The use of SigmaHat for Modelling of Electrically Large Practical Radar Problems

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***Abstract*—SigmaHat is a computational electromagnetic (CEM) tool developed to solve practical radar and electronic warfare (EW) electromagnetic (EM) scattering from electrically large and electrically very large scenes. The software is an ideal tool for radar and EW engineers to design and investigate various systems as well as gain insight into the underlying scattering mechanisms from complex geometries. This paper demonstrates the capability of SigmaHat as a tool to solve practical radar and EW problems.**

Keywords*— Asymptotic solver, Computational Electromagnetic, CEM, Electronic Warfare, Radar Cross Section, Radar, Physical Optics, Shooting and bouncing rays

I. INTRODUCTION

Radar cross section (RCS, σ) is a key factor in the radar equation that is fundamental to all radar designs. The RCS is a highly complex and often most uncertain quantity that is effected by many factors. High frequency and bandwidth applications and the need for higher fidelity models have created a large market for computational electromagnetic (CEM) tools. These tools are rapidly becoming part of the mainstream of radar engineering. It is necessary for radar and electronic warfare (EW) design engineers to compare various test designs against one another before commencing in the detail design phase. Various analysis tools can be used to model a radar and EW system. Part of these analysis tools are CEM solvers that can be used to obtain insight into the highly complex RCS factor, for a range of targets and environments of interest.

These CEM techniques are split into full-wave methods, numerically solving Maxwell's equations, and asymptotic methods that approximate the scattering from a target. The asymptotic methods make high frequency approximations which are valid for electrically large targets [1], [2]. Full-wave methods, although very accurate, require significant computational resources when applied to electrically large targets. Despite significant advances in computing power, these solvers are still not efficient for solving electrically large scattering problems. Asymptotic solvers have become the most convenient way to solve electrically large EM problems for radar engineers. Although many papers have been published that describe the theory and implementation of these CEM methods, they usually do not provide much information on the areas of applicability, especially when considering a radar engineering point of view.

SigmaHat is a CEM tool that implements an asymptotic solver to calculate the RCS of various platforms. Various comparisons to other CEM solvers have been performed and the main advantage of SigmaHat's development is that it is aimed at addressing the specialised requirements related to radar and EW applications. The generation of RCS datasets for electrically large and electrically very large complex scenarios is of great importance in these fields. SigmaHat is ideal for parallelisation, which speeds up the calculation process significantly. A SigmaHat Lite version is also available for Hardware in the loop (HIL) scenario simulations, which enables the simulation of a dynamic environment using SigmaHat generated scattering points [4]. In 2015 an introductory paper, that investigated the performance of SigmaHat, was published [3]. It also reported initial benchmark results comparing the accuracy and performance of SigmaHat to another commercial CEM software tool, FEKO. This paper is an expansion from [3] and describes the use of SigmaHat to solve practical radar and EW problems relating to the backscatter from complex electrically large targets.

II. SIGMAHAT BACKGROUND

SigmaHat is a CEM tool developed to solve scattering problems involving electrically large and very large scenes, with the focus on radar and EW applications. These scattering datasets are required for non-cooperative target recognition (NCTR), signature library generation and radar and EW systems' test and evaluation to name a few. The accuracy requirements for these applications are usually less strict compared to accuracy requirements for antenna modelling. This allows for a trade-off between accuracy and computational efficiency. SigmaHat is an asymptotic tool that makes use of the Shooting and Bouncing Rays (SBR) approach with Physical Optics (PO). An illustration of the SBR+PO method is provided in Fig. 1. SigmaHat also calculates edge diffraction with incremental length diffraction coefficients (ILDC). It isprimarily implemented in Matlab, which is well suited to high performance rapid prototyping of numerical computations. SigmaHat accurately accounts for structural shadowing and multiple scattering [5]. More features were added to SigmaHat after the overview paper published in 2015 [3]. Absorbing materials were added to SigmaHat's solver and SigmaHat now provides an interface to EW software scenario planners and HIL systems, developed by the CSIR. It has a scattering extraction toolbox which can be used to represent the scattering from a target with a finite number of scattering points.

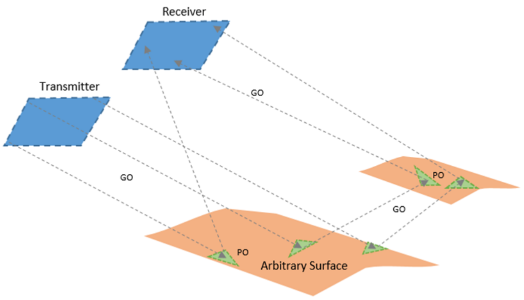


Fig. 2. SBR with PO.

The main focus of SigmaHat was for practical RCS modelling for EW and radar applications. The most significant and important scattering mechanisms from a target were identified and implemented in SigmaHat. Table I lists the scattering mechanisms which SigmaHat account for.

TABLE I. SCATTERING MECHANISMS

Scattering Mechanism	**Contribution to RCS**	**Modelled in SigmaHat**
Specular reflection	Large	Yes (PO)
Multi-reflection	Large	Yes (SBR)
Cavity return	Large / Medium	Partially (SBR)
Edge diffraction	Medium / Small	Yes (ILDC)
Tip / corner diffraction	Small	No
Traveling / creeping waves	Small	No

SigmaHat is an ideal tool for radar and EW engineers to help build a fundamental understanding of the target scattering characteristics. Such knowledge and data is crucial for system and algorithm design, as well as during testing and evaluation. It is also advantageous to use SigmaHat for EW system and doctrine design research. The software toolbox can provide a very cost effective way of augmenting RCS measurements, which are often costly and incomplete, by filling in gaps or extrapolating with high fidelity simulated RCS data. The main advantage of SigmaHat is its ability to solve electrically very large scenarios with high computational efficiency, which is not always possible with other commercial products. Scattering signatures of many full-scale targets have been calculated with SigmaHat and these include aircraft, ships, land vehicles and sea surfaces.

A number of papers are available on benchmark tests performed for SigmaHat. SigmaHat has also been used for target polarisation recognition performance modelling of a F18 and F35 at X-band in [8]. The performance of SigmaHat's SBR with PO was compared to a full-wave solver in [6]. The CAD model used was a Boeing 1:25 scale model over a frequency sweep from 2 GHz to 18 GHz. The results compared well to the full-wave solver with an 84% reduction in memory usage and a factor 133 time speedup in execution time.

Another recent study illustrated the advantages of SigmaHat in terms of resource efficiency and computational accuracy. This investigation was conducted the Boeing 1:25 scale model at Ku-band (17 GHz) and X-band (10 GHz). SigmaHat was the most efficient in terms of run-time and memory usage compared to the RL-GO method in FEKO. It used 3.5 times less memory and was 1.3 times faster than the fastest FEKO simulation [7]. The simulation of the Boeing scale model was also compared to two different full-wave simulations, at X-band and Ku-band (10 GHz to 17 GHz). SigmaHat's PO with SBR obtained the most efficient score in terms of computational time, memory requirements and accuracy [2].

III. SIGMAHAT FEATURES

SigmaHat includes many post-processing analysis tools that radar or EW engineers can use to visualise and interpret simulated RCS data. These tools include (i) High Resolution Range (HRR) profile processing, (ii) Inverse Synthetic Aperture Radar (ISAR) image processing, (iii) Statistical analysis, (iv) Feature Selective Validation (FSV) method, (v) Real Beam Image (RBI) visualisation, (vi) Target rotating part animation, (vii) Polar RCS plots, (viii) HRR ring plots, (ix) Sea surface modelling – convenient interface with the Matlab based WAFO toolbox.

A feature that has been used often is the Real Beam Image (RBI). RBI's are an intermediate result of the SBR algorithm that contains the scattered field intensity in an angularly distributed format. Radar and EW engineers can use RBI's to visualise the scattering from each facet of the target. This provides cardinal insights into the design of a target or flight path, where scattering returns originate, which features on the target produce large scattering points, how many rays should be launched etc. These images are formed without any post-processing time required. It can also be used in conjunction with antenna gain patterns to investigate, for example, the scattering distribution received by monopulse radar [9].

SigmaHat provides the user the opportunity to animate certain geometries on a target, for example the blades on a helicopter, or a propeller on an aircraft, to name a few. This feature allows for micro-Doppler investigation of targets with rotating parts including Jet Engine Modulation (JEM) and Helicopter Blade Modulation (HBM), these outputs can be used for target classification.

Another feature of SigmaHat is the ability to add absorbing material to certain parts of a target. This allows radar and EW engineers to investigate the scattering from targets that are not entirely made of PEC materials. An illustration of absorbing material is provided in Fig. 2. A cylinder on an arbitrary plane is modelled as PEC and with at 10 dB absorber, the difference in scattering from the RBI is evident.

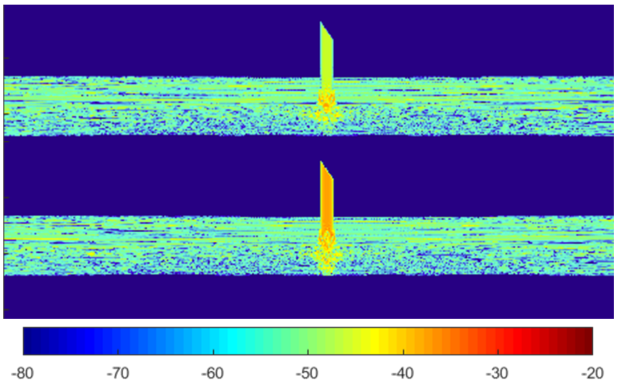


Fig. 2. RBI cylinder PEC versus 10 dB absorber on an arbitrary plane.

IV. SIGMAHAT CAPABILITY DEMONSTRATIONS

In [5], the RCS investigation considered was (i) target detectability, (ii) doctrine development and (iii) target recognition. Three CEM methods were investigated to determine which can be used for RCS studies in radar and EW engineering. Two CEM techniques implemented in FEKO were used viz., the full-wave solver MLFMM and Large element PO. The PO with SBR as implemented in SigmaHat was also used for this investigation. The RCS obtained with generic cruise missile is illustrated in Fig. 3.. It is evident that SigmaHat provides RCS data with suitable accuracy for use by radar engineers. From the other results in [5] it is evident that SigmaHat does account for multiple scattering which is a crucial factor when considering complex electrically large targets.

Benchmark simulations were recently performed for SigmaHat using an object designed by Sandia Laboratory that is an implementation of Cylinders, referred to as a SLICY model. This is a target created from canonical structures including cylindrical surfaces, corner reflectors and flat plates, used to represent various scattering mechanisms including specular scattering, multiple-reflections (corners and cavities), diffraction and creeping waves. For CEM validation it is ideal to have a well-defined target model that can be used as a benchmark for various CEM solvers [10], [11] . The SLICY has the following dimensions: 1.5 m (W), 2 m (D), base 1 m (H), closed cylinder 0.6 m (H) and 0.24 m (rad), open cylinder 0.3 m (H) and the square dihedral has a height of 0.3 m. ISAR simulations were performed of the SLICY with SigmaHat and FEKO 2018 using RL-GO. Accurate agreement between the two ISAR images is noted in Fig. 4. The large scattering from the flat plates are observed at the bottom of the image. The top-hat reflection from the open cylinder is noted and the shadowing caused by the dihedral on the closed cylinder is evident. The following table illustrates the runtime comparison between the two solvers. Both the SigmaHat and FEKO simulations were conducted on an Intel 2 GHz processor on 35 cores. SigmaHat had a 400 time reduction in runtime compared to FEKO's 2018 RL-GO solver.

TABLE II. RUNTIME SIGMAHAT VERSUS FEKO

Solver	CPU Time per Core	Total Runtime
SigmaHat	29 seconds	17 minutes
FEKO RL-GO	3.2 hours	113 hours

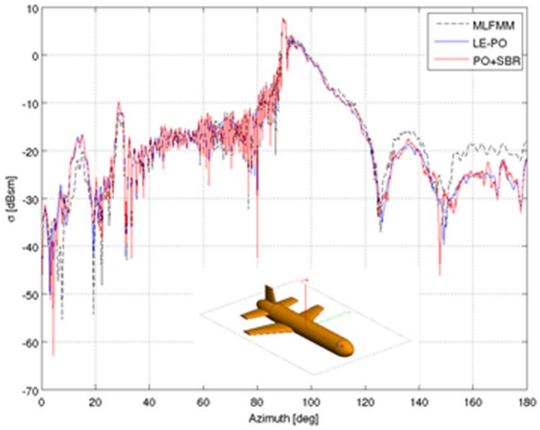
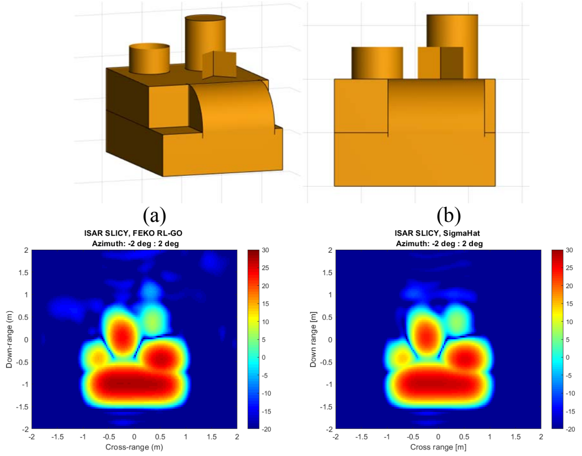


Fig. 3. RCS: generic cruise missile, 12 GHz, VV-polarization

Another example of compact range measurements compared to SigmaHat and MLFMM is of a 1:25 Boeing 707 scale model [2]. The CAD model used for CEM simulations was laser scanned from the target measured in the compact range. The monostatic scattering measured and simulated at 10 GHz is provided in Fig. 5. Good agreement is noted over critical azimuth ranges. These ranges include (i) left and right broadside flashes (-90°), (ii) left and right wing flashes (-45°, 45°).

Simulations of full-scale F14, F15 and F16 CAD models were performed at a center frequency of 10 GHz (81 frequency samples), at 6 MHz steps (total bandwidth of 480 MHz), Fig. 6 [12]. These resulting HRR profiles provide ample information on the scattering from the targets with regard to its aspect angle and can be used for target recognition research.



(a) (b)

(c) (d)

Fig. 4. SLICY (a) Isometric view, (b) Imaging angle view, (c) SigmaHat ISAR (b) FEKO RL-GO ISAR. 10 GHz center frequency, 486 MHz bandwidth, -2° to 2° in 0.06°

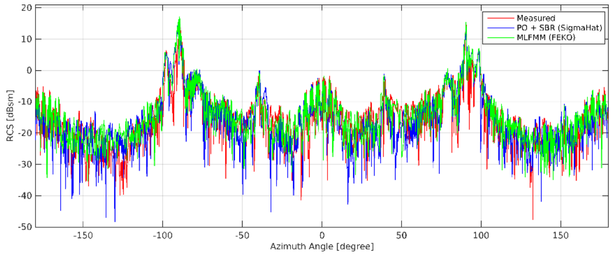
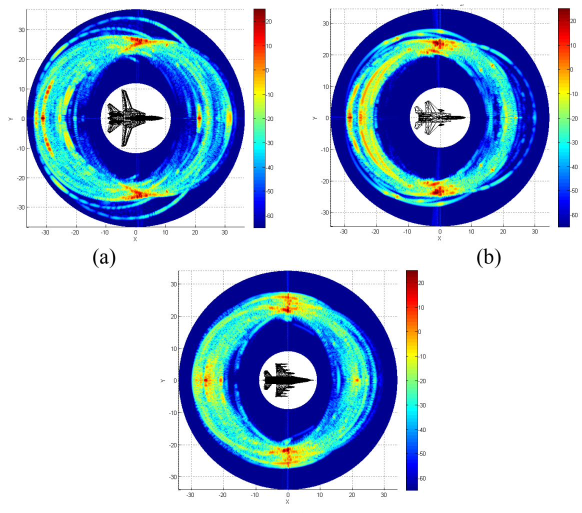


Fig. 5. Boeing 1:25 scale model, compact range measured data versus full-wave and SigmaHat simulaitons.



(a) (b)

(c)

Fig. 6. HRR profiles simulated in SigmaHat (a) F14, (b) F15, (c) F16 at 10 GHz.

A measurement trial of an Altas Angel aircraft, Fig. 7, was performed with an X-band radar. The HRR profiles were also simulated in SigmaHat to compare to measured data and demonstrate the usefulness of the RCS measurements. Two CAD models were used for CEM simulation purposes. The first CAD model, referred to as the base CAD, had a stationary propeller whereas the second CAD model had a rotating propeller (animated in SigmaHat). It was evident that the CAD with a rotating propeller better represents the measured data [13]. The HRR profiles comparing the stationary and animated model are provided in Fig. 8. Distinct differences between the scattering at the propeller of the aircraft is noted.

Examples of electrically very large scenes simulated in SigmaHat include an Arleigh Burke Class Destroyer on a sea surface. The CAD model of the Arleigh Burke Destroyer was obtained from a free online CAD repository and the sea surface was modelled using the WAFO toolbox [14]. The total length of the destroyer is 154 m and was simulated at 1 GHz (electrical size of 513λ). The sea surface was modelled using the WAFO incorporated functionality in SigmaHat for a sea state of 4. From the RBI, Fig. 9, the design engineer can develop a good understanding of what is important to model and take into account in RCS analysis of a naval environment.

Non-Cooperative Target Recognition, is an active field of research that attempts to automate the detection and identification of targets. There is a pressing requirement for recognition of all airborne targets, in all scenarios. SigmaHat's ability to animate parts of a target and simulate the RCS of the target with its animated features is ideal for extracting micro-Doppler features. An example of such a simulation is the Cessna 172. The propeller was animated and the resulting Doppler is provided, Fig. 10. The micro-Doppler features are noted in the vertical flashes caused by the rotating propeller.

Another field where the animation of parts proved useful is research into the effect of wind turbines on radars. These simulations where performed at 3.1 GHz, with a 130° azimuth coverage an elevation angle of -1°. The simulation was animated for 1500 ms (120° rotation). This simulation took approximately 3.2 days on a Xeon cluster, clocked at 2.7 GHz, with 32 cores. The CAD model used of the wind turbine and the resulting Doppler spectrum is provided in Fig. 11. Note that the blade flashes are comparable to the measurements reported in [15].

V. SCATTERING EXTRACTION TOOLBOX

SigmaHat has a scattering extraction toolbox that is used in the CSIR's hardware in the loop (HIL) systems as well as the SEWES simulator. The scattering points of a target are extracted and used in a threat simulator to predict the performance of radar or EW systems. These scattering points are generated in such a manner that the resynthesised RCS is representative of the scattering from the target. Fig. 12, an example of the scattering points extracted of a F18 at 0° azimuth.

VI. 3D ISAR

SigmaHat has a host of post-processing analysis tools which can be used for a variety applications by radar and EW engineers. This gives an insight into the scattering hotspots on a target in three dimensional space. A 3D ISAR simulation of the Cessna 172 was performed and the resulting image is provided in Fig. 13, [16].

VII. 3D RBI

A real beam image is a unique implementation to SigmaHat. It gives the radar or EW engineer detailed insight into the scattering contribution from areas on targets, even though this is a totally synthetic view. SigmaHat was recently improved to visualise the RBI as a 3D RBI. The raytracing technique is used to determine the exact intersection point on the target from which the scattering is observed. This implementation shows the scattering from a target in three dimensional space. A limited configuration simulation of an Arleigh Burke Class Destroyer at 1 GHz with an incident angle at 0° elevation and 30° azimuth was performed in SigmaHat. The 3D RBI plot of this simulation is provided in Fig. 14. By adjusting the viewing angle it is clear which features of the target geometry are contributing to the scattering from the target. Note the target viewing angle is independent of the illumination angle. The shadow-region created by the asymptotic solver, PO, is clearly visible as a full-coverage simulation was not performed.

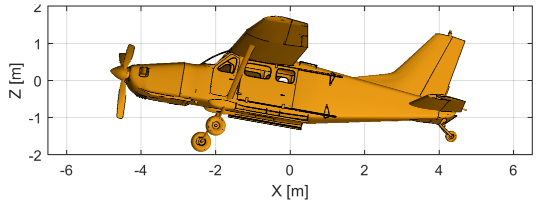
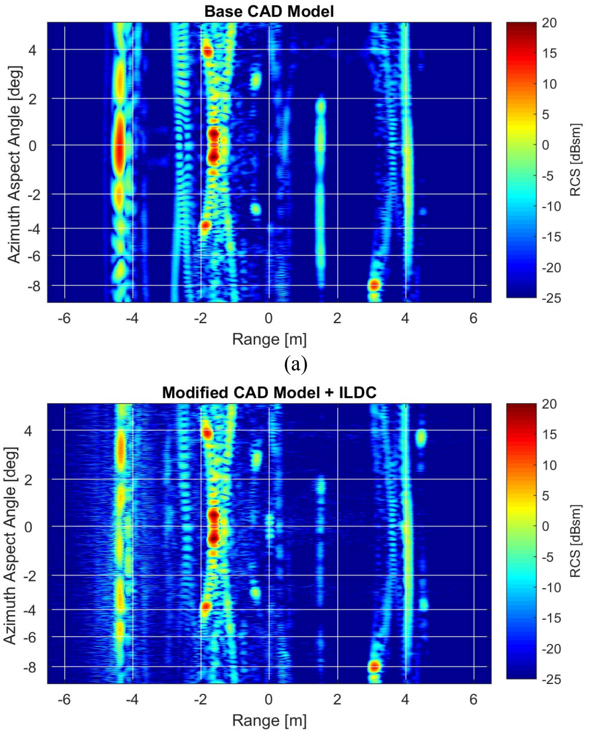


Fig. 7. Atlas CAD model used for radar measurements and simulations



(a)

(b)

Fig. 8. Comparison of the SigmaHat simulated results (a) Base CAD model, with no moving parts (b) Animated CAD model with rotating propeller.

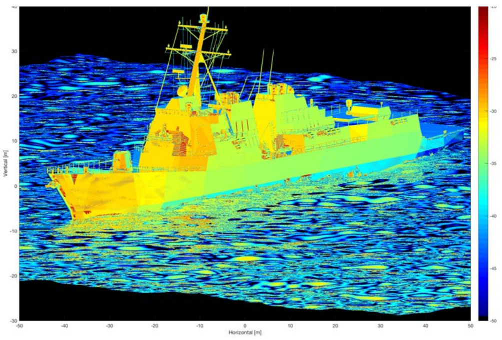


Fig. 9. Arleigh Burke Class Destroyer RBI, on a WAFO sea surface.

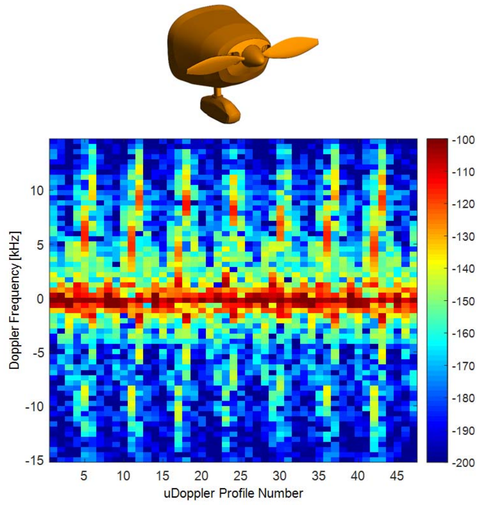


Fig. 10. Micro-Doppler of Cessna 172 with rotating propeller generated in SigmaHat.

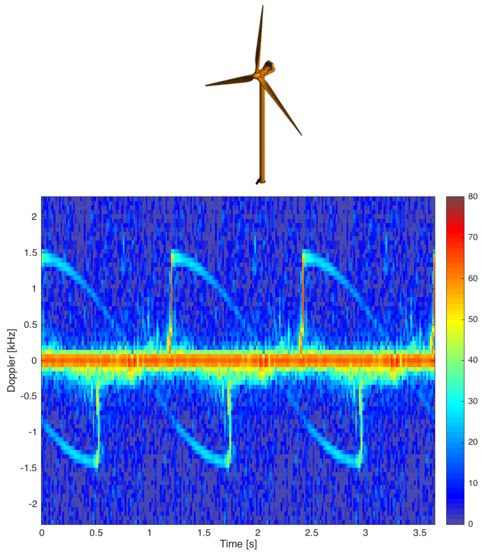


Fig. 11. Wind turbine CAD (Vestas V100) and the resulting micro-Doppler simulated and animated in SigmaHat.

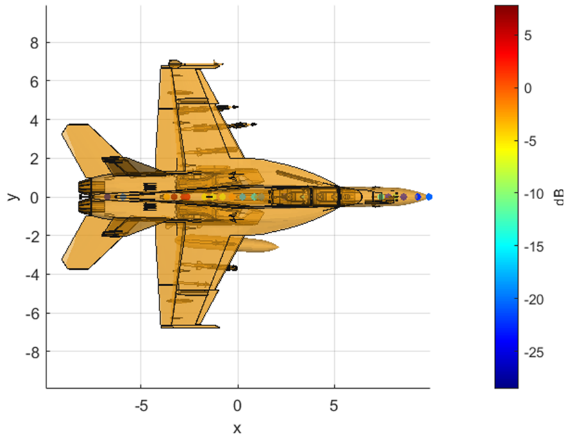


Fig. 12. F18 24 scattering points extracted at an azimuth and elevation angle of 0°, x-band.

VIII. CONCLUSION

SigmaHat provides a fast and efficient CEM solver which can be used to simulate the scattering for electrically large and very large scenes. It further includes a post-processing suite that can be used for data analysis and visualisation by radar or EW engineers. This paper discusses and illustrates the usefulness to employ SigmaHat to solve practical radar and EW problems. The benchmarking of SigmaHat against other commercially available software packages as well as measured data is also discussed in the paper. As illustrated, good comparison is achieved between the simulated results generated with SigmaHat and various FEKO solvers. The RCS calculated by SigmaHat also compared well with measured datasets. SigmaHat showed improved computational efficiency for electrically large targets, compared to FEKO. SigmaHat is ideal for solving practical radar and EW scattering problems of complex electrically large scenes, efficiently.

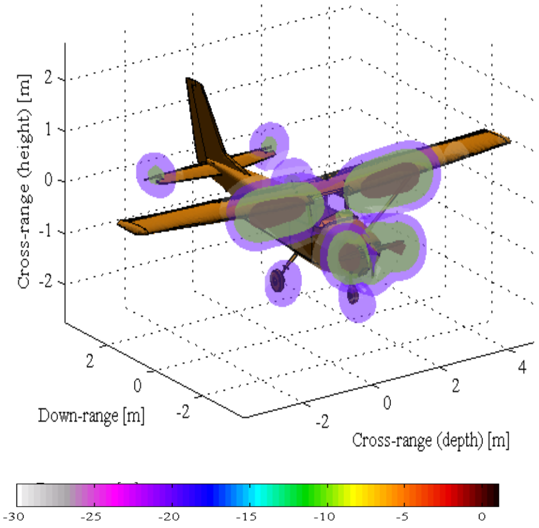


Fig. 13. Cessna 172 3D ISAR image generated in SigmaHat.

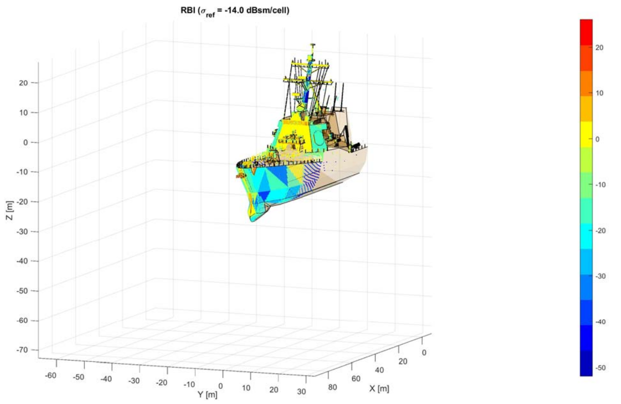


Fig. 14. 3D RBI: Arleigh Burke Class Destroyer, 1 GHz. Incident angle elevation at 0° and azimuth at 30°.

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