Dynamic RCS Modelling of Launch Vehicle Prior to Launch for Estimation of Real-time SNR

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Abstract. The Radar Tracking System plays a crucial role in tracking launch vehicles by providing continuous trajectory information in order to assess their performance in real-time for range safety purpose. The target Radar Cross Section (RCS) determines radar tracking efficiency and highly depends on both the target characteristics and the radar parameters. A good amount of RCS is warranted for space-based applications for easy detection and continuous tracking by the radar. It is essential to model and simulate the RCS fluctuations of the launch vehicle prior to launch for estimating the real-time received Signal to Noise Ratio (SNR) variations for its dynamic trajectory. This modelling will aid in selecting the best radar configuration to obtain a good amount of SNR in real-time and it also provides guidance for the radar operation in tracking the target. This paper analysed the RCS fluctuations of the launch vehicle for its dynamic trajectory prior to launch by software simulation and also compute the expected real time launch vehicle SNR variations.

1. Introduction
Present Radar applicability, the RCS estimation is exceptionally noteworthy analysis in detection and tracking of space-based targets. RCS is a scattered power measured in a given direction when a target is exposed by an incident wave[1]. An object's RCS is an indicator of its degree of radar visibility. The higher the RCS from the target, it will be readily detected by the radar. The higher RCS is mandatory for space and civilian applications, whereas in certain cases, such as fighter aircraft, ships and missiles, very low RCS design is necessary to avoid enemy radar detection [2]. It determines not only the objects' existence, but also the target’s estimated shape and size. RCS is the calculation of the capability of a target to represent radar signals in the direction of the receiver of the radar. Theradar range equationis basis for the design and calculation of the RCS of the targets. The effect of RCS on the radar power obtained by the radar range equation [3] is given by

\[ P_r = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R^4} \]  

Eq (1)
Where, \( P_t \) and \( P_r \) are transmitted and received powers, \( G_t \) and \( G_r \) are transmitting and receiving antenna gains, \( \lambda \) is the operating wavelength, \( R \) is the radar range and \( \sigma \) is the target’s RCS. The echo intensity is defined specifically by the object’s RCS [4] shown as below

\[
\sigma = 4\pi \lim_{R \to \infty} R^2 \frac{|E_{\text{scat}}|^2}{|E_{\text{inc}}|^2} \quad \text{Eq (2)}
\]

Where, \( E_{\text{inc}} \) is the incident wave’s electric-field intensity impinging on the target and \( E_{\text{scat}} \) is the scattered wave’s electric-field intensity at the Radar and \( R \) is the distance of the far field. Due to broad variations in its RCS patterns from one aspect angle to another, RCS of the target is expressed in the logarithmic scale for convenience [5]. The below expression for RCS is dB relative to a square meter [6].

\[
\text{RCS (dbsm)} = 10 \log_{10} \sigma \quad \text{Eq (3)}
\]

Factors that affect the RCS of a target: The RCS of a target depends on many parameters that are divided into two groups [7]:

A. Target Aspects: RCS of a target depends on its Absolute size of the target, Type of Material, Smooth Surfaces, Shape, Directivity and Orientation [8].

B. Radar Aspects: Radar parameters such as Frequency, Polarization and Aspect angle are influence the RCS characteristics of the target [9].

There are different methods to predict the RCS of the targets. The exact RCS prediction is very difficult, even for simple targets, so the alternative is an approximate method. Majority of approximate methods are valid in optical region, even these methods have their own strengths and limitations [20].

2. Need for RCS Modelling of Launch Vehicle

Radar system determine the range, angle and velocity of objects by tracking activity. The RCS is an important parameter of the study that deals specifically with dynamic space targets tracking that have a profound effect on the efficiency of the tracking radar [10]. Satellite Launch Vehicle (SLV) is used to carry satellites to space from the Earth's surface in order to place them in their intended orbits. Launching of SLV from the launch pad is potentially dangerous and challenging task. Satish Dhawan Space Centre (SDSC), India’s Space Port, is responsible for launching different launch vehicles for developing the space base infrastructure of the Indian Space Program. SDSC is equipped with various radars to track the launch vehicle in tracking mode of skin or transponder. The Radar Tracking System plays a crucial role in providing launch vehicle trajectory information in real-time. The radar tracking data is useful to evaluate the real time performance of launch vehicle for range safety [11]. The real time radar tracking data will be verified by Range Safety Officer (RSO), if any abnormality is detected, RSO will enforce the required action to prevent catastrophic accidents within the defined duration [12].

Due to RCS variations in real time radar tracking, there are possibilities of tracking brakes with abrupt signal dips, which is an unacceptable situation for RSO to assess the performance of the launch vehicle during the launch [13]. Therefore, it is very essential to get the good amount of signal from the target to track by the radar continuously. It is important to estimate and evaluate the signal strength variations for its dynamic trajectory before launch, because of the high criticality involved in real-time monitoring of the launch vehicle [14]. This innovative method of RCS prediction prior to launch, directs the selection of the optimum radar parameters to get a good amount of signals from the target and also provides guidelines for radar operational methodology to be followed in real-time.

This paper describes a reliable RCS estimation methodology and SNR computation of a complex launch vehicle target for its dynamic trajectory prior to launch.
3. RCS Modelling and Simulation of Typical Launch Vehicle

RCS estimation of full scale launch vehicle is usually carried out in static or dynamic configurations. Dynamic scattering characteristics have a very high practical importance in space and defence application research in both the static and dynamic aspects. External field calculation is the primary way to obtain a target’s dynamic scattering characteristics. Dynamic measurement results will accurately represent the real scattering characteristics of the target because of the external field [21].

Dynamic RCS measurements are difficult due to the consideration of target full size, relevant conditions, and data processing techniques etc., [15]. The RCS modelling and simulation of launch vehicle facilitates to compute the real-time expected signal strength variations for its entire trajectory before the launch. The Full scale launch vehicle 3D modelling and its trajectory information is input the dynamic RCS simulation software. The simulated RCS values are taken for SNR computation by taking the monostatic radar parameters. The RCS simulation methodology and SNR computation steps are shown in the following block diagram Fig.1

![Block Diagram of Simulation Method](image1)

**Step-1: Launch Vehicle 3D Modelling as per Actual Dimensions**

Launch Vehicles are built with simple arbitrary objects such as sphere, cube, rectangle, triangle, circular plates, cone, etc. [16] with distinct phases. The typical launch vehicle with its actual physical dimensions is shown in Fig.2. The full-scale 3D launch vehicle is designed with design Computer Aided Design (CAD) software and 3D model of the launch vehicle is shown in Fig.3. The launch vehicle 3D model was designed based on actual physical dimensions of each stage [17]. The launch length is 44.4m and width is 2.8m. The designed launch vehicle 3D model will be used as an input for the RCS simulation.

![Typical Full scale Launch Vehicle](image2)

![Launch Vehicle 3D Model](image3)
Step-2: Trajectory Data for Simulation

The trajectory is pre-programmed path in real-time to be pursued by the launch vehicle. In real time flight mode, the target positional parameters like range, azimuth, elevation, altitude and aspect angle etc, change with respect to time. The aspect angle is the angle between target and the radar. The pre-flight trajectory data is 10Hz sample data which is used for RCS simulation is shown in Table-1.

| Time (sec) | Range (Km) | Aspect Angle (Degrees) |
|------------|------------|------------------------|
| 10.91      | 7.560      | 90.0                   |
| 11.01      | 7.564      | 89.8                   |
| 11.11      | 7.557      | 89.7                   |
| 11.21      | 7.555      | 89.6                   |
| 11.31      | 7.560      | 89.5                   |
| ..         | ..         | ..                     |
| 654.02     | 481.448    | 16.592                 |

Table-1: Pre-flight Trajectory Data

Step-3: Launch Vehicle Dynamic RCS Simulation by SOFTWARE

The 3D model of the target is input to POFACET simulation software used for predicts the RCS of launch vehicle target. It is well established simulation software tool with high processing capabilities and implemented with the physical optics approach [18]. It uses MATLAB scientific computational features and GUI functions for efficient RCS calculations [19]. The Full scale launch vehicle RCS simulation is carried for its entire trajectory with the monostatic radar approach. Aspect angle of the launch vehicle changes from 10° to 90° in real time. The simulated launch vehicle RCS variations values with respect aspect angle (θ) is shown in linear plot Fig.4 and Polar plot in Fig.5.

Fig.4 RCS variations in Linear plot

Fig.5 RCS variations in Polar plot
Step-4. SNR Computation of Launch for its Real Time Trajectory

The launch vehicle tracking will be carried out in real time by monostatic radar where the same antenna is used for transmission and reception of EM signals. The expected real time SNR computation is performed based on the simulated RCS values by using radar range equation is given in Eq-1. The Monostatic Radar parameters used to track the launch vehicle in real time are taken for SNR computation with the following parameters summarized in below Table-2.

| Table-2. Radar Parameters for SNR Computation |
|------------------------------------------------|
| **Radar parameter**   | **Symbol** | **Value** |
| Peak Power (KW)        | $P_t$      | 1000      |
| Frequency of Operation (MHz) | $f$ | 3000    |
| Gain of Antenna (dB)   | $G_t, G_r$ | 40        |
| Target Range (Km)      | $R$        | As per Trajectory |
| Target Cross Section (RCS) | $\sigma$ | Simulated |

Table 2. Radar Parameters for SNR Computation

4. Results and Discussions

The pre-flight SNR variations of the launch vehicle for its dynamic trajectory is computed based on the simulated RCS data. RCS variations with respect to aspect angle is showed in below Fig.6.

![Fig. 6 RCS variations with Aspect angle](image)

From Fig.6 can be seen the RCS values of the dynamic launch vehicle depends on aspect angle of the target seen by the radar. Maximum RCS observed at highest aspect angle of 90 deg. It is also observed, when aspect angle increases from 120sec to 190sec, corresponding increment in RCS is reflected. Similarly, constant RCS values is observed when there is no change in aspect angle from 190sec to 210sec. After 210 sec, both are in decreasing trend in the trajectory. It demonstrates that when aspect angle is increased, more RCS fluctuations are observed and vice-versa.

The pre-flight launch vehicle’s RCS and SNR variations with respect to aspect angle and RCS are shown in Fig.7.
Fig. 7. Time Vs RCS and SNR variations with Aspect angle

From Fig. 7 can be seen that the computed SNR variations are dependent on the simulated RCS data. Initially, more SNR observed due to more Aspect angle and RCS values. SNR values are decreasing with increasing the range as per radar range equation. It is also observed that the RCS values are independent of range. The SNR fluctuations of the launch vehicle throughout its trajectory are computed based on the corresponding simulated RCS data. These pre-flight computed SNR variations are expected in real-time tracking. This simulation study provides good feedback to configure the suitable radar parameters to get good amount of signal from the launch vehicle target continuously in real time tracking. It also improves the radar operation methodology to be followed in the real-time for better tracking by the radar.

5. CONCLUSION

In this paper, the need for RCS prediction of launch vehicle for its real time dynamic trajectory prior to launch was presented. Pre-launch modelling and RCS estimation of the launch vehicle with proven simulation software was carried out for its real-time trajectory. The pre-flight SNR variations are computed based on simulated RCS by taking the monostatic radar parameters. The launch vehicle's RCS variation in the trajectory depends on the target size and the aspect angle. The pre-flight computed SNR variations provide good feedback to configure suitable radar parameters to get a good amount of signal to track the target for its given trajectory. In real time, this study alerts the radar operator in order to follow successful operating methodology where the obtained signal goes beyond the threshold values.

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