

Project 3

B-21 IR/RCS Signature Trade Study

Background

Across Block 3 you learned that an aircraft is not hidden until it is hidden in *every* band. Radar cross section (L25–L27), infrared emission (L21–L24), and the visual and acoustic bands (L28) each give a defender a way to find you. Lesson 28 closed the block with one rule: because the defender only needs *one* band to succeed, your detection range is set by your **loudest** band,

$$R_{\text{det}} = \max_b R_b.$$

Reducing a band that is not the limiter buys nothing until it becomes the limiter. Signature management is therefore a budget: spend where the limiter is, expect the limiter to move, and balance the package.

This project makes that budget real. A B-21 penetrating-strike sortie must survive a layered threat that watches in three bands at once. Your group is the B-21 signature-management cell. You are given a fixed **investment budget** and a menu of signature treatments, and you must recommend the package that buys the most survivability. Every treatment costs weight, money, and maintenance, so you cannot buy them all. Choosing well is the project.

Scenario: a Three-Band Threat

The target area is defended by three threats, one in each of three bands. Each is specified by the signature it can just detect (σ_{ref} or J_{ref}) at a stated reference range (R_{ref}), consistent with the Block 3 range laws.

Table 1: Notional three-band threat mix. Reference values are the signature each threat can just detect at its reference range.

Threat	Band	Reference detection	Role
Surveillance radar (EWR)	VHF	$\sigma_{\text{ref}} = 2 \text{ m}^2$ at 90 km	Long-range tracking
Fire-control radar (TTR)	X	$\sigma_{\text{ref}} = 0.03 \text{ m}^2$ at 45 km	Cues the SAM shot
MANPADS seeker (IR)	MWIR	$J_{\text{ref}} = 300 \text{ W/sr}$ at 8 km	Lethal to 6 km; tail-on

The baseline B-21 nose-on signature (from `B21.SignaturePattern.csv`) is $\sigma_{\text{VHF}} = 2 \text{ m}^2$, $\sigma_{\text{X}} = 0.032 \text{ m}^2$, and a stern in-band intensity of $J = 300 \text{ W/sr}$. The radars illuminate the aircraft **nose-on** during ingress; the MANPADS engages **tail-on**. The full aspect pattern is in the CSV for you to exploit.

Detection Model

Radar detection range. Each radar sees the aircraft through the fourth-power law you have used since Block 1:

$$R = R_{\text{ref}} \left(\frac{\sigma}{\sigma_{\text{ref}}} \right)^{1/4}.$$

Because of the fourth root, it takes about 12 dB of RCS reduction just to halve the detection range, and the payoff is band-specific: shaping and RAM help at X-band but do little at VHF, where the airframe is large next to the wavelength.

IR engagement range. The MANPADS seeker acquires the stern signature at

$$R = R_{\text{ref}} \sqrt{\frac{J}{J_{\text{ref}}}},$$

capped by its lethal envelope (6 km). A DIRCM defeats the terminal lock outright, driving its effective range to zero.

The loudest-band rule. Detection is a union across the three threats, so the range that matters is the largest:

$$R_{\text{det}} = \max(R_{\text{VHF}}, R_{\text{X}}, R_{\text{IR}}).$$

Your survivability is set by whichever threat sees you first.

Investment Menu and Budget

Table 2 is the menu of signature-management investments (`SignatureMenu.csv`). Each row lists the band effect (in dB of signature reduction), a cost, and a weight. Your package must satisfy

$$\sum \text{cost} \leq 10 \quad \text{and} \quad \sum \text{weight} \leq 5.$$

Table 2: Signature-management menu. dB values are signature reductions in each band; DIRCM defeats the MANPADS lock.

ID	Investment	Band effect	Cost	Weight
A	Broadband X-band RAM	X −8, VHF −1	3	2
B	Planform / edge realignment	X −10, VHF −4	4	1
C	Structural low-band treatment	VHF −6, X −1	5	3
D	Plume / exhaust suppression	IR −6	3	2
E	Low-emissivity skin coating	IR −3, X −1	2	1
F	DIRCM	defeats MANPADS lock	5	1
G	EMCON + contrail discipline	cueing / visual (no dB)	1	0

The dB reductions of any investments you select add within each band. The budget is deliberately too small to buy everything, so a good package is one that spends where it moves R_{det} the most.

Analysis Tools

Signature pattern. `B21_SignaturePattern.csv` gives the baseline RCS at VHF and X-band and the IR intensity, tabulated every 5° of aspect. Nose is 0° ; tail is 180° .

Investment menu. `SignatureMenu.csv` holds the seven treatments of Table 2 in machine-readable form.

Starter script. `L29_Project3Starter.m` reads the baseline signature, applies one *example* package (X-band RAM plus plume suppression), and scores it against the three threats with the loudest-band rule. It also plots the fourth-power trade for the X-band radar. The example package is a deliberately ordinary choice; beating it within the budget is where your analysis begins.

Your Task

This project is a group effort. Groups are assigned in class at L29. Work the analysis as a team; every member must be able to explain every result.

1. **Signature-to-detection pipeline.** Build the model that turns a baseline signature and a chosen package into the three threat ranges and R_{det} . Verify it against the starter's baseline ($R_{\text{det}} \approx 90$ km) and its example package before scaling up.
2. **Budget optimization.** Search the menu under the cost and weight caps for the package that **minimizes** R_{det} . Identify the binding (loudest) threat at baseline and show how the limiter moves as you invest. State the best R_{det} you can achieve and the package that reaches it.
3. **The terminal threat.** The radars set the detection corridor, but the MANPADS is lethal in the target area. Decide how, and whether, to spend on it, and defend that choice against the R_{det} you give up to afford it.
4. **Aspect.** Using the full pattern, show how R_{det} changes with aspect (a heat map, or a worst-aspect analysis). Contrast nose-on ingress with tail-on egress.
5. **Recommendation.** Close with a one-slide prioritized package: what to buy first, what it buys, what you deliberately left on the table, and the residual risk you are accepting.

Deliverables and Logistics

- **Results presentation** at L30: 10 minutes plus 5 minutes of Q&A. Every group member speaks. Walk your peers through your approach, what you tried, what worked and what did not, and your recommendation.
- **Submission:** slides (PDF) and all analysis code, submitted before the start of L30.
- **Late deliverables** require coordination with the instructor at least 24 hours before the deadline; non-coordinated late submissions receive a zero.
- **Individual Project Quiz 3** (open book, 15 minutes) is taken in class at L30 and covers the project work and Block 3 topics (signature components, IR seekers, RCS scaling, the loudest-band trade).

Grading

Element	Weight
Signature/detection model correctness (range laws, loudest-band, units)	30%
Budget optimization and the moving-limiter argument	20%
Terminal MANPADS trade and its defense	15%
Visualization and communication	20%
Recommendation and operational insight	5%
Q&A and individual ownership of results	10%

Innovation bonus (up to +5%). Awarded for going beyond the baseline ask in a substantive way: an aspect heat map that reveals where the aircraft is loud, a threat-conditioned probability of kill, a cost-versus- R_{det} Pareto front that frames the whole trade space, an honest report of an approach that did or did not work, or reusable, documented code other groups could pick up. Executing the baseline cleanly earns full credit; the bonus rewards judgment and creativity on top of it.