Applications of Epsilon™
A Radar Signature Prediction and Analysis Tool

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1 Abstract

Epsilon™ has been under development for over a decade now. The hybridisation of many techniques has been engineered to form the core solver and an overview of this is given. The paper presents the philosophy of the virtual engineering concept upon which the tool is based and shows how industrial designs are ported from their native CAD systems for analysis and diagnostic work providing a new dimension to the concurrent engineering concept.
The code has been developed to run on both conventional workstations and PCs as well as parallel computing architectures such as networked workstations and dedicated parallel computers. The paper will discuss the problems that have needed to be overcome to achieve this degree of versatility.
The code facilitates a high degree of automation in its computation of a full phasor vector solution to the diffraction patterns of targets and the paper explains the analysis procedure right from the source CAD to production of a delivered result. The scope of application of the code extends far beyond bulk RCS and its use for radar signatures, which are pulse length and PRF dependent, and range dependent will also be covered.
Microwave imaging uses of the code such as ranging, SAR, ISAR and holography using both conventional Fourier processing, Wavelet processing and a variety of super-resolution procedures will also be introduced.
Industrial application uses such as electromagnetic design, which is usually carried out in concert with other CAE activities, are explained along with diagnostics for repairing retro-designs for improved survivability.
The wider role that the code now plays in physical level simulation modelling for engagement performance prediction and the benefits this brings to procurement executives as well as platform and threat designers is also covered.
Some worked examples are shown, and use of recent industrial projects will be used to give a perspective on how the code is used on real projects.
An outline vision of the future for the code is introduced along with an informed perspective of where the next layer of problems lie, which must and will be addressed to reach the next generation of computational electromagnetic tools. It will be stressed that industrial relevance and usability is what has made Epsilon™ so successful, and that this fundamental fact limits the rate at which new techniques are introduced.

2 Overview of Core Solver

Epsilon™ is a computer program designed to predict the RCS of a target directly from its geometrical description. The geometry defining the target used is described via parametric cubic spline representation, and is generated by the PATRAN CAD/CAE system. This description is read into the Epsilon™ Graphical User Interface through the Patran Neutral File (PNF) format, which then allows simulation parameters to be defined and the run controlled.

Epsilon™ uses a range of high frequency methods to calculate the RCS, including:

- Kirchoff form of Physical Optics
- Mitzner Incremental Length Diffraction Coefficient form of the Physical Theory of Diffraction
- Shooting Bouncing Rays for multiple scattering and re-entrant structures

These techniques and algorithms are further discussed in [7].

As Epsilon requires parametric cubic geometry, operation of the code is dependent upon the availability of the PATRAN CAD/CAE system for pre and post processing of the target. Models from other CAD/CAE systems can be analysed by importing the design into PATRAN using an International Graphics Exchange Standard (IGES) file, or other exchange standard (often there is an in-built link between the main industry standard systems). In this way the user can carry out model creation in whatever CAD/CAE system they choose, and then import the design into PATRAN so that the radar signature can be analysed.

3 Philosophy of Virtual Engineering Concept

Virtual engineering in this context is the design and analysis of a target using computers and CAD/E codes to engineer a vehicle to within multi-discipline performance windows. It relies upon the vision that if the physical sciences are understood and CAE running on sufficiently powerful computers can subject the CAD to the relevant physical environmental disturbances, then the virtual model will perform as the real thing.

3.1 Re-use of CAD data for Analysis and Design

The role of CAD is central to the whole philosophy. The CAD undergoes several revisions from an initial space model to visualise a concept, to multi-layered solid model(s) upon which to build FE representations for CAE. Industry standard CAD/E supports IGES allowing designs, FE model and results to be ported between the various systems. It is not uncommon for several CAD/E systems to be employed in the design/analysis cycle.

3.2 Concurrent Engineering

Concurrent engineering is the multidiscipline approach to the design cycle. The concept here is that a design change will potentially affect several performance parameters. It is necessary to concurrently engineer all performance disciplines that are coupled to a design change. For example, to achieve a desired radar signature it may be essential to place severe restrictions on communication antenna sites. This will potentially lead to link budget, EMC, Radhaz and SIMOP issues. Before a design change can be accepted, suitable engineering solutions to all the coupled factors need to be found.

4 Architecture Issues

The code was originally developed on a stand alone PC, which back in the late 1980's was quite unusual to be running UNIX. Whilst it had very poor performance by today's standards, it provided a robust and secure platform for the initial development. The language of choice was FORTRAN 77 with no extensions. The use of an ANSI standard language, without indulging the programmer with the many proprietary extensions, has had a considerable payoff over the period of the codes use and subsequent development. At the outset the geometry descriptions were mandated to be the PATRAN Neutral file format from the MacNeal-Schwendler Company Ltd. (MSC) parametric cubic surface patch descriptions. There has always been a need with Epsilon to have the backing CAD package. This has proven to be beneficial in terms of concentrating the development on the electromagnetic scattering areas and not on geometry description issues.

4.1 The Challenges

The challenges faced by the development team are a mixture of technical and business challenges. In the early days the code was sponsored by DERA under a sequence of contracts, which culminated in the Release 9.2 of the Serial code in spring 1994. The development team at

RMR realised that whilst the code had reached a significant level of sophistication there were still plenty of algorithm refinements, speed improvements and most importantly usability improvements necessary to take a good research code and produce a serious engineering tool. Figure 1 shows the overall progression of the code in terms of the supporting platforms and architectures.

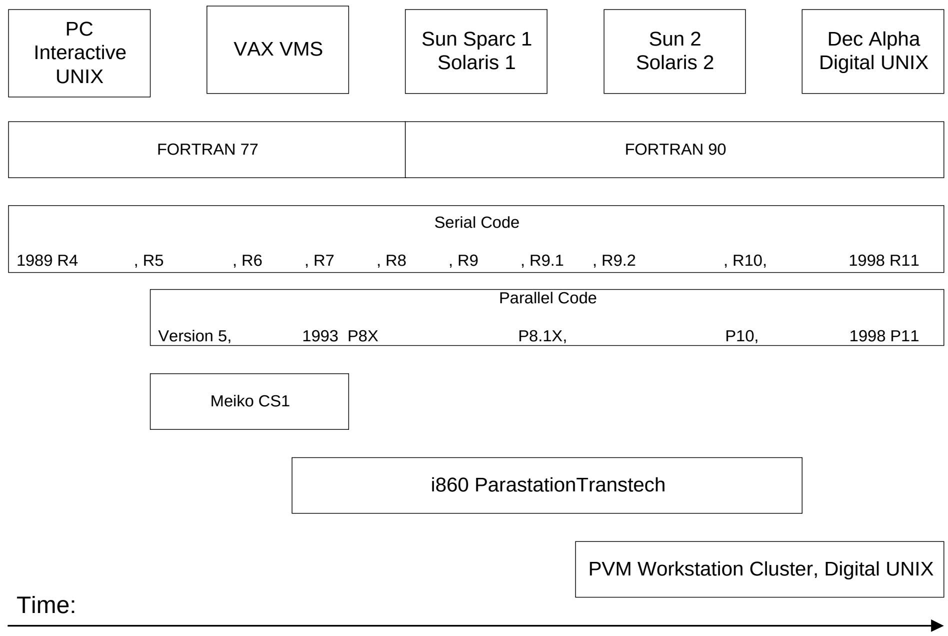

Figure 1 Architecture progression

Early on, the development team realised that the formulation of the scattering boundary integration, and the reliance on ray tracing methods indicated that the code would always be facing run time challenges. There is always a new requirement to predict an electrically larger target, turn round the prediction faster and always more data points in azimuth and frequency are needed, particularly for imaging applications.

Recognising that for an engineering tool to succeed there was a need to identify low cost parallel platforms and a code designed to perform well on these architectures. RMR invested private venture funding to port the code to a parallel architecture. This work was originally done on a Meiko CS1 as is reported in [1]. Whilst the CS1 port proved the principle, it never represented a low cost platform, however the CsTools communications harness also supported workstation clusters of SUN Sparc machines, and these represented an attractive platform on which to exploit the code, as is reported in [2].

In 1992 the i860 processor, and more particularly its' availability on Transputer cards, allowed the construction of a powerful parallel computer within a much more modest budget. Porting Epsilon^{TM} to this platform entailed the construction of a proprietary communications. The utilisation at that stage of a harness independent interface layer, allowed rapid integration of the code to the new platform, which naturally supported a fully featured FORTRAN77 by default. This harness independent layer has served well in subsequent ports to PVM [3].

4.2 Non Technical Issues

RMR has continued to exploit the code for consultancy work, radar training courses and of course sales of the code. Funding is generated from the support monies of customers and re investment of profits from sales of the code. This model of continuous development which now concentrates on code efficiency, and usability issues probably marks Epsilon™ as an unusual instance of this code class. The choice of architecture is driven by cost and customer preference. The current version of Epsilon™ uses Digital Alpha platforms that currently provide an attractive 'low' cost performance ratio.

5 Detailed Process

This section describes a typical project cycle, where Epsilon™ is a key tool in managing signature. These days designers of combat systems have a classical concurrent engineering task involving many facets of operational performance, engineering constraints, system integration and on top of all this Signature Management. RCS is one of a group of signatures that needs consideration and will strongly influence the design of many platforms, since it is principally a passive signature and very reliant on body shaping [4].

5.1 Problem Definition

This is of course the key to the whole process:

- How can the RCS be designed?
- What are the design goals?
- What is a reasonable target?
- How can the resulting design be measured to confirm it meets the design goals?

For Naval platforms, [4] discusses the issues briefly. Design targets for contemporary platforms are:

- Low signature in principal threat directions.
- The ability to change signature characteristics depending on the current role of the vehicle.
- To be able to conceal most of these signatures from the principle threat systems designers.

Clearly the Radar signature control activity will involve generating more that just a couple of RCS elevation cuts of a single geometry. The ability to provide Radar image information, dynamic signatures and signature impact on the threat systems is vital [9].

5.2 CAD Data exchange

Having advised on a RCS design program to meet the specific signature requirements, the next stage is to make the design geometry available for analysis, this is typically achieved by direct transfer from the designers CAD system. Whilst data interchange standards are developing principally around the STEP standard, RMR find that 90% of data interchange is still reliant on IGES. Many geometrical descriptions convert into the native PATRAN neutral format with a few days of CAD effort, however building complex targets from drawings or 2D plans can be very intensive, requiring the efforts of a trained draftsman.

5.3 Analysis Design

The analysis need to be designed around the design requirements. What are the threat bands, threat sectors and what is the success fail criteria? Is this an RCS reduction exercise, placing RAM and making shape modifications, or is it a dynamic signature exercise where the aim is to subvert or confuse a remote surveillance threat? Without a clear design, a lot of effort can be wasted in generating practically useless information, which is difficult to interpret and fails to help the designer.

5.4 The Analysis

With a clear plan and objective measures defined, the signature prediction activity can commence. Release 11 of Epsilon™ has a graphical MMI, which facilitates the user in prediction definitions. The prediction parameters are saved, ready for recall and re-use on design revisions. The predictions are submitted, often as a sequence of script files that run overnight with low supervision requirements. Post prediction analysis can range from plotting the results, to Radar image generation and pulse synthesis.

5.5 The Value Added

Clearly for radar signature design to be truly effective the analyst must have a broad range of radar systems knowledge including threat systems as well as a fund of signature reduction methods and the technical ability to manage a complex analysis program.

6 Analysis Options and their application

This section addresses the various types of radar signatures that are relevant to signature management.

6.1 Bulk RCS

Bulk RCS is in fact the only true measure of RCS in accordance with its fundamental definition. Whilst the mathematical formulation is simple and can be found in countless texts, the following verbal description is offered.

The RCS of an object is a parameter designed to give a measure of a target's reflectivity to a given electromagnetic disturbance, which is independent of the measuring system. This requirement implies that a steady state measurement is made, further implying that the illuminating signal in space is sufficiently long for all transient scattering effects to be insignificant at the time of measurement. Additionally the amplitude and phase curvature of the illuminating field must be sufficiently small to have no affect on the measurement.

It is true to say that, whilst there are other reasons, failure to give adequate attention to the above is one of the most common reasons why different radars will measure a different signature for the same target. This is also the main reason radar measurement and predictions sometimes give different results.

6.2 Range Profiling

This can be thought of as the 1D spatial impulse response of the target, which is given by the Fourier Transform of the frequency transfer function. As RCS prediction codes such as Epsilon^{TM} give a phasor vector solution in the frequency domain, the range profile is easily obtained from a sequence of RCS predictions.

Care must be taken however as range profiling radars can differ widely in the way they gather their data and this must be understood when virtual range profiling is undertaken. A classic difference is that some radars concentrate their time bandwidth product into a single, relatively short duration pulse, whilst others spread this over a sequence of pulses. The two methods can sometimes produce quite different results as one, or both, fail to generate steady state.

6.3 SAR and ISAR

These are essentially 2D versions of the above, and the same cautions apply. There is also an extra layer of problems relating to this extension to 2 dimensions, which cannot be dealt with in this paper. Some insight into these is given in [8].

6.4 Pulse Synthesis

Pulse synthesis in this context is recognition of the fact that many radar to target interactions do not measure RCS but a signature which is dependent on either waveform or range or both. This is particularly true of seekers with short pulse lengths and short ranges, and of ship targets, which disappear over the horizon at relatively short ranges.
The Epsilon^{TM} tool allows calculations to take these factors into account and predict signatures relevant to specific radars rather than generic and sometimes misleading RCS.

7 Super-Resolution Techniques

RMR have reported on the applications of super resolution techniques to target signature characterisation and simulation in [5] and [6]. This work is a direct offshoot of the Epsilon^{TM} tool, in that the raw frequency domain data is predicted by Epsilon^{TM}.

7.1 Imaging

ISAR imaging, as described in the previous section is based around Fourier and Wavelet Transforms. The information content is the principle tool for NCTR and target classification systems. In principle the raw data source could be measured, however the environment and Radar factors that effect the data are practically impossible to remove from measured data. For certain applications it is very important to have data that is not "contaminated" by the real factors that distinguish measured signatures from predicted ones.

7.2 Equivalent Multi point models

The principle application for the super Resolution technique has been in the field of target signature simulation within the 'Victory' simulator described in the next section. The super resolution technique takes band limited scattering data from the target of interest and performs what amounts to data compression, resulting in an equivalent multi point model. Several techniques have been evaluated including IMP and MUSIC. These algorithms started as 1D direction finding tools but over the evolution of the technique have been extended to 2 and 3D.

The generation of "complex target" equivalent scattering models has now been refined to a 2.5D process and optimised for scatterer locality. This has involved addressing the issue of cross range spreading effects and tuning the 2.5D merge process.

7.3 RCS Re-synthesis

The re-synthesis process is mathematically simple, and involves the vector sum of the incident illumination function with the distributed scattering matrices of the complex target.

$$E_s = \sum_n \sum_m E_n SM_m$$

Equation 1.

Where E_s is the scattered signal, E_n is the nth component of the illumination signal and SM_m is the mth scattering portion of the scattering characteristic of the complex body. Epsilon™ has of course been refined to generate a full scattering matrix for each desired frequency aspect pair. Maintaining polarisation orientation requires care, and this is driving the Epsilon™ development in the direction away from the traditional azimuth / elevation sweep definition, towards a table driven method of spot illumination definitions.

7.4 Constraints on modelling technique

This re-synthesis is clearly valid for in band bulk RCS. The out of band performance is surprisingly good for most targets where RCS vs frequency is an n^{α} law where α is nearly unity. For pulse re-synthesis the model is good for pulses up to the bandwidth of the original predicted ISAR data but will gradually degrade and become not fit for purpose for higher bandwidth signals. With the 2D process the illumination angles are subdivided into sectors, typically 10 degrees in azimuth and 10 degrees in elevation. The ISAR data is generated in the middle of the sector and the scattering model is bounded by the sector extent. Whilst it is clear that the Bulk signature is exactly correct in the centre, it is also clear that extrapolation is being used as the re-synthesis reaches the edge of the sector.

8 The Victory Service

'Victory' is the result of a teaming between Roke Manor Research and the UK Defence Evaluation Research Agency (DERA) to exploit their combined capabilities in the field of RCS Prediction and Anti Ship Missile (ASM) Countermeasure Simulation. Over the past ten years a sequence of development phases have continually enhanced and upgraded the capability to become one of the world's most advanced simulator of its class, exploiting the latest state of the art techniques. This initiative offers a highly cost effective route to ship builders, navies and procurement authorities wishing to evaluate new threat and ship design concepts for radar signature control using realistic physical simulation methods.

8.1 The Simulated Environment

Physically realistic models of ships are prepared from IGES CAD drawings to ensure that the vessels correspond faithfully to their real world counterparts. RCS prediction from these CAD models uses the Epsilon™. The prediction data is used to produce a 2.5D weighted impulse model from ISAR image data, which accurately represents the ships radar signature within the engagement simulation. Realistic environment characteristics include signal multipath, atmospheric effects and clutter from rain or sea, and roll, pitch and yaw movements on the vessel induced by the selected sea state are added by the simulation.

Pulse level modelling implemented in Victory uses a powerful high fidelity method, based on the underlying physical equations rather than employing a non-deterministic statistical approach. The use of this physical modelling technique means that the simulation is fully traceable and can be used against any tracking, guidance or fuzing algorithm, which can be expressed as a coded computer model. Configurable generic models are available for the detailed representation of ship targets, pulse level models of missiles and active ECM devices.

8.2 Target Audience

The framework is sufficiently flexible to accommodate third party models allowing a wide diversity of use whilst preserving the contributor's intellectual property embodied in their models. The Victory simulator hardware is based upon a networked cluster of high power DEC Alpha computers which together provide a powerful compute processing resource. The simulator's software framework which provides the interface between the Operating System (VMS) and the threat and target models is implemented in ADA, but the individual models can be written in any programming language that uses the DEC calling standard.

9 Future Directions

Epsilon is principally customer driven, which is perhaps being influenced most by the signature management requirements for new systems. There is a tendency in this role to support either the design house, or the procurement agency. Epsilon™ sits as an independent tool, driven by the market. This independence allows rapid reaction to the end user needs with little or no constraints from in house dictate or policy.

9.1 Speed Issues

The basic calculation techniques have much scope for speed improvements. The basic design philosophy has been to first "Get it Right" and then "Get it Fast". For release 12 RMR have been optimising the Ray Tracing algorithms, and have already realised a seven fold speed improvement with the 'alpha' version of the code.

9.2 Hybrid Techniques

For installed antenna performance analysis, the current methods of handing over the scattering characteristics generated in a rigorous solver code such as Zeta or NEC are cumbersome. The usefulness of a multi solver, Electromagnetic workbench is clear from signature design applications. Integrating dynamic signature modulations from moving parts, and installed antenna solutions is clearly the next step in CEM analysis.

9.3 De Skilling the Analysis process

The next step in usability is to build in expert knowledge into the solver, so that more of the right analyses are done and less-expert users are guided to perform analysis that really contribute to the design process. Clearly to be able to integrate heterogeneous solver codes to answer a real EM question will require a lot of problem description, and checking of the problem definition against a knowledge base of proven good practice.

10 Success Ingredients

What has made Epsilon™ such a successful code?

10.1 Historical Factors

When the design of Epsilon^{TM} started in the mid 1980s, the available compute power for a given budget resulted in relatively long run times. At that time a popular method for achieving faster run times was to transform the surface boundary problem into a line boundary problem using a Green's function. Epsilon^{TM} did not employ this method as the design team considered the approach would lead to a number of problems in practice.

- The method is only good for RCS prediction, and as has been pointed out, concentrating on this parameter rather than more realistic radar signatures is somewhat limiting.
- The designer's CAD representation would be compromised, leading to concerns about validity from not utilising a 'single geometry model' concept.
- Extra man-hours would be necessary to remodel the geometry, and in the case of large complex models this results in a non-feasible approach.
- The run time issue was seen to be something of an artefact, as the real issue was elapsed time from presenting the requirement to achieving the result.

10.2 Design Philosophy

Epsilon's design philosophy has had two fundamental threads, which are the key to its now relatively large user group.

- Epsilon works from the designers' original curved geometry model, requiring little or no rework.
- Automation is kept high, so the 'human in the analysis loop' factor is minimised leading to a user-friendly system which gives user independent results.

Affordable compute speed increases at a rate that continually shrinks the run time element of elapsed time from presenting the requirement to achieving the result.

10.3 Non Engineering Factors

Epsilon^{TM} has been continually updated every year, and has been offered on a wide range of computers from PC's to parallel computers, and can thus be used in a commensurate range of establishments. It is highly configurable, whilst retaining its automation of use. Its customer base has independently validated it.

11 References

[1] Galloway P.E.R and Simpson S.H.W 1991. 'Parallelisation of Radar Cross Section (RCS) Prediction for Electrically Large Targets', Proc. European Simulation Multi-conference 1991.

[2] Galloway P. E. R., 'The Operation and Control of Large Parallel Simulations on a Network of Sun Workstations Using CSToolsTM', Proc. European Simulation Symposium, Dresden 1992.

[3] 'PVM3 User's Guide and Reference Manual' ORNL/TM-12187. Oak Ridge National Laboratory, Oak Ridge, TN 37831-6367. May 1993.

[4] Simpson S H W, 'Electromagnetic Design for Low Observability ', "SMI Low Observables, Counter Low Observables and Stealth", February 1998

[5] S. H. W. Simpson, P. E. R. Galloway, C. D. L. Bell, 'Complex Target Signature Generation', Proc. ICSP, Beijing 1996.

[6] Simpson S H W, Galloway P E R, 'Extended Target Simulation at a Physical Level', Proc. AGARD SPP Symposium on 'Radar Signature analysis and Imaging of Military targets', Ankara, Turkey, October 1996, CP-583

[7] Knott, Shaeffer & Tuley, 'RADAR Cross Section', Artech House, 1993

[8] Smyth A, 'Polar Reformatting Techniques for Simulated ISAR', To be presented at the International Radar Symposium, IRS 1998, Munich Germany.

[9] Welsh T D, Brittan S, 'Simulation of Glint Characteristics of Complex Targets', To be presented at the International Radar Symposium, IRS 1998, Munich Germany.