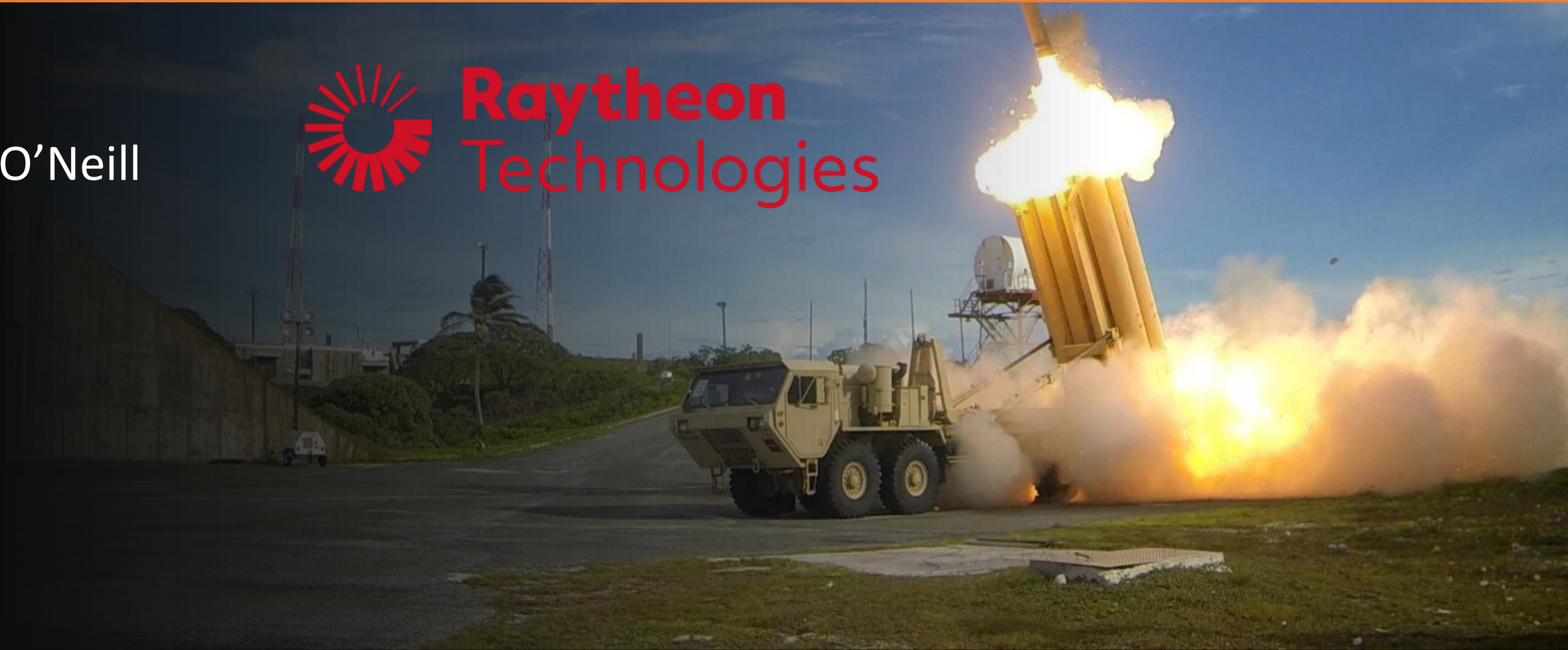
THAAD

Terminal High Altitude Area Defense

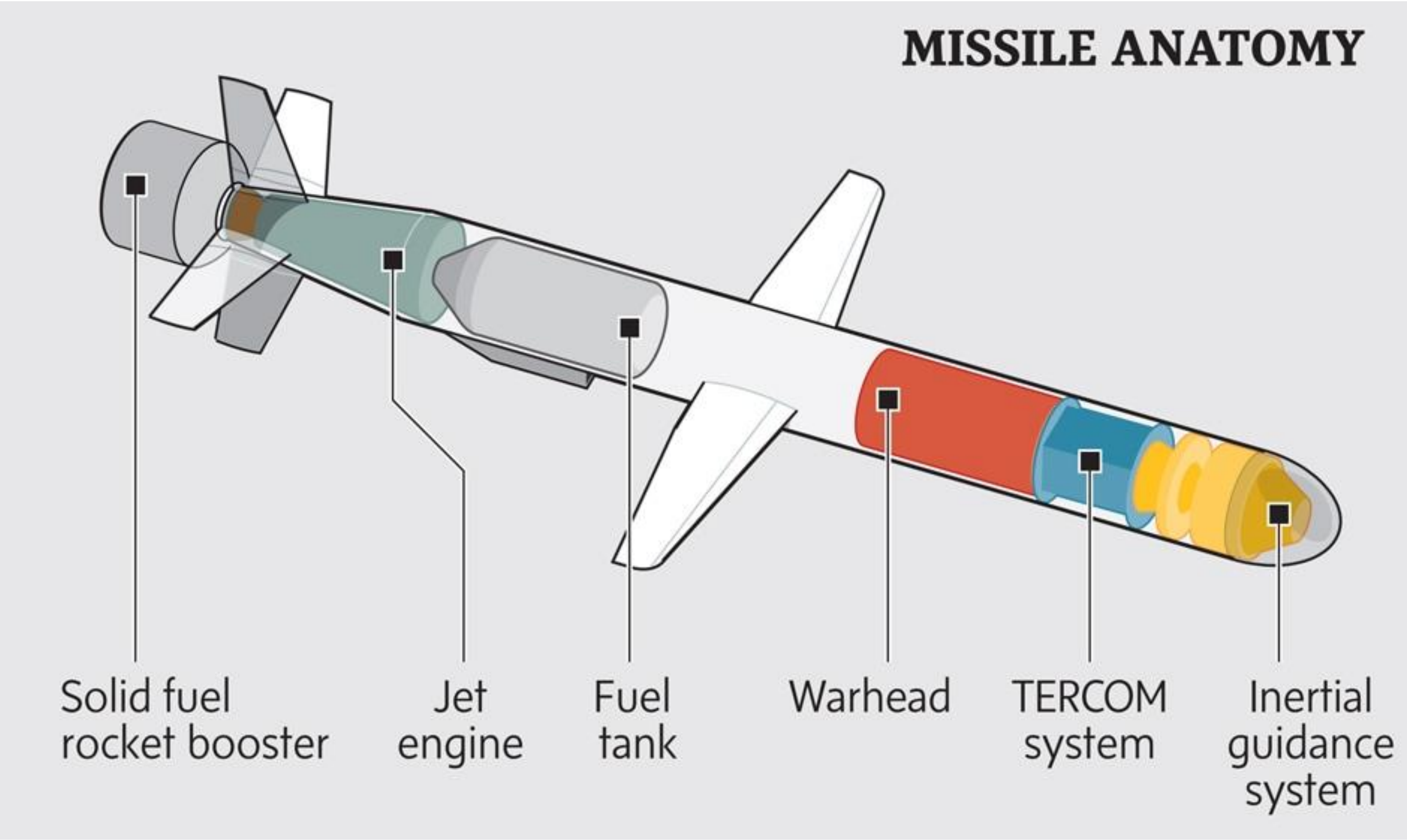
GENERAL OVERVIEW

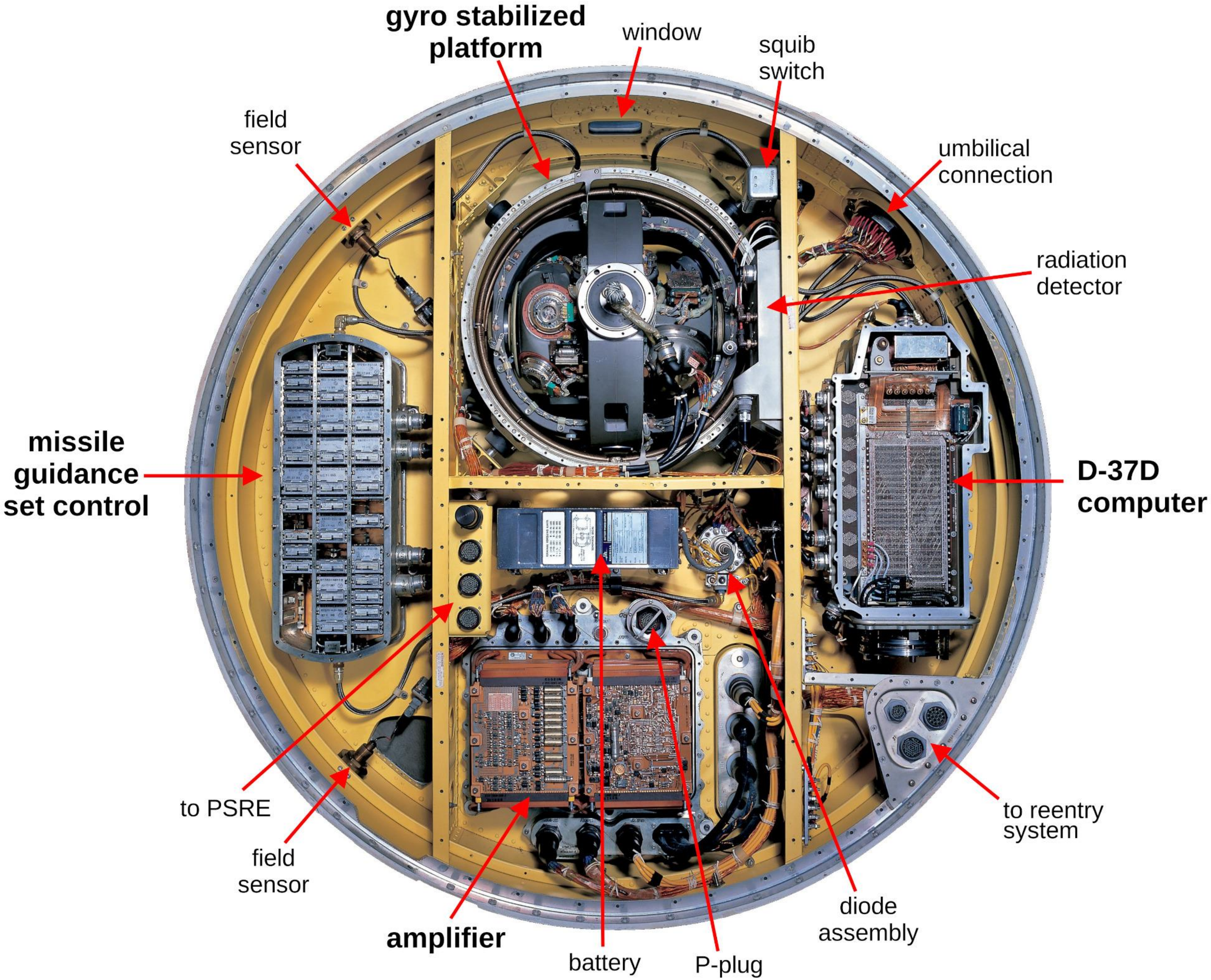
BY IDEO-LAB – Speaker Guillaume O'Neill

MARCH 2026

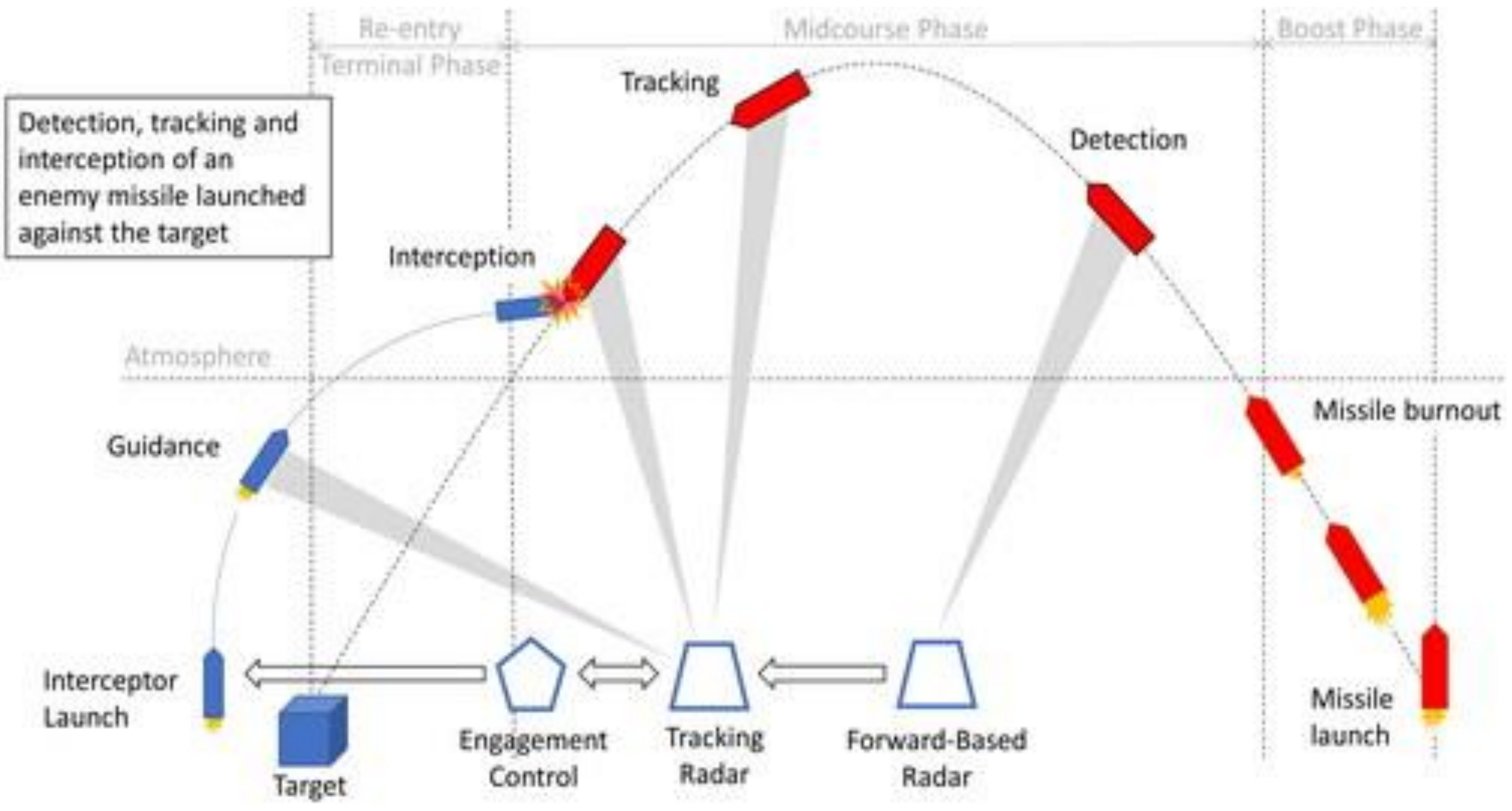


THAAD : The Basis


MISSILE ANATOMY
Solid fuel rocket booster
Jet engine
Fuel tank
Warhead
TERCOM system
Inertial guidance system

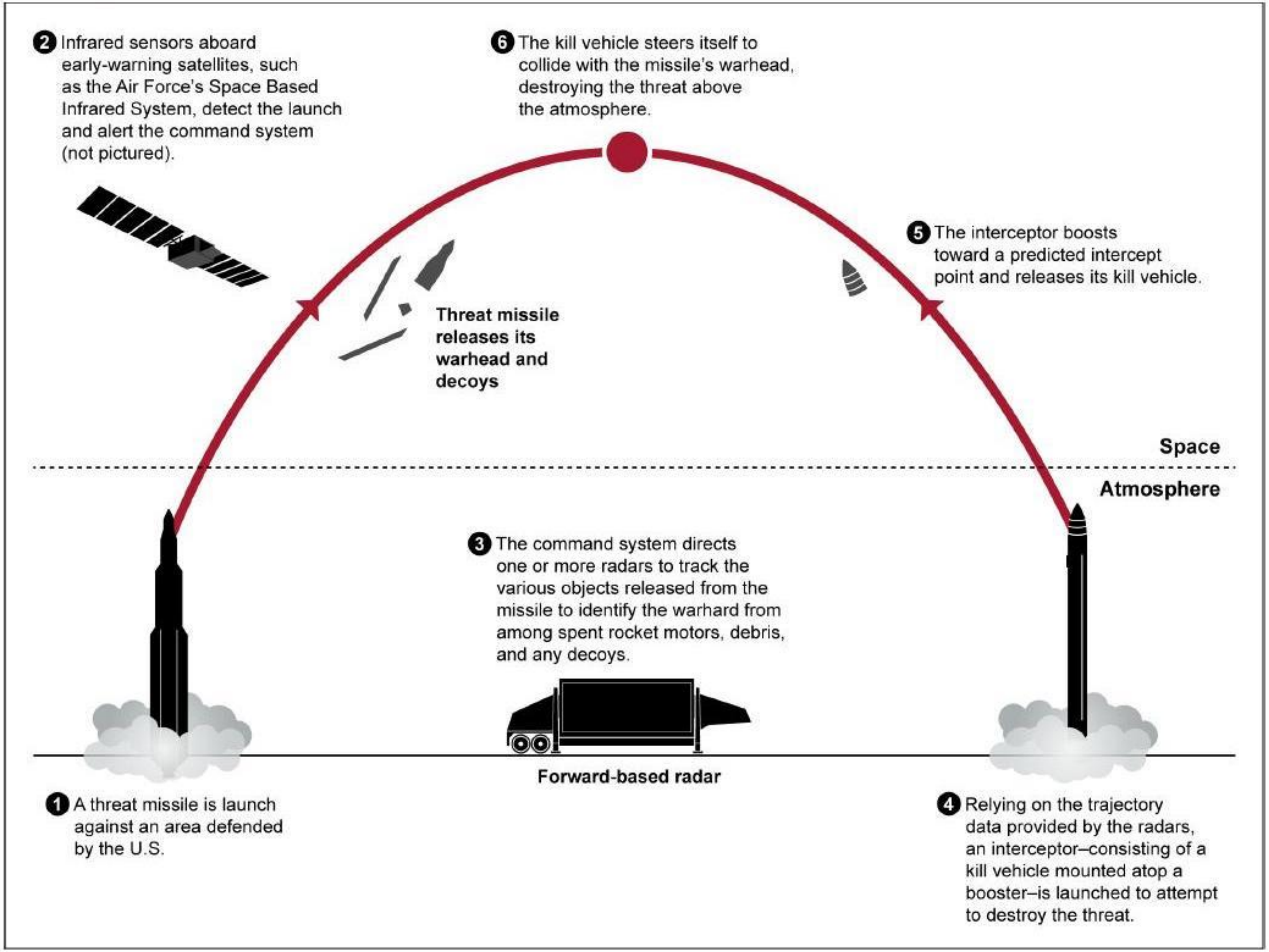


gyro stabilized platform
window
squib switch
field sensor
umbilical connection
radiation detector
missile guidance set control
D-37D computer
to PSRE
field sensor
to reentry system
amplifier
battery
P-plug
diode assembly



Re-entry
Terminal Phase
Midcourse Phase
Boost Phase
Detection, tracking and interception of an enemy missile launched against the target
Tracking
Detection
Interception
Atmosphere
Missile burnout
Guidance
Interceptor Launch
Target
Engagement Control
Tracking Radar
Forward-Based Radar
Missile launch

```
+--------------------------------------------------+
| Infrared Seeker                                  |
| (target acquisition and tracking)                |
+--------------------------------------------------+
| Guidance Computer                                |
| (navigation + intercept algorithms)              |
+--------------------------------------------------+
| Inertial Navigation System (INS)                 |
| accelerometers + gyroscopes                      |
+--------------------------------------------------+
| DACS Thruster Ring                               |
| lateral divert and attitude control              |
+--------------------------------------------------+
| Communication Link Receiver                      |
| mid-course radar updates                         |
+--------------------------------------------------+
| Power Supply + Thermal Control                   |
+--------------------------------------------------+
```



Source: GAO analysis of MDA data.

Historical Context & Genesis

THAAD History

Terminal High Altitude Area Defense

THAAD is a U.S. **missile defense system designed to intercept** and destroy short, medium, and intermediate-range ballistic missiles during their terminal (final) flight phase.

Deployment 2010s

- **THAAD** batteries deployed to protect allies
- **Operational in South Korea, Guam, UAE,** etc.
- Part of integrated missile defense systems

Key Milestones 2006

- First THAAD successful intercept test in 1999
- System reaches **Initial Operational Capability** (IOC) in 2008

Origins Early 1990s

- Program initiated by the U.S. Army in response to ballistic missile threats

2006 Key Milestones

- First THAAD successful **intercept test in 1999**
- System reaches **Initial Operational Capability** (IOC) in 2008

Origins

Gulf War shows vulnerability to ballistic missiles

Agenda Historical

1. Historical Context & Genesis
2. Project Timeline & Key Milestones
3. Budget, Costs, and Scale
4. Industrial Partners & Workforce
5. Summary Technical Profile

1. Historical Context & Genesis

The THAAD program was born out of a critical vulnerability exposed during the **1991 Gulf War**. While the Patriot missile system was used to intercept Iraqi *Scud* missiles, it was designed for aircraft defense, not high-speed ballistic missiles. The U.S. realized it needed a "high-tier" interceptor to stop missiles much higher in the atmosphere.

- **Concept Origin (1987):** Initial studies began under the Strategic Defense Initiative (SDI), famously known as "Star Wars."
- **Official Launch (1992):** The formal Demonstration and Validation contract was awarded to move from theory to hardware.
- **Primary Objective:** To create a "theater" defense system capable of protecting large areas (cities or bases) rather than just a single point.

2. Project Timeline & Key Milestones

The road to success was famously rocky. During the 1990s, the program faced **six consecutive flight test failures**, leading many to doubt if "Hit-to-Kill" technology was even possible.

- **1995:** First flight test (White Sands Missile Range).
- **1999:** First successful intercept after a string of high-profile failures.
- **2000:** Transition to the Engineering and Manufacturing Development (EMD) phase.
- **2005:** First successful intercept of the "production-representative" version.
- **2008: First Operational Battery** activated at Fort Bliss, Texas.
- **2013 – Present:** Global deployment to Guam, Israel, South Korea, and the United Arab Emirates.

3. Budget, Costs, and Scale

The THAAD is widely considered one of the most expensive and sophisticated defensive assets in the U.S. inventory.

Category	Estimated Cost
Total Program R&D	Over **$30 Billion**
Complete Battery Cost	**$800 Million to $1.5 Billion** (includes Radar, 6 Launchers, 48 Interceptors, and TOC)
Single Interceptor (Missile)	**$12 Million to $15 Million**
Export Deals	Saudi Arabia signed a deal worth approx. **$15 Billion** for 44 launchers and 360 missiles.

4. Industrial Partners & Workforce

The project is managed by the **U.S. Missile Defense Agency (MDA)**, but the hardware is a collaborative effort between the titans of the aerospace industry.

The "Big Players"

- **Lockheed Martin (Prime Contractor):** Responsible for the Interceptor, the Launchers, and overall system integration.
- **Raytheon Technologies:** Built the "Eyes" of the system—the **AN/TPY-2 X-band Radar**, which is the world's most powerful mobile ground-based radar.
- **Aerojet Rocketdyne:** Developed the solid rocket booster and the liquid **DACS** (Divert and Attitude Control System).
- **Honeywell:** Provided the high-precision **Inertial Navigation Systems (INS)** and flight computers.

Team Size

At its peak development and production, the program supported:

- Over **2,000 engineers and specialized technicians** at Lockheed Martin alone.
- A supply chain of over **400 subcontractors** across 40 U.S. states.

5. Summary Technical Profile

- **Weight:** 900 kg at launch.
- **Speed:** Hypersonic (Mach 8.24 or **2.8 km/s**).
- **Altitude:** Up to 150 km (reaching both the upper atmosphere and the edge of space).
- **Range:** Over 200 km.
- **Warhead:** None. It uses **Kinetic Energy** to vaporize the target on impact.

Pro-Tip: THAAD is unique because it is "dual-mode." Most missiles work only in the atmosphere (using fins) or only in space (using thrusters). THAAD's software and propulsion are designed to transition between the two seamlessly, making it one of the most versatile interceptors ever built.

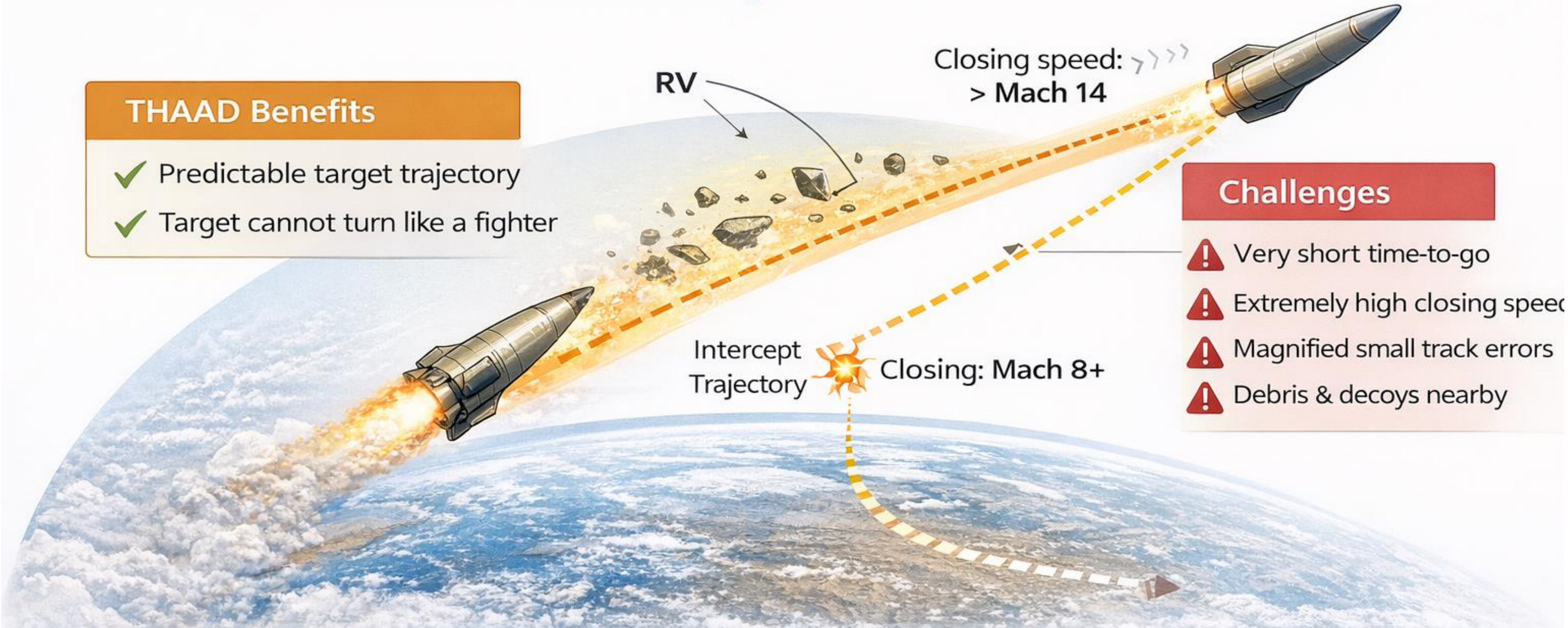
AGENDA THAAD OVERVIEW

1. Strategic Purpose and Concept of Operations	2. System Architecture	3. Interceptor Missile Architecture	4. Guidance and Interception Physics	5. Divert and Attitude Control System (DACS)
6. Radar System: AN/TPY-2	7. Fire Control System (TFCC)	8. Engagement Timeline	9. Interception Envelope	10. Mobility and Deployment
11. Deployment Locations	12. Countermeasures and Limitations	13. Performance and Test Record	14. Industrial Architecture	15. Strategic Role in Modern Missile Defense

THAAD as an engineering system


THAAD Strategic Purpose
Terminal High Altitude Area Defense for Ballistic Missile Defense
Exo-atmospheric
(space)
RMBM <1000 km
SRBM (<1000 km
Terminal Phase
MRBM (<3000 km
IRBM (3000–5500 km
Theater Missile Defense
Protection of High-Value Assets
Layered Defense Integration

Terminal Ballistic Geometry



- **Short time-to-go:** mere seconds until impact
- **Extremely high closing speed:** closing velocity typically exceeds Mach 14
- **Magnified errors:** small tracking errors become more critical during final interception phase.
- **Debris & decoys** nearby: false targets can create con-

- **Debris / decoys** nearby
  - False targets can create confusion and complicate interception

- **Short time-to-go:** mere seconds until impact
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At system level, THAAD is best understood as a **closed fire-control loop**:

1. **Detect / acquire** target with AN/TPY-2
2. **Estimate trajectory** and classify the lethal object
3. **Predict intercept basket** and shot doctrine
4. **Launch interceptor** on an inertially guided trajectory
5. **Update in flight** with radar-based track refinements
6. **Handover to onboard IR seeker** on the kill vehicle
7. **Perform terminal divert maneuvers** for hit-to-kill collision

Public references describe the interceptor as roughly **6.2 m** long, around **0.4 m** in diameter, with a **single-stage solid booster** and a **liquid-fueled kill vehicle** that uses a **gimbaled infrared seeker** and **hydrazine-powered divert thrusters**. Publicly cited defended-range figures are about **150–200 km**, with intercepts possible both endo- and exo-atmospherically. Missile Threat

That architecture matters because THAAD sits in a very specific design niche: **higher and farther out than Patriot**, but much lower-altitude and shorter-ranged than **SM-3 / Arrow-3 style exo-atmospheric midcourse systems**. It is therefore optimized for the **late-middle / terminal engagement problem** rather than the broad-area midcourse problem.

1. Strategic Purpose and Concept of Operations

THAAD (Terminal High Altitude Area Defense) is a **U.S. Army mobile ballistic missile defense system** designed to intercept **short-, medium-, and intermediate-range ballistic missiles (SRBM/MRBM/IRBM)** during their **terminal phase**, both:

- **Endo-atmospheric** (inside atmosphere)
- **Exo-atmospheric** (space)

The system is designed to defeat:

Threat class	Range
SRBM	<1000 km
MRBM	1000–3000 km
IRBM	3000–5500 km

Primary objectives:

- **Theater missile defense**
- **Protection of high-value assets**
- **Layered defense integration with other systems**

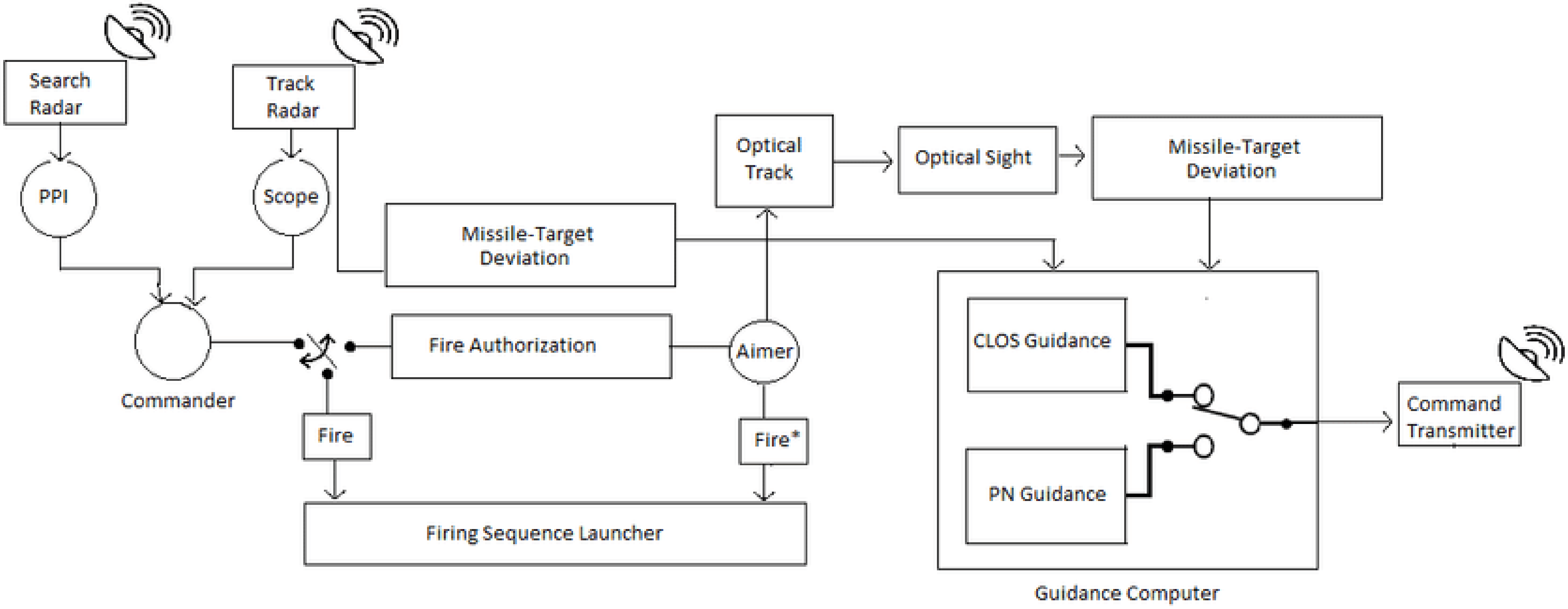
Typical layered architecture:

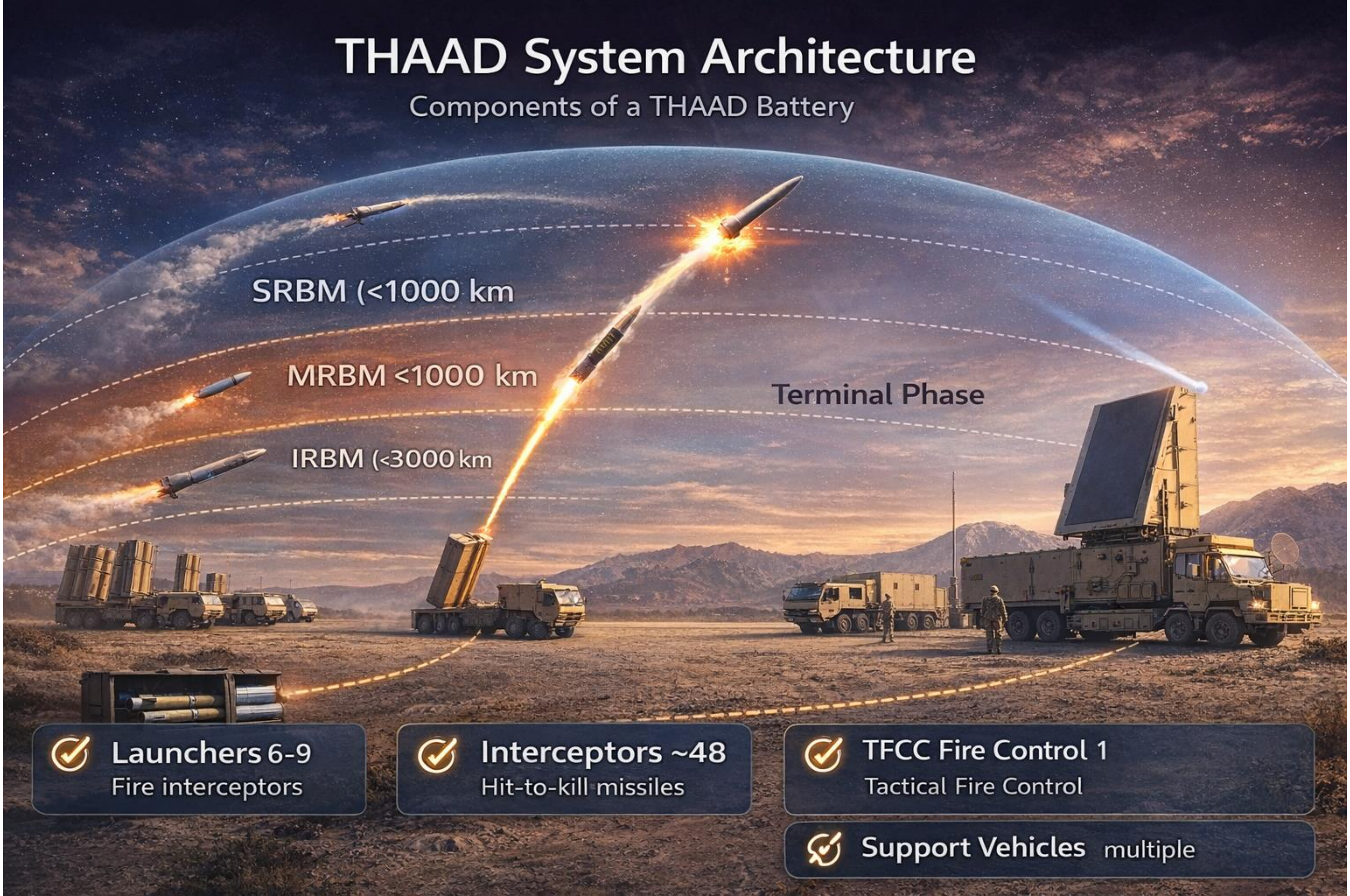
Layer	System
Exo-atmospheric	Aegis Ballistic Missile Defense / SM-3
High terminal	THAAD
Low terminal	MIM-104 Patriot (PAC-3)

2. System Architecture

A **THAAD battery** contains several subsystems:

Component	Quantity	Function
Launchers	6–9	Fire interceptors
Interceptors	~48	Hit-to-kill missiles
Radar	1	AN/TPY-2 X-band radar
Fire Control	1	TFCC (Tactical Fire Control)
Support vehicles	multiple	power, comms


Search Radar
Track Radar
PPI
Scope
Commander
Missile-Target Deviation
Optical Track
Optical Sight
Missile-Target Deviation
Fire Authorization
Aimer
Fire
Fire*
Firing Sequence Launcher
CLOS Guidance
PN Guidance
Guidance Computer
Command Transmitter


THAAD System Architecture
Components of a THAAD Battery
SRBM (<1000 km
MRBM <1000 km
IRBM (<3000 km
Terminal Phase
Launchers 6-9
Fire interceptors
Interceptors ~48
Hit-to-kill missiles
TFCC Fire Control 1
Tactical Fire Control
Support Vehicles multiple

Additional Important Aspects of THAAD - 2026

- 1. Engagement Doctrine (Shoot–Look–Shoot)
- 2. Kill Vehicle Infrared Seeker
- 3. Hit-to-Kill Physics
- 4. THAAD Radar Modes
- 5. Radar Power and Sensitivity
- 6. Battery Composition
- 7. Integration in the Global Missile Defense Network
- 8. Cost of the System
- 9. Testing Record
- 10. Political and Strategic Impact
- 11. Future Evolution
- 12. Space Tracking Integration
- 13. Thermal Protection of the Kill Vehicle
- 14. Launch Time
- 15. Real Intercept Geometry

THAAD Software Architecture

Interceptor Guidance Algorithms (Kalman / GNC)

- Kalman Filter Sensor Fusion
- Guidance Loop

Sensor inputs:

```
INS measurements
infrared seeker
radar mid-course updates
```

Kalman filtering performs:

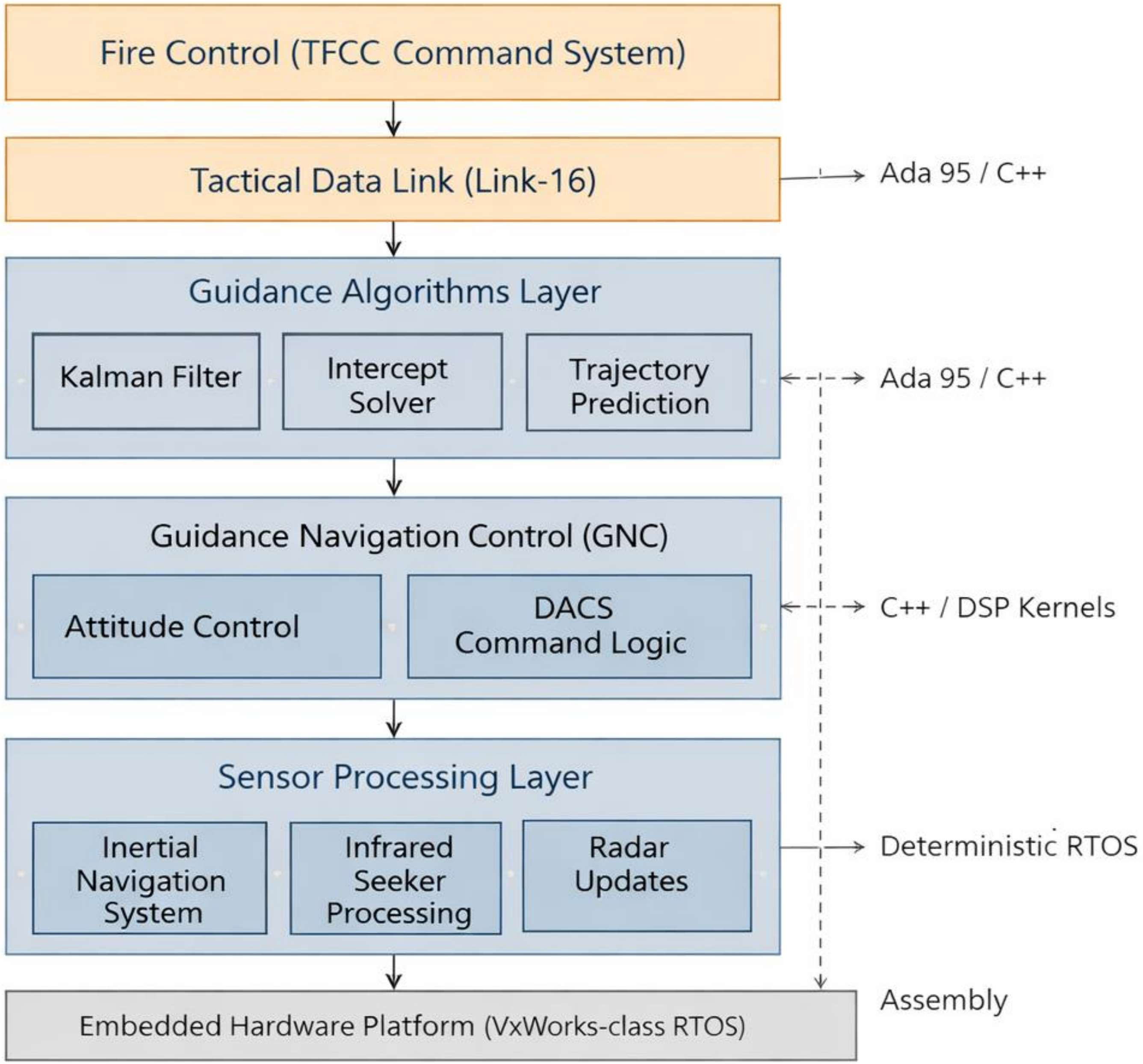
```
prediction step
correction step
noise filtering
```

Output:

```
estimated target trajectory
optimal intercept vector
```

```
Sensor measurement
        ↓
State estimation
        ↓
Intercept solution
        ↓
Control law computation
        ↓
DACS thruster command
```

Missile Guidance Software Architecture



THAAD Software Architecture

Programming, RTOS, and Core Guidance Software

1. Programming Languages

Missile defense software prioritizes **determinism, reliability, and safety** over modern language trends.

Typical languages used in systems comparable to THAAD:

Ada (Ada 95 / Ada 2005)

- Primary language for safety-critical defense systems.
- Designed for the **U.S. Department of Defense**.
- Strong typing prevents common errors such as:
  - buffer overflows
  - numeric overflow
  - memory corruption.

Used mainly for:

- guidance software
- flight control logic
- safety-critical mission code.

C / C++

Used where **high performance and hardware interaction** are required.

Typical domains:

- radar signal processing
- mathematical modeling
- sensor fusion algorithms
- hardware abstraction layers.

The **AN/TPY-2 radar processing software** likely uses large C++ codebases for:

- tracking algorithms
- target discrimination
- beamforming signal processing.

Assembly

Used only in **ultra-time-critical routines:**

Examples:

- sensor interrupt handlers
- DSP kernels
- real-time control loops.

2. Real-Time Operating System (RTOS)

THAAD does not use general-purpose operating systems like Windows or Linux.

Instead it uses a deterministic Real-Time Operating System.

Typical candidates:

- VxWorks
- Integrity RTOS
- proprietary defense RTOS

Key RTOS properties

Deterministic scheduling

Critical tasks are guaranteed to execute **within strict timing bounds.**

Example:

```
DACS thruster command latency
< 10 milliseconds
```

This ensures that a guidance correction is never delayed.

Priority-based execution

Tasks run according to **hard real-time priorities:**

Example task hierarchy:

```
Priority 1  Flight control loop
Priority 2  INS update
Priority 3  radar data ingestion
Priority 4  telemetry communication
Priority 5  diagnostics
```

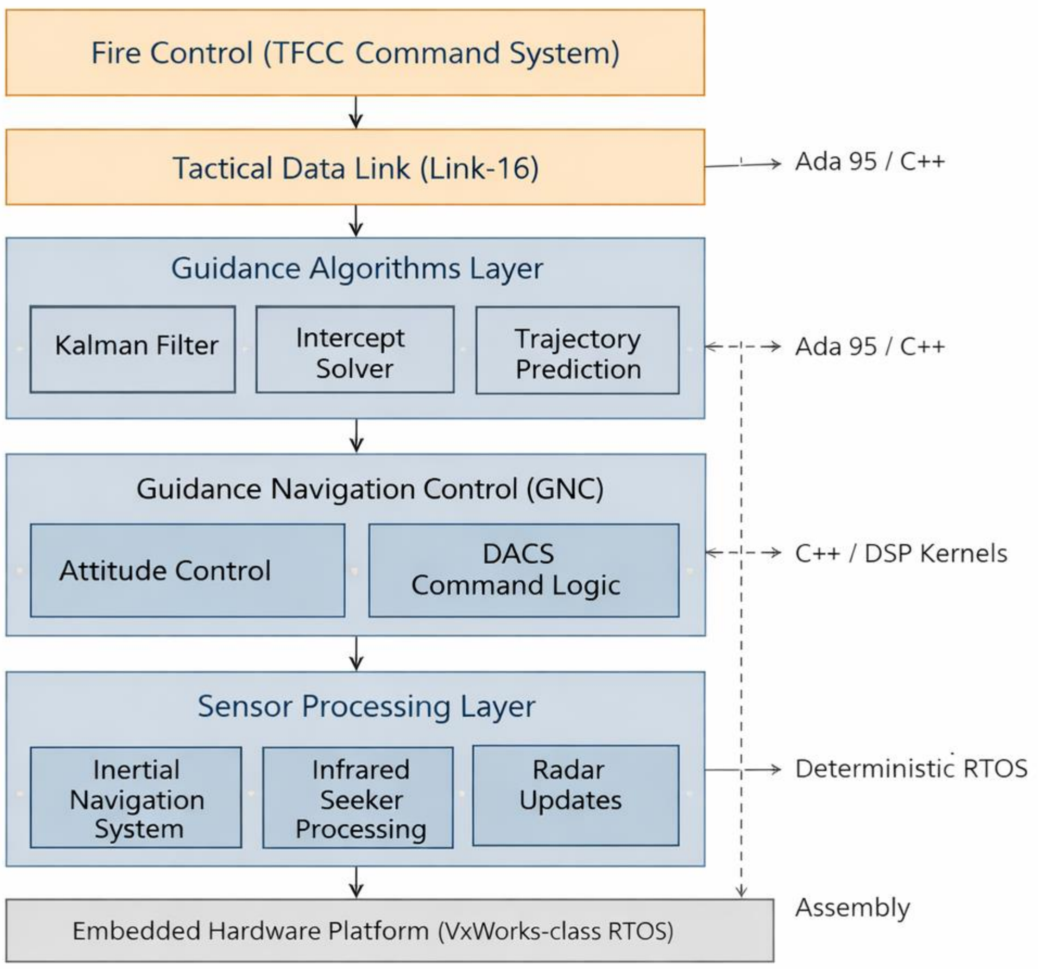
Partitioned software architecture

RTOS partitioning isolates subsystems:

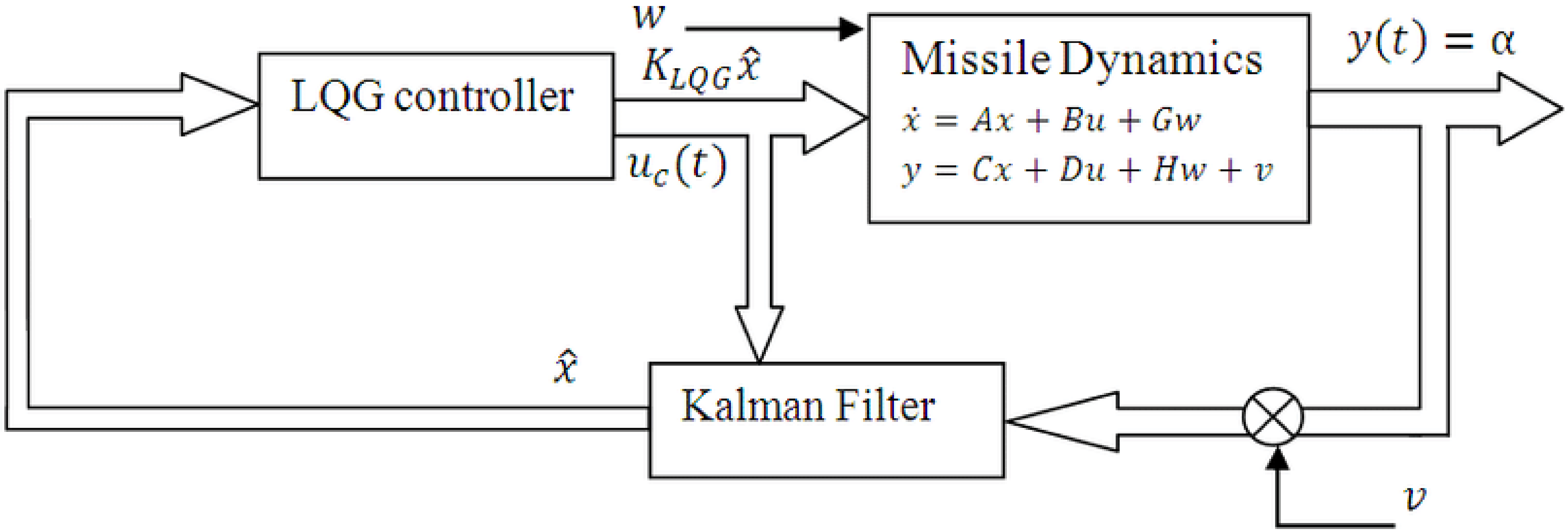
```
+-----------------------------+
| Guidance Navigation Control |
+-----------------------------+
| Radar Data Processing       |
+-----------------------------+
| Communication Stack         |
+-----------------------------+
| Diagnostics / Telemetry     |
+-----------------------------+
```

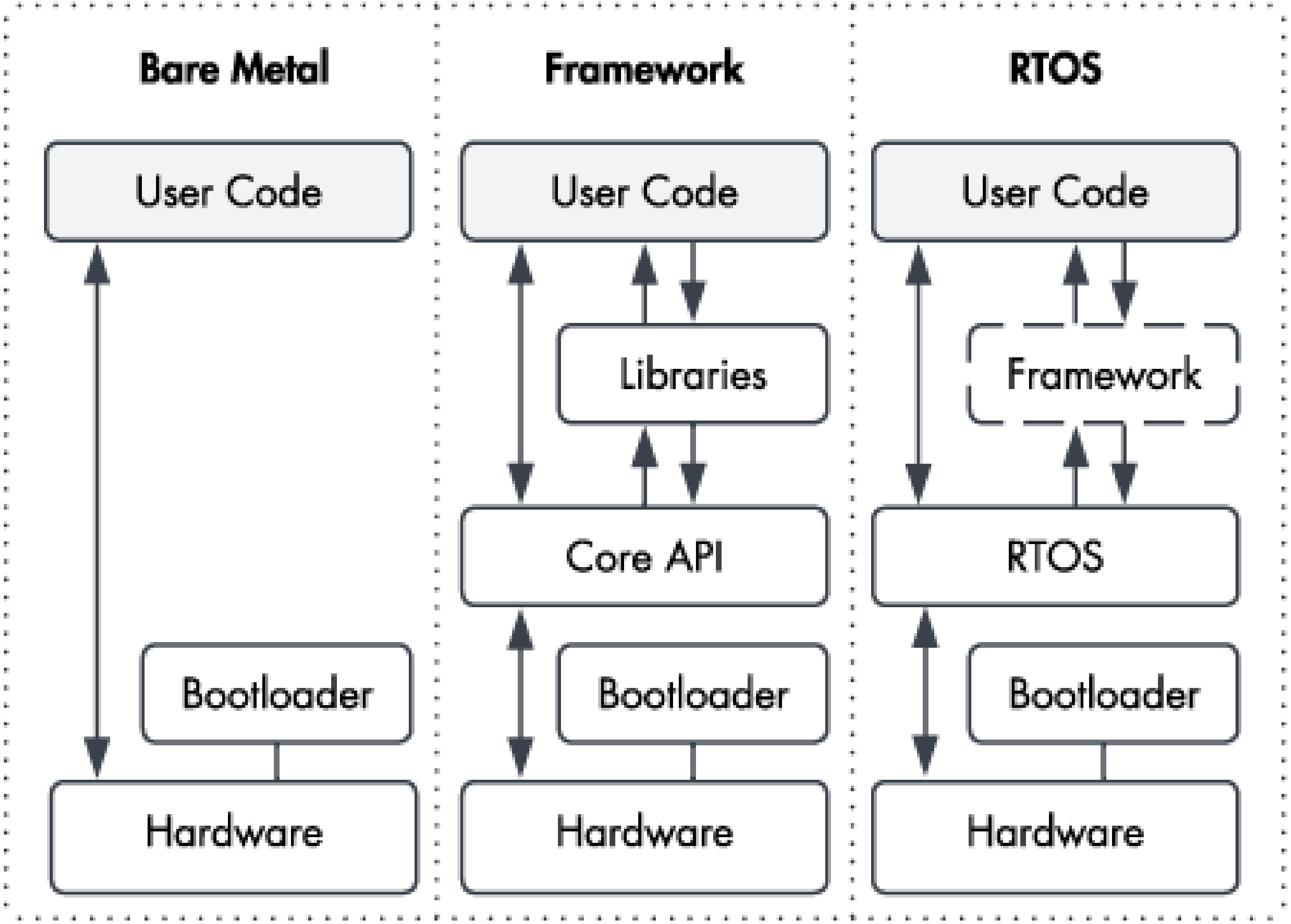
If a module fails, **critical flight control remains operational.**

Missile Guidance Software Architecture



```
+-------------------------------------------------------+
|                 Mission / Fire Control                |
|           (TFCC – Command & Engagement Logic)        |
+-------------------------------------------------------+
|                 Tactical Data Links                   |
|                  Link-16 / Radar uplink               |
+-------------------------------------------------------+
|                  Guidance Algorithms                  |
|   - Kalman Filter                                     |
|   - Target State Estimation                           |
|   - Intercept Geometry Solver                         |
+-------------------------------------------------------+
|              Guidance Navigation Control (GNC)        |
|   - Attitude control loops                            |
|   - DACS thruster commands                            |
|   - Trajectory correction                             |
+-------------------------------------------------------+
|             Sensor Processing Layer                   |
|   - Inertial Navigation System (INS)                  |
|   - Infrared seeker processing                        |
|   - Radar mid-course updates                          |
+-------------------------------------------------------+
|                  Real-Time Operating System           |
|                (VxWorks / proprietary RTOS)           |
|  Deterministic scheduling / task isolation            |
+-------------------------------------------------------+
|               Embedded Hardware Platform              |
|     CPU / DSP / FPGA / IMU / radar interfaces         |
+-------------------------------------------------------+
```


w
LQG controller
$K_{LQG}\hat{x}$
$u_c(t)$
Missile Dynamics
$\dot{x} = Ax + Bu + Gw$
$y = Cx + Du + Hw + v$
$y(t) = \alpha$
Kalman Filter
$\hat{x}$
v


Bare Metal
Framework
RTOS
User Code
User Code
User Code
Libraries
Framework
Core API
RTOS
Bootloader
Bootloader
Bootloader
Hardware
Hardware
Hardware

The software architecture of the THAAD system is built on the principle of **High-Assurance software.** It requires deterministic performance—meaning the system must produce the exact same result within the exact same microsecond, every single time.

1. Programming Languages

In the world of missile defense, reliability is prioritized over "trendy" features.

- **Ada (primarily Ada 95):** This is the backbone of THAAD. Ada was specifically designed for the U.S. Department of Defense to be "safety-critical." It prevents common programming bugs (like memory leaks or arithmetic overflows) that could cause a missile to fail mid-flight.
- **C / C++:** These are used for hardware abstraction layers and high-speed signal processing. C++ is often used for the complex mathematical models within the **AN/TPY-2 Radar** software.
- **Assembly:** Used sparingly for the most time-critical instructions within the missile's onboard processor to squeeze out every bit of performance.

2. The Real-Time Operating System (RTOS)

THAAD does not use a standard OS like Windows or Linux, which are "best-effort" systems. It uses a **RTOS** (Real-Time Operating System), such as **VxWorks** or a proprietary equivalent.

- **Deterministic Execution:** The RTOS ensures that a critical task (like firing a **DACS** thruster) is never interrupted by a lower-priority task.
- **Hardware Partitioning:** It isolates different software "bricks" so that if the communication logs fail, the guidance and propulsion systems remain unaffected.

3. Core Software Bricks

The system is divided into highly specialized functional modules:

Guidance, Navigation, and Control (GNC)

This is the "brain" of the propulsion system.

- **Kalman Filters:** Sophisticated algorithms (written in C++ or Ada) that fuse data from the **Inertial Navigation System (INS)** and the **Infrared Seeker**. It "guesses" the target's next move based on physics and adjusts the thrusters accordingly.
- **Control Loops:** High-frequency loops that manage the **DACS** (Divert and Attitude Control System) to stabilize the Kill Vehicle at Mach 8+.

Radar Data Processing

The software for the AN/TPY-2 radar is one of the most complex in existence.

- **Discrimination Algorithms:** These "bricks" analyze the radar returns to tell the difference between a real nuclear warhead and a piece of metal debris or a decoy.
- **Target Tracking:** It calculates a "probability ellipse" to tell the missile where to fly.

Tactical Data Links (Link 16)

- **Communication Stack:** A software layer that allows the missile to "talk" to the ground station. This uses standardized military protocols to receive mid-course target updates while traveling at hypersonic speeds.

4. Simulation and Verification Bricks

Since you can't test a $100M missile every day, the software is developed using:

- **MATLAB / Simulink:** Used for the initial design of the propulsion control laws.
- **Digital Twins:** Every THAAD missile has a digital software counterpart used to simulate thousands of "what-if" scenarios.
- **HWIL (Hardware-in-the-Loop):** The actual flight software is run on real missile hardware connected to a supercomputer that simulates the "outside world," tricking the sensors into thinking they are flying.

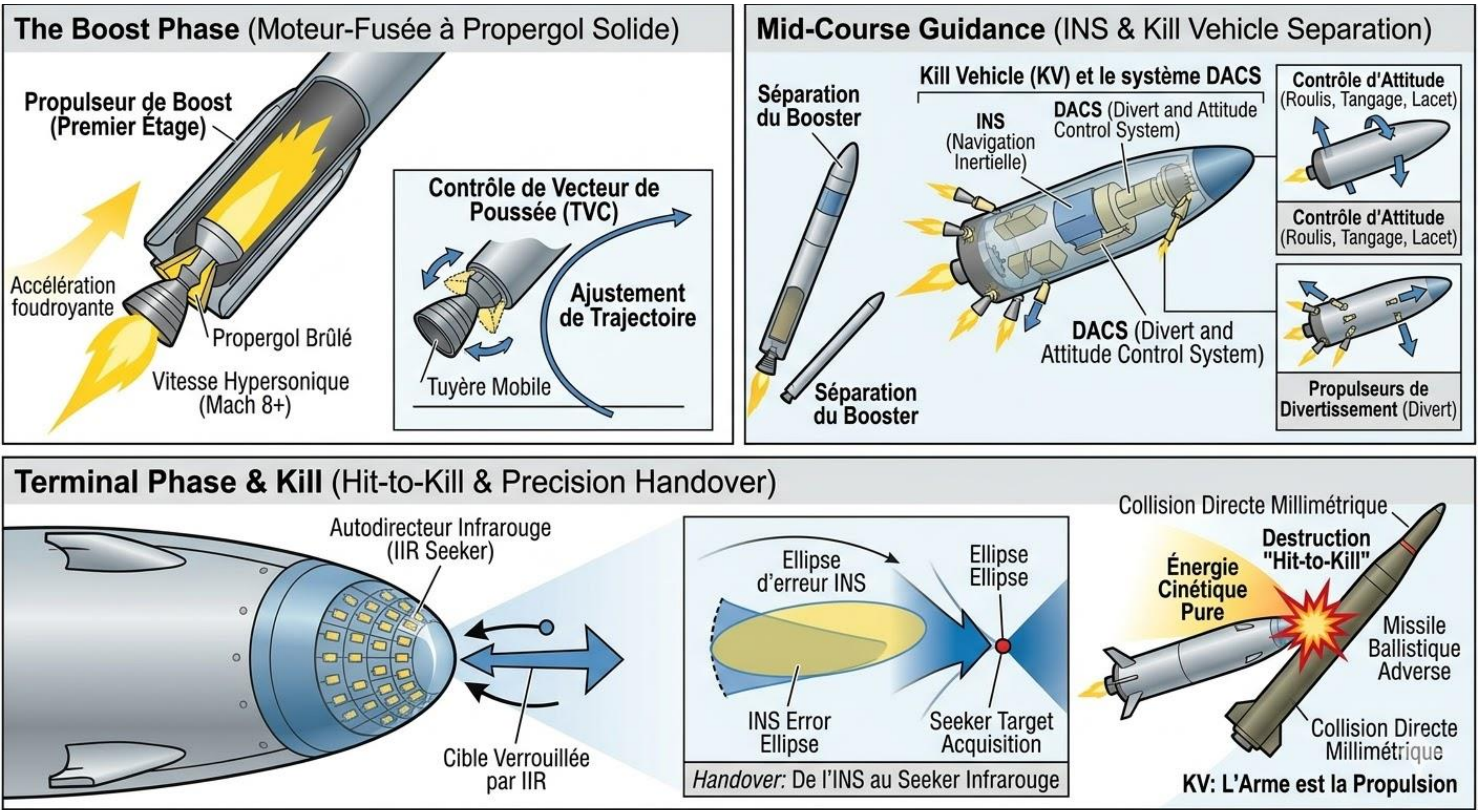
Quick Wit Tip: In this field, a "bug" isn't just an annoying popup; it's a multi-million dollar firework. That's why the software undergoes more testing than the physical hardware itself!

2. Propulsion & Guidance

Propulsion & Guidance

It's a fascinating combination of "blind" dead reckoning and high-tech "vision." Since the propulsion system is so powerful, the missile needs a brain that can keep up with those massive G-forces.

The **Inertial Navigation System (INS)** is that brain. Here is how it coordinates with the propulsion to ensure the interceptor doesn't just fly fast, but flies *accurately*.



The Boost Phase (Moteur-Fusée à Propergol Solide)
Propulseur de Boost (Premier Étage)
Accélération foudroyante
Propergol Brûlé
Vitesse Hypersonique (Mach 8+)
Contrôle de Vecteur de Poussée (TVC)
Ajustement de Trajectoire
Tuyère Mobile
Mid-Course Guidance (INS & Kill Vehicle Separation)
Séparation du Booster
Kill Vehicle (KV) et le système DACS
INS (Navigation Inertielle)
DACS (Divert and Attitude Control System)
DACS (Divert and Attitude Control System)
Séparation du Booster
Contrôle d'Attitude (Roulis, Tangage, Lacet)
Contrôle d'Attitude (Roulis, Tangage, Lacet)
Propulseurs de Divertissement (Divert)
Terminal Phase & Kill (Hit-to-Kill & Precision Handover)
Autodirecteur Infrarouge (IIR Seeker)
Cible Verrouillée par IIR
Ellipse d'erreur INS
Ellipse Ellipse
INS Error Ellipse
Seeker Target Acquisition
Handover: De l'INS au Seeker Infrarouge
Collision Directe Millimétrique
Destruction "Hit-to-Kill"
Énergie Cinétique Pure
Missile Ballistique Adverse
Collision Directe Millimétrique
KV: L'Arme est la Propulsion


Propulsion & Guidance
INS and Thrust Vector Control (TVC) Ensure Accurate Missile Flight
Boost Phase
Steering Commands
Thrust Vector Control (TVC)
Mid-Course Guidance
• AN/TPY-2 Radar provides ongoing target data via a radio link
Boost Phase
• INS uses accelerometers and gyroscopes to track position, orientation, and velocity
• TVC tilts the nozzle to correct the trajectory.
Boost Phase
• INS uses accelerometers and gyroscopes to track position, orientation, and veloc
Tiltable Nozzle
Mid-Course Guidance
• AN/TPY-2 Radar provides ongoing target data via a radio link.
• INS refines flight path using external radar data.
Mid-Course Guidance
• AN/TPY-2 Radar provides ongoing target data via a radio link.

1. How the INS Guides the Propulsion

The INS is a self-contained navigation aid that uses **accelerometers** and **gyroscopes** to track the missile's position, orientation, and velocity without needing external references (like GPS, which can be jammed in a war zone).

- **During the Boost Phase:** The INS constantly calculates the missile's flight path. If the wind or a slight engine misalignment pushes the missile off course, the INS sends a command to the **Thrust Vector Control (TVC)** to tilt the nozzle and correct the trajectory.
- **The "Mid-Course" Update:** While the missile is screaming toward the target, it receives data updates via a radio link from the ground-based **AN/TPY-2 Radar**. The INS takes this external data and integrates it with its own internal calculations to refine the flight path.

2. Handover: From INS to the Infrared Seeker

The propulsion system relies on the INS until the very last seconds of the flight. This is called the **Handover Phase**.

- **Pointing the Camera:** The INS knows roughly where the target should be. It uses the **Attitude Control** thrusters to point the missile's nose (the Infrared Seeker) toward that specific patch of sky.
- **The Final Sprint:** Once the Infrared Seeker "locks on" to the heat signature of the enemy warhead, the INS moves into a secondary role. The Seeker now provides the "vision," and the **DACS (Divert and Attitude Control System)** provides the "muscles" for those final, violent lateral shifts to ensure a direct hit.

3. The Challenges of Hypersonic Navigation

Navigating at $2.8\ \mathrm{km/s}$ (approx. $10,000\ \mathrm{km/h}$) presents a massive thermal challenge.

- **Window Cooling:** The friction of the air at these speeds creates immense heat. If the seeker window gets too hot, the infrared sensor would be blinded by its own heat.
- **Precision Timing:** At these speeds, being off by just **one millisecond** in calculations means the propulsion system will move the missile several meters wide of the target. The INS must process data at incredible speeds to prevent a "near miss."

> **Think of it this way:** The INS is like a world-class sprinter running with their eyes closed, counting their steps perfectly based on a map they memorized. The Infrared Seeker is the sprinter opening their eyes for the last 5 meters to make sure they hit the finish line tape exactly in the center.

3. Interceptor Missile Architecture


THAAD Interceptor Missile Architecture
Hit-to-Kill kinetic interception missile
Gimbaled IR Seeker
Uplink of Midcourse Upodates to interceptor
AN/TPY-2 Data Link
Uplink of Midcourse
Updates to interceptor
Hit-to-Kill Collision
Very High Relative Speed Collision
Liquid-Fueled Kill Vehicle
Mach 8+ Speed
Single-Stage Solid Propulsion
Booster Separation
Length
~6.2 m
Diameter
~0.37 m
Mass
~900 kg
Speed
Mach 8+

3. Interceptor Missile Architecture

THAAD uses **hit-to-kill kinetic interception.**

No explosive warhead.

Energy of collision destroys the target.

Physical parameters

Parameter	Value
Length	~6.17 m
Diameter	~0.37 m
Mass	~900 kg

3.1 Two-stage Architecture

3.1 Two-stage Architecture

The interceptor consists of:

1. **Solid rocket booster**
2. **Kill Vehicle (KV)**

Booster

Responsibilities:

- Launch acceleration
- Midcourse trajectory shaping
- Separation at exo-atmospheric altitude

Solid propellant:

- Composite solid fuel
- High thrust short burn

Estimated burn time:

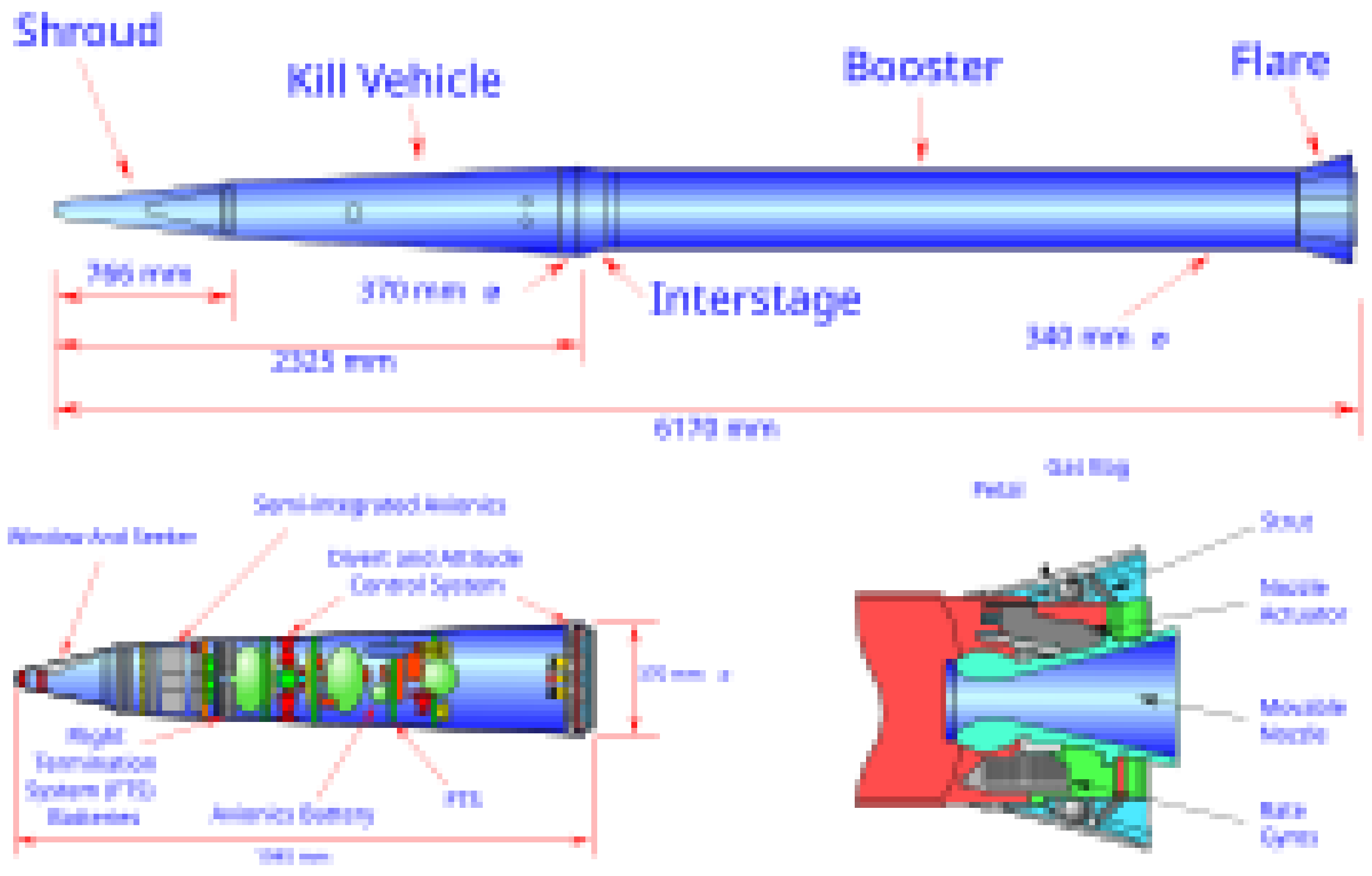
~20 seconds.

Kill Vehicle (KV)

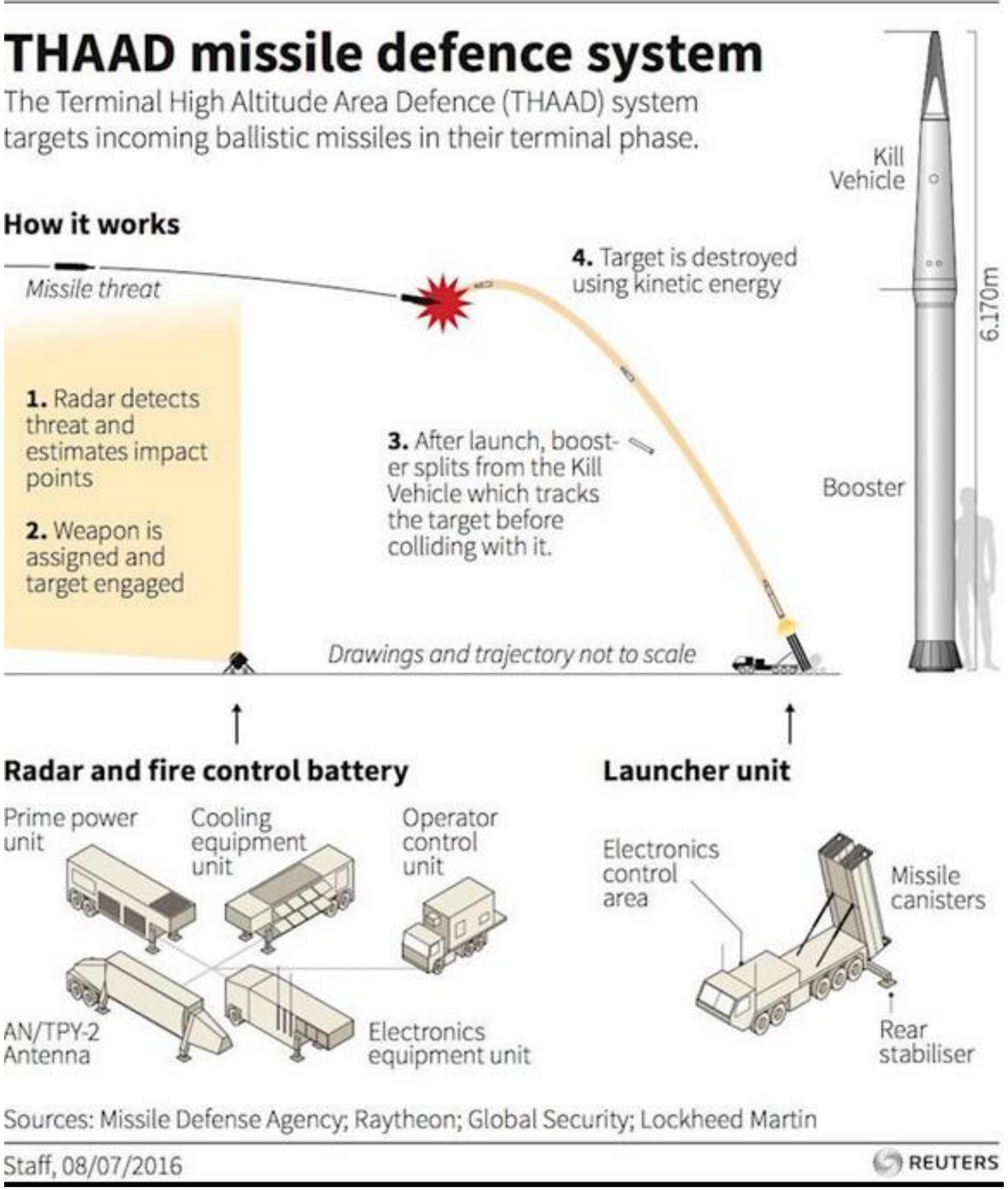
The **kinetic kill vehicle** is the real interceptor.

Components:

Subsystem	Function
IR seeker	target acquisition
DACS thrusters	maneuvering
onboard computer	guidance
IMU	inertial navigation
telemetry	data link


Shroud
Kill Vehicle
Booster
Flare
370 mm ⌀
Interstage
340 mm ⌀
2325 mm
6170 mm


What is THAAD?
DEFENCEHQ
THE TIMES OF INDIA
Terminal High Altitude Area Defense (THAAD) is a US missile defence system that intercepts short to intermediate-range ballistic missiles in the final stage of flight using hit-to-kill technology.
1 Missile detected
Satellites and radar detect a ballistic missile launch.
5 Hit-to-kill impact
Interceptor destroys the missile by direct collision.
4 Mid-course guidance
Interceptor receives tracking updates from radar.
2 Radar tracking
AN/TPY-2 radar tracks trajectory and predicts impact point.
3 Interceptor launched
Launcher fires a THAAD interceptor towards the target..
Key components
AN/TPY-2 radar
Interceptor missiles
Launchers
Fire control system


THAAD missile defence system
The Terminal High Altitude Area Defence (THAAD) system targets incoming ballistic missiles in their terminal phase.
How it works
Missile threat
1. Radar detects threat and estimates impact points
2. Weapon is assigned and target engaged
3. After launch, booster splits from the Kill Vehicle which tracks the target before colliding with it.
4. Target is destroyed using kinetic energy
Drawings and trajectory not to scale
Kill Vehicle
Booster
6.170m
Radar and fire control battery
Prime power unit
Cooling equipment unit
Operator control unit
AN/TPY-2 Antenna
Electronics equipment unit
Launcher unit
Electronics control area
Missile canisters
Rear stabiliser
Sources: Missile Defense Agency; Raytheon; Global Security; Lockheed Martin
Staff, 08/07/2016
REUTERS

Kill vehicle infrared seeker physics (KV)

- **3.1 Why infrared?**
- **3.2 What the gimbal buys you**
- **3.3 Seeker processing chain**
- **3.4 Atmospheric transition problem**

3.1 Why infrared?

In terminal ballistic defense, the incoming reentry vehicle can be a good IR target because of:

- aerodynamic heating during reentry
- thermal contrast against cold sky / space background
- hot structural features or boundary-layer heating
- residual temperature differences between real RV and lighter objects

The seeker is therefore not "seeing a shape" like a camera in daylight. It is measuring **radiant intensity** across spectral bands and tracking the target's apparent centroid and thermal evolution.

3.2 What the gimbal buys you

A **gimbaled seeker** decouples line-of-sight pointing from full-body missile attitude. That improves:

- target acquisition basket
- off-boresight tracking
- line-of-sight stability
- robustness during aggressive divert maneuvers

This matters because a pure body-fixed seeker would force the kill vehicle to steer the entire body to keep the target centered, increasing control burden and possibly wasting divert fuel.

3.3 Seeker processing chain

Public specifics are classified, but the standard chain is:

1. **Acquire** target inside seeker field-of-view
2. **Suppress background** and clutter
3. **Segment candidate hot objects**
4. **Compute centroid / shape / temporal behavior**
5. **Correlate with uplinked track file**
6. **Select aimpoint**
7. **Drive guidance law** into DACS commands

The real difficulty is not simply locking onto "something hot." It is making sure the seeker stays on the **correct lethal object** as geometry changes rapidly and background / clutter / blooming effects evolve.

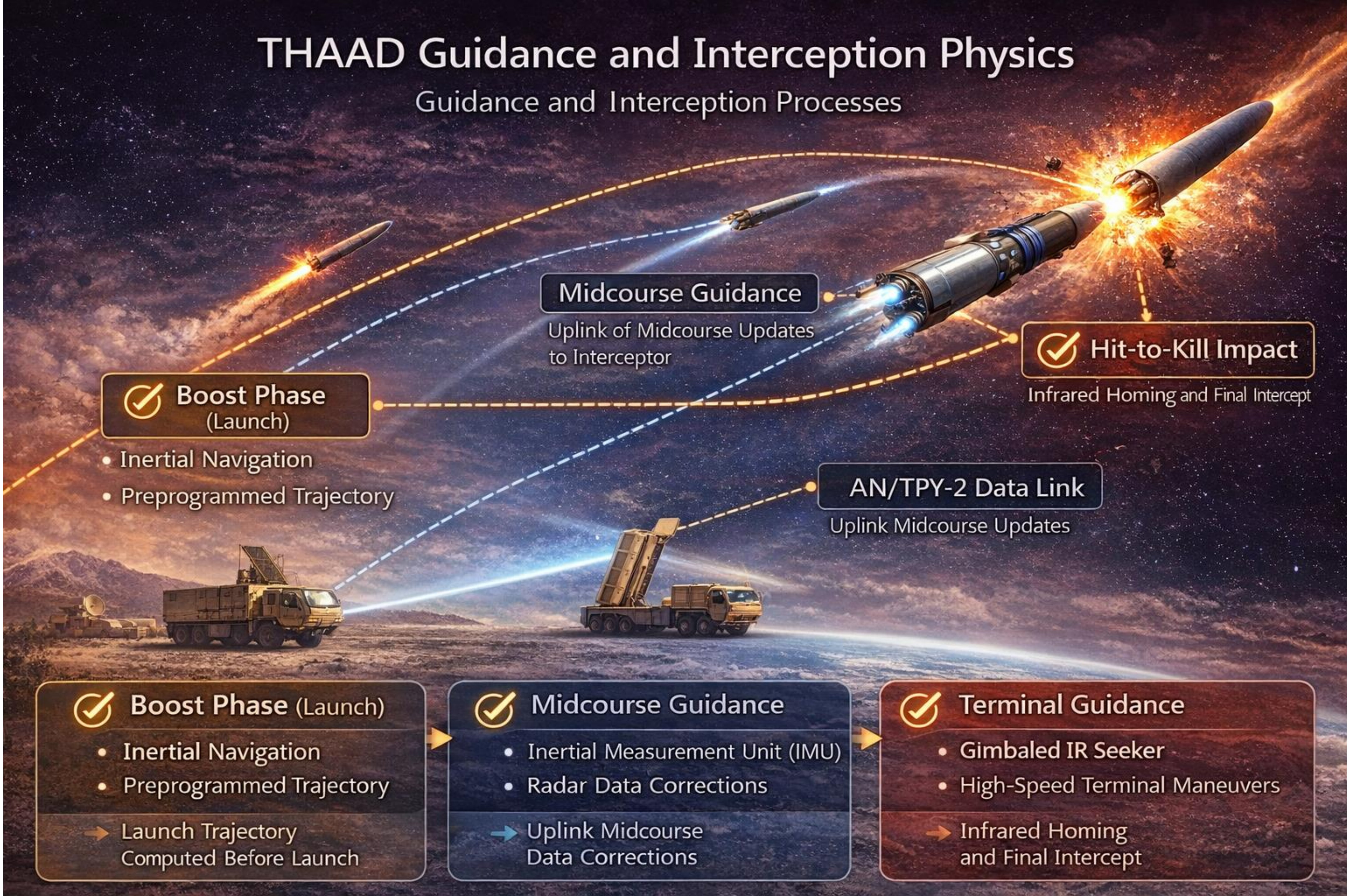
3.4 Atmospheric transition problem

THAAD is unusual because it can engage both **endo- and exo-atmospherically**. That means the seeker and control logic have to tolerate very different scenes:

- in exo: dark background, no aerodynamic forces, cleaner line-of-sight
- in endo: atmospheric attenuation, heating bloom, plasma / shock effects, greater clutter and dynamic pressure

That dual-regime capability is one reason THAAD is technically distinct from a purely exo-atmospheric interceptor like SM-3 or Arrow-3. Missile Threat +3

4. Guidance and Interception Physics



THAAD Guidance and Interception Physics
Guidance and Interception Processes
Midcourse Guidance
Uplink of Midcourse Updates to Interceptor
Hit-to-Kill Impact
Infrared Homing and Final Intercept
Boost Phase (Launch)
Inertial Navigation
Preprogrammed Trajectory
AN/TPY-2 Data Link
Uplink Midcourse Updates
Boost Phase (Launch)
Inertial Navigation
Preprogrammed Trajectory
Launch Trajectory Computed Before Launch
Midcourse Guidance
Inertial Measurement Unit (IMU)
Radar Data Corrections
Uplink Midcourse Data Corrections
Terminal Guidance
Gimbaled IR Seeker
High-Speed Terminal Maneuvers
Infrared Homing and Final Intercept

Guidance and Interception - AGENDA

- 4.1 Boost Phase (Launch)
- 4.2 Midcourse Guidance
- 4.3 Terminal Homing
- 4.4 Hit-to-Kill Physics

4.1 Boost Phase (Launch)

Booster uses:

- Inertial navigation
- preprogrammed trajectory

Inputs from:

- TFCC
- radar tracking solution

Trajectory solution is computed before launch.

4.2 Midcourse Guidance

After booster separation:

Kill vehicle performs exo-atmospheric navigation.

Uses:

- Inertial Measurement Unit (IMU)
- uplink data corrections

Ground radar provides:

- updated target vector
- velocity
- predicted intercept point

4.3 Terminal Homing

The infrared seeker activates.

Seeker detects:

- hot reentry vehicle
- ballistic warhead signature

Guidance algorithm:

Proportional Navigation (PN).

Simplified form:

$$a = N \cdot V_c \cdot \dot{\lambda}$$

Where:

- a = lateral acceleration
- N = navigation constant
- V_c = closing velocity
- $\dot{\lambda}$ = line-of-sight rate

4.4 Hit-to-Kill Physics

No explosives.

Destruction energy:

$$E = \frac{1}{2}mv^2$$

Typical intercept velocity:

~3 km/s.

Kinetic energy:

≈ 4.5 gigajoules

Equivalent to:

~1 ton TNT.

5. Divert and Attitude Control System


THAAD Divert and Attitude Control System (DACS)
Precision Hydrazine Thrusters for Lateral Maneuvering
Monopropellant Thrusters
Hydrazine Fuel (H_2N_2)
Hydrazine-Fueled Pulse-Controlled Jets
Rapid On-Demand Thrust
Four DACS Divert Thrusters
Hydrazine Fuel (H_2N_2)
Purpose:
Lateral Maneuvering
Fine Trajectory Correction
Final Collision Alignment
Hydrazine-Fueled Pulses for Extreme Maneuverability
Rapid On-Demand Thrust Adjustments
Sub-10 Millisecond Response Time

5. Intercept geometry calculations

- 5.1 The “intercept basket”
- 5.2 Terminal ballistic geometry
- 5.3 Simplified 2D intercept example

5.1 The “intercept basket”

Fire control does not aim at a single point; it predicts an **intercept volume** or basket where a feasible hit is likely, given uncertainty in:

- target state estimate
- atmospheric model
- interceptor performance
- seeker acquisition window
- maneuver margins

If the covariance ellipse on target position grows too large, shot doctrine may change:

- earlier launch
- ripple shot / salvo
- handoff to lower-tier system
- no-shot if probability of kill is too low

5.2 Terminal ballistic geometry

For a reentry vehicle, the path is steep and fast. THAAD benefits because:

- the target trajectory is more predictable than an aircraft's
- the target cannot pull high sustained lateral g like a fighter

But it is still hard because:

- time-to-go is short
- closing speeds are very high
- small track errors are magnified
- debris / decoys may be nearby

5.3 Simplified 2D intercept example

If target and interceptor move in 2D with constant velocities over a very short interval, intercept time can be approximated by solving:

$$\mathbf{r}_0 + (\mathbf{v}_T - \mathbf{v}_I)t = 0$$

In reality, THAAD is solving a much more complex problem:

- target descending on a curved ballistic path
- interceptor accelerating, then separating
- gravity and atmosphere changing by altitude
- kill vehicle using impulsive or quasi-throttle divert control

So actual fire control uses filtered state estimation and repeated refinement, not a one-shot closed-form solve.

5. Divert and Attitude Control System (DACS)

The kill vehicle uses a **DACS thruster system.**

Purpose:

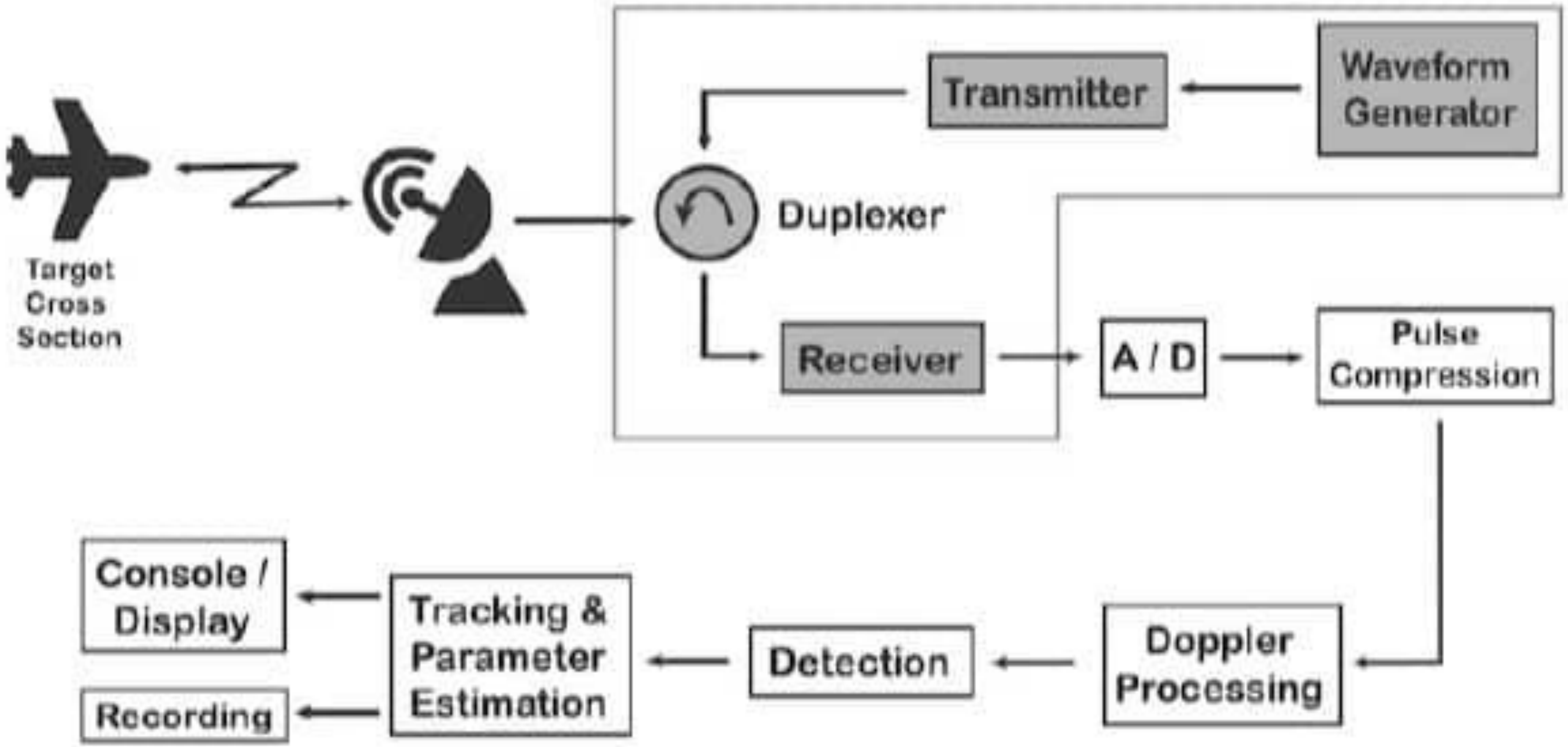
- lateral maneuvering
- fine trajectory correction
- final collision alignment

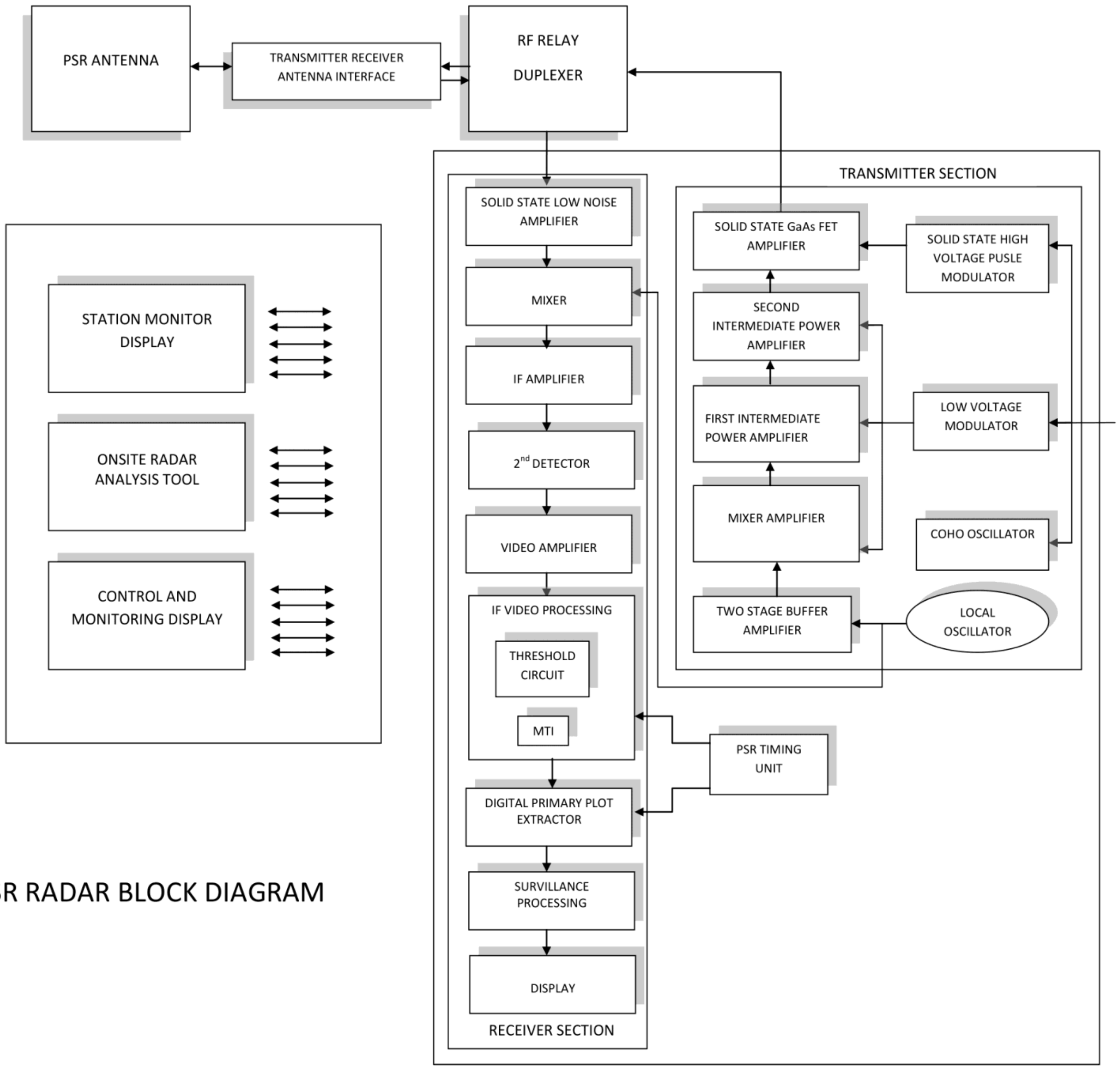
Key features:

- monopropellant thrusters
- pulse-controlled jets
- extremely fast response (<10 ms)

DACS must provide **very high lateral acceleration** to correct intercept geometry.

6. Radar System: AN/TPY-2


Target
Cross
Section
Transmitter
Waveform
Generator
Duplexer
Receiver
A / D
Pulse
Compression
Console /
Display
Recording
Tracking &
Parameter
Estimation
Detection
Doppler
Processing



PSR RADAR BLOCK DIAGRAM

AN/TPY-2 Radar System

The AN/TPY-2 is a powerful, X-band, ground-based radar used by the THAAD system.

X-Band Range Capability
up to 1,000 km

X-Band Precision
ability to detect small objects in space

Phased Array Radar
Highly advanced phased array for precise tracking

Mobile Deployment
Truck-mounted, relocatable within hours

Key Performance Parameters

Frequency	8.55-10 GHz (X-band)
Max: Range	up to 1,000 km
Power Output	>25,000 watts
Mobility	rapidly truck deployable

RADAR – SPECIFICATION AGENDA

- 2.1 Search and cueing
- 2.2 Detection
- 2.3 Tracking
- 2.4 Discrimination
- 2.5 Fire-control quality track

Signal Processing Flow

```
Radar Pulse Transmission
        ↓
Echo Reception
        ↓
Analog → Digital Conversion
        ↓
Pulse Compression
        ↓
Doppler Filtering
        ↓
Clutter Rejection
        ↓
Target Detection
        ↓
Track Formation
        ↓
Target Classification
```

Track & Discrimination

Track Generation

The radar generates **track objects.**

Each track contains:

```
position (x,y,z)
velocity vector
acceleration
confidence probability
```

Discrimination

Algorithms determine whether an object is:

```
real warhead
decoy
debris
fragment
```

This step is **extremely computationally intensive.**

2. Radar signal-processing pipeline: what AN/TPY-2 is doing

Publicly, RTX describes AN/TPY-2 as an **X-band missile-defense radar** that can **detect, track, and discriminate** ballistic missiles, and operate in **forward-based mode** or **terminal mode.** In terminal mode it is the dedicated radar guiding THAAD; in forward-based mode it supports earlier cueing for the wider missile-defense architecture. rtx.com

From an engineering standpoint, the signal-processing chain looks like this:

2.1 Search and cueing

AN/TPY-2 is usually not staring blindly at the whole sky. In a real architecture, it benefits from external cues such as space-based warning and battle-management networks; GAO's BMDS description explicitly places AN/TPY-2 and C2BMC inside a wider sensor-cueing chain. gao.gov

That means the radar can narrow search volume and spend more time on:

- higher update rates
- finer range resolution
- discrimination processing
- multi-object track maintenance

2.2 Detection

At X-band, the radar benefits from **short wavelength**, which improves angular and range resolution against relatively small ballistic objects. RTX explicitly frames this as enabling the radar to see targets more clearly and distinguish actual threats from non-threats such as debris. rtx.com

In simplified radar terms, the received power follows the usual monostatic radar relationship:

$$P_r \propto \frac{P_t G^2 \lambda^2 \sigma}{R^4}$$

where:

- P_t: transmitted power
- G: antenna gain
- λ: wavelength
- σ: radar cross section
- R: range

Because R^4 dominates, **track quality collapses fast with range**, which is why cueing, beam scheduling, and track management are just as important as raw transmit power.

2.3 Tracking

Once detected, the radar estimates:

- range
- range rate
- azimuth / elevation
- acceleration consistency
- object-separation behavior

A ballistic target is not just one dot. During terminal engagement, the radar may see:

- warhead / RV
- booster remnants
- fragments
- penetration aids
- staging debris

So the processor must maintain a **multi-hypothesis track file**, pruning or reweighting tracks over time.

2.4 Discrimination

This is one of the hardest engineering problems. RTX says AN/TPY-2 is designed to **discriminate threats from non-hostile objects**, and public THAAD descriptions emphasize discrimination as a core role. rtx.com +1

The likely public-domain discrimination features are:

- **ballistic consistency**: does the object follow a physically plausible RV trajectory?
- **radar cross-section stability**: tumbling debris often scintillates differently
- **micro-motion / attitude clues**
- **deceleration profile in atmosphere**: lighter decoys or debris slow differently
- **object separation timing**
- **fused cueing** from external sensors or interceptors

In short: THAAD's radar is not merely "finding a missile." It is solving a **classification problem under time pressure**.

2.5 Fire-control quality track

Not every track is good enough for launch. A THAAD shot needs a **fire-control solution** precise enough to define:

- launch time window
- predicted intercept point
- handover basket for the seeker
- backup shot doctrine if track covariance is too high

This is where the distinction between **surveillance track** and **engagement-quality track** becomes critical.

6. “Real engagement simulation”

Phase A: Threat launch

External warning system detects launch and cues the architecture. BMDS networking then points radar resources toward the threat sector. GAO describes exactly this kind of chain involving space-based warning, C2BMC, and AN/TPY-2 tracking. gao.gov

Phase B: Radar acquisition and track formation

AN/TPY-2 acquires the ballistic object stack and builds one or more candidate tracks. Early in the engagement, the system may still be uncertain which track corresponds to the actual lethal body. RTX and CSIS both describe AN/TPY-2 as a radar that detects, tracks, and discriminates ballistic missiles. rtx.com +1

Phase C: Engagement-quality solution

Fire control predicts an intercept basket and commits a launcher. Public descriptions of THAAD batteries consistently identify launchers, AN/TPY-2, and fire-control/communications as the core architecture. gao.gov +1

Phase D: Booster flyout

The interceptor launches, climbs, and shapes its trajectory to enter the proper kinematic corridor. The booster does the bulk of the energy delivery; the kill vehicle is for precision, not gross range extension.

6. what a notional THAAD shot looks like

Phase E: Separation and handover

Near the terminal engagement region, the kill vehicle separates and begins onboard sensing. Uplinked track refinement narrows the seeker search window.

Phase F: Seek, discriminate, divert

The seeker acquires the target, computes line-of-sight rate, and DACS performs lateral corrections. If the object cloud is complex, the challenge is not "hitting something" but hitting the **right object**.

Phase G: Kinetic collision

The kill vehicle achieves body-to-body impact. With hit-to-kill, lethality comes from relative kinetic energy rather than blast-fragmentation warhead effects.

DOT&E says THAAD has demonstrated this capability across SRBM/MRBM/IRBM representative targets, but also stresses that **more complex engagement conditions and realistic raid scenarios remain an area for future testing.** That is an important realism check. dote.osd.mil

6.1 Radar specifications

Parameter	Value
Band	X-band (8–12 GHz)
Range	>1000 km
Array type	Active phased array
Mode	search + track
Beam steering	electronic

6.2 Radar capabilities

Functions:

- ballistic missile detection
- trajectory discrimination
- warhead vs decoy separation
- fire control targeting

Key features:

Extremely narrow beam

Allows:

- high angular resolution
- small object detection

Discrimination algorithms

Uses:

- radar cross-section analysis
- trajectory behavior
- thermal signatures

7. Fire Control System (TFCC)

THAAD Fire Control and Communications (TFCC)

The TFCC (THAAD Fire Control and Communications) is the command center.

Threat Evaluation

Detect incoming missile

- Detect incoming missile

Intercept Calculation

- Compute intercept geometry

Launch Control

Fire interceptor

- Fire interceptor

Sensor Fusion

Link 16 tactical network

Aegis Combat System naval BMD

Sensor Fusion

Link 16

Aegis Combat System
naval BMD

SBIRS
early warning satellites

7. Fire Control System (TFCC)

The TFCC (THAAD Fire Control and Communications) is the command center.

Functions:

Function	Description
Threat evaluation	detect incoming missile
Intercept calculation	compute intercept geometry
Launch control	fire interceptor
Data fusion	integrate external sensors

7.1 Sensor Fusion

THAAD can integrate with:

Network	Function
Link 16	tactical network
Aegis Combat System	naval BMD
SBIRS	early warning satellites

Engineering strengths of THAAD

- 7.1 Dual-regime intercept
- 7.2 X-band discrimination advantage
- 7.3 Mobile battery architecture
- 7.4 Layered-defense fit

7.1 Dual-regime intercept

It can engage both **inside and outside the atmosphere**, which increases defended battlespace and gives a better chance to kill a warhead before lower-tier defenses have to act. Missile Threat +1

7.2 X-band discrimination advantage

AN/TPY-2's X-band operation gives high-resolution tracking and discrimination, which is exactly what you want when sorting RVs from debris. RTX explicitly highlights detection, tracking, and discrimination as core functions. rtx.com

7.3 Mobile battery architecture

GAO and Army references describe THAAD as a mobile, battery-organized system; the Army also documents current operational batteries, including in Guam. gao.gov +2

7.4 Layered-defense fit

THAAD is neither too low nor too strategic; it fills the "upper terminal" layer between Patriot-class systems and large-area midcourse systems such as SM-3. gao.gov +1

8. Engagement Timeline


THAAD Engagement Timeline
T+0 sec
Enemy Missile Launch Detected by
Satellite Infrared
T+60 sec
Radar Acquisition
Trajectory estimated
T+150 sec
Midcourse Updates
from Radar
T+90 sec
Intercept Solution Calculated
Launcher Fires THAAD interceptor

8. Engagement Timeline

T+90 sec

Intercept solution calculated.

Launcher fires THAAD interceptor.

T+150 sec

Midcourse updates from radar.

T+180–240 sec

Terminal homing.

Kill vehicle impact.

T+0 sec

Enemy missile launch detected by:

- satellite infrared

T+60 sec

Radar acquisition.

Trajectory estimated.

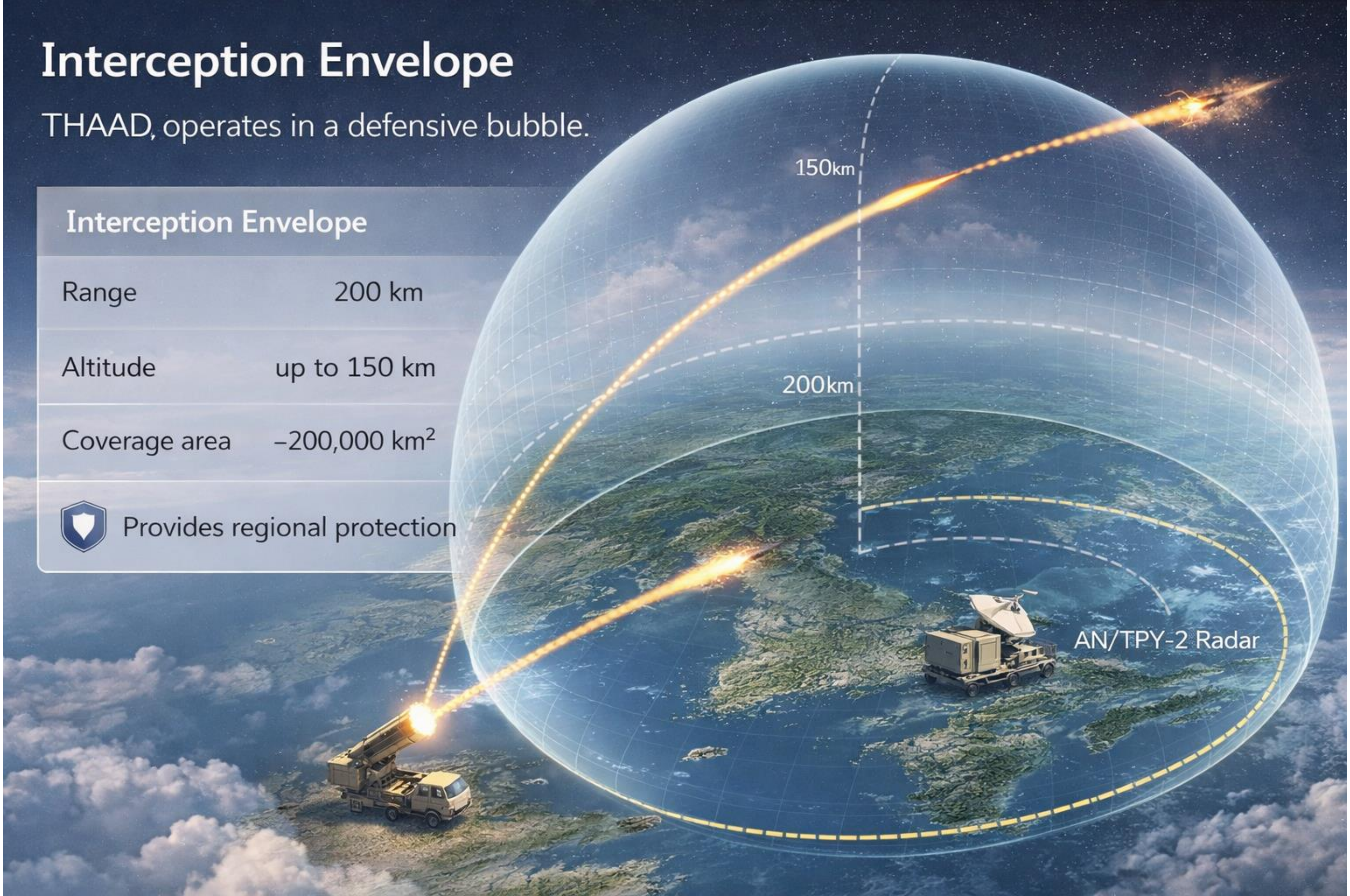
T+90 sec

Intercept solution calculated.

Launcher fires THAAD interceptor.

9. Interception Envelope


THAAD Interception Envelope
Altitude: 150 km
Range: 200 km
Coverage:~200,000 km²


Interception Envelope
THAAD, operates in a defensive bubble.
Interception Envelope
Range 200 km
Altitude up to 150 km
Coverage area –200,000 km²
Provides regional protection
150km
200km
AN/TPY-2 Radar

9. Interception Envelope

THAAD operates in a **large defensive bubble.**

Approximate envelope:

Parameter	Value
Range	200 km
Altitude	up to 150 km
Coverage area	~200,000 km^2

This enables **regional protection.**

10. Mobility and Deployment


THAAD – Mobility and Deployment
Fully Road Mobile – Rapid & Flexible Deployment
Launcher Vehicle
Heavy Tactical Truck
Vertical Launch
Transportability
C-17 Transport
Full Battery
Road Transport
Rapid Redeployment
Deploy
Set Up & Connect
Operational


THAAD – Mobility and Deployment
Fully Road Mobile with Rapid Redeployment Capability
Launcher Vehicle
Heavy Tactical Truck
Vertical Launch System
8x8
Wheeled Chassis
~30 Tons
Total Weight
Quick Setup
< 30 min
Vertical Launch
Transportability
C-17 Transport
Full THAAD Battery
Road Transport
Rapid Redeployment
Rapid Deployment
Global Reach
Road Mobile
Operational in Hours

10. Mobility and Deployment

THAAD is fully road mobile.

Launcher vehicle:

- heavy tactical truck
- vertical launch

Transportability:

Method	Capability
C-17 transport	full battery
road transport	rapid redeployment

11. Deployment Locations


THAAD Deployment Locations
Global Deployments for Strategic Missile Defense
South Korea
DPRK Missile Defense
Guam
Pacific Defense
Guam
Pacific Defense
UAE
Gulf Defense

11. Deployment Locations

Known deployments include:

Country	Purpose
South Korea	DPRK missile defense
Guam	Pacific defense
Israel	regional defense
UAE	Gulf defense

12. Countermeasures and Limitations

Countermeasures and Limitations

Challenges Posed to THAAD Missile Defense

Decoys and MIRV

Modern ballistic missiles may deploy:

- decoys
- multiple warheads (MIRV)

Radar discrimination becomes difficult.

Hypersonic Glide Vehicles (HGVs)

THAAD is **less effective** against

- maneuvering, low-trajectory hypersonic threats

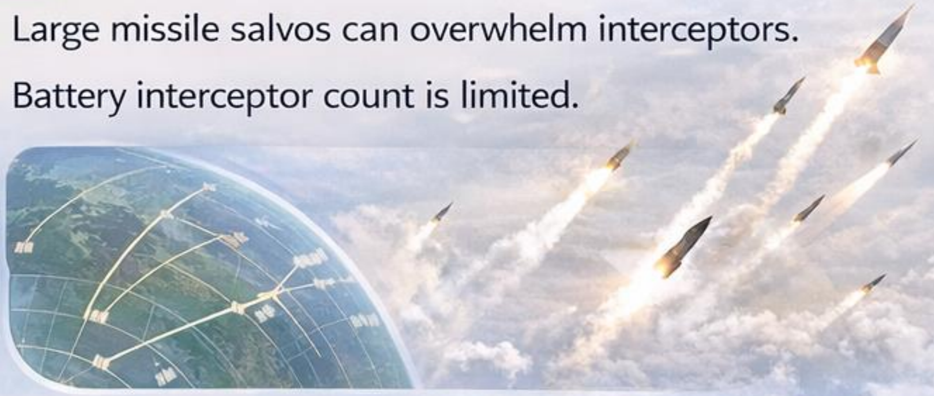
Examples:

- Avangard
- DF-17

Saturation Attacks

Large missile salvos can overwhelm interceptors.

Battery interceptor count is limited.



Saturation Attacks

Large missile salvos can overwhelm interceptors.

Battery interceptor count is limited.

DF-17

12.1 Decoys and MIRV

Modern ballistic missiles may deploy:

- decoys
- multiple warheads (MIRV)

Radar discrimination becomes difficult.

12.2 Hypersonic Glide Vehicles

THAAD is **less effective** against:

- maneuvering hypersonic vehicles
- low-trajectory glide systems

Examples:

- Avangard
- DF-17

12.3 Saturation Attacks

Large missile salvos can overwhelm interceptors.

Battery interceptor count is limited.

13. Performance and Test Record

13. Performance and Test Record

THAAD testing success rate:

~90%.

Key test milestones:

Year	Event
2006	first successful intercept
2017	IRBM intercept
2020	integrated BMD tests

14. Industrial Architecture

THAAD Industrial Architecture

Major Contractors

14. Industrial Architecture

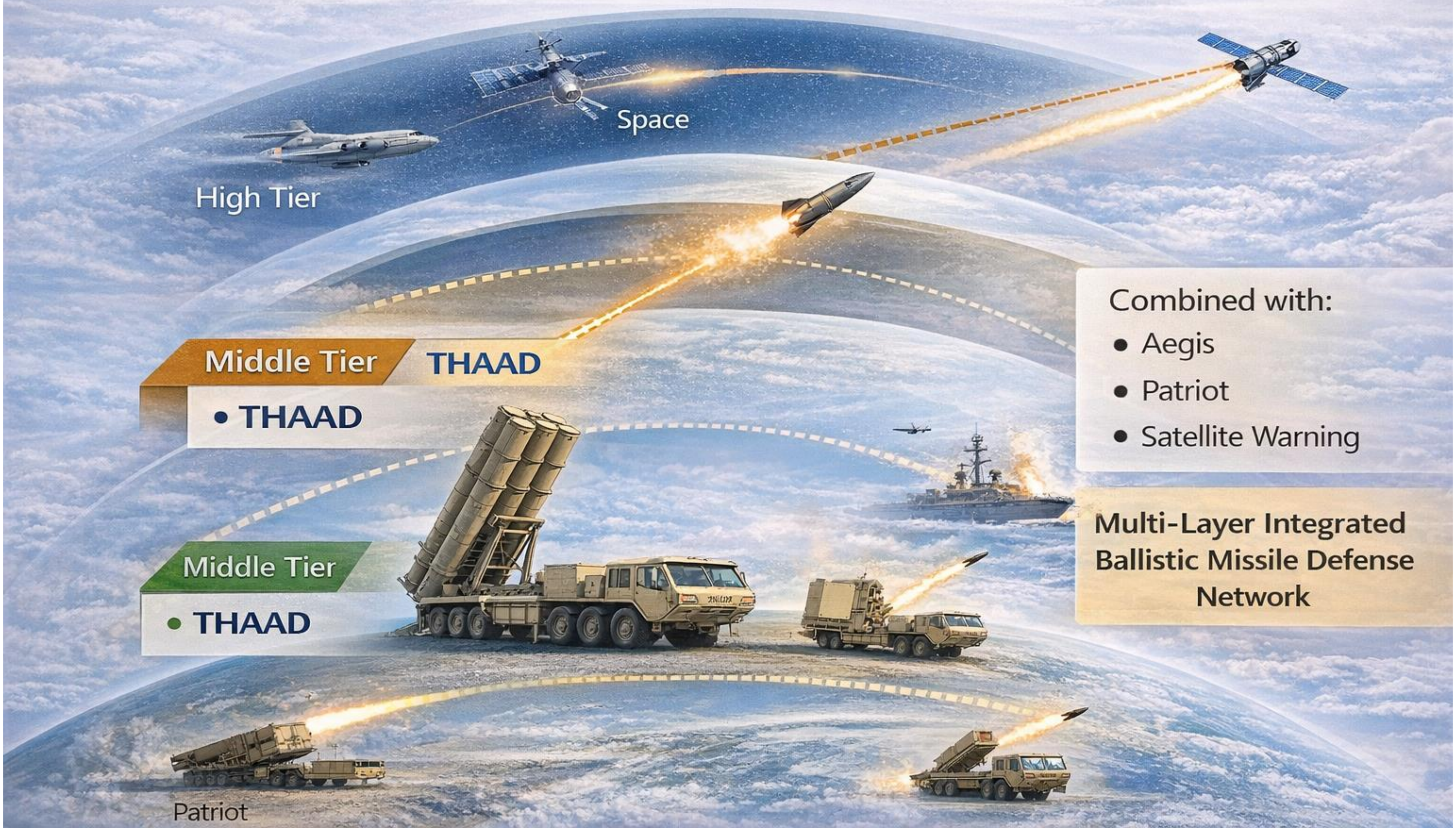
Major contractors:

Company	Role
Lockheed Martin	prime contractor
Raytheon Technologies	radar
Boeing	components

15. Strategic Role in Modern Missile

THAAD: Strategic Role in Modern Missile Defense

Provides **critical middle layer** in missile defense



15. Strategic Role in Modern Missile Defense

THAAD provides a **critical middle layer** in missile defense.

Advantages:

- high-altitude intercept
- wide coverage
- kinetic kill reliability

Combined with:

- Aegis
- Patriot
- satellite warning

It forms a **multi-layer integrated ballistic missile defense network.**

Engineering limitations of THAAD

1 It is still a terminal system

2 Complex raid / saturation stress

3 Public test gap

4 Not optimized for broad midcourse area defense

.2 Complex raid / saturation stress

DOT&E explicitly notes the need for more testing under complex and realistic raid scenarios. That is a polite but important point: many missile-defense systems look strong in controlled single-shot tests and become much more stressed under simultaneous track, discrimination, and inventory pressure. dote.osd.mil

3 Public test gap

DOT&E's FY2024 report says the last flight test using a THAAD interceptor was in FY2019 and that the next is scheduled in FY2027, creating a notable flight-test gap. That does not prove poor capability, but it does reduce the amount of fresh public evidence on current performance against evolving threats. dote.osd.mil

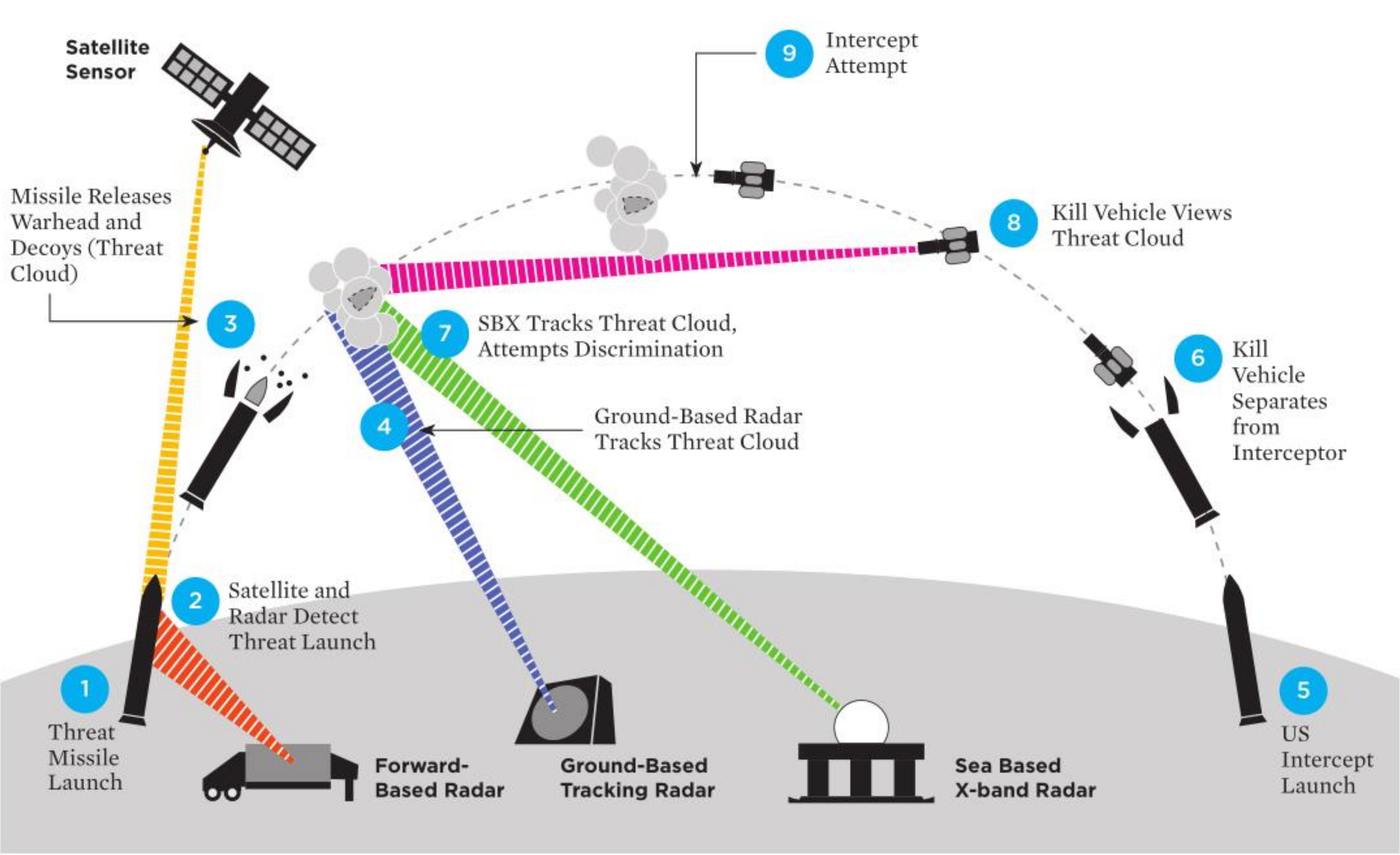
4 Not optimized for broad midcourse area defense

Its defended footprint is significant, but still much smaller than what SM-3 Block IIA is designed to provide from maritime or Aegis Ashore positions. Missile Threat +1

THAAD vs S-400 vs S-500 vs Arrow-3 vs SM-3

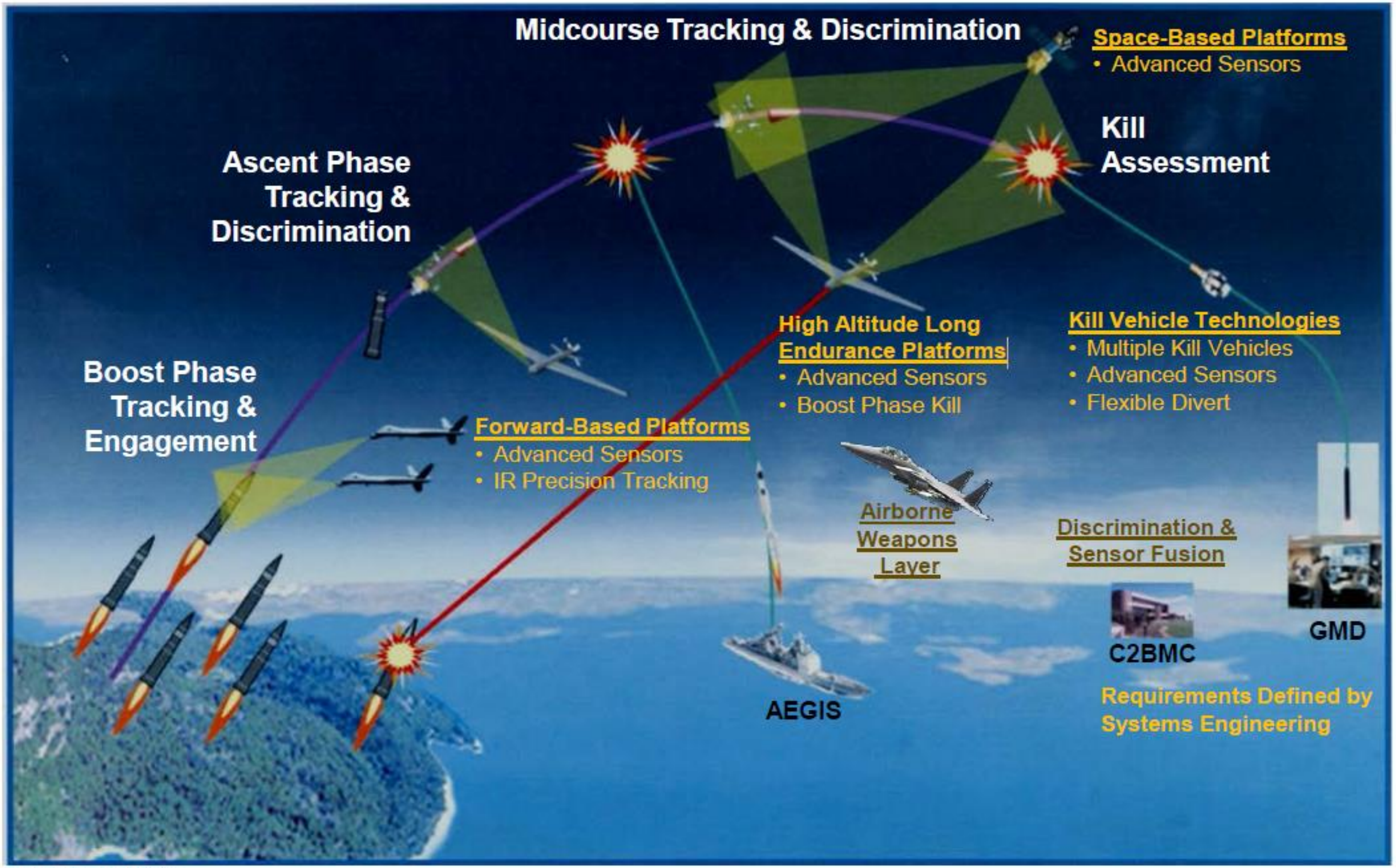
Additional Important Aspects of THAAD

Anatomy of an Intercept



The GMD system involves a complex, global network of components. The launch of the threat missile (1) is detected by forward-based radars, if present, and satellite-based infrared sensors (2). The threat missile releases its warhead and decoys (in this example the decoys are balloons, and a balloon contains the warhead; together they are referred to as the "threat cloud") (3), and the ground-based radar begins tracking the threat cloud (4). Based on information from this radar, the GMD system launches one or more interceptors (5), each of which releases a kill vehicle (6). If a discrimination radar, such as the Sea Based X-band Radar, is in place it will observe the threat cloud to try to determine which object is the warhead (7) and pass this information to the kill vehicle. The kill vehicle also observes the threat cloud to attempt to determine which object is the warhead (8). It then steers itself into the path of the chosen object and attempts to destroy it with the force of impact (9).

Technology Contributions to the BMDS



Engagement Doctrine (Shoot–Look–Shoot)

One important concept in missile defense operations is the **intercept doctrine** used during engagements.

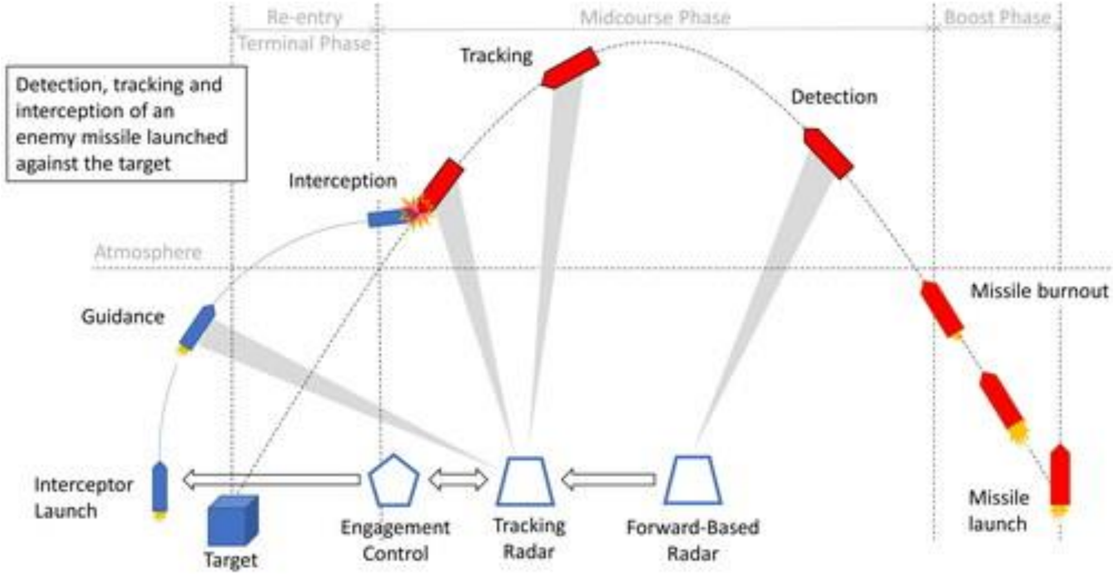
THAAD commonly employs a strategy known as:

Shoot–Look–Shoot

Concept

Rather than relying on a single interceptor, the system evaluates the intercept outcome before deciding whether to launch another interceptor.

This approach significantly increases the overall probability of destroying the incoming missile.



Process

```
Interceptor launched
Radar evaluates intercept success
If kill not confirmed -> second interceptor fired
```

Why this doctrine is used

- **Hit-to-kill interceptors do not guarantee a 100% success rate**
- Sensors must confirm whether the target was actually destroyed
- A second interceptor dramatically improves the probability of success

---

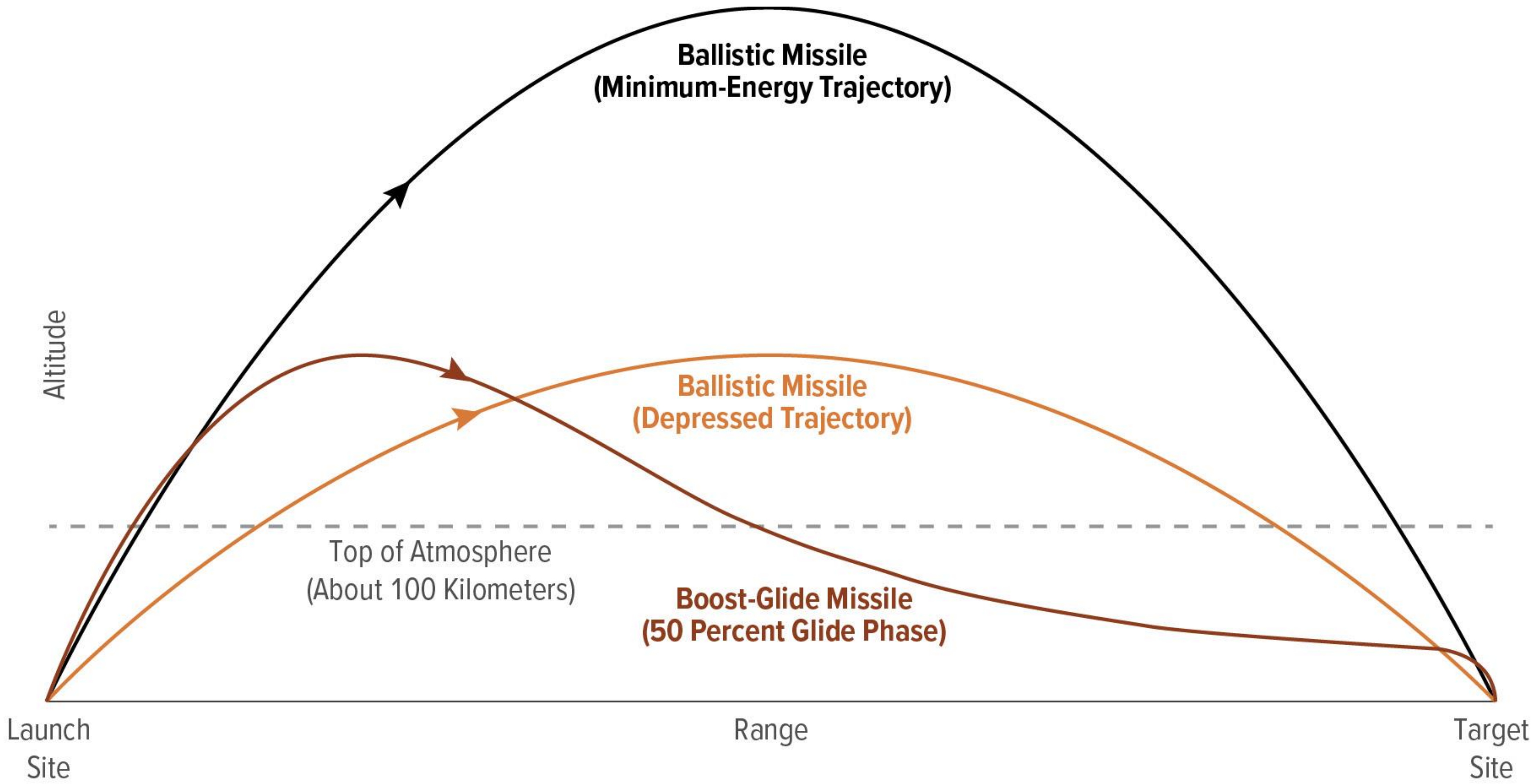
Example

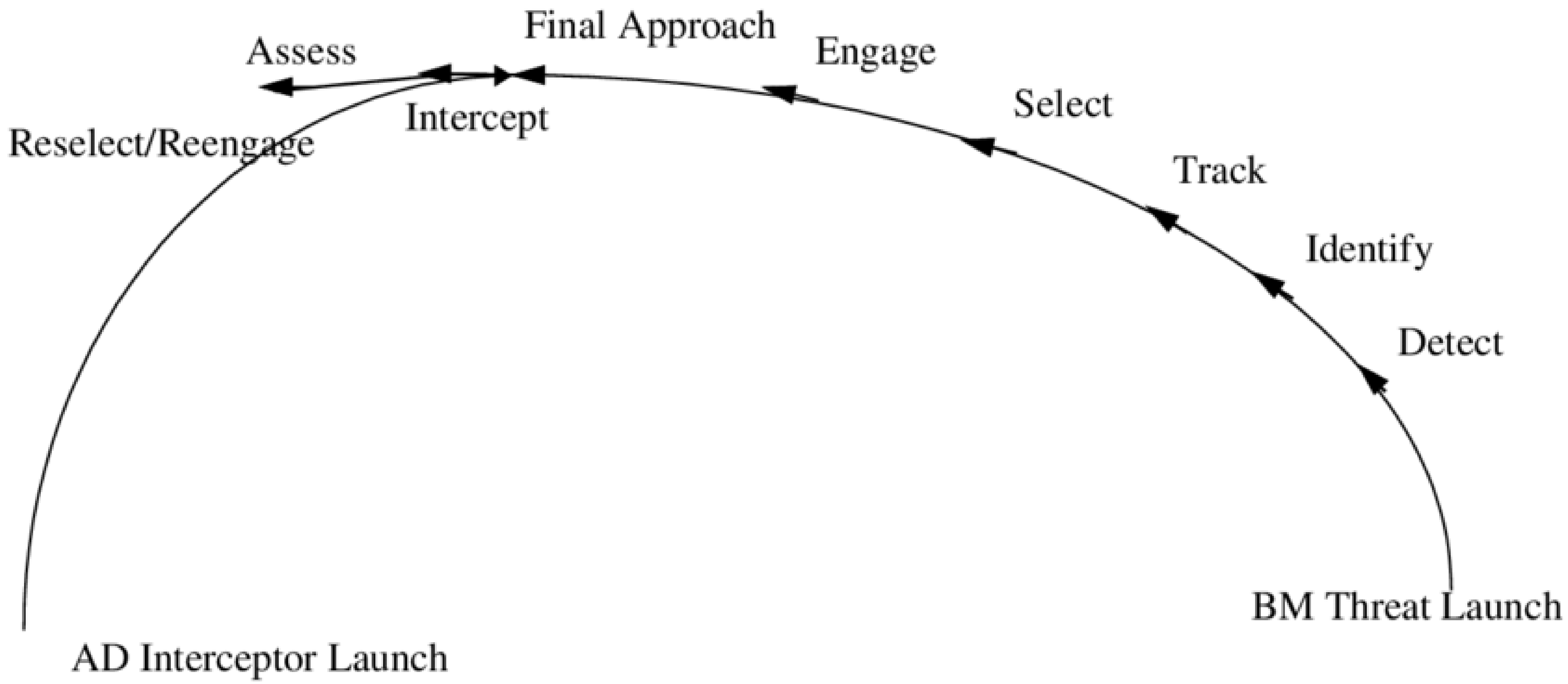
```
Single interceptor PK ≈ 0.8
```

If two interceptors are used:

```
P(success) = 1 − (1 − 0.8)²
           = 0.96
```

This means the success probability increases from **80% to 96%**.


Ballistic Missile
(Minimum-Energy Trajectory)
Ballistic Missile
(Depressed Trajectory)
Altitude
Top of Atmosphere
(About 100 Kilometers)
Boost-Glide Missile
(50 Percent Glide Phase)
Launch
Site
Range
Target
Site


Final Approach
Assess
Engage
Select
Intercept
Reselect/Reengage
Track
Identify
Detect
BM Threat Launch
AD Interceptor Launch