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A Vision for Passive, Proliferated Sensor Networks

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A Report of the CSIS Missile Defense Project

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Contents

Bringing Proliferated Sensing Down to Earth

The diffusion of precision strike has made air and missile defense (AMD) more necessary–and more of a target. Widespread surveillance and targeting capabilities have made it easier for adversaries to find weaknesses in AMD systems, while standoff munitions have expanded their reach in attacking them.[1] As service strategies now emphasize, U.S. forces may more often find themselves fighting within an adversary's "weapons engagement zone."[2] In this environment, survival not only depends on dispersing or concealing, but on proliferating: presenting so many targets that an adversary cannot defeat them all.[3]

Proliferation has thus become a common theme in military strategies and acquisition plans. The Pentagon has embarked on major efforts to build affordable mass, buying fleets of drones and replacing handfuls of satellites with hundreds.[4] New operational concepts offer frequent refrains about how proliferated assets–especially in the air and space domains–will improve performance and survivability.[5] Those insights should now be applied to the air and missile defense mission.[6]

Much remains to be done to bring this philosophy to earth. Today's AMD sensors still consist of "a relatively small number of dedicated assets with high-emission signatures" that are susceptible to suppression.[7] Achieving a more survivable sensor architecture will require many means of camouflage, concealment, and deception, such as radar signature management and decoying. Another approach could be to supplement these scarce and exquisite radars with a network of proliferated, surface-based sensors, allowing AMD networks to withstand "the specter of complex and integrated air and missile attack."[8]

Iranian state media released videos of an IRGC naval exercise in 2020, including the above still frame depicting a Hormuz surface-to-surface missile striking a replica of the American TPY-2 radar during Iran's "Great Prophet 14" exercise

Photo: IR of Iran Broadcasting[9]

Proliferation alone is insufficient for survival; it will be equally important to reduce the observability of AMD sensors.[10] The energy emitted by AMD radars offers a signature for adversaries to target (see photo above).[11] The use of passive systems—sensors that receive energy rather than emit it—can therefore make a meaningful contribution. Historically, passive sensors—including electro-optical/infrared (EO/IR), acoustic, and radiofrequency sensors—have lacked the range and resolution of traditional air defense radars.[12] Yet when combined in a mesh, with modern machine learning systems to make sense of them, passive sensors hold considerable promise, not only for tracking targets, but also for building a more capable and resilient defense.

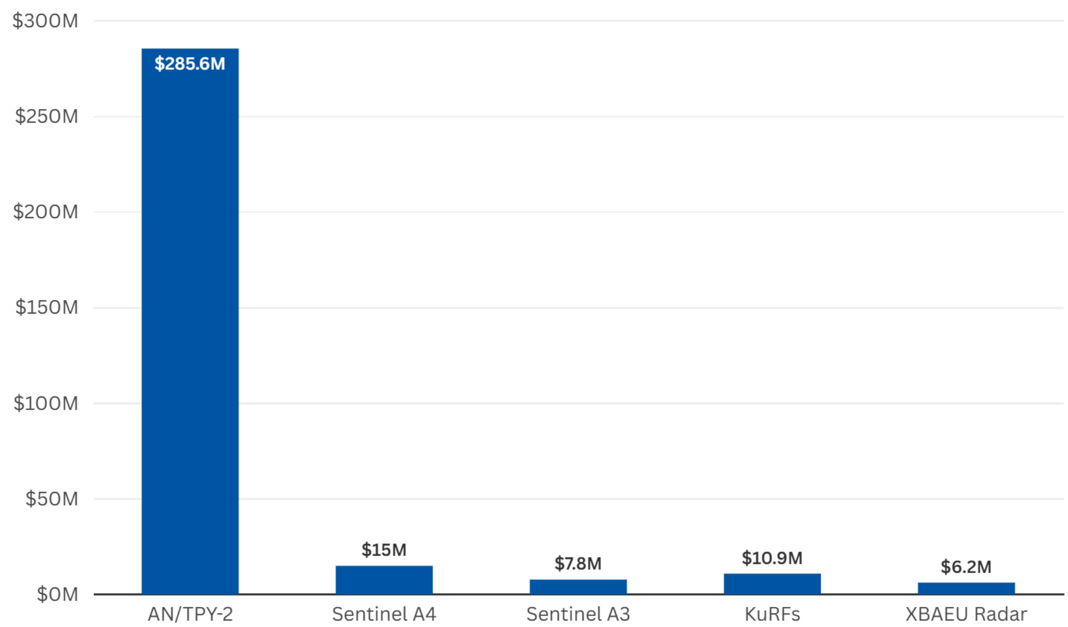
"Because Army forces employ an increasing number of capabilities that emit electromagnetic radiation that enemies can target, leaders must apply emission control measures . . . As risk to the force increases, leaders increase their emissions control measures."

U.S. Army FM 3-0: Operations (2022)

A new vision is needed to make AMD sensor architecture more passive and proliferated, augmenting the active sensors at its core. The technical means to do so largely already exist. Ukraine has deployed acoustic sensor networks, like its over 9,500-sensor Sky Fortress system, to conserve the use of high-end AMD radars and foil Russian air attacks.[13] While related operational concepts have been explored for years, the need to field them has grown more urgent.[14] Their benefits will become even more important should a direct conflict between the United States and another strategic peer arise.

To explore this vision, this report considers passive and proliferated sensor networks for detecting three threat categories: aerial threats, hypersonic weapons, and ballistic missiles. A notional architecture of meshed passive sensors, with analysis of site selection, logistics, weather, and other considerations, informs this alternative vision for air and missile defense. The report's first section will review passive and EO/IR sensing as a modality, contrasting it with radar and other methods. The second section will construct a notional defense design of meshed EO/IR sensors, assessing implications for mission planning, sustainment, networking, and all-weather operations. EO/IR is not the only form of passive sensing, and it has many challenges. Understanding those challenges, however, will help underscore the different considerations needed for broader integration of passive sensor architectures.

Figure 1: Estimated Radar Unit Costs (FY 2025 dollars)



Radar cost data derived from public purchases, reported in successive president's budget requests.
Source: CSIS Missile Defense Project; data from the Department of Defense Comptroller.

BOX 1

Ukraine's Sky Fortress and Zvook: Acoustic Sensing for Air Defense

Long before the invention of radar, air defenders relied on acoustic devices–rudimentary listening horns and ear trumpets–to detect the sound of incoming aircraft.[15] Now, with air defense radars in short supply and under constant attack, Ukraine has reintroduced acoustic methods for detecting Russian drone and missile strikes.[16] Their successful employment against Russian and Iranian drones has helped reinvigorate interest in passive, proliferated sensors for air and missile defense.

Ukraine's acoustic sensor networks bear little resemblance to the horns used a century ago. Homegrown sensor networks like Zvook ["Sound"] and Sky Fortress connect hundreds to thousands of low-cost microphones across the battlefield, using artificial intelligence to classify, triangulate, and target incoming weapons.[17] These detections, when fed into Ukraine's Delta and Virazh command-and-control networks, can be accurate enough to predict drone positions, azimuths, and trajectories, cue air defense systems, and enable shootdowns–contributing to the defeat of 80 out of 84 drones in one recent attack.[18] The sensors pick up drones' distinctive sounds and cue the system, telling air defenders where to look.

These acoustic sensors can be proliferated in a way traditional air defense radar systems cannot. Unlike air defense radars, which can cost hundreds of thousands or millions of dollars per unit, each microphone in the 270-sensor Zvook network costs approximately $500 and consists of a small microphone, a plastic acoustic mirror, and support electronics.[19] Meanwhile, initial variants of the Sky Fortress system used repurposed Android smartphones in weather-resistant housings installed on cell towers, with roughly similar unit costs.[20]

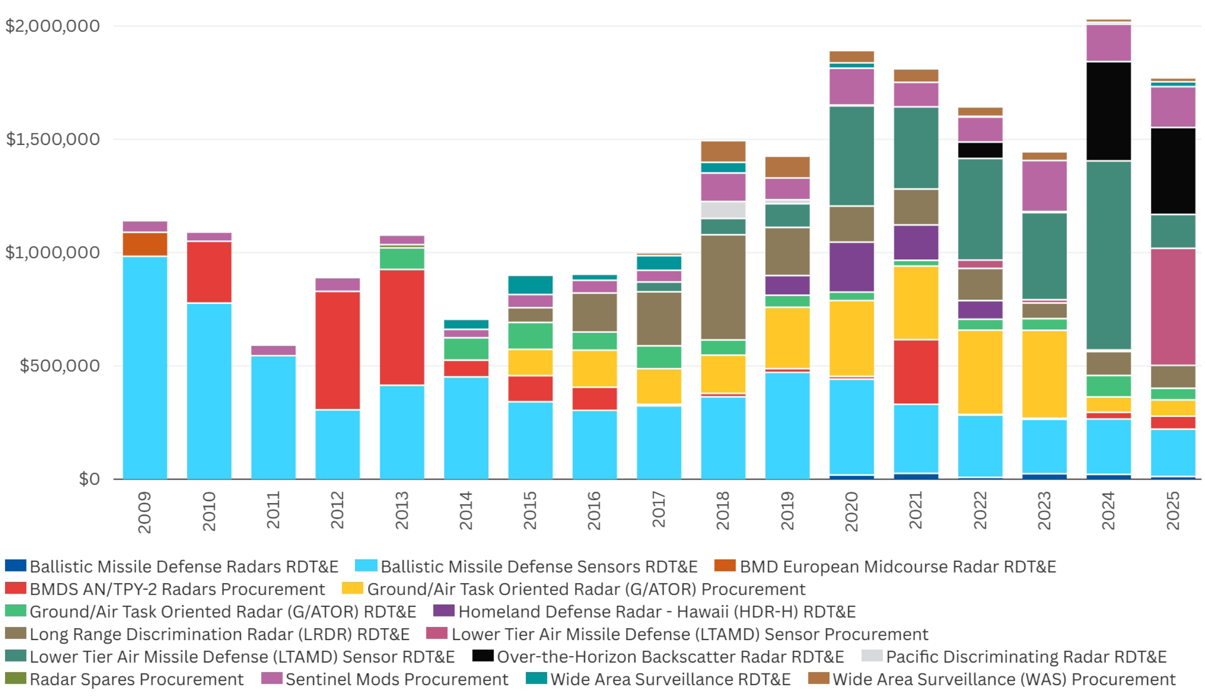
Despite their limited range–Zvook sensors can detect drones and cruise missiles at five and seven kilometers, respectively, and Sky Fortress can detect these at two–Ukraine has considerably expanded sensor coverage at minimal cost.[21] As of 2024, Sky Fortress numbered between 9,500 and 12,500 sensors, covering 80 percent of Ukraine's territory and costing roughly $3 million to roll out its first 65 percent.[22] Zvook is estimated to require 8,000 sensors to cover Ukraine, with similar unit economics. Most remarkably, both systems have been funded through private donations.[23]

Aside from being cost-effective, these acoustic sensor networks add novel capabilities to Ukraine's air defense networks. Emitting no radiofrequency energy, these sensors can locate targets within five-degree sectors, enough to cue air defense radar.[24] Where earlier attempts at acoustic sensing had detection rates as low as 76 percent, the Zvook system, continuously trained on threat sounds, reportedly detects targets at a 98.4 percent rate.[25] Further, the deep learning algorithms powering these networks can classify munition types by sound–so accurately that Russia has attempted to alter or muffle drone engines (to little effect).[26] Additional developments might allow the deployment of acoustic sensors at sea and to directly guide defensive drones and effectors.[27]

These characteristics pose a substantial challenge for Russian attackers. Unlike radar, acoustic sensors do not emit radiofrequency energy, which Russia might normally use to locate them. The sensors themselves can be deployed in austere locations, with minimal size, power, and communications bandwidth requirements. And by cueing air defense radars to target incoming threats, they enhance the survivability of entire air defense networks, shrinking the window of time for high-end radars to radiate and potentially reveal themselves.[28]

These sensor networks exemplify an emerging paradigm in air defense sensing: increasingly proliferated, passive, and robust. While these sensors cannot provide high-fidelity target tracks, they are good enough to confirm the presence of potential low-flying threats, route defenders, and cue defensive radars.[29] Ukraine's Virazh air defense planning system now ingests 40 unique data sources–acoustic sensors, legacy Soviet radars, and even user-submitted missile sightings–to build an air picture.[30] The quantity and diversity of sensors, as well as their tight integration, has allowed Ukraine to preserve its air defenses amid significant resource constraints.

Figure 2: Ground-Based AMD Sensor Modernization Programs, 2009–2025



Source: CSIS Missile Defense Project; data from the Department of Defense Comptroller.

The Passive Sensing Paradigm

Today's ground-based air and missile defenses largely depend on radar to spot incoming threats. In many ways, radar is an ideal modality: With only a single sensor, an air defense radar can resolve the position, velocity, and heading of a threat in three dimensions, day and night, with limited interference from harsh weather conditions. As such, many of the back-end algorithms used to track threats, identify friends and foes, and complete interceptions were developed in the radar age. Existing air defense systems are highly capable, but they are also single points of failure, emitting energy that can be detected.[31]

Passive sensors, including EO/IR sensors, represent a different paradigm. Radar must radiate energy to illuminate targets and detect them. The required energy supply only increases with distance; for the radiofrequency beam to shine even further, larger antennas, or multiples more energy, are needed. By contrast, EO/IR, acoustic, and passive radiofrequency sensors simply collect the energy emitted from the threat objects themselves.

Passive sensing presents some advantages for survivability. Radar emissions can betray defenders' locations, making them vulnerable to attack. By not emitting energy, passive sensors make it challenging for adversaries to find and suppress air defenses. EO/IR represents one category of passive sensing, but it is not the only one. Ukraine's Sky Fortress consists of acoustic sensors that listen for sound energy. Their microphones do not emit easily detectable signals, and neither do the passive radio receivers of the U.S. Army's Long Range Persistent Surveillance (ALPS) system (Box 2). Passive sensors have been explored for survivable air defense detection, and as a category they are now worth revisiting, with the aim of spreading sensors with smaller power, emissions, and operational footprints through the battlespace.[32]

BOX 2

Passive Radar

While not investigated in this case study, passive radar encompasses a family of approaches for detecting airborne targets without emitting radiofrequency emissions. A typical method is to detect incidental wireless broadband or TV signals that reflect off of them: so-called "emitters of opportunity."[33] When profiled correctly, these opportunistic reflections offer unique signatures, aiding the detection of low-flying or low-observable targets.

Passive radar has historically required considerable computing power to function, processing many signal returns from multiple emitters of opportunity.[34] As such, exponential improvements in computing hardware have made these systems more viable than before.[35] Advancements in computing, along with other innovations, like in photonic signal generation and processing, may further drive passive radar's range and precision.[36]

Multiple services have already begun to develop and deploy passive radar systems. Systems like the Army Long-Range Persistent Surveillance (ALPS) sensor offer the wide-area detection needed to detect low-flying, low-signature systems like cruise missiles, and have already been deployed to the CENTCOM, EUCOM, and INDOPACOM theaters.[37] Further development of the ALPS system, budgeted at $31 million in FY 2025, is expected to continue through 2029, with new hardware to be fabricated by 2027.[38]

Army Long-Range Persistent Surveillance (ALPS) passive radar.

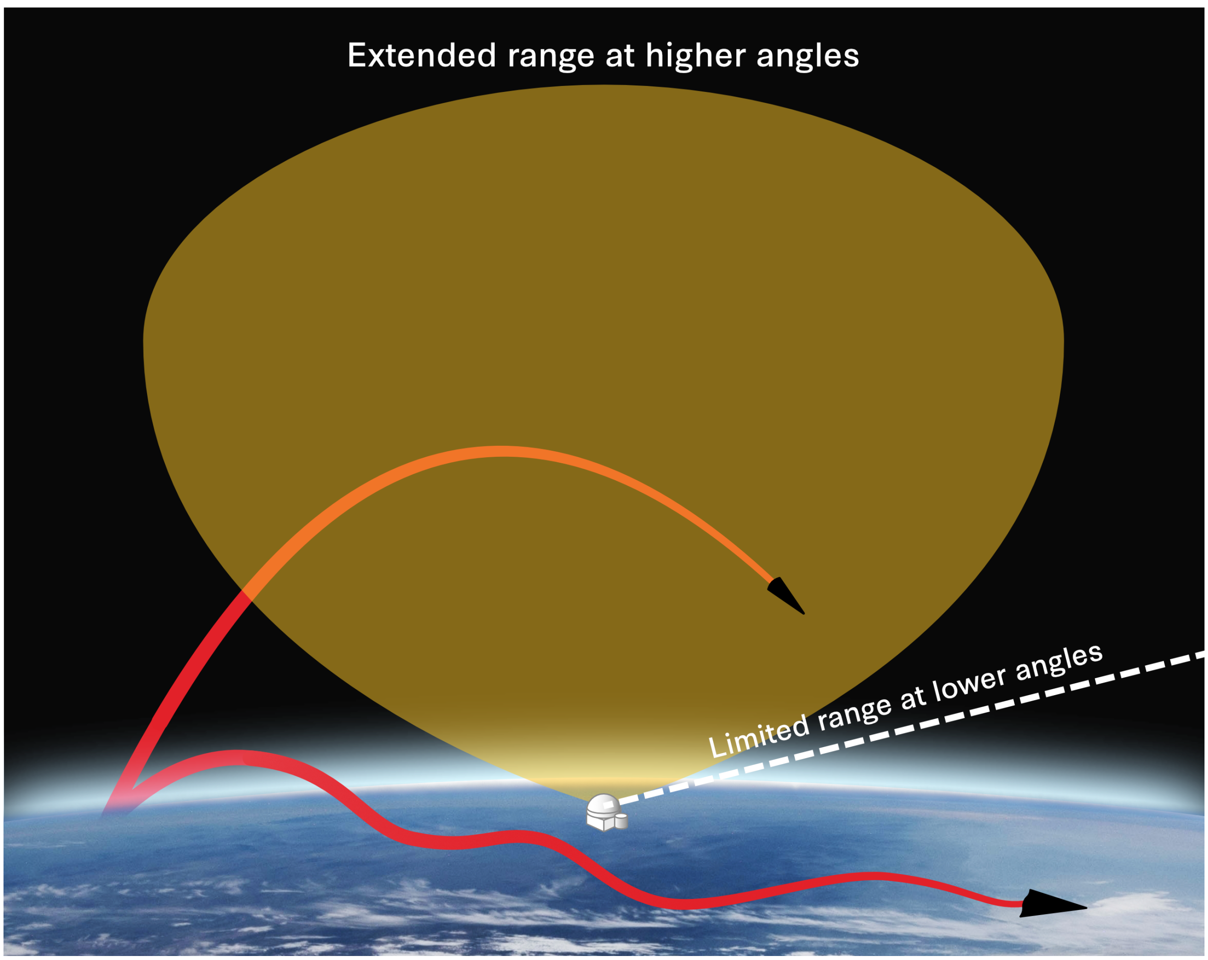
Photo: Leidos

The EO/IR sensors assessed here present significantly different tradeoffs in power, footprint, and range. Because they passively detect their targets' infrared emissions, they consume less power; these advantages become especially pronounced with faraway targets like satellites. A sensor network that simultaneously enables space situational awareness and hypersonic cueing has now become possible.

Unlike radar, however, the EO/IR sensors assessed in this case study do not detect targets in three dimensions, and detection can be significantly attenuated by turbulence, clouds, haze, and the position of the sun. Still, EO/IR sensors offer a novel mix of capabilities, with the potential to serve as space surveillance assets and lower-tier air defense sensors at once.

One tradeoff to consider is these sensors' field-of-view and viewing angle limitations. Many ground-based systems, including radar and EO/IR sensors, face range limitations at lower viewing angles.[39] At low angles, the amount of atmosphere an EO/IR sensor must peer through increases, with more absorption and scattering effects that interfere with detection.[40] The detection range of an EO/IR sensor thus depends heavily on the elevation of the target. Looking directly above, an EO/IR sensor may be capable of detecting satellites over 1,000 kilometers overhead—much further than a lower-tier air defense radar. At 20 degrees of elevation, however, the EO/IR sensor may only be capable of detecting aircraft tens of kilometers away (Figure 3).[41] The coverage of such a sensor looks less like a dome and more like an ogive, with the furthest detection distances at the highest point (Figure 3).

Figure 3: EOIR Coverage Characteristics

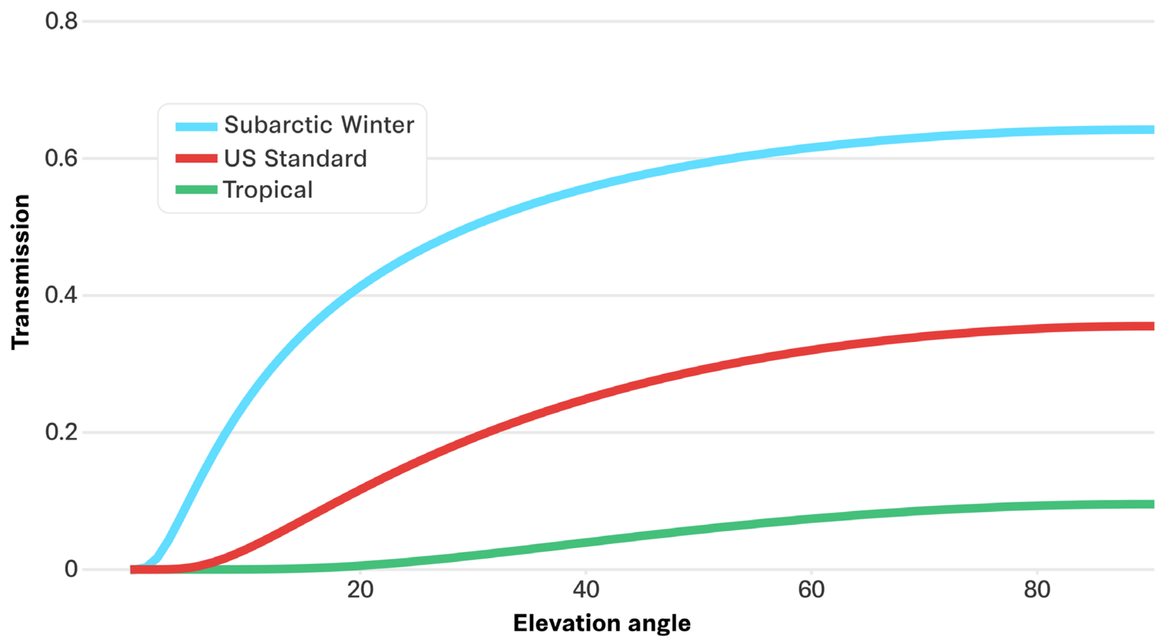


EOIR sensors offer extended performance at high elevations and degraded performance at lower elevations, presenting unique coverage advantages. Not to scale.
Source: CSIS Missile Defense Project.

Another consideration involves weather sensitivity: The range of EO/IR sensors can be dramatically affected by weather changes and by the sun's position relative to a target. Infrared light does not penetrate weather and atmospheric conditions as readily as radio waves do. In hazy weather conditions, it can be expected that detection distance might fall by orders of magnitude.[42] While radar can also be subject to weather-related disruptions, planning EO/IR sensing missions would need to involve greater attention to, and prediction of, weather change (Figure 4).

Finally, a single EO/IR sensor does not resolve target data in three dimensions. With only a two-dimensional field of regard, a sensor's functionality may be limited to space surveillance or radar resource management, rather than air and missile defense. With space-based tracking, coverage with two sensors at once (known as stereo tracking) is necessary to triangulate a missile's position and track it in three dimensions. Nevertheless, it may become possible to combine EO/IR sensors with radar or (low-emission) laser ranging sensors, as Germany did in its 1990s Reconnaissance and Engagement of Air Targets (Aufklärung und Bekämpfung von nicht ballistischen Flugkörpern) program, or ABF, which derived actionable cueing data with only one sensor (Box 2).

Figure 4: Ground-to-Space Atmospheric Transmission by Elevation, Mid-wave Infrared (MWIR) (5 μm), Various Atmosphere Types (LOWTRAN 7)



Atmospheric transmission is highest at high elevations and lowest at near-horizontal elevations, where lower-altitude threats fly. Look angle can substantially influence the range of an infrared sensor. At lower elevation angles, a sensor must look through a substantially longer column of air, with associated haze, turbulence, and extinction (attenuation) effects. EO/IR sensors perform best when witnessing targets at near-vertical angles.
Source: CSIS Missile Defense Project; data from the Department of Defense.[43]

In sum, EO/IR sensing offers favorable characteristics compared to radar: reduced size and power, no radiofrequency emissions, increased sensitivity to weather conditions, increased range against high-altitude targets, and decreased range against low-altitude targets. For these reasons, EO/IR approaches remain dominant for space-based sensing, with their tight constraints on size, weight, and power. Similar considerations apply to proliferated sensing on Earth—EO/IR sensors can operate in remote locations, unattended, and with minimal power.

A case study on EO/IR sensors stands in sharp contrast to the philosophies guiding air defense design today. Passive sensors do not have to replace active ones to be relevant. Identifying both the strengths and limitations of EO/IR sensors is critical to determining their place in a defense design.

A Reaper UAV with MTS-C infrared missile-tracking sensor.

Photo: Missile Defense Agency

BOX 3

Germany's ABF Advanced Technology Demonstrator

The use of EO/IR sensors for ground-based air defense has been successfully demonstrated before. One such example was Germany's Reconnaissance and Engagement of Air Targets (ABF) prototyping effort, which ran from 1997 to 2003.

To meet requirements for survivable, non-emitting sensors—termed "silent-mode air surveillance"—Germany's Ministry of Defense (MoD) contracted the firm Diehl VA/BGT to develop ABF in 1997. The initial system adapted existing imaging infrared seeker technologies to produce a ground-based sensor capable of detecting air targets at distances of up to 20 kilometers, depending on target signature and weather. The system occupied a roughly refrigerator-sized footprint.

Photo: NATO STO.[45]

The ABF camera system consisted of four wide-angle search sensors and a higher-resolution verification sensor.[44] Each search sensor used a mid-wave infrared sensor with a 256-by-256-pixel resolution; these were housed on a horizontally rotating platform covering a 360-degree azimuth. Each sensor could cover a negative 5 to positive 80-degree elevation angle using a mechanically stepped optic, providing different fields of view for different elevation angles. The sensor operated with a 9-degree field of view at lower elevation angles and a 23-degree field of view at the highest, where background clutter was lower.

Due to their lower resolution, ABF's search sensors were only capable of detecting potential targets, requiring a second, higher-resolution sensor to distinguish them from clutter and other objects. This verification sensor was housed on a movable gimbal and had a similar resolution with a narrower field of view of 1 degree.[46] Accepting cues from the search sensors, the sensor would slew to confirm potential targets.

While EO/IR sensors usually resolve targets in two dimensions, ABF could track targets in three dimensions by integrating a laser rangefinder with its camera system. The rangefinder, housed alongside the verification sensor, would derive the range-to-target data needed to triangulate a target's position and calculate velocity and heading.

The MoD first successfully tested ABF in late 1999. On a test range in northern Germany, ABF successfully tracked several drones, attack aircraft, and helicopters flying various maneuvers, as well as head-on launches of several SA-7 surface-to-air missiles in the near vicinity. The ABF test and development program concluded in 2003. Since then, the MoD has focused its EO/IR sensing developments on seekers and missile warning systems such as the Passive IR Missile Warner (PIMAWS) advanced technology demonstrator.[47]

The technologies behind each of ABF's major components have improved dramatically since 1997, making it reasonable to believe that modern approaches could offer considerably better performance. Resolution is often a limiting factor for EO/IR sensor performance and field of view; yet today, 1028-by-1028, 2000-by-2000, and 4000-by-4000-pixel-resolutions are a commodity product, in comparison to the 256-pixel resolutions considered for ABF.[48] The target-detection methods used by ABF—basic local contrast, high-pass and statistical correlation algorithms—have been eclipsed by recent advancements in machine learning and computer vision.[49] The hardware used to ingest, store, and process image data is also now orders of magnitude more capable.[50] Where ABF's designers discussed gigabit sensor data rates as a design limitation, today's consumer-grade cameras offer multiple gigabits of data transfer speed.[51] Although the physics of EO/IR sensing remain unchanged, the cameras, computer hardware, and vision algorithms enabling it have benefitted most from recent technical change.

Defense Design for Meshed Sensors

"[The United States] must build the resiliency of our constellation of sensors . . . from the seabed to the Karman Line. It must be resilient. It must be redundant. It must include the elements of graceful degradation, so that if one thing is out, it's just a small loss in capability but it still provides enough. And we've got to work tirelessly to close those gaps."

Samuel Paparo, INDOPACOM Commander[52]

Many considerations affect the design of a proliferated sensor network, including line of sight and terrain obstruction, sustainment and mobility challenges, network bandwidth, and weather constraints. Site selection for a sensor mesh of hundreds or thousands of sensors is a fundamentally different problem from the siting of only one—a problem that is no longer solvable with current planning approaches. Efficiently covering a battlespace with distributed sensors is not an exercise in placing arbitrary grids.[53] Indeed, the task of designing sensor meshes for complex terrain is famously difficult.[54] It is a form of mathematics' famous "art gallery problem," where discovering the minimum number of assets needed is formally impossible.[55]

To unpack these considerations, this report constructs a notional laydown of proliferated EO/IR sensors in Poland. The geography of Poland offers a useful test case for considering meshed sensors, with a mix of relevant topographies and an area comparable to theaters of interest, including in the Indo-Pacific. Initial laydowns were derived from a custom Python script that imports an open-source digital elevation model (DEM) of the area and calculates the sensors' lines of sight against targets at varied altitudes. The script implements a genetic optimization algorithm

(NSGA-II) and binary search to approximate a sensor laydown that provides 99.5 percent coverage with the minimum number of sensors.

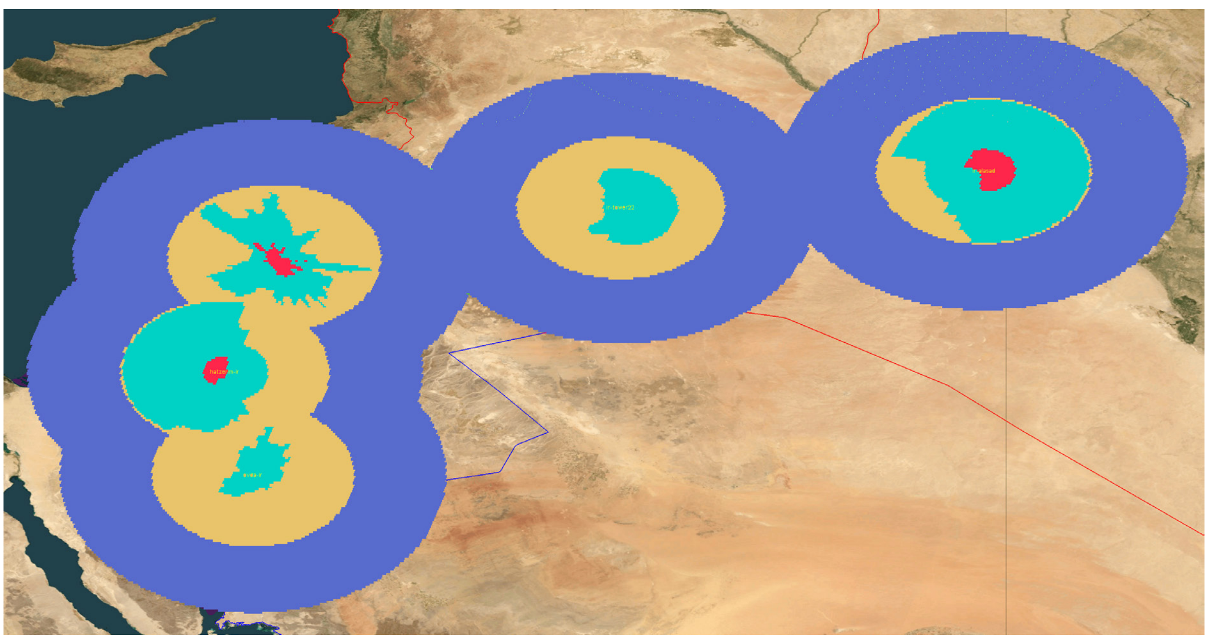
The resultant laydowns were then imported to SmartSET, an air and missile defense planning tool, to model specific engagements. The research team constructed an attack scenario involving 20 generic intermediate-range ballistic missile threats—including lofted and depressed trajectories—and four generic hypersonic glide vehicles.

The following imagery and sections describe the considerations made in this case study. On the whole, the study demonstrates the important contribution that meshed, passive sensors can provide to an air and missile defense design. They do not replace radars, but such networks can usefully improve the detection, tracking, and warning time of an architecture.

MISSION PLANNING CONSIDERATIONS

Ground-based sensors face limits to their ability to track low-flying airborne targets. Both Earth's curvature and surrounding terrain features block ground-based sensors' line of sight at lower viewing angles, limiting maximum range (Figure 5). This is why deployments at higher elevations are often preferable: While a 5-meter-high, mast-mounted sensor could view a low-flying cruise missile (250-meter altitude) as far as 64 kilometers, that same sensor on a 5,000-meter aerostat could see as far as 309 kilometers, or 382 percent further.[56]

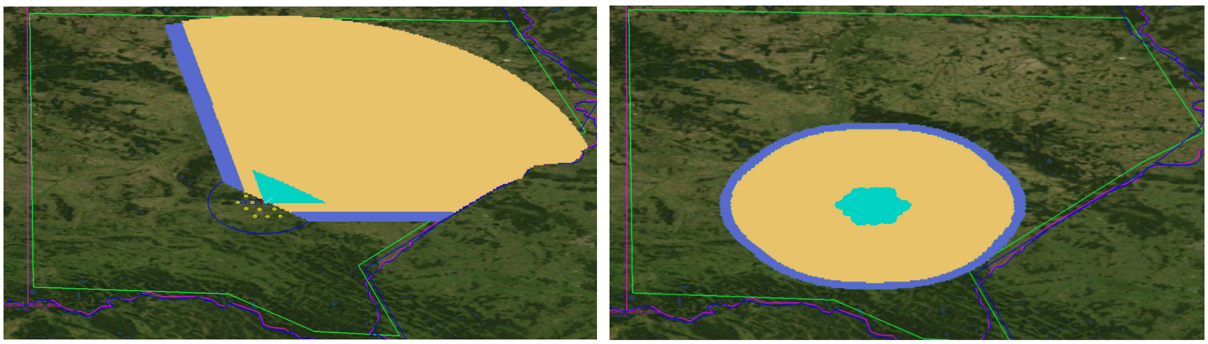
Figure 5: Line of Sight Constraints Against Unmanned Aerial Systems (UAS), Aircraft, and Hypersonic Threats



Surface-based sensor coverage in this Middle East scenario is dramatically affected by surrounding terrain and target altitude. The coverage of various threat classes is shown in different colors, with 250-meter altitude threats in red, 1000-meter threats in blue, 10,000-meter threats in yellow, and 20,000-meter threats in purple.
Source: CSIS Missile Defense Project.

These facts alone explain why proliferated approaches can be so valuable for ground-based sensor architectures. If high-end sensors already face line-of-sight constraints on their maximum range, a mesh of smaller, shorter-range sensors may perform similarly to a mesh of longer-range ones—at least against lower-flying targets. Alternatively, passive sensors with long detection ranges at high elevations, like EO/IR sensors, could bolster coverage against high-flying targets and satellites. Finally, a proliferated sensor network would allow sensors to be based in regions that offer multiple angles of view, allowing them to peer behind the coverage "shadow" cast by elevated terrain (Figure 6).

Figure 6: Coverage Footprints: Notional Patriot-Class Radar (1), IR Sensors (19x)



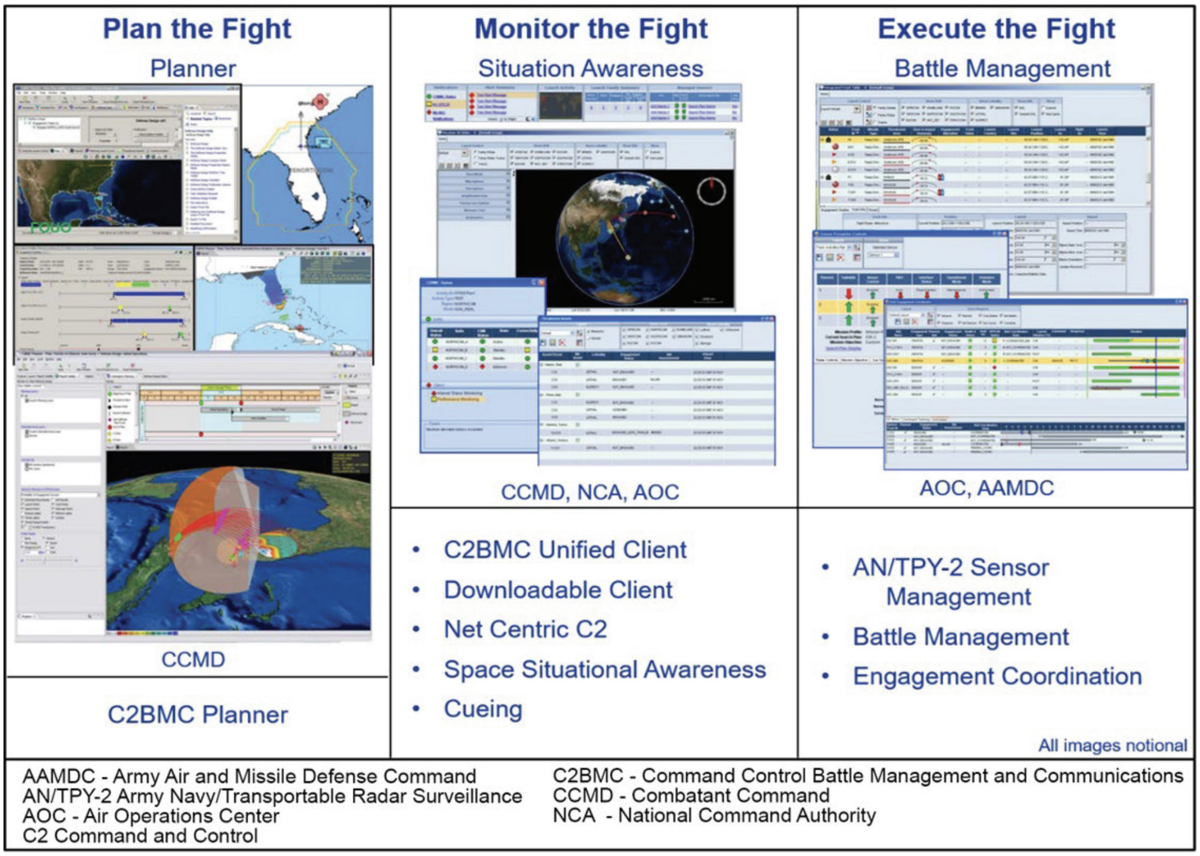
Coverage against 1 kilometer- (blue), 10 kilometer- (yellow), and 20 kilometer- (purple) altitude threats, assuming 10-degree elevation constraint on IR sensors and 5-degree elevation constraint on radar.
Source: CSIS Missile Defense Project.

The challenge, however, comes with planning meshed laydowns. To select a site for a single Patriot air defense radar system, Army air defense planners are instructed to "determine the optimum FU [fire unit] locations based on geographical constraints, assets to be defended, and threat AAAs [areas of approach]" using a color-coded elevation map, "visualiz[ing] ridges and valleys which define the most likely air avenues of approach."[57] Site selection for even an individual radar is an involved process in which potential missile launch sites, tactical mobility, and other considerations are accounted for (Figure 7). With more sensors involved, these problems balloon in complexity, involving "long lead times in many instances" and the coordination of multiple echelons of planners.[58]

> *"A defense design is usually focused on the capabilities of a single BMD element."*
>
> *FM 3-27: Army Global Missile Defense Operations (2023)*[59]

Computational approaches are needed to determine where to place proliferated sensors. In an era of single, exquisite sensors, this process may simply entail choosing the most elevated regions on the map. With large-scale networks, however, the complexity of this problem explodes, as each sensor's position affects the placement of others, and each sensor's coverage varies based on its position.[60]

Figure 7: Screenshots of Joint Sensor Placement Planning Utilities, Including C2BMC Planner

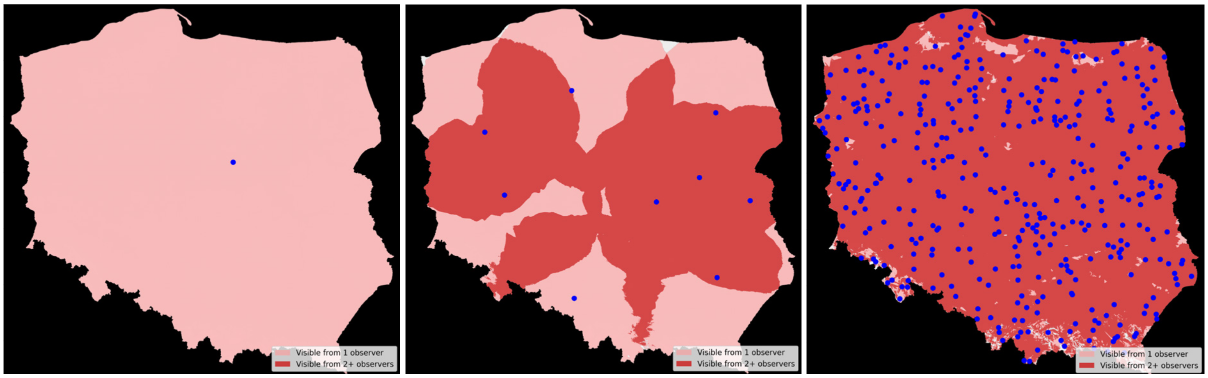


The U.S. Army describes C2BMC Planner as its software suite for "coordination of multiple theater defense designs into larger, regional defense plans," assisting in "optimizing sensor coverage and weapons systems placement before deploying an element." In an era of proliferated sensors, the magnitude of optimization problems these planning suites must solve will increase significantly. Source: U.S. Army.[61]

The task of maximizing coverage while minimizing the number of sensors needed—a so-called "covering problem"—is formally unsolvable. But heuristic algorithms can approximate a near-optimal design. The use of such methods to optimize air defense sensor laydowns, especially against low-flying, terrain-shaded targets, has been studied for some time. Some authors, for instance, have demonstrated a "greedy" heuristic: An algorithm searches a terrain map for the highest-covering point, places a sensor, and, with that area covered, searches for the second-best point, repeating until the map is covered.[62]

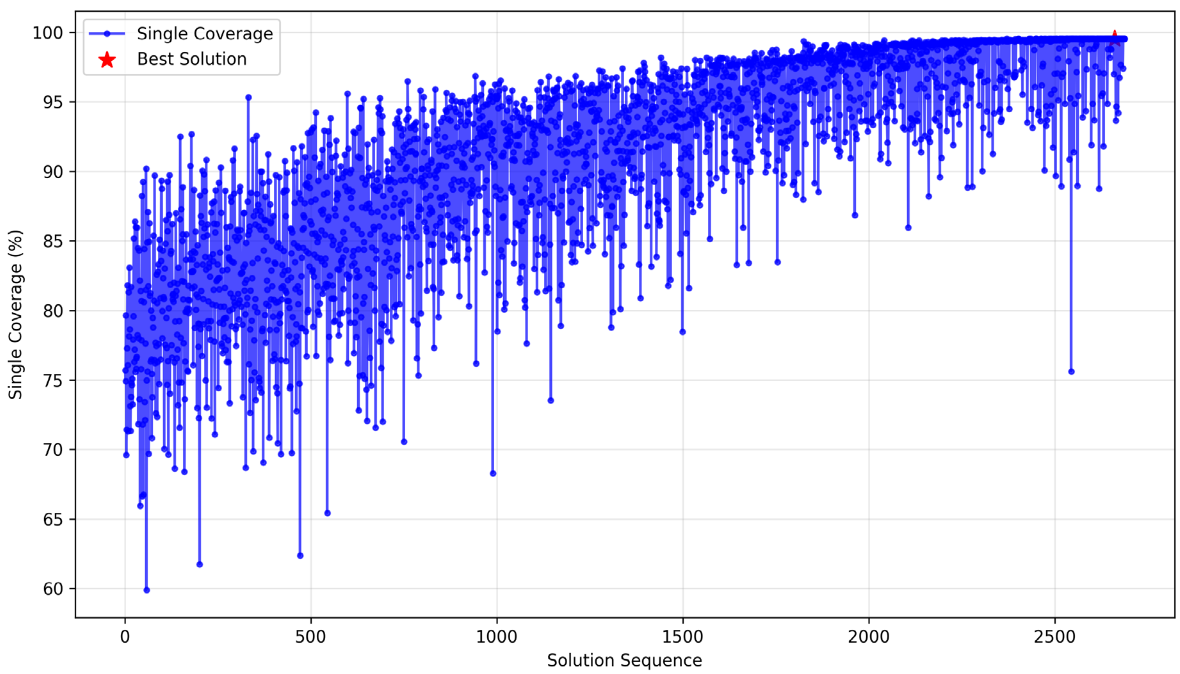
Another approach, employed here, is to use genetic algorithms to search for an optimal design. Using this approach, an algorithm repeatedly tests designs, iterating on the best performers and discarding the worst. This process, which approximates natural selection, eventually converges on a near-optimal design for maximizing coverage with the minimum number of observers (Figure 9). The configurations of these designs for hypersonic/ballistic missile, aircraft, and cruise missile/drone threats (Figure 8) were calculated over several days using a custom optimization script.

Figure 8: Optimized Ground-Based EO Sensor Lines of Sight for Hypersonic, Aircraft, and Cruise Missile/Drone Targets



The following images represent line-of-sight-optimized laydowns for covering Poland with meshed sensors. The number needed for 99.5 percent coverage changes significantly given the altitude of the target. Left: 20-kilometer target, 1 sensor. Center: 2-kilometer target, 9 sensors. Right: 200-meter target, 396 sensors.
Source: CSIS Missile Defense Project.

Figure 9: Optimization of Sensor Coverage over Time

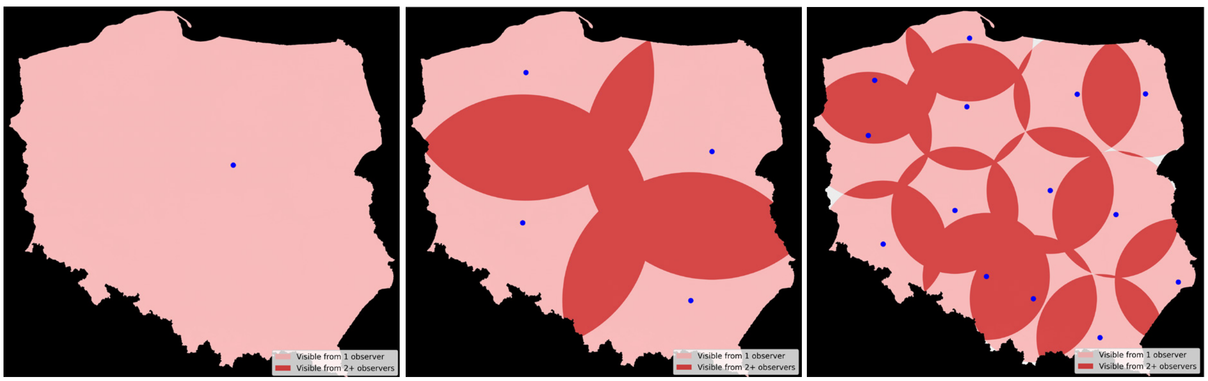


Source: CSIS Missile Defense Project.

What constitutes an optimal site selection depends on the expected altitude of the threat (Figure 8). To detect hypersonic and ballistic weapons—typically at altitudes over 20 kilometers—line-of-sight constraints are such that a single sensor with horizon-limited viewing angles could provide complete coverage. Against a 2-kilometer altitude target—like tactical aircraft—the number of sensors needed expands to nine. Against a target at 200 meters—typical of UAS—the number of sensors needed grows dramatically to 396.

These numbers would presumably expand even further if stereoscopic tracking—covering all targets with at least two sensors—were a requirement. To reduce computing time, these architectures were not computed in this study. Indeed, while many air- and space-based infrared tracking systems use stereoscopic viewing (two-sensor viewing) to resolve targets in three dimensions, several past EO/IR systems considered combined simple EO detection with laser rangefinding to do the same.

Figure 10: Sensor Coverage Requirements Against 20-Kilometer Altitude Hypersonic Threat, by Minimum Viewing Angle (Elevation)



Limits on a sensor's minimum viewing angle (elevation) can also affect the number of sensors needed for coverage. Left: no elevation constraints, 1 asset; Center: 5-degree minimum elevation, 4 assets; Right: 10-degree minimum elevation, 14 assets. Source: CSIS Missile Defense Project.

As emphasized before, however, EO/IR sensors face unique challenges in detecting targets at lower viewing angles, where the column of atmosphere through which they look is considerably longer. As shown in Figure 10, coverage of a 20-kilometer altitude, hypersonic-class target requires 4 sensors if viewing angles are restricted to 5-degree elevation or higher, and 14 sensors if viewing angles are restricted to 10-degree elevation or higher. For even larger architectures, these viewing constraints can multiply the required assets dramatically: Nearly 400 sensors are needed for counter-UAS coverage, for instance (Figure 8).

Air defense planning is challenging, and more sensors dramatically increase the computational intensity of mission planning, demanding new tools and approaches.[63] It is no longer a matter of manually searching for a highest point.[64] For such distributed systems to be viable, policymakers must tolerate larger numbers of sensors than is optimal, reduce the marginal cost of additional sensors, or procure mission planning systems capable of optimizing mesh sensor placement.

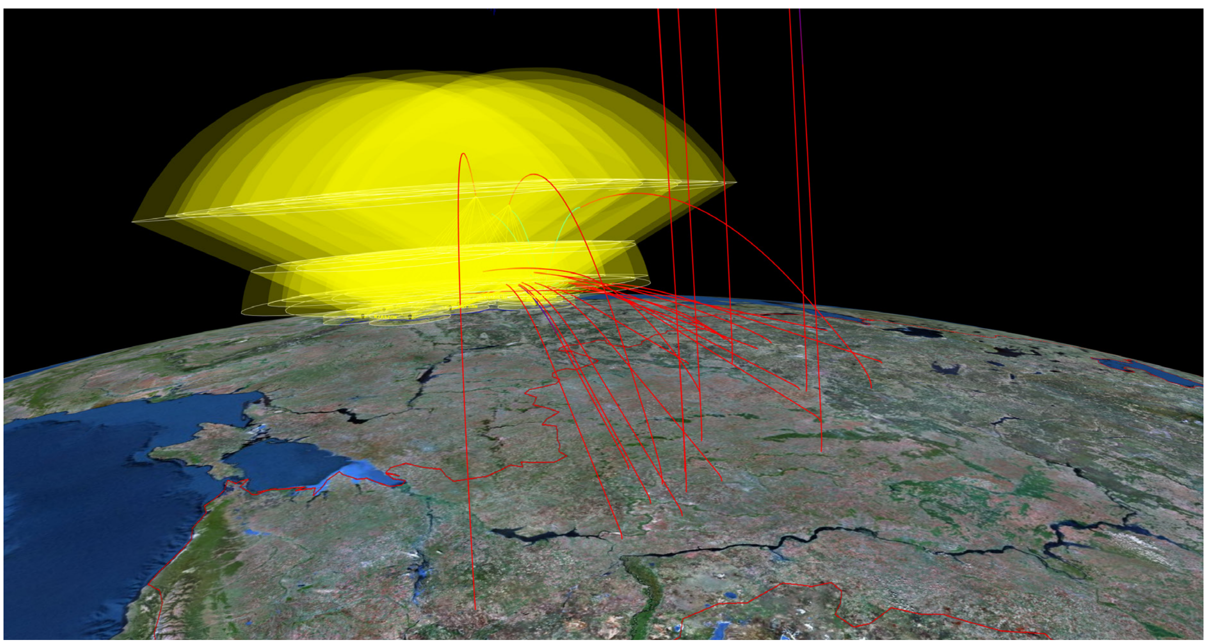
Nevertheless, there may be circumstances in which simplified laydowns might contribute. Even a forward picket of lower-tier sensors could aid existing radars, cueing them to search a specific volume, reducing the time they spend emitting, speeding target acquisition, and potentially extending engagement distances. As demonstrated in Ukraine, meshed sensors have allowed air defenders to keep high-value radars concealed in a non-emitting mode until needed.

As stressed above, the approach here represents a different philosophy, prioritizing emissions control and operational flexibility over raw radar capability. Even early and imprecise cues of a target's general position can extend the battlespace of existing systems and enhance their survivability.

These benefits can be illustrated by means of a scenario. In a notional attack drawn up for the purposes of this study, EO/IR sensors' long detection range at higher elevations allows for enhanced coverage against high-flying ballistic missile threats, with even a few assets providing useful coverage. Additionally, an EO/IR sensor mesh can enhance the survivability of existing radar architectures by reducing the amount of time a radar needs to be active.

In the attack scenario depicted below, the 14-sensor configuration developed in Figure 10 was emplaced in SMARTSet, a modeling tool for assessing specific engagements. The scenario involved a salvo of 24 missiles launched from Russia, including 4 notional hypersonic glide vehicles and 20 generic intermediate-range ballistic missiles (IRBMs), aimed at NATO facilities in western Poland.

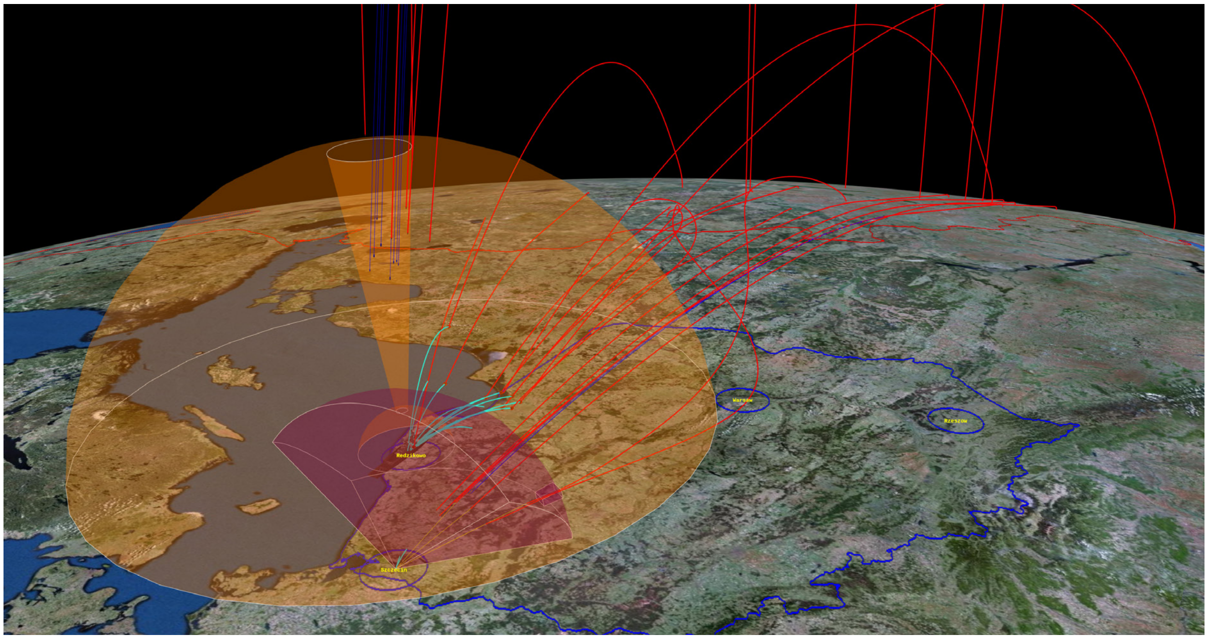
Figure 11: Meshed Sensor Design Imported into Attack Scenario



The resultant meshed sensor design of 14 assets, assuming reduced coverage at 10 degrees minimum elevation, was imported into SmartSET and tested against a simulated attack involving 20 ballistic missiles and 4 hypersonic glide vehicles.
Source: CSIS Missile Defense Project.

To model interceptions, a notional Patriot battery in Szczecin and the Aegis Ashore site in Redzikowo were included, both with and without the mesh of generic EO/IR sensors (Figures 11, 12). Given limitations on processing, each EO/IR sensor was modeled as being capable of providing 3D tracking individually, perhaps with an ABF-like laser rangefinding system (Box 3). If requirements on two-sensor stereo tracking become necessary, then it can be assumed that the number of sensors needed would be 28 or fewer.

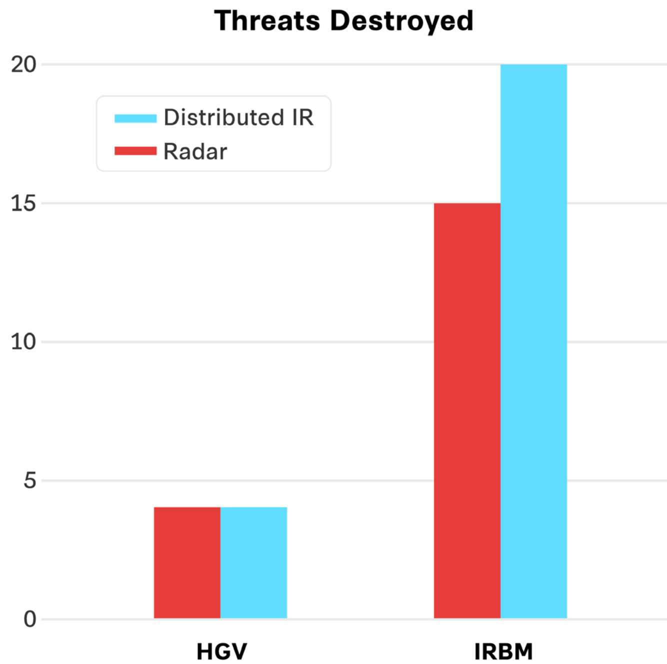
Figure 12: Comparison Defense Design (Notional Aegis Ashore, Patriot) and Attack Scenario



A reference sensor laydown, involving a notional Aegis Ashore and Patriot radar system and interceptors, was produced in SmartSET for comparison with the meshed sensor network. Both designs were equipped with a combination of notional Standard Missile and Patriot interceptors.
Source: CSIS Missile Defense Project.

While inputs were intentionally genericized, a comparison between a defense with meshed sensors and one without resulted in 26 percent more interceptions (five more IRBMs) with a sensor mesh (Figure 13). The architecture was also able to detect and engage targets earlier—up to 3 minutes and 44 seconds for one hypersonic glide vehicle target—on account of the forward-based sensors. These results illustrate one potential scenario for EO/IR sensor meshes to contribute to existing defenses, particularly for higher-altitude targets like hypersonic and ballistic missiles (Figures 11, 12, 13).

Figure 13: Engagement Scenario Intercept Results



Assuming such proliferated sensors provide sufficient data quality to support intercepts, an architecture equipped with distributed EOIR sensors intercepted 26 percent more missiles than one without, in the notional scenario depicted here.
Source: CSIS Missile Defense Project.

SUSTAINMENT AND MOBILITY CONSIDERATIONS

Deploying a distributed surface-based sensor mesh will involve specialized approaches to logistics and sustainment. While deploying many assets across wide areas will create new challenges, the use of lower-footprint sensors could reduce the high manning and transport requirements of existing systems. Moving a basic Patriot unit—a minimum engagement package (MEP)—requires up to seven C-17 flights (Figure 14). In early 2025, the task of moving just one Patriot battalion to the Middle East reportedly entailed 73 C-17 flights.[65] A proliferated sensor network, with broader distribution and leaner manning, might create new opportunities for strategic mobility and new challenges for tactical mobility.

> *"When choosing a location, staff planners must consider accessibility, connectivity, protection of sites, equipment, Soldiers, potential interference, and host nation support when planning to place the system in theater. An additional factor that must be considered during site selection is the need to protect friendly forces and facilities by dispersing of(sic) radio frequency emissions locations."*
>
> *FM 3-27: Army Global Missile Defense Operations (2023)*[66]

At a tactical level, deploying and resupplying many assets across wide areas will introduce novel, if solvable, problems. Logistical needs create new wrinkles for mission planners—requirements for proximity to roads, for instance, might add some constraints on the optimal placement of assets.[67] Requirements for physical protection of assets, meanwhile, could be mitigated with modern encryption and tamper resistance techniques, but manned protection of a sensor grid would pose an additional challenge.

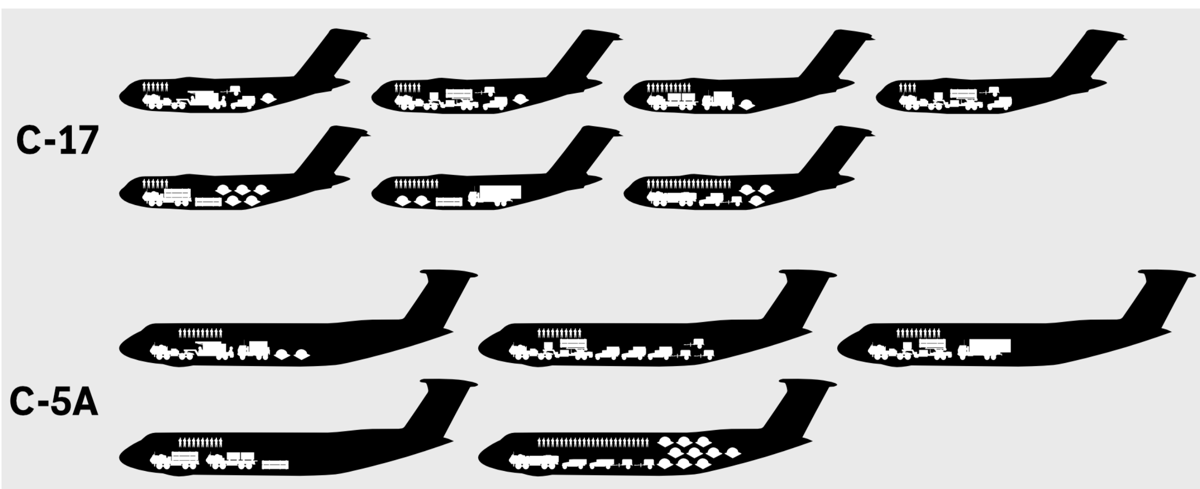
At an operational level, realizing proliferated sensor networks will require the services to further integrate existing analytic tools for mobility planning with air and missile defense mission planning. Sensors connected to centralized power supplies could open civilian power grids to enemy attack, demanding distributed grids with high-performance battery, solar, generator, or fuel cell supplies.

Additionally, the physical communications backbone that connects gridded assets will need engineering and placement as careful as that required by the sensors themselves.

To that end, the Joint Force could learn from prior experience in deploying distributed ground systems. Contemporary space surveillance telescope networks routinely deploy sensors in remote locations with minimal human attendance.[68] The Air Force, meanwhile, already operates a network of 400 unattended siloes for the nation's ground-based nuclear deterrent, relying on remote monitoring and anti-tampering measures to secure the force.[69] The Army's Patriot forces are likewise shifting toward using distributed communications nodes, such as the Remote Interceptor Guidance-360 (RIG-360), across the battlefield.[70] Finally, experience in Ukraine suggests that sensors could be collocated with existing assets, including cellular infrastructure.

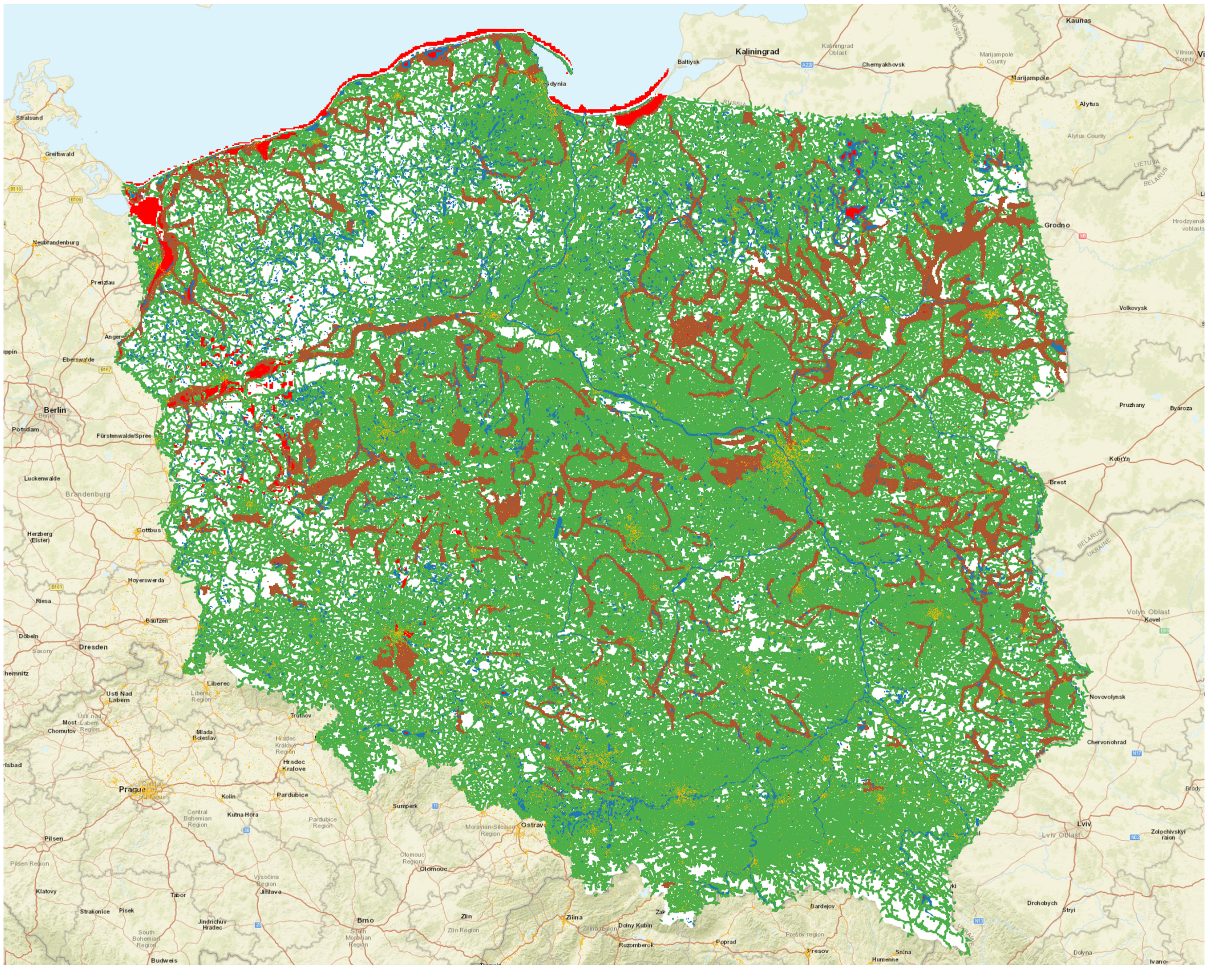
The capacity to move dozens or hundreds of sensors into a theater has expanded considerably. Many geographies are favorable for distribution: In the Poland scenario, for instance, most landmass surveyed falls within one kilometer of a road, with few exclusions for muddy, swampy, or challenging soil (Figure 15). In other maritime theaters, services, startup firms, and national laboratories have experimented with unmanned small ships and other swarming assets that could base potential sensor networks.[71] The sustainment challenges associated with proliferation are solvable, provided adequate resourcing and initiative.

Figure 14: Strategic Airlift Requirements for a Single Patriot Minimum Engagement Package



Spread over seven C-17 aircraft, this configuration includes a radar set, launcher with 4-pack (x2), engagement control station, battery command post, electric power plant, guided missile transporter with 4-pack, small repair parts transporter, fuel tanker, intermediate support element Humvee, reconnaissance, selection, and occupation of position Humvee, Humvee, trailer (x4), 4-pack missile pallet (x2), 463L pallet (x13), and personnel (x61). Spread over five C-5 aircraft, this configuration includes one fewer 4-pack missile pallets, one fewer 463L pallets, one fewer Humvees, five additional personnel, an additional utility support trailer, and an additional commander Humvee and troop Humvee.
Source: CSIS Missile Defense Project; data from the U.S. Army.

Figure 15: Mobility Limitations in Poland Scenario



Green: regions within one kilometer of road. Brown: soils described by European Soil Database as "muddy," swampy, or impassible terrain. Red: regions exceeding 5 percent grade. Blue: water.
Source: CSIS Missile Defense Project; terrain data from European Soil Database; OpenStreetMap.

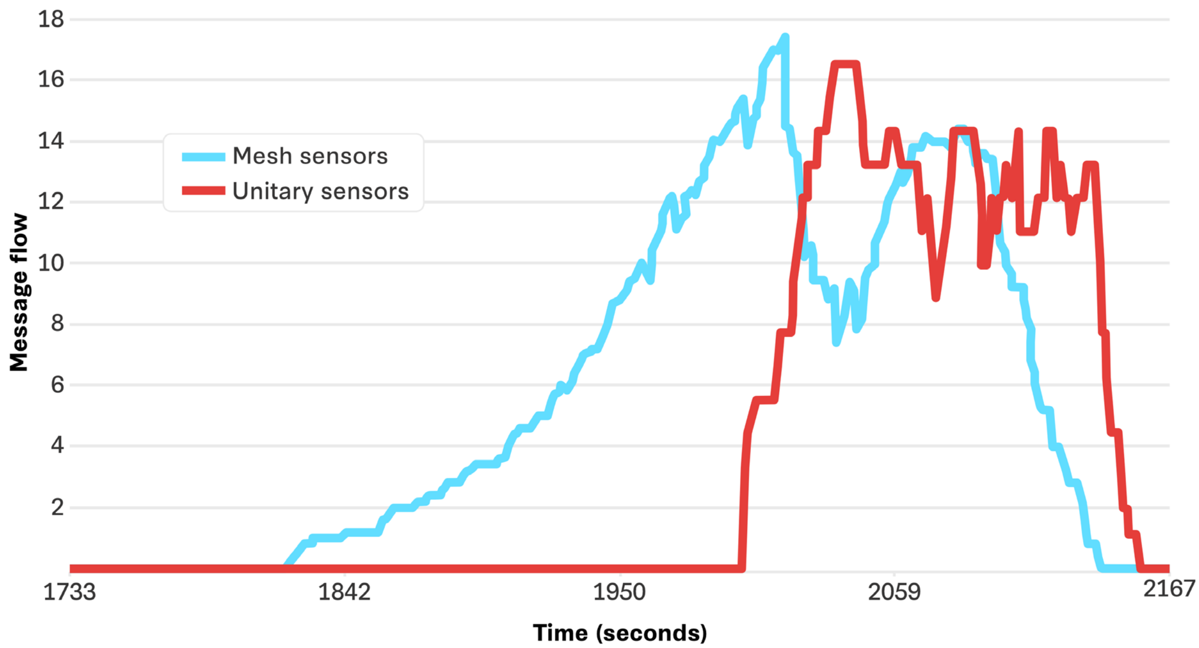
NETWORK CONSIDERATIONS

A sensor architecture with so many nodes will generate a considerable amount of data to process and transmit. Prior wide-area EO sensor systems, such as Gorgon Stare, generated petabytes of raw imagery data during operation, increasing computing needs and posing a challenge to analysts.[72] Such an architecture will consume considerable communications bandwidth. Even in the notional scenario discussed above, the network of distributed sensors generated significantly more communications than one without (Figure 16).

In the decade since Gorgon Stare, system architects have increasingly reduced those data bandwidth challenges by preprocessing on the edge. The Proliferated Warfighter Space Architecture (PWSA) Tracking Layer satellites, for instance, preprocess their raw imagery feeds into two-dimensional tracks, which are downlinked to warfighters. Germany's legacy ABF program used more rudimentary filtering algorithms to form target tracks and discard unnecessary information.[73] While full-quality telemetry will occasionally be needed to improve tracking algorithms, architecting a proliferated ground-based system will entail special attention to data reduction, taking advantage of the increased availability of high-performance compute.

In many respects, the edge processing problem has eased significantly. Power, weight, and radiation hardness requirements are substantially less constrained than with spacecraft, allowing the provision of more onboard computing power.

Figure 16: Data Packets Exchanged During Russia-Poland Attack Scenario



Sensor meshes require considerable communications bandwidth to handle the large number of assets involved. In the scenario developed in Figures 11 and 12, the flow of messages between sensors and C2 systems begins earlier and peaks higher than in the baseline case.
Source: CSIS Missile Defense Project.

More crucially, the technologies enabling rapid edge processing have advanced significantly in the past two decades; multi-gigapixel image processing pipelines are now commodity products, as are the graphics processing units and embedded computing systems to support new tracking algorithms.[74] The broader industry for computer vision has exploded: Between 2010 and 2025, submissions to the Computer Vision and Pattern Recognition conference exploded 655 percent, while the performance of computer vision hardware has roughly doubled every two years.[75] Actors seeking to build a distributed EO/IR system would benefit from the deep ecosystem of hardware, algorithmic, and software advancements already available today. However, the vulnerabilities of AI/ML algorithms to adversarial attacks (e.g., spoofing, data poisoning) must be carefully considered and mitigated through robust security measures and continuous monitoring.

WEATHER CONSIDERATIONS

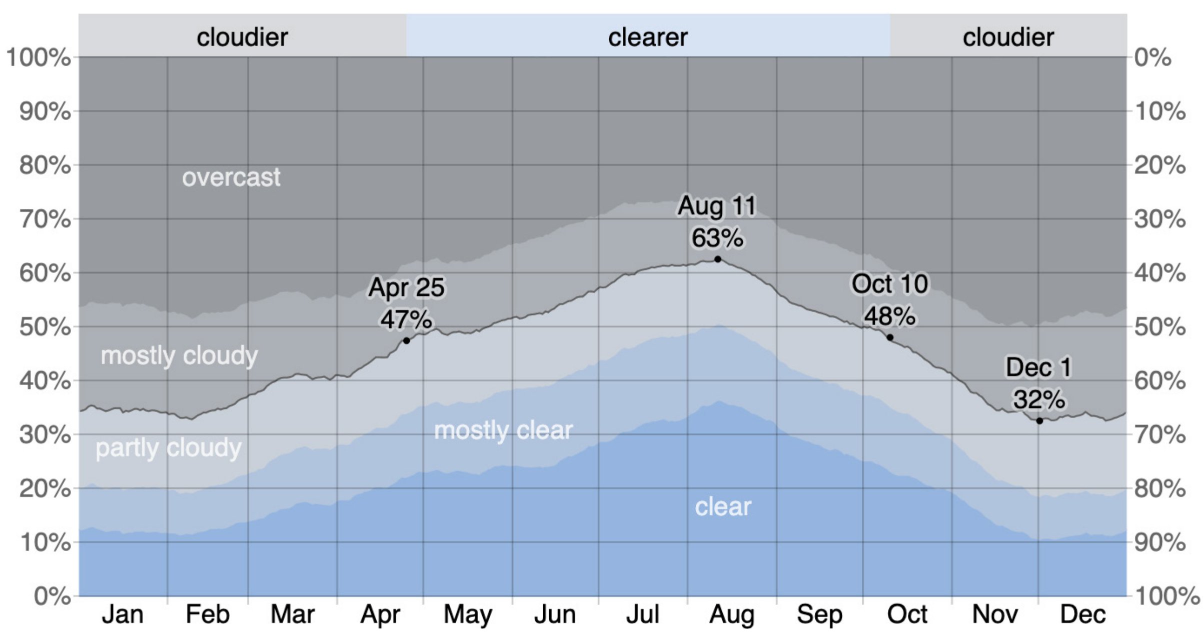
Perhaps the most significant challenge for a meshed EO/IR sensor architecture involves inclement weather. While EO/IR modalities can offer meaningful footprint and range advantages for high-altitude targets, poor weather can reduce their viewable distance by several orders of magnitude (Figure 18).

In fairness, the challenges posed by weather affect force design for a wide range of emerging capabilities. High-energy lasers and other directed-energy systems, seen as necessary for future threats, will face similar constraints in foggy, misty, and hazy environments.[76] In that sense, implementing an EO/IR sensor network could be a forcing function for integrating the next generation of military weather prediction and measurement systems.[77] Better understanding of turbulence, distributed placement of weather sensors, and new AI models for prediction might revolutionize joint planning for a number of capabilities, outside of EO/IR sensors alone.

Future mission planners working with directed-energy systems or EO/IR sensors must create force designs that change with predicted weather conditions and interface with existing, weather-robust sensors and interceptors. It may, for instance, be possible to dynamically reallocate sensor laydowns for best- and worst-case weather conditions and team them with existing radars to maintain ideal coverage.

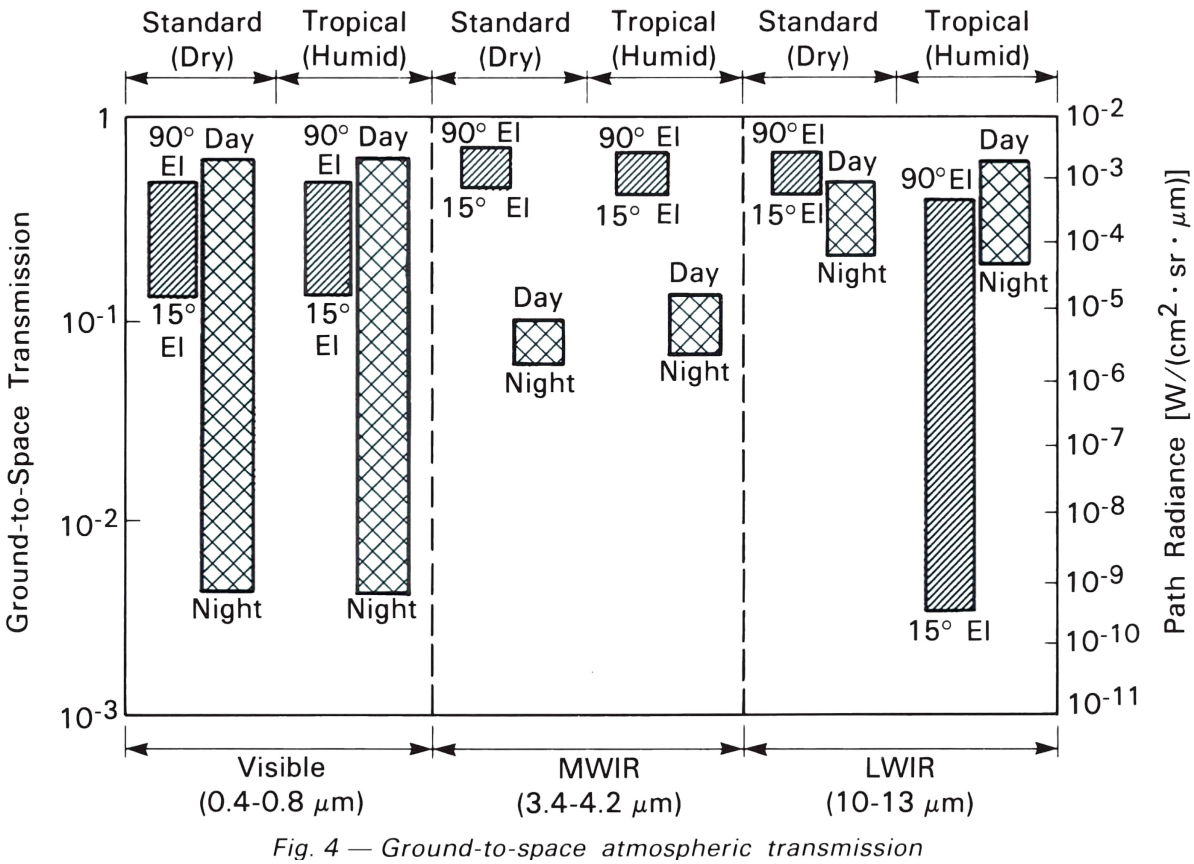
Further, the EO/IR case study considered here is just one type of passive sensing. The challenges posed by weather underscore the need to integrate meshed sensors with other passive sensing modalities and existing, active architectures. Passive, multistatic radar, passive radiofrequency detection, acoustic systems, and other approaches all stand to play potential roles.

Figure 17: 2024 Cloud Coverage Trends, Poland (Rzeszów–Jasionka Airport)



Source: Weather Spark.[78]

Figure 18: Atmospheric Transmission by Elevation, Day/Night, Humidity



Day and night temperatures, tropical and standard environments, and other factors can have a marked impact on the performance of passive EO/IR sensors.

Source: MIT Lincoln Laboratory.[79]

Hiding in Plain Sight

The era of massed air and missile threats is already here.[80] Adversaries are finding and fixing friendly forces, and they aim to destroy the ability of air defenses to see and make sense of the battlespace. What is needed is a thicket of sensors—both high- and low-end—to survive this environment. As Army doctrine exhorts, air defenders must "account for being under constant observation and all forms of enemy contact."[81] To date, however, the AMD sensing force structure has remained too heavily reliant on handfuls of exquisite, large-signature surface-based radars.

Proliferation, distribution, and emission control are all needed adaptations, both to protect and qualitatively improve existing air and missile defenses. The use of new phenomenologies like EO/IR and passive radar could help cover difficult regions, conserve radar resources, and discriminate real targets from false ones. These capabilities could backfill long-lead-time sensing capabilities, like the Space Force's Proliferated Warfighter Space Architecture, as they come online. It is, in sum, a matter of realizing the 2018 National Defense Strategy's call to "deploy, survive, operate, maneuver, and regenerate in all domains while under attack" and the 2022 version's emphasis on "effective coordination of distributed forces."[82]

A proliferated, passive, and surface-based sensor network would by no means replace the need for active radar systems in the air and missile defense mission. Several important considerations and problems would need to be overcome. These include challenges in deploying many assets at scale, difficulties in networking and planning such deployments, and fundamental hurdles with inclement weather. Most importantly, variation in the number of sensors needed for coverage—up to nearly 400 in a Poland-sized notional scenario, depending on target class—will determine the extent of what is possible. This report does not attempt to engineer individual sensors and cost a bill of materials. However, by describing the total quantities needed for various coverage scenarios, it informs analyses on unit economics for meeting desired future price targets.

In sum, such an architecture could substantially improve an overall defense design. Integrating multiple sensors and viewing targets at multiple angles could increase the performance of existing systems.[83] The above case study is a suggestion that even a network of 14 sensors could add redundancy for midsize-nation hypersonic missile defense scenarios, especially for high-altitude targets (Figures 10, 11, 12, 13). While larger networks are needed to defeat low-flying threats, a smaller sensor network could offer valuable tracking or cueing support against ballistic missiles, expanding decision timelines by minutes and increasing the number of missiles intercepted by up to a quarter in one scenario. An airborne layer of passive sensors would further improve sensing capability and confound enemy suppression.[84]

The case studies considered here validate a new vision for air and missile defense: bringing proliferated sensing down from the heavens and into the hands of warfighters on earth. The decreasing cost of microelectronics, networking equipment, sensors, and software have made it possible to innovate; battlefield experiences in both Ukraine and the Middle East have provided the imperative to do so. Faced with the threat of complex and integrated attack, the existing air and missile defense architecture would benefit from a more proliferated, passive, and ultimately resilient posture. Doing so would, at long last, better align AMD operations to the strategic environment of today.

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