### Title and Subtitle

The Post-GPS Era: Leveraging Advances in Precision Navigation and Targeting to Enable the Kill Chain in an A2/AD Environment

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### Abstract

Over the past twenty years adversaries have sought to counter America's demonstrated asymmetric military and technological advantages by developing anti-access/area-denial (A2/AD) capabilities, such as global positioning system (GPS) jammers, and advanced integrated air defense systems (IADS), which deny key enablers of the kill chain. Recent advances in precision navigation and timing (PNT) technologies have the capability to mitigate America's reliance on GPS by enabling self-contained, GPS-quality positional awareness, immune from jamming. These PNT advances can overcome airpower's vulnerabilities to GPS jamming and improve its capability against advanced IADS, thereby enabling enhancing kill chain operations in an A2/AD environment requiring standoff precision-strike capability. This paper first addresses the threat of GPS jamming and IADS on the kill chain, then describes the "fix" offered by three emergent PNT technologies—Chip-Scale Combinatorial Atomic Navigator (C-SCAN), the cold-atom inertial navigation unit, and the Adaptive Navigation System (ANS)—their impact on the kill chain, and an operational concept for their use.

### Subject Terms

GPS Jamming, A2/AD, PNT, Kill Chain

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FUTURE WAR PAPER

The Post-GPS Era: Leveraging Advances in Precision Navigation and Timing to Enable the Kill Chain in an A2/AD Environment

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# Table of Contents

Disclaimer ......................................................................................................................................... i  
Table of Contents ............................................................................................................................. ii  
Introduction ..................................................................................................................................... 1  
The Kill Chain and the Threat of GPS Jamming and IADS to its Effectiveness ......................... 2  
The Fix: Advanced PNT Systems Adapted to Aerial Platforms ................................................... 3  
Impact of PNT Technologies on the Kill Chain ............................................................................. 7  
Tying It Together: An Operational Concept for Advanced PNT and the Kill Chain ................. 12  
The Way Forward ............................................................................................................................ 14
One of the distinctive capabilities of the U.S. Air Force, and indeed American airpower, is global precision attack, defined as "the ability to hold at risk or strike rapidly and persistently, with a wide range of munitions, any target and to create swift, decisive, and precise effects across multiple domains." Since the 1980s, the United States has developed an asymmetric advantage in its ability to rapidly locate and strike targets through the synergy of intelligence, surveillance and reconnaissance (ISR), command and control (C2), and precision strike. This process of prosecuting dynamic targets is commonly referred to as the "kill chain." In recent conflicts, America has been able to rely upon a relatively permissive threat environment, in which airpower has rapidly established air supremacy against legacy systems and then employed ISR and strike aircraft enabled by Global Positioning System (GPS) satellites to quickly locate, target, and strike targets with precision guided munitions (PGMs) at will.

However, over the past twenty years adversaries have sought to counter these asymmetric advantages by developing anti-access/area-denial (A2/AD) capabilities, which deny key enablers of the kill chain. Adversaries have proliferated jammers capable of disrupting GPS signals, which America relies upon to find, fix, and strike targets. They have also invested in advanced integrated air defense systems (IADS), capable of denying access to American airpower by imposing prohibitive risk on the employment of non-stealth aircraft within their threat rings.

Recent advances in precision navigation and timing (PNT) technologies have the capability to mitigate America’s reliance on GPS by enabling self-contained, GPS-quality positional awareness, immune from jamming. These PNT advances can overcome airpower’s vulnerabilities to GPS jamming and improve its capability against advanced IADS, thereby enabling and enhancing kill chain operations in an A2/AD environment requiring standoff precision-strike capability. This paper first addresses the threat of GPS jamming and IADS on
the kill chain, then describes the “fix” offered by emergent PNT technologies, their impact on the kill chain, and an operational concept for their use before suggesting a way forward.

**The Kill Chain and the Threat of GPS Jamming and IADS to its Effectiveness**

The kill chain, characterized by its sequential steps: find, fix, track, target, engage and assess, is a useful framework often used by the U.S. Air Force for conceptualizing the dynamic targeting process. The concept is equally applicable to Special Operations Forces’ targeting of high value individuals as to the mechanics of a modern fighter pilot making an air-to-air missile kill. In the context of this paper, which focuses on aerial systems, the kill chain is the location and fixing of targets, and the production of desired kinetic or non-kinetic effects through the use of sensors, weapons, and interconnected C2 networks.

With the worldwide proliferation of theater and tactical GPS jammers, reliance on GPS has become a critical vulnerability for American airpower. These powerful and inexpensive jammers reveal the difficulty and likelihood of the United States having to operate in GPS-denied environments in the future. For example, North Korea has fielded a Russian-built jammer, which can effectively deny GPS signals out to 400 kilometers (nearly 250 miles), using only 24 watts of power. The regime has demonstrated its willingness to jam GPS, degrading air and shipping operations near Seoul for days at a time in both 2010 and 2012. These GPS signals are weak and susceptible to barrage jamming; their strength is likened to seeing a 20 watt light bulb from 12,000 miles away! GPS jammers are also inexpensive; commercial-grade transmitters can be purchased for hundreds of dollars, and Russia and China have demonstrated a willingness to sell this and other military technology to a myriad of potential adversaries. While the commander of Air Force Space Command recently said, “big jammers are called targets,” touting airpower’s ability to “identify, geolocate and destroy those targets in a campaign,” he
also conceded that "we’re going to have to learn to fight through GPS jamming." High-value
targets will likely be defended by dozens of concealed jammers, and adversaries would
conceivably deploy hundreds of GPS jammers theater-wide on the ground and in the air in an
A2/AD environment, quickly moving and replacing destroyed systems. Therefore, America
must be prepared for sustained operations in a GPS-denied environment over enemy airspace,
and potentially for hundreds of miles beyond; the U.S. cannot assume that it will be able to
suppress or destroy GPS jammers against a determined enemy.

Complicating America’s ability to exercise the kill chain in a GPS-denied environment is
the threat posed by advanced IADS, which was developed and exported by Russia and China to
create “no-go” zones for most non-stealth aircraft, and which severely limits the ability of
American airpower to shape the battlespace. Advanced IADS coupled with GPS jamming render
useless much of America’s airborne ISR fleet, which is not survivable and largely ineffective at
standoff ranges, yet provides the persistent ISR that is necessary to complete the kill chain.
Also, due to limitations of range, access, operational risk or the lack of available stealth aircraft,
America must continue to rely on standoff weapons in order to strike targets within these IADS,
which are also susceptible to GPS jamming and a lynchpin to the “kinetic” side of the kill chain.

The Fix: Advanced PNT Systems Adapted to Aerial Platforms

Three developments in PNT technology, the Chip-Scale Combinatorial Atomic
Navigator (C-SCAN), the cold-atom inertial measurement unit (IMU), and the Adaptive
Navigation System (ANS), could eliminate the kill chain’s dependence on GPS by enabling
continued operational access, surveillance, targeting, and strike in an A2-AD environment. C-
SCAN is a microchip-sized IMU, capable of maintaining GPS-quality precision over a period of
minutes, while able to withstand the shock, g-forces, and temperature extremes that air-launched
weapons must withstand. An output from the Defense Advanced Research Project Agency’s (DARPA’s) micro-PNT program portfolio, C-SCAN integrates solid-state and atomic inertial sensors in order to replace bulky gyroscopes, while offering GPS-quality performance over long periods. These sensors are very compact, have relatively short warm-up and integration times, high resolution of motion detection, and low power consumption, which are the characteristics necessary for integration onto medium- and long-range air-delivered “smart” weapons. Importantly, the C-SCAN is also projected to be less expensive than current-generation tactical IMUs, such as those on JDAM, with a projected cost of about $1,500 per unit.

C-SCAN aims to deliver GPS-quality, self-contained precision navigation for up to twenty minutes time of flight (TOF), as opposed to a maximum of about 30 seconds for current-generation tactical IMUs, such as the one found on the hybrid GPS/INS Joint Direct Attack Munition (JDAM). C-SCAN’s TOF specifications also put it in the “sweet spot” of current-generation air-launched precision weapons’ capabilities: 98% of America’s air-delivered precision weapons currently have TOFs of less than twenty minutes, and almost all of them are critically dependent upon GPS. The IMU is now in component-level testing, and according to DARPA, will likely be ready for full system testing in about five years. However, while C-SCAN is ideally suited for short-TOF weapons, it doesn’t sufficiently address the requirement for persistent PNT in a GPS-denied environment.

The cold atom IMU is a self-contained PNT device capable of achieving highly precise navigation over a long period of time at a fraction of the drift rate of current navigation grade IMUs. Cold atom IMUs operate by using lasers to super-cool a cloud of Rubidium atoms in a vacuum to a temperature very close to absolute zero, and then measuring interference between atoms in two states of matter. Atom interferometry involves measuring the relative
acceleration and rotation of a cloud of atoms within a sensor case. The cold atom IMU is very accurate in six degrees of freedom, rotation, and acceleration, over a comparatively long period of time. In addition, cold atom IMUs are already far along in their development: second-generation IMUs are projected to be ready for operational testing in FY15. Cold atom IMUs should be able to maintain precise positional awareness over a period of hours without updates, making them particularly well suited for high-endurance Unmanned Aerial Systems (UASs).

Second-generation cold atom IMUs are slightly smaller than ring-laser gyro INSs now found on tactical aircraft, and are expected to be capable of 10g performance, making them compatible with fighter-type aircraft. Like all IMUs, however, the drift rate depends on the scale and frequency of accelerations; therefore, it is particularly well suited for UASs flying relatively benign profiles, and will be made more accurate with periodic updates. Cold atom IMUs should have the capacity to replace current navigation grade IMUs on aircraft, but while ultimate cost estimates are not yet available, they are more expensive than current generation IMUs. As a long-term solution for aircraft-based PNT, however, cold atom IMUs are attractive: they are small and have no moving parts, so reliability and cost should both improve over time. Most PNT systems today rely on GPS to provide necessary updates and redundancy for IMUs; ANS is another new technology that can provide this redundancy and GPS-free PNT.

Adaptive Navigation System, as a mature, “near-precision” (short of GPS quality) technology, has the potential to supplant other IMUs by providing high-quality updates and redundancy using a variety of non-traditional signals for navigation. This technology incorporates non-navigation signals from sources such as very-low frequency (VLF) waveforms used by naval vessels, television, radio, and cell phone towers, as well as natural phenomena such as lightning strikes, which create electrical disturbances that are picked up by ground
stations around the world. One ANS technology uses “signals of opportunity” to compare time
difference of arrival for certain signals to those at reference stations in order to determine
position. For example, a cloud-to-ground lightning strike (which occurs globally at a rate of 45
strikes per second) creates a VLF signal that is capable of traveling thousands of kilometers
within the earth’s ionosphere. An aircraft receives this signal, and its ANS correlates this with
one received at one of many VLF “reference stations” around the world (usually for
communication systems), in addition to other sensor inputs, to geolocate its position. Another
ANS technology is terrain matching, which compares stored digital terrain images to sensor
images, a technique that the Tomahawk cruise missile has used for years.

Adaptive Navigation Systems are truly “plug and play”; it makes use of existing
communication, radar, antennas, and other sensors found on aircraft and weapons (or added on,
if necessary) to achieve or supplement on-board PNT. Using advanced fusion algorithms to
correlate multiple non-traditional navigation sources, ANS could be a low-cost addition to
navigation systems currently in development, as well as future platforms and weapons. The most
likely use of ANS would be to supplant other airborne IMU systems, which might need position
and velocity updates in lieu of GPS availability over extended periods in a GPS-denied
environment. However ANS can be used as a stand-alone PNT system, such as with small
UASs, using passive sensors, magnetometers, and terrain matching technology to provide a
viable alternative to GPS. ANS is a fairly mature technology; DARPA plans to test it in
conjunction with a cold atom IMU in FY15. In addition, in only three years, ANS is slated for
further testing with Air Force Research Labs (AFRL), for integration with current and future
platforms. Having examined C-SCAN, the cold atom IMU, and ANS and their potential for
testing and fielding over the next five to ten years, it is instructive to look at specific applications
for these technologies in an A2/AD environment with respect to the kill chain.

**Impact of PNT Technologies on the Kill Chain**

Within the kill chain process, the foundational and most critical steps are the capability to “find, fix, and target” fleeting enemies. While a myriad of strategic, tactical and non-traditional ISR sensors are capable of this task, most of America’s capability and capacity rests in dedicated ISR aircraft, especially its burgeoning fleet of “drones” fielded over the past 15 years. UASs rely upon GPS corrections to maintain navigational and sensor awareness. In a GPS-denied environment, many UASs become practically unusable. Without accurate navigation sources or IMU updates, most UASs are unable to maintain positional awareness, and are also unable to effectively cue sensors, generate and transmit targeting data, or engage targets. UASs are also susceptible to “spoofing” attacks, where false GPS data is fed via ground stations to airborne platforms, causing inaccurate positional data. Iranian engineers claimed that they “hacked” the GPS signals of the highly secretive RQ-170 stealth UAS, and forced it to land, intact, on Iranian soil. The cold atom IMU, with its endurance and precision accuracy, would solve the problem of GPS-denial for virtually any tactical aircraft, although it is particularly suited for UASs.

America’s first priority for airborne cold atom IMUs should be UASs, since they are especially vulnerable to GPS-denied environments and they are also the ideal platform for high-endurance, persistent ISR necessary to find emerging targets. This allows for persistent navigation, targeting, and sensor cueing in a sustained GPS-denied environment. Stealth UASs, such as the RQ-170, the recently-acknowledged RQ-180 high-endurance stealth UAS, the Navy’s Unmanned Carrier Launched Surveillance and Strike (UCLASS) now in development, and other follow-on aircraft are particularly important to enable ISR, and thus the kill chain, within range of advanced IADS. Given the effective range of GPS jammers, non-stealth ISR
aircraft, such as the RQ-4 Global Hawk high-endurance UAS, U-2, and RC-135 will likely be exposed to GPS jamming even while orbiting outside the range of advanced IADS. The sensors and capabilities of these important assets are similarly affected by GPS jamming, and their benign flight profiles also make them prime candidates for a self-contained IMU. Therefore, the cold atom IMU should be explored for adaptation onto all current ISR platforms.

One of the most promising capabilities for the development of the kill chain is the small UAS, which is being incorporated into the forces of the U.S., its allies, and potential adversaries. With thousands of small UASs already in the U.S. inventory and a seemingly insatiable demand for more, small UASs represent an important element of future ISR capability with respect to the kill chain. A particularly important development is the incorporation of “swarm” technology, where UASs autonomously communicate and cooperate with one another to provide ISR or other battlefield effects. While small UASs are today most likely to be used in permissive air environments and relatively close to ground units, their potential use in a contested air environment is also promising. Launched from aircraft outside the range of enemy air defenses, small, relatively inexpensive UASs could be used singularly or as a swarm to detect, fix, and jam enemy air defenses, and provide critical ISR against high-value targets. However, the weak link for all of the small UASs currently deployed is their reliance on small GPS receivers for guidance, since the cost and weight of traditional IMUs are prohibitive. To address this, ANS is currently being incorporated into small UASs, to enable a low-cost, low-weight solution. Using terrain matching enabled by onboard ground sensors, as well as signals of opportunity from passive sensors, small UASs can incorporate ANS technology to provide a robust PNT capability. In addition, networking UASs can potentially increase their PNT accuracy, as positional data can be shared, correlated, and filtered between aircraft.
Turning next to the “kinetic” half of the kill chain—track, engage, and assess—currently both PGMs and the platforms that target and deliver those weapons are critically reliant upon GPS to strike targets. The F-22 and F-35, as the backbone of America’s fighter fleet for the next two decades, are uniquely capable as both ISR and strike platforms and must be capable of sustained operations in GPS-denied areas. Additionally, the Air Force’s Long-Range Strike Bomber (LRS-B), as America’s next-generation long-range, penetrating stealth bomber (due to enter service in the 2020s), must also include the capability to operate with full capability in a GPS-denied environment. Against targets deep inside enemy territory (and therefore within GPS-denied airspace), or far from airbases (such as the Chinese mainland), the LRS-B will give much-needed endurance and flexibility needed to shorten the kill chain in A2/AD environments. While these aircraft likely include the capability to update their IMUs via on-board sensors, the cold atom IMU would enable a necessary, robust capability throughout the kill chain for sustained operations without GPS.

While an accurate PNT solution is clearly needed for locating and destroying targets over enemy territory, this is equally important when delivering weapons from standoff ranges against targets pre-determined or “dynamic” targets. When delivering “smart” weapons, delivery aircraft must hand-off high-quality position and velocity data to the weapon at launch. Otherwise, without a good “starting point,” smart weapons have difficulty with orientation and navigation via on-board sensors, especially in a GPS-denied environment. Thus, for all tactical aircraft, accurate, sustained PNT is a must; in order to effectively “finish” the kill chain, however, smart weapons must also be equally capable.

As has been noted, C-SCAN’s size and high-quality PNT over a twenty minute TOF means it is well-suited for integration with air-delivered smart weapons, especially long-range
smart weapons that are particularly susceptible to GPS jamming. One of the main objectives of C-SCAN is the capability for “plug and play” modification of existing GPS-guided weapons, in particular the Small Diameter Bomb (SDB), which is one of the most prolific standoff weapons in the U.S. arsenal and the primary air-to-ground weapon of America’s fifth-generation fleet.\textsuperscript{25} With a range in excess of 40 nautical miles (NM), depending on launch speed and altitude, the SDB gives the U.S. military an important capability to strike targets outside the range of many IADS systems, particularly when incorporated onto stealth aircraft. The next-generation SDB (SDB-II) is now in testing, and adds an important capability of receiving in-flight target updates via datalink by on-board or off-board sensors (such as from an overhead ISR asset), as well as terminal guidance by on-board sensors such as millimeter-wave radar, semi-active laser homing, and uncooled thermal imaging. This capability will give commanders an important standoff, flexible targeting option against mobile or pop-up targets. However, unlike JDAM, SDB has virtually no capability without GPS guidance, since its on-board IMU is incapable of providing the necessary precision on its own.\textsuperscript{26} Therefore, future blocks of this weapon should maintain architecture capable of integrating C-SCAN into the weapon’s guidance.

With the size of C-SCAN compatible with (or smaller than) existing IMUs, it should feasibly integrate onto future variants of other smart weapons currently in design and testing phases. The C-SCAN’s small size enables it to fit into current versions of the JDAM, and would be especially useful if incorporated into the JDAM-ER (extended range), enabling larger warheads with an SDB-like range of over 40 miles.\textsuperscript{27} Current long-range standoff weapons, such as the Joint Stand Off Weapon (JSOW) and the Joint Air-to-Surface Standoff Missile and its extended range variant (JASSM/ER, now in operational testing), have TOFs that exceed C-SCAN’s twenty-minute specification. However, C-SCAN could still be a useful addition for
sustained GPS guidance. When coupled with ANS, datalink, and on-board terminal seekers, C-SCAN might still provide “near precision” navigation and targeting (much better than current IMUs) over an extended TOF, getting the weapons close enough to their targets to enable their on-board terminal sensors to still locate and destroy their targets autonomously. Each of these weapons incorporate in-flight datalink updates and organic sensors, making adaptive navigation an important and feasible capability for long TOFs, IMU “updates,” and redundant navigation.  

In ten to fifteen years, developers of the next generation of standoff weapons should look to fully integrate C-SCAN and ANS into every compatible platform; this combination ensures robust, inexpensive, and redundant navigation and targeting in any environment. C-SCAN might also enable another emerging weapon, promising a dramatic leap in capability to shorten the kill chain and hold theater-wide targets at risk in any environment.

Hypersonic missiles offer a quick-strike capability against targets many hundreds of miles away in only a matter of minutes, but have key technological hurdles to overcome before they are operational. Hypersonic weapons have already been successfully tested, and have been identified by the Air Force Long-Range Hypersonic Roadmap as a key capability aimed for a fielding date in the 2020s. However, achieving PNT at hypersonic speeds is a difficult technological challenge, which when coupled with GPS jamming, threatens the ability to accurately strike with necessary precision. Hypersonic vehicles lose the ability to receive communications and guidance (including GPS) data at extreme speeds due to a plasma field created around the platform. These weapons rely upon internal IMUs to navigate until they slow down and descend towards a target, at which point they pick up GPS guidance. In a GPS jamming environment, terminal guidance could be prevented. Hypersonic weapons should incorporate C-SCAN IMUs, which would offer an autonomous PNT capability both for GPS
jamming and plasma blackout. In light of this, DARPA is working with Air Force Research Labs (AFRL) to incorporate C-SCAN technology onto its hypersonic test vehicles.\(^{32}\) With Mach-5+ speeds, hypersonic missiles capable of being launched from fighter or bomber aircraft with in-flight retargeting capability would be able to cover a 1,000 NM range in under twenty minutes, offering commanders unprecedented speed and reach. In fact, Lockheed recently acknowledged work by its “Skunk Works” division on a hypersonic High Speed Strike Weapon, aimed at fulfilling this requirement.\(^{33}\) If fielded, this capability would offer a “game changing” strike capability in A2/AD environments, significantly shortening the kill chain against time-sensitive, high value targets deep behind enemy lines, or far away from American bases.

**Tying It Together: An Operational Concept for Advanced PNT and the Kill Chain**

As an operational concept and a means for finding and striking time critical targets, the kill chain is not new. Furthermore, developing faster weapons or improving operational reach is not necessarily the only, or best means of shortening the kill chain, and aerial platforms are not exclusive components of the kill chain. Just as important is a focus on improving and integrating ISR, cyber, and command and control capabilities, sensor-to-shooter connectivity, and decision-making processes, however, these are beyond the scope of this paper\(^{34}\) Nevertheless, advanced PNT technologies play an integral role in preserving, and potentially expanding the tactical asymmetry of rapid targeting that the United States has enjoyed for the last two decades, which is now threatened by fielded A2/AD capabilities such as GPS jamming and advanced IADS.

Accepting the notion that GPS jamming will be ubiquitous throughout a theater of operations (at least for some period of time in the beginning of a campaign) and will degrade the PNT capability of GPS-reliant airborne platforms, the technologies addressed in this paper will help ensure continued access to battlespace, sensor capability, targeting, and kinetic strike which
is necessary for completion of the kill chain. When combined with fifth generation fighters, bombers, and stealthy ISR platforms, cold atom IMUs supplemented by ANS technology will enable airborne platforms to find, fix, and target high-value targets early in a campaign, and begin to “roll back” the advanced IADS, which prevent legacy platforms from operating with impunity. In order to do so, these fifth-generation platforms will likely require additional electronic warfare support. To this end, air-launched decoys such as the Miniature Air Launched Decoy (MALD) and its jammer variant (MALD-J), fitted with a C-SCAN IMU, would accompany a strike package to force IADS to transmit, and enable the location and rapid targeting of these threats.35 Additionally, a fleet of small, expendable “swarm” UASs, incorporating C-SCAN IMUs and cooperative ANS, could be launched from outside IADS ranges to loiter ahead of strike packages, locate, jam, and pass targeting data to strike aircraft.

Completing the kill chain, F-35s would launch a salvo of SDB-II smart weapons from outside lethal detection ranges, which would be guided by C-SCAN IMUs immune to GPS jamming, receiving in-flight updates of target position via datalink from off-board ISR assets. In the early stages of a campaign against an A2/AD enemy, certain high-value targets, such as a theater ballistic missile (TBM), would also need to be targeted and struck, but might be beyond the range or capability of airborne platforms or weapons against a layered advanced IADS threat. In this case, an RQ-180 stealth UAS using a cold-atom IMU would locate and pass targeting data for the TBM via datalink. An Air Force bomber, loitering outside the range of enemy IADS, would receive a “smack” tasking from the Air Operations Center and launch a hypersonic missile from 500 NM away.36 The missile, using C-SCAN guidance, would receive updated positional data in its terminal phase via datalink from the UAS overhead, and arrive at the target in less than ten minutes. The UAS would then be in a position to assess battle damage—the last step of
the kill chain—and pass this information to commanders in real time. As enemy IADS are
“rolled back” and air superiority is attained, the fleet of legacy ISR platforms and strike aircraft
could be brought to bear against the enemy, increasing airpower’s capacity to shape the
battlespace and complete the kill chain against dynamic targets. Predators, Reapers, and
hundreds of small UASs would reassert America’s tactical asymmetry by fully enabling its kill
chain capability and capacity to rapidly find, fix, and strike targets at will. While the elements of
the kill chain haven’t changed, this manifestation of the process would be difficult, if not
impossible to conduct today in an advanced A2/AD environment, but would be made possible by
leveraging new PNT technology and other capabilities due to be fielded in the coming decade.

The Way Forward

The United States must continue to research, develop, test, and field advanced PNT
technologies in order to enable continued kill chain operations in a GPS-denied A2/AD
environment. With its dependence on GPS a critical vulnerability, America must leverage
advances in cold atom, C-SCAN, and ANS technologies to fix this problem with an aim to
develop “plug and play” capabilities with existing aircraft and weapons as much as possible.
This would ensure current aircraft and weapons are made more robust and capable against
modern threats, and also reduce the expense of fielding all-new weapons systems. As PNT
technologies mature and further testing occurs in the next several years, developers of new
airborne ISR and strike weapons systems must incorporate advanced PNT into these systems in
order to avoid costly retrofits. Also, as ISR aircraft, strike aircraft, and weapons become
increasingly networked via secure datalink, the most promising capability for PNT is the
incorporation of C-SCAN IMUs and ANS onto current and the next-generation of weapons,
where “cooperative” sharing of ANS data could increase PNT redundancy and reliability. In
addition, hypersonic missile technology must also continue to be developed and fielded at a size and cost comparable to current standoff weapons, incorporating a C-SCAN IMU to enable precision navigation and targeting from extended ranges. This will represent a “game-changing” capability for American commanders and policy makers, quickening the kill chain against high-value targets from nearly anywhere in theater.

Cold atom IMUs must also be incorporated onto the LRS-B and all other future tactical aircraft, as well as legacy high-endurance UAS platforms such as the RQ-4 Global Hawk and the stealth RQ-170, which, given their suite of sensors, also makes them uniquely capable of incorporating ANS technology. Given ISR’s importance to the critical “find, fix, and target” steps of the kill chain, their integral role in using the kill chain to target IADS and thus help establish air superiority, and their relatively benign profiles suited for the technology, high-endurance stealth UASs (such as the Navy’s UCLASS and the RQ-180 UASs) should be given priority for fielding the cold atom IMU.

American airpower is losing the race to maintain dominance in an A2/AD environment. In an era of declining budgets and painful tradeoffs between force structure, readiness and modernization, it would be easy to cut investments in PNT technology. However, since America can expect its next adversary to deny access and degrade GPS in order to counter asymmetric advantages, advanced PNT is a capability that must be preserved. Moreover, its applications extend well beyond the kill chain, including for navigation in environments where GPS is naturally denied, such as urban canyons, indoors, or underwater. C-SCAN, cold atom, and ANS offer every American military service key PNT capability improvements, in every domain. With proper investments, America can ensure that its capability for rapid, dynamic, and global precision attack, enabled through the kill chain, remains viable well into the future.
ENDNOTES


11 Lin Haas (PNT Program Manager, DARPA), interview with author, August 28, 2013.

12 Lin Haas (PNT Program Manager, DARPA), interview with author, August 28, 2013.

13 Lin Haas (PNT Program Manager, DARPA), interview with author, August 28, 2013.

14 Lin Haas (PNT Program Manager, DARPA), interview with author, August 28, 2013.

15 Lin Haas (PNT Program Manager, DARPA), interview with author, August 28, 2013.


32 Lin Haas (PNT Program Manager, DARPA), interview with author, August 28, 2013.
36 “Smack” is an immediate tasking from the Joint Forces Air Component Commander to immediately strike a selected target without further target correlation or collateral damage estimates.
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