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RCS Modeling and Validation of Full Scale Launch Vehicle for its Real Time Dynamic Trajectory

Surender Veerabathini[#,*], P. Sudhakara Reddy[$] and P. Ramana Reddy[#]

[#]Jawaharlal Nehru Technological University Anantapur, Ananthapuramu - 515 002, India
[$]Annamacharya Institute of Technology & Sciences, Rajampet - 516 126, India
[*]E-mail: sdpt2020@gmail.com

ABSTRACT

Radar Cross Section (RCS) plays a significant role in detecting and tracking the space-based objects such as launch vehicles, missiles, aircrafts etc. In space applications, Radar systems are used to track and provide real-time trajectory information of the satellite launch vehicles after the lift off from the launch pad for range safety purpose. RCS is a critical key parameter that determines tracking performance of the Radar and it is highly dependent on both Radar operating parameters and the target characteristics. For space-based applications, a good quantity of RCS is required for quick detection by the Radar for continuous tracking. In order to choose the best Radar tracking configuration for real time tracking of the launch vehicle, it is required to model and simulate the launch vehicle's RCS fluctuations prior to launch in order to predict the real time Signal to Noise Ratio (SNR) for its complete dynamic trajectory. This modeling and simulation methodology will help to choose the optimum Radar configuration for obtaining a good quantity SNR in the real-time launch. This study also provides good guidance to Radar operators for the effective Radar operation during real time space object tracking. This paper demonstrates, the real-time RCS fluctuations of a typical ISRO launch vehicle through simulation for its dynamic trajectory using physical optics based EM software prior to launch. Furthermore, the simulation results are validated with real time monostatic Radar tracking data, which showed good agreement.

Keywords: Radar Cross Section (RCS); Launch vehicle; Monostatic radar; Real-time; Dynamic trajectory; Aspect angle; Polarisation

NUMENCLATURE

σ	Radar Cross Section
K	Boltzmann constant
λ	Wave length
F	Noise Figure

1. INTRODUCTION

In recent years, the target detection system has been field of interest for many space and defense applications[1]. The simulation of RCS can significantly contribute towards a wide range of radar communications and electronic warfare engineering applications. RCS is a vital research parameter for space-based applications, especially when dealing with dynamic space targets tracking that profoundly affects the Radar performance. It is an estimate of the power distributed in a given spatial direction when an incident wave illuminates a target[2]. The size, shape, and aspect angle of the launch vehicle seen by the Radar shall contribute the RCS variations for the given trajectory.

Radar is an electromagnetic system that detects and locates objects by sending electromagnetic signals towards the object and processing the return echoes to determine the target's trajectory. The influence of RCS on the Radar received power is expressed by the Radar range equation. The reflected power is calculated by multiplying the effective area of the target by the incident power density.

The reflected power is calculated by multiplying the effective area of the target by the incident power density. The reflected power is calculated by multiplying the effective area of the target by the incident power density. It's known as backscattering cross section or object echo. The object's RCS explicitly describes the intensity of the echo and its formal definition[3] is

$$\sigma = 4\pi \lim_{R\to\infty} R^2 \frac{|E^{scat}|^2}{|E^{inci}|^2} \tag{1}$$

Where, E^{inci} is incident electric-field strength strikes upon the target and E^{scat} is reflected electric-field strength at the Radar receiver with far field distance is R. Because of large variations in RCS patterns, RCS is depicted for convenience in the logarithmic scale. The RCS units expressed in decibels[4] per square meter is formally showed as:

$$RCS(dBsm) = 10log_{10}(\sigma) \tag{2}$$

RCS relies on target parameters like material properties, shape, size and orientation and similarly it also depends on parameters of the Radar such as aspect angle, frequency and polarization of transmit and receive signals. The target RCS can be controlled depending on the application. There are

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different techniques are available to enhance or reduce the RCS of the target. The higher the RCS value, the simpler an object is to detect and identify and vice-versa. The higher RCS is warranted for simple detection and tracking of the space based civilian targets such as rocket, aircraft, ship, etc in homing environment. However, in certain defence applications such as missiles, ships, fighter aircrafts tracking, need a very less RCS design to avoid detection by the foe Radars[5] in hostile environment. The targets RCS determines not only the existence of the objects, but also gives their approximate size and shape of the target[6].

2. NEED FOR LAUNCH VEHICLE RCS MODELING PRIOR TO LAUNCH

The launch vehicles are complex targets that follow pre-determined paths to keep the satellites in the space. Satish Dhawan Space Centre (SDSC) SHAR, India's Spaceport, is responsible for providing the Indian Space Program's launch base infrastructure by launching different satellites. The Launch Vehicle is a vehicle that is used to launch satellites into space from the earth's surface. The activity of launching satellites is potentially hazardous and complex in nature that necessitates ensuring range safety. The Range Safety is very important to ensure the safety of infrastructure and life of the personnel during launching of the satellites at any launch station. In the field of space launch vehicle transportation, range safety is to be ensured by a system that continuously monitors the LV behaviour after the lift off from the launch pad at T+0 sec during the countdown phase. The tracking data of the Radar plays a key role in real time by obtaining launch vehicle positional information to verify its performance after the lift-off from the launch pad for range safety[7].

SDSC SHAR is equipped with L-band, S-band and C-band radars for launch vehicle tracking in real-time to meet the range safety requirements. Range Safety Officer (RSO) will verify the Radar real time tracking data with respect to pre-defined trajectory, if any deviation is detected, RSO will execute the required action within the specified of period of time to prevent catastrophic incidents[8].

The modelling and simulation of a target RCS able to make good contribution towards various Radar engineering applications. The modeling of RCS characteristics of the LV prior to launch is most essential feature to analyze the scattering properties of the target for SNR variations. These RCS simulation studies of simple and complex space objects are decisively important in order to improve the Radar detectability. SDSC consists various ground-based tracking Radars to track the launch vehicles in transponder (beacon) and skin mode[9].

Practically, launch vehicle as a complex target moves in the space, its RCS exhibits significant fluctuations. In this scenario, there is a possibility of Radar may encounter the tracking breaks with sudden signal dips during the real time, which misleads the estimation of the launch vehicle trajectory as well as estimation of instantaneous impact point of the separated stages[10], ultimately lead to loss of lives and damage to critical space infrastructure of the country. Therefore, in real time, it is to be ensured to get adequate quantity of signal continuously from the LV target in order to identify and track by the Radar for the purpose of range safety.

3. LITERATURE REVIEW

Theoretical estimation of RCS measurements for complex space targets such as launch vehicles, missiles, airplanes etc, is very difficult due to the fact that all realistic phenomena such as full scale target, relevant environmental conditions[11] and complexity in data processing etc,. Several methods of RCS prediction with their own characteristics and impediments are described in detail. The RCS prediction methods are broadly categorized into 1. Exact methods 2. Approximate methods[12]. The Exact methods are very laborious even for simple objects because they required solving complex mathematical equations with target boundary conditions taken into account. Method of Moments and Finite Different Time Domain are some examples of the Exact Methods. The other category is Approximate Methods in which prediction of RCS is simple and takes less time. In the optical region, most of the approximate techniques are valid and each technique has its own set of benefits and drawbacks. Geometrical Theory of Diffraction, Geometrical Optics, Physical Theory of Diffraction, Physical Optics and Method of Equivalent Currents are most extensively utilized approximate approaches. The Approximate methods have become feasible and alternative due to the less complexities related with exact RCS predictions[13].

3.1 Physical Optics Surface Current Computation

The Physical Optics (PO) method describes that the induced current is simply proportional to the incident magnetic field intensity on the portions of the body that are directly illuminated by the incident field. The current is stand to zero on the shadowed portion of the target[14]. Hence

$Js = \{2nxHi$ portion that is illuminated and

$Js = 0$ portion that is shadowed

where, Js the induced current density and Hi is the intensity of the incident magnetic field at the surface. The above Js is a single facet's induced scattered field. A model with many triangular facets is used to approximate a large target. The incident electromagnetic waves are transformed on the scattering surfaces of the target's facets under analysis into equivalent surface currents[15]. The induced surface fields and integrates them by using super position to obtain scattered field from the entered target. The RCS in that direction is computed once the scattered field is known. This is done for each of the user-selected observation directions. The scattered waves have same polarization as that of the receiving antenna.

The PO approximation technique is one of the most suitable RCS prediction methods for estimating the RCS of complex targets. It's a high frequency method in which the target's size exceeds the Radar's operating wavelength[16]. This method is computationally less intense and easy to implement. Hence, it is popularly used for estimating the RCS of the complex targets in optical region. A target's RCS will have large variations that depend on operational frequencies. Depending on the size of the target, RCS variations with respect to frequency are classified into the Rayleigh region, the Resonance or Mie region and the Optical region[17].

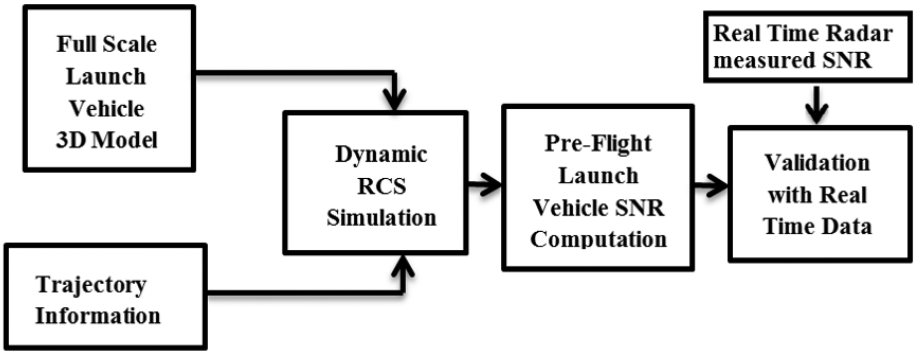

Figure 1. Simulation methodology of SNR computation.

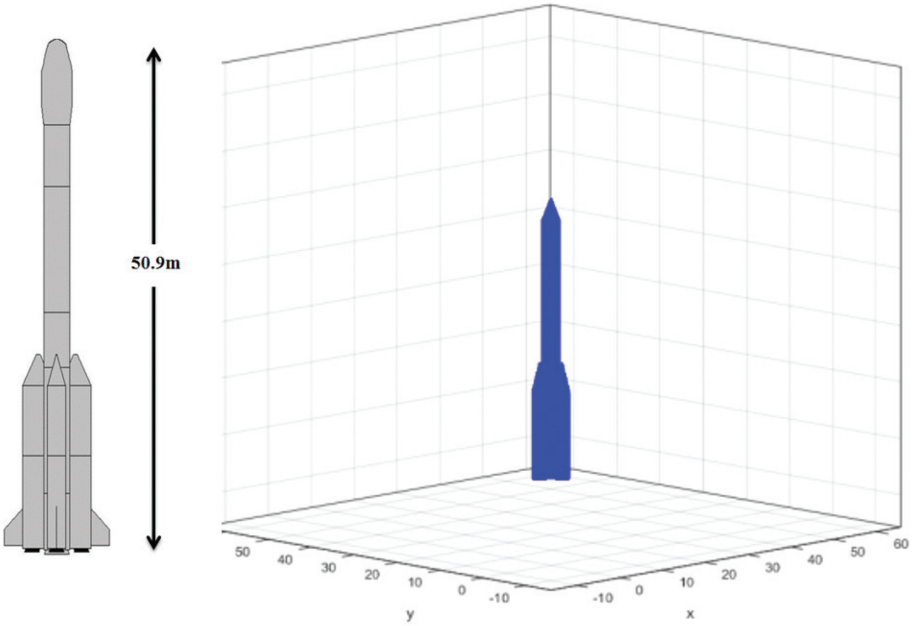

Figure 2. Typical launch 3D model as per actual dimensions.

4. SWERLING MODEL

In radar applications, the targets are moving and have relative motion with the radar. The radar cross section varies slowly or rapidly depending on the characteristics of the target. Swerling target models describe the statistical properties of the radar cross section of objects with complex formed surfaces. The fluctuation of the target's reflected signal is based on its relative RCS model. Swerling defined the RCS of a reflecting object based on the chi-square probability density function with specific degrees of freedom[18].

This fluctuating RCS is referred to as the target's dynamic radar cross section. In a given scan, dynamic RCS varies with amplitude or phase. Swerling Target Model II, where RCS values change more quickly and vary from pulse to pulse. This model applies to a target composed of many independent scatterers with roughly equal areas, such as aeroplanes, launch vehicles, and missiles. The RCS density of probability is given by the Rayleigh-Function below Eq.3 :

$$P(\sigma) = \frac{1}{\sigma_{avg}}.exp\left(\frac{-\sigma}{\sigma_{avg}}\right) \tag{3}$$

where, σ avg is the arithmetic mean of all values of RCS of the reflecting object

There are various RCS computing software packages[19] such as POFACETS, EPSILON, CADRICS and CST Simulation Software etc, exists for target RCS estimation. POFACET simulation software is used to predict the full scale RCS of the launch vehicle target implemented with the PO method. It's a well-known simulation software tool that is used for the RCS estimation of complex targets with high processing capabilities[20]. It makes use of MATLAB's scientific computational features and Graphical User Interface functions to perform error-free efficient RCS calculations[21].

In launch vehicle tracking applications, the static RCS measurements are insufficient. It is essential to know the dynamic RCS characteristics of the launch vehicle in motion. A reliable methodology for modelling and RCS estimation of a typical full-scale ISRO launch vehicle, as well as SNR computation for its real-time dynamic trajectory prior to launch, is provided in this work using proven software. The pre-flight simulated SNR results are validated with its real-time monastic Radar SNR measurements.

Table 1. Typical ISRO launch vehicle trajectory

Pre-flight LV trajectory data		
Time (sec)	**Range (Km)**	**Aspect angle (Degrees)**
T+0	(Lift off) 6.421	88.749
0.1	6.421	88.739
0.2	6.421	88.730
….	….	….
1.0	6.421	88.728
5.0	6.531	85.556
10.0	6.534	70.024
50.0	12.162	15.995
275.3	517.405	8.231

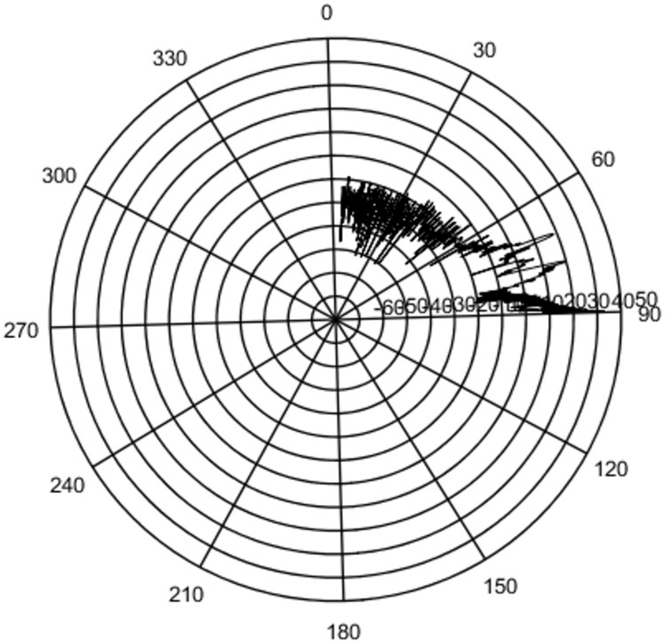

Figure 3. RCS (dBsm) fluctuations wrt aspect angle (deg) in polar plot.

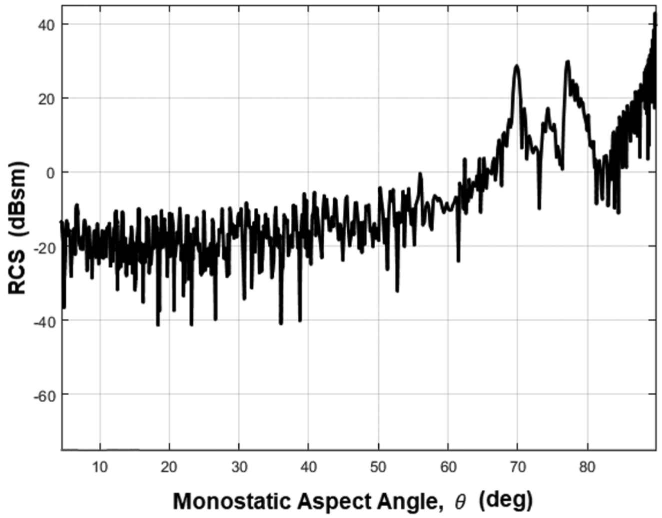

Figure 4. RCS fluctuations in linear plot.

4. RCS ESTIMATION

4.1 RCS Modeling and SNR Computation of a Typical ISRO Laucnh Vehicle Prior to Laucnh

The launch vehicle RCS modeling and estimation facilitates to compute the expected real- time SNR fluctuations prior to the launch. The following steps are adopted for RCS estimation and SNR calculation of a typical full scale launch vehicle target for its real-time dynamic trajectory as shown in Fig. 1.

Step-1: 3D Modeling of Full Scale Launch Vehicle

The complex target like launch vehicle is usually built in stages using simple arbitrary objects[22] like triangles, cone, rectangle, cube, sphere etc, and stages are separate in the space as per pre-planned program. With the design software, a full-scale launch vehicle in 3D model is created according to actual dimensions[23] shown in Fig. 2. The material properties of the launch vehicle target is also considered while designing 3D model of the LV target. RCS estimation software takes the designed 3D model as input.

Step-2: Trajectory Information Input for Dynamic RCS Simulation

The launch vehicle's trajectory provides launch vehicle target's positional parameters such as range, azimuth, elevation, aspect angle which will change with respect to time. During the flight mode, target makes real-time motion along the trajectory with respect to stationary Radar. The typical pre-flight launch vehicle trajectory parameters are shown in the Table 1.

Step-3: Dynamic RCS Simulation of Launch Vehicle

Import the Launch Vehicle Full Scale 3D model to the Physical Optics based RCS estimation software for carry out simulation to predict the Dynamic RCS variations of the launch vehicle target. It is a well-proven software simulation tool that is used for estimate RCS of the complex targets with high processing capabilities as per given trajectory data[24] shown in Table.1. The RCS simulations are performed with the monostatic Radar method in dynamic condition for all given aspect angles in the trajectory. During the simulation, the launch vehicle stage separation sequence also considered in the trajectory as per separation events and results are plotted in polar plot and linear plot. The simulation results shown in Fig. 3 and Fig. 4 respectively.

Step-4: Pre-Flight Launch Vehicle SNR Computation for its Real Time Dynamic Trajectory

The pre-flight SNR values are computed based on simulated RCS data for a given typical launch vehicle trajectory by using Radar range equation (Eq. 4). For free space propagation, range equation[25] of the Radar is determined by

$$SNR = P_s/P_n = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R^4 K T_0 B F L s} \tag{4}$$

where, SNR is Signal to Noise Ratio, P_s and P_n are received signal and noise powers, P_t is radiated power, G_t and G_r are gains of transmitter and receiver antenna of Radar respectively, λ is the transmitting signal wavelength, R is expressed the range and σ (sigma) is target RCS, K is Boltzmann constant,

T_0 is reference temperature (in kelvin), B is effective Noise Bandwidth, F is Noise Figure and Ls is System losses.

The following Radar parameters are taken into account while computing the SNR values are summarised in Table 2.

5. MONOSTATIC RADAR SNR MEASUREMETS DURING REAL TIME

During the real time, launch vehicle tracking carried out by monostatic tracking Radar in which same antenna is used for transmitting and receiving the signals in skin mode and provides trajectory information about the target such as SNR, range, azimuth, elevation and altitude etc. During real time, the launch vehicle travel in a predefined trajectory and stages are separated as per planned sequence which is controlled by onboard computer. The target's RCS is a function[26] of its aspect angle i.e., elevation angle θ and the azimuth angle φ. The launch vehicle is being tracked by radar for a typical flight sequence shown in Fig. 5.

Table 2. Radar parameters for SNR computation

Radar parameter	Value
Radar type	Monostatic
Peak power (KW)	1000
Frequency of operation (MHz)	3000
Pulse width (nano sec)	1000
Gain of antenna (dB)	39
Receiver sensitivity (-dBm)	110
K is Boltzmann constant	1.3806 X 10^{-23}
To is reference temperature (kelvin)	587.78
B is effective noise bandwidth	1.4 MHz
Ls is system losses	6dB
F is noise figure	1.4
Target range (Km)	Input Trajectory file
Aspect angle	Input Trajectory file
Target RCS	Simulated Data (as per Step-3)
Polarization	Horizontal

During the real-time, the Radar configuration parameters are selected as per Table 2. The target tracking parameters during real time trajectory including SNR values are logged in Radar Data Processing System.

6. VALIDATION OF PRE-FLIGHT SNR ESTIMATION DATA USING REAL-TIME RADAR EASUREMENTS

The simulated SNR values are validated by comparing with real time measured Radar SNR values for a given trajectory and validated results are shown in Fig. 6.

7. RESULTS AND DISCUSSIONS

Prior to launch, RCS modeling of a typical launch vehicle's dynamic trajectory is carried out by proven software. The pre-flight expected SNR values are computed with estimated RCS data and compared with the Radar real-time measured SNR values. The SNR variations in both cases are plotted and shown in Fig. 6.

7.1 Inferences

- The pre-launch simulated SNR variations are good agreement with real-time Radar tracking SNR data for a typical launch vehicle for its dynamic trajectory
- Initially up to T+25sec, higher SNR values were observed in both simulated and measured methods due to high aspect angle (ie, 80°)
- In the real-time radar measurements, 20dB signal reduction (dip) observed at T+120sec due to separation of first stage of the launch vehicle due to reduction in size

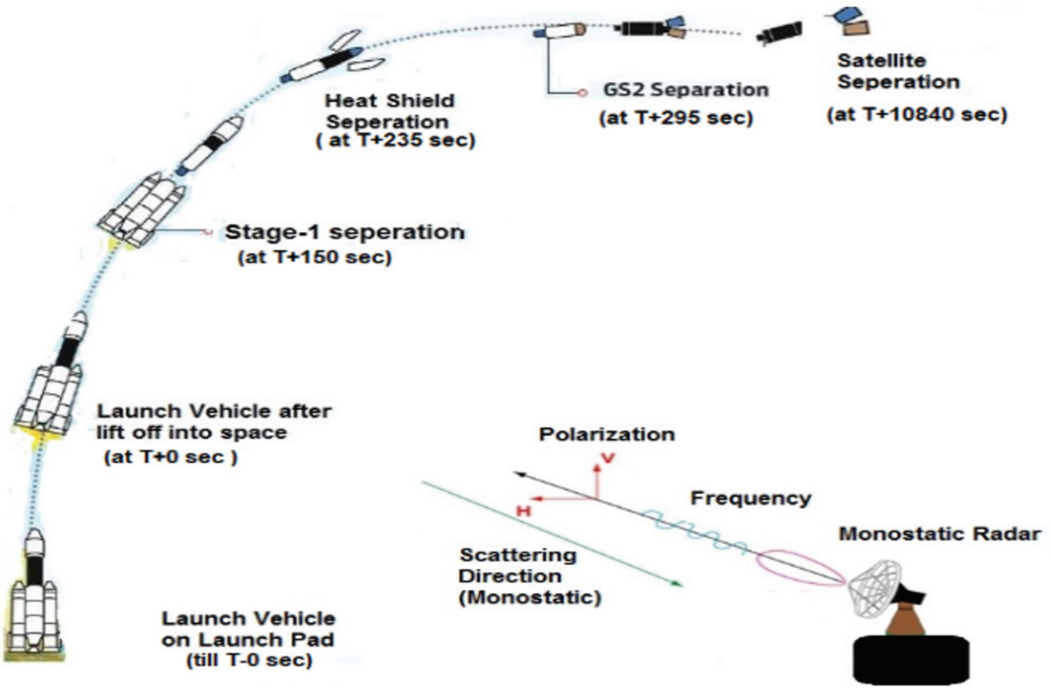

Figure 5. Launch vehicle flight sequence.

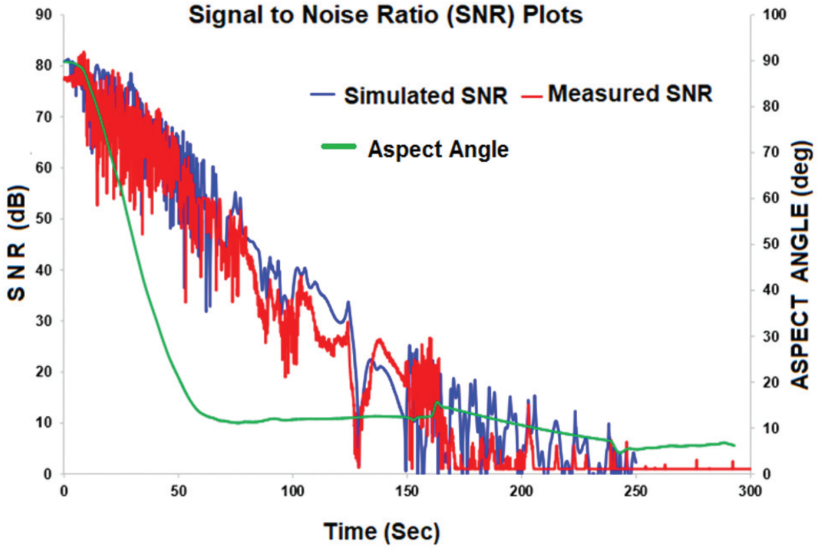

Figure 6. Real-time radar and estimated SNR results.

of the vehicle. The same signal reduction was appeared in the simulation due to reduction in RCS

- At T+150 sec onwards, more signal fluctuations were observed till LOS (Loss of Signal) due to low aspect angle. Minimum 10° aspect angle is ensured to get good amount of signal
- At T+250 sec onwards, Radar received SNR touching the 0dB line where radar received signal is equivalent to noise floor of the receiver i.e., -110 dBm. Radar receiver cannot detect the signal whose values are below 0 dB (i.e., receiver sensitivity) as shown in the plot
- Pre-launch computed SNR values shows around 3 to 5 dB more, which may be due to the environmental conditions like flame attenuation, multipath reflections etc., are not being considered in simulations.

The overall result shows that the launch vehicle's RCS depends on the aspect angle seen by the Radar and physical geometry of the launch vehicle in its dynamic trajectory. It also seen that minimum 10° degree of aspect angle is to be ensured to get good amount of signal from the launch vehicle. The target SNR values are observed in decreasing trend when range is increased as per radar range equation.

8. CONCLUSIONS

The need for RCS estimation and pre-flight SNR fluctuations for a typical ISRO launch vehicle's dynamic trajectory was discussed. The typical launch vehicle modeling and its RCS estimation carried out with proven software for its dynamic trajectory path and preflight SNR values also computed well before the real-time flight. The pre-flight computed SNR results were compared with real-time Monostatic Radar measured SNR values. With the exception of a few intervals due to non-consideration of environmental factors during software simulations, the both SNR results shows good agreement.

This novel methodology of Dynamic RCS estimation of a launch vehicle for its expected trajectory prior to launch is imperative to choose the best Radar tracking configuration to obtain sufficient amount of signal from the launch vehicle target during real time for continuous tracking to meet the range safety requirements. This approach also facilitates the Radar operator to perform effective Radar operation by pre-empting the signal strength dips due to RCS fluctuations in dynamic environments during real time. This methodology being implemented for optimizing the Radar tracking parameters for tracking any type of launch vehicle for its given trajectory in order to meet the range safety requirements at during the real time launching activity.

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CONTRIBUTORS

Mr Surender Veerabathini obtained his ME (Microwave Engineering) from Birla Institute of Technology (BIT), Ranchi. Presently working as Scientist/Engineer-SG at Satish Dhawan Space Centre (SDSC)-SHAR, Sriharikota. His areas of interest are: Tacking radars, telecommand, telemetry systems, microwave communications, avionics systems and testing.
In the current study, he conceived the concept carried out the literature survey and complete experimental work with interpretation, simulation and analysis of result.

Dr Sudhakara Reddy Penubolu obtained his PhD from SVU, Tirupati, Andhra Pradesh, India. Presently, he is working as Professor at AITS Engineering College, Rajampet, AP, India. His areas of specialisation are: VLSI in biomedical and wireless engineering, medicine and digital arithmetic engineering.
In the current study, he has guided in simulation methodology, reviewed the progress of work and provided various valuable suggestions.

Prof P. Ramana Reddy obtained his PhD in Electronics and Communication Engineering from Jawaharlal Nehru Technological University (JNTU), Anantapur, Andhra Pradesh, India. Presently, he is working as a Professor in ECE Dept, JNTUA College of Engineering, Anantapur, Andhra Pradesh, India. His areas of specialisation are: Signal and Image Processing.
In the current study, he has given the idea, reviewed the results, continuously provided the guidance and given many valuable inputs.