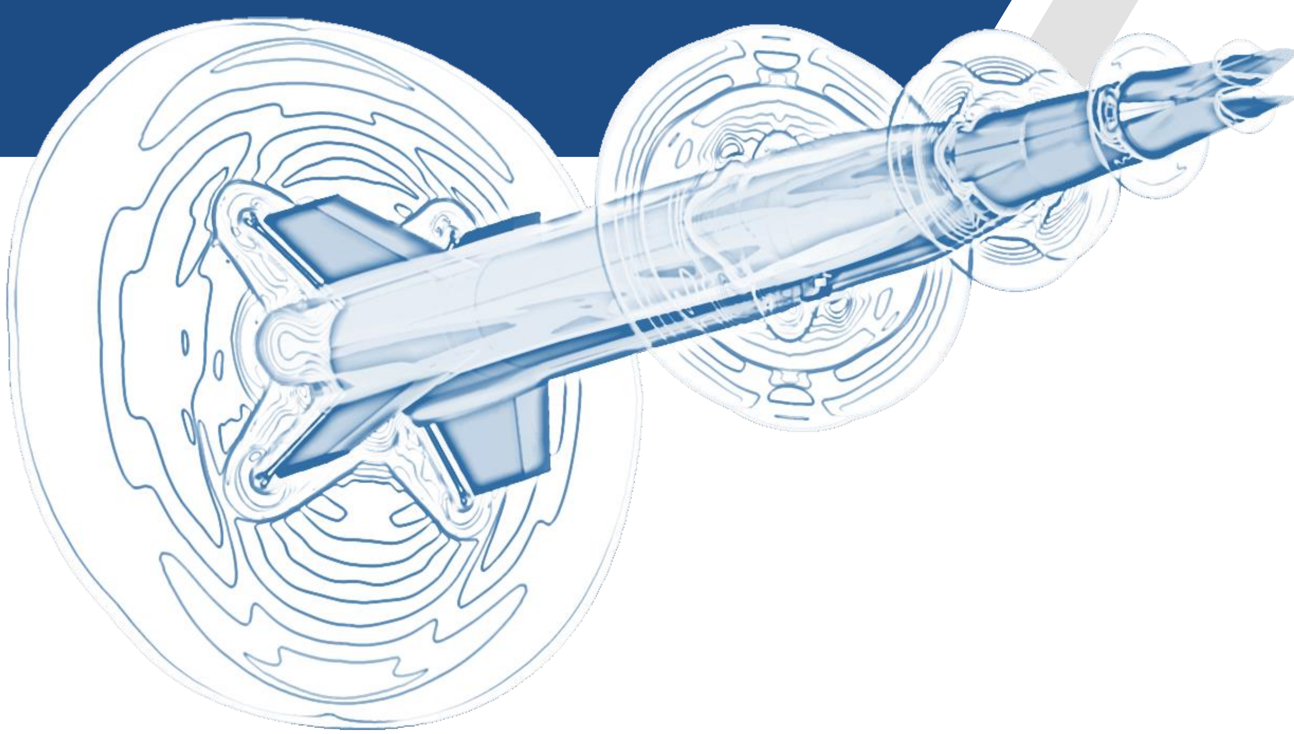
Integrated Air and Missile Defence Centre of Excellence

Overview of International Hypersonic Weapons Programmes and Potential Ways to Exploit Physical Phenomena Around Hypersonic Weapons to Improve Surveillance Capabilities (Detection and Tracking)



EXTENDED ABSTRACT

Overview of international hypersonic weapons programmes, and potential ways to exploit physical phenomena around Hypersonic Weapons to improve surveillance capabilities (Detection and Tracking)

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Introduction

Hypersonic vehicles are much different from other types of high-speed vehicles (such as ballistic missiles), because, despite their high speed, can be also maneuverable. This combination of flight characteristics renders them very hard to track and almost impossible to intercept. On the other hand, the design, manufacturing, and operation of such vehicles requires several breakthroughs in sectors like gas-dynamics, Computational Fluid Dynamics (CFD), propulsion, flight-control, and material science, in order for such vehicles to be able to withstand the complicated flow effects, instabilities, accelerations, and heat loads occurring during a hypersonic flight. Despite the above difficulties, the major military players are willing to pay the required cost for the development of such vehicles, as they could have a strong impact on doctrine and conduct of future military operations. Three different types of hypersonic vehicles for military applications can be identified:

1. Exo-atmospheric ballistic missiles.
2. Hyper-glide vehicles (HGVs) (wave-riders).
3. Hypersonic cruise missiles.

The first type includes the well-known rocket-powered ballistic missiles, which operate in hypersonic speeds (partially within their atmospheric flight regime). The second type includes unpowered vehicles, which are boosted to a high altitude (around 100 km) by carrying rockets, and after their release, are gliding at hypersonic speeds (over Mach 8) for very long distances by utilizing the wave-riding effect. During their flight they have the ability to maneuver, therefore their flight-path is not predictable (contrary to the exo-atmospheric ballistic missiles). They are designed for flying at high altitudes ($\sim$ 100 km), where rarefied gas conditions exist. The third type of hypersonic vehicles corresponds to vehicles powered by ScramJet (Supersonic Combustion Ramjet – SCRJ) engines; in such engines, the flow is supersonic throughout the engine (which has no rotating parts), while the combustion takes place also in supersonic conditions. Their flight speed is about Mach 5, where the ScramJet engine shows its maximum efficiency, while they fly at lower altitudes, as their air-breathing engine requires high-density air for the combustion.

Main Developers

In the race for the development of hypersonic vehicles there are major and secondary countries. Major countries are U.S.A., Russia, China and India. Secondary countries are Iran and North Korea. However, extensive scientific research on hypersonic flight is also conducted in Australia, Japan, France, U.K. and Germany. Actually, two-thirds of the total number of scientific publications on hypersonic flight originate from the U.S.A. and China.

At the time of this report the **U.S.A.** is the country with the most known hypersonic programs. There is enough public information about the country's hypersonic programs but technical details, such as the specific geometry of the vehicles, materials used and booster details are still proprietary.

The *OPERATIONAL FIRES* (*OpFIRES*) is a ground-launched system that uses a hypersonic boost glide missile system to penetrate enemy air defenses and rapidly engage time-sensitive targets; it is developed by the Defense Advanced Research Project Agency (DARPA) in cooperation with Lockheed Martin. It is a hypersonic glide vehicle which glides through the upper atmosphere during flight and then dives to hit the target. This system performed a successful test flight during July 2022, although information about the flight duration and maximum altitude are not disclosed.

The Boeing X-51 *Waverider* is a research unmanned hypersonic platform, which was designed as a missile sized demonstration vehicle, in order to showcase scramjet operation from Mach 4.5 to 6. The X-51 completed several test flights between 2010 and 2013. Its last flight has been recorded as the longest flight of a scramjet engine to date.

The *Southern Cross Integrated Flight Research Experiment* (*SCIFiRE*) is a product of the collaboration between US and Australia for over 15 years. This vehicle is powered by an air-breathing scramjet engine. It will be capable of Mach 5 and it is expected to enter service within a period of 5 to 10 years.

USA					
Project Name	**Organization**	**Type**	**Speed (Mach)**	**Expected date to service**	**Status**
OPERATIONAL FIRES (OpFIRES)	DARPA	Hypersonic glide missile	5	-	Under development
BOEING X-51 WAVERIDER	Defence Advanced Research Project Agency (DARPA)	Unmanned research experimental aircraft	5	-	Under development
Southern Cross Intergrated Flight Research Experiment (SCIFIRE)	USA/Australia	Hypersonic Cruise missile	5	Before 2030	Under development
Long Range Hypersonic Weapon (LRHW)	United States Army	ICBM	5	Before 2023	Under development
Advanced Hypersonic Weapon (AHW)	US Army Space and Missile Defence Command (USASMDC) / Army Forces Strategic Command (ARSTRAT)	Hypersonic Glide Vehicle (HGV)	5+	Before 2025	Under development
Hypersonic Air-Breathing Weapon Concept (HAWC)	DARPA	Hypersonic Cruise Missile	5+	Before 2025	Under development
Hypersonic Technology Vehicle HTV-3X	USAF	Hypersonic Glide Vehicle (HGV)	5-10	-	Cancelled
SR-72 Blackbird	Lockheed Martin	Hypersonic Reconnaissance UAV	6	Before 2030	Under development
AGM-183 Rapid Response Weapon (ARRW)	Lockheed Martin	Hypersonic air-to-ground missile - glide vehicle	5+	Before 2025	Under development
Hypersonic Technology Vehicle HTV-2	DARPA	Hypersonic glide Vehicle	20+	Before 2025	Cancelled

A summary of known US hypersonic programs.

The *Long-Range Hypersonic Weapon* (*LRHW*) is a surface-to-surface hypersonic missile under development by the US Army. It's a ballistic missile that will boost the Common Hypersonic Glide Body (*C-HGB*) warhead to Mach 5. It can be launched from sea or land. Till today this system has been tested two times, in October 2017 and in March 2020.

The *Advanced Hypersonic Weapon* (*AHW*)) is a hypersonic glide vehicle, capable of flying inside the planet's atmosphere at hypersonic speeds. It is designed to have a 6000 km range and a flight time of 35 minutes. During November 2011 the *AHW* was launched from the Pacific Missile Range Facility (PMRF) in Hawaii, to the Reagan Test Site on the Marshall Islands. The vehicle successfully hit the target located about 3700 km away launch site. This test was conducted to demonstrate hypersonic boost-glide technologies and trial the capability for atmospheric flight at long-ranges.

The *Hypersonic Air-breathing Weapon Concept* (*HAWC*) program aims to develop and demonstrate critical technologies to enable an effective and affordable air-launched hypersonic cruise missile. It's a kinetic energy weapon without an explosive warhead. At least 3 successful flights have been conducted till September 2021. A test has been performed on July 18, 2022, during which the weapon obtained a speed of Mach 5 at an altitude of 18 km and travelled more than 300 nautical miles.

The *HTV-3X* vehicle, also known as the *Blackswift*, is a vehicle based on DARPA's *HTV-2* and it was supposed to have formed the basis for development of a reusable Hypersonic Cruise Vehicle, an unmanned aircraft capable of taking off from a common runway while carrying a payload of 5400 kg to strike targets up to 16,650 km away. The *Blackswift* flight demonstration vehicle was supposed to be powered by a hybrid of a turbojet engine and a ramjet, an all-in-one power plant. Unfortunately, *HTV-3X* did not receive any more funding and was cancelled on October 2009.

Very few information exists about the Lockheed Martin *SR-72*, also called "*Son of Blackbird*", which is a vehicle with top speed in excess of Mach 6. It is intended mainly for surveillance, intelligence and reconnaissance. During November 2018 Lockheed Martin announced that a prototype of the *SR-72* was scheduled to fly by 2025. This vehicle will be similar in size to the SR-71, at over 30 m long and with similar range, with entry into service estimated at 2030.

AGM-183 Air-Launched Rapid Response Weapon (ARRW) (Images credit: airandspaceforces.com, Lockheed Martin).

Another system developed by the US is the *AGM-183A* Air-Launched Rapid Response Weapon (*hyper ARRW*), being a hypersonic missile manufactured by Lockheed Martin to be used by USAF. It is claimed to have a maximum speed of Mach 5+ and an operational range of about 1,600 km. It uses a boost-glide system, which is propelled to hypersonic speed by a rocket, on which it is mounted before gliding to the target. A few tests have been performed for the *AGM-183A* but some of them failed, due to technical issues. The first successful test was performed on May 14, 2022, where the weapon demonstrated separation capability from a B-52H Stratofortress. The USAF conducted another successful test of the missile on July 12, 2022, while another successful test was reported on December 9, 2022. This test concerned a fully operational prototype; the basic functionality of the complete AGM-183A vehicle has been demonstrated through this test, providing the opportunity to become the first-ever operational air-launched hypersonic weapon in the US inventory.

The *Hypersonic Technology Vehicle 2* (*HTV-2*) is an experimental gliding vehicle or an unmanned rocket-launched maneuverable vehicle, developed as part of the DARPA Falcon project and predecessor of *HTV-3X*, estimated to fly in the Mach 20 range and cover 17,000 km in 49 minutes. Two flight tests have been reported so far; the first was conducted on April 22, 2010. During this test the vehicle flew for a distance of 7,700 km over the Pacific Ocean at a speed of Mach 20 and an altitude of 160 km. The flight duration in total was 30 minutes, but 9 minutes after launch communication with the vehicle was lost. A second flight test was performed on August 11, 2011, during which again contact was lost with the vehicle 9 minutes after launch and the autopilot terminated the flight violently.

For the **Russian** hypersonic programs not much information is available to the public and those available should be treated with caution. Currently, two Russian hypersonic missiles are known to date. The first has the codename *Kh-72M2* also known as *Kinzhal*, while the second is known with the codename *Avangard*.

Kinzhal is claimed to have a range of more than 2000 km and a speed of Mach 10. It has the ability to carry conventional and nuclear warheads. The maximum operating altitude for that missile is 20 km. This means that it can be fired from bombers or other type of military aircraft. The *Kinzhal* project started in December 2017. In November 2019, the first launch of *Kinzhal* took place and the missile hit a ground target at a speed of Mach 10 (according to the Russian News Agency). The *Kinzhal* uses a conventional rocket engine with solid propellant fuel; *Kinzhal* has a length of 8 m, a diameter of 1 m and weight of 4300 kg. It is claimed being an air-launched version of the Iskander short-range ballistic missile (SRBM). The *Kinzhal* missile has been used by Russia in the war against Ukraine.

On the other hand, the *Avangard* is a hypersonic gliding vehicle able to maneuver. It is powered by its own propulsion system for which details are not known. The claimed speed is Mach 20-27, but there are serious doubts about the vehicle's performance.

India has its own hypersonic program, developing the *BrahMos* missile platform. The platform is developed by *BrahMos Aerospace* and there are several variants, in order the missile to be able to launch from mobile launchers to ships. The hypersonic version of the platform is called *BrahMos-II*. Till today, there are not any *BrahMos-II* prototypes operational, but the company claims that it will be ready for testing by 2024. It is expected to have a range of about 290 km and a speed of over Mach 6. No more information has been published till today. Another hypersonic platform announced recently from India is *Shaurya*. This is a nuclear-capable hypersonic missile, with a range of 750 km which can reach speeds of Mach 7.5. It's a surface-to-surface weapon, comprising of a two-stage missile that uses solid propellant. It weighs about 6 tons and can carry nuclear and conventional payloads of up to 1 ton.

Very little information can be found about **China's** hypersonic program. China has been developing a hypersonic missile since 2014, under the code name *DF-17*. This prototype uses the booster from the already known DF-16, which is a short-range ballistic missile. The vehicle uses a two-stage solid rocket to propel it to the outer atmosphere, while it can carry nuclear or conventional warheads with a range of 1800-2500 km. A test launch of this vehicle took place on November 1, 2017. The missile flew about 1400 km in range and started its hypersonic glide at an altitude of 60 km. At that altitude the glide vehicle separated from the boosters and continued flying to the target. The total flight duration was about 11 minutes.

Propulsion systems

In order to achieve hypersonic speeds propulsion systems different from conventional ones are needed. Conventional turbojet engines use mechanical compression in the inlet, driven by a turbine located downstream of the combustion process, to provide an amount of the airstream compression. The maximum

Mach number a turbojet can reach is usually 3.5, but this is a theoretical limit as this number is constrained by the maximum allowable blade temperature. On the other hand, ramjets rely on the compression inherent in capturing and slowing a supersonic airstream to subsonic, where combustion occurs. Generally, in order for a ramjet to operate efficiently, a minimum supersonic speed must be maintained. Finally, scramjets capture the incoming airstream like the ramjets but instead of slowing it down to subsonic speed they compress it at the inlet and they allow the combustion to occur at supersonic speeds.

Both ramjets and scramjets can operate at supersonic and hypersonic speeds. Due to the inefficiencies occurring when slowing the flow down to subsonic speed, the ramjet is very difficult to operate at speeds above Mach 5. Scramjets can be used above Mach 5, but below that limit they are not able to operate efficiently. Both of these engines must be coupled with a booster that will accelerate the vehicle to the engine's operating speed. In order to be able to achieve hypersonic speeds the vehicle must be as light as possible. The scramjet is an ideal engine for such vehicles, as it doesn't require an oxidizer fuel tank, which adds to the vehicle's weight. These engines collect oxygen from the atmosphere; thus, they yield great weight savings.

Surveillance methods

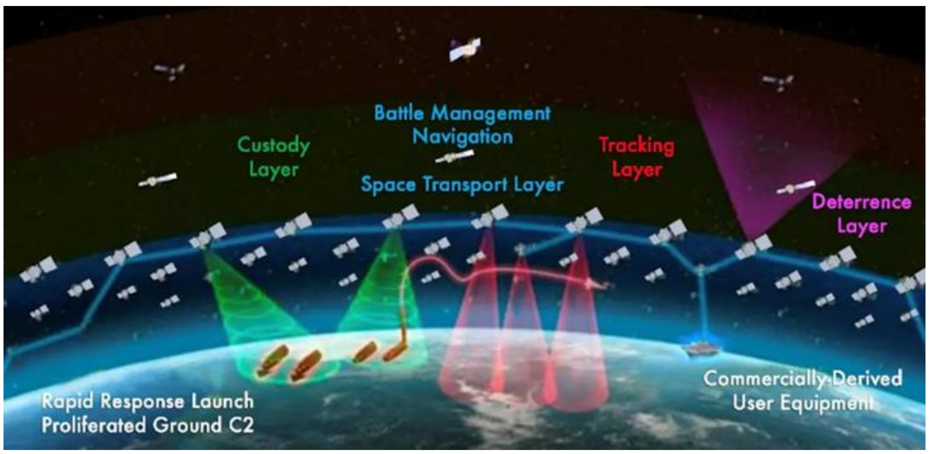
Hypersonic missiles are very hard to track and detect. Due to the fact that they are maneuverable, fast, and fly at low altitude, they can keep their target as a secret till the very last minute. Current interception systems assume of the interception of a ballistic object such as an ICBM. The path of such object is easy to predict, because it is based on momentum and gravity. On the other hand, hypersonic gliding vehicles are something entirely different. They are launched by a ballistic missile and are completely unpowered after separation. However, instead of flying on a predictable ballistic path, like traditional reentry vehicles, they dive back in the atmosphere. There, they experience drag, which slows them down. However, due to their shape, they also experience aerodynamic lift, which allows them to glide on the atmosphere, and counterbalances their weight. Thus, they can fly as far, if not further, as a warhead on a ballistic trajectory launched on the same booster. The first benefit of such a trajectory is that they stay closer to the ground, as their altitude is between 30 km to 100 km, so it is harder to detect them from the ground. Conventional radar and optical sensors being blocked by the curvature of the Earth, so they can approach their target without being detected until the last moment, which makes defending against them very complicated. For lower flying hypersonic cruise missiles, the situation becomes even worse. Nowadays surveillance systems are split into two main categories: (**a**) Geostationary constellations, (**b**) Low-orbit systems.

MIDAS was the first system deployed by DSP (Defense Support Program) in USA. It was launched in 1970 and was a constellation of typically 3 primaries and 3 backup satellites in geostationary orbit. This orbit provided a constant view of a third of the globe to each satellite, making the detection of transient infrared events easier and allowing them to play a useful role 100% of the time. USSR developed a similar system, called Oko (Eye), which was launched in 1972. However, it used Molnya orbits instead of geostationary, and took a lot more time to become operational. After about 30 years of operations, MIDAS was eventually replaced by SBIRS (Space-Based Infra-Red System). SBIRS is also in geostationary orbit, and added infrared sensors presumably carried by US signal intelligence satellites in Molnya orbit for better polar coverage.

Even though SBIRS has extraordinary capabilities, these are not enough. They can only detect missiles with their engines firing, which occurs for only a small part of their flight. For the most part, the vehicles, along with the booster that carries them, are either completely passive or make slight course corrections, so their heat signature is very small. This means that they are not detectable over that background, so a satellite can only see them when they are over the Earth's horizon.

Moreover, another challenge is to differentiate the real threat from the decoys that will likely be launched with the real weapon and have a similar radar signature. This means that, detecting small differences in infrared signatures of small objects, is a task best performed by satellites that are not too far away. Initial plans for SBIRS included a low-orbit component to perform that midcourse tracking and discrimination task. However, its scope was reduced to two proof-of-concept satellites, called STSS (Space Tracking and Surveillance System), launched in 2009.

U.S.A. is currently planning a new constellation of lower-orbit tracking-layer satellites, which will be able to detect a missile from liftoff, all the way to its terminal phase. Such a system will comprise the first ingredient of a future "missile warning/missile tracking/missile defense" integrated system (with no such system currently available). These satellites are designed to provide the initial missile warning/missile tracking capabilities of the future National Defense Space Architecture (NDSA). The project contains the development of infrared satellite constellations in two different orbital layers, along with related ground facilities. The U.S. Space Development Agency (SDA) and Space Force's Space Systems Command (SSC) each have responsibility for a different "layer" of missile-tracking satellites: SDA will be responsible for a constellation at low-Earth orbit (LEO), while SSC will be responsible for a constellation at medium-Earth orbit (MEO).



In 2020, the SDA awarded L3Harris and SpaceX a contract to build out Tranche 0 of the tracking layer for the National Defense Space Architecture (U.S. DoD).

SDA's constellation includes two layers of space-based platforms, the **Transport Layer** and the **Tracking Layer**. The Transport Layer (a communication layer) will provide "assured, resilient, low-latency military data and connectivity worldwide to the full range of warfighter platforms". It is planned to comprise from 300 to more than 500 satellites in low-Earth orbit (LEO) (from 750 kilometers to 1,200 kilometers in altitude). The Tracking Layer will provide global indications, warning, tracking, and targeting of advanced missile threats, including hypersonic missile systems. The idea of using a large constellation of distributed, low-cost, small satellites for the Tracking Layer is that such a system will be more responsive, flexible, and resilient to an enemy anti-satellite attack.

The second ingredient of the project, Space Systems Command's (SSC) new constellation of satellites, will orbit higher in medium-Earth orbit (MEO), at around 10,000 to 20,000 kilometers, so as to be harder to reach by ground-launched, anti-satellite weapons.

Currently, SpaceX and L3Harris companies were awarded contracts to construct the Tracking Layer's "Tranche 0" proof-of-concept, planned to be launched in 2023. The Tranche 1 Tracking Layer contracts were awarded to L3Harris Technologies, and Northrop Grumman Strategic Space Systems. Each contractor will build 14 satellites with a wide field-of-view (WFOV) overhead persistent infrared (OPIR) sensor that will become part of Tranche 1 of the Tracking Layer of the overarching early warning constellation. Additional contracts have been awarded to General Dynamics Mission Systems and Iridium, so as to establish the ground Operations and Integration (O&I) segment for the Tranche 1 Tracking Layer.

Northrop Grumman's proposed Tranche 1 Transport Layer (T1TL) mesh satellite communications network, a constellation of 42 low-Earth orbit satellites, aims to provide resilient, low-latency, high-volume data transport.

Conclusions

The envisaged advantages that the use of hypersonic vehicles can provide (even in the form of the huge cost that a possible adversary nation has to pay for effective countermeasures), increases continuously the push for their development. The main question concerns the ability to survey, to track, and finally to successfully intercept such weapons. Such an integrated ability seems that, currently, does not exist in any nation, although major ingredients are being developed around the globe. Two are the main (controversial) issues: effectiveness in surveillance and the related cost. Cost-effective solutions are needed in order to nullify the high-cost hypersonic development programs of the possible adversaries. The U.S. future National Defense Space Architecture seems to be in that direction, and could form a good example of a decentralized, distributed, interconnected system for effective surveillance and tracking of such vehicles. Some of the key characteristics that such a system should have, are listed below:

- Design of surveillance and tracking systems with open architectures, continuously upgraded and ready to integrate new components and new technologies (as they come available), from different developers and different countries.

- Upgrade existing airborne and surface-based surveillance systems and integrate them into the aforementioned architectures. Such upgrade may include new hardware (more powerful computational systems, additional sensors), and new software (new data-analysis algorithms, new data-fusion algorithms, new tracking algorithms).

- To support the upgrade of existing (and development of future) surveillance and tracking systems, the signatures and possible flight-patterns of existing and under-development vehicles should be analyzed (through simulation, and using available information from their field testing – if possible).

- Mid-term/long-term development of large constellations of low-cost small satellites, for surveillance, tracking and interconnection (to be considered as consumables).

- Use of LEO for better observability, as well as for their lower cost to lunch and put into orbit.

- Development and deployment of low-cost highly-effective IR sensors, for the low-cost satellites.

- Invest in the development of new, and exploitation of existing Artificial Intelligence (A.I.), data mining, and data fusion technologies, for the fast, accurate, and robust information extraction from massive data from the distributed sensors (surface-based, airborne, and space-based). The very short available time-window is maybe the most critical issue to be solved.

- Advancement of technologies for rapid replacement of damaged satellites and rapid re-distribution of satellites after attack, to increase the resilience of the system.

- The investment on such systems could additionally cover the need of surveillance and tracking of more conventional but continuously spreading threats, such as subsonic and supersonic cruise missiles, SRBMs and MRBMs.

- Invest on the (long-term) development of hypersonic interceptors.

Summarizing all of the above, we can conclude that current technologies can be used for the development of such surveillance and tracking systems. It turns out that the most effective method to intercept a hypersonic threat is the direct collision. The interceptor's path must be calculated from real time data in order to precisely intercept the target. However, in this situation the target flies much faster than the currently available interceptors, so cooperation of different systems is a necessity for the collection of the required data to calculate a successful interception path. Furthermore, two facts must not be ignored in the design and implementation of an interception path. Firstly, this type of hypersonic vehicles can maneuver and, subsequently, maneuvering significantly influences the relative motion between the hypersonic vehicle and the interceptor. Secondly, interceptors during their flight have a specific range of speeds, especially at the terminal phase, where their kinetic energy is consumed by high-g maneuvers to reach their target. Considering all of the above, the effective interception of hypersonic vehicles is still an open issue.