IMS2025 Student Design Competition

Radar Tracking Challenge: Amplifying Rocket RCS with Retro-Reflective Systems

Introduction

Rockets engineered, manufactured, and launched by enthusiastic amateur, student or research/university groups have been an ever-fascinating tool for experiential learning, practical, low-cost entry to rocket science as well as a launch platform for, e.g., CanSat missions. Typical parameters of those rockets are, e.g., a length of about 3m and an apogee height of about 1000 m. One open challenge is how the trajectory of such a rocket can be precisely tracked, such that rocket control and steering can be optimized, ground-based instruments can be pointed, and, e.g., payload ejection can be controlled.

In this novel format of an IMS student design challenge, organized through a unique collaboration between the MTT-S TC-29 Microwave Aerospace Systems, ESA, and the Czech Rocket Society (CRS), student teams shall design an essential subsystem to enable radar-based rocket tracking. In an ESA-led project, a modified long-range FMCW radar system based on a commercial, automotive radar platform operating in the 76-81 GHz frequency band has been designed for aerospace applications and will be used to track rockets. However, **the radar cross-section of the rockets, typically made of compound materials, must be higher to be detected by the radar up to the apogee height**.

Hence, in this challenge, **student teams shall design a conformal retro-reflective system to increase the RCS of the rocket so that it can be tracked by the radar for the entire flight duration**. The mechanical concept is illustrated in Figure 1. The teams can decide whether to use a passive structure or if active components shall be integrated. Tight constraints on the system are provided so the designs can be incorporated into the rockets. The team with the best design according to the defined FoM wins!

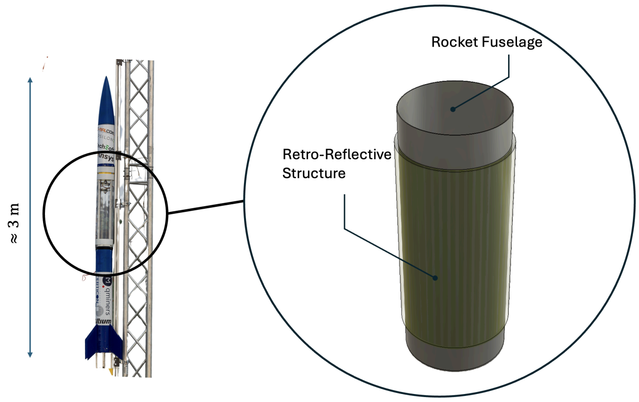


Figure 1: Illustration of the conformal retro-reflective structure mounted on the rocket fuselage.

Compared to a regular IMS SDC, in this "extended IMS SDC," the winning teams will be given the unique opportunity to integrate their system into a rocket designed by CRS and launch their system in 2026! The additional funds for traveling to the rocket launch in the Czech Republic, as well as support for the travel cost, will be requested from MTT-S Adcom, which has already been discussed in advance of submitting this proposal.

Design specifications and rules

Rocket Dimensions and Mechanical Constraints

The system shall be designed to be integrated into a variant of the “Sherpa” type of rocket designed by CRS, as illustrated in Figure 1. Typical structural parameters of the rocket are:

- Rocket length: $l_{rocket} \approx 3\ m$
- Rocket diameter: $d_{rocket} \approx 153\ mm$

The RCS-increasing structure (antenna array, etc.) needs to be a structure conformal to the rocket body and will be attached around the rocket fuselage. Due to aerodynamic reasons, the maximum additional radius added to the rocket, i.e., **the thickness of the retro-reflective structure, is limited to** $t_{refl} = 5\ mm$. The **maximum allowed length of the reflective conformal structure is** $l_{refl} = 300\ mm$. Not all the space available for the reflective structure needs to be used. Variants could, e.g., consist of single patches, stripes, or rings on the fuselage if everything is contained in the maximum available volume. Extra space for, e.g., supporting electronics or power supply is available inside the payload bay. Here, **an optional internal rectangular cuboid volume of size** $17.5\ mm \times 48.5\ mm \times 53\ mm$ **is available**. To connect the internal electronics in the box to the reflective surface, a maximum of up to four holes in the fuselage are allowed, each with a maximum diameter of 2 mm. The mechanical design specifications are illustrated in Figure 2.

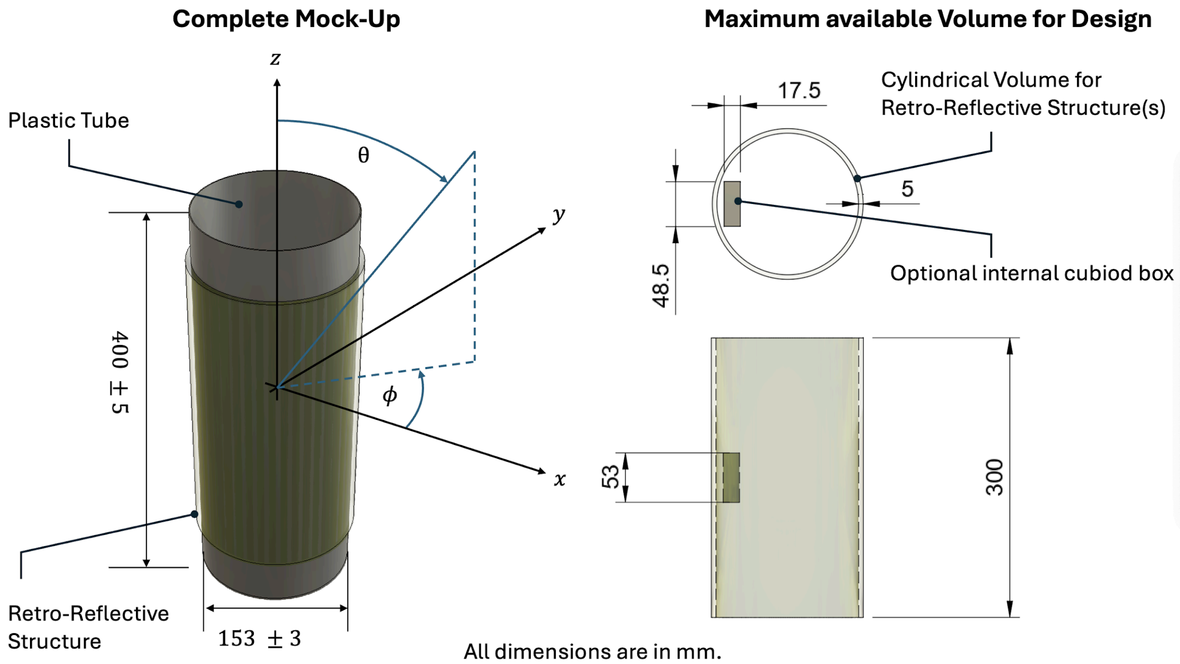
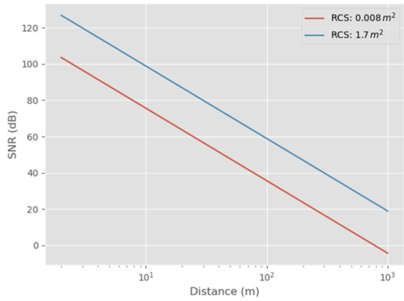


Figure 2: Mechanical design specifications and reference coordinate system..

Radar Specification

The Radar system is based on the TI AWR1843 integrated automotive radar frontend. Using a custom PCB design, high-gain lens horn antennas are connected to the front end to boost the maximum detectable target range. Linear polarization with the same direction on both TX and RX is used (the co-pol component of the target RCS is measured).



Parameter	Value
Frequency	79 GHz
Measurement duration	20 ms
Transmit power	14 dBm
Feedline losses	8 dB
Noise figure	12 dB
Antenna gain	33.5 dBi

Figure 3: Photograph of long-range FMCW radar, SNR vs. distance for different RCS, and some key parameters of the radar system.

The radar uses the chirp-sequence FMCW waveform, where speed estimation is done by tracking the phase of subsequent sweeps. A typical waveform configuration is provided in Table 1.

Table 1: Typical waveform configuration.

Parameter	Typical Value
Center Frequency	79 GHz
Transmit Power	14 dBm
Feedline Losses	8 dB
Antenna Gain	33.5 dBi
Sweep Bandwidth	50 MHz … 500 MHz
Sweep Duration	200 us
Measurement Duration	20 ms

Using this configuration, at 50 MHz sweep bandwidth the radar is able to detect a sphere of diameter $d_{sp} = 5\,cm$ ($RCS \approx 0.008\,m^2$) up to $r_{max} = 320\,m$ and a similar size trihedral corner reflector with edge length $5\,cm$ ($RCS \approx 1.8\,m^2$ at $f = 79\,GHz$) up to $r_{max} = 1200\,m$ (detection threshold is $SNR_{min} = 15\,dB$).

System to be provided for evaluation at IMS

The system provided by the student teams for evaluation at IMS needs to be a fully functional mock-up as illustrated in Figure 1. Therefore, **a plastic tube of diameter** $d_{tube} = d_{rocket} \pm 3\,mm$ **and length** $l_{tube} = 400\,mm \pm 5\,mm$ **must be prepared**, and **the retroreflective system (conformal retroreflective structure and optional internal box) must be incorporated**. If the additional internal box is used, it must be mounted inside the tube. Either a regular stock tube from a hardware store can be chosen, or a 3D printed model can be used. All components need to be mechanically securely attached to the plastic tube so that the system can survive a drop test, mimicking acceleration forces to the rocket, as further specified below. In addition, the retroreflective structures need to adhere tight to the fuselage, considering the subsonic rocket velocity in the range of 100 to 180 m/s.

The main criterion of this SDC is the RCS which can be achieved by the designed system. Any approach, may it be passive or active, is allowed as long as the following requirements and constraints are fulfilled:

- Mechanical constraints for the cylindrical conformal structure as well as the internal box as defined above

- In case of active battery powered designs: a minimum operational time of 2h
- Mechanically robust to survive a drop test

Evaluation process

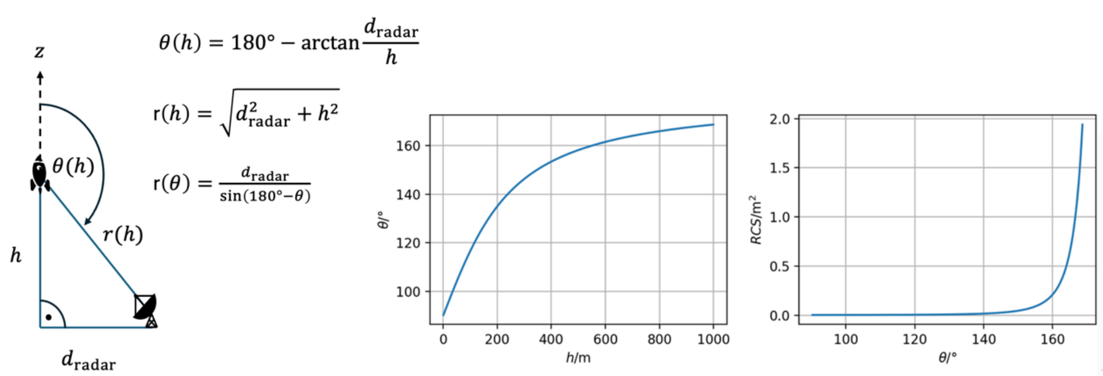
The evaluation process will be conducted according to the following steps:

1. Student teams hand over their design to the evaluation committee at the IMS exhibit, all systems will be presented next to each other on a table
2. The accordance with the mechanical constraints are tested by the evaluation committee
3. RCS is measured using a FMCW Radar System Evaluation kit using a maximum bandwidth of 500 MHz (or less) at a center frequency of 79 GHz. Therefore, the designs are mounted on a rotational stage at a distance of 10 m, and RCS is measured on both principal planes. Specifically, this means $RCS(\theta = 90°, \phi)$ and $RCS\left(\theta, \phi = \phi_{min}\right)$, where $\phi_{min} = argmin_{\phi}[RCS(\theta = 90°, \phi)]$, is measured (compare Figure 2). This is done since the roll of the rocket cannot be controlled, hence the angle ϕ during a launch is unknown. To ensure that the rocket can be tracked also in worst-case conditions, the RCS along θ is consequently measured at $\phi = \phi_{min}$. If the design is an active system, it will be activated at this point, and for each system, the activation time will be noted down as t_0. As a reference, a corner reflector assembly of edge length 5cm is measured on the rotational stage before the student design evaluation.
4. The system is dropped on suspended platform with shock absorbers 2x from a height of 1m
5. Two hours after t_0 for each system the measurement of step (3) is repeated

Scoring

Scoring is based on the following criteria

- **RCS**: Ideally, the rocket would have an isotropic RCS of $RCS(\theta, \phi) \geq 1.8\ m^2$ for $0^{\circ} \leq \theta \leq 90°$ and $0^{\circ} \leq \phi \leq 360°$, because then it could be detected with the radar system at any orientation. It can be considered that the radar will be located at a distance $d_{radar} = 200\ m$ from the launch site and an almost straight ascend of the rocket can be assumed. Then, for altitude $h = 0\ m$ we have $\theta = 90°$ and the higher the altitude, the larger θ will become, approaching $\theta \rightarrow 180°\ for\ h \rightarrow \infty$. Consequently, RCS must increase with increasing θ. With $d_{radar} = 200\ m$ we have $\theta(h = 1000m) \approx 168°$ and we need $RCS(\theta = 168°) \geq 1.8m^2$, which is quite challenging to achieve with a



retroreflective structure conformal to the rocket fuselage.

Since according to the radar equation received power decreases proportional with the power of four of the range, we can deduce for the minimum required RCS vs θ

$$RCS_{req}(\theta) = RCS_{req,h=1000} \cdot \left(\frac{r(\theta)}{1000\,m}\right)^4 = 1.8\,m^2 \cdot \left(\frac{200\,m}{1000\,m\,(180°-\theta)}\right)^4$$

From this we can derive a single **Figure of Merit for the RCS**: the angle θ, where the RCS realized by the design drops below $RCS_{min}(\theta)$ for the first time.

- **Mechanical constraints**: All components will be measured to verify accordance with the mechanical constraints; violation of the maximum available volume results in failure. Each cubic centimeter used of the available rectangular cuboid space $V_{CUBE,max} = 44.98\,cm^2$ within the payload bay results in a reduction of the scoring, i.e. solutions which do not require any internal electronics but solely use the outer conformal structure are preferred.

- **Operation time of the system**: The operational time of the system needs to be at least 2h; if the RCS after 2h has reduced by more than 3dB from the value obtained at evaluation step (3) in any direction, it is considered as failure

- **Drop test**: if the RCS in the second measurement after the drop test has reduced by more than 3dB in any direction from the initial value obtained at the evaluation step (3), it is considered a failure

Binary pass/failure decisions

- Maximum available volume
- RCS after 2h + Drop test not reduced by more than 3dB in any direction

FoM for ranking

$$FoM_{RCS} = \left\{RCS\left(\theta, \phi = \phi_{min}\right) < RCS_{min}(\theta)\right\} / 1^{\circ}$$

$$FoM_{MECH} = 1 - \frac{V_{CUBE,USED}}{V_{CUBE,max}}$$

$$FoM_{TOT} = FoM_{RCS} + w_{MECH} \cdot FoM_{MECH}$$

Name and number of supporting MTT-S Technical Committee

MTT-TC-29 Microwave Aerospace Systems

Contact information

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Equipment information

- Tables
- Power
- Laptop with evaluation software (Python)
- Radar System for evaluation + cables to connect to laptop
- Motorized rotation stage + cables to connect to laptop
- Low-RCS fixtures for mounting Mock-Ups on rotation stage (e.g. made from Rohacell)
- Cardboard box with some shock absorbing material (for the drop test)
- Caliper, tape measure (metric)