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A future endo-atmospheric interceptor: what threats and what technologies?[1]

Missile defense is currently undergoing fundamental changes. Essentially aimed at the interception of threats from proliferating states since the 1990s, it focused on the development of exo-atmospheric interceptors able to engage long-range missiles at stand-off range and also to limit the consequences of the destruction of devices potentially equipped with weapons of mass destruction. Endo-atmospheric interception has therefore long been considered mostly relevant to point or area terminal defense against SRBMs and MRBMs that are operating at the lower end of their range (1,200-1,500 km).

However, the evolution of ballistic missiles and the emergence of hypersonic missiles are giving endo-atmospheric interceptors increasing importance. This includes today targets such as short- and medium-range missiles against which they are currently defined to operate, but will also include in the future longer-range missiles designed to fly all or part of their trajectory within the atmosphere in order to maneuver. Therefore, while Europe is still lagging behind with regard to the design of exo-atmospheric interceptors, it is still well placed to design future systems capable of engaging missiles that, regardless of their range, tend to more systematically operate in the atmosphere. However, capitalizing on European industries' current capabilities requires to anticipate the

1. This note is the executive summary of a study also available on website of the Fondation pour la Recherche Stratégique.

nature of future threats and to make long-term technological choices.

Threat evolutions

- ***Maneuvering warheads and quasi -ballistic missiles***

The growing importance of endo-atmospheric interceptors results from the modernization of ballistic missile navigation and guidance systems, which enable them to pursue parts of their trajectory within the atmosphere, increasing their maneuverability and accuracy. Therefore, accuracy no longer decreases with range, and allows for the development of very long-range missiles which follow ballistic trajectories and are then guided after their re-entry into the atmosphere (concept of maneuvering warhead or maneuvering missiles) or, alternatively, shorter range missiles that have so-called quasi-ballistic flights (the missile is guided all through the atmosphere, or over most of its course). In addition to accuracy, guiding and maneuvering a missile in the atmosphere enhances its penetrability against missile defense. Whereas the trajectory of a ballistic missile is predictable, allowing the defense to plan a predicted interception point to engage the interceptor, altitude, speed or even direction of the incoming missile or warhead is constantly evolving and cannot be precisely anticipated. This advantage explains their growing use.
Currently, maneuvering warheads are mostly used by China on missiles with ranges up to 3,000 km, but also by India and Pakistan. Iran is developing a maneuvering warhead for its Shahab-3 (Emad) missiles and North Korea is attempting to adapt the technology on a long-range version of the Scud C. Russians and Americans are working on intercontinental-range programs, Russia having possibly finalized a warhead. Russia, China, the US, Iran, India and Pakistan also extensively use short-range (500 to 800 km) quasi-ballistic missiles, some of which can operate on a terminal maneuvering mode. Airborne Kinjal-type quasi-ballistic missiles (Russia) significantly extend the range of quasi-ballistic missiles (1,500 to 2,000 km) and represent a major evolution of the threat.

- ***Hyper velocity***

However, maneuvering missile or warheads and quasi-ballistic missiles can be vulnerable to missile defenses, either during their exo-atmospheric flight or during the final phase of their atmospheric trajectory, during which their velocity significantly decreases. Hypersonic gliders are developed to address these vulnerabilities. Although launched by a ballistic missile, their reentry begins early in the flight, preventing the risk of interception, at altitudes above a hundred kilometers. They then glide along the upper atmosphere at high speeds over long distances. Non-strategic gliders are expected to glide over several thousand kilometers at speeds that may be comprised between 8 Mach and 10 Mach, and can maneuver over most of their flight. Gliding altitudes are generally comprised between 60 and 30 km but could be lower for short range glider.
Scramjet technology, which is complex to develop, allows to envisage speeds above 5 Mach over shorter distances (currently around a thousand kilometers) at altitudes between 20 and 30 km. Lighter than gliders, scramjet-powered cruise missiles aim at providing naval or air light platforms with a hyper-fast striking capability. Russia and the United States plan to deploy their first missiles respectively within a few years (Zyrkon for Russia) and early in the next decade. The high-supersonic missiles developed for anti-ship purposes (Russian Kh-32 for instance) also represent a significant threat, operating at speeds that are now in excess of 4 Mach in the terminal phase of their flight. Developed over many years, these systems are capable of adopting complex trajectories throughout their flight and are used in saturation attacks, rendering interception difficult.
The use of high-supersonic/hypersonic missiles must be seen as complementary to that of maneuverable, quasi-ballistic and ballistic missiles. All these weapon systems are currently hard to intercept, given the fact that anti-missile defenses are generally optimized for anti-ballistic or terminal interception at low altitudes (15 to 20 km) and at close range. Intercepting vehicles flying at very high speeds, over distances greater than several hundred kilometers and at altitudes comprised between 30 km and 60 km is therefore a real challenge. The same goes for intercepting maneuvering warheads whose trajectory in the atmosphere is shorter but that can nevertheless reach a hundred kilometers when combined with an MRBM and which demonstrate high maneuvering capacity.

Intercepting future threats: identifying technologies for future missiles

- ***Suggested interception spectrum and advantages of ramjet-powered solutions***

Intercepting very fast maneuvering vehicles requires that the interceptor itself can maneuver and operate at high speeds or, alternatively, that it can operate where the target's maneuvering capability is reduced, namely above altitudes of 30 to 40 km. One potential solution lies in the use of solid propulsion. However, since the target can begin its maneuvering phase at distances well over 100 km downrange with no predictable trajectory, keeping the interceptor at high speeds over such distances would require the use of several propulsion stages. The development of interceptors powered by scramjet makes it possible to anticipate very high interception speeds at very long ranges. Yet, this option faces complex problems of propulsion management, which would severely limit the flight domain of an interceptor. Scramjet (and ramjet) are also limited in their flight altitude and rapidly decrease in performance above 30 km, due to oxygen scarcity. The missile's maneuverability, which depends on its aerodynamic surfaces, would also be affected. The addition of second stage with solid propulsion could overcome these limitations and bring interception altitudes to areas where the target is not very maneuverable, but at the cost of a significant increase in the interceptor's weight and a deterioration of its performance.

Nonetheless, optimizing interception at altitudes of 20 to 30 km is an option. The use of a ramjet powered missile makes it possible to combine maneuverability, speed, and flexibility of use along with the conception of a light interceptor. Given the fact that the target's very high speed substantially reduces reaction time, the interception would have to take place at distances that are above existing endo-atmospheric interceptors' ranges (below 50 km against complex missiles). In parallel, most of the flight of the interceptor would take place in a dense atmosphere, imposing to propel it continuously, so that it can maneuver during the flight and have sufficient energy at the end of the trajectory to engage the target. High-performance ramjets, flying at speeds up to Mach 5, hold out the prospect of interception of targets flying at high supersonic speed but also at the low end of the hypersonic speed. This solution is much more reliable than a scramjet and more effective than bulky solid propellant interceptors. The interception range can be substantially increased and brought to around 100 km, without unduly increasing the weight of the missile. Despite the fact that such an interceptor would not be able to engage maneuvering vehicles deployed by strategic-range delivery vehicles, it would still remain effective against hypersonic targets deployed by short- to medium-range vehicles, but also against scramjet-powered missiles, high-supersonic missiles and agile aircrafts operating at long range. However, the development of a high-performance ramjet requires significant technological progress in the fields of materials, navigation and guidance, propellants and flight management. All these technologies would be reusable in the design of hypersonic systems.

- ***Materials***

The design of an interceptor powered by a high-performance ramjet raises issues related to materials very similar to those posed by hypersonic technologies. For this kind of missile, the intensive use of composite materials will be required, to lighten structures - for instance, these ceramic materials can replace titanium - but also to resist heating and abrasion, on the structures as well as in the inner part of the missile. The use of composite materials based on ceramic matrices offers interesting possibilities for external structures (leading edges, air intakes, aerodynamic surfaces) and for engine components. Research on composite materials is also crucial with regard to guidance. They are critical in the design of radomes and optical windows that are resistant to very high temperatures. Research focuses in particular on silicon carbides, which offer advantageous thermal and structural performances at acceptable costs.

The sharp increase in relative interception speeds also requires to extend the range of the interceptor's terminal guidance systems in order to provide the missile with enough time to adapt its trajectory to the target's movement. Tripling the radar detection range can lead to an increase in the power of an antenna by a factor of 20 and requires the development of a new generation of components. Combining electromagnetic and infrared sensors into a single sensor also represents a critical research line. The development of high-performance terminal guidance systems is one of the major challenges in the development of very high velocity interceptors. In parallel, the need for high maneuverability may lead to design new steering systems, mixing aerodynamic surface and pyrotechnic device, in order to reduce reaction time of aerodynamics actuators.

- ***Algorithms and artificial intelligence***

Missiles propelled by high performance ramjet, flying at high speed in the atmosphere and intercepting target at hypersonic relative speed cannot rely on the traditional navigation and control systems to achieve their objectives but also on current algorithms. The complex flight domain management of the high performances ramjet must be adapted to advanced guidance laws, taking into account the high velocity and maneuverability of targets. The more systematic use of artificial intelligence thus seems desirable, both in the management of the missile's behavior and in its relationship to the architectures and engaged targets. Besides, it is difficult to conceive that such interceptors would not be integrated into highly automated or even partially autonomous sensor architectures also managed by artificial intelligence.

- ***Alternative propulsion***

The need for high velocity maneuverable interceptors could lead to the use of liquid propellants, that are more energetic than current solid propellants. Green propellants, currently being developed in space propulsion to replace hydrazine and its derivatives, offer interesting prospects with an energy potential approximately 30% higher than solid propellants. However, it features higher complexity and a higher inert mass, in particular due to the engine required for propulsion. The concrete advantages of reintroducing liquid propulsion for interceptors have to be assessed thoroughly, knowing that being stable, less polluting and toxic as well as impact-resistant, green propellants can nevertheless provide solutions for second stages of light missiles, as evaluated a few years ago in the United States on AMRAAM. They could represent an interesting option for the propulsion stage designed to operate at high altitude, when a ramjet or a scramjet is no longer effective. They can also eventually represent credible alternatives to solid propulsions for long-range interceptors.

Industrial inputs and civil benefits

The definition of a family of new-generation of ramjet interceptors is not exclusively a military issue, since the critical performance of the propulsion and the challenge linked to navigation, guidance, control and operation are such that their development will rely on numerous civil technologies. A similar approach to the US approach on hypersonic technologies should be observed: as early as the 2000s, the U.S. situated hyper-velocity in a strong civil-military dimension, aiming to promote access to space through the development of low-cost propulsion systems and, more virtually, to develop air transport.
In a long perspective, high performance ramjet may be used in combined propulsion for reusable space launchers, notably in the framework of reactive launch strategies for microsatellites in low orbit. Moreover, the optimization of ramjet performances and their combination with turbojet propulsion is announcing the development of high-speed fuel-efficient aircrafts. As a result, more immediate developments can be expected in air transport and military aviation.
Technically within reach, especially with regard to air transport and military aviation, the development of such aircrafts will nevertheless demand advanced composite materials, with very high mechanical resistance, but produced at lower costs. The search for synergies between the defense, space and air transport sectors must therefore be optimized. Such an approach could permit already successful industrial sectors in Europe to identify sustainable opportunities. Additive printing is also likely to reinforce this transformation, not only by lowering costs, but also by making production lines more flexible. This is one of the areas where the contribution of military technologies is likely to have the most direct impact on the civilian sector.
The industrial logic is probably strictly reversed in terms of artificial intelligence. The dynamism of the civilian sector is such that the nature of the involvement of military research can be questioned. An excessive dependence of the defense industry vis-à-vis civil industry may indeed generate major vulnerabilities, since artificial intelligence systems that can be foreseen for anti-missile

defenses will be responsible for managing complex systems of systems, which will rely heavily on data. Ignoring the specificity of the military system may ultimately lead to the integration of uncontrolled artificial intelligence elements, which could cause weapon systems to malfunction without the operators being able to fix the problem. This issue goes far beyond air and missile defense, but this represents one of the military sectors where the integration of artificial intelligence will be the fastest and most complex, requiring the defense industries a thorough reflection to adapt to this challenge.

The prospects offered by green propellants are easier to anticipate, with environmental concerns (REACH regulation in Europe) pushing for the replacement of hydrazine and its derivatives for space launchers. Although the environmental impact of missile propellant is much less important than that of space launchers, the example of depleted uranium munition shows that the defense sector cannot neglect environmental factors. Moreover, research on green propellants in the defense industry will participate in a broader dynamic, with potentially significant consequences for both civilians and defense industries. The more systematic use of stable, low-toxicity and high-energy ergols could reconfigure considerable parts of the industry for heavy propellers in favor of liquid propulsion. The emergence of reusable and reactive launcher technologies increases the probability of such a development. Therefore and although space propulsion differs from small diameter missile propulsion, there are obvious technological synergies.

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