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Space surveillance with correlation based radar

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<b>14. ABSTRACT</b> The purpose of this project is to develop, analyze, simulate and do a feasibility study of correlation-based radar for tracking and imaging fast moving objects in Low Earth Orbit (LEO). In the proposed tracking and imaging modality, illumination is ground-based, distributed and asynchronous, while the receivers are mounted on sparsely deployed drones at an altitude to minimize atmospheric effects. The feasibility study is in the X-band, with an important feature being the required accuracy of the recorded signals and their synchronization. The coherent cross correlations of these recorded signals are used for tracking and imaging with a theoretically predicted resolution in the wavelength range (3 cm). The theory also shows how atmospheric inhomogeneity effects are controlled by correlation-based imaging when the receivers (but not the illuminating sources) are at an altitude, roughly above the tropopause. The number of receivers needed is also addressed theoretically but signal-to-noise ratio issues will be addressed in this project as will be some different ways in which the cross correlations can be used so as to enhance received signal strength without reducing resolution. The key features of the proposed space surveillance modality are relatively inexpensive ground-based illumination (distributed, asynchronous), drone-based receivers that have some advanced technological requirements, and an effective and model-free way to minimize effects of inhomogeneities by using cross correlations.					
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## FINAL REPORT OF AFOSR GRANT FA95501810519

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This AFOSR-DESI grant was awarded in August 2018 for research on "Space surveillance with correlation-based radar". Along with the PI, George Papanicolaou, the research team members were: Howard Zebker, Electrical Engineering Department, Stanford University, Arlen Schmidt, Visor Corporation, Palo Alto, CA, Arnold Kim and Chrysoula Tsogka, Applied Math Unit, University of California, Merced. This two year grant ended in October 2021, after a one year no cost extension.

### Goals and Objectives

The main objective of this research was to advance the theory of correlation based imaging for synthetic aperture radar, especially for space surveillance of satellites, as well as using real data from a conventional synthetic aperture radar setup that attempted to assess the effect of using correlations. The experiments were designed and carried out by A. Schmidt and the data analysis by Stacie Huang, a Stanford PhD student in Electrical Engineering that graduated in June 2021. The theoretical objectives were to introduce more effective methods for denoising and deblurring images, especially in connection with satellite imaging.

### Work Completed

Although the theory advanced quite substantially, especially in publications [3] and [8] for satellite imaging, the experimental setup we used was limited to only two receivers and this in turn limited severely the scope of what could be done with cross correlations. This was a cost-based limitation since we could not afford a more elaborate, and more realistic, receiver setup. Nevertheless the benefits of using correlations were demonstrated in [10], which only covers a small part of the data and the calculations that were carried out. The detailed description of the experimental setup and the data acquired are available from A. Schmidt and the PI. The theoretical objectives were largely attained in publications [5] and [9] as we describe next.

### Results and New Findings

Regarding the theoretical part that involves image denoising, we point out publication [5] where a new techniques is introduced, the noise collector, that allows dealing with a much higher level of noise in images than was expected before. The noise collector attempts to estimate the noise in the image, that is, to image it as well before removing it. This

is a new and perhaps counter-intuitive idea, to the best of our knowledge, that might at first appear to be computationally too costly and hence prohibitive but in fact it is not as is shown in [5]. The noise collector technique is extended to correlation based imaging in [9] in a surprising way because at first it appears that all calculation are now to be carried at the square of the size of the image, a completely unrealistic prospect computationally. But again we show in [9] that the level of computation needed is comparable to that of the usual correlation based imaging. And now the noise level that can be tolerated and removed is much higher. A lot more can be done in this area and this is now research in progress. In satellite imaging we showed in [8] how to image the rotation of low earth orbit satellites in an effective way. Here too a lot more can be done, especially when dealing with constellations of satellites and relatively high noise levels.

### Impact

The main impact of this research is in theory at this time, paper [8] for satellite rotation estimation and [5] for denoising strong noise effects. But the noise collector ideas and techniques are likely to have much wider impact as we show in [9]. Impact will also come from using these techniques in connection with large constellations of satellites as they are used in communications at this time, and in imaging in the near future.

### Publications

- (1) Synthetic aperture imaging with intensity-only measurements, M. Moscoso, A. Novikov, G. Papanicolaou and C. Tsogka, IEEE Computational Imaging, DOI: 10.1109/TCI.2019.2919272, pp. 87-94 (2019)
- (2) Low rank plus sparse decomposition of synthetic aperture radar data for target imaging, M. Leibovich, G. Papanicolaou and C. Tsogka, IEEE Computational Imaging, DOI: 10.1109/TCI.2019.2956879, pp. 491-502 (2019)
- (3) Generalized correlation based Imaging for satellites, Matan Leibovich, George Papanicolaou, and Chrysoula Tsogka, SIAM J. Imaging Sci., 13(3), pp. 1331–1366. (2020)
- (4) Synthetic aperture imaging and motion estimation using tensor methods, Matan Leibovich, George Papanicolaou, and Chrysoula Tsogka, SIAM Journal on Imaging Sciences 13 (4), pp. 2213-2249 (2020)
- (5) The Noise Collector for sparse recovery in high dimensions, M. Moscoso, A. Novikov, G. Papanicolaou and C. Tsogka, PNAS, Vol. 117 (21), pp. 11226-11232 (2020)
- (6) Imaging with highly incomplete and corrupted data, M. Moscoso, A. Novikov, G. Papanicolaou and C. Tsogka, Inverse Problems, DOI: 10.1088/1361-6420/ab5a21 (2020)
- (7) Three-dimensional imaging from single-element holographic data, M. Moscoso, A. Novikov, G. Papanicolaou, and C. Tsogka, Journal of the Optical Society of America A, Vol. 38, Issue 2, pp. A1-A6 (2021)

- (8) Correlation based Imaging for rotating satellites, Matan Leibovich, George Papanicolaou, and Chrysoula Tsogka, *SIAM Journal on Imaging Sciences* 14 (1), 271-303 (2021)
- (9) Fast signal recovery from quadratic measurements, Miguel Moscoso, Alexei Novikov, George Papanicolaou and Chrysoula Tsogka, *IEEE Transactions on Signal Processing* 69, pp. 2042-2055 (2021)
- (10) S. Huang, H. A. Zebker, A. Nguyen, G. Papanicolaou and A. Schmidt, "Performance of Correlation-Based Imaging with a Bistatic Configuration Toward Resilient Multistatic Imaging of Space Debris," 2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS, Brussels, Belgium, 2021, pp. 2707-2710, doi: 10.1109/IGARSS47720.2021.9553595.