RCS AND SCATTERING SIMULATION FOR RADAR SYSTEMS

Simulation and analysis of radar signal scattering and radar cross section (RCS) are important, increasingly popular tools for a growing list of applications involving radar sensing. RCS is an important consideration not only in the design of radar systems, but also in the design of objects that must be optimized to evade or invite radar detection.

Altair provides a complete, customizable solution for accurate scattering and RCS analysis that is being used across several industries. Central to this solution is Altair® Feko®, Altair's tool for electromagnetic modeling and simulation.

Feko has been a leader in high-frequency electromagnetic simulation for over 20 years. It's the leading tool for antenna design, antenna placement and coupling, virtual test drives and flights, radio frequency interference, radar and radio coverage and planning, and spectrum management. This document examines how Feko—in conjunction with other Altair solutions for design simulation, exploration and optimization, structural assessment, and thermal analysis—can help engineers quickly develop and validate their designs for either radar detection systems or objects that must be optimized to either evade or invite radar detection.

What is RCS?

Radar cross section (RCS) is a measurement that describes an object in terms of its scattering properties when exposed to incident electromagnetic fields. Incident energy from those fields may be reflected, scattered in multiple directions, or absorbed by the object.

An object's RCS is a function of the object's size, shape, and material properties. RCS is defined as: the quotient of the scattered power density to the incident power density in a specific observation direction for a specific combination of incident and observation directions.

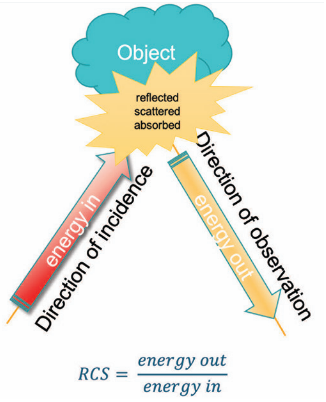


Figure 1: Radar cross section

Why is RCS Important?

There are two key scenarios in which structures' scattering properties are important. The first of these scenarios is the design of systems that detect objects with non-cooperative technology.

An example of this first scenario is the design of an automotive collision avoidance radar system. Such a system would consist of a monostatic radar with a collocated transmitter and receiver. The signal transmitted by the radar transmitter is partially scattered, partially absorbed, and partially reflected by the target object. The receiver detects the reflected portion of the signal.

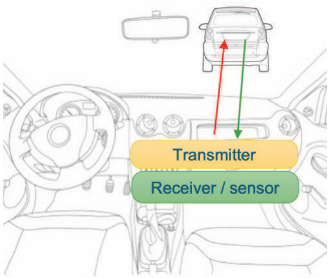


Figure 2: A monostatic collision avoidance radar system

In this scenario, the engineer's goal is to design the system so that it can detect targets (in this example, other vehicles) with the expected RCS characteristics for the application.
The second scenario is the design of objects with the intent to increase or inhibit the ability of transmitters to detect them by non-cooperative means. Examples of this scenario include military stealth aircraft design and commercial aircraft design.

In the case of a stealth aircraft, a design goal is to minimize RCS and thus reduce the probability of detection by enemy air-defense radar systems. In contrast, the goal in designing the RCS of a commercial aircraft is to maximize its probability of detection by air traffic control radar systems.

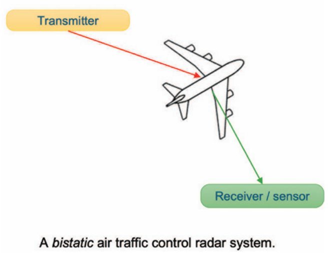


Figure 3: A bistatic air traffic control radar system

Feko's RCS Simulation and Analysis Capabilities

A complete RCS simulation and analysis solution requires various tools for:

- Construction and definition of the scatterer (radar target)
- Specification of the simulation parameters
- Solving the electromagnetic problem
- Flexible post-processing that helps users make correct design decisions

These tools can be divided into three groups:

- Advanced meshing and geometry tools
- General and specialist solvers
- Advanced post-processing and reporting capabilities

We'll look at each of these groups in turn.

Advanced Meshing and Geometry Tools

For modeling the radar target, Feko offers tools for CAD construction and import and fixing, including:

- Faster model clean-up and meshing with Altair® HyperMesh®
- Altair® SimLab® for the construction of very complex models or models with many faulty parts
- Advanced capabilities like NURBS-based conformal meshing and its related basis functions

Besides its shape, the materials from which an object is constructed are also critical to RCS calculations. Feko provides efficient and accurate methods to deal with:

- Metal and dielectrics (including losses and multi-layer structures)
- Coatings (thick or thin, including losses)
- Characterized surfaces to efficiently consider radomes, Frequency Selective Surfaces (FSS), polarizers, and periodic structures

Furthermore, when designing an object for RCS performance, one must often design the materials that will be used to construct the object. To that end, Feko includes purpose-built tools for the design and characterization of FSS, radomes, and periodic structures.

General and Specalist Solvers

Once engineers have accurately defined and described a target object in terms of its geometry and materials, they must then turn to a solver to compute the object's scattering properties.
Feko offers a range of powerful, accurate, and reliable solvers (see Figure 4), that allow engineers to choose a solver that's well suited to the parameters of their specific application.

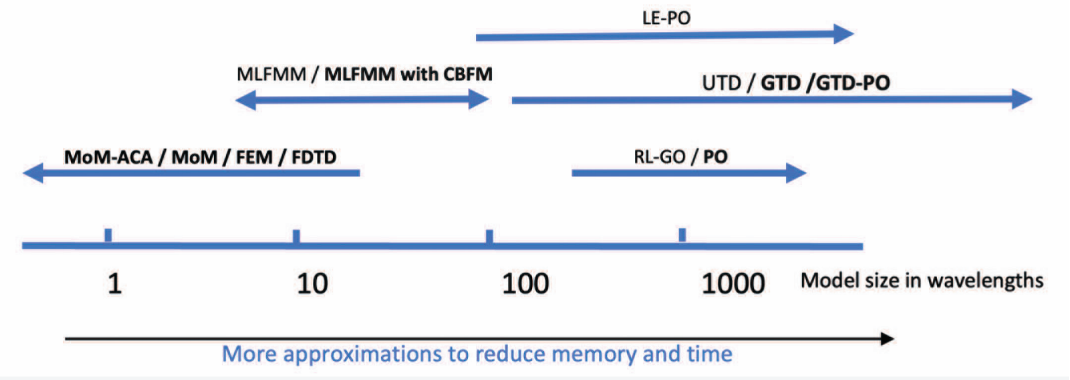


Figure 4: Feko offers a variety of solvers to match the circumstances and scale of almost any calculation

Not all of these solvers may be used directly for scattering calculations, but they're often crucial in designing and analyzing different parts of the scatterer so that the RCS calculation can be performed.

Some recent additions to the Feko stable of solvers that can be used directly in RCS calculations include:

- MLFMM using the Characteristic Basis Function Method (CBFM)
- Asymptotic GTD (Geometrical Theory of Diffraction), PO (Physical Optics), and GTD-PO
- Method of Moments Adaptive Cross Approximation (MoM-ACA)

Why Are All These Solvers Needed?

Depending on the shape and composition of the scattering object – as well as the degree of accuracy required for a specific analysis – different solvers (or combinations of solvers) will yield different characteristics. Having a range of solvers at their disposal allows engineers to balance accuracy and efficiency. Choosing the right solver for a specific calculation will produce a sufficient degree of accuracy to answer the engineer's questions while making the best possible use of available run-time and memory resources.

For example, take two RCS calculations for the ship shown in Figure 5.

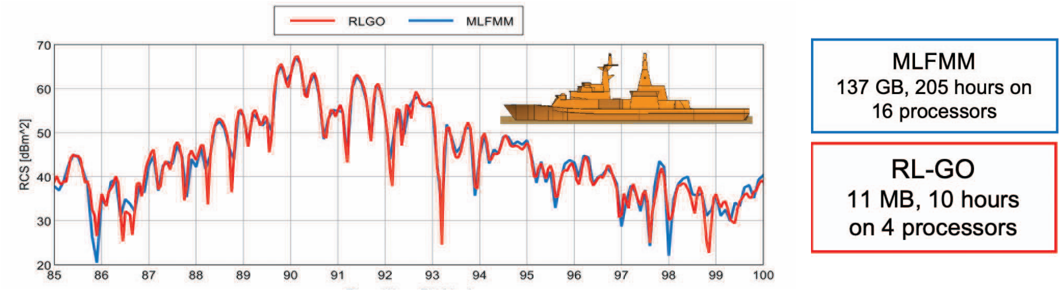


Figure 5: Comparison of MLFMM and RL-GO RCS calculations for a ship

Calculating the ship's RCS using the full-wave Multi-Level Fast Multipole Method (MLFMM) produced a highly accurate solution (the blue curve), but required 205 hours to complete using 16 processors and 137 gigabytes of memory. In contrast, using the asymptotic Ray Launching Geometrical Optics (RL-GO) method for the same calculation required only 10 hours on four processors and 11 megabytes of memory to produce a solution (the red curve) that was accurate enough and often very close to the MLFMM solution.

Having many solvers available lets engineers choose the one that's best for their specific problem.

Advanced Post-Processing and Reporting Capabilities

Once a set of scattering problems has been solved, the results must be analyzed to draw the correct conclusions and make effective design decisions. To aid engineers in that analysis, Feko offers integrated, easy-to-use post-processing and visualization tools.

Feko provides both 2D and 3D visualization and post-processing tools for effective reporting and analysis of simulation results. An RCS polar plot with an overlay of the target object, like that shown in Figure 6, makes it easier to see the directions in which RCS is calculated.

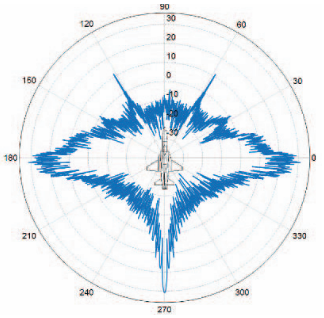


Figure 6: RCS polar plot with target object overlay

Likewise, an animated 3D view of the multi-directional results of a bistatic RCS simulation, as shown in Figure 7, helps users visualize the directions in which energy is scattered for a given incidence. Other quantities can be processed and viewed to assist with design decisions and problem analysis. Current, near-field, and ray-tracing visualizations are all useful in evaluating and diagnosing problems.

For example, Figure 8 shows a ray-tracing visualization based on an asymptotic solution for the monostatic collision avoidance radar system shown earlier. This can be used to pinpoint the areas of a vehicle from which the most scattering would reach the aperture of a 77 GHz automotive receiver array when illuminated from a transmitter located next to the array. While not a true RCS calculation, such a visualization can be useful in understanding the target object's radar properties.

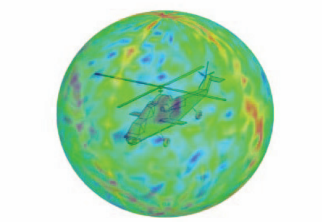


Figure 7: 3D view of multi-directional RCS results

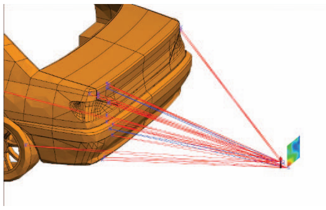


Figure 8: A ray-tracing visualization

Flexible, Powerful Scripting Tools

Feko also provides highly specialized RCS views like Inverse Synthetic Aperture Radar (ISAR, Figure 9) and High Range Resolution Profiling (HRRP, Figure 10) to enable the calculation and visualization of important radar concepts.

These visualizations rely upon highly flexible scripting tools within POSTFEKO to enable advanced data analyses, like extracting the probability density function of a target's RCS for a defined sweep of angles of incidence (Figure 11).

POSTFEKO is Feko's post-processing component. Its scripting tools can help reproduce results that would typically be measured by radar systems. They're useful in troubleshooting, understanding, and predicting practical radar performance.

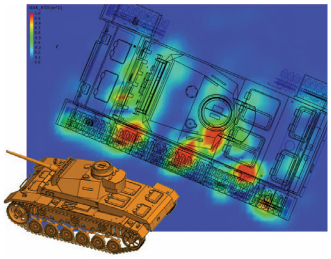


Figure 9: ISAR plot for hotspot analysis

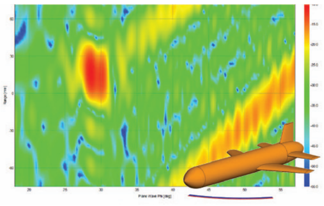


Figure 10: Plotting HRRP over a range of incident directions

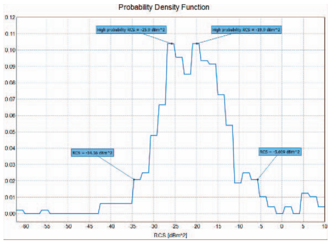


Figure 11: RCS probability density over a range of incidence angles

Dynamic and Time-Variant Scenarios

Most radar applications involve time variance and dynamic scenarios. Objects may be moving relevant to one another, as in the collision avoidance radar scenario shown in Figure 12.

WinProp, the propagation modeling tool within Feko, includes capabilities to analyze such time-dependent scenarios (Figure 13), allowing users to make informed design decisions.

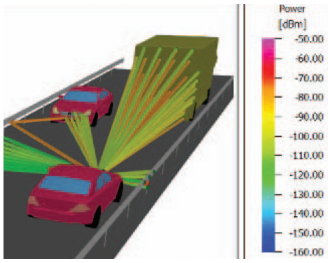


Figure 12: A dynamic, time-variant scenario

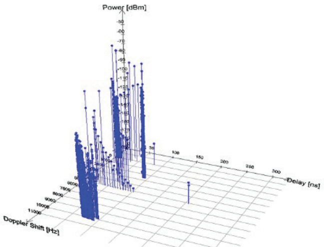


Figure 13: Doppler shift analysis in WinProp

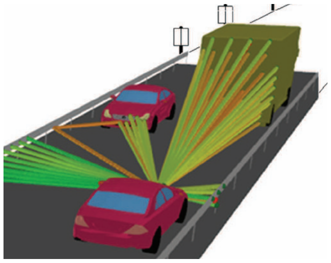


Figure 14: Scenario for validating an anti-collision radar

Validating the Solution

In complex dynamic scenarios—like the development of radar systems or roadside infrastructure for self-driving vehicles (Figure 14), for example—how can we determine whether a design solution is good enough?

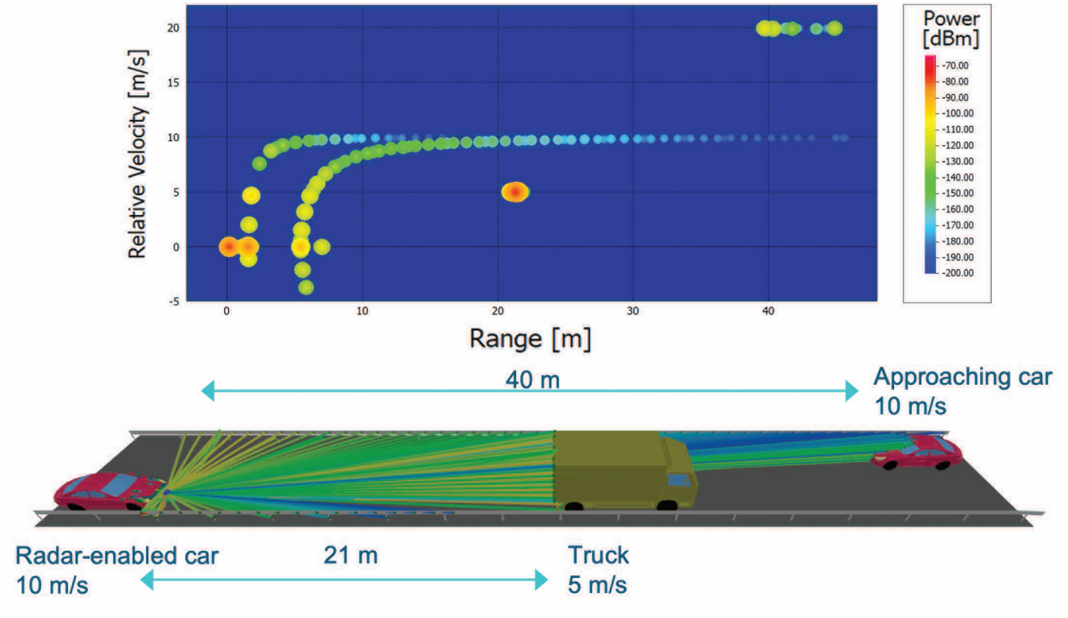


Figure 15: Doppler heat map with range and relative velocity along the axes and signal strength as colors

Such scenarios are extremely complex. They may involve multiple targets, both moving and stationary, in a highly dynamic environment. Real-world testing of preliminary designs is likely to be impractical and even dangerous. Furthermore, the mathematical challenge of a full-wave simulation for problems of such scale may be cost-prohibitive.

Practical alternatives for dealing with such scenarios, such as asymptotic methods, propagation modeling, and post-processing tools, are all included in Feko and WinProp.

WinProp enables this type of scenario analysis. It allows users to consider both time dependence and the properties of the radar systems involved, thereby safely and efficiently helping engineers predict problems and pinpoint areas that need further design work.

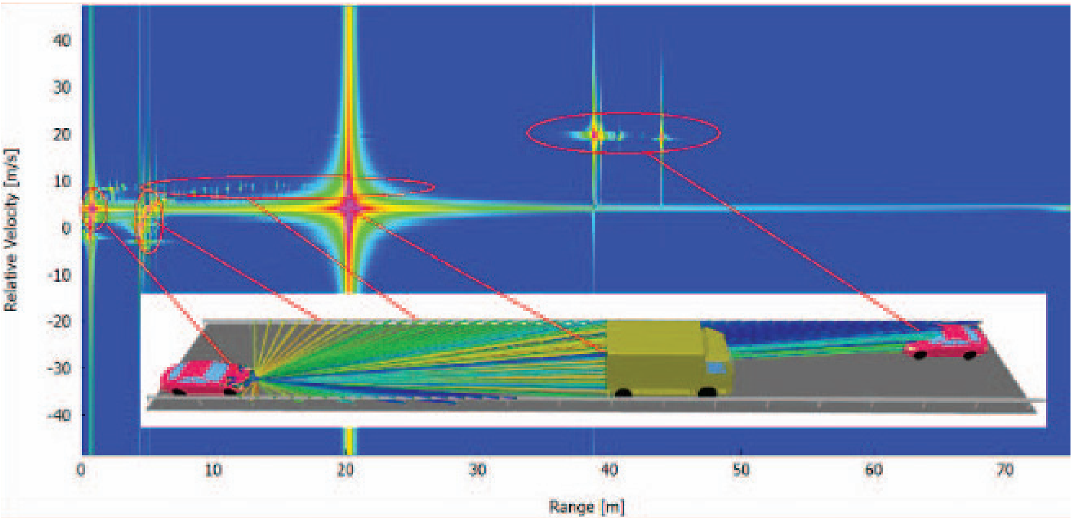


Figure 16: Radar data prediction including artifacts caused by signal processing of FM-CW chirp

During design, the radome's shape and layers of its structure may change. A frequency-selective surface (FSS) may be applied to its surface to control reflection or transmission. Feko can work with complex parametric shapes and analyze complex layered structures. It also has special design and analysis tools for FSS. None of these factors pose a problem for Feko in evaluating RCS performance for viable design choices.

The effects of supersonic flight must also be accounted for. High speed means friction against the radome surface. Friction creates heat, mechanical deformation, and changes in the radome's material properties – Feko can't account for these factors on its own.

Mitigating radome thermal deformation effects on RCS requires a multiphysics, multi-disciplinary simulation approach.

Fortunately, a robust workflow to optimize performance in multiphysics situations has been established. Figure 18 illustrates the steps of this workflow starting at the upper left.

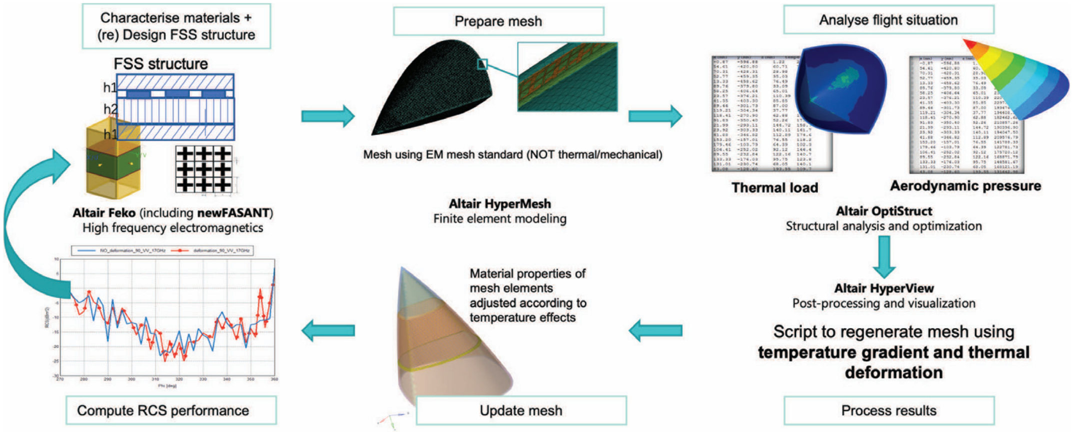


Figure 18: An established, robust simulation workflow to optimize performance

1. Use Feko to design an initial FSS structure.
2. Leverage the mesh from Feko in Hypermesh.
3. Analyze the structure in terms of thermal load and aerodynamic pressure using Altair® OptiStuct®.
4. Extract in-flight temperature gradients and effective thermal deformations using an Altair® HyperView® script for postprocessing and analysis.
5. Update the properties of the materials in the mesh (in HyperMesh) using the results generated by HyperView.
6. Input the updated mesh into Feko and compute the RCS performance of the radome under thermal load in flight.
7. Use the results of the thermal load analysis to compensate for the changes in the frequency selected surface and update the radome design.

This is an iterative process that will normally require several repetitions of the steps above. It's also a very complex process to implement manually. However, by using the parametric modeling available in Feko and choosing sensible constraints on our design goals, this workflow can be completely automated.

The workflow steps can be coordinated using Altair® HyperStudy® and various process automation tools. The process can then be integrated further, using Altair's high-performance computing (HPC) and cloud infrastructure with job scheduling to achieve a fully automated design flow. What's more, all the tools and capabilities needed to support this workflow are available through the unique Altair Units licensing model.

Other WinProp visualization possibilities that can prove useful in such a scenario might include a Doppler heat map (Figure 15), or predictions of artifacts (and their impact on the radar image) caused by the signal processing of FM-CW chirp in the radar system (Figure 16).

Dealing with Large Problems

Scattering and RCS problems require many independent solutions for their different parts. Each of these may represent a significant mathematical calculation, even when using the most efficient approaches.

High-performance computing (HPC), good workload management, and load balancing are critical to dealing with problems that involve electrically large targets, multiple frequencies, and many angles of incidence.

HPC is crucial to solving RCS problems quickly. A proper HPC environment will include:
- Good computing infrastructure
- Highly parallelized solvers with multiple CPU/GPU support
- Good scaling and memory efficiency in a scaled and multi-node environment

Workload management is required to manage concurrent jobs in terms of where they run, how many run at the same time, and so forth. This enables the concurrent calculation of multiple solutions and thus allows many tasks to be submitted together.

Load balancing enables immediate job submission to untasked nodes as they become available. Load balancing is extremely important to efficient RCS calculation, as individual solution run times can vary significantly for different frequencies and angles of incidence.

Workload management and load balancing—like that provided by Altair® PBS Professional®—are needed to leverage HPC capacity effectively. They're very important aspects in scenarios like RCS analysis where there may be a high variance in resources required for each solution. Scheduling the right resources at the right time eliminates bottlenecks and helps ensure computing resources aren't sitting idle while jobs are waiting for processing.

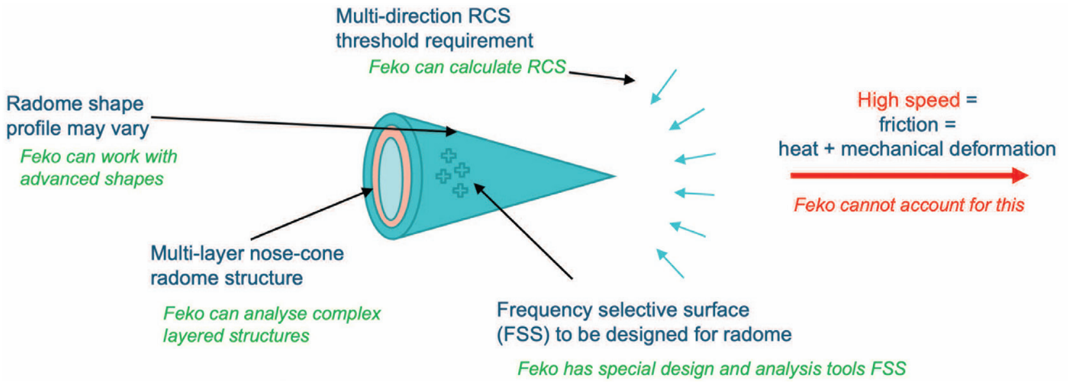


Figure 17: Designing an aircraft nose radome for supersonic flight

RCS Multiphysics Workflows

Non-electromagnetic considerations can also have an impact on radar and on RCS analysis and design. To account for these non-electromagnetic impacts, Feko may be used in conjunction with other Altair specialist tools and solvers to realize highly efficient multiphysics design workflows.

Take the case of a radome for a supersonic aircraft (Figure 17). A part of the aircraft specification will normally require specific performance with regard to RCS.

The Altair Units Licensing Model

Altair Units is a unit-based subscription software licensing model. This flexible licensing model enables customers to instantly access all of Altair's software tools—as well as more than 150 partner products—as they're needed and whenever they're needed.

Altair Units makes accessing the tools you need easier and more cost-effective than obtaining licenses for individual applications. Customers can seamlessly run any of our applications on demand, either locally or in the cloud.

Validation

How well do Feko's RCS simulations reflect reality? To answer this question, we'll look at results from some scientific studies that made comparisons between Feko simulations and actual radar measurements.

The first is a comparison of an MLFMM (HOBF) monostatic RCS simulation at 18 GHz with actual measurements using a scale model of an aircraft (Figures 19 and 20)[1]. For the purposes of the design, the simulation (in blue) provides a very good approximation of the measured RCS (in red).

Next is a comparison between two asymptotic simulations with actual measurements using a scale model of an electrically large, complex aircraft over a broad frequency band.[2] The first (Figure 20) used physical optics (PO). The second (Figure 22) used ray launching geometrical optics (RL-GO). In both cases, the results agreed very well when the simulated geometry accurately represented the actual geometry of the object being measured.

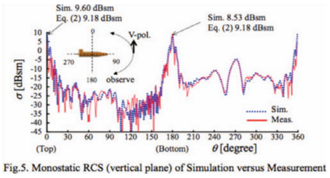


Fig.5. Monostatic RCS (vertical plane) of Simulation versus Measurement

Figure 19: Monostatic RCS (vertical plane) – MLFMM (HOBF) simulation vs. measurement

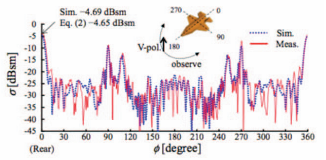


Figure 20: Monostatic RCS (horizontal plane) – MLFMM (HOBF) simulation vs. measurement

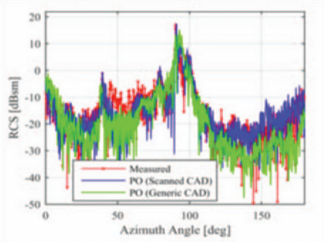


Figure 21: RCS at 17 GHz measured and simulated in Feko with PO using scanned and generic CAD models

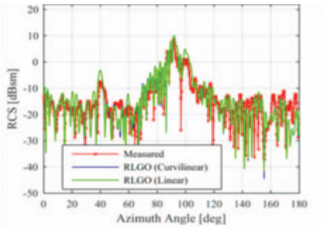
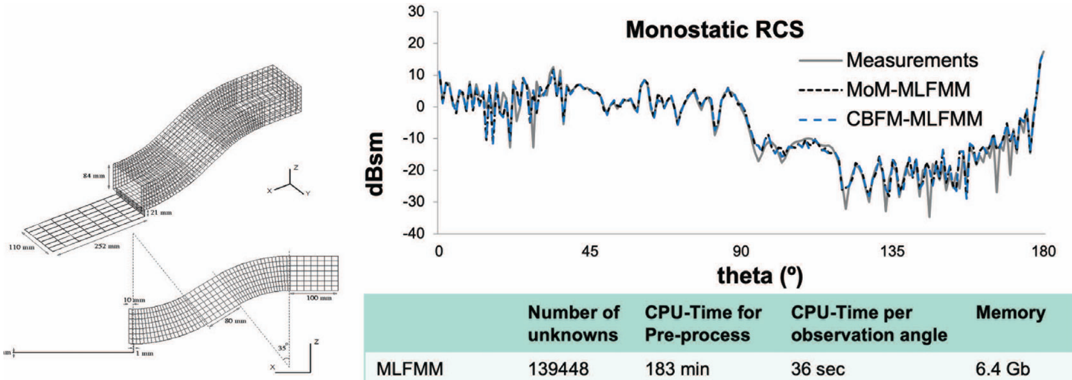


Figure 22: RCS at 3 GHz measured and simulated in Feko with RL-GO using linear and curvilinear meshes considering one interaction



	Number of unknowns	CPU-Time for Pre-process	CPU-Time per observation angle	Memory
MLFMM	139448	183 min	36 sec	6.4 Gb
CBFM-MLFMM	17632	204 min	13 sec	1.7 Gb

Figure 23: Monostatic RCS for the COBRA cavity – CBFM-MLFMM vs measurement

Next, we have a comparison featuring the Characteristic Basis Function Method (CBFM), one of Feko's newer solver capabilities used to accelerate the MLFMM solution. CBFM reduces the number of unknowns to be solved, thereby reducing the memory requirements and necessary simulation time for each observation angle. There's a penalty for calculating the basis functions, but when there are many observation angles, this penalty is negligible. In the case shown in Figure 23, CBFM-MLFMM produced very accurate results compared to actual measurements of a well-known standard radar target.[3]

Going back to an earlier example, we can compare an asymptotic approximation (RL-GO) with a full-wave method (MLFMM) simulation. As we saw earlier, the agreement over the full angular range (as shown in Figure 24) is very good.

Memory and timing for 600 angles of incidence:

- MLFMM: 137 gigabytes, 205 hours elapsed time on 16 processors
- RL-GO: 11 megabytes, 10 hours on 4 processors

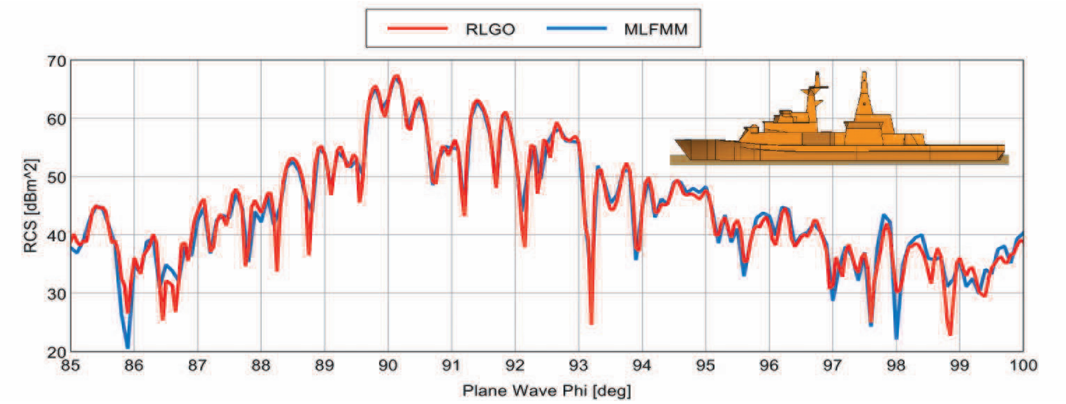


Figure 24: Comparison of RL-GO and MLFMM calculations of RCS for a ship

Asymptotic approximations should, of course, be used with care. But when applied correctly, they can significantly reduce the consumption of computing resources.

Finally, it's important to ensure our postprocessing approaches are correct. Figure 25 compares post-processing simulations of high-resolution range profile (HRRP) and inverse synthetic aperture radar (ISAR) images based on physical optics (PO) with actual radar system HRRP and ISAR measurements of a windmill fan.[4] In the figure, the simulations are shown below the radar measurements.

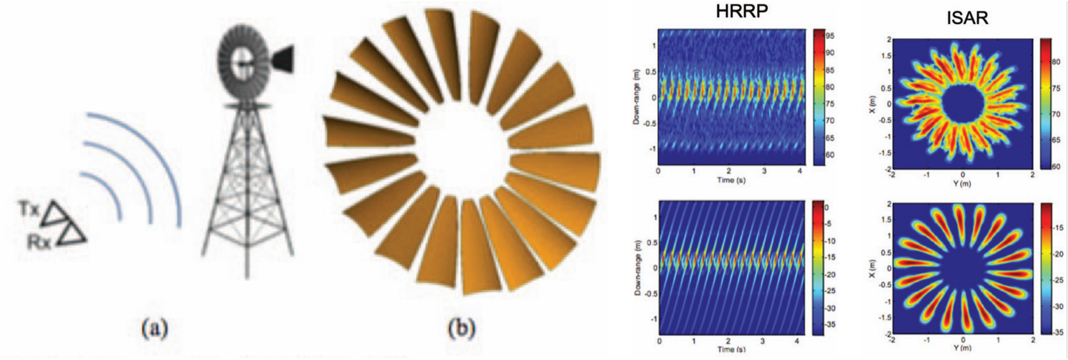


Figure 25: Measurement vs. simulation for HRRP and ISAR based on PO, 3.1-3.5 GHz

Conclusions

Scattering and RCS simulation and analysis are important to a growing list of applications where radar and remote sensing approaches are being used. This is true not only in aerospace and defense applications, but also in automotive, mass transportation, and other high-tech application sectors.

Altair provides a complete, powerful, and customizable solution for leveraging accurate scattering and RCS simulation and analysis for any imaginable frequency and application area. Integration into workflows with other Altair tools enables automated, highly integrated multidisciplinary analysis and innovation.

For a detailed demonstration of Feko's RCS simulation, analysis, post-processing, and integrated multiphysics workflow capabilities, be sure to view Altair's webinar on this topic, which can be found at https://web.altair.com/esd-webinar-series-aerodefense. The webinar includes a step-by-step demonstration of a simple RCS calculation and analysis workflow, from the definition of target object geometry to the RCS calculation using both full-wave and asymptotic methods and finally through post-processing visualization and analysis.

REFERENCES

[1] T. Chisaka et al, Calculated and Measured RCS Values of a Scale Model Airplane, ACES March 2014.

[2] Pienaar, C., et al, RCS Validation of Asymptotic Techniques Using Measured Data of an Electrically Large Complex Model Airframe, ACES Journal, January 2017.

[3] The COBRA cavity - designed by EADS Aerospatiale Matra Missiles for the EM JINA 98 Workshop

[4] Li, C. et al, ISAR Imaging of a Windmill - Measurement and Simulation, EUCAP 2014.