The Air Domain and the Challenges of Modern Air Warfare

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It is difficult to imagine a modern world without flight and its associated technologies. The *speed* possible in the air domain shrinks time: A modern airliner travels 25 times faster than the fastest cruise ship on the Atlantic and seven times faster than the fastest locomotive in the 1950s. Militarily, operating in the air domain provides *vantage*: the ability to see not only over the next hill, but also over the horizon. It provides *maneuverability* unencumbered by mountain ranges, roads, river crossings, or rocky shoals at sea. Although navalists frequently remind us that 70 percent of the world is covered by oceans, 100 percent of the world is covered by air. The air domain is physically linked to every other domain, thus providing *flexibility* in operations, while its *range* provides an avenue for access anywhere in the world, anytime.

Over the past century, exploitation of the air domain's speed, vantage, maneuverability, flexibility, and range changed the nature of warfare. Specifically, it:

- Created new asymmetries that broke the stalemate of trench warfare after World War I, enabling combined-arms maneuver warfare that is with us today;
- Extended the reach of fleets and shore defenses beyond the sight of observation towers or the range of naval surface fires, making control of the air a requisite for operations on the sea;
- Allowed rapid insertion and resupply of forces at great distance from supporting bases; and
- Allowed air forces to go "over not through" the front lines of opposing armies, disrupting rearward logistics, denying maneuver, and taking war directly to capitals.

Today, from a military perspective, the degree to which the United States can exploit the air domain in its favor to find and hold at risk any target (fixed, mobile, hardened, and deep inland) anywhere on the globe is a key differentiator that makes it a military superpower.

Understanding the complexity of modern air power begins with a basic understanding of the air domain itself. This means understanding the air domain's unique attributes; how one can access and use the domain while exploring the limits of height and speed for platforms that operate in it; the domain's unique attributes of speed, range, persistence, and payload that have allowed the United States to dominate conflicts for the past 25 years; and current key shifts in the domain, driven by the evolution of technology and the return of state-based competition, and their implications for future military requirements.

Attributes of the Air Domain

The Atmosphere: Home to the Air Domain. The Department of Defense defines the air domain as "the atmosphere, beginning at the Earth's surface, extending to the altitude where its effects upon operations become negligible."[1] At its most fundamental level, the atmosphere is composed of air, a mixture of gases consisting of 21 percent oxygen, 78 percent nitrogen, and 1 percent argon, carbon dioxide, and other gases.[2]

The composition of air is perhaps its most extraordinary and important characteristic because it determines the very nature of the domain and dictates what can and cannot be done in it and drives the characteristics of the platforms that fly through it. Because these gases have mass, the distribution of the atmosphere is not uniform. For example, due to gravitational effects, nearly 50 percent of atmospheric mass is contained below 18,000 feet at the equator, 90 percent is contained below 52,000 feet, and 99.99 percent is contained below 330,000 feet or an altitude of 100 kilometers.[3] While some international organizations such as the Fédération Aéronautique Internationale define 100 kilometers as the beginning of space, the United States does not recognize a formal boundary either by treaty or by policy.[4]

The atmosphere is divided into several layers that are of varying degrees of significance to military operations.

- The lowest level, the troposphere, varies in height from the surface to 60,000 feet at the equator to 30,000 feet over the poles. All weather occurs in the troposphere. The top of the troposphere, called the tropopause, is the "cap" where summer thunderstorms flatten out to form an anvil shape. In the troposphere, the wind blows west to east in the Northern Hemisphere and east to west in the Southern Hemisphere. Temperature decreases by about 3.5 degrees Fahrenheit with every 1,000 feet of climb. Wind speed changes significantly with altitude, averaging 75 miles per hour from the west at 35,000 feet over the central United States in winter to as much as 200 miles per hour in the strongest jet streams.

- Above the troposphere is the stratosphere, which extends to about 180,000 feet. The stratosphere is where the ozone layer is located, and it is free from clouds and weather. Wind diminishes significantly with altitude in the stratosphere. Most of today's military operations occur in the troposphere and the stratosphere.

- Above the stratosphere at an altitude of about 34 miles is a region of the atmosphere that has proven easy to transit but difficult to operate in persistently. In this region, there is enough air to cause drag and surface heating but not enough to support aerodynamic control or air-breathing engine combustion.

- Sitting above the stratosphere, extending to 260,000 feet, is the mesosphere. Here, meteors burn up due to atmospheric heating. The ionosphere, which causes high-frequency radio waves to bounce off the atmosphere enabling long-range amateur radio operations, begins in this region.

- Above the mesosphere lies the final layer of the atmosphere, the thermosphere, which extends to as much as 600 miles above the Earth depending on solar activity. Atmospheric drag caused by gases in the lower portion of this layer limits the lowest unpowered, stable satellite orbit to roughly 120 miles.

Accessing the Air Domain for Military Advantage. From its earliest days, competition in the air domain has been enabled by constantly advancing technology. Warfighting in the air domain, however, is fundamentally a human endeavor, and as one learns about airspace technologies, it is important to keep technology in perspective. Technology enables access to and exploitation of the air domain, but humans marshal this technology to gain advantage over others as a tool of statecraft and war. Competition in the air domain therefore centers on maintaining or denying this advantage and depends not only on mastery of technology, but also on its artful and creative organization and application in strategy and tactics.

The characteristics of air and the atmosphere make five modes of access to the air domain possible: lighter-than-air flight, heavier-than-air flight, missiles, ground-fired or sea-fired projectiles, and the electromagnetic spectrum.

Lighter-than-air flight is achieved by trapping gases lighter than oxygen and nitrogen, like hydrogen or helium, or heated air in a sealed casing. Because the gas inside the casing is lighter than the surrounding air, lift is produced. The volume of air contained in that casing, coupled with the characteristics of the gas inside, determines its lifting ability. This allows exploitation of the air domain using hot-air balloons, gas-filled balloons, or powered airships (dirigibles and blimps). Lighter-than-air aircraft can provide persistence and relatively heavy lift, but this means of access is both slow and heavily affected by weather.

Lighter-than-air flight was exploited in World War I by Germany, which used dirigibles, or powered airships, to bomb central London, and in World War II by the United States, which used blimps for antisubmarine warfare patrols.[5] Although the speed of heavier-than-air platforms made them dominant over their lighter-than-air brothers, a role remains for balloons and powered airships today. Tethered balloons (aerostats) extending up to 14,000 feet line the U.S. border with Mexico and have been used in Iraq to provide persistent surveillance coverage.[6] Powered airships used by the logging industry to extract harvested timber from remote areas could provide a slow-speed, heavy-lift logistics option for military purposes.[7] High-altitude balloons also offer military utility as a backup to space-based capabilities like communications satellites.[8]

Heavier-than-air flight, on the other hand, uses aerodynamic forces to produce and sustain lift. Aerodynamic lift is produced by moving an airfoil (wing) through volume of air or fluid. Design differences between the upper and lower surfaces of the airfoil force the air to move faster across the upper surface as the wing is propelled through the air. This creates an area of lower pressure on the top of the wing that generates lift. There are other factors involved, but if one produces enough aerodynamic lift to overcome the force of gravity, then a heavier-than-air machine can fly.[9]

There are two other forces at play in the creation of aerodynamic lift: the thrust required to propel a wing though the air to generate lift and the drag that the wing creates through the process of creating lift. Thus, balancing the problems of lift, gravity, thrust, and drag makes flight possible using vehicles that are powered (airplanes, cruise missiles, helicopters, tilt rotors, and quad copters) and unpowered (towed gliders, lifting bodies, and air-delivered guided munitions). Aircraft provide a reusable form of access to the air domain and offer an incredible degree of flexibility with regard to speed, range, payload, and endurance for military operations.

Missiles use the brute force of expanding, burning gases provided by liquid-fueled or solid-fueled rocket engines to overcome the effects of gravity and gain access to the air domain. As the vehicle accelerates, it takes on aerodynamic characteristics and can be controlled using aircraft-like control surfaces until it reaches mid-stratosphere. Above this altitude, small thrusters or gimbaled engines controlled by guidance systems allow the highest levels of precision in movement and endgame placement.

Missiles deliver high-speed effects in both the air and space domains without the risk associated with manned flight, but there are trade-offs. Lift is created on the sheer power of their engines, making this form of access markedly less efficient than winged aircraft. Moreover, missiles used for attack or defense are not reusable; an aircraft can return to base and reload with ordnance, but a missile is a one-time shot.[10]

Projectiles like bullets, mortars, rockets, and bombs use a controlled explosive charge, propellant, or the momentum gained by a parent platform to overpower the aerodynamic effects of weight and drag temporarily in order to enter and transit the air domain. Aimed downward, air-launched munitions provide an additional and incredibly potent axis of fire against land-based and sea-based targets. Aimed upward, ground-fired projectiles provide a low-cost, effective way to deny an enemy use of the air domain in a limited area. For example, the vast majority of aircraft losses in Vietnam were due to anti-aircraft artillery rather than surface-to-air missile defenses.

Today, new technologies like electromagnetic rail guns can fire projectiles from land-based or sea-based platforms at hypersonic speeds to attack other surface targets or defend against low-flying, supersonic cruise missiles and high-speed ballistic missile warheads.[11] In addition, long-range, precision-guided rocket artillery teamed with unmanned intelligence, surveillance, and reconnaissance (ISR) capabilities like satellites or "drones" are changing the way armies view fires.[12]

Finally, *the electromagnetic spectrum* provides a less obvious but equally powerful method of accessing the air domain to enable, disrupt, or deny air operations. This includes use of voice and data communications to direct and employ forces; optical, infrared, laser, and radar-based sensors to detect objects in the air domain and guide weapons; high-power lasers to deny optical sensors or to attack incoming aircraft, missiles, or bombs;[13] high-powered microwaves to disrupt operation of airborne vehicles and weapons;[14] electromagnetic decoys to confuse an opponent's systems;[15] and modern jamming techniques to deny, disrupt, or spoof radars, communication, and space-based navigation systems like the Global Positioning System (GPS).

The electromagnetic spectrum can be manipulated through combinations of low-observable (stealth) technology and active electromagnetic countermeasures to increase the survivability of both aircraft and munitions against increasingly sophisticated air defenses. This electromagnetic method of accessing the air domain also enables cyberspace effects to shape every aspect of offensive and defensive air operations.

Leveraging these five methods of access, nations develop offensive and defensive capabilities to gain or deny advantage across the spectrum of warfighting domains, but the air domain is more complex than simply pitting system against system. Sanctuary or advantage can lie in operating at high or low altitude, operating at speed, operating from range versus operating forward, hiding in the noise of the electromagnetic spectrum, or increasing weapons accuracy to reduce repeated exposure to the threat.

The U.S. has taken several different investment strategies within the air domain since the 1950s. From the opening days of the jet age through the 1970s, it pursued a "higher, farther, faster" strategy. As the Soviet Union mastered its integrated air defense system (IADS), U.S. efforts moved to a low-altitude strategy that stayed in place through the opening days of Operation Desert Storm, when precision and stealth capabilities became dominant. A closer look at the limits of altitude and speed in the air domain therefore helps one to understand the constraints of the operating environment.

Defining the Air Domain's Upper Limit. Defining the upper limit of the air domain, "where its effects on operations becomes limited," is difficult. As noted, most military operations occur in the troposphere and lower stratosphere. Commercial aircraft operate up to about 40,000 feet, while military aircraft routinely operate as high as 60,000 feet. "Controlled airspace" over the United States ends at 65,000 feet. Operations above this altitude are sometimes called "near space."

The glider-like wings of the U-2 aircraft enable it to operate at the very edge of controlled flight while flying at subsonic speeds in the 70,000-foot regime.[16] Due to the thinning atmosphere, however, operations above this altitude require either increasing supersonic speeds with altitude to produce adequate lift or, paradoxically, no speed at all. For example, the Mach 3.0 SR-71 operated near 85,000 feet,[17] while the Mach 3.0 Mig-25 holds the absolute manned takeoff to altitude record of 123,523 feet.[18] On the other hand, the highest manned balloon reached 135,890 feet,[19] and unmanned balloons have reached the top of the stratosphere at over 176,000 feet.[20]

Going higher still requires different forms of propulsion and materials. Rocket planes carried aloft by a mother ship, like the 1960s-era X-15 (transported to high altitude by a B-52 bomber) or Virgin Galactic's Spaceship One flights, operate in the mesosphere and beyond in what are known as "suborbital" operations. Spaceship One holds the altitude record for an air-launched rocket plane at 367,487 feet or 70 miles, but it does not have the ability to persist in this regime for any meaningful length of time.[21]

Achieving persistence in the flight regime above the stratosphere is technically difficult, but it can be realized through atmospheric "skipping" where platforms use their speed to "skip" off denser layers of atmosphere at hypersonic speeds like a rock skipping across water. Such a capability offers a range of military benefits between the air and space domains (roughly 34 miles to 120 miles above the Earth), making it possible to maneuver and maintain altitude without the limitations of orbital mechanics that are imposed by operations in space.[22]

A hypersonic glide vehicle (HGV), a capability being pursued by the United States, Russia, and China, can be deployed from an intermediate-range ballistic missile to enable such atmospheric skipping.[23] An alternative approach might be found in new propulsion techniques such as air-breathing, plasma-fueled engines, which are in early research and development.[24]

Defining the Speed Limit in the Air Domain. Mach numbers play a crucial role in understanding the difficulty of going higher and faster in the atmosphere. A Mach number is a speed expressed as the percentage of the speed of sound. For example, Mach .82, a typical airliner speed, is 82 percent of the speed of sound. Mach 1.0 occurs at 667 knots (nautical miles per hour) at sea level.[25] Above Mach 1.0 in the atmosphere, shock waves form on the nose and tail of an aircraft. If these shock waves reach the ground, sonic "booms" are heard and felt along the flight path as the shock waves pass by in close succession.

The basic formulation of aerodynamics that balances lift, draft, gravity, and thrust works well up to speeds of about .80 Mach or the beginning of the "trans-sonic" speed regime. Here, compressibility of air becomes a factor. Unlike water, air compresses as its velocity over a surface increases. As one goes faster, this changes the drag profile of traditional airfoils, requiring substantially more energy to sustain speed or go faster. In addition, shock waves begin to form in this flight regime that disrupt normal airflow over the airfoil.

For traditional, straight-wing airfoils, these pressures shift suddenly as one approaches the speed of sound, resulting in buffeting and loss of control. This phenomenon sets the speed limit of propeller-driven aircraft, even in a steep dive, due to drag increases and shock wave formation on the propeller blades.[26] Thus, "the sound barrier" was a significant obstacle in military aviation until it was broken in October 1947 thanks to propellerless propulsion, thin wing designs, and new control surfaces.[27]

Today, aircraft designed to go faster than .80 Mach have swept wings and other design features to reduce the effects of transonic drag. Since airliners cruise at speeds of .8 to .87 Mach, research into the transonic drag reduction, transonic airfoil optimization, and engine efficiency in the transonic regime remains important for airplane and engine companies.

Two speed regimes are relevant militarily in the air domain above Mach 1.0: supersonic (Mach 1.2–Mach 5.0) and hypersonic (Mach 5.0–Mach 10.0). Each regime poses different problems for designers.

Supersonic speed increases the range of air-to-air missiles, improves responsiveness for intercepts, expands the flight envelope for operations, and allows sustained high-altitude flight.

In the supersonic regime, designers must solve the problem of creating a subsonic airstream in the engine to support combustion despite air entering the engine at supersonic speed. To accomplish this, most military fighter aircraft utilize afterburning turbofans, which use a combination of inlet design and a spinning compressor to squeeze and slow the airflow coming into the engine to subsonic speed before injecting fuel and burning it.[28] Afterburning turbofans are far less efficient than the subsonic "high bypass" turbofans used by the airlines, although research is underway to improve their efficiency during subsonic flight.[29]

As one goes faster than about Mach 3.0, however, turbofan engines reach material limits to handle high heat and pressures. To go faster with an air-breathing engine, a ramjet is required. A ramjet uses a movable fixed inlet to achieve compression without rotating parts. Combustion still occurs in subsonic air, however. Ramjets can operate to Mach 6.0 but work best in the Mach 2.0–Mach 4.0 range. For example, a combined-cycle turbojet/ramjet engine enabled the SR-71 to reach speeds above Mach 3.0. While Mach 3.0 speed provided survivability against air defenses through the 1980s, this speed regime would become well within the capability of air defense systems like the Russian SA-20 and U.S. Patriot and Aegis by the 1990s.[30]

To improve survivability and reduce reaction time for today's most contested airspace, one must maneuver at hypersonic speeds. The cost to operate above Mach 5.0 within the atmosphere has risen at exponential rates with increasing speed due to shifts in structural material requirements to mitigate extreme heat and special requirements for air-breathing engines to handle extreme speeds.[31] Both China and the United States are actively pursuing research to reduce cost in these areas.[32]

To reduce the cost of hypersonic speed, air-breathing engines are more desirable than rocket engines because they produce more thrust for a given amount of weight. Moreover, the combination of speed and better fuel efficiency enables a hypersonic vehicle to travel longer distances on a small amount of fuel, in turn allowing for vehicles that are more compact.[33] For example, a powered hypersonic vehicle travels 560 miles on only eight minutes of fuel at Mach 7.0.

To achieve this, a scramjet engine that can sustain combustion in supersonic airflows is needed. Because these engines do not operate below Mach 4.5, a scramjet-powered hypersonic vehicle requires a rocket-motor "kick start" to accelerate to its engine start speed. Research into these engines is ongoing. In 2004, NASA's X-43 achieved 10 seconds of powered flight at Mach 9.6, the fastest jet-powered flight on record.[34] In 2013, the Air Force X-51A testbed achieved 240 seconds of hypersonic flight with a scramjet at Mach 5.1, the longest powered flight of a scramjet on record. Given the capability of improving modern air defenses and the growing importance of striking mobile targets, air-breathing hypersonic vehicles and weapons are likely to become an area of intense competition.[35]

Denominators for Exploitation of the Air Domain

Having discussed the speed and altitude attributes of the air domain, one must consider the denominators that are needed to exploit it. These break down into two major areas: being able to project power through range, persistence, and payload and being able to see and act using the electromagnetic spectrum.

Range, Persistence, and Payload. The ability of aircraft in the air domain to operate and survive at range and persist over time with intelligence, surveillance, and reconnaissance sensors and flexible weapons is key to exploiting the domain. This capability connects the air domain with other domains through missions like counterair, strike, close air support, ISR overwatch, airborne anti-submarine warfare, assault aviation, or airborne cyberspace operations. Twenty-five years after Desert Storm, the success of U.S. operations in largely permissive air environments has solidified the perception that American air power is an omnipresent force with an unblinking eye that wields a rapid, precision hammer.

TABLE 2

Effect of Distance on Sortie Production

Distance from Base (nautical miles)	Total Sortie Duration (hours)*	Sorties per Aircraft/Day**	Pilot Manning (per aircraft)***
650	4.7	~2.90	1.5
1,300	7.4	~2.00	2.0
1,950	10.1	~1.55	2.5
2,600	12.8	~1.25	3.5

* Assumes 2.0 hour on-station time.

** Assumes 1.5 hour regeneration time and 6.0 hours maintenance non-availability per day per aircraft. Times vary by aircraft, maintenance manning, and carrier deck cycles.

*** 12.0 hour sustained pilot duty day, 125 hours maximum per 30 days.

SOURCE: Author's calculations.

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Unlike the land and sea domains, where persistence consists of holding ground or patrolling in a geographically limited area, persistence in the air is about radius of action that leverages the speed and vantage that the air domain provides. For example, an aircraft loitering at 20,000 feet that is 80 miles away from a U.S. ground patrol in Syria is within easy radio contact of the ground patrol, can immediately bring sensors to bear, and can arrive overhead at Mach 1.0 in eight minutes. Should tensions escalate, other airborne forces can mass quickly. Should fuel run low, air refueling tankers arrive to provide inflight refueling. Thus, the operation can quickly scale and protract, especially in permissive environments (areas where there is little or no threat to U.S. air operations). Range and persistence make this possible.

Range and persistence are related concepts that revolve around fuel. For example, a pilot can travel point to point at speed, translating fuel into range, or orbit around a point at speed, translating fuel into persistence. Thus, fuel on board, expressed as combat radius or the unrefueled mission radius of action, is critical to exploitation of the air domain as well as to force posture and basing. For example, the United States developed air refueling in the 1950s to allow basing of jet bombers in depth from all sides of the Soviet Union. Without air refueling, aircraft could be based only within the range of the aircraft, which was strategically disadvantageous. As air refueling capability was incorporated into fighters, the idea of assured air refueling allowed designers to trade fuel capacity (which translates to weight) for airframe maneuverability (which also translates to weight) that was needed for air-to-air combat. Thus, the combat radius of most of today's U.S. fighters is 550–650 nautical miles. As a result, operations beyond this range require refueling about every two hours.

These basic time, combat radius, and distance economics incentivized a 60-year U.S. reliance on forward basing and forward carrier stations to project power in the air domain.[36] (See Figure 2.) There were good reasons for this approach. Operating from range taxes human endurance. In 2001, for example, fighters operating from the Arab Peninsula to Afghanistan had to transit 1,200 miles each way to fly around Iran. Thus, a six-hour mission time over Afghanistan required an 11-hour sortie that consisted of four to five air refuelings from four to five different air refueling aircraft. These air refueling aircraft transited similar distances with similar sortie durations. Thus, sustained operations from range require more pilots, more aircraft, and more fuel.

Forward basing, on the other hand, allows commanders to use aircraft and pilots multiple times per day.[37] This enables a high tempo of operations and allows persistence through multiple revisits or cycling of aircraft across the battlespace. Forward-based air refueling tankers enhance this capability for fighter/attack-sized aircraft, allowing aircraft to operate well beyond their organic combat radii and ensuring that enough fuel is always airborne and available. (See Figure 2.)

The ability to base forward also allowed the United States to divest aircraft with large payloads like the Navy's A-6 and the Air Force's fleet of bombers, since a higher number of sorties from fighter-sized aircraft at forward bases could make up the difference in payload. Recognizing this fact, China has invested in a new generation of ballistic and cruise missiles designed to hold forward bases and aircraft carriers at risk through massed, raid-style attacks designed to overwhelm active defenses.[38] In addition, China is taking other measures to increase U.S. force requirements by expanding the range of contested airspace. (See Figure 2.)

As forward bases come under increasing threat, which in turn drives increased basing distances, pressure on the air refueling force becomes extreme unless the organic combat radius of combat aircraft is increased. Protecting large air refueling tankers is difficult. Sheltering of forward-based air refueling tankers has proven unaffordable at scale thus far and was not attempted during the Cold War.[39] Left unsheltered, these aircraft are particularly susceptible to attacks using a variety of weapons, ranging from ballistic and cruise missiles to rockets and mortars to sniper rifles. In addition, the short combat radii of today's force increase the vulnerabilities of tankers in flight, since they must operate closer to the expanded threat envelopes of modern threat systems to provide adequate fuel for operations as illustrated in Figure 2.

Improved combat radius may therefore become increasingly important to exploitation of the air domain for power projection. Fortunately, the capabilities of modern missiles are rendering fighter maneuverability less important, allowing airframe weight to be traded for fuel. However, a greater emphasis is needed on larger payloads to make up for the potential loss of high-sortie production from forward bases and on unmanned operations to improve human abilities to sustain protracted operations from range.

The Electromagnetic Spectrum. In addition to projecting range, persistence, and payload, exploiting the air domain requires the capability to see, decide, and act. It is therefore difficult to separate operations in the air domain from the electromagnetic spectrum or the electromagnetic spectrum from weather. The relevant portions of the electromagnetic spectrum within the context of the air domain include visible light; infrared light, which is used for sensing temperature; and all radio frequencies, which enables communications and various forms of radar. From eyeballs to radar, if it is detected in the air domain, it is by and through the electromagnetic spectrum.

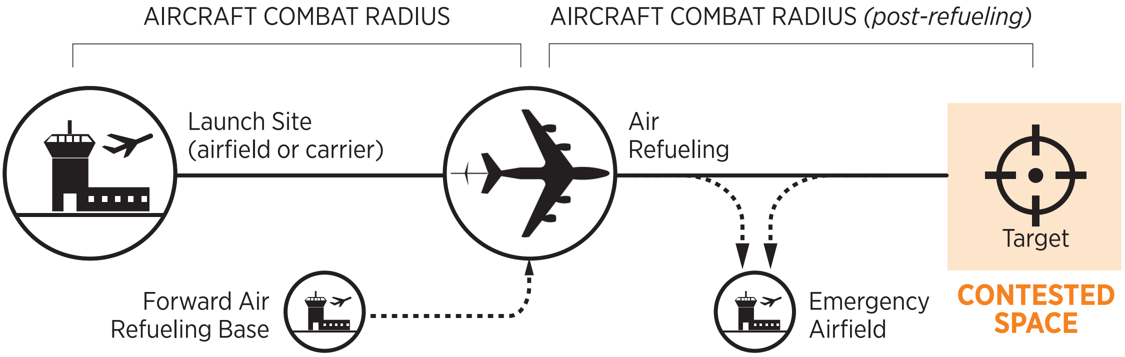
Weather, on the other hand, presents hazards like thunderstorms and severe icing, as well as wind and temperature, that affect operations. Most important, however, it shapes the degree to which the electromagnetic spectrum can be exploited. The line of sight distance to the horizon from an aircraft operating at 35,000 feet is 229 miles, but how much of this distance is usable? Looking up into the stratosphere, a great deal may be: The weather is generally clear, and the background is cold and free from clutter, perfect conditions for visible, infrared, and radar sensors.

Looking down toward the thicker atmosphere and the ground is another matter. In the visible spectrum, dust and clouds may obscure the view. For example, clouds cover most of North Korea more than 50 percent

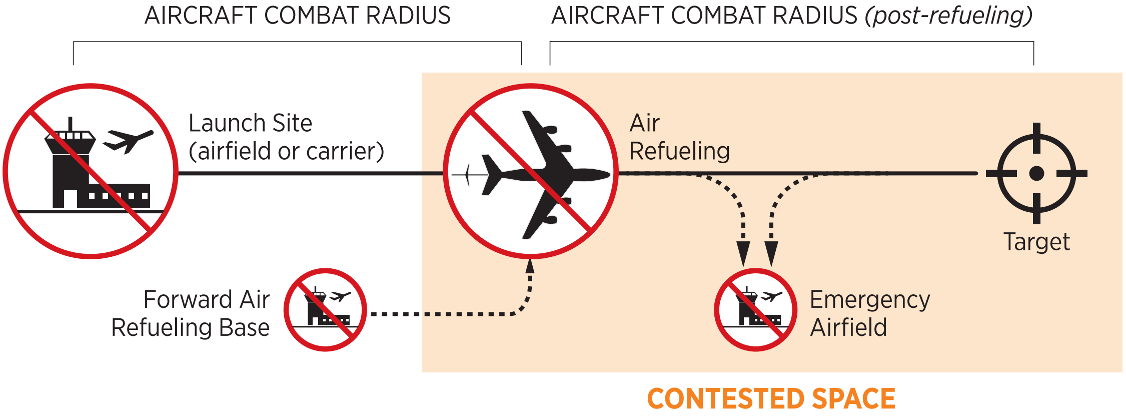
FIGURE 2

How the U.S. Projects Air Power

Historically, the U.S. has been able to project air power by using airfields, carriers, and air refueling systems to minimize the size of contested space — the area in which aircraft would engage in conflict.



China is investing in missile systems that would significantly hinder the U.S.'s forward operating launch points, which would as a result make the contested space much larger.



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of the time from May to September. In the infrared spectrum, water vapor may attenuate temperature signatures, and clouds may block them completely. In the radar spectrum, synthetic aperture radar provides a means to see through clouds, but power dissipates rapidly with range (i.e., 1/range^4), and rain attenuates signals at higher frequencies. In addition, airborne radars must contend with the "ground clutter" moving below them, complicating their operation.

Moreover, aircraft are limited in the amount of power they can produce and the sizes of radar antenna they can carry. Thus, antenna size tends to herd aircraft radars into a narrow range of operating frequencies and power. This means that a true all weather, day/night ISR capability requires a combination of sensors to be effective and that aircraft may be required to fly close to an area of interest for its sensors to "see" it, especially if the target is mobile.

Meanwhile, actors accessing the electromagnetic spectrum on the ground or at sea are not limited by power or radar size as aircraft are. They can develop powerful radars to detect and target air vehicles and employ severe jamming to disrupt airborne radar and precision navigation like the Global Positioning System. In addition, ground-based radars have the advantage of looking up away from clutter. This dynamic of air-based and ground-based competition in the air domain through the electromagnetic spectrum is what eventually forced the development of stealth.

As competition between nation-states intensifies, the competition to place sensors close enough to "find" targets, especially mobile ones, versus defensive efforts to prevent these actions will continue. Stealth, enhanced by active electronic countermeasures, remains relevant and essential for survivability in this environment in order to hold mobile and deep targets at risk. Other approaches, such as hypersonic speed or employing large numbers of vehicles to saturate defenses, also enhance survivability and may become key contributors to this competition. The question then becomes: How may the character of the domain change as technology advances?

Key Shifts Likely to Affect the Air Domain

Because exploitation of the air domain depends on technology that is constantly advancing, competition in the domain has never stood still. As technology accelerates and renewed nation-state competition drives new moves to counter U.S. capabilities, at least four key shifts are underway that are likely to alter the character of the air domain.

First, exploitation of the air domain is no longer just about aircraft. The proliferation of mobile advanced air defenses, mobile ballistic missiles, land-launched and sea-launched hypersonic boost glide systems, and air-launched powered hypersonic vehicles provides new means to deny air refueling, attack forward bases, and deny forward carrier stations through the air domain. This undercuts the force posture assumptions on which the present force is built. Given this development, increased combat radius of aircraft, larger payloads, and expanded use of long-range unmanned systems improve the ability of the U.S. to operate from range.

Second, the most important targets are mobile. The increasing importance of countering the above-described mobile targets increases the importance of ISR and the ability to direct forces in contested environments. Fully leveraging the leading edge of technology in the electromagnetic spectrum improves the ability of the U.S. to hold these targets at risk. This includes technologies for advanced sensors, penetrating stealth, survivability to "stand in," and alternatives to GPS navigation.

Third, weapons in flight are under increased risk. The maturation of directed energy and improved capability of ground-based point defenses may cause traditional weapons to come under increased threat. Increasing weapon speed or employing saturation tactics with large "flocks" of weapons improves the probability of weapon arrival. Either approach requires survivability to "stand in" or penetrate, increased payloads, and greater depths of weapons magazines.

Fourth, the threat from "low end" uses of the air domain is growing. The rise of machine learning, object recognition, and improved battery technology may enable small drones or quad copters to contest the air domain at the tree level. This capability may be used to disrupt airfields and to project power locally even in permissive environments. Research into countering machine learning and new capabilities to counter emerging small, swift, and robotic capabilities improves the ability of the U.S. to adjust to this threat.

Conclusion

The ability of military forces to exploit the air domain has revolutionized warfare over the past century. Exploiting the domain to find and hold targets as risk at global ranges remains a differentiator of U.S. power. Shifting technology, however, threatens to erode this advantage and presents challenges to the U.S. model of power projection. Sustaining that advantage will require more stealth platforms with C4ISR (command, control, communications, computers, intelligence, surveillance, and reconnaissance) capabilities and the ability to adapt to unforeseen changes in the air domain, as well as those it supports.

Endnotes

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25. As with the maritime domain, operations within the air domain use nautical miles per hour or "knots" to quantify speed. One nautical mile is equal to one minute of latitude, 6,076 feet, or 1.15 statute miles on a car's odometer. The true speed of sound in knots varies by altitude and pressure. Notwithstanding this, a rule of thumb in aviation is to view the Mach number with the decimal point moved one place to the right as "nautical miles per minute" along the ground, discounting the effect of headwinds or tailwinds. Thus, .82 Mach is roughly 8.2 miles per minute, which equates to 492 knots along the ground with zero wind when multiplied by 60 minutes.

26. The speed record for a turboprop aircraft in level flight is held by the TU-114 at 478 knots or .73 Mach. See Aerospaceweb.org, "Tupolev Tu-114 Rossiya," last modified March 17, 2011, http://www.aerospaceweb.org/aircraft/jetliner/tu114/ (accessed August 1, 2017). Helicopters experience a different problem related to airfoil speed, called dissymmetry of lift. Helicopter blades can experience a condition in which the blade going forward in the direction of flight produces more lift than the blade going opposite the direction of flight. This can place the helicopter out of control when operating at speed unless countermeasures are taken in design.

27. There are claims that the jet-powered ME-262 exceeded the speed of sound in dives during World War II, but experts doubt that this happened. Shock waves prevented the testing of high-speed performance in wind tunnels of the time, and high speed in dives claimed many lives during World War II and in follow-on testing. For more, see PBS, "Faster Than Sound," *NOVA*, October 14, 1997, https://www.youtube.com/watch?v=_WFBe6cDrBg (accessed August 1, 2017).

28. Air entering the intakes of a turbofan engine is slowed by inlet shape, doors, or small flaps on the engine surface. A spinning compressor then sucks in the air and squeezes it, but this compression creates significant heat and pressure. For example, in the latest production F-16s, the air is squeezed 30 times before it is burned. The combustion process increases the temperature of this high-pressure air to nearly 2,750 degrees Fahrenheit before it exits into the afterburner section. This produces about 14,000 pounds of "non-afterburning" thrust, or about 3.5 times the engine's weight. Bumping large amounts of fuel into this hot exhaust and burning it in an afterburner increases thrust to nearly 32,000 pounds—more than seven times the engine's weight. Engines like this deliver tremendous performance across a wide operating envelope, enabling aircraft like the F-16 to fly at supersonic speeds from the surface to 50,000 feet. See General Electric, "F110-GE-129 Turbofan Engines," https://www.geaviation.com/sites/default/files/datasheet-F110-GE-129.pdf (accessed July 24, 2017).

29. As demand for greater range increases, the Air Force Research Laboratory is exploring a "three stream" afterburning turbofan engine that shares some attributes with high-bypass engines for use during subsonic flight and then reverts to a less efficient mode for supersonic flight. This could improve engine fuel efficiency by up to 25 percent, translating to greater range. See Bill Carey, "GE, Pratt & Whitney Win Contracts for Next-Generation Engine," *AINonline*, July 1, 2016, http://www.ainonline.com/aviation-news/defense/2016-07-01/ge-pratt-whitney-win-contracts-next-generation-engine (accessed August 1, 2017).

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31. Above Mach 3.0, surface heating of the air vehicle becomes an issue, so different materials are needed in the hypersonic regime. Traditionally, titanium has been the metal of choice for handling high temperatures in aviation because it is strong and about half the weight of stainless steel. For example, an SR-71's titanium skin reached 500 degrees Fahrenheit during high-speed flight at Mach 3.0. The material limit of titanium, however, is 800 degrees Fahrenheit. See George Tzong, Richard Jacobs, and Salvatore Liguore, *Air Vehicle Integration and Technology Research (AVIATR), Task Order 0015: Predictive Capability for Hypersonic Structural Response and Life Prediction: Phase 1–Identification of Knowledge Gaps, Volume 1–Nonproprietary Version*, Air Force Research Laboratory, Air Vehicles Directorate, Wright-Patterson Air Force Base, Final Report, September 2010, p. 72, www.dtic.mil/get-tr-doc/pdf?AD=ADA535837 (accessed August 1, 2017).

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33. This comparison of weight to thrust is called specific impulse. For a comparison of engine performance, see Dora E. Musielak, Aerospace Engineering Consulting, “Propulsion Comparison,” in “Fundamentals of Pulse Detonation Engine (PDE) and Related Propulsion Technology,” p. 10, https://info.aiaa.org/tac/PEG/HSABPTC/Public%20Documents/Dora%20Musielak%20Publications/Fundamentals%20of%20PDE%20Propulsion_Musielak.pdf (accessed August 1, 2017).

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36. Since Vietnam, most air bases and carrier stations have been within 750 nautical miles of the adversary’s capital.

37. Single-place aircraft sustained duty day is 12 hours. Multi-place aircraft sustained duty day is 16 hours. The U.S. Air Force limits pilot flying time to 56 hours per seven consecutive days, 130 hours per 30 consecutive days, and 330 hours per 90 consecutive days.

38. Similarly, though to a lesser extent, Russia has improved its existing stock of sea-launched and air-launched cruise missiles and has developed a pair of new intermediate-range cruise and ballistic missiles in violation of the Intermediate Nuclear Forces Treaty. Moreover, both Russia and China are going to some lengths to demonstrate their respective capabilities, with Russia launching long-range cruise missile attacks across Iraq and into Syria in 2016 and China conducting frequent attacks against scale mockups of U.S. facilities on its ballistic missile ranges in the Gobi Desert. See Michaela Dodge, “Russian Intermediate-Range Nuclear Forces: What They Mean for the United States,” Heritage Foundation *Backgrounder* No. 3028, July 30, 2015, http://www.heritage.org/europe/report/russian-intermediate-range-nuclear-forces-what-they-mean-the-united-states. For images of these ranges, see Thomas Shugart, “Has China Been Practicing Preemptive Attacks on U.S. Bases?” War on the Rocks, February 6, 2017, https://warontherocks.com/2017/02/has-china-been-practicing-preemptive-missile-strikes-against-u-s-bases/ (accessed July 28, 2017).

39. Congress appropriated $128 million for a single hardened air refueling hanger on Guam in the National Defense Authorization Act for Fiscal Year 2014, Public Law 113–66. This is about one-half the $246 million sticker price of a new KC-46. During the Cold War, tankers were based away from forward areas, and no attempt was made to shelter them. The increased range of the threat, the distances of the Pacific, and the operational requirements of the F-35 are key differences today. See Alan J. Vick, *Air Base Attacks and Defensive Counters: Historical Lessons and Future Challenges* (Santa Monica, CA: RAND, 2015), http://www.rand.org/content/dam/rand/pubs/research_reports/RR900/RR968/RAND_RR968.pdf (accessed July 29, 2017).