An inverse modelling framework for SAR imagery analysis built on SARCASTIC v2.0

Michael Woollard, Hugh Griffiths, Matthew Ritchie
Electronic and Electrical Engineering Department
University College London
London, WC1E 7JE
Email: {michael.woollard.15,h.griffiths, m.ritchie}@ucl.ac.uk

***Abstract*—The analysis and interpretation of SAR imagery is widely recognised to be a challenging problem. The number and nature of non-intuitive effects often complicate human visual analysis, whilst the wide variation of target scattering behaviour over extended operating conditions is well-known to hinder automated processing. In these paper, we demonstrate how the SARCASTIC simulation engine is being extended to support answering analytical questions which would typically require significant input from expert analysts through inverse modelling approaches. This is a critical step towards enabling the exploitation of SAR collections at scale, which will become increasingly important as New Space continues to increase the number of taskable sensors on orbit.**

I. Introduction

Synthetic Aperture Radar (SAR) ??

The SARCASTIC framework [1] combines high throughput and explainable outputs to fill this capability gap, enabling the development and deployment of new technologies for next-generation SAR systems.

Of particular note for addressing inverse modelling problems, SARCASTIC provides the ability to simulate and interrogate the underlying compensated phase history data (CPHD) for each individual pulse in a collection, providing unique insights and capabilities compared to other simulators.

This paper presents an overview of the current development approach to new modelling techniques based on the SARCASTIC v2.0 engine. SARCASTIC is capable of supporting full-complex phase-sensitive simulations at high fidelity and providing diagnostic outputs whilst maintaining near-realtime performance on small targets. Larger and more complex scenes are handled efficiently and scalably by the high-performance raytracing engine.

The ability to ?? This enables the application of inverse modelling techniques to iteratively interrogate a collection and refine hypotheses about the targets under investigation. This capability is currently being used to develop novel ATR processing for hyperfine-resolution systems in defence applications.

A. Applications

The approaches taken to analysis of SAR collections vary widely depending on the precise use case. The following examples are chosen as representative of the commonly encountered challenges for SAR analysts where inverse modelling is likely to yield improvements.

1) Model-aided exploitation and geometry extraction: ?? This can be seen as an application of a knowledge based system, where *a priori* knowledge about the nature of a scene or target is leveraged to restrict the solution space that must be searched. For example, aeroplanes parked outside hangers are almost always resting on their undercarriage [2], which restricts the pose space for a given model against which a candidate target should be compared. It is also possible to apply similar principles to automate the process of building site models from remote sensing data [3]. This approach is particularly effective when an area of interest is under long-term surveillance and can form the basis for change detection frameworks.

Determining the gemometry responsible for a particular response in a SAR image ??. A number of canonical scattering models have been proposed [4]. ??

It is well-known that polarimetric information can be used to characterise scatterers and reveal information about the underlying physical geometry [5]. A variety of decomposition methods have been proposed to extract this information from imagery; Cameron's [6] and Pauli's are commonly used examples.

In the SARCASTIC context, these models can be used to seed an initial CAD model for a scene or target. Simulations can then be run and compared to the real collection to identify areas for improvement or higher-order interactions. This can be particularly beneficial for identifying and explaining complex multipath signatures.

2) Change detection: ?? In certain applications, it is important to be able to detect macro-scale changes within a scene before a geometry-matched repeat pass can be achieved by the imaging platform. An alternative approach is to model the scene and use this model to predict the expected collection from a different look angle or angles. Transferring knowledge from previous observations in this way enables ??. Whilst coherency is lost due to the change of baseline, ??

3) Image understanding: The requirement to reason about the contents of a scene imaged with remote sensing capabilities has been actively studied since the dawn of photoreconnaissance. Investigations into the automation of this process can be traced back to the Cold War era.

ACRONYM was an early model-based approach to computer vision, with a particular focus on symbolic and geometric reasoning [7][8][9]. The SCORPIUS program, part of the Strategic Computing Initiative [10] aimed to create an automated photographic interpretation system and successfully applied many of the research results from the ACRONYM project to real imagery. However, this work ultimately failed to deliver an operational system.

The Research and Development for Image Understanding Systems (RADIUS) project was initiated by the CIA Office of Research and Development in conjunction with DARPA to advance the state of image exploitation technology through the application of automated systems to aid photographic imagery analysts [11]. Its primary difference from the SCORPIUS program was that the intent was explicitly to develop a human-in-the-loop system, with a focus on aiding the analyst rather than attempting to automate the process.

Applying this philosophy to SAR exploitation, there are obvious benefits on offer from the fusion of model-based processing and analyst expertise. One of the most common problems for an analyst is the characterisation of variation from a known baseline; determining that an imaged vehicle is a novel variant, for example. Other causes of variation from the reference library model, such as battle damage or field modification, can be formulated as inverse problems in which hypotheses regarding iterative modifications to the base model are trialled and refined. This moves the analytical approach from the Classification/Identification/Recognition domain towards Characterisation and Fingerprinting [12].

4) Automated target recognition: The use of simulators to provide synthetic data in order to train automatic target recognition (ATR) approaches is commonplace. Well-known package such as MOCEM [13] and Xpatch [14] have been demonstrated to ?? [15][16][17]. However, the ATR paradigm typically struggles with several ??

Such activities require exceptionally large volumes of sample data for development, testing and validation before deployment. This is especially true when novel operating modes or sensor configurations are under consideration, and no existing platform can provide relevant data in sufficient volume.

II. Framework Description

The proposed framework builds on the SARCASTIC v2.0 simulation package. Consider the base simulator as a forward model for generating a SAR collection from a template phase history dataset (containing the metadata which describes the collection geometry and RF parameters) and a geometric description of the target scene. In this paper, we introduce the concept of an inverse model taking as inputs the products generated by SARCASTIC and outputting ??. This results in a closed-loop approach which allows for iterative refinement of image understanding. The overall processing flow is illustrated in Figure 1.

Within the SARCASTIC toolbox, "sarcastic" simulates phase history, whilst "SARTrace" generates trace information tracking which CAD facets each ray has interacted with. Ray indexing is preserved across both datasets; this allows the formation of complex queries based on diverse criteria (e.g.

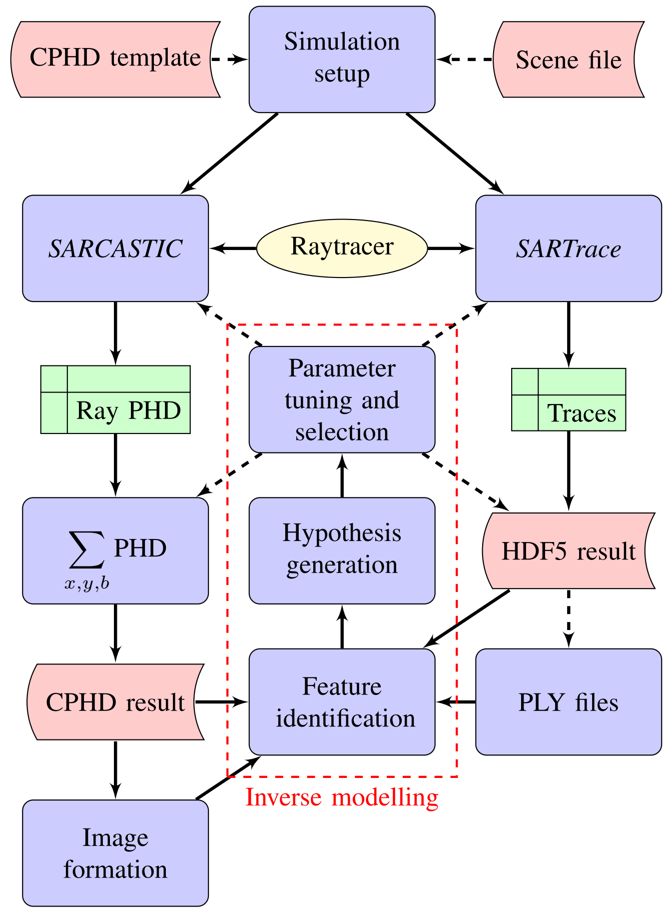


Fig. 1: Top-level flow diagram of the inverse modelling process

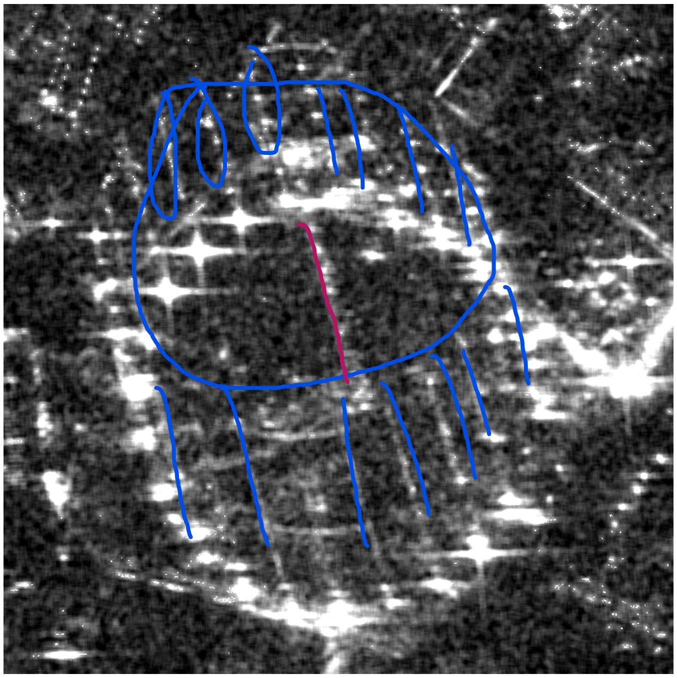
scattered power, pulse-to-pulse statistics, CAD segmentation, multipath). A crucial feature of the proposed architecture is the shared raytracing engine which underpins both tools. This ensures that the results in both phase history and trace domains share a common indexing, which can be used to extract coupled information in both domains based on cues identified in either.

The use of industry standard data formats, especially CPHD, allows a simulated "digital twin" to be created based on a real SAR capture and subsequently processed through the same pipeline as data from the real sensor. This enables direct comparison between the two instances throughout the process.

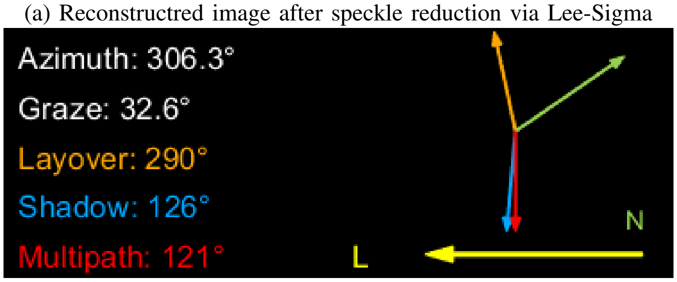
This framework can be used to apply a wide range of feature extraction methods and inverse modelling approaches. The common data standards used for both real and simulated data allow direct comparison between paired collections. This in turn permits rapid exploitation of new collections once a new analytic has been validated against simulated data.

III. Results

To demonstrate the potential of this modelling approach, we will walk though an example problem which is representative of ??



(a) Reconstructred image after speckle reduction via Lee-Sigma



(b) Imaging geometry information

Fig. 2: Kennington Holder Station, imaged at 16 cm resolution by UMBRA-06

A. Collected data and initial hypothesis

Umbra Space recently released 16 cm resolution imagery of London as part of their Open Data Catalogue.

Consider the high-resolution imagery of Gasholder No. 1 at Kennington Holder Station, better known as The Oval Gasholders, shown in Figure 2. The structure is a 19th century gasometer, primarily constructed of wrought iron. There are 24 vertical supports linked by multiple rows of horizontal lattice girders, forming a cylindrical outline. To produce the image shown here, a Lee-Sigma filter has been applied to the original GeoTIFF for speckle reduction.

A typical analytical problem would be to determine the geometry, nature and purpose of this structure from a SAR collection. If its purpose was successfully determined, the ability to determine its state (i.e. percentage of capacity currently utilised) from subsequent SAR passes would be of interest.

A cursory visual inspection of the amplitude imagery, when considered with information on the imaging geometry, suggests that the structure is symmetrical ??. The layover

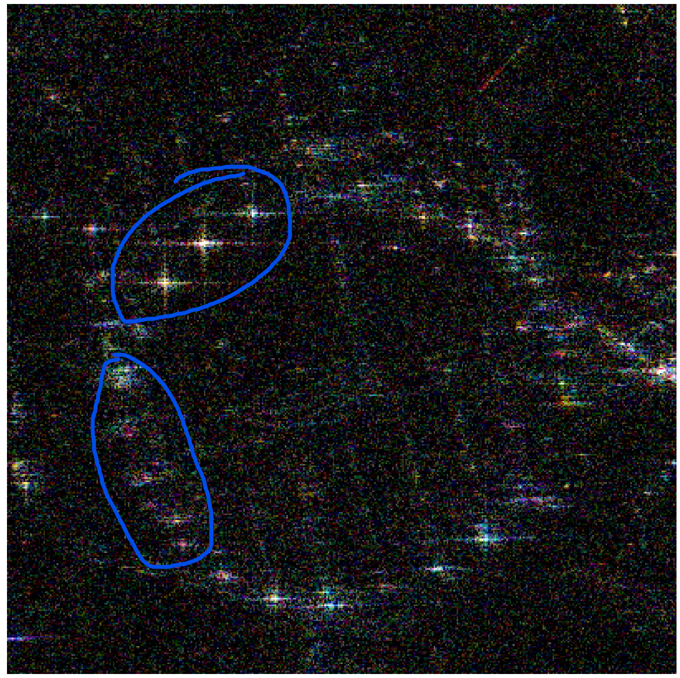


Fig. 3: Colour Subaperture Image of the gasholder

direction aligns with a number of strong linear features, most of which appear to be terminated at the lowest point by a strong scattering centre. This scattering centre could reasonably be hypothesised to be a dihedral glint response, correlating with the layover features to suggest a wall-like structure with significant height.

With access to the complete phase history data for the original collection, we can create a Colour Subaperture Image (CSI) of the target as shown in Figure 3. This has been rendered using the Taser tool from the MATLAB SAR Toolbox [18]. Several of the prominent scatters demonstrate slightly separated responses of diffent colours, which is characteristic of surfaces with different normals intersecting (e.g. rectangular sections).

B. Testing the initial hypothesis

Let us consider how we may apply the SARCASTIC tools to this problem. A simple CAD model can be used to test the theorised locations of the vertical supports, validating

Using the scene files capacity to place multiple instance of the same model in a scene, we can now apply a circular symmetry constraint (parametrised by radius and centre) and generate a simulation for an assembly comprised of several identical components. The hypothesised vertical support structure ??. Adding a roughened ground plane to provide a reference surface can avoid ??

Exploiting the fact that SARCASTIC produces CPHD collections as a native output, we can process the simulated result with Taser in the same way as the original collection to produce a CSI product. This is presented here as Figure 4. An anti-clockwise rotation of approximately 50 degrees shows

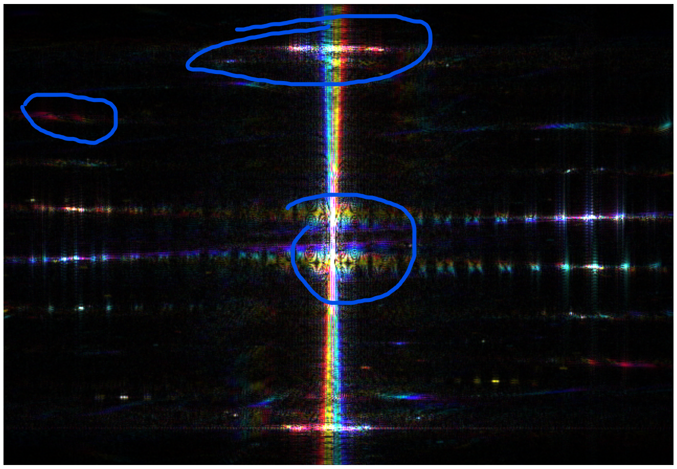


Fig. 4: CSI derived from simulated CPHD collection

good alignment of the respective colours for each support signature.

C. Refinement

??

Having located the vertical supports, we could now investigate the horizontal lattice components. Of initial interest would be determining the number and spacing of these components. Adding simple ??. The scene file will mirror this

Further investigating the ??

Author note: We hope to enhance these results in the final paper with a demonstration of automatic feature extraction from the image being utilised to reduce the degree of human-in-the-loop reliance. We are currently testing several methods based on classical computer vision approaches, but are not yet in a position to present this work concisely within the current draft. Please also note that Umbra are currently using a newer version of the CPHD standard than is supported in the production SARCASTIC release. We are hoping to pull through full support from the experimental release before the final submission, which should yield cleaner results .

IV. Conclusions and Future Work

In this paper, it has been demonstrated that SARCASTIC is capable of supporting analytical investigations which are naturally suited to the implementation of inverse modelling solutions. Simulating phase history rather than image domain data is shown to be vital to realising the full benefit of these opportunities. A practical demonstration of the analytical approach using a real SAR collection has been shown as a proof of concept.

Integrating the inverse modelling process into the SARCASTIC workflow provides a number of opportunities to deliver novel insights based on subaperture techniques and pulse-to-pulse analysis. The ability to create a "digital twin" of a real collection and iteratively refine it offers unique opportunities for realising actionable intelligence outcomes from high-volume SAR collections. Applying change detection over diverse baselines ??

Future work will focus on identifying gaps in ?? and expanding the range of inverse models supported.

Acknowledgements

This research was funded by the Defence Science and Technology Laboratory, UK. (DSTL/JA140892)

The SAR imagery shown is drawn from the Umbra Open Data Program. Umbra Synthetic Aperture Radar (SAR) Open Data was accessed on 09/12/2023 from https://registry.opendata.aws/umbra-open-data.

References

[1] M. Woollard, D. Blacknell, H. Griffiths, and M. A. Ritchie, "SARCASTIC v2.0 — High-performance SAR simulation for next-generation ATR systems," *Remote Sensing*, vol. 14, no. 11, p. 2561, 2022.

[2] J. L. Mundy and A. Heller, "The evolution and testing of a model-based object recognition system," in *[1990] Proceedings Third International Conference on Computer Vision*. IEEE, 1990, pp. 268–282.

[3] M. Quartulli and M. Datcu, "Stochastic geometrical modeling for built-up area understanding from a single sar intensity image with meter resolution," *IEEE Transactions on geoscience and remote sensing*, vol. 42, no. 9, pp. 1996–2003, 2004.

[4] J. A. Jackson, B. D. Rigling, and R. L. Moses, "Canonical Scattering Feature Models for 3D and Bistatic SAR," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 46, no. 2, pp. 525–541, 2010.

[5] S. Demirci, O. Kirik, and C. Ozdemir, "Interpretation and analysis of target scattering from fully-polarized ISAR images using Pauli decomposition scheme for target recognition," *IEEE Access*, vol. 8, pp. 155 926–155 938, 2020.

[6] W. L. Cameron, N. N. Youssef, and L. K. Leung, "Simulated polarimetric signatures of primitive geometrical shapes," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 34, no. 3, pp. 793–803, 1996.

[7] R. A. Brooks, R. Creiner, and T. O. Binford, "The acronym model-based vision system," in *Proceedings of the 6th international joint conference on Artificial intelligence-Volume 1*, 1979, pp. 105–113.

[8] R. A. Brooks, "Symbolic reasoning among 3-d models and 2-d images," *Artificial intelligence*, vol. 17, no. 1-3, pp. 285–348, 1981.

[9] ——, "Model-based three-dimensional interpretations of two-dimensional images," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, no. 2, pp. 140–150, 1983.

[10] A. Roland, P. Shiman, W. Aspray *et al.*, *Strategic computing: DARPA and the quest for machine intelligence, 1983-1993*. MIT Press, 2002.

[11] O. Firschein and T. M. Strat, *RADIUS: Image understanding for imagery intelligence*. Morgan Kaufmann, 1997.

[12] N. NATO, "Nato glossary of terms and definitions (stanag 3680, aap-6)," 2000.

[13] C. Cochin, P. POULIGUEN, B. DELAHAYE, D. le HELLARD, P. GOSSELIN, and F. AUBINEAU, "Mocem-an'all in one'tool to simulate sar image," in *Synthetic Aperture Radar (EUSAR), 2008 7th European Conference on*. VDE, 2008, pp. 1–4.

[14] M. Hazlett, D. J. Andersh, S. W. Lee, H. Ling, and C. L. Yu, "XPATCH: a high-frequency electromagnetic scattering prediction code using shooting and bouncing rays," in *Targets and Backgrounds: Characterization and Representation*, W. R. Watkins and D. Clement, Eds., vol. 2469, International Society for Optics and Photonics. SPIE, 1995, pp. 266 – 275. [Online]. Available: https://doi.org/10.1117/12.210627

[15] C. Cochin, J.-C. Louvigne, R. Fabbri, C. Le Barbu, L. Ferro-Famil, A.-O. Knapskog, and N. Odegaard, "Mocem v4-radar simulation of ship at sea for sar and isar applications," in *EUSAR 2014; 10th European Conference on Synthetic Aperture Radar*. VDE, 2014, pp. 1–4.

[16] A. O. Knapskog, L. Vignaud, C. Cochin, and N. Odegaard, "Target recognition of ships in harbour based on simulated sar images produced with mocem software," in *EUSAR 2014; 10th European Conference on Synthetic Aperture Radar; Proceedings of*. VDE, 2014, pp. 1–4.

[17] D. J. Andersh, S. W. Lee, J. T. Moore, D. P. Sullivan, J. A. Hughes, and H. Ling, "Xpatch prediction improvements to support multiple ATR applications," in *Radar Sensor Technology III*, vol. 3395. SPIE, 1998, pp. 108–119.

[18] W. Schwartzkopf, T. Cox, F. Koehler, and R. Fiedler, “Generic Processing Of SAR Complex Data Using the SICD Standard in Matlab,” in *IGARSS 2019 - 2019 IEEE International Geoscience and Remote Sensing Symposium*, 2019, pp. 4438–4440.