THE AIRSPACE POWER JOURNAL: HYPERSONIC HORIZONS
2025, VOL. 01, NO. 01
DOI: 10.82498/WNE9-0P90

THE IMPERISHABLE DOME:
REDEFINING NEXT GENERATION AIR DEFENCE IN THE HYPERSONIC AGE

DR. HAMAD AL KAABI, HALCON, UAE

The emergence of hypersonic weapons has outpaced current air defence architectures, exposing critical vulnerabilities in threat detection sensors, interceptors, and command-and-control (C2) structures. National air defence strategies must therefore evolve towards an integrated kill-web architecture combining directed energy weapons (DEWs), kinetic interceptors, and persistent ground/space-based sensing. Recent conflicts in various regions, have emphasised the urgency of these adaptations as missile speeds, trajectories, and manoeuvrability increasingly exceed the capabilities of legacy systems. Conventional radar and sequential (C2) processes are insufficient against hypersonic threats that exploit the threat detection sensor blind zones. Space-based infrared constellations, AI-enhanced fusion, and dynamic tasking of interceptors are vital to building resilience and responsiveness. Ultimately, defending against hypersonic missiles is not only about intercepting fast-moving objects, but about establishing a defence ecosystem capable of early warning, rapid decision-making, and precise engagement across all domains and altitudes. Only such integrated, layered approaches can maintain strategic stability in the hypersonic age. This paper presents a strategic and technical re-evaluation of air defence architectures designed to meet this new era of velocity, complexity, and unpredictability.

Keywords
Hypersonic, Air Defence, Hypersonic Glide Vehicle, Directed Energy Weapons, Kinetic Interceptor,

Introduction: The Rising Threat of Hypersonics

The rise of hypersonic missile technology represents a paradigm shift in the character of air and missile warfare, compressing decision timelines, expanding threat envelopes, and exposing critical vulnerabilities in traditional defence architectures. Weapons such as Russia’s Kinzhal and Avangard, and China’s DF-ZF, have demonstrated operational capabilities that bypass radar horizons, exploit atmospheric manoeuvre, and challenge both regional and strategic deterrence frameworks. Their ability to travel at speeds exceeding Mach 5 while executing unpredictable flight profiles has rendered the concept of reliable intercept increasingly tenuous (Zohuri, McDaniel, Lee, & Rodgers, 2019).

This paper’s unique contribution is the proposal of an integrated “kill-web” framework, combining persistent multi-domain sensing, AI-driven sensor fusion, automated command-and-control (C2)

CONTACT: Dr. Hamad Al Kaabi ✉ hamadsaif.alkaabi@halcon.ae HALCON, UAE

networks, and layered kinetic and directed-energy effectors, as the foundational architecture for next-generation air defence in the hypersonic era. By moving beyond linear, sensor-to-shooter chains towards resilient, distributed, machine-speed networks, the proposed approach provides a blueprint for defeating manoeuvring threats under extreme temporal and operational constraints.

Hypersonic systems present challenges that are as much about physics as about speed. Scramjet propulsion, boost-glide trajectories, and plasma sheaths that disrupt (RF) and (GPS) signals not only complicate guidance and tracking (Waltrup et al., 2002; Haidn, 2008) but also demand a shift toward multi-orbit sensing architectures, over-the-horizon radar networks, and AI-enabled (C2) capable of operating at machine speed with human-on-the-loop oversight.

This paper proceeds in three stages: it first examines the technologies underpinning hypersonic weapons, then analyses the vulnerabilities of current air defence systems, and finally proposes an integrated kill-web architecture supported by real-world examples and forward-looking operational imperatives. By framing both the technical and strategic stakes, the study positions the kill-web concept as a necessary evolution to ensure credible defence and deterrence in the hypersonic age.

Critical Technologies Behind Hypersonic Missiles

As a first step, it is essential to develop a robust understanding of the critical propulsion and guidance technologies used in hypersonic systems. On the propulsion front, scramjets sustain Mach 5–15+ flight by compressing and combusting supersonic airflow—yet they demand precise inlet geometry, face ignition instability, and contend with intense thermal loads exceeding 2000K (Waltrup et al., 2002; Drummond et al., 2001). Liquid rocket engines, like those powering the Kh-47M2 Kinzhal, remain simpler and more compact, but struggle with vibration loads and cooling challenges (Haidn, 2008; Siva, 2018).

Equally critical is the navigation challenge posed by plasma formation around the missile at hypersonic speed. The electromagnetic blackout disrupts (RF) communications and (GPS), forcing missiles to rely on onboard solutions to maintain precision (Cooper, 2018). Promising guidance architectures now integrate inertial navigation systems (INS) with satellite (LOS) corrections sourced from low Earth orbit (LEO) constellations.

SpaceX's Starlink demonstration aboard a Starship prototype, where onboard cameras and telemetry were successfully streamed through plasma during re-entry, showcased that high-bandwidth communications can persist through partial plasma sheath conditions (Hofacker, 2024). This implies that constant connectivity with satellite networks—even under plasma loading—can restore mid-flight positional data.

A next-generation hypersonic missile could integrate (INS), plasma-resistant data links, and multi-satellite LOS updates to maintain a high-precision track. This hybrid navigation method would offer more reliable accuracy than (GPS) or (INS) alone, which suffer from drift or blackout. Leveraging commercial (LEO) constellations or dedicated (ISR) satellites offers a path to overcome plasma-induced guidance loss, ensuring that hypersonic weapons stay on target.

Limitations of Current Air Defence Systems

Existing air defence systems are insufficient against hypersonic threats. As Fontana and Di Lauro (2022) explain, radar systems—while highly accurate—are geographically constrained by the Earth's curvature, leaving them blind to incoming threats until they are well within engagement range. Specifically, ground-based radars such as AN/TPY-2 and SPY-1 systems cannot detect beyond the radar horizon, giving defenders limited time to react when facing a hypersonic missile traveling at Mach 5+.

Moreover, the trajectory of hypersonic glide vehicles (HGVs) often remains within the upper atmosphere (altitudes of ~30–70 km), allowing them to evade traditional exoatmospheric ballistic tracking systems, further compounding sensor latency (See Figure 1). In other words, HGVs fly in a radar/sensor blind zone—too low for space-based exoatmospheric sensors, and too fast and erratic for ground-based systems, thereby delaying detection and tracking.

Fontana and Di Lauro also highlight a key trade-off: while space-based infrared (IR) sensors provide early detection capability, they lack the precision needed to guide an interceptor without assistance from radar. Conversely, radar offers precision but reacts too late when acting alone. This sensor asymmetry exposes gaps in tracking continuity and leads to missed intercept windows. These constraints mean that legacy systems designed to counter ballistic missiles or slow-moving cruise threats are no longer sufficient in the hypersonic era.

It is critical to highlight that traditional (C2) architectures are structured around sequential sensing and hierarchical decision-making, processes that are inherently too slow to counter weapons that travel extremely fast. Current (C2) architectures typically integrate data from radars, sensors, and reconnaissance assets, analyse, classify, and prioritise detected threats, assist commanders and provide options for interception, issue orders to and synchronize air defence units, facilitate communication and manage data links, allocate specific weapon systems, and maintain a real-world operational picture of the battlefield. Hypersonic threats dramatically compress decision timelines due to the reduced time available for detection, tracking, identification, threat assessment, and interception decisions. Furthermore, hypersonic systems such as HGVs can execute unpredictable trajectory shifts mid-flight, negating radar tracking assumptions. These challenges raise serious potential issues for current (C2) models, forcing systems to operate with shortened decision loops and with less certainty.

Even the best interceptor missiles won't be effective against hypersonic threats unless supported by systems that combine multi-sensor data, maintain continuous tracking, and enable real-time decisions. To deal with these fast-moving weapons, air defence systems need to move beyond relying only on ground-based radar. Instead, they must use all available sensor data—whether from space, air, or ground—and process it quickly so they can detect, decide, and respond in just seconds.

Directed Energy Weapons and Kinetic Interceptors

While Directed Energy Weapons (DEWs) offer ground-breaking speed-of-light interception capabilities, a comprehensive air defence must also include proven kinetic interceptors. (DEWs) such as high-energy lasers (HELs) are particularly effective for neutralising fast, small, or swarming threats, thanks to their precision targeting and rapid-firing capabilities. Johnson (2024) emphasises that (DEWs) provide near-instantaneous engagement timelines, deep shot capacity, and low cost-per-shot—typically measured in dollars versus hundreds of thousands for interceptors—making them highly attractive for defending high-value assets under saturation attack.

The recent maritime crisis in contested regions revealed major gaps in air defence sustainability. Naval forces expended large volumes of kinetic munitions to defend against waves of low-cost unmanned aerial vehicles (UAVs) and missiles, creating concerns over magazine depth and cost asymmetry. While (DEWs) were not deployed in that engagement, senior commanders highlighted their potential to mitigate these problems by providing low-cost, unlimited-response options for swarm defence (Johnson, 2024).

However, (DEWs) are not a silver bullet. Their performance can be degraded by environmental factors such as rain, fog, or atmospheric turbulence. Moreover, high-energy lasers currently require substantial onboard power and cooling, limiting their deployment to larger platforms or forward-operating bases.

This is where kinetic systems remain critical. In May 2023, a Patriot PAC 3 missile system successfully intercepted a hypersonic class missile—one of the few confirmed defeats of such a weapon in combat. This event was a significant milestone, refuting the belief that hypersonic weapons are categorically unstoppable. It showcased the value of advanced radar tracking, multi-layered cueing, and interceptor manoeuvrability in defeating even Mach 10+ targets in the terminal phase. The system's active radar seeker and agile control fins allowed it to adjust course just seconds before impact, underscoring the importance of precise last-mile engagement.

It is worth noting that hypersonic weapons are constantly advancing and defeating highly manoeuvrable threats with unpredictable flight paths such as hypersonic glide vehicles is an emerging critical requirement for armed forces. In order to meet this threat, kinetic interceptors will need to look towards the latest propulsion technologies. One promising technology for greatly improving the manoeuvrability of last mile interceptors is thrust vector control technology. Air-to-air missiles such as the AIM-9X Sidewinder have achieved high rates of engagement success due to their ability to pivot mid-flight through redirecting the engine exhaust. However, thrust vectoring through fluid injection techniques enable even greater manoeuvrability, offering split-second response times.

The future of air defence must be layered and hybrid. As shown in Figure 2, (DEWs) and kinetic interceptors offer distinct and complementary capabilities in defeating hypersonic weapons. In environments where (DEWs) are deployed, they may serve as the first layer of defence, but they do not function as long-range kinetic interceptors. Kinetic interceptor systems like Patriot, THAAD, and SM-6 remain indispensable for urban and high-priority site defence, especially when atmospheric or line-of-sight conditions impair laser systems. Only by integrating both forms into a coordinated architecture can a defence system adapt to the full range of modern air threats, including hypersonic weapons.

Space-Based Sensor Constellations

Space-based sensor constellations offer one of the most promising solutions to the tracking challenges posed by hypersonic weapons. Unlike ballistic missiles, which follow predictable arcs into space, HGVs fly within the upper atmosphere at variable altitudes and speeds, often below radar horizons and outside the detection envelope of traditional ballistic missile warning satellites. Ground-based radar systems are effective but suffer from line-of-sight constraints, especially against high speed, manoeuvrable threats.

To address these gaps, a shift toward persistent, space-based infrared (IR) sensing is essential. Satellites in (LEO) provide high-resolution thermal imaging, capable of detecting the intense heat signatures generated by hypersonic vehicles during boost, glide, and terminal phases. Meanwhile, geostationary Earth orbit (GEO) platforms offer wider coverage and continuous monitoring over fixed regions, making them useful for strategic early warning.

The U.S. Space Development Agency's (SDA) Proliferated Warfighter Space Architecture (PWSA) includes a dedicated (LEO) Tracking Layer, designed to provide global, persistent detection and tracking of advanced missile threats, including hypersonic glide vehicles. Tranche 1 is deploying now, with Tranche 2 scheduled by 2027, offering fire-control-quality infrared tracking to support layered missile defence (Space Development Agency, 2024).

Fontana and Di Lauro (2022) note that infrared sensors can detect launches within seconds due to the thermal plumes produced by missile propulsion systems, even through partial atmospheric interference. Forden (2006) expands on the strategic implications of such systems, arguing that space-based surveillance improves technical tracking. The tracking accuracy is crucial as it may prevent international crises by reducing false alarms. In previous high-alert scenarios (e.g., the 1979 NORAD incident), space sensors provided crucial confirmation that no actual missile launches were underway. Without that confidence, false alarms could have escalated into nuclear conflict. The same principle applies to hypersonic defence: early, accurate, and persistent detection reduces the chance of miscalculation and enables faster, more proportionate responses. In addition, air defence systems must be designed with independent verification pathways and sensor redundancy to prevent false alarms from triggering strategic overreactions.

Sauter (2004) contributes critical design insight, showing that constellation layout directly influences coverage timelines and engagement success. His study proposes a (LEO) constellation of as few as 21 satellites, configured to maximise revisit rates and ensure overlapping fields of view for trajectory confirmation. Sauter's modelling uses a mix of circular and elliptical orbits, optimised through genetic algorithms, to support mid-course tracking and enable what he terms "multiple intercept opportunities" — allowing cueing data to be handed off between satellites, even as the threat manoeuvres.

Incorporating such constellations into the broader kill web architecture ensures that hypersonic missiles can be tracked throughout their entire flight profile. This real-time space-based data can then cue both kinetic and directed energy interceptors with far more precision than radar alone. Space-based sensors thus play a pivotal role not only in early warning, but also in mid-course correction, target verification, and kill-chain resilience. Without them, the layered defence of hypersonic threats remains incomplete.

Toward an Integrated Kill-Web Architecture

Bringing together the core challenges discussed in previous sections ranging from unpredictable hypersonic trajectories to sensors limitations—future air defence must evolve into a resilient, multi-domain system built on the principles of integration, automation, and speed. As shown in Figure 3, the central concept is a kill web architecture: a layered, distributed defence network that fuses sensors, command elements, and interceptors across land, sea, air, and space to operate as a unified response mechanism against hypersonic threats.

This architecture begins with persistent detection and tracking, enabled by a constellation of space-based infrared sensors in both (LEO) and (GEO) orbits. These sensors can detect the intense thermal signatures of hypersonic weapons from launch through terminal glide. To maintain continuous awareness despite high speed and evasive manoeuvres, redundant sensors and independent verification systems are essential—both to cue interceptors and to avoid false alarms (as emphasised by Forden, 2006). This space-based surveillance feeds data into an AI-enhanced sensor fusion layer, combining IR, radar, and optical tracking to build a coherent, real-time threat picture.

From there, this fused data is processed by an automated (C2) system that makes use of real-time analytics, predictive targeting, and dynamic tasking. Recent research underscores that AI-enhanced (C2) architectures are increasingly capable of operating at machine speed, compressing detect-to-engage cycles and reducing human cognitive overhead in mission-critical environments (SCSP, 2024).

As Materak (2023) notes, this (C2) layer must be capable of decision-making on compressed timelines—detect, classify, decide, and respond within seconds. It must also dynamically assign tasks to the most appropriate interceptors, accounting for environmental conditions, sensor coverage, and threat geometry. However, achieving full machine-speed coordination across domains also demands unprecedented interoperability and automation, as legacy platforms often struggle to share sensor data or execute joint responses under the compressed timelines imposed by hypersonic threats (GAO, 2023).

In terms of engagement, the architecture deploys a layered mix of interceptors. At mid-range, kinetic interceptors such as SM-6, THAAD, or other manoeuvrable missiles handle the bulk of intercept attempts.

At the terminal phase, a combination of kinetic systems (Patriot, NASAMS) and (DEWs) provides point defence. (DEWs) are not designed for long-range intercepts but excel at short- to medium-range engagements (typically 5–10 km), where they can neutralise fast or swarming threats with low latency and deep shot capacity.

Their effectiveness is best realised in environments like urban areas, naval platforms, or airbases—where they complement kinetic systems in dealing with saturation attacks or intercepting terminal-phase threats. Kinetic interceptors remain essential for last-mile engagements against manoeuvring hypersonic threats, as demonstrated by a successful Patriot engagement against a hypersonic-class missile. This kinetic layer is essential in conditions where (DEWs) may be degraded by atmospheric effects or power constraints.

In sum, the kill web architecture is not defined by any single breakthrough, but by the synchronisation of many interdependent systems: space-based sensing, AI-driven fusion, adaptive (C2), and layered interceptors. It replaces the old linear kill chain with a nonlinear, domain-agnostic defence network, enabling fast, adaptive, and resilient responses to one of the most complex threats of the modern age. Only through this comprehensive integration can air defence evolve to match the velocity, altitude, and unpredictability of hypersonic weapons.

Conclusion: Strategic Implications and Recommendations

Hypersonic weapons are reshaping the battlespace, compressing reaction timelines and outpacing the legacy paradigms of linear missile defence. This study has demonstrated that a distributed, AI-enabled kill-web architecture, anchored in persistent multi-domain sensing and layered effectors, is the most viable path to countering this class of threats.

The operational imperatives emerging from this analysis are threefold: Invest in persistent, multi-orbit surveillance and AI-enabled sensor fusion to maintain continuous custody of hypersonic threats across their entire trajectory; develop layered effectors, integrating directed-energy weapons for rapid, low-cost point defence with kinetic interceptors for mid-range and terminal-phase engagements; and automate distributed, network-centric (C2) with human-on-the-loop oversight, enabling machine-speed decisions under extreme temporal compression while preserving responsible command authority.

By prioritising these capabilities, future air defence networks can transition from reactive, vulnerable, and linear constructs to proactive, resilient, and distributed kill-webs capable of deterring and defeating next-generation hypersonic threats. In doing so, the kill-web paradigm not only preserves operational relevance but also defines the cornerstone of 21st-century integrated air and missile defence.

References

Cooper, J. (2018) ‘Russia’s invincible weapons: today, tomorrow, sometime, never?’, Changing Character of War Centre Occasional Paper, Pembroke College, University of Oxford.

Drummond, J.P., Bouchez, M. and McClinton, C.R. (2006) ‘Overview of NATO background on scramjet technology’, NASA Technical Report, NASA Technical Reports Server.

Fontana, S. and Di Lauro, F. (2022) ‘An overview of sensors for long-range missile defence’, Sensors, 22(24), 9871. https://doi.org/10.3390/s22249871

Forden, G. (2006) ‘A constellation of satellites for shared missile-launch surveillance’, MIT Program on Science, Technology and Society Working Paper, pp. 1–21.

Haidn, O.J. (2008) ‘Advanced rocket engines’, in Advances on Propulsion Technology for High-Speed Aircraft. Paper 6. Neuilly-sur-Seine: NATO Research and Technology Organisation, pp. 1–40.

Hofacker, C. (2024) ‘Putting Starship’s plasma in perspective’, Aerospace America, 1 April. Available at: https://aerospaceamerica.aiaa.org (Accessed: 8 July 2025).

Johnson, B. (2024) ‘The coming of age of directed-energy weapons and the Red Sea crisis’, Center for International Maritime Security – Red Sea Topic Week, pp. 1–12.

MacDonald, T. (2025) ‘Tracking mobile missiles’, Journal of Strategic Studies, 48(2), pp. 297–333. https://doi.org/10.1080/01402390.2024.2435961

Materak, W. (2023) ‘The evolution of air threats in future conflicts’, Safety & Defense, 9(1), pp. 24–30.

Sauter, L. (2004) ‘Satellite constellation design for mid-course ballistic-missile intercept’, MSc thesis, Massachusetts Institute of Technology.

Siva, V. (2018) ‘Theoretical investigation of liquid-propellant rocket-engine performance’, International Journal of Engineering Research and Applications, 8(3), pp. 38–41.

Space Development Agency (2024) Tracking Layer Fact Sheet, Proliferated Warfighter Space Architecture (PWSA), August.

Available at: https://www.sda.mil/wp-content/uploads/2024/09/Tracking-Layer-Fact-Sheet.pdf (Accessed: 29 July 2025).

Special Competitive Studies Project (SCSP) (2024) Reimagining Military C2 in the Age of AI, SCSP Defense Paper Series.

Available at: https://www.scsp.ai/wp-content/uploads/2024/12/DPS-Reimagining-Military-C2-in-the-Age-of-AI.pdf (Accessed: 29 July 2025).

U.S. Government Accountability Office (GAO) (2025) Defense Command and Control: Further Progress Hinges on on Establishing a Comprehensive Framework, GAO-25-106454. Available at: https://files.gao.gov/reports/GAO-25-106454/index.html (Accessed: 29 July 2025).

Waltrup, P.J., White, M.E., Zarlingo, F. and Gravlin, E.S. (2002) ‘History of U.S. Navy ramjet, scramjet, and mixed-cycle propulsion development’, Journal of Propulsion and Power, 18(1), pp. 14–22. https://doi.org/10.2514/2.5955

Zohuri, B., McDaniel, P., Lee, J. and Rodgers, C.J. (2019) ‘New weapon of tomorrow’s battlefield driven by hypersonic velocity’, Journal of Energy and Power Engineering, 13(5), pp. 177–196. https://doi.org/10.17265/1934-8975/2019.05.002

Appendix

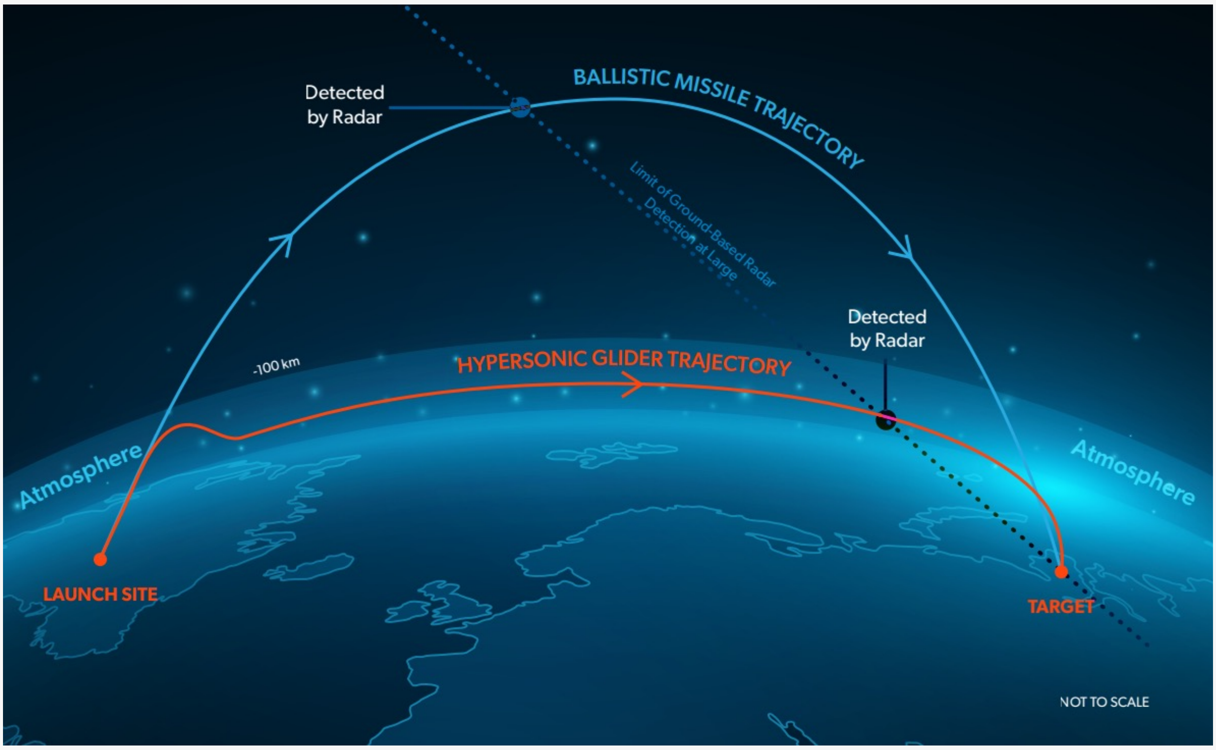

Figure 1: Graphic of radar blind zones in detecting and tracking ballistic missiles and hypersonic glide vehicles trajectories.

DIRECTED ENERGY WEAPONS (DEWS)	DIRECTED ENERGY	LAST-MILE INTERCEPTORS
Uses focused energy (e.g. lasers, microwaves) to disable targets	Mechanism Of Action	Kinetic impact via guided missiles or projectiles
Near-instantaneous (speed of light)	Speed Of Engagement	Seconds (depends on missile velocity and intercept range)
Extremely low (e.g. ~$12 per laser shot)	Cost Per Shot	High (can exceed $1M per missile)
Virtually unlimited (limited by power supply)	Magazine Capacity	Finite (limited by onboard missile inventory)
High - performance degrades in fog, rain, or dust	Weather Sensitivity	Low — generally less affected by weather
Short to medium (line-of-sight required)	Operational Range	Medium to long (depending on missile type)
Minimal - no explosive debris	Collateral Damage	Potential for fragmentation and blast effects
Requires cooling systems and high-power generation	Maintenance & Logistics	Requires missile resupply and launcher upkeep
Emerging - prototypes and limited fielding	Maturity & Deployment	Mature — widely deployed and battle-tested
Drones, loitering munitions, small projectiles	Ideal Targets	Cruise missiles, ballistic threats, aircraft

Figure 2: Table comparing the capabilities and characteristics of (DEWs) and last-mile kinetic interceptors.

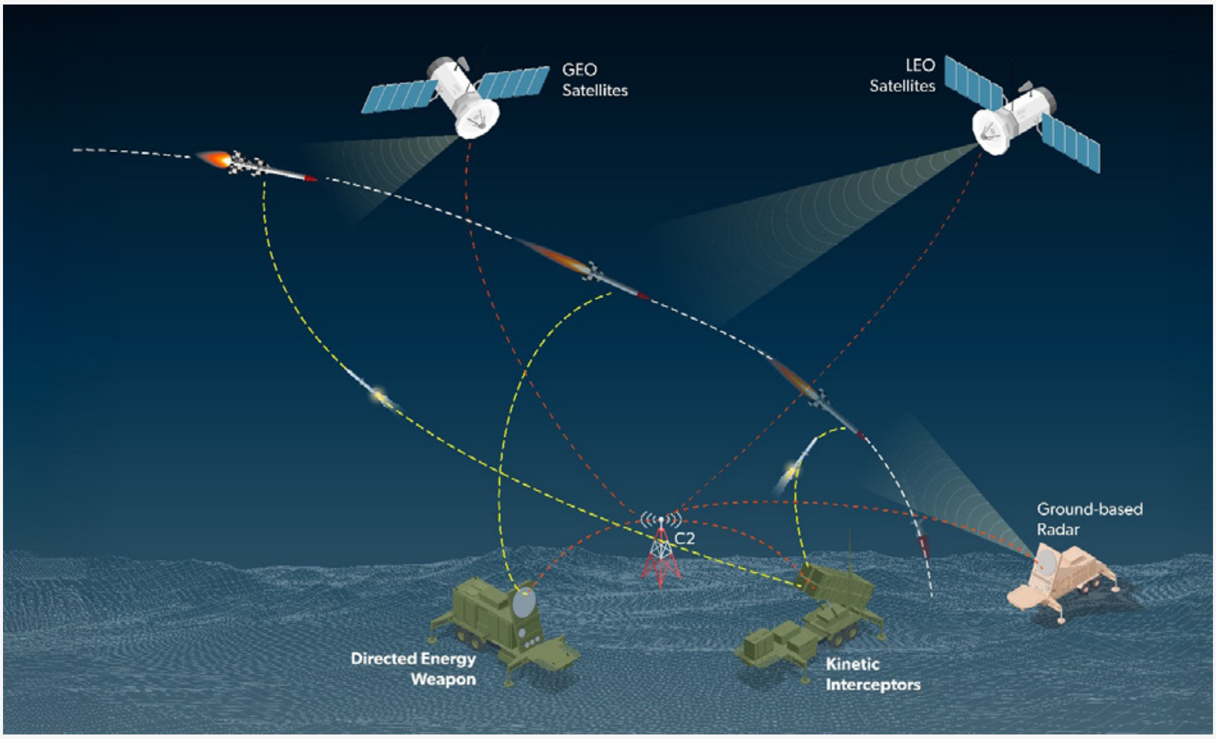

Figure 3: Conceptual architecture of a multi-layered kill web for hypersonic missile defence.