SMWD 2023, KTH Royal Institute of Technology, Stockholm, 23rd - 25th May 2023

THz SAR Image Autofocusing based on the Integration of Compressed Sensing into the Backprojection Process

Yevhen Ivanenko*(1), Viet T. Vu(1), and Mats I. Pettersson(1)
(1) Department of Mathematics and Natural Sciences, Blekinge Institute of Technology, 37179 Karlskrona, Sweden
{yevhen.ivanenko,viet.thuy.vu,mats.pettersson}@bth.se

1 Introduction

Exploration of THz frequencies provides opportunities for the realization of new applications in future 6G systems. One of the potential applications is short-range high-resolution remote sensing, which is of great interest in the area of logistics, security, and indoor imaging. To perform remote sensing with high resolution, the synthetic aperture radar (SAR) principle can be used.

THz SAR imaging is an active research topic with the aim of designing an imaging system that can be mounted on various dynamic platforms. The current state-of-the-art THz SAR systems include ground- and rail-based realizations. Different THz SAR systems have been developed to perform high-resolution imaging at frequencies up to 1.1 THz; see [1–9] for details.

The performance of THz SAR imaging systems is sensitive to phase errors. Practically, phase errors occur due to path deviations, which can be caused by platform vibrations, speed variations of SAR platforms, accelerations, etc. To handle this issue, the backprojection algorithms [10–12] are natural solutions for THz SAR imaging systems due to their internal motion-compensation procedure, which is efficient if the deviation information is a priori known. However, if the path deviation is unknown, an additional motion-compensation procedure as an add-on to the backprojection algorithms is necessary. This refers to autofocusing.

In this presentation, we propose an autofocusing algorithm based on compressed sensing, which is incorporated into the backprojection algorithm as a natural extension. The algorithm eliminates phase errors based on the optimization procedure for a single range bin. The components of the backprojection algorithm, such as the interpolation sinc kernel and range distance between the SAR platform and a point in the image plane, are used under the construction of the sensing matrix.

2 Problem Formulation

In practice, modern frequency-modulated continuous wave (FMCW) SAR systems, which operate at THz frequencies and can potentially be mounted on UAV platforms, can be sensitive to phase errors due to path deviation, e.g., caused by platform vibrations. Consider a setup for two-dimensional monostatic SAR imaging, which is based on an FMCW radar. The radar transmits the frequency-modulated continuous wave signal. Suppose that there is a scatterer in the SAR scene under illumination. The signal received due to the scatterer is down-converted to the intermediate frequency domain and then range-compressed.

Let the slant range plane be the defined image plane into which the samples of the range-compressed signal are backprojected. Furthermore, let the global backprojection (GBP) algorithm be the image formation algorithm. In the presence of path deviation of the SAR platform, the actual range distance between the platform and the scatterer in the scene under illumination can be expressed as $R_{\mathrm{act}} = R + \Delta R(\tau)$, where R denotes the range distance estimated for the ideal path by and ΔR the path deviation containing errors in the azimuthal and range directions for given aperture position at azimuth time τ. Consequently, the path deviation causes phase errors, which can be included in the representation of the reconstructed SAR scene. To restore an accurate SAR image reconstruction, phase errors have to be eliminated.

Consider a single range bin of the reconstructed SAR scene for a fixed range. Each pixel of the reconstructed image over the given bin is obtained based on the GBP algorithm using the sinc interpolation procedure. The range bin of the reconstructed SAR scene can be described by the linear measurement model in the matrix form, where the sensing matrix is underdetermined and well established to represent sparsely a SAR echo in the image plane for a given range. The compressed sensing theory is utilized to estimate phase errors by solving the convex-relaxed constrained l_1 optimization problem. The optimization procedure is repeated iteratively with updated phase-error input information until the difference between two adjacent phase-error estimates satisfies the required threshold.

3 Conclusions

In this contribution, the autofocusing procedure based on the compressed-sensing approach has been incorporated into the GBP algorithm as an additional motion-compensation procedure. The proposed algorithm requires a single measured range bin as an input to estimate phase errors. The algorithm uses the advantages of the backprojection algorithm to construct the sensing matrix. The performance of the algorithm will be tested on real data acquired through the outdoor SAR imaging experiment with a wideband 154 GHz FMCW radar. The main conclusion is that the additional autofocusing-based motion-compensation procedure reduces the phase errors caused by speed variation, acceleration, and path deviation and improves the image reconstruction in terms of quality, e.g., an improvement of about 23.6% of the $-3\,\text{dB}$ azimuthal resolution is obtained with the autofocusing approach.

Acknowledgements

This work was supported by the ELLIIT research environment under the project Multistatic High-resolution Sensing at THz, Project-ID A17. The authors would like to acknowledge 2π-Labs GmbH for providing the radar system for data acquisition.

References

[1] M. Caris, S. Stanko, S. Palm, R. Sommer, A. Wahlen, and N. Pohl, "300 GHz radar for high resolution SAR and ISAR applications," in *2015 16th International Radar Symposium (IRS)*, Dresden, Germany, Jun. 24–26, 2015, pp. 577–580.

[2] Y. Zantah, F. Sheikh, A. A. Abbas, M. Alissa, and T. Kaiser, "Channel measurements in lecture room environment at 300 GHz," in *2019 Second International Workshop on Mobile Terahertz Systems (IWMTS)*, Bad Neuenahr, Germany, Jul. 1–3, 2019, pp. 1–5.

[3] A. Batra, V. T. Vu, Y. Zantah, M. Wiemeler, M. I. Pettersson, D. Goehringer, and T. Kaiser, "Sub-mm Resolution Indoor THz Range and SAR Imaging of Concealed Object," in *2020 IEEE MTT-S International Conference on Microwaves for Intelligent Mobility (ICMIM)*, Linz, Austria, Nov. 23, 2020, pp. 1–4.

[4] T. Bryllert, K. B. Cooper, R. J. Dengler, N. Llombart, G. Chattopadhyay, E. Schlecht, J. Gill, C. Lee, A. Skalare, I. Mehdi *et al.*, "A 600 GHz imaging radar for concealed objects detection," in *2009 IEEE Radar Conference*, Pasadena, CA, USA, 2009, pp. 1–3.

[5] S. Saqueb, N. Nahar, and K. Sertel, "Fast two-dimensional THz imaging using rail-based synthetic aperture radar (SAR) processing," *Electronics Letters*, vol. 56, no. 19, pp. 988–990, 2020.

[6] A. Batra, J. Barowski, D. Damyanov, M. Wiemeler, I. Rolfes, T. Schultze, J. C. Balzer, D. GÃ¶hringer, and T. Kaiser, "Short-Range SAR Imaging From GHz to THz Waves," *IEEE Journal of Microwaves*, vol. 1, no. 2, pp. 574–585, 2021.

[7] J. Schorlemer, C. Schulz, N. Pohl, I. Rolfes, and J. Barowski, "Compensation of sensor movements in short-range fmcw synthetic aperture radar algorithms," *IEEE Transactions on Microwave Theory and Techniques*, vol. 69, no. 11, pp. 5145–5159, 2021.

[8] S. Kueppers, T. Jaeschke, N. Pohl, and J. Barowski, "Versatile 126–182 GHz UWB D-band FMCW radar for industrial and scientific applications," *IEEE Sensors Letters*, vol. 6, no. 1, pp. 1–4, 2021.

[9] Y. Ivanenko, V. T. Vu, J. Barowski, H. Hellsten, and M. I. Pettersson, "Phase control in interpolation for backprojection of THz FMCW SAR signals," in *2022 23rd International Radar Symposium (IRS)*, Gdansk, Poland, Sep. 12–14, 2022, pp. 10–15.

[10] L.-E. Andersson, "On the determination of a function from spherical averages," *SIAM Journal on Mathematical Analysis*, vol. 19, no. 1, pp. 214–232, 1988.

[11] A. F. Yegulalp, "Fast backprojection algorithm for synthetic aperture radar," in *Proceedings of the 1999 IEEE Radar Conference. Radar into the Next Millennium (Cat. No. 99CH36249)*, Waltham, MA, USA, April 20–22, 1999, pp. 60–65.

[12] L. M. H. Ulander, H. Hellsten, and G. Stenström, "Synthetic-aperture radar processing using fast factorized back-projection," *IEEE Trans. Aerospace and Electronic Systems*, vol. 39, no. 3, pp. 760–776, 2003.