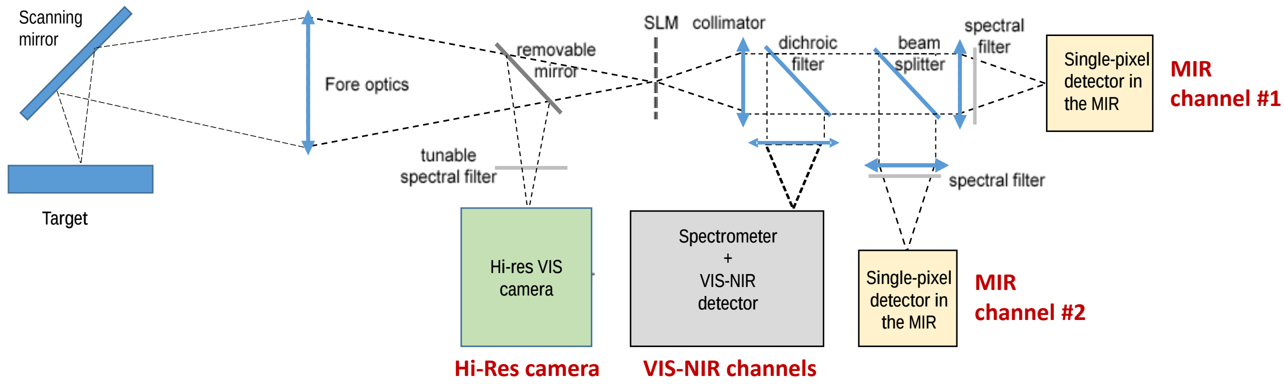

Figure 1 - Schematic diagram of the optical section of the demonstrator.

The acquisition of a series of measurements – each corresponding to the integrated value of the image modulated by a given coding mask applied to the SLM – is used for the reconstruction of a super-resolved image of the target by using suitable algorithms. The super-resolved image will feature a number of pixels equal to that applied to the SLM by the coding mask. Typically, in our demonstrator, we expect to achieve at least a 4-fold super-resolution factor. In addition, by applying the CS paradigm and leveraging on image sparsity, the image can be reconstructed by acquiring a total number of measurements smaller than the number of pixels of the reconstructed image. From preliminary tests, we expect to achieve Compression Ratio of 50%. Besides image reconstruction, we are also exploring the feasibility of information extraction directly from the acquired random projections, paving the way to on board data processing.

4. APPLICATION PRODUCTS AND IMPACT

The proposed concept is expected to bring significant improvements in terms of spatial resolution of geostationary observations, opening up new potential applications and services. Starting from the preliminary configuration of a geostationary platform-based SURPRISE-like payload with a 4-fold improved spatial resolution, we performed a preliminary analysis of the impact in several application fields, from meteorology to ocean color and land monitoring.

Meteorology would be a first target: with an improvement up to 4-fold of the spatial resolution compared to state-of-the-art instruments, the SLM would provide very valuable information for weather forecast. For instance, it would become possible to follow the path of storms and hurricanes with increased precision. Local weather and atmospheric phenomena would become accessible (e.g. over coastal, urban or mountainous areas). In general, we considered clouds and aerosols monitoring as a medium to high potential target for SURPRISE. Depending on the application, addressing this thematic can be covered at least partially by the necessity to retrieve atmospheric properties. Meteorological applications could highly benefit from the provision of medium spatial resolution.

Land monitoring requirements much preferably ask for very high spatial resolution combined to daily revisit, which do not match with the SURPRISE preliminary concept. However, sub-daily revisit, even combined with medium spatial resolution, from a GEO can be helpful for computation and/or validation of BRDF of ground targets (through variability according to solar illumination angle) as well as filling observation gaps in case of clouds superimposing the ground targets. We therefore consider land monitoring as another high potential target for SURPRISE.

Fire detection and monitoring could highly benefit from the improved spatial resolution. A GEO concept with (at least) medium resolution could be very valuable. The lack of TIR sensing ability must preferably be compensated, either by technological evolution of SLM, by synergy with another sensing device, or ground processing algorithms evolution (e.g. through synergy with other products). Despite this limitation, we consider fire monitoring as a high potential target for SURPRISE.

A GEO ocean color mission can be another potential concept for SURPRISE. Whereas VNIR spectral range is compulsory, additional UV and/or SWIR bands can be an advantage. Only fine spatial details for coastal waters and inland waters cannot be reached. Potential synergy with high spatial resolution LEO missions can be envisaged in a systemic approach, for which sub-hourly water monitoring would be most beneficial. We consider water monitoring as a high potential target for SURPRISE, although possibly challenging in terms of signal-to-noise ratio.

In conclusion, the main improvement obtained from SLM technology will be the access to super-resolution, which will alleviate the main shortcoming of the observation from GEO orbit, while still benefiting from the nearly continuous observation. Another interesting benefit is the native encryption offered by the compressed sensing technology, which could prove useful for sensible data (e.g. trans-boundary pollution events).

5. CONCLUSIONS

CS and SLM technology can enable the development of a novel class of EO instruments featuring enhanced capabilities in terms of spatial resolution, on-board data processing and encryption.

In the frame of the EU-funded SURPRISE project, a demonstrator of a super-resolved CS instrument is under development, whilst the relevant impact on EO application products is being investigated. The demonstrator relies on the use of a SLM as a core element of a compressive architecture to implement a super-resolved instrument working in the VIS- NIR and MWIR with at least a 4-fold increased spatial resolution.

6. ACKNOWLEDGEMENTS

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