



Hypersonic Counter Measures

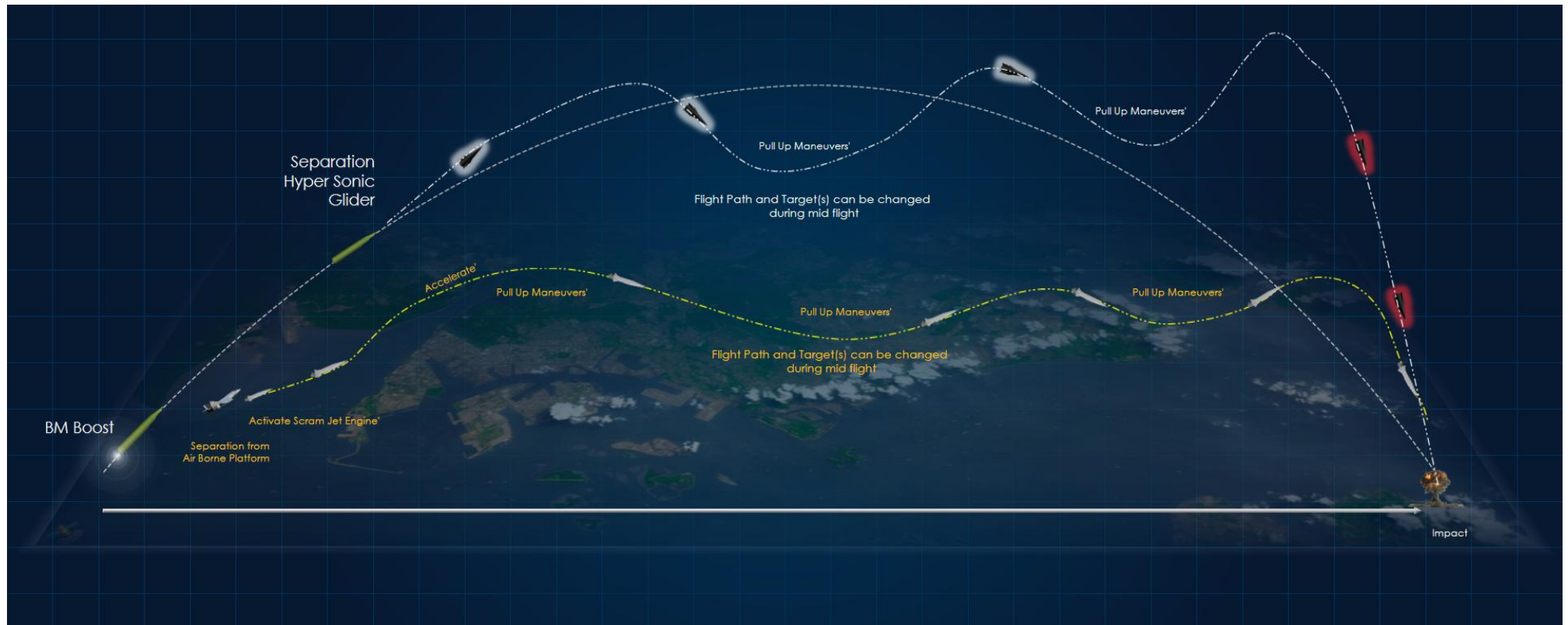
Hypersonic Defense

The Department of Defense (DOD) is working on next-generation interceptors, which aim to strike and eliminate hypersonic missiles where they are most vulnerable—in their midcourse or glide-phase. For example, DARPA's Glide Breaker could come online in 2026, while the Missile Defense Agency (MDA) is developing the Glide Phase Interceptor with a 2027-to-2028 timeline. They are part of a host of programs to evolve and upgrade the U.S. missile defense system and the DOD's sensing, tracking and engagement architecture currently designed for ballistic missiles.

While the hypersonic interceptor programs are running in parallel, concurrent inter-agency projects to build an improved missile warning and tracking sensor layer are underway. The U.S. Space Force's Space Systems Command, with MDA and the Space Development Agency, is overseeing the next-generation overhead persistent infrared (Next Gen OPIR) program to develop resilient constellations of sensor satellites to detect, track and disseminate timely data on missile launches.

- https://www.microwavejournal.com/articles/38581-hypersonic-missile-defense-requires-advanced-solutions?gad_source=1&gad_campaignid=22062257718&gclid=Cj0KCQjw64jDBhDXARIsABkk8J7n92CBQuko93GxKGiq8LMWxWzRgWTTLyKm7NNLqK2ojSIhUhuoC7YaAr8UEALw_wcB
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Hypersonic threat characteristics



<https://www.thalesgroup.com/en/worldwide/defence-and-security/magazine/hypersonic-defence-introduction>

Defense Basics

One of the most effective defense penetration techniques is to collapse the battlespace by minimizing the engagement time available. **The primary techniques available to collapse the battlespace for the offensive missile designer to exploit are [1] speed, altitude, and radar cross section (RCS).** The defense system in turn must utilize faster missiles, elevated and more powerful ISR sensors, and radars with data links and sophisticated signal processing techniques to counter these offensive techniques. **After collapsing the battlespace, the offensive missile designer needs to drive down the probability-of-kill (Pk) or probability-of-raid annihilation (PRA) for the defensive systems that have obtained an engagement opportunity [2].** Offensive missile tactics and raids can be used to reduce Pk or PRA. Tactics can include jamming and maneuvers either in combination or separately [1–9]. Jamming is employed to delay detection by the radar and missile seeker and to deny the radar and missile seeker accurate range and angle estimates.

- Boord, Warren J.; Hoffman, John B.. Air and Missile Defense Systems Engineering (pp. 43-44). CRC Press. Kindle Edition.

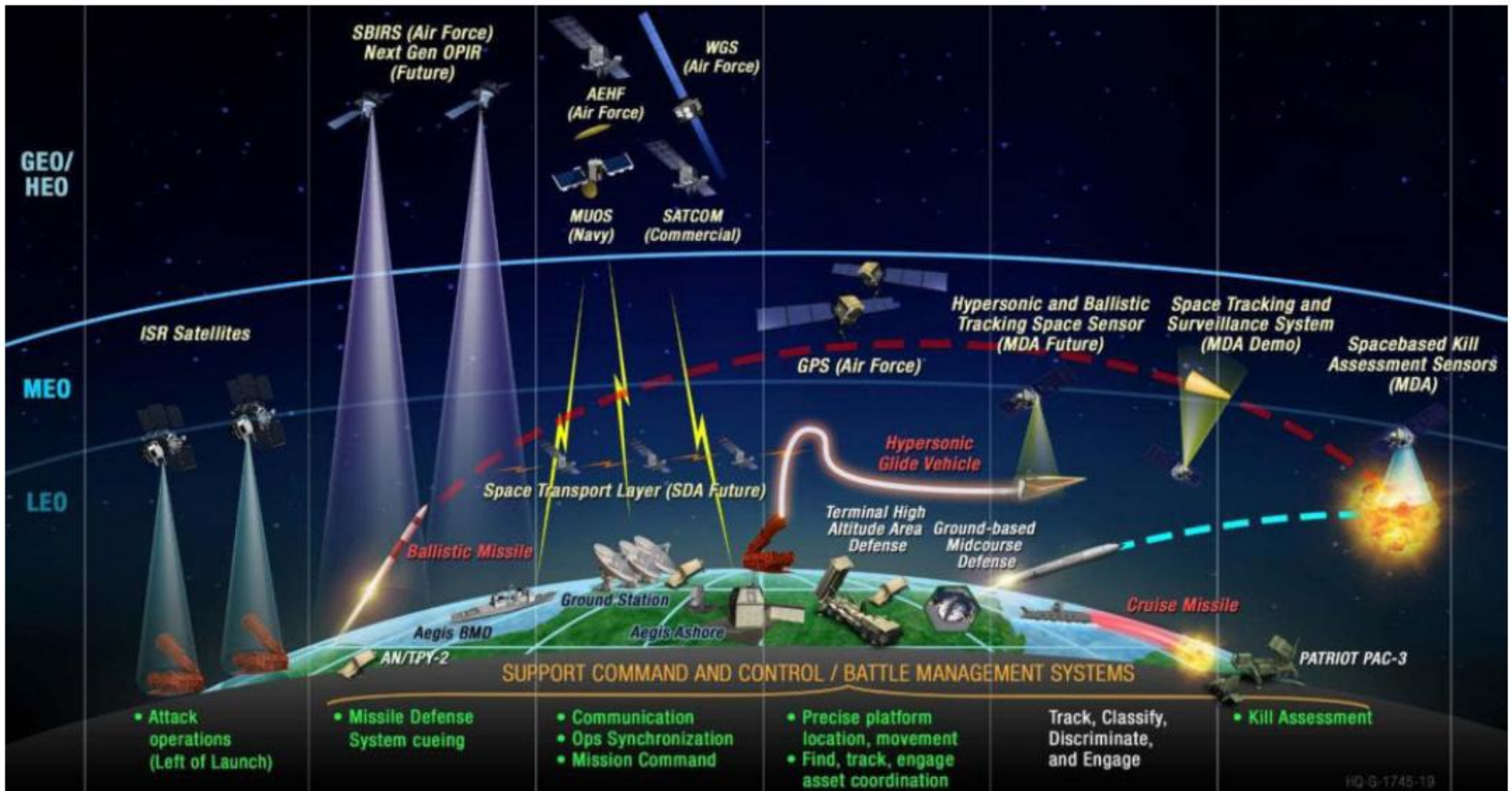


Defense Basics

A missile defense system essentially has four functional requirements that combine to provide defense against an incoming missile. These elements require balancing and, as such, this presents the missile defense systems with engineering challenges. These elements are intelligence, surveillance, and reconnaissance (ISR); detection and tracking; weapons control; and engagement. Ballistic missile defense is divided into three parts: boost, midcourse, and terminal intercept engagement phases. Cruise missile defense is typically divided into three components: area, self-, and point defense phases. Self-defense and point defense phases may utilize the same system components but have different mission requirements. These elements and missions combine to provide a layered defense capability to maximize defense performance.

- Boord, Warren J.; Hoffman, John B.. Air and Missile Defense Systems Engineering (p. 43). CRC Press. Kindle Edition.

Future Concepts for Defense



Missile Defense Layers



<https://thebulletin.org/2021/09/biden-should-guide-missile-defense-his-own-way/>

Measures of Effectiveness

According to Boord, Warren J.; Hoffman, John B.. Air and Missile Defense Systems Engineering (p. 61). CRC Press

- Reaction time—How
- Firepower—How Defense penetration technique resistance—When
Environmental resistance—When
- Continuous availability—When
- Contiguous coverage in theater—Where

Measures of Effectiveness

My list (using multiple sources)

- Probability of Intercept (P_i): The probability that the system successfully detects, tracks, engages, and intercepts the target.
- Time to Intercept (TTI): The time from detection or launch to the point of intercept.
- Coverage Area / Footprint: The geographic area the system can protect.
- Survivability / Redundancy: The system's ability to withstand or recover from attacks or failures.
- False Alarm Rate: The rate of false detections or unnecessary launches.
- Discrimination Capability: The ability to distinguish real warheads from decoys/chaff/flares.
- Mobility / Deployability: How quickly and flexibly a system can be moved and set up.
- Cost per Kill / Mission Cost: The average cost of intercepting a single threat, factoring interceptor use, operations, and logistics.
- System Availability / Uptime: The percentage of time the system is fully functional and ready.

Systems and their MOE

System

Key MOE Focuses

Patriot PAC-3

Short TTI, mobile, low Pk per interceptor

THAAD

High-altitude intercept, good Pi, high Pk

Aegis BMD

Naval mobility, large coverage, strong discrimination

Iron Dome

Low cost-per-kill, high availability, urban intercept focus

Patriot PAC-3

The Patriot PAC-3 (Patriot Advanced Capability-3) is a highly advanced, combat-proven surface-to-air missile (SAM) system designed for air defense and missile defense. It is part of the Patriot Missile System family developed by Lockheed Martin and deployed by the United States Army and several allied nations.

The PAC-3 variant represents the most advanced configuration of the Patriot system, focused primarily on:

- Ballistic missile defense (BMD)
- Cruise missile defense
- Aircraft interception

Advanced threat engagements (e.g., hypersonic glide vehicles under future upgrades)



Patriot PAC-3

Feature	Description
Hit-to-Kill Technology	Destroys incoming threats by direct collision (kinetic kill) rather than explosive warhead detonation.
High Agility and Maneuverability	Uses advanced solid-fueled rocket motors, aerodynamic controls, and attitude control thrusters for exceptional maneuverability.
Radar-Guided	Employs track-via-missile (TVM) guidance, using the AN/MPQ-65 radar for targeting.
Compact Missile Size	Smaller than earlier Patriot missiles, allowing 16 PAC-3 missiles per launcher (compared to 4 PAC-2 missiles).
Ballistic Missile Defense Focus	Optimized for engaging short- and medium-range ballistic missiles in their terminal phase.
Advanced Warhead	Uses a lethality enhancer for additional effects near the target if needed.

Patriot PAC-3 Specifications

Attribute	Value
Missile Length	~5.2 meters (17 feet)
Missile Diameter	~0.255 meters (10 inches)
Launch Weight	~312 kg (687 lbs)
Speed	Over Mach 4.5
Range	Up to ~35-60 km (ballistic targets); varies based on threat profile.
Altitude Intercept Capability	Up to ~20 km (varies with target type)
Propulsion	Single-stage solid rocket motor
Guidance	Inertial navigation with radar terminal guidance (TVM)

Patriot PAC-3 Components

Component	Function
AN/MPQ-65 Radar Set	Multifunction phased-array radar for detection, tracking, and engagement.
Engagement Control Station (ECS)	Command-and-control hub of the Patriot battery.
Launcher Station (M901)	Canisters with up to 16 PAC-3 missiles per launcher.
Missile Rounds (PAC-3 MSE/CRI)	The interceptors themselves, loaded into canisters.

Aegis BMD

- Platform: Deployed on Ticonderoga-class cruisers, Arleigh Burke-class destroyers, and Aegis Ashore installations.
- Purpose: To provide midcourse and terminal phase intercept of short-, medium-, and intermediate-range ballistic missiles, and increasingly, maneuvering hypersonic threats.
- Core Technologies:
 - Aegis Combat System (ACS)
 - SPY-1 / SPY-6 radar
 - Standard Missile family (SM-3, SM-6)
 - Command and Control Battle Management & Communications (C2BMC)



Aegis BMD

- Aegis Combat System
 - Integrated software and sensor suite that controls detection, tracking, fire control, and missile launch.
 - Evolved through Baseline upgrades:
 - Baseline 9: Open architecture, multi-mission (BMD + AAW)
 - Baseline 10: Adds SPY-6(V)1 radar, full integration with hypersonic defense.
- Radar System
 - SPY-1D(V): Original Aegis radar (phased array, S-band)
 - SPY-6 (AMDR): Gallium Nitride (GaN)-based next-gen radar with 30× sensitivity, scalable to ship size

Aegis BMD

Missile	Role	Notes
SM-3 Block IA/IB/IIA	Intercept ballistic missiles in space (exo-atmospheric)	Uses hit-to-kill kinetic warhead
SM-6	Terminal intercept of ballistic & hypersonic glide vehicles (HGVs)	Dual-capable: AAW + BMD

Aegis BMD

Real-World Tests & Deployments

- **FTM-44 (2020):** SM-3 Block IIA successfully intercepted ICBM-class target
- **FTT-21 (2023):** Demonstrated SM-6 capability against HGV-like target
- **Pacific and Mediterranean:** Constant deployment aboard Navy destroyers
- **Joint NATO ops:** Works with radars in Spain, Israel, Japan, and more

Aegis BMD

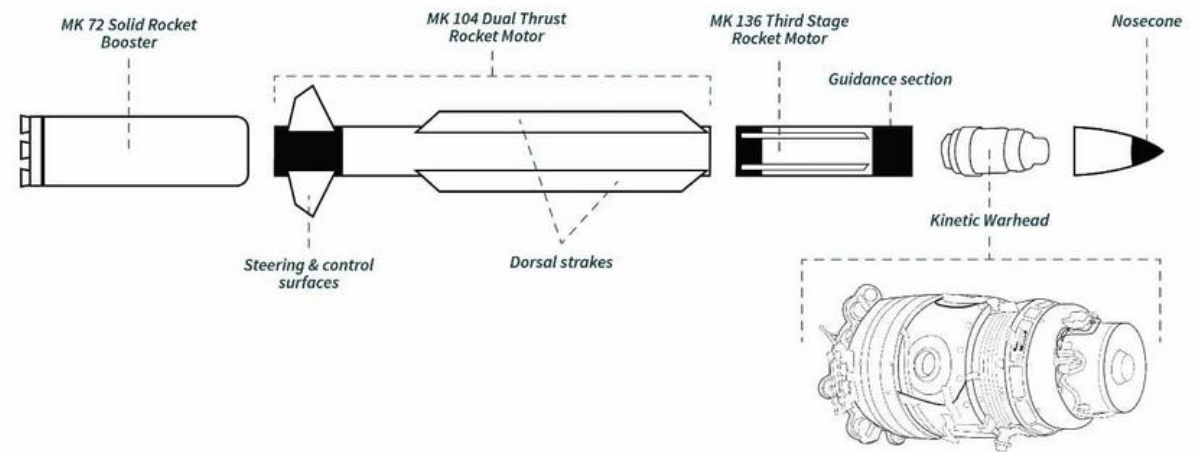
Feature	Aegis BMD
Platforms	Ships, Aegis Ashore
Missiles	SM-3 (exo), SM-6 (endo/hypersonic)
Radar	SPY-1D(V), SPY-6 GaN AESA
Networked Sensors	C2BMC, HBTSS, TPY-2, satellites
Use Cases	BMD, hypersonic defense, air/missile superiority

SM-3

- The Standard Missile-3 (SM-3) is an exo-atmospheric missile defense interceptor used for theater ballistic missile defense. Part of the the Aegis Weapon System, it uses a hit-to-kill kinetic kill vehicle to intercept ballistic missiles during the midcourse of their flight path. SM-3s are unique due to being the only Standard Missile designed to operate in the vacuum of space. The first Aegis BMD ships fielded SM-3 Block I interceptors in 2005, and the first Block IA interceptors deployed in 2006.¹ All of the current SM-3 variants fire from Mk 41 Vertical Launching System (VLS) cells on both Aegis-equipped ships and Aegis Ashore sites.

- <https://missilethreat.csis.org/defsys/sm-3/>

Standard Missile-3 Block IA/IB
RIM-161



SM-3 Profile

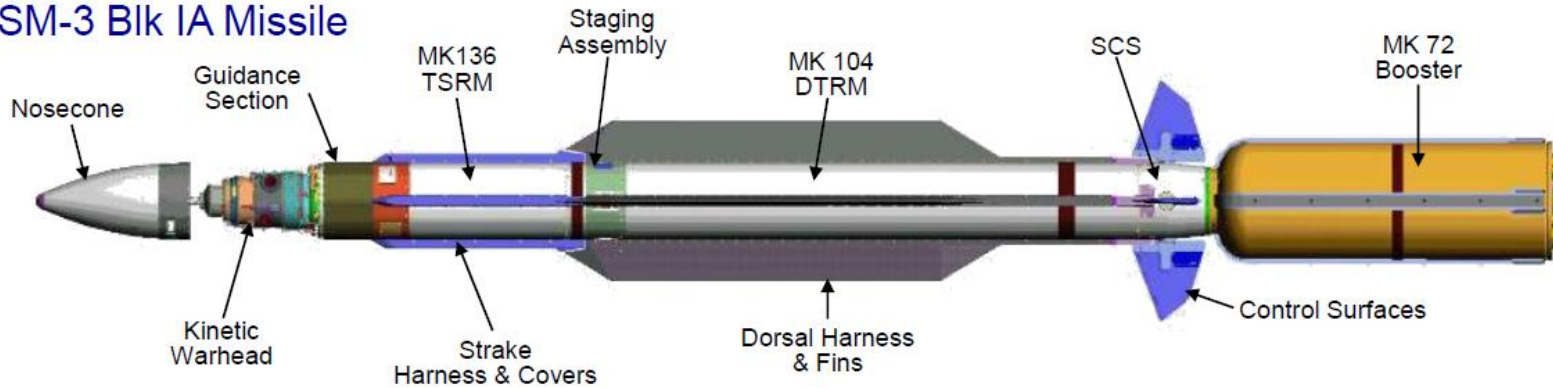
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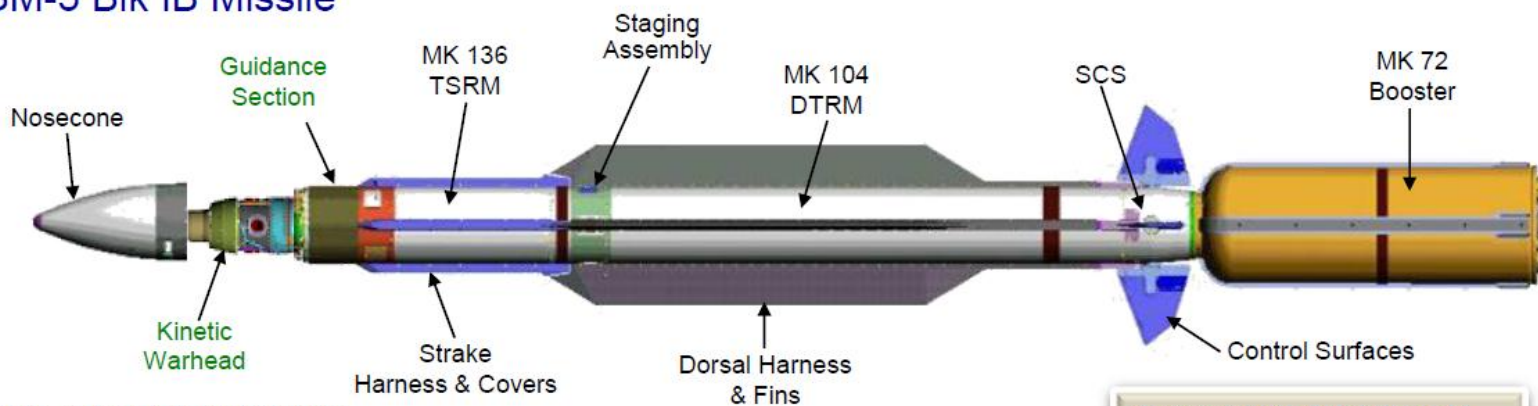
Aegis BMD SM-3 Missile Profile

Aegis BMD

SM-3 Blk IA Missile



SM-3 Blk IB Missile



Common with SM-3 Block IA
 Changed for SM-3 Block IB

TSRM – Third Stage Rocket Motor
 DTRM – Dual Thrust Rocket Motor
 SCS – Steering/Control Section

Approved for Public Release: 11-MDA-6487 (1 Dec 11)

Aegis BMD The Way Ahead_IWS Conf_6 Dec 2011 Slide 6

SM-6

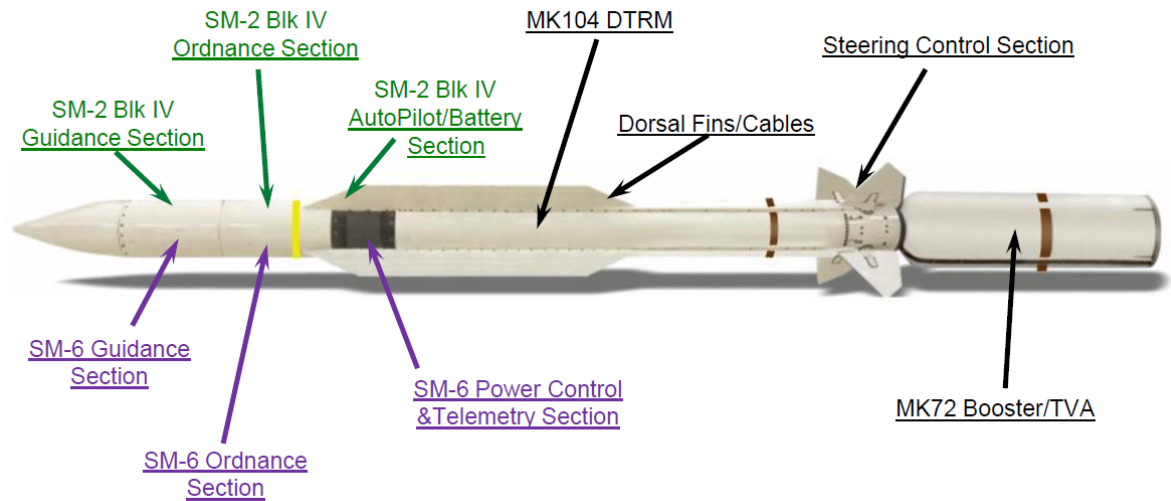
The Standard Missile 6 (SM-6) is a highly versatile and advanced shipborne surface-to-air and surface-to-surface missile developed by Raytheon for the United States Navy. Designed to provide extensive engagement capabilities against various threats, the SM-6 offers defense against ballistic missiles, air threats, and cruise missiles while also serving in an anti-surface role. The missile combines key technologies from previous Standard Missile variants and the Advanced Medium-Range Air-to-Air Missile (AMRAAM) program, incorporating a solid rocket booster and dual-thrust rocket motors from the SM-3 series, the airframe of the SM-2 series, and the active seeker and nosecone of the AMRAAM.

- <https://armyrecognition.com/military-products/navy/weapons-systems/missiles/sm-6-standard-missile-6>



Aegis BMD SM-6 Missile Profile

Aegis BMD



BLACK = Common
PURPLE = SM-6 Unique
GREEN = SM-2 Bk IV Unique

SM-6 Variants

SM-6 Block IA This SM-6 configuration is designed to address hardware and software improvements and advanced threats. In November 2014, the Block IA successfully intercepted a subsonic cruise missile over land, marking the second successful flight test of the SM-6 variant. This SM-6 variant was again successfully tested in June 2017 during a land-based test at White Sands Missile Range in New Mexico. The successful test advanced the missile to the sea-based testing phase, possibly paving the way for low-rate production by the end of the year.

SM-6 Dual I The Dual I is designed to counter ballistic missiles in the terminal phase of their trajectory as well as cruise missiles and other air breathing threats. Dual I upgrades include a more powerful processor that runs a more sophisticated targeting software that allows the SM-6 Dual I to identify, track, and intercept targets descending from the upper atmosphere at high velocity. During an intercept test in July 2015, the SM-6 Dual I demonstrated its dual-mission capability when it successfully intercepted a short-range ballistic missile target, in addition to two different kinds of cruise missile targets.

SM-6 Block IB

Unveiled in 2025

The SM-6 Block IB (RIM-174B) is the highly anticipated next iteration of the U.S. Navy's versatile Standard Missile-6 (SM-6) family. It builds upon the proven capabilities of earlier variants—Block I, IA, and IAU—by introducing significant enhancements in propulsion, speed, and mission flexibility.

<https://www.navalnews.com/event-news/sna-2025/2025/01/new-u-s-navy-hypersonic-missile-design-unveiled-at-sna-2025/>

<https://www.19fortyfive.com/2025/01/u-s-navys-sm-6-block-1b-a-game-changer-in-missile-defense/>

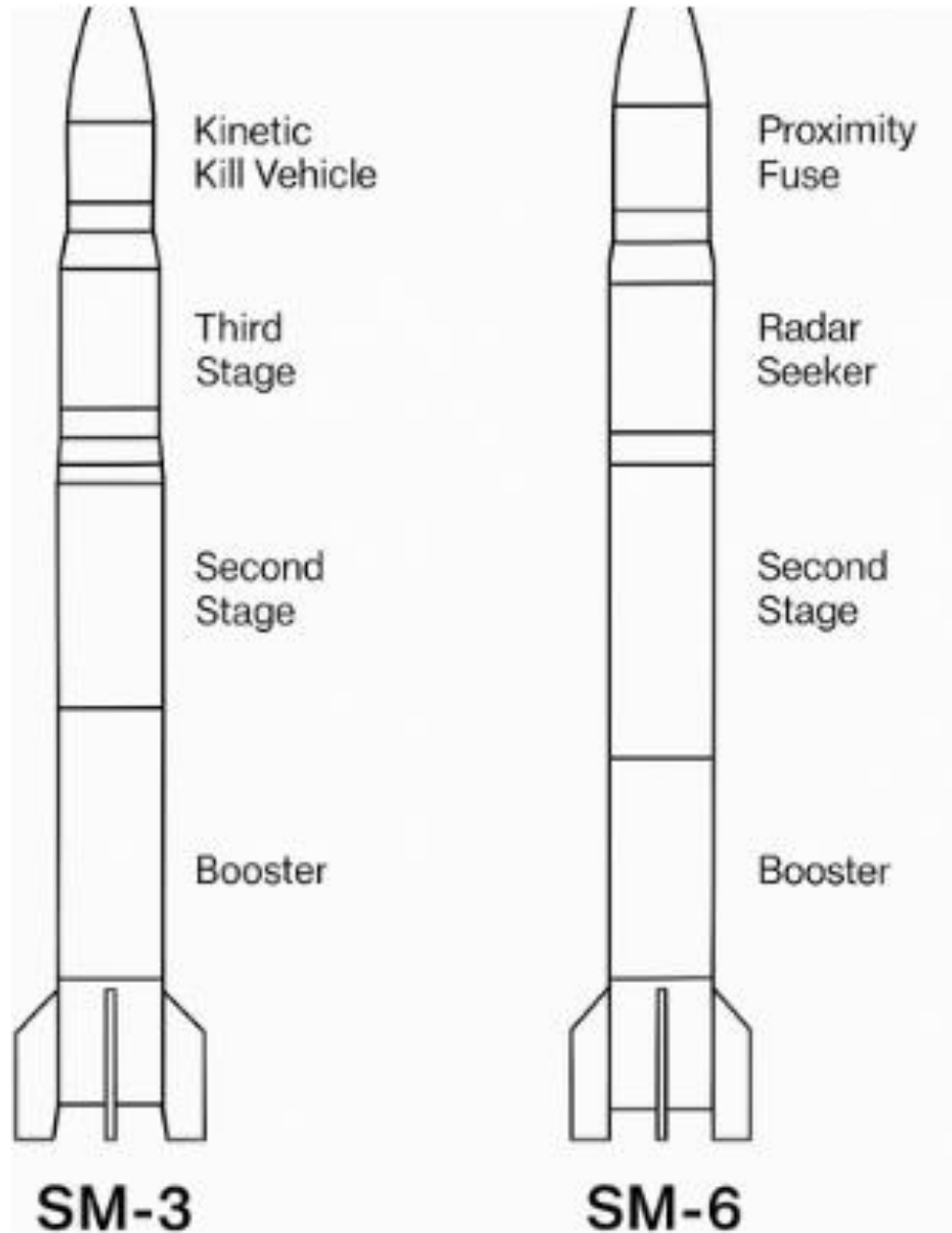
Aegis BMD: SM3 v SM6

Feature	SM-3	SM-6
Full Name	Standard Missile 3	Standard Missile 6
Primary Role	Exo-atmospheric intercept of ballistic missiles	Multi-role: endo-atmospheric missile defense, air defense, anti-surface
Interceptor Type	Hit-to-kill kinetic warhead	Blast-fragmentation proximity warhead
Targets	Midcourse ballistic missiles (MRBM, IRBM, ICBM)	Reentry vehicles, hypersonic glide vehicles (HGVs), cruise missiles, aircraft
Flight Environment	Exo-atmospheric (space)	Endo-atmospheric (within atmosphere)
Guidance	Midcourse INS + IR seeker (LEAP)	Active radar seeker + INS + datalink
Interceptor Phase	Midcourse (space)	Terminal phase (atmosphere)
Speed	~Mach 10+ (Block IIA)	~Mach 3.5+
Range	~2,500+ km (Block IIA)	~460 km (air targets), ~370 km (missiles)
Deployment Platforms	Aegis ships, Aegis Ashore	Aegis ships (also planned land variants)
Variants	Block IA, IB, IIA	SM-6 Block I, IA, II, Block IB (future)

Aegis BMD SM3 v SM6

Feature	SM-3	SM-6
Booster Stage	3-stage solid-fuel booster	2-stage booster (from SM-2)
Kill Vehicle	LEAP (Lightweight Exo-Atmospheric Projectile) kinetic kill vehicle	Proximity fuse + radar seeker warhead
Seeker Type	Midcourse infrared (non-emitting)	Active radar (fire-and-forget capable)
Launcher Type	Mk 41 VLS	Mk 41 VLS

**Aegis
BMD SM3
v SM6**



Ground-based Midcourse Defense (GMD)

The Ground-based Midcourse Defense (GMD) system is the only operational U.S. system specifically designed to defend the U.S. homeland from long-range ICBM attacks during their midcourse phase. It combines:

- Space-based sensors
- Ground-based interceptors
- Advanced command and control

Although highly capable against certain threats, it faces challenges with:

- Decoys/countermeasures.
- Advanced maneuverable threats like hypersonic glide vehicles (HGVs).

GMD remains central to U.S. homeland missile defense strategy, with significant future upgrades underway through the Next Generation Interceptor (NGI) program.



A-135 ABM

The A-135 Anti-Ballistic Missile (ABM) system is a Russian missile defense system designed to protect the Moscow region against incoming intercontinental ballistic missiles (ICBMs). It was developed during the Cold War and remains operational today, with continuous upgrades.

There are two variations:

- The Gorgon (Mach 7)
- The Gazelle (Mach 17)





Sky Bow III

- The Sky Bow III (Tien Kung III) is a Taiwanese surface-to-air missile (SAM) system, developed as part of Taiwan's indigenous defense efforts to counter aerial and ballistic missile threats—particularly from the People's Republic of China. It is the third generation in the Tien Kung ("Sky Bow") series, and represents a major technological leap in Taiwan's missile defense capabilities. Speed Mach 7.

THAAD

The THAAD missile—short for Terminal High Altitude Area Defense—is a highly advanced, mobile anti-ballistic missile (ABM) system developed by the United States Missile Defense Agency (MDA) and manufactured by Lockheed Martin. It is designed to intercept and destroy short-, medium-, and intermediate-range ballistic missiles during their terminal (descent or reentry) phase using a hit-to-kill approach—destroying the target by kinetic energy without explosives. The THAAD system is fully mobile and typically deployed via truck-based units. It consists of:

- Interceptors: The missiles themselves, stored and launched from canister launchers.
- Launcher Vehicle: Typically carries 8 missiles in a vertical launch configuration.
- AN/TPY-2 Radar:
 - High-resolution X-band radar for long-range missile tracking and discrimination.
 - Can operate in forward-based mode (detect launch) or terminal mode (track target).
- Fire Control and Communications (TFCC):
 - The command-and-control brain of the system.
 - Connects with the Missile Defense Command, Control, Battle Management and Communications (C2BMC) network.
- Support Systems: Power units, cooling systems, and satellite uplinks.

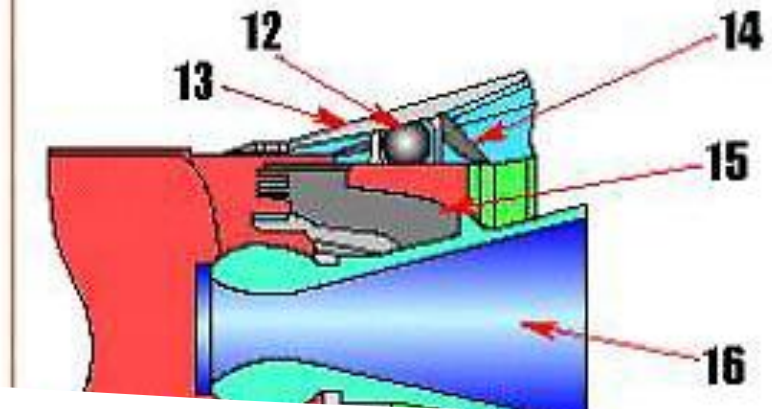
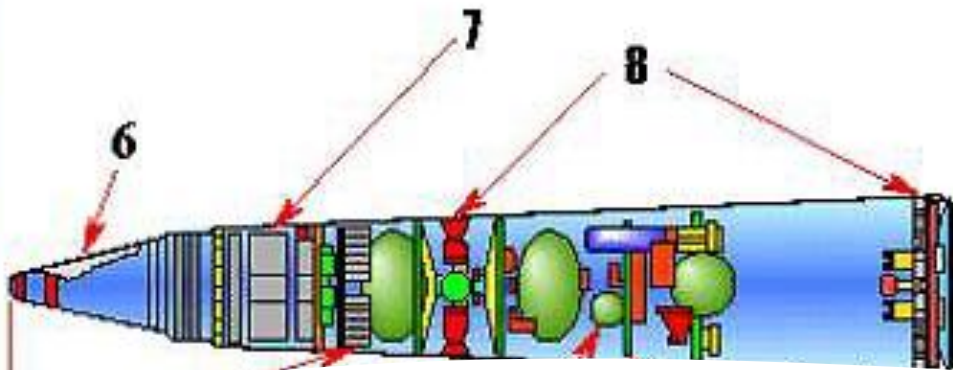
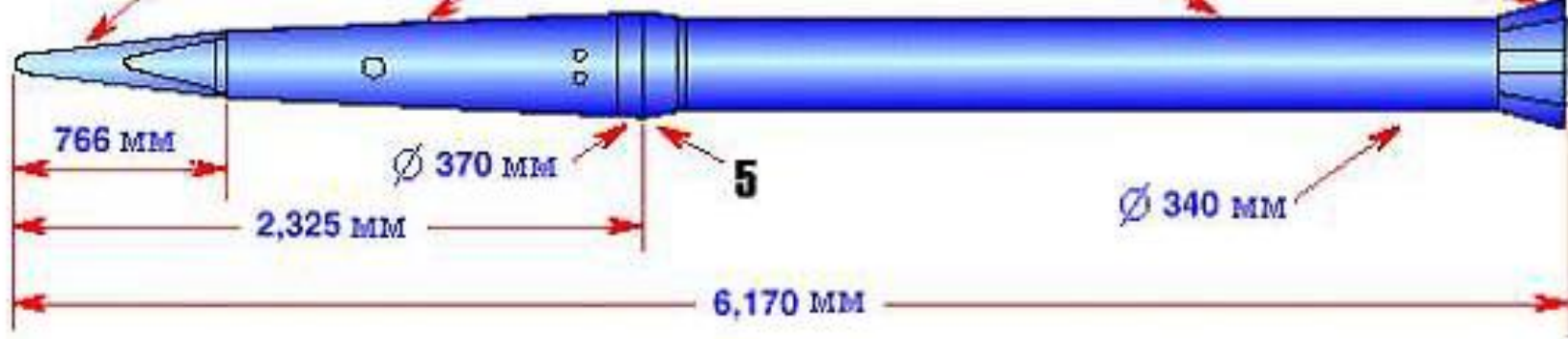
THAAD

Feature	Specification
Missile Length	~20.5 ft (6.25 m)
Missile Diameter	~14.5 in (0.37 m)
Weight	~1,300 lbs (590 kg)
Interceptor Speed	> Mach 8 (~6,100 mph or 9,800 km/h)
Range	Estimated 200 km (125 miles)
Altitude Ceiling	Up to 150 km (93 miles / exoatmospheric range)
Guidance	Inertial + GPS midcourse, terminal IR seeker
Warhead	None – hit-to-kill kinetic interceptor
Kill Mechanism	Direct collision with the target (no explosive)

THAAD

- THAAD intercepts ballistic threats during their descent phase, either endoatmospheric (within the atmosphere) or exoatmospheric (just outside).
- It engages targets after midcourse corrections and uses infrared homing for precise final guidance.
- The missile maneuvers using thrusters and aerodynamic control surfaces in the terminal phase.
- <https://www.lockheedmartin.com/en-us/products/thaad.html>





THAAD

1. Front bay with guidance system
2. Fighting unit
3. Corpus
4. The skirt.
5. Transition bay
6. Guidance system window
7. Integrating device
8. Trajectory deviation control system
9. Emergency Blast System
10. Batteries .
11. FTS
12. A gas tank.
13. Hollow wall
14. Display
15. Nozzle controls
16. Movable (controlled nozzle)
17. Fuel supply control

PAAMS/Sea Viper

- PAAMS (Principal Anti-Air Missile System), also known in the UK as Sea Viper, is a sophisticated naval air defense system designed to provide multi-layered protection against a wide range of aerial threats, including:
 - Enemy aircraft
 - Unmanned aerial vehicles (UAVs)
 - Anti-ship cruise missiles
 - Ballistic missile threats (future variants)
- It is a joint European program involving the United Kingdom, France, and Italy, developed primarily by MBDA with radar systems by Thales and BAE Systems.

PAAMS/Sea Viper - Features

Feature

Description

Multi-Function Missile System

Capable of area defense and point defense against air threats.

Automatic Target Tracking & Engagement

Fully automated from detection to intercept.

Vertical Launch Capability

Uses **Sylver Vertical Launching System (VLS)** for rapid, all-azimuth response.

Highly Agile Missiles

Aster missiles capable of engaging maneuvering supersonic targets.

Integrated Radar System

Employs advanced phased-array radars for 3D tracking and fire control.

Specification	Aster 15	Aster 30
Max Range	~30 km (short-to-medium range)	~120+ km (long-range defense)
Speed	Mach 3+	Mach 4.5+
Guidance	Inertial + Data Link + Active RF Homing	Same
Maneuverability	Extremely high, capable of engaging agile targets	Same
Warhead Type	High-explosive fragmentation	High-explosive fragmentation

PAAMS/Sea Viper Specifications

S-550 missile system

Feature	Description
Altitude Coverage	Likely >200 km, possibly up to 500–700 km
Target Types	ICBMs, SLBMs, HGVs, satellites (LEO/MEO)
Speed	Hypersonic interceptors (Mach 10+)
Warhead	Kinetic or fragmentation; non-nuclear , though some reports suggest an optional nuclear version
Guidance	Active radar + inertial + optical terminal guidance
Radar Integration	Works with new-generation AESA radars , possibly derived from S-500/Don-2N lineage

- The S-550 missile system is a next-generation Russian strategic missile defense system, reportedly under development or in early deployment. It is part of Russia's advanced air and space defense ecosystem, intended to operate above the capabilities of the S-500 Prometey, focusing on space-based and strategic threats such as ICBMs, hypersonic glide vehicles, and satellites.



S-550 missile system

- Russia officially disclosed the S-550 in late 2021, with President Putin directing its development alongside the S-350 and S-500 systems
- State media and unnamed defense ministry sources reported the system passed state trials and entered operational service in December 2021, describing it as a “new, unrivaled mobile strategic missile defense system”
- According to Rostec’s CEO, the S-550 has extended target detection and interception range, reportedly exceeding that of the S-500, capable of engaging ballistic missiles, hypersonic weapons, and satellites in low Earth orbit (LEO)/

S-500 "Prometey"

- The S-500 "Prometey" (also known as 55R6M "Triumfator-M") is Russia's most advanced next-generation surface-to-air missile (SAM) system, designed for multi-layered air and missile defense. It is intended to:
 - Defend against advanced aerial threats, including stealth aircraft and UAVs.
 - Intercept ballistic missiles, including intercontinental ballistic missiles (ICBMs).
 - Engage hypersonic glide vehicles (HGVs) and hypersonic cruise missiles under certain conditions.
 - Provide protection against space-based threats, including some low-orbit satellites.
- The S-500 represents the successor and complement to the S-400 Triumph system, emphasizing anti-ballistic missile (ABM) and anti-hypersonic defense.

S-500 “Prometey” - Specifications

Specification	Value/Capability
Engagement Range (Air Targets)	Up to 600 km (373 miles) for some targets (e.g., AWACS, aircraft).
Engagement Range (Ballistic Targets)	Approx. 500-600 km for ballistic missiles.
Intercept Altitude	Up to 200 km (124 miles) — reaching near-space altitudes.
Missile Speed	Hypersonic (potentially exceeding Mach 15+ for some interceptors).
Radar Range	Detects targets up to 2,000 km depending on target type and size.
Number of Simultaneous Targets	Capable of engaging multiple aerial and missile threats simultaneously.

S-500 “Prometey” Components

Component	Description
Command and Control (C2) Vehicle	Manages battle operations and coordinates intercepts.
Radar Systems	Advanced phased-array radars for long-range detection and missile guidance (may include 91N6A(M) or newer variants).
Launch Vehicles (TEs)	Mobile Transporter-Erector-Launcher trucks carrying interceptors (highly mobile system).
Missile Reload Vehicles	Resupply missile stocks for rapid re-engagement.

A-235 “Nudol” System

The A-235 "Nudol" is a Russian ground-based anti-ballistic missile (ABM) and anti-satellite (ASAT) defense system under development as a replacement or supplement to the legacy A-135 missile defense system protecting Moscow and critical national assets.

The system is designed to:


- Intercept intercontinental ballistic missiles (ICBMs) and other strategic ballistic threats.
- Engage and destroy low Earth orbit (LEO) satellites in space (ASAT role).
- Provide missile defense for Russia's central regions, particularly around Moscow.

The A-235 is part of Russia's multi-layered strategic defense shield and forms a component of its nuclear deterrent infrastructure.



Nudol

- The destruction of *Kosmos 1408* (Soviet ELINT Satellite) in November 2021 is widely attributed to the PL-19 Nudol, demonstrating:
 - Kinetic kill capability
 - Ability to strike satellites in low Earth orbit
 - Significant concerns over space debris and international condemnation
 - This test confirmed Nudol's dual-role nature: not just ABM, but space denial.



A-235 “Nudol” System- Capabilities

Capability	Details
Intercept Range (ABM Role)	Estimated hundreds to thousands of kilometers (midcourse and potentially terminal intercepts).
Intercept Altitude (ASAT Role)	Up to ~1,500 km or more (capable of LEO satellite destruction).
Target Speed	Designed to engage ICBMs, SLBMs , and satellites moving at orbital velocities (~7+ km/s).
Deployment Mobility	Mobile launchers enable rapid relocation and deployment.

HQ-26 (Maritime Interceptor)

The HQ-26 is a reported next-generation maritime-based long-range interceptor missile currently under development by China. It is intended for use aboard advanced Chinese naval platforms such as Type 055 guided-missile destroyers. The HQ-26 is believed to be an evolution of China's existing HQ-9B and HQ-19 missile systems but with a primary focus on:

- Ballistic missile defense (BMD)
- Hypersonic weapon interception
- Extended air defense at sea

Though many details about HQ-26 remain classified or speculative, it is viewed as China's counterpart to the U.S. Standard Missile-3 (SM-3) used in the Aegis Ballistic Missile Defense System.

HQ-19

- HQ-19- Chinese anti-ballistic and anti satellite system. It is reported to have a speed of 10,000 m/s (MACH 29). Although it reportedly entered limited service by 2018, the HQ-19 was first displayed publicly at the 2024 Zhuhai Airshow, confirming its operational maturity and readiness for full deployment. In June of 2025 it was announced that Pakistan would be acquiring this missile.





HQ-26 (Maritime Interceptor) - Specifications

Attribute	Value/Range
Missile Type	Multi-stage kinetic interceptor
Intercept Speed	Likely >Mach 10 (hypervelocity)
Range	Estimated 1000+ km for exoatmospheric targets
Intercept Altitude	Potentially 150+ km (exoatmospheric capability)
Propulsion	Solid-fueled multi-stage motor
Launch Platform	Type 055 Destroyers (and possibly future Chinese warships)
Guidance	Likely inertial navigation + midcourse data-link updates + homing sensor (possibly IR seeker)

HQ 29

- This has not yet been formally announced by China, but since June 2025, rumors have been circulating. The twin-canister setup suggests a missile with substantial kinetic energy, speed, and range, comparable to the American Ground-Based Interceptor (GBI) and Russia's Nudol anti-satellite system.

Methods of destroying in bound missiles

- **Hit-To-Kill:** The interceptor uses high-speed navigation, onboard seekers (IR or radar), and precise guidance to ram the threat, often at Mach 8–15.
- **Proximity-Fused Explosive Warhead:** Interceptor detonates near the target, shredding it with shrapnel. Less precise, but still effective against aircraft, cruise missiles, and ballistic targets in terminal phase.
- **Directed Energy:** Uses lasers or high-power microwaves to damage or disable the target mid-flight (more details in lesson 6).
- **Electronic Warfare / Cyber Jamming:** Disrupts guidance or detonation systems of incoming missiles.

Methods of destroying in bound missiles

Method	Precision	Speed Needed	Atmosphere	Warhead Type
Hit-to-Kill	Very high	Very high	Exo & Endo	Kinetic only
Proximity Explosive	Moderate	Moderate	Endo	Fragmentation
Directed Energy (Future)	High	N/A	Endo	Laser/MW
EW/Cyber	Variable	N/A	N/A	Non-kinetic

Sensor Fusion / Battle Command Systems

- Systems like Aegis BMD, IBCS, and Patriot/THAAD networks aggregate data from diverse sensors (satellite, ground, sea) to maintain continuous tracking

Interception & Shoot-Down Systems

Aegis Sea-Based Terminal (SBT) and SM-6 Block IAU are optimized for intercepts during the final descent

Interception & Shoot- Down Systems

**THAAD and
Patriot batteries**
offer
complementary
coverage during
final approach

Electronic & Countermeasure Tactics

Hypersonic vehicles may deploy **decoys, chaff,** or **electronic jamming** to confuse radar and seeker systems

Ongoing development of **false-target generators** to dilute incoming missile detection in dense threat environments.



Russia's -300 and S-400

The S-300 (NATO: SA-10/20/23 series), developed from the 1970s by Almaz-Antey, is a highly mobile, multi-target surface-to-air missile (SAM) system capable of intercepting aircraft, cruise missiles, and some short-to-medium-range ballistic missiles.

- Range: 75–150 km (air targets), up to 40 km altitude; ballistic target coverage ~35–40 km .
- Warhead: Fragmentation; 133–143 kg warheads.
- Radar Capacity: Can track ~100 targets, engage 12 simultaneously.
- Mobility: Mounted on wheeled (S-300P) or tracked (S-300V) vehicles, allowing repositioning in 5–7 minute

Russia's S-300 and S-400

Successor to S-300, the S-400 entered service in 2007, incorporating advanced radar, extended-range missiles, and multi-layer defense .

Performance:

- Detection range: ≈ 600 km; tracks ~ 300 targets & engages ~ 36 simultaneously
- Speed: Interceptors reach \sim Mach 14 ($\sim 17,000$ km/h)
- Altitude envelope: Engages threats from ~ 10 m to ~ 30 km altitude



Russian S-400 Triumph system -U.S. Patriot - THAAD (Terminal High Altitude Area Defense)

Feature	S-400 Triumph	Patriot PAC-3	THAAD
Country	Russia	United States	United States
Primary Role	Long-range multi-layer air & missile defense	Short- to medium-range air & missile defense	Terminal-phase ballistic missile defense
Deployment	Mobile, land-based	Mobile, land-based	Mobile, land-based
Entered Service	2007	~1980s (PAC-3 in 2000s)	~2008

Russian S-400 Triumph system -U.S. Patriot - THAAD (Terminal High Altitude Area Defense

Capability	S-400	Patriot PAC-3	THAAD
Max Range (air)	Up to 400 km (40N6)	~70–160 km (PAC-3 MSE)	~200 km (ballistic targets)
Max Range (missile)	Up to 60 km (ballistic), 400 km (aero)	~30–40 km (ballistic)	~200 km (ballistic)
Altitude Coverage	10 m – 30 km+	60 m – 24 km	40–150 km (exo-/endo-atmospheric)
Warhead	Blast-frag (proximity-fused)	Hit-to-kill kinetic (PAC-3)	Hit-to-kill kinetic
Target Types	Aircraft, cruise, SRBM, MRBM, HGV	SRBM, aircraft, cruise, UAVs	MRBM, IRBM, possibly ICBM (final phase)

Russian S-400 Triumph system -U.S. Patriot - THAAD (Terminal High Altitude Area Defense – vs hypersonics

Threat Type	S-400	Patriot PAC-3	THAAD
Cruise Missiles	Yes	Yes	No
Ballistic Missiles	Yes (SRBM/MRBM, not ICBM)	Yes (limited)	Yes (SRBM/IRBM)
Hypersonic Glide Vehicles	Claimed, but not proven	No	Developing integration with SM-3 / GPI

Countermeasure Summary

Phase	Countermeasure Techniques
Boost	Space or ground-based lasers, sensor alerting
Mid-course	Satellite + radar tracking, sensor fusion
Terminal	SBT, SM-6, THAAD, Patriot interceptors
Supportive	Electronic jamming, decoys, chaff dispersal

Stream vs Azimuth raid

A stream raid is defined as a raid where a group of similar offensive missiles fly the same trajectory, but the trajectories are separated in time [2,3]. Modern radars should have sufficient range resolution to detect and track each offensive missile in the raid. However, sometimes, modern radar may ignore trailing targets that occur in the same beam or at the same indicated angle.

Boord, Warren J.; Hoffman, John B.. Air and Missile Defense Systems Engineering (p. 48). CRC Press. Kindle Edition.

An azimuth raid is a raid where the offensive missiles fly toward a common target from different azimuth angles. The raid timing is such that all of the offensive missiles will arrive simultaneously. This scenario is judged to be a worst-case scenario from an engagement timeline perspective.

Boord, Warren J.; Hoffman, John B.. Air and Missile Defense Systems Engineering (p. 49). CRC Press. Kindle Edition.



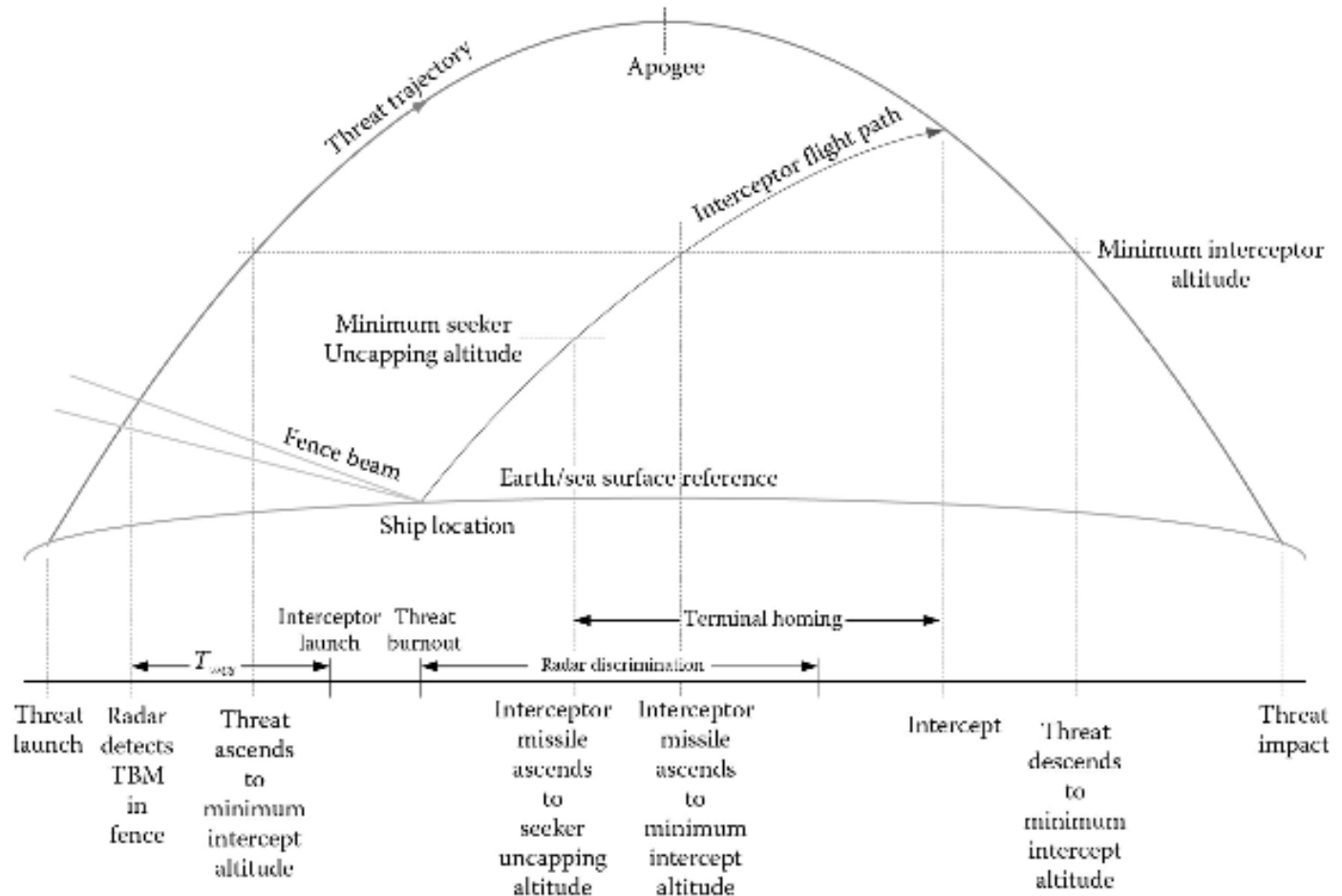
Probability of Kill

After collapsing the battlespace, the offensive missile designer needs to drive down the probability-of-kill (Pk) or probability-of-raid annihilation (PRA) for the defensive systems that have obtained an engagement opportunity

-Boord, Warren J.; Hoffman, John B.. Air and Missile Defense Systems Engineering. CRC Press.

Ship Based Missile Defense

Figure 4.2



-Boord, Warren J.; Hoffman, John B.. Air and Missile Defense Systems Engineering. CRC Press.

Defense penetration techniques (DPTs)

Defense penetration techniques (DPTs) are defined as the design measures employed by the potentially hostile adversary in their offensive air and missile systems that are intended to defeat the defensive systems defending those assets desired to be destroyed. As discussed earlier, cruise or ballistic missile defense is attempted by one of three means. Either a hard or soft kill solution is employed or in combination. The adversarial offensive missile design team can break up the problem into four generic flight phases to design counters necessary to defeat the entire system. This set will be referred to here as the time-phased defense penetration design options. These options are designated as follows:

- Countersurveillance and search phase
- Counterdetection and track phase
- Counterengagement and missile phase
- Counterpoint defense phase
- It is based on the adversary design approach that resistance to these measures and techniques is found.

Performance requirements cannot be established until each of these time-phased defense penetration options (DPOs) are evaluated and a set of them is selected to be addressed in the AMD system design.

Glide Phase Interceptor (GPI)

The Glide Phase Interceptor (GPI) is a cutting-edge missile defense system under development by the U.S. Missile Defense Agency (MDA) in collaboration with Japan's Ministry of Defense. Its primary objective is to intercept and neutralize hypersonic glide vehicles (HGVs) during the glide phase of their flight—a challenging segment where these weapons maneuver at high speeds within the upper atmosphere.

Launch Platforms: GPI is designed for deployment from the U.S. Navy's Aegis-equipped destroyers and Aegis Ashore installations, utilizing the standard Mk 41 Vertical Launch System.

Interceptor Design: The system features a multi-stage solid-fuel booster to rapidly reach the target area, followed by a re-ignitable upper stage for energy management. The kill vehicle employs advanced multimode seekers (including infrared and potentially radar) and high-thrust divert thrusters to achieve hit-to-kill accuracy against maneuvering hypersonic threats.

Integration with Defense Systems: GPI will integrate seamlessly with the Aegis Weapon System and the Command and Control, Battle Management, and Communications (C2BMC) network, enhancing the layered missile defense architecture.

Glide Phase Interceptor (GPI)

Development Timeline

- **Initial Contracts:** In November 2021, MDA awarded concept design contracts to Lockheed Martin, Northrop Grumman, and Raytheon. By June 2022, Northrop Grumman and Raytheon advanced to the next development phase.
- **Prime Contractor Selection:** In September 2024, Northrop Grumman was selected as the sole prime contractor for GPI's engineering and manufacturing development.
- **Projected Deployment:** While initial plans aimed for deployment by 2032, funding constraints have pushed the expected fielding to around 2035.

Glide Phase Interceptor

GLIDE PHASE INTERCEPTOR
Purpose-built counter hypersonic defeat capability

Reliable, layered defense against adversarial hypersonic threats.

- Advanced seekers for low and high-altitude threat tracking
- Developed in a digital environment that enables adaptability and affordability
- Energy flexible design for maximum containment of current and future threats
- Modular design facilitates multi-mission capability

The infographic features a central image of a missile in flight, angled upwards from the bottom left towards the top right. The background is a blue sky with light clouds. A white L-shaped graphic is in the top right corner. Four callout boxes with icons describe the missile's capabilities: a radar icon for advanced seekers, a circuit icon with a dollar sign for digital development, a shield with a lightning bolt for energy flexibility, and a gear icon for modular design.

https://cdn.northropgrumman.com/-/media/Project/Northrop-Grumman/ngc/Glide-Phase-Interceptor-Infographic-003.pdf?rev=208cb6e24b0d44cfa7137d1f67f7ea87&_gl=1*1kky1pr*_ga*MTlyNjQzMzczOC4xNzUxMjk2ODk1*_ga_7YV3CDX0R2*czE3NTEyOTY4OTQkbzEkZzAkDDE3NTEyOTY4OTgkajU2JGwwJGgw

DARPA Glide Breaker

DARPA showed off concept art of the interceptor portion of Glide Breaker for the first time at its D60 Symposium, which honors the organization's 60th anniversary, in September 2018. The agency's Tactical Technology Office had previously hosted a gathering to explain the project and its requirements to interested parties in July 2018.

"The objective of the Glide Breaker program is to further the capability of the United States to defend against supersonic and the entire class of hypersonic threats," DARPA said in an announcement for the July 2018 Proposers Day. "Of particular interest are component technologies that radically reduce risk for development and integration of an operational, hard-kill system."

So far, there are few other publicly available details about the program. In its budget request for the 2019 Fiscal Year, DARPA did not ask for any money for Glide Breaker specifically or for research and development of hypersonic defense systems broadly.

<https://dsiac.dtic.mil/articles/darpa-starts-work-on-glide-breaker-hypersonic-weapons-defense-project/>

DARPA Glide Breaker

-
- The Glide Breaker program, initiated by the Defense Advanced Research Projects Agency (DARPA) in 2018, aims to develop technologies to intercept hypersonic weapons during their glide phase—a challenging segment of flight characterized by high speeds and maneuverability. This initiative is part of the U.S. efforts to enhance defense capabilities against emerging hypersonic threats.
 - Objective: Develop a kinetic "hit-to-kill" interceptor capable of neutralizing hypersonic glide vehicles (HGVs) during their glide phase, which occurs in the upper atmosphere at speeds exceeding Mach 5.
 - Approach: Unlike traditional missile defense systems, Glide Breaker focuses on intercepting threats during the glide phase, prior to their terminal descent, requiring advanced propulsion and control systems to match the speed and maneuverability of HGVs.

AGM-183A Air-Launched Rapid Response Weapon

The AGM-183A Air-Launched Rapid Response Weapon (ARRW) is a hypersonic missile developed by Lockheed Martin for the U.S. Air Force. Designed to provide rapid, long-range strike capabilities, ARRW employs a boost-glide mechanism, where a rocket booster propels the missile to hypersonic speeds before releasing an unpowered glide vehicle that maneuvers toward its target.

- Speed: Capable of exceeding Mach 5, with some reports suggesting speeds up to Mach 20.
- Range: Approximately 1,600 km (1,000 miles).
- Launch Platforms: Compatible with B-52H Stratofortress bombers; potential for integration with B-1B Lancer, B-21 Raider, and F-15E Strike Eagle.
- Design: Utilizes a solid-fueled rocket booster to achieve hypersonic speeds, after which the glide vehicle separates to navigate to the target.

Railgun vs Coilgun

The railgun and the coilgun (or Gauss gun) are both types of electromagnetic projectile launchers, but they differ significantly in design, working principles, and technological challenges.

Feature	Railgun	Coilgun (Gauss Gun)
Type of Electromagnetism	Lorentz force (linear current + magnetic field)	Electromagnetic induction (magnetic fields via solenoids)
Acceleration Method	Electric current flows through parallel rails and projectile, generating magnetic force to propel it	Magnetic fields from sequentially pulsed coils (solenoids) attract and accelerate a ferromagnetic or conductive projectile
Contact vs. Non-contact	Requires physical contact with rails (creating electrical circuit)	No physical contact required with coils; relies on induced magnetic fields
Direction of Force	Perpendicular to current and magnetic field	Along the axis of magnetic field generated by coils

Railgun vs Coilgun

Feature	Railgun	Coilgun
Projectile Type	Electrically conductive armature (metallic)	Typically ferromagnetic or conductive slug
Wear and Tear	High erosion due to friction and arcing on rails	Minimal wear—no physical contact between projectile and coils
Control	Simpler trigger mechanism (just electrical pulse)	Requires precise timing control of coil sequences
Power Efficiency	Higher instantaneous power but lower efficiency due to losses	Generally more efficient at low power, but less effective at extreme velocities
Achievable Speed	Up to Mach 6–7 (very high, e.g., 2–3 km/s)	Typically subsonic to low hypersonic , depending on system size and complexity
Heat & Maintenance	High heat generation and rail damage	Less heat; easier to maintain but limited by coil heating and switching speed

Railguns

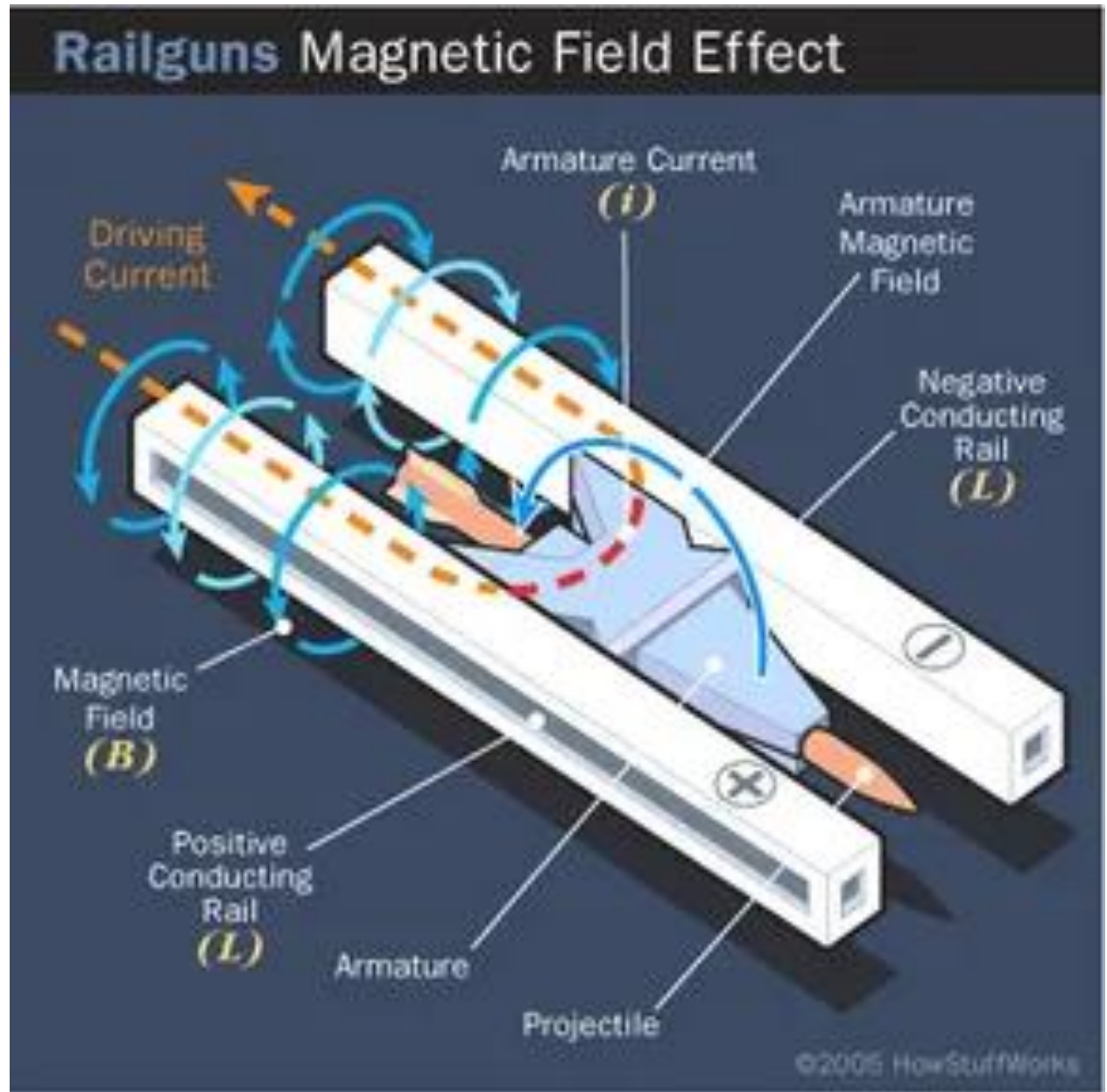
A railgun is a type of electrical weapon that uses electromagnetic force to propel a projectile at high speeds. It is an interesting area of engineering because it combines elements of electrical, mechanical, and materials engineering. Unlike traditional firearms that use chemical combustion to generate force, a railgun relies on the principles of magnetism to generate an extremely high-velocity launch. This makes railguns an attractive option as they can launch projectiles over long distances with incredible accuracy and speed.



Railguns

- A rail gun is an advanced electromagnetic weapon that uses electrical energy instead of chemical propellants to launch projectiles at extremely high velocities. It operates on the principle of Lorentz force, which accelerates a conductive projectile along a pair of metal rails using a powerful electric current.
- Structure: Two parallel metal rails act as conductors. A conductive projectile (often called an "armature") sits between them.
- Electromagnetic Acceleration: A high current (often millions of amperes) flows from one rail, through the armature, to the other rail. This creates a magnetic field and an associated Lorentz force that accelerates the armature down the rails at extreme speeds (up to Mach 7+).
- Projectile: Typically non-explosive, relying on kinetic energy to destroy targets. Can penetrate armor or destroy ships, aircraft, or missiles through raw impact energy.

Railguns



ONR/Bae Systems 32 MJ railgun

- Name: Electro-Magnetic Laboratory Rail Gun (EMRG)
- Developer: BAE Systems, under contract with the U.S. Office of Naval Research (ONR)
- Purpose: Long-range, high-velocity naval weapon system for future surface combatants
- Muzzle Energy: Up to 32 megajoules (MJ)—equivalent to the energy needed to launch a car at 100 mph
- 2021: Project cancelled after Navy reallocation of resources



ONR/Bae Systems 32 MJ railgun

Specification	Detail
Muzzle Energy	Up to 32 MJ (typical shot ~25–32 MJ)
Projectile Type	Hypervelocity Projectile (HVP)
Projectile Mass	~10 kg (~23 lbs), non-explosive
Muzzle Velocity	~2,520 m/s (~Mach 7.3)
Range	~100–220 nautical miles (180–400 km)
Rate of Fire	Initial goal: 10 rounds/min
Barrel Length	~10 meters (33 feet)
Guidance	GPS-aided INS; some tests involved steerable fins or magnetic control (in later HVP iterations)

MARAUDER

- The Magnetically Accelerated Ring to Achieve Ultra-high Directed-Energy and Radiation (MARAUDER) was a classified U.S. Air Force Research Laboratory (AFRL) project in the early 1990s aimed at developing a novel directed-energy weapon. The concept involved accelerating toroidal plasma structures—doughnut-shaped rings of ionized gas—to extremely high velocities using electromagnetic forces, effectively creating a plasma-based railgun.

Railguns

- Although the U.S. invested around \$500 million in its Electromagnetic Railgun (EMRG) program, it ceased funding in 2022 due to power and durability issues. China, however, continues its efforts; its recent test, while unsuccessful, used AI to enhance performance, showing Beijing's dedication to railgun development.
- Railguns have had durability issues. After firing multiple shots from the railgun, the barrel can degrade. However, this has been improving steadily.
- Guidance is an issue for hitting targets at a distance.
- **USNS *Trenton* (JHSV-5/T-EPF-5)**, was the first ship to mount a railgun.
<https://news.usni.org/2015/04/14/navsea-details-at-sea-2016-railgun-test-on-jhsv-trenton>

Railguns

- The Japan Self-Defense Forces have offered an official look at the turret-mounted electromagnetic railgun now installed on the test ship JS Asuka. The Japanese Ministry of Defense's Acquisition Technology & Logistics Agency (ATLA) has been working on railguns since the mid-2010s, which could be a future armament for Japanese warships and could also be employed in a ground-based mode.
- In 2023, ATLA said that it had successfully conducted test firings of a prototype railgun at sea from an unspecified platform, which the organization claimed at the time was a first-of-its-kind achievement for any country. Imagery ATLA released from that testing showed the weapon installed on a test mount rather than the full naval turret now installed on JS *Asuka*.
- <https://www.twz.com/sea/railgun-installed-on-japanese-warship-testbed>

Railguns

- China is also apparently leading in practical military applications of artificial intelligence (AI). This is important because AI could conceivably, in China's case, help Chinese scientists develop next-generation weapons at a faster clip than can the Americans. Indeed, this has been the case with the development of China's railgun technology. A railgun is simply a weapon that uses electromagnetic force to rapidly launch projectiles at targets at fast speeds.
- <https://nationalinterest.org/blog/buzz/us-military-freaked-china-has-railgun-213319>

Railgun

- China has introduced its latest innovation in defense technology: the Metal Storm mobile electromagnetic gun system. This state-of-the-art weapon, mounted on a 6x6 military truck chassis, is designed to serve as a terminal defense solution against modern threats such as First-Person View (FPV) drones, cruise missiles, and Anti-Tank Guided Missiles (ATGMs). Electromagnetic guns, often categorized into railguns and coilguns, represent a leap forward in projectile technology. These systems utilize electromagnetic forces to accelerate projectiles to extraordinary velocities, bypassing traditional chemical propellants. Railguns, for example, leverage magnetic fields generated by immense electrical currents to propel a projectile along conductive rails. This mechanism allows for muzzle velocities far exceeding those of conventional firearms, making electromagnetic guns ideal for intercepting fast-moving or hardened targets.

Plasma Railgun

Like a typical railgun there are two parallel electrodes to accelerate an armature. However, in a plasma railgun the armature and ejected projectile consists of plasma (hot ionized particles) rather than a solid 'bullet'. They produce very high muzzle velocities but currently only operate in a vacuum making them unsuitable for weapons. They are used in physics research particularly high energy physics. They have also been considered as the basis for plasma propulsion for spacecraft.

Teleforce

Tesla had a theoretical gun similar to the railgun. Tesla envisioned Teleforce as a defensive weapon that could project a beam of charged particles to disable or destroy enemy aircraft and ground troops. Tesla himself described it as follows: “My apparatus projects particles which may be relatively large or of microscopic dimensions, enabling us to convey to a small area at a great distance trillions of times more energy than is possible with rays of any kind. Many thousands of horsepower can thus be transmitted by a stream thinner than a hair, so that nothing can resist. The nozzle would send concentrated beams of particles through the free air, of such tremendous energy that they will bring down a fleet of 10,000 enemy airplanes at a distance of 200 miles from a defending nation's border and will cause armies to drop dead in their tracks.”

Tip-and-Cue Coordination

- Tip and Cue is a novel Earth observation strategy foreseeing the collaboration of multiple space assets to enhance observation. In its canonical form, it entails two satellites: a tip satellite -- equipped with wide field-of-view sensor -- scanning for anomalies and tasking a second satellite to zoom in (cueing satellite), provided with a high-resolution/low-swath imager.
- This project aims to lay the foundation for the integration of AI into this concept, by developing mission simulation software capable to model distortions due to off-nadir acquisitions and benchmarks to demonstrate its potential focusing on whale-detection use case.
- <https://cin.philab.esa.int/databases/projects/laying-the-foundation-for-ai-based-tip-and-cue>



Part II

Detection methods




Space- Based Sensors

- Hypersonic and Ballistic Tracking Space Sensor (HBTSS) satellites provide birth-to-death tracking, crucial for early detection and targeting data relay.
- The HBTSS is an advanced space-based infrared tracking system designed to detect, track, and provide fire-control quality data for incoming hypersonic glide vehicles (HGVs) and ballistic missiles—from launch to intercept (“birth-to-death”)
- It is part of the Proliferated Warfighter Space Architecture (PWSA), serving specifically within the tracking layer of a multi-tier constellation

Over-the-Horizon (OTH) & Ground-Based Radars

OTH radars extend early warning range but lack precision.



Modern AESA radars like AN/TPY-2 (GaN-upgraded) and LTAMDS offer rapid beam scanning and advanced discrimination in the terminal phase

AN/TPY-2 X-Band Radar

- X-Band Phased-array radar (8.55–10 GHz) used in two modes:
 - Forward-Based Mode (FBM): Long-range detection of missile launches to cue interceptor systems.
 - Terminal Mode (TM): Collocated with THAAD batteries to guide interceptors toward descending warheads
- Deployed from 2004, with 12 radars in NATO and allied sites (Israel, Japan, Turkey, South Korea, Qatar)
- The 13th AN/TPY-2, delivered May 2025, is the first GaN-equipped unit (Gallium Arsenide), deployed with a new THAAD battery.

Feature	Specification
Antenna aperture	9.2 m ² (≈12.8 m × 2.6 m) (missilethreat.csis.org)
T/R Modules	~25,300 GaAs (upgrading to GaN)
Power Requirement	~1.1 MW for radar electronics; total system ~2.1 MW
Cooling	~290 gal/min glycol/water circuit

Gallium nitride (GaN)

- Gallium nitride (GaN) is favored in radar systems due to its superior performance characteristics compared to traditional materials like silicon. It enables higher power, increased efficiency, and smaller, more robust radar systems, particularly in active electronically scanned array (AESA) radars.
- Gallium nitride, or GaN, is a semiconductor material with high breakdown voltage and high electron mobility. Similar to gallium arsenide (GaAs), the high electron mobility enables high frequency operation; unlike GaAs, however, the high breakdown voltage of GaN supports high electric field strength in the device. By operating at a higher voltage, GaN-based amplifiers are able to provide a much higher output power in a smaller space.



Gallium Nitride (GaN)-based radar architecture

Property	Value	Impact on Radar Design
Bandgap	3.4 eV	Higher breakdown voltage
Electron saturation velocity	2.5×10^7 cm/s	Faster signal switching
Thermal conductivity	~1.3–2.5 W/cm·K	Better heat dissipation
Power density	5–10× that of GaAs	Smaller, lighter modules

Gallium Nitride (GaN)-based radar architecture

Feature

GaN Benefit

Range

Increased detection range by 2–3× due to high ERP (Effective Radiated Power)

Resolution

Higher bandwidth enables better range and Doppler resolution

Target Discrimination

Tracks smaller or stealthy targets

Jammer Resistance

Fast frequency hopping and sidelobe suppression

Size/Weight

30–50% reduction in SWaP (Size, Weight, and Power)

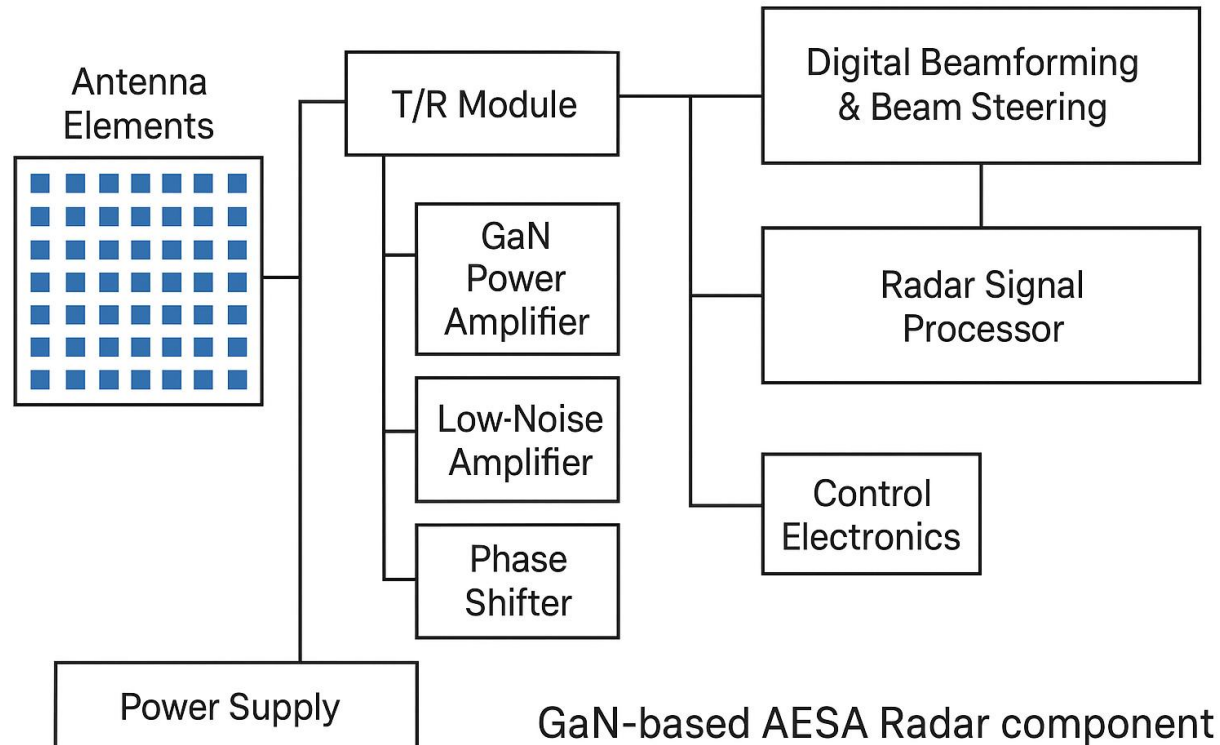
Operational Life

GaN lasts longer under stress and extreme environments

Gallium Nitride (GaN)-based radar architecture

Metric	Typical GaN AESA Value
Output Power per T/R Module	~8–15 W (X-band)
Total Array ERP	~100 kW+
Range Resolution	<1 m (depending on bandwidth)
Beam Switching Time	~10–50 μ s
Max Simultaneous Tracks	1000+
Operating Temp Range	-40°C to +85°C

Gallium Nitride (GaN)-based radar architecture



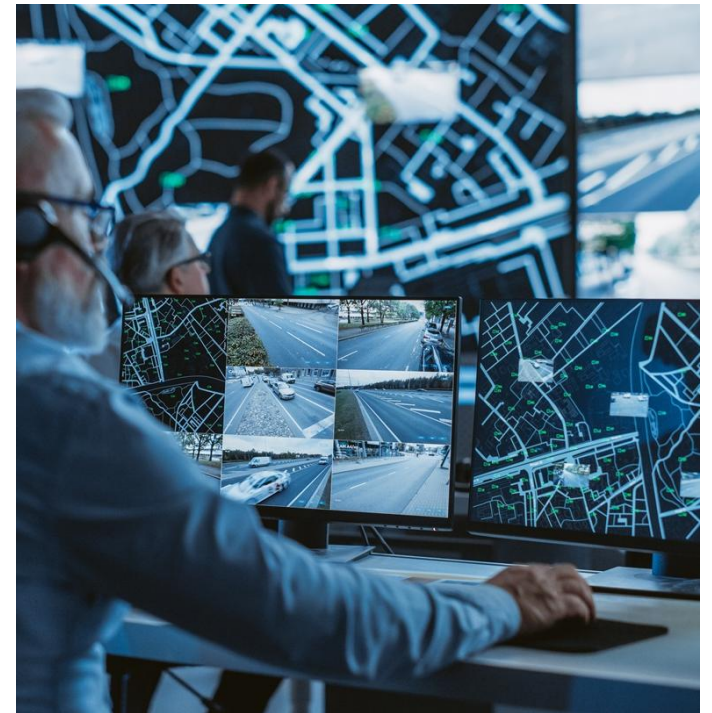
Overhead Persistent Infrared (OPIR)

OPIR (Overhead Persistent Infrared) refers to space-based infrared (IR) sensor systems designed to provide continuous (“persistent”) global coverage from orbit. Their primary mission: detect, track, and characterize missile launches and other high-energy events on Earth. They “see” the infrared signatures of rocket plumes, hypersonic gliders, and other heat-generating targets against the cooler Earth background.

Rockets and missiles produce intense IR emissions from hot exhaust gases during launch and flight.

Satellites in geosynchronous (GEO) or highly elliptical orbits (HEO) stare at large areas of Earth with sensitive IR sensors. Data is processed to:

- Detect launches (missile warning).
- Track trajectories (missile defense).
- Characterize events (discrimination between decoys, warheads, or non-threats).



Hypersonic and Ballistic Tracking Space Sensor (HBTSS)

- The Hypersonic and Ballistic Tracking Space Sensor (HBTSS) is a dedicated satellite-based sensor system developed by the U.S. Missile Defense Agency (MDA), in collaboration with the Space Development Agency (SDA). It's designed to detect, track, and deliver fire-control-quality data on hypersonic glide vehicles (HGVs) and ballistic missile threats from launch to intercept.
- A key component of a multilayered space sensor architecture, HBTSS enhances already-deployed Overhead Persistent Infrared (OPIR) systems, such as wide-field warning satellites, by providing more focused and precise medium-field-of-view (MFoV) tracking capability.
- Prototype HBTSS satellites were successfully launched in early 2024, marking a major step toward operational capability.

Proliferated Warfighter Space Architecture (PWSA).

- The Proliferated Warfighter Space Architecture (PWSA) is a next-generation U.S. military space architecture developed by the Space Development Agency (SDA). Formerly known as the National Defense Space Architecture (NDSA), it was rebranded in early 2023 to better reflect its role in delivering capabilities directly to warfighter. Hundreds to thousands of small, low-cost satellites designed to be resilient, if some are lost, the overall system remains operational. New capabilities are added in regular, two-year tranches, enabling rapid fielding and frequent upgrades.

Kalman Filter

- Kalman filter (KF) is an algorithm that estimates the state of a system (e.g., position, velocity, orientation) from a series of noisy measurements.
- Example: A satellite's radar measurements of position are noisy. The KF fuses those with a motion model to estimate the "true" trajectory.
- Think of it as a statistical predictor-corrector:
 - **Predict** where the system should be based on physics.
 - **Update** using sensor measurements, weighted by their uncertainty.

Kalman Filter

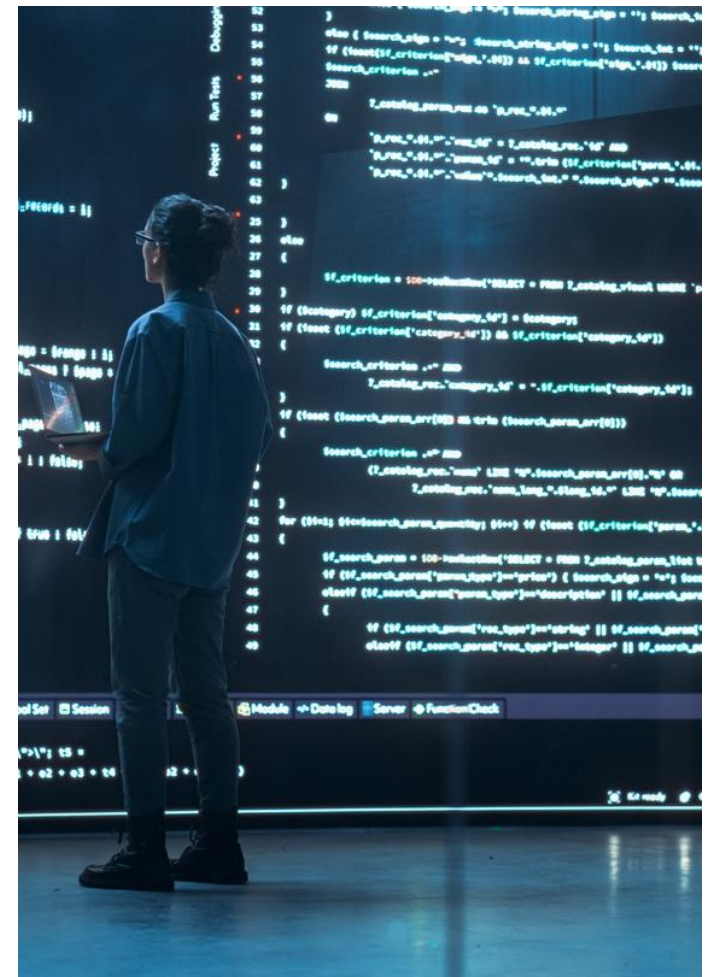
Aerospace systems involve dynamic vehicles (aircraft, spacecraft, missiles) and noisy sensors (radar, GPS, IMU). The Kalman Filter is ideal because it:

- Predicts motion using physics-based models (Newton's laws, orbital mechanics).
- Corrects predictions using sensor inputs, weighted by reliability.
- Smooths out noise, giving a stable, best estimate of state.



EKF

- The Extended Kalman Filter (EKF) is a state estimation algorithm that extends the Kalman filter to nonlinear systems by linearizing them around the current estimate. It's widely used in tracking, navigation, and control, from hypersonic missile defense to spacecraft guidance and autonomous vehicles.
- **Prediction step:**
 - Predict next state using nonlinear model $f(x)f(x)f(x)$.
 - Predict error covariance.
- **Update step:**
 - Compute measurement prediction using $h(x)h(x)h(x)$.
 - Linearize with Jacobians.
 - Compute Kalman gain.
 - Correct the state estimate with the measurement residual.
- This repeats at each time step.



Unscented Kalman Filter (UKF)

- Unscented Kalman Filter (UKF), which is widely used in aerospace navigation and tracking when the system is highly nonlinear. The Kalman Filter (KF) works only for linear systems. The extended KF (EKF) handles nonlinear systems by linearizing with Jacobians, but this approximation can be poor (especially with strong nonlinearities or poor initial guesses). The UKF avoids explicit linearization. Instead, it uses a deterministic sampling technique (“unscented transform”) to capture the mean and covariance of a probability distribution undergoing a nonlinear transformation.
- Note: The Jacobian matrix is a generalization of the derivative for functions with multiple inputs and multiple outputs.