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Development of systems and algorithms for a extreme high resolution compressive all-sky tracking camera (XCATCAM) for space situational awareness

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14. ABSTRACT
The continuous tracking of moving space objects for space situational awareness (SSA)—in particular space debris that is in low Earth orbit—demands an extreme resolution all-sky imaging system that has yet to exist, and if built, it would be at the expense of a colossal SWAP-C and a big data problem. Moving objects in a fixed background can be detected and tracked by difference imaging. However, the tracking information from the noticeable moving space objects in the sky is marginal—very sparse—in contrast with the full dimensionality of the space-time datacube where the objects' optical traces are embedded, turning the use of a traditional imaging system into a waste of sensing resources. The goal of this project is the development of the technology needed for a scalable wide field-of-view (FoV) compressive tracking system that is able to track the paths of moving objects in the sky at a very high spatial resolution using fewer sensing elements (pixels) than would be needed in conventional difference imaging. Based on compressed sensing and advances in computational imaging, we plan to develop the mathematical modeling for the forward and inverse compressive tracking problem, considering that the tracking information is contained into a sparse set of high resolution curves of the space-time datacube. The project also encompasses the search for the optimal spatial and temporal coding strategies for sampling the optical projections needed for effective compressive target tracking. Finally, we will implement a compressive tracking system by modifying an imaging camera with a phase-only spatial light modulator placed at the pupil plane, and perform on-sky demonstrations using a telescope mount to compensate for sidereal motion. An array of compressive tracking cameras will enable the envisioned extreme resolution compressive all-sky tracking camera (XCATCAM), that can result in a small/low SWAP-C tracking system that could be deployed all over the world, and will serve the SSA community for real time all sky coverage of moving space objects and debris, while also potentially benefiting the astronomy community in finding transient events.

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Final Performance Report for SOARD Grant FA9550-19-1-0293

"Development of Systems and Algorithms for an Extreme High Resolution Compressive All-Sky Tracking Camera (XCATCAM) for Space Situational Awareness"

July 1st 2022

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Abstract: In this report we summarize our accomplishments under Grant FA9550-19-1-0293. Recognizing that the continuous detection and tracking of moving space objects at low Earth orbits is a challenging and demanding task in terms of implementation costs and operational hassle due to the big data nature of the problem when solved via traditional imaging solutions, this project proposes the development of a scalable extreme high resolution compressive all-sky camera for space situational awareness purposes. Under the paradigm of computational imaging and the use of compressed sensing as a theoretical mathematical framework, the research is focused on the development of coding strategies to capture moving objects within a dense, high resolution space-time grid using low resolution, low-cost imaging detectors. As part of our research effort, we report on our findings for exploiting and expanding the rolling shutter mechanism—inherent in the readout circuitries of CMOS imaging detectors—as a potential coding strategy for compressed space-time datacubes. We also present findings in recovery algorithms for compressive measurements using different representation bases. Finally we show the prototype we have mounted to test the herein novel architectures in the sky in the near future.

The principal investigator for this effort is Professor Esteban Vera, assisted in the conduct of this research by a postdoc and several graduate and undergraduate research assistants.

I INTRODUCTION

Motivation

The continuous tracking of moving space objects for space situational awareness (SSA)—such as cubesats and space debris that are travelling in low Earth orbit (LEO)—would demand an extreme resolution all-sky imaging system. With current technology based on camera arrays, such a camera could be built at the expense of a colossal SWAP-C, which can be improved by using modern multiscale optics camera array solutions [1]. Thus, it is conceivable to scale a camera array towards a 1 arcsec resolution per pixel, leading to a one terapixel hemispherical all-sky camera. However, if this terapixel camera is ever built, and if it moreover works as a video camera, it will create an unforeseen big data problem in terms of data acquisition, transmission, storage and processing.

The detection of objects that are moving within a static background can be achieved by subtracting consecutive frames from a conventional image sequence. In particular for SSA, the tracking information from the noticeable moving space objects in the sky is marginal—very sparse—in contrast with the full dimensionality of the space-time datacube where the objects' optical traces are embedded, turning the use of a traditional imaging system into a waste of sensing resources. This fact gives raise to the potential use of computational imaging [2] design techniques to jointly optimize the sensing resources in terms of algorithms, sensors, and optics. Computational imaging exploits compressive sensing algorithms [3] as a tool to unify sensing and compression at once.

Objectives

Moving space objects can be regarded as point objects that follow curved trajectories in the space-time datacube. As the dimensionality of these trajectory curves is very sparse in contrast with the full dimensionality of the space-time datacube, the goal of this project is the development of the technology needed for a scalable wide FoV compressive tracking system able to track the paths of moving objects in the sky at a very high spatial resolution using fewer sensing elements (pixels) than would be needed in conventional difference imaging.

The specific objectives are:

1. (SG1) Develop the mathematical modeling for the forward and inverse compressive tracking problem considering the temporal dimension
2. (SG2) Develop optimal, but practical coding strategies for compressive target tracking
3. (SG3) Implement a XCATCAM prototype for laboratory tests and on-sky demonstrations

II. STATUS OF EFFORT

Based on compressed sensing and advances in computational imaging, we are developing the mathematical modeling for the forward and inverse compressive tracking problem, considering that the tracking information is contained into a sparse set of high-resolution curves of the space-time datacube. In this regard, our current efforts are devoted to the search of the optimal spatial and temporal coding strategies for sampling the optical projections needed for effective compressive target tracking. In this sense we have devised two development tracks for compressive coding, one at the electronic readout level, and the other at the optical coding level.

On the electronic coding side, and as an interesting alternative to lower down the costs of the proposed camera array system, we are exploring the use of cheap CMOS detectors with rolling shutter. Even though the rolling shutter is seen as a nuisance to imaging systems, we have developed ways for properly modelling its effect on the sampling of the space-time datacube, and devised algorithms on how to recover the information of moving objects from snapshots of a rolling shutter camera array. During this period, we completed the experimental setup and demonstration of the concept, finally publishing the results [A].

Inspired by the results, we moved further and proposed a modification to the rolling shutter mechanism, which by shuffling the order how the scanlines are built, we were able to recover richer motion information during a single shuffle rolling shutter snapshot. We devised a novel scheme for the coding design by using the concept of sphere packing, whereby we want to have as far as possible samples in the spacetime, assuring optimal coverage and thus reconstruction. After being successful with simulations, we implemented the idea emulating the coding via a DMD in the lab, and published our results [B].

On the optical coding side, we have pursuing studies on finding the optimal combinations of phase coded apertures. Given its success in lensless approaches, we started to consider the usage of optical diffusers to encode the optical tracking information. On top of that, we have investigated compressive recovery algorithms, finding a couple of suitable candidates to recover optical traces from compressive measurements. Also, we report on the different setups used for obtaining tracking information from a series of observing trials. Finally, we show our current setup for testing the newly designed imaging devices on sky, to be held in the near future.

III. RESEARCH AND DEVELOPMENT ACCOMPLISHMENTS

In this section we briefly describe our research and development performed during this reported year under this grant.

Compressive Rolling Shutter

During the first year, we studied the potential of cheap CMOS sensors for acquiring high-speed moving objects, which has been carried on by a Msc student as an integral part of his thesis defended at the beginning of 2021. Preliminary reported results were presented in a conference, and this time we are presenting the experimental proof-of-concept that allowed us to publish this idea in Optics Express [A].

CMOS sensors use the rolling shutter as an efficient means for reading out the measured pixels. Nonetheless, the rolling shutter generates unwanted artifacts when imaging dynamic scenes. This nuisance can be turned into an opportunity if we consider that each row of the array is exposed at different times, sampling the space-time volume electronically. Therefore, an array of synchronized cameras with CMOS sensors placed at different spatial orientations should provide with sufficient sampling diversity of the space-time datacube for extracting temporal information from snapshots.

To complement the simulations made in the previous term, we built the proposed camera array starting with two cameras oriented at 90 degrees from each other, observing the beam of an electronic oscilloscope. Results from the acquisition from the 2 cameras and reconstructed video frames are shown in Fig.1 (a) and (b), respectively.

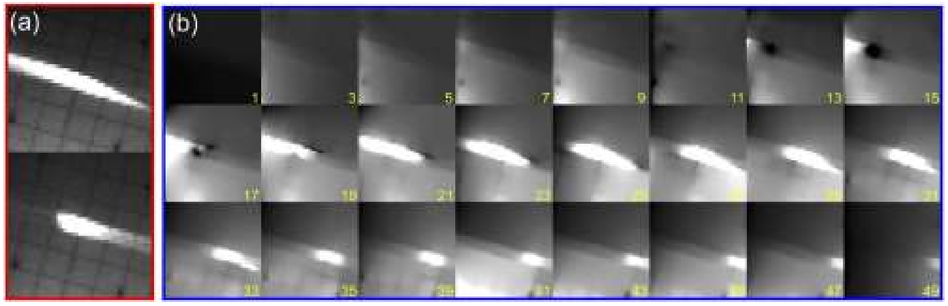

Fig.1 Experimental results of a simple moving scene captured with a two-camera array. (a) RS captured images with the camera oriented with angles of 0∘ and 90∘, respectively; (b) 24 out of 51 reconstructed frames.

Then, we extended the array to a 4 camera, all rotated 90 degrees from each other, thus improving the sampling diversity. Results observing videos of a sinusoidal and triangular waveform are reconstructed from the 4 snapshots, as seen in Fig.2.

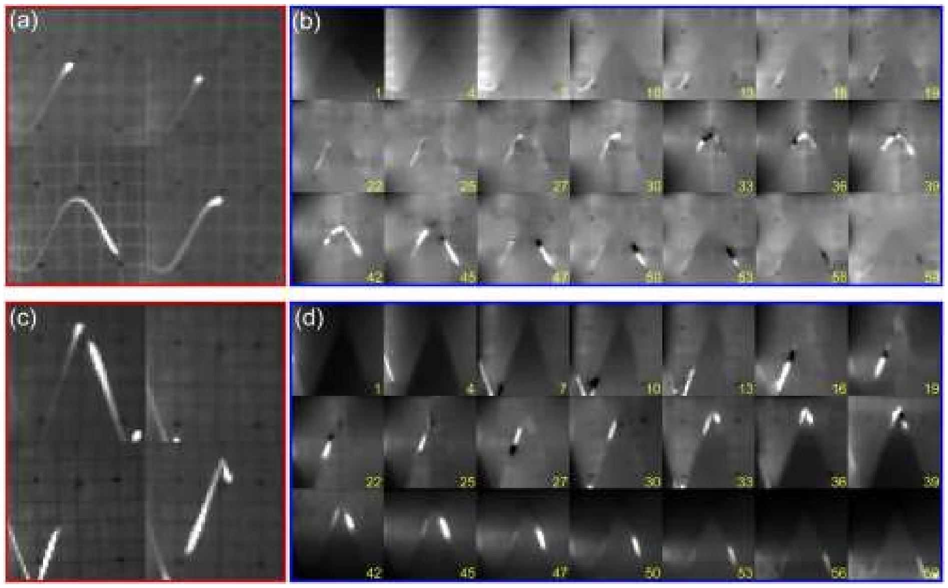

Fig.2 Experimental results for two different scenes using the 4-camera array. (top) Sine wave scene measurements (a) and reconstructed frames (b); (bottom) Triangular wave scene measurements (c) and reconstructed frames (d).

The proposed camera array can exploit the advantages of the rolling shutter as a form of temporal compression by taking advantage of the knowledge of the sampling scheme. We devise that this approach is a good starting point to sample the movement of natively sparse, fast-moving objects, without requiring high speed cameras.

Shuffled Rolling Shutter

Inspired by the idea that better sampling diversity in the space-time are helpful to reconstruct videos, we elucidated the idea of modifying the original rolling shutter mechanism. The rolling shutter works scanning row-by-row sequentially, and as when in our previous work, diversity can only be improved by adding more cameras. Therefore, why not modifying the mechanism in such a way that the row that is being scanned is not necessarily spatially continuous forming a line as before. In this way, at every new sampled row, we give opportunities for other spatial positions to be sampled as well instead of waiting until the last row is sampled. See Fig.3 to understand the proposed differences.

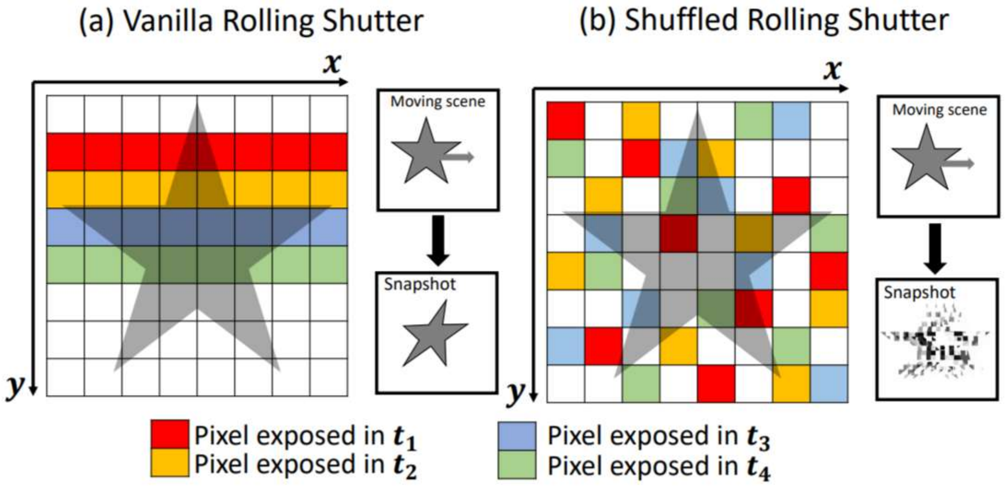

Fig.3 Spatio-temporal sampling scheme for the (a) normal rolling shutter and the (b) shuffled rolling shutter.

We devise that there are several ways on how we can shuffle the row position for every column, so one part of our preliminary study is to understand what sampling strategy could be more convenient, being random an option. We finally found that by maximizing the distance between the samples in the space-time, using a spahere packing optimization approach, we were able to obtain better results than random coding. Motion in the scene produce artifacts in the captured image of either the traditional or shuffled rolling shutter. However, we argue that it is easier to recover motion from the shuffled rolling shutter since it provides with better sampling diversity within the space-time datacube. As previously published in [C2], please observe how the image of a moving fan would look when using the proposed shuffled rolling shutter in Fig.4(a), and how we are able to retrieve video frames of the high-speed moving fan as seen in Fig.4(b).

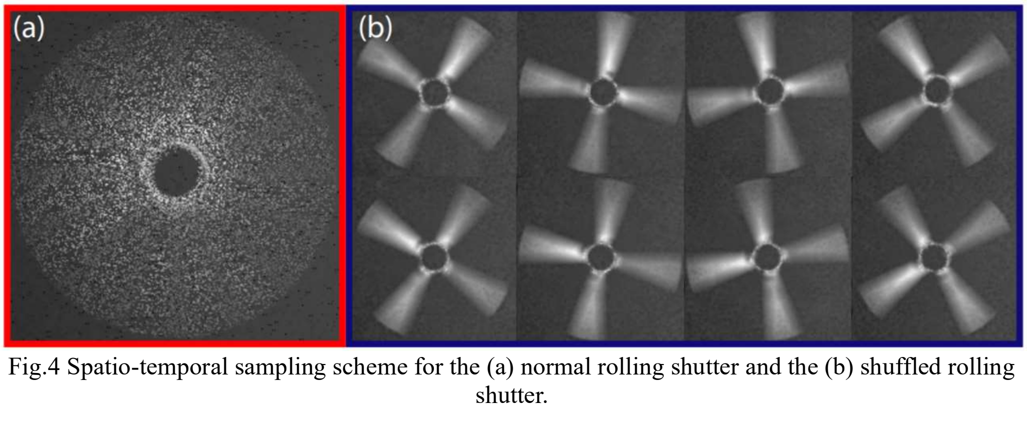

Fig.4 Spatio-temporal sampling scheme for the (a) normal rolling shutter and the (b) shuffled rolling shutter.

We implemented in the lab the compressive temporal system using a DMD, finally obtaining competitive results when compared to even an equivalent high-speed camera, as seen in Fig.5. These results were published in [B].

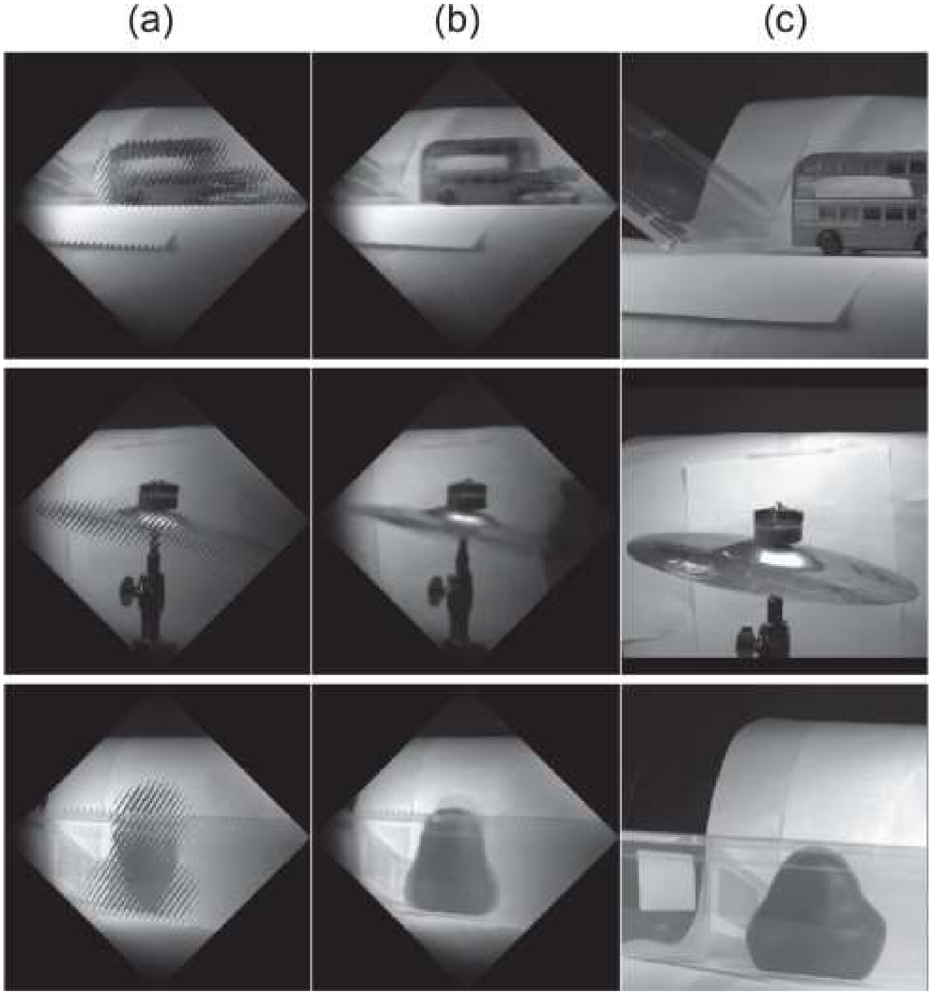

Fig.5 Capturing and recovery of high-speed videos from snapshots. (a) captured snapshot; (b) recovered videos; (c) videos from high-speed camera at 500fps

Compressive Sampling for tracking

One of our MSc students have been exploring sparse transforms that could be well suited to represent optical traces from moving objects in the sky. So far, we have devised to interesting transforms. Firstly, the Ridgelet transform, as a sort of generalization of the Wavelet transform, is able to separate portions of the image that follow lines, as shown in the filtered image in Fig.6.

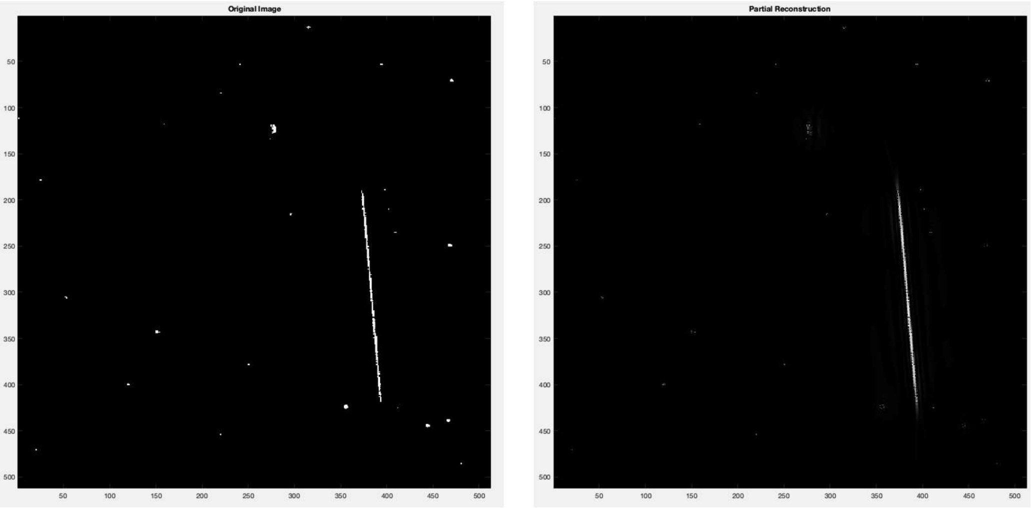

Fig.6 Ridgelet transform applied to a 30s exposure night sky image.

Secondly, and as seen in Fig.7, we have found that the Multiscale Component Analysis (MCA) could be a different option, this time based on a couple of dictionaries that can separate Gaussian distribution from line distributions within an image, which seems as a great fit to our problem for sparsifying optical traces. We can observe the results of applying MCA to a night sky image in Fig.8, where we can observe how the stars in the background can be separated from the optical traces that were generated by moving space objects in the scene during integration time.

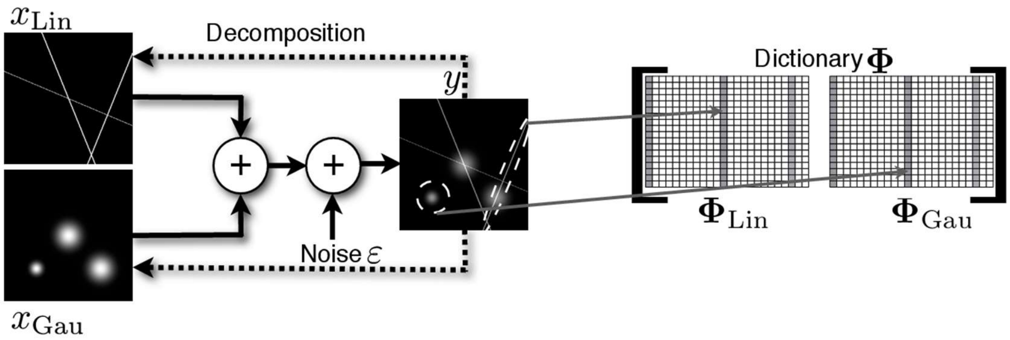

Fig.7 Multiscale Component Analysis scheme.

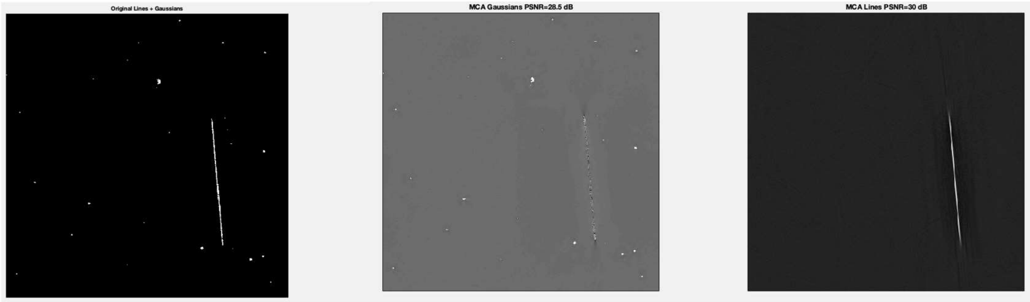

Fig.8 MCA applied to a real 30s exposure of the night sky. Notice that 2 images are generated splitting stars from optical traces.

Further work will include to test the ability of both sparse recovery algorithms to recover optical traces from compressive measurements obtained by adding a diffuser plate at the pupil plane of our telescope.

Hardware platform for the XCATCAM

Concurrently with the coding research effort at the hardware and optical level, we have been working on building the test platform for the on-sky demonstration of the XCATCAM once developed. Mounted on an equatorial mount, we now use a small telescope (250mm) attached to a 60Megapixel Sony CMOS cooled camera, so we can perform longer exposures without a big hit in singla-to-noise. A sample image of the system is shown in Fig.8, where we can observe the FoV and some optical traces left by a satellite. Notice that these images will be used as ground-truth to compare with our compressive tracking system.

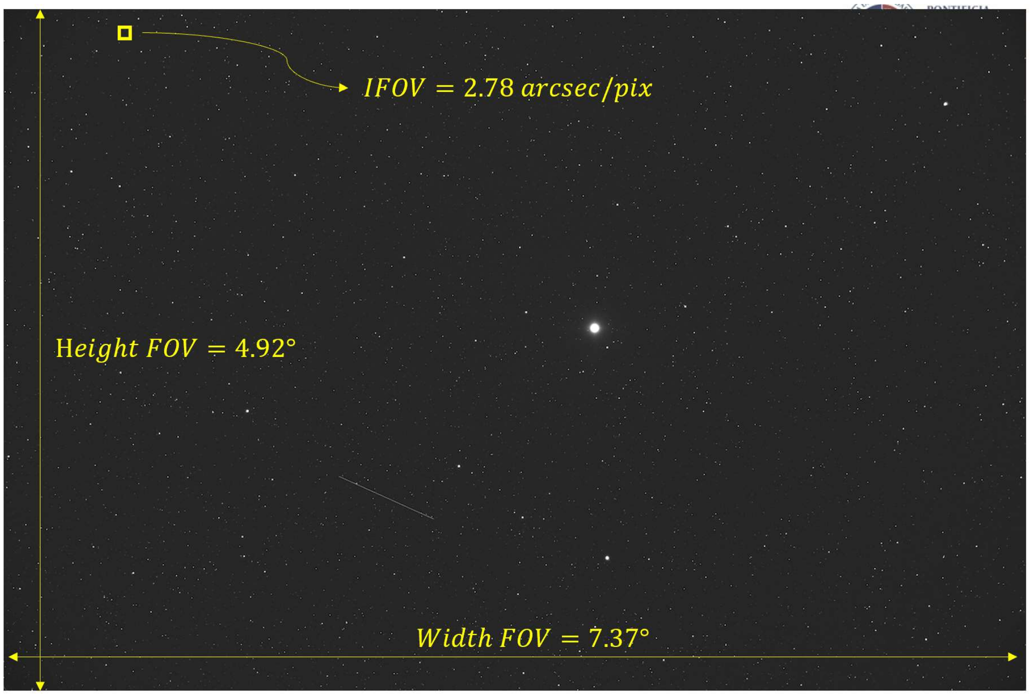

Fig. 8 Night sky picture using our testbed system using a 250mm telescope attached to a 60Mpixel Sony CMOS camera, all mounted on an automatic equatorial mount.

We are currently working on integrating our snaptshot compressive temporal imaging system in Fig.9 with the telescope in Fig.10.

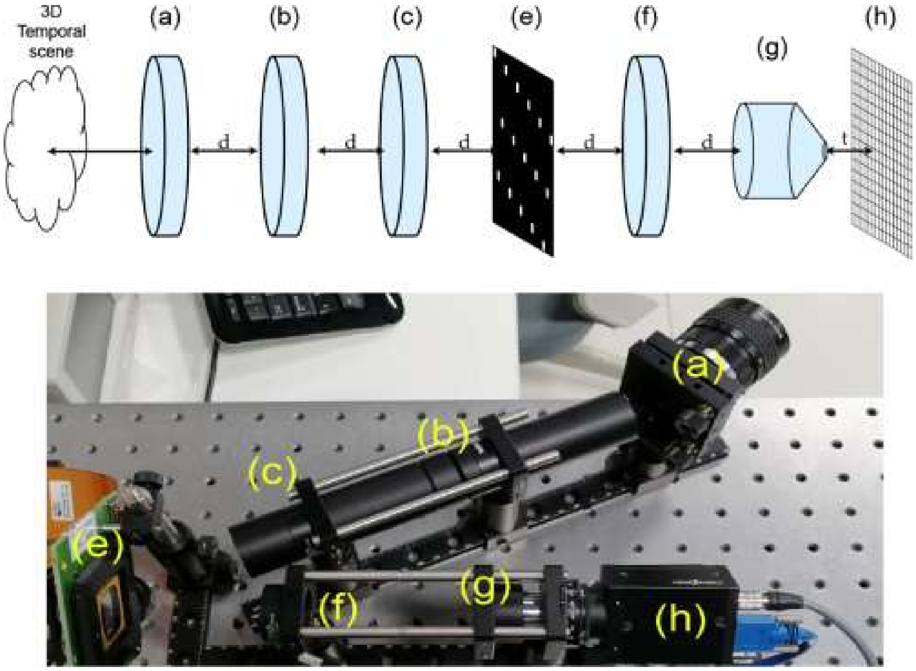

Fig. 9 Snapshot compressive temporal imaging using DMD.

V. PERSONNEL SUPPORTED

Dr. Esteban Vera, Principal Investigator
Dr. Nelson Diaz, Postdoctoral Research Associate (started March 2020)
Felipe Guzman, Phd in Electrical Engineering Thesis (started 1/2021)
Pablo Olguin, Msc in Electrical Engineering (finished 03/2022)
Vicente Westerhout, Electronics Engineering Undergraduate Thesis (started 1/2021)
Felipe Guzman, Msc in Electrical Engineering Thesis (finished 12/2020)
Pablo Olguin, Electronics Engineering Undergraduate Thesis (finished 12/2020)

VI. PUBLICATIONS

JOURNALS
[A] Felipe Guzmán, Pablo Meza, and Esteban Vera, "Compressive temporal imaging using a rolling shutter camera array," Opt. Express 29, 12787-12800 (2021)
[B] Esteban Vera, Felipe Guzmán, and Nelson Díaz, "Shuffled rolling shutter for snapshot temporal imaging," Opt. Express 30, 887-901 (2022)

CONFERENCE PROCEEDINGS
[C1] F. Guzmán and E. Vera, "Compressive Rolling Shutter Camera Array," in Imaging and Applied Optics Congress, OSA Technical Digest (Optica Publishing Group, 2020), paper CW4B.2.
[C2] F. Guzmán, N. Díaz, and E. Vera, "Improved Compressive Temporal Imaging

using a Shuffled Rolling Shutter," in OSA Optical Sensors and Sensing Congress 2021 (AIS, FTS, HISE, SENSORS, ES), paper JTh6A.9.

VI. CONCLUSIONS

In this project we pushed the state-of-the-art towards efficiently sampling the space-time datacube using different sampling schemes. First electronically, using the opportunities given by the rolling-shutter mechanism, and then by devising optical encoding strategies. Even though the system was tested with normal videos, by using the proposed shuffled rolling shutter scheme, it would be feasible to capture in a simgle shot a long integration of events that could cross the field-of-view when observing the night-sky. We envision to have a video recorded at 1 frame per hour to sufficiently capture the desired information. Reconstruction algorithms can later exploit either the Ridgelets transform, or even use neural network priors, to reconstruct for the optical traces in the space-time datacube, which will enable the capture of moving objects at high spatial resolution and wide coverage, using minimal sensing resources. The continuation of this project should include on-sky testing for validation purposes, which can later lead to a scalable solution for space situational surveillance.