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Intensity-Only Synthetic Aperture Radar Imaging

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Final Report

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14. ABSTRACT
PI Kim and Co-PI Tsogka have worked on developing and analyzing the performance of efficient and robust algorithms for solving the inverse scattering problem in complex media. The major advances of this work pertain to imaging using intensity-only measurements. By leveraging diversity created by adequate multiple illuminations of the imaging region and using the polarization identity, i.e. an explicit algebraic relation that relates the inner product of two complex vectors to
norms of those vectors, intensity measurements are converted to interferometric measurements. Diversity in the illuminations may be created by considering multiple frequencies, plane-waves with different angles of incidence, multiple source locations or combinations of the above. Once the interferometric measurements are recovered, imaging maybe performed using traditional L2-methods, MUSIC, or sparsity promoting L1-minimization. The main advantage of the developed methodology is that there is no need for phase retrieval. Moreover, this approach reconstructs images over the entire imaging region simultaneously. There is no scanning or slicing of the region required. The method is general and should be useful for a broad variety of intensity-only inverse scattering problems ranging from microwave to optical imaging regimes. Major accomplishments of this project are 19 publications of original research with 3 additional manuscripts submitted for
publication. The PI and Co-PI also gave numerous presentations of this research at professional conferences and hosted mini-symposia to foster collaborations with other leading researchers. Additionally, this project helped to support a graduate student, Omar DeGuchy, on the application of machine learning to synthetic aperture radar imaging problems.

15. SUBJECT TERMS
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Final Report for AFOSR Grant FA9550-17-1-0238

Arnold D. Kim and Chrysoula Tsogka

September 1, 2020

Accomplishments

Over the grant award period, Kim and Tsogka have worked on developing and analyzing the performance of efficient and robust algorithms for solving the inverse scattering problem in complex media as indicated by the list of publications (appeared and submitted) given below.

We want in particular to emphasize our major advances on imaging using intensity-only measurements. By leveraging diversity created by adequate multiple illuminations of the imaging region and using the polarization identity, *i.e.* an explicit algebraic relation that relates the inner product of two complex vectors to norms of those vectors, intensity measurements are converted to interferometric measurements. Diversity in the illuminations may be created by considering multiple frequencies, plane-waves with different angles of incidence, multiple source locations or combinations of the above (cf. [6, 9, 10, 21]). Once the interferometric measurements are recovered, imaging maybe performed using traditional ℓ_2-methods, MUSIC, or sparsity promoting ℓ_1-minimization. The main advantage of the developed methodology is that there is no need for phase retrieval. Moreover, this approach reconstructs images over the entire imaging region simultaneously. There is no scanning or slicing of the region required. The method is general and should be useful for a broad variety of intensity-only inverse scattering problems ranging from microwave to optical imaging regimes.

A challenging imaging setup arises for the synthetic aperture problem when a single transmitter/receiver is used to collect intensity measurements. In this setting the field cross-correlations are asynchronized over the measurement locations, so the proposed method needs to align them first in order to image coherently. In [10, 21] an algorithm that allows to synchronize field cross-correlations at different locations has been proposed and analyzed. This enables us to recover the interferometric data up to a single global phase that is common to all measurement locations. Therefore the recovered data are coherent over space and frequency and they can be consequently used to form high-resolution three dimensional images.

We note that our publication [9] was selected for *Spotlights in Optics*, which showcases only two publications each month produced in Optical Society of America journals. The summary written by David Paganin is given below.

Kac's famous question, of how one might hear the shape of a drum, has an optical analog that is addressed in the present paper. Authors Kim and Tsogka develop and implement a means to see the shapes and locations of multiple scattering objects, using intensity measurements of scalar optical fields that are taken over a single plane. This approach to the optical inverse-scattering problem employs source diversity via a set of plane-wave illuminations at different angles of incidence. An algebraic relation, dating back to a 1935 paper by Jordan and von Neumann, is then employed to convert the scattered intensity measurements to effective interferometric measurements. These effective interferograms are the key stepping stone via which the shapes and locations of the scatterers are subsequently determined. The method is elegant, effective, and ingenious. I warmly recommend this paper to your attention.

Over the award period, Kim and Tsogka have actively encouraged UC Merced Applied Math graduate students to apply to the Autonomy Technology Research Center Summer Program. The following UC Merced students were accepted into this summer program.

- 2018 – Omar DeGuchy (Ph.D. 2020)
- 2019 – Jacqueline Alvarez, Ashley De Luna (M.S. 2020), Ali Heydari, and Alex Ho
- 2020 – Jacqueline Alvarez

All these students have reported very positive experiences with this summer program. We look forward to sending more of our graduate students to this summer program in the future.

Another positive accomplishment of this project is that our results have led us to pursue many new avenues of research. For example, we are currently developing and testing methods that open the capability to use MUSIC for SAR imaging problems. Our modification of MUSIC offers a effective and robust imaging method with high resolution and good stability properties. Additionally, we have begun to study subsurface imaging problems in which targets are located beneath an interface separating two different media. There are several important applications for this problem that are of interest to the Air Force. Some examples include detection of wells and tunnels, assessment of bunkers, interrupting power or fuel lines, and targeting of camouflaged objects. These problems are challenging because important information about the target is lost by reflection and transmission of waves across the interface. Frequency-dependent absorption makes the inverse problem even harder, as the Greens function is now decaying exponentially with distance. Using the methods we have developed in this project, we have been developing a theoretical and computational framework to study forward and inverse scattering problems for subsurface imaging. We will be submitting a proposal to the AFOSR this fall with our research plan concerning this problem.

List of publications over the grant period

1. C. Tsogka, D. Mitsoudis and S. Papadimitropoulos, "Imaging extended reflectors in a terminating waveguide," SIAM J. Imaging Sci., **11**(2), 16801716 (2018).

2. L. Borcea, E. Karasmani and C. Tsogka, "Incoherent source localization in random acoustic waveguides," Waves in Random and Complex Media, 1-26, 2018.

3. J. Fournier, J. Garnier, G. Papanicolaou and C. Tsogka, "Correlation-based imaging of fast moving objects using a sparse network of passive receivers," in proceedings of 52nd Asilomar Conference on Signals, Systems, and Computers, 1618-1622 (2018).

4. C. Carvalho, S. Khatri, and A. D. Kim, "Asymptotic analysis for close evaluation of layer potentials" J. Comput. Phys. **355** (15), 327-341 (2018) (https://doi.org/10.1016/j.jcp.2017.11.015).

5. P. González-Rodríguez, A. D. Kim, M. Moscoso, and C. Tsogka, "Quantitative subsurface imaging in strongly scattering media," Opt. Express, **26**(21), 27346-27357 (2018).

6. M. Moscoso, A. Novikov, G. Papanicolaou and C. Tsogka, "Robust multifrequency imaging with MUSIC," Inverse Problems, **35**(1), 015007 (2018).

7. J. Fournier, J. Garnier, G. Papanicolaou and C. Tsogka, "Matched-filter and correlation-based imaging for fast moving objects using a sparse network of receivers" SIAM Journal on Imaging Sciences, **10**(4), 2165-2216 (2017).

8. B. Ilan and A. D. Kim, "Radiative transfer of light in strongly scattering media," *Light Scattering Reviews, vol. 3: Radiative Transfer and Light Scattering*, A. Kokhanovsky, ed. (Springer, 2019).

9. A. D. Kim and C. Tsogka, "Intensity-only inverse scattering with MUSIC," *Journal of the Optical Society of America A* **36**, 1829-1837 (2019). [This paper was selected for Spotlights in Optics (`https://www.osapublishing.org/spotlight/summary.cfm?id=421989`)]

10. M. Moscoso, A. Novikov, G. Papanicolaou and C. Tsogka, "Synthetic aperture imaging with intensity only measurements," *IEEE Transactions on Computational Imaging,* **6**, pp. 87-94, 2020.

11. M. Moscoso, A. Novikov, G. Papanicolaou and C. Tsogka, "Imaging with highly incomplete and corrupted data," *Inverse Problems*, **36**(3), 035010 (2020) (https://doi.org/10.1088/1361-6420/ab5a21)

12. M. Moscoso, A. Novikov, G. Papanicolaou and C. Tsogka, "The Noise Collector for sparse recovery in high dimensions," *Proceedings of the National Academy of Sciences* **117** (21), 11226-11232 (2020) (https://doi.org/10.1073/pnas.1913995117)

13. M. Leibovich, G. Papanicolaou and C. Tsogka, "Low Rank Plus Sparse Decomposition of Synthetic Aperture Radar Data for Target Imaging," *IEEE Transactions on Computational Imaging*, **6**, pp. 491-502, 2020.

14. C. Carvalho, S. Khatri, and A. D. Kim, "Asymptotic approximation for the close evaluation of double-layer potentials," *SIAM Journal on Scientific Computing* **42**, A504-A533 (2020) (https://doi.org/10.1137/18M1218698).

15. O. DeGuchy, J. Alvarez, A. D. Kim, R. Marcia and C. Tsogka, "Forward and inverse scattering in synthetic aperture radar using machine learning," *Proc. SPIE 11511, Applications of Machine Learning 2020,* 115110S (19 August 2020) (https://doi.org/10.1117/12.2568302)

16. Md. I. Khan, S. Ghosh, R. Baxter, and A. D. Kim, "Modeling broadband cloaking using 3D nano-assembled plasmonic meta structures," *Optics Express* **28**, 22732-22747 (2020) (https://doi.org/10.1364/OE.395840).

17. M. Leibovich, G. Papanicolaou and C. Tsogka, "Generalized correlation based imaging for satellites," *to appear in SIAM Journal Imaging Sciences.*

18. C. Tsogka, D. A. Mitsoudis and S. Papadimitropoulos, "Imaging in three-dimensional waveguides with partial aperture data," *to appear in Journal of Theoretical and Computational Acoustics.*

19. S. Khatri, A. D. Kim, R. Cortez, and C. Carvalho, "Close evaluation of layer potentials in three dimensions," *to appear in Journal of Computational Physics.*

Manuscripts submitted for publication

20. M. Leibovich, G. Papanicolaou and C. Tsogka, "Low rank plus sparse decomposition of synthetic aperture radar data for target imaging and tracking," submitted, 2019.

21. M. Leibovich, G. Papanicolaou and C. Tsogka, "Correlation based Imaging for rotating satellites," submitted, 2020.

22. M. Moscoso, A. Novikov, G. Papanicolaou and C. Tsogka, "Three dimensional imaging from single element holographic data," submitted, 2020.