Synthetic Aperture Radar Systems

Introduction

WIPL-D software suite is state-of-the-art full wave electromagnetic (EM) solver based on the method of moments (MoM). It applies surface integral equations (SIE) incorporating direct solution of the system of linear equations. Many of the software characteristics are unique and offer a great advantage over other commercially available software tools: quadrilateral mesh instead of triangular one, higher order basis functions (HOBFs) and smart reduction of expansion orders. Simulation time is further reduced by using parallel execution of the code on both central processing units (CPUs) and graphical processing units (GPUs).

Synthetic Aperture Radar (SAR) is a technique which uses signal processing to improve the resolution beyond the limitation of physical antenna aperture. In SAR, physical movement of the actual antenna is used to synthesize electrically large antenna aperture. In general, the electrical size of the radar targets is very large (at the order of hundreds or thousands of wavelengths at the highest frequency of interest) in majority of practical applications. On the other side, as antenna position in SAR changes during the time, target RCS have to be calculated for large number of different antenna positions. For these reasons, calculation of target RCS in a SAR system is a challenging task.

WIPL-D Time Domain Solver (TDS) uses fast Fourier transform (FFT) to estimate the frequency spectrum, determines the minimum number of frequency samples needed for the analysis, and converts the results from frequency domain into time domain, after the frequency analysis is done. It offers zero padding to reduce number of frequency points to minimum.

Due to the electrical size of radar targets, its scattering analysis is often performed by using high frequency methods, such as physical optics or shooting and bouncing rays. However, an inherent characteristic of these methods is the limited accuracy. Applicability of these techniques in SAR systems is further restricted by the fact that simulation time linearly increases by increasing the number of transceiver positions. Usage of full-wave method resolves problem with high accuracy, but it generally has very high requirements regarding the memory and computing time. This application note will demonstrate how WIPL-D software can be used for efficient electromagnetic analysis in SAR systems.

WIPL-D software suite has been improved with a feature named Field Generators. It allows import of radiation pattern from one project into other projects or usage of analytically defined patterns. Here, by replacing real radar antenna by an equivalent far-field source, the problem with different transceiver positions is reduced to multi excitation problem. As a direct LU-decomposition of linear system solver is used, once we have LU decomposed MoM matrix, only inexpensive forward and backward substitution are applied for calculation of each new excitation, i.e., a position of transceiver. In this way, a significant increase of the number of transceiver positions leads to a very slight increase of the total simulation time, and allows us to have a very efficient simulation overall.

Simulation Description

The simulation problem is a rail SAR system using linear frequency-modulated (FM) chirp signal. The frequency spectrum of the radar signal is wideband, approximately up to 40 GHz (99.9% of its energy, is in the frequency range between 22 GHz and 40 GHz). It uses a horn antenna as the transceiver. This antenna moves along the predefined line and takes 201 positions during the measurement procedure. Linear FM-chirped signal is used as the time-domain excitation and it is given by:

$$E = E_0 \cdot \cos(2\pi f_c \tau + 2\pi(m - 801) f_d \tau)$$

where f_d is given by $f_d = \frac{B}{1601}$, B is equal to 32 GHz, while f_c is equal to 16 GHz. The constant m takes values between 1 and 1601.

The object which represents a radar target is a scaled model of Airbus A320. Model is downscaled about 100 times, and its length is about 30 cm, and its wingspan is about 27 cm. The electrical length of the model is about 40 wavelengths, while wingspan is about 36 wavelengths at 40 GHz. The horn antenna moves from the point (-0.8 m, 0 , 0) to the point (0.8 m, 0, 0) along the rail of SAR system.

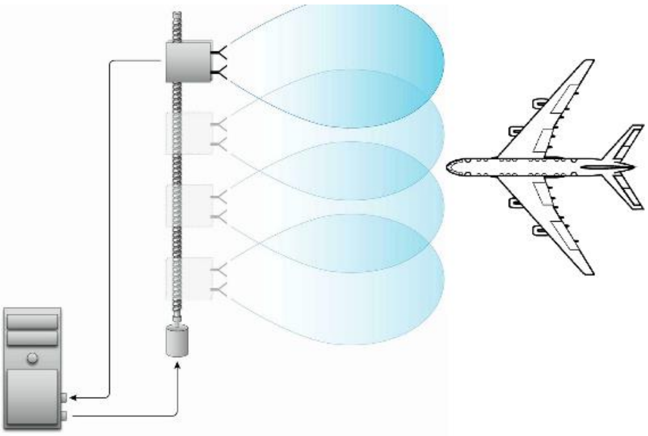


Figure 1. Rail SAR system with airplane model as a target

The first simulation model is the one where actual horn antenna illuminates the aircraft. The result of interest is the back-scattered signal in the time-domain. In order to calculate the time-domain response, WIPL-D TDS calculates the frequency spectrum of the excitation signal, based on the maximum allowed loss of the signal energy. For the particular example, it yields 339 frequency samples in the frequency range from approximately 22 GHz to 40 GHz. In this way the total number of frequency samples needed for the complete analysis is minimized. All the other frequency samples that are needed for FFT are filled with zeros, i.e., the zero-padding technique is used.

The total number of unknown coefficients in the model is 62 474 (the model is symmetrical which reduces number of unknown coefficients two times). Additionally, two smart reduction techniques are applied in order to further reduce number of unknowns, without significantly affecting the accuracy (antenna placement reduction and shadow plane reduction).

Simulation Results

The first simulations are carried out to confirm applicability of smart simulation reductions.

Table1. Applicability of reductions techniques.

Reduction technique	Number of unknowns	Simulation time[h]
No reduction	31 237	4.2
Antenna placement	19 841	2.5
Antenna placement and shadow reduction	16 302	1.9

Simulations where carried out using the following computer configuration: Intel Xeon CPU E5-2660 v2 @2.20 GHz (2 processors), 128 GB of RAM, and 4 hard-disk drives with I/O speed around 100 MB/s. GPU expander Xpander Rackmount 8, 5U Gen3 is connected to the machine. Expander is equipped with 8 identical GeForce GTX 680 GPUs.

An extension of CPU and GPU accelerated kernel was used for all simulations. Namely, multi frequency problem is automatically subdivided into a set of single frequency problems, which are simulated in parallel in a number of processes which is equal to number of available GPUs. After the simulation of all subprojects is finished, output files are automatically merged together. Each process, i.e. single frequency simulation, uses its own part of hardware resources, which lead to full utilizing of available hardware resources.

Comparing the data given in Table 1, we can conclude that smart reduction significantly reduces number of unknowns, as well as the overall simulation time. The signal in the backward direction, obtained by simulation with full number of unknowns, and signals obtained using different types of reduction, are presented together in Figure 2. The details of the reflected signal are enlarged and presented as an inset the traces are very similar (the discrepancy is around 2%) so smart reductions of approximation orders still leads to an accurate analysis.

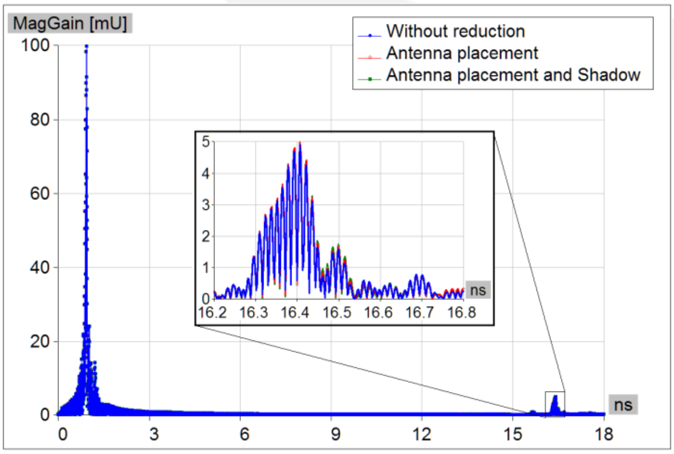


Figure 2. Influence of smart reduction.

The distance between the antenna and the airplane model is about 160 wavelengths at the lowest frequency from the signal spectrum and for the antenna position nearest to the airplane. Therefore, even in this worst case, the airplane model is in the far-field zone of the used antenna. Consequently, the influence of the airplane on the surface current distribution over the horn is negligible. This allows us to replace the antenna model by the appropriate far field source, while keeping the accuracy of the analysis intact. Thus, we can use WIPL-D Field generators to replace the actual horn with its radiation pattern. As expected, model with far-field sources gives practically the same results as model with full antenna model. We estimate that the time-domain response discrepancy between these two models is below 1%.

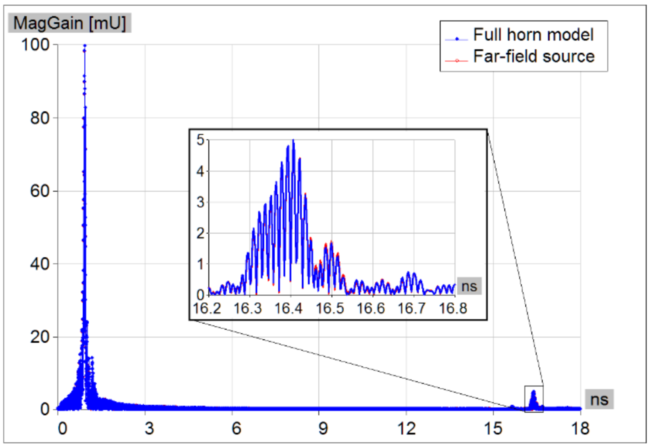
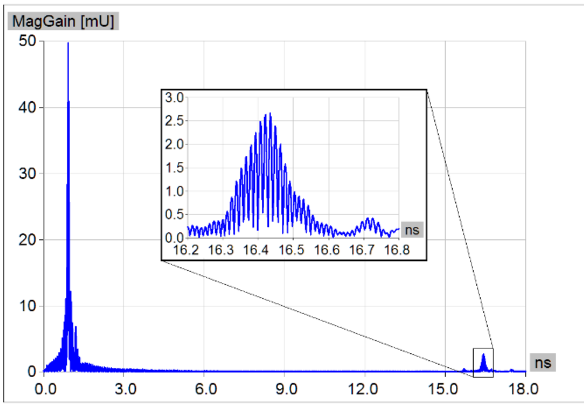


Figure 3. Comparison of signal in backward direction for full-wave model and model with far-field sources

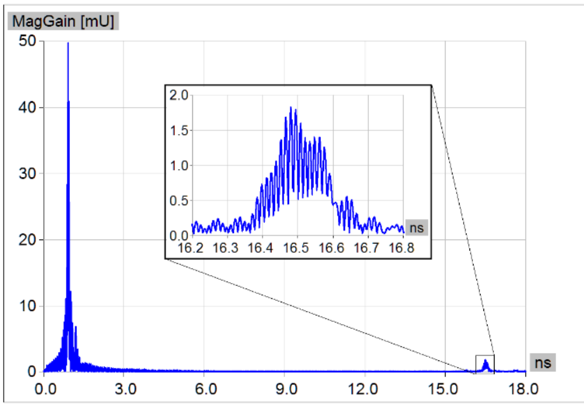
Finally, the entire scenario is simulated with one (A)Symmetry plane to reduce the number of positions to 101. The total simulation time on abovementioned configuration is 8.4 hrs. Each of two simulated models (one with symmetry and another one with anti-symmetry plane) require one half of this time, i.e., approximately 4.2 hrs. Of that time about 2 hrs is used for matrix fill-in and LU decomposition, while calculation of the output results for 101 antenna positions takes another 2.2 hrs.

Therefore, the simulation time which would be increased 101 times, if the regular MoM procedure is used for every antenna position, is increased a little less than 2 times when far-field sources are used.

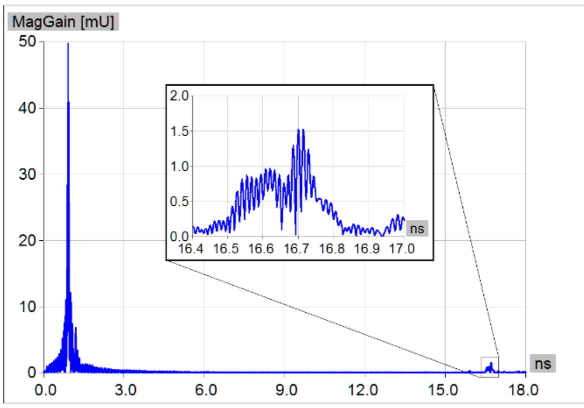
Signal in backward direction for 4 positions of the antenna, namely x = 0.2 m, x = 0.4 m, x = 0.6 m, and x = 0.8 m, are shown below.



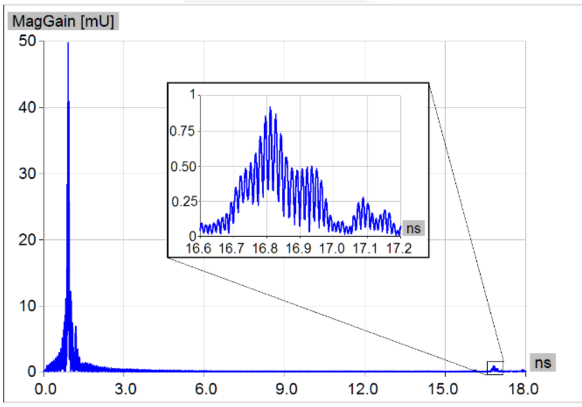
a) x = 0.2m



b) x = 0.4m



c) x = 0.6m



d) x = 0.8m

Figure 4. Signal in backward direction for different antenna positions.

Conclusion

We have described an approach for efficient numerical analysis of rail SAR system. The approach is based on MoM-SIE using higher order basis functions, reductions of unknown coefficients needed for the analysis, and the far-field equivalent sources. The time-domain results are obtained using FFT applied to obtained frequency samples, with zero padding used to reduce number of frequency samples. The simulation was additionally speed up by using multi GPU platform, where each frequency point is simulated at single inexpensive GPU card. For the GPU expander with 8 identical GPU cards, the simulation time has been increased roughly 8 times.

Finally, by replacing real radar antenna by an equivalent far-field source, the problem with different transceiver positions is reduced to multi-excitation problem. Expensive direct LU-decomposition is run only once. Inexpensive forward and backward substitution are applied for calculation of each new excitation, i.e., a position of transceiver. Instead to increase simulation time 101 times for 101 position, the simulation time was only increased two times.

In the illustrative example, the needed analysis time is reduced for approximately 50 times, making it possible to simulate 40 wavelengths long airplane model illuminated from 101 SAR antenna positions in around 9 hrs.