Inverse Synthetic Aperture Radar Simulators as Software-defined Countermeasure Systems: Security by Obfuscation and Deception for Electronic & Computer Networks Warfare

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1. Introduction

In the eighth episode of season five of the 1962 series of "Mission: Impossible" head operative Peter Graves inflates a life-sized plastic decoy detailing himself so to confuse in order to escape his opposing counterparts. It comes as no surprise that this episode is distinctively titled "Decoy". A decoy is a person, device or event of at least lesser and of preferable minimal value that serves purposes of security by distraction and obfuscation. This function is performed by introducing one or many replicas of a person, device or event in order to conceal the valuable original asset from the adversary interest groups that are actively seeking the friendly beneficiary with malevolent intent.

In our case the valuable asset is a military naval vessel or fleet that requires protection from airborne threats of enhanced electromagnetic nature or advanced radar surveillance and tracking sensor technologies. This work promotes the thesis that the current state of affairs in the field of modern air defence at sea demands distraction and obfuscation solutions based on software defined radar systems. Specifically the generation of the concept of coherent deception that is used to oppose high range resolution radar systems is argued to be more straightforward when performed by software-defined radar systems based on simulator sub-systems than by using dedicated to particular countermeasures hardware platforms of electronic protection for two main reasons. First with a simulator system it is easier to adjust the false target properties to the actual target properties so the adversary will not be able to distinguish the real target thus providing initial targeting hindrances. And then the convenience of adding reality enhancement effects, like the various noise and glint elements found in an actual returned high range resolution radar signal, thus increasing the confidence of the adversary regarding the validity of the contact. Therefore with a simulator system it is easier to adapt to sensor technology limitations and to incorporate the laws of physics in the countermeasure design always keeping in mind that the ultimate goal is to deceive the radar operator and radar system loop with emphasis on the human element. The executive summary of this project is shown in Figure 1 in a visual form.

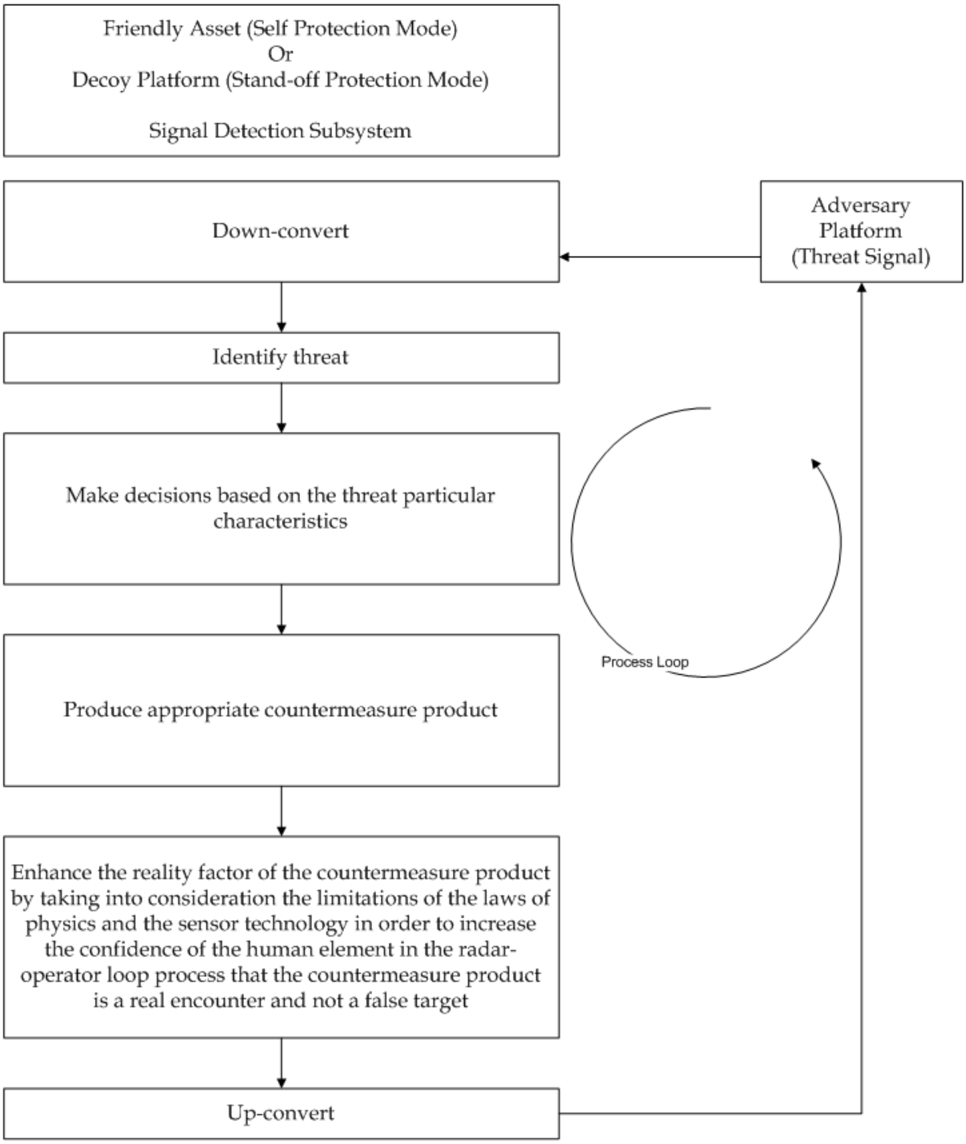


Fig. 1. Visual executive summary of the project.

In this chapter we will create a virtual environment that is considered to accept as inputs the just-in-time characteristics of a threat signal, pass them through a transfer function which is a simulator system and then produce false target images that are realistic because they abide by the current sensor technology limitations and the prevalent laws of physics.

In section 2 we argue that since coherent countermeasures are different from conventional naval countermeasures the concept of air defence at sea when high range resolution miniaturised sensors are involved needs to be reinvented. Here the literature review is presented for ISAR simulators and coherent countermeasures because our contribution is the amalgamation of these two fields. In section 3 we apply the concepts of conceptual modelling to the field of coherent countermeasures. In section 4 we present our implementation procedure, in the forms of the computing methodology, the algorithm design and the final simulator implementation. The results of this work can be found in section 5. Here the simulator is proven to be able to produce ISAR images affected by higher reflectivity on lower coordinates and angular glint effects which is a common case with extended military targets. Also we argue that the computing methodology can be reused in the domain of computer networks warfare by presenting the dual problem space decomposition for the case of a computer network jammer device. We also discuss the project success factor by ascertaining the ability of the current effort to be able to implement a simulator prototype of the initial conceptual model. Finally in section 6 concluding remarks are given and we also make a recommendation for future work by suggesting that the simulator should be recoded with the use of concepts from the field of parallel programming in order to increase its execution speed.

2. Coherent Countermeasures for Air Defence at Sea & ISAR Simulators

Distance is an integral factor in countermeasure activities. When the decoy signal is produced on-board the friendly asset it is called self-protection and when it is produced off-board it is called stand-off protection [Hill, 1988]. The large volume and weight of the countermeasure technology up to the 1990’s demanded solutions of self-protection. Stand-off protection was usually performed either by friendly platforms that were far away from the threat signal or chaff systems, that is low value passive elements that would attract the threat away from its target because they exhibited greater radar cross section than the protected platform. For the above reasons conventional radar countermeasure techniques fell into two major categories: angle deception and range deception. In the first case an example is Inverse Gain Jamming. With this method the jamming function is performed by transmitting replicas of the adversary signal back to the hostile sensor. A strong replica when the illuminating signal is weak and vice versa either evens out the phases or over compensates the sensor producing either way the deception effect. With the second method an example is Range Gate Pull-Off (RGPO). The hostile radar concentrates on the target by placing a range gate of a few hundred meters around the target. Because it no longer looks for other signals it is termed that the radar has locked on the target. The RGPO method breaks the lock by making the hostile radar lose this gate thus producing the deception effect. Both methods work for conventional radar systems and will not deceive a high resolution sensor [Wiegand, 1991]. Both above countermeasure methods are applied to conventional radar tracking systems, like the monopulse method. But they are not efficient when the target is viewed by a high range resolution system in stand-off mode or when the missile platform is equipped with a miniaturized high range resolution sensor (ISAR mode). Therefore the problem of air defence at sea needs to be re-invented for there is a need for direct ISAR countermeasures that would oppose a miniaturized high range resolution radar sensor.

2.1 Review of the State of the Art

We will perform a literature review on conventional ISAR simulators and then on coherent deception techniques in order to be able to draw comparisons and build the foundations of our work.

2.1.1 ISAR Simulators

Earlier studies by [Shillington et al, 1991] have described a technique used to simulate ISAR images of a ship model while under angular motions such as yaw, pitch and roll. [Porter et al 1994] have presented the theoretical analysis of SAR techniques as can be applied to ISAR imaging of ship targets. Emphasis is given in the exploitation of information resulting from the point spread function. Also foundations are laid towards the study of interference effects (glint). [Haywood et al, 1994] have introduced the ISARLAB software package which is a comprehensive set of functions that emulate the particular functions of an ISAR system. And [Emir et al, 1997] have developed a simulation program which can generate ISAR images of ships. The method is based on the localization of dominant scatterers and has applications in evaluating the performance of automatic ship classifiers.

Recent studies by [Wong et al, 2006] have clearly presented the mathematical basis of the Inverse Synthetic Aperture process. [Ling et al, 2006] have investigated the acquisition of top or side view ISAR images with the proper cross range scaling. The technique is based on the measurement of slopes of the two main feature lines of the ship, which are the center line and the stern line. This process has the advantage of using only the acquired image to complete its tasks. [Lord et al, 2006] have investigated methods to obtain three dimensional radar cross section (RCS) images using the ISAR concept. Results are provided towards the degradations effect of specular multipath effects on the final image. [Rice et al, 2006] have described a method of ISAR image classification based on a comparison of Range-Doppler imagery to existing three dimensional ship reference models. This technique uses a sequence of ISAR images in order to estimate the dominant ship motion. In all above indicative work there is no mention of the computing force that provides the motion of the radar and target platforms.

Our work makes an attempt to fill in the details of an ISAR simulation analysis in a virtual reality environment which is supported by a software defined radar system.

2.1.2 Coherent Deception Techniques

Using a simulator in the context of a software defined radar system falls under the coherent deception electronic attack technique. In this manner multiple targets can be generated which must have features nearly identical to the real ship target. And in order to ensure correct geometry and realistic false target velocities there is a need to take into account an estimation of the range, velocity and heading of the threat signal, as stated in [Baldwinson, 2008]. From [Yuan] it is concluded that is is beneficial to implement the false target signal entirely algorithmically. The purpose of the research is to obscure the real target into a cloud of other plausible yet false targets as stated by [Rui]. The analysis in [Xiaohan] states that the fake target mask, which are mainly coordinates and backscatter intensities, are stored in advance and that the Doppler's slope is important in the deception imaging process because it helps the threat signal to focus on the false target. We address this point in our simulations. Further false target geometry explanations can be found in example in [Rongbing, 2007] where a geometry and signal model is presented. For an ASIC (application specific integrated circuit) approach [Fouts et al 2005] have implemented the first documented hardware-based complete false target generator system. Nevertheless the exact contents of the look-up table that synthesizes the target are not fully discussed.

3. Conceptual Modelling for Coherent Countermeasures

We need to establish the fact that an ISAR simulator can be used as a software-defined radar system in order to perform coherent countermeasure activities. For that reason we have implemented an ISAR simulator which addresses the reflectivity solution of an extended naval target as seen by an airborne high range resolution sensor [Kostis et al, 2005; Kostis et al, 2006; Kostis et al, 2007; Kostis, 2008]. We found that the design could easily be extended to accommodate an added value which is a glint effects generator [Kostis EUSAR, 2008; Kostis et al, PCI2007]. For ISAR countermeasures purposes we argue that by injecting glint effects in the digital signal processing process the simulator can now produce more realistic results [Kostis, 2008]. This added value is necessary in order to add realistic effects to the false target as stated by [Neri, 2007]. For this value added process there are two methods of creating angular glint, Poynting vector and phase gradient. The first method is discussed in [Chen] where glint is calculated by the deviation of the Poynting vector and the heading vector. The second method is discussed in [Ming] where and RCS (radar cross section) based compensation method is presented. For our purposes we have used the approaches found in [Schleher] and [Shirman] where they base the glint estimation on the transversal component of the interconnecting vector between the two interfering sources.

From our work stems the research question of how useful, economic and straightforward it would be for this ISAR simulator to support a software defined radar system in order to perform electronic warfare functions. In this section we present the conceptual modelling steps of the simulator. And in the next section we present the results that bear the proof that this software defined system is capable to produce functions of security by obfuscation.

We are considering the case that the threats are equipped with high resolution microwave (radar) sensors that are capable of resolving the ship target in slant, cross and even height ranges while always tracking their most prominent points. Relevant effective soft-kill methods, which means deceive rather than destroy, is the capture of the threat signal in digital radio frequency memory, its down-conversion, its injection with false target reflectivity data by digital signal processing means, its up-conversion and final re-transmission to the threat sensor [Neri, 2007].

Our major contribution is at the provision of an Interferometric Inverse Synthetic Aperture Radar simulator which can generate realistic false target effects by adding glint noise to the false target reflectivity solution. The threat signal always tries to compensate for this noise as it is an inherent characteristic of an extended target.

3.1 Application Domain Definition

The task of Application Domain Definition is given to the SMEs that have authoritative information about the actual situational context. Usually at this point in time the SMEs will hold several meetings with the SEs and discuss the theoretical and practical milestones that have to be observed during the course of the project. Usually at this stage the SEs will have only superficial knowledge about the subject matter. On the other hand SEs that can perform the task of SMEs are valuable for any particular situation. We now explain the operational abilities of High Range Resolution radar systems by presenting a short relevant theoretical background. The main theoretical aspects for ISAR imaging are in order of logical progression: SAR imaging, spotlight mode of SAR imaging leading to ISAR imaging.

A SAR system has an antenna aperture which is synthesised by the combination of relatable parts rather than the real dimensions of its physical antenna. The SAR imaging principle is based on two foundations:

- Coherence.

- Sampling. The digitisation of continuous processes. The synthetic array is made up in a radar digital signal processor.

The major advantage of SAR systems is much better slant and cross range resolutions. A numerical example will be utilised to illustrate all the above in mathematical terms. Starting with a conventional 10GHz radar with an antenna aperture of 3 meters looking down to a target 10 Km away, the cross range resolution is :

$$\Delta x = \frac{\lambda}{d} R = \frac{0.03}{3} 10000 = 100m \qquad (1)$$

This azimuth resolution is very low because a single resolution cell is illuminated at any one time. For example two ships less than 100 meters apart at the same range would appear as only one echo. Thus they cannot be resolved by the radar of Figure 2.

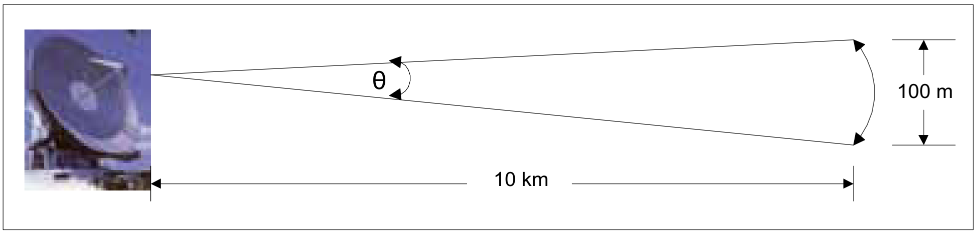


Fig. 2. Conventional Radar Angular Resolution or Real Aperture Radar (RAR).

Now assuming stationary targets and employing an airborne SAR system at the same frequency and range the azimuth resolution $\Delta\chi$ can be brought from 100 meters down to 3 meters, as shown in Figure 3.

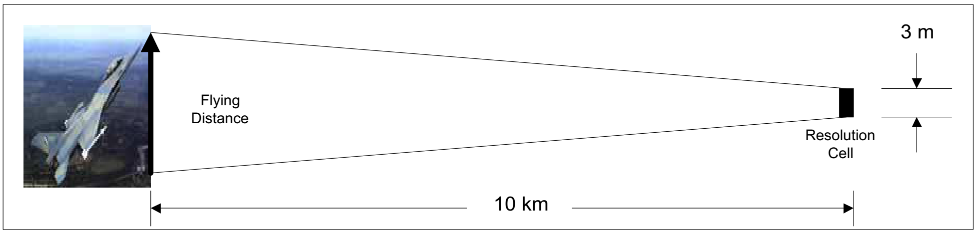


Fig. 3. Synthetic Aperture Radar (SAR).

The fly time should equal the distance of :

$$\Delta x = 3m = \frac{\lambda}{d} R \Rightarrow R = \frac{3d}{\lambda} = \frac{3*3}{0.03} = 300m \qquad (2)$$

Therefore when the airborne synthetic aperture system flies for 300 meters around or across the target the azimuth resolution becomes much finer at only 3 meters long.

When the radar beam is focused on one point in space the concept is call Spotlight Synthetic Aperture Radar, as shown in Figure 4.

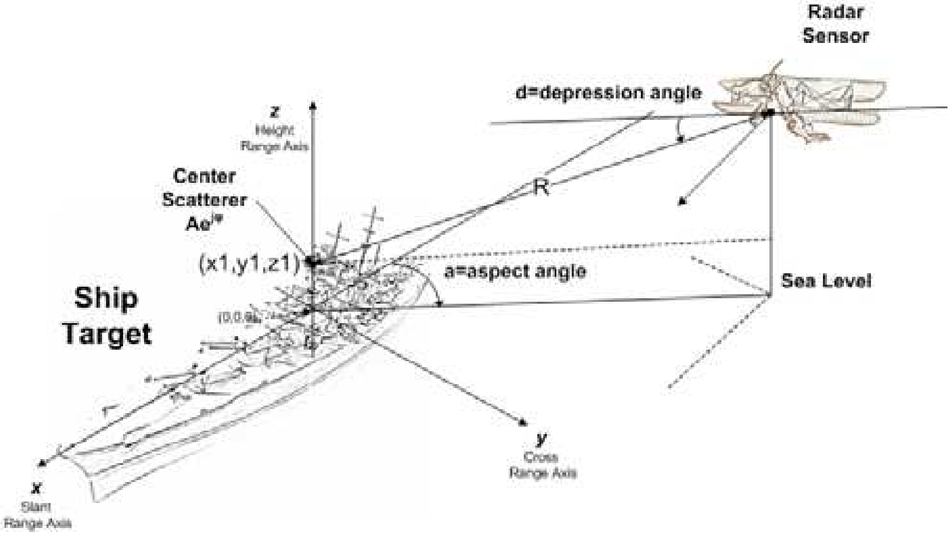


Fig. 4. Spotlight Synthetic Aperture Radar.

Spotlight SAR is the dual of the Inverse Synthetic Aperture Radar concept that will be used to image the naval target. The duality is that in Spotlight SAR the radar is moving where the target remains still. In ISAR imaging the radar is still where the target provides the motion that synthesizes the extended antenna aperture that leads to the higher resolution image.

In order to create false targets an introductory procedure is shown in Figure 5 [Kostis et al, IOP MST 2009].

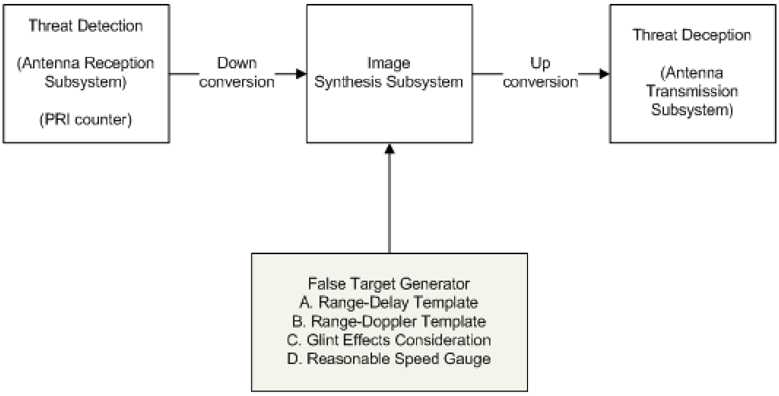


Fig. 5. The position of the False Target Generator Subsystem

Care must be given to the False Target Generator subsystem. Its outcome must resemble a signal that has all the necessary characteristics of an inverse scattering coming from a true target. For example the signal must contain mild or severe elements of angular glint noise. In other words the reality factor is decided by the ability of the false target generator subsystem.

3.2 Problem Space Decomposition

The entities and processes that must be represented for the successful accomplishment of the simulation are defined. For this project the list of entities as shown in Table 1.

	Simulation	Reality
1	Target cartesian coordinates plus inherent amplitude & phase	Target physical properties & electromagnetic signature
2	Radar slant range and cross range cartesian coordinates with respect to the center of the target	Most prominent appears to be the middle of the ship for this project. But it could be in the stern or the bow of the ship.
3	Sea-level distance from radar to target	FM height finder radar (altimeter) on airborne platform
4	Radar operational parameters	ISAR system particulars
5	Aspect angle from radar to target	Change of aspect angle from radar to target provides the resolution acquisition process

6	Glint Effects	Physical Phenomenon
7	Pace Engine	Target movement due to forces of nature
8	ISAR processor details	Range-Doppler processing
9	ISAR system output	Slant Range Profile and ISAR Image of target

Table 1. Entities

Now we can draw the necessary associations between the entities and come up with the corresponding processes, as shown in Table 2. Again as above the comparison between the reality and the simulation is strongly taken into account.

	Simulation	Reality
A	Provide information to the Pace Engine of target Cartesian coordinates to the pace engine	Physical presence and movement of target
B	Provide information to the Pace Engine of radar two-dimensional (slant ranger and cross range) coordinates	Physical presence and movement of radar
C	Provide information to the Pace Engine of radar's third (height range) dimensional coordinates	Measurement - captures reality with a sensor
D	Provide information to the ISAR Processor about the radar's operational parameters	Instrumentation – operational information
E	Aspect angle variation	Caused by changes in target/radar location
F	Glint Effects Injection	Digital Signal processing Conditioning (Masking)
G	From Pace Engine to rotated points database	Caused by changes in time
H	From Pace Engine Database to ISAR Processor	Recording Process – processes history of target in computer memory
I	From points database to ISAR processor	Computer process – Range-Doppler Processing - translates reality to computer memory

Table 2. Processes

3.3 Entity Abstraction Degree

The representational abstraction of the involved entities is finalized in this step. The level of accuracy, precision, resolution and fidelity of the entities and processes is determined. The main element that can have various levels of detail is the target's initial reflectivity solution at an aspect angle of forty-five degrees. First the extended naval target is modelled as an isotropic or directive point scatterers model, as shown in Figure 6 [Kostis et al, IJSSST 2009].

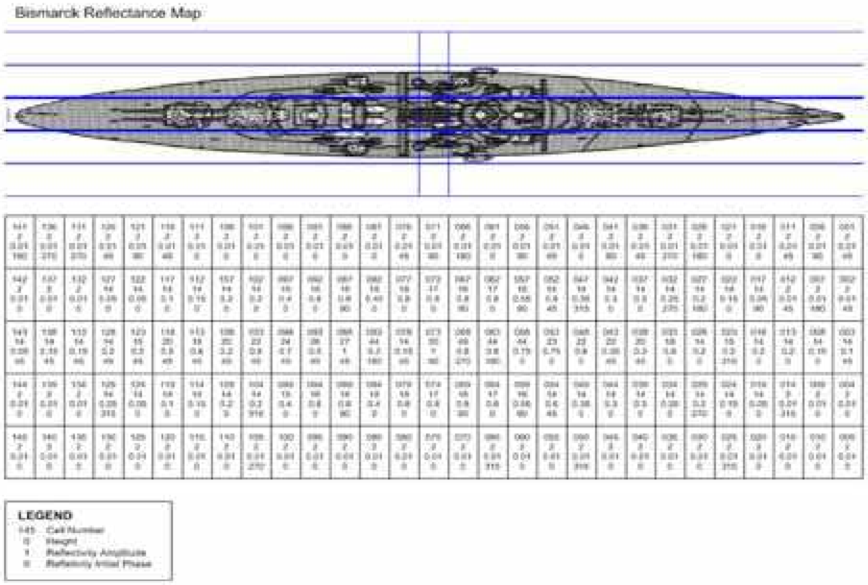
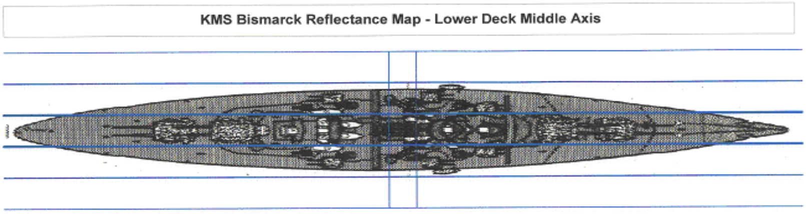


Fig. 6. Single Layer Model

Then the false target is synthesised by taking the reflectivity grouping of multiple layers across the ship superstructure. An example is shown in Figure 7, where another layer is included in the calculations.



143 1 5 45	138 14 15 45	133 14 15 45	128 14 20 45	123 15 20 135	118 20 50 45	113 18 60 45	108 20 20 45	103 22 60 135	098 24 70 45	093 26 50 45	088 27 100 45	083 44 10 180	078 14 10 45	073 30 10 90	068 49 10 270	063 44 10 180	058 44 75 0	053 23 75 45	048 22 60 0	043 22 35 45	038 20 30 45	033 18 60 0	028 14 20 0	023 15 20 315	018 14 20 0	013 14 20 0	008 14 15 0	003 1 10 45	5/5
						155 20 0			154 60 270			153 10 90	152 40 135	151 20 0	150 40 0	149 80 180		148 50 0		147 80 90		146 40 0							4/5
												161 20 0	160 40 270	159 20 0	158 80 0	157 80 90		156 20 0											3/5
												167 20 0	166 20 0	165 10 0	164 20 315	163 30 90		162 20 0											2/5
													172 80 0	171 20 0	170 25 90	169 60 45		168 20 0											1/5

LEGEND

145	Cell Number
1	Height
1	Reflectivity Amplitude
0	Reflectivity Initial Phase

Fig. 7. Middle layer reflectivity generation.

Now the inverse scattering modelling is affected by the pace engine. The Pace engine is the computing moving force that proceeds the points on the ship in time to new locations from their initial values depending on the motion of the ship. The movement is performed by an affine transformations module that provides roll, yaw, pitch and translations functions. All time processions actions are placed into the context of a three-dimensional environment, which is depicted in Figure 8.

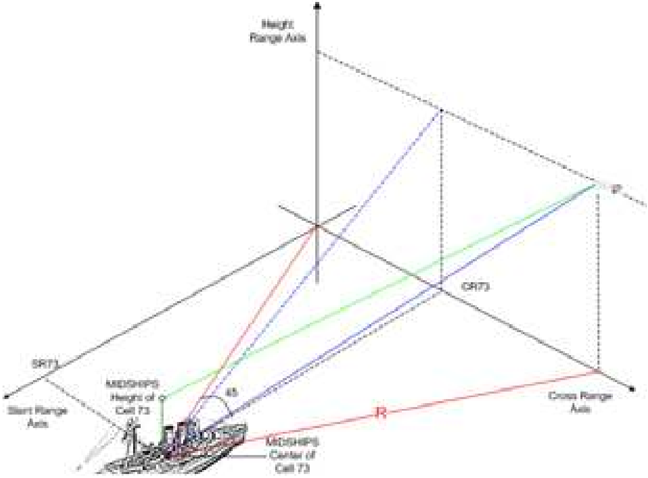


Fig. 8. Synthetic Environment Modelling

And the graphical representation of the inverse scattering is shown in Figure 9.

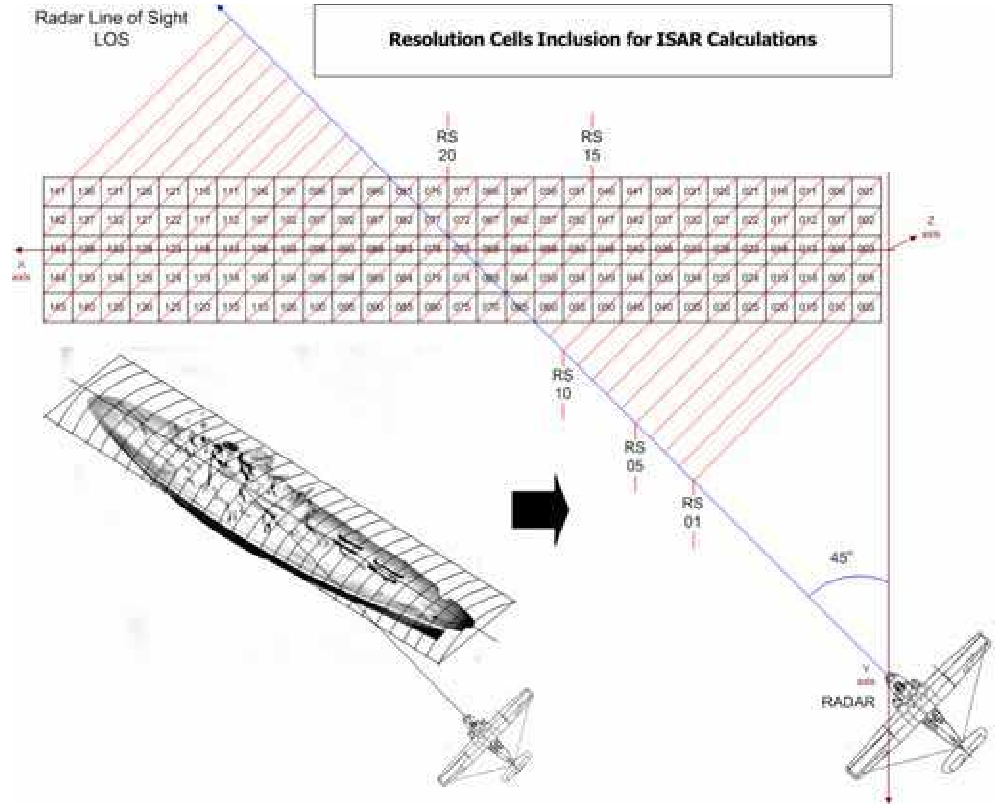


Fig. 9. Theoretical implementation (Polar Format Approximation)

3.4 Entity Relationship Identification

The relationships among the entities are identified in this design phase. It is ensured that all constraints and boundary conditions are properly imposed by the simulation context. All operational and functional requirements are taken into consideration, as shown in Figure 10.

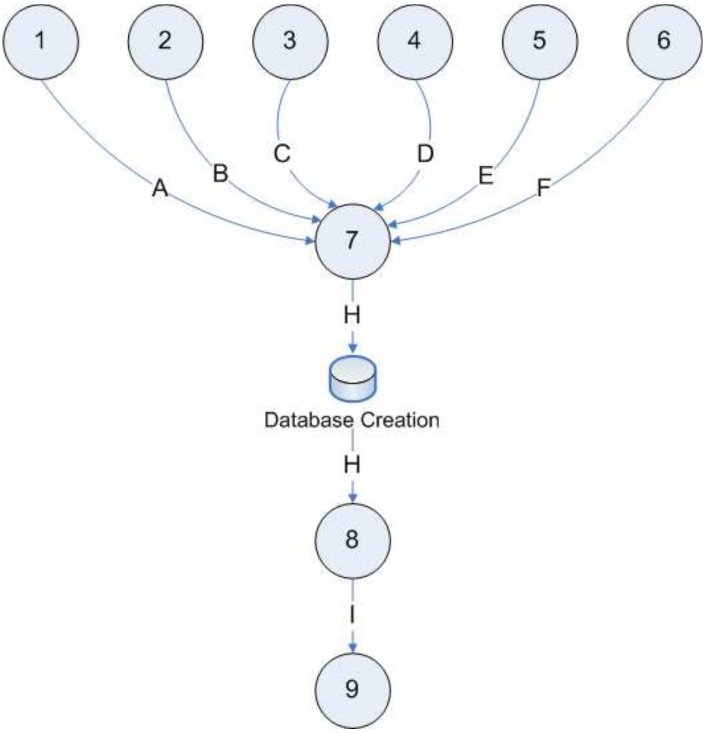


Fig. 10. Entity Relationship (E-R) identification

4. Implementation Procedure

The implementation procedure follows the rules of a complex system. In other words many individual components or transfer functions of the simulator when combined give a unique property or emergence to the output. Also the current implementation is process oriented. Every point on the target is passed through all transfer functions of the simulator in order to produce its corresponding output. The emergence of the system becomes obvious when all the points are put together in a graph. Each individual point cannot tell its tale. All of the points produce top view images or side view images of the target. This decision depends on the building blocks of the simulator.

4.1 Computing Methodology

The set of methods that define the processes and the order of this project is to be achieved is shown in Figure 11.

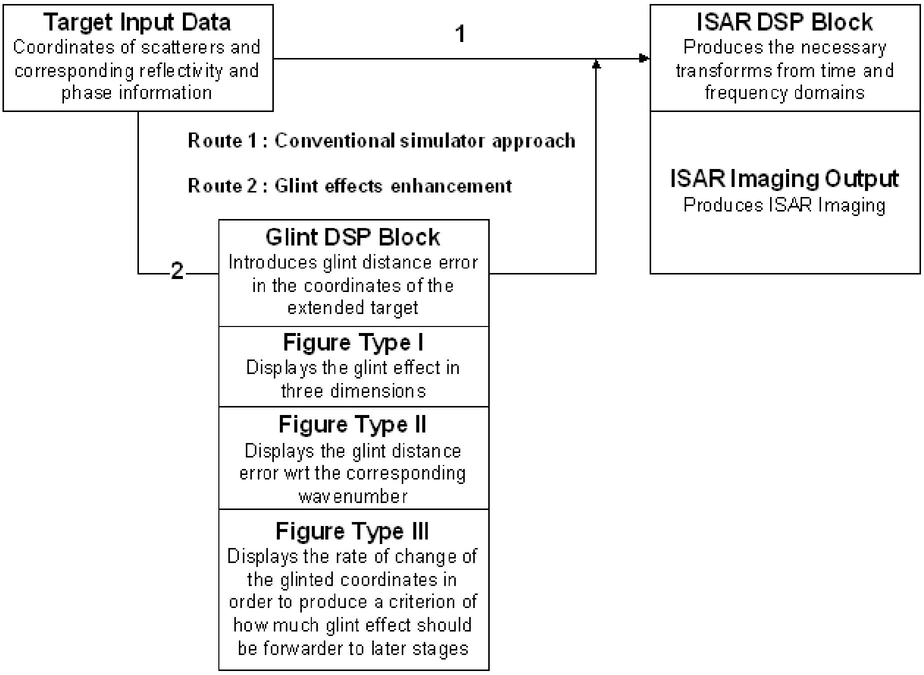


Fig. 11. Computing Methodology

4.2 Simulator Implementation

The simulator software implementation followed the process oriented technique as shown in Figure 12.

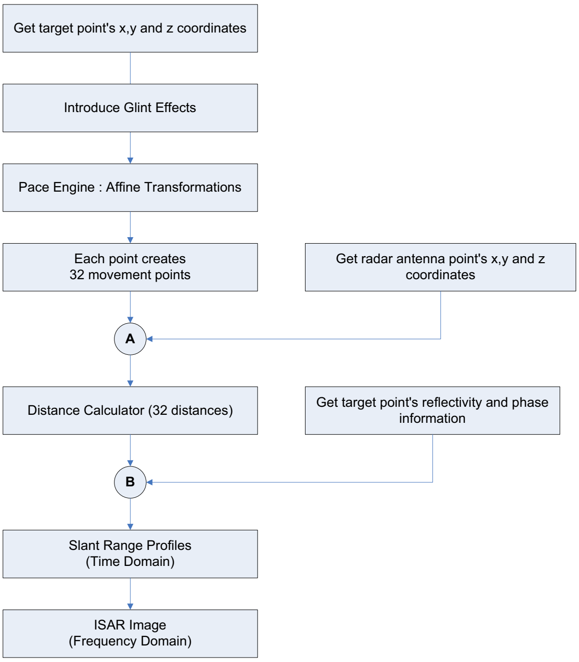


Fig. 12. Simulator Implementation of the FB-14 modular software system

The conceptual design and software implementation steps are now complete. The process resulted in the creation of the FB-14 software defined radar system. The system design is highly modular. That means that the context of the software defined radar system can be easily verified, validated, reused and extended. We then move on to assess the results obtained from our efforts.

5. Simulation Results

The results correspond to ISAR images expected to be obtained by the range Doppler method. These results were formally presented at the International Journal of Systems, Science & Technology. There is a value added function that adds glint effects to the output in order to increase the validity of the output which was presented at the Measurement, Science & Technology Journal of the Institute of Physics.. The third stage of this project was presented at NATO SET-136 Specialist's Meeting on Software Defined Radar.

5.1 Single Layer & Multi-Layer Model Results

Invoking the single layer model which involves only the top points of the superstructure, the output of Figure 13 is created.

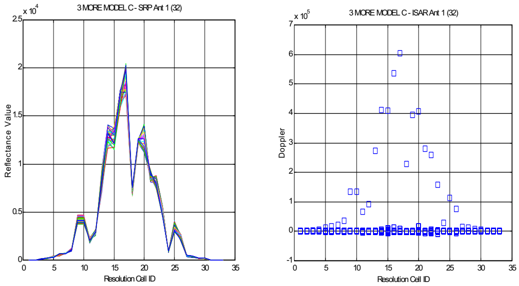


Fig. 13. Single Layer Slant Range Profile and corresponding ISAR image

Next by invoking the multiple layer model which involves the top and middle points of the superstructure, the output of Figure 14 is created.

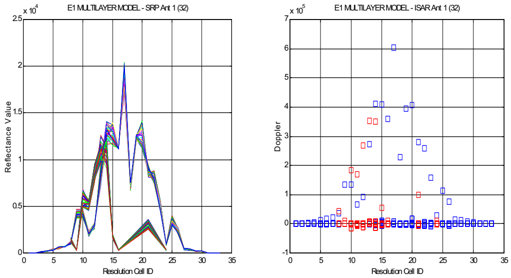


Fig. 14. Multiple Layer Slant Range Profile and corresponding ISAR image

5.2 ISAR Reflectivity Results & Issues for Military Targets

Military targets are different from civilian targets in the fact that there are many high reflectivity centers of reflectivity on lower coordinates. These high reflectivity values distort the ISAR image accordingly and killed ISAR operators look for these distortions in order to classify or even identify a radar contact. Our simulator can produce such effects as shown in Figure 15. Outputs of two antennas situated on a baseline of one meter away from each other are shown in order to demonstrate how different the image can be even when the antennas are very close to each other.

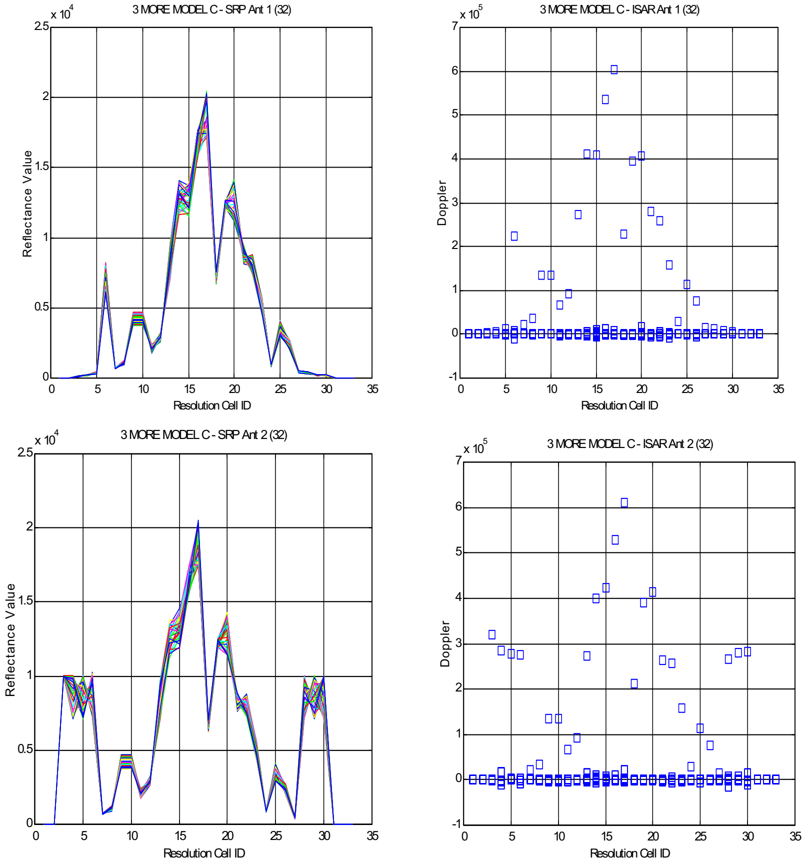


Fig. 15. ISAR Shortcomings Effect using the Single Layer Model.

5.3 Angular Glint Results & Issues for Military Targets

In order to increase the validity of the simulator output to the adversary radar-operator system the phenomenon of angular glint is introduced.

The first result is inspired by [Skolnik, 2001] and demonstrates the glint effect in a three dimensional synthetic environment with respect to the real target points. We call this component Glint Effect in 3D at the target and is shown in Figure 15(a).