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ACHIEVING ROBUST AND RESILIENT NAVIGATION AND TIMING FOR DEFENSE APPLICATIONS

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The Crisis in Navigation and Timing

Over the past 30 years, the increasing availability of highly accurate position, velocity, and time (PVT) information has transformed the U.S. military. It has affected almost every aspect of operations, and influenced fundamental changes in the force structure. As one example, air strike planners have transitioned from asking "How many aircraft will it take to destroy this target?" in the Vietnam era, to now asking "How many targets can this aircraft destroy?"

Force size, force structure, logistics, and even the size of munitions and weapons systems are predicated on highly accurate PVT.

This transformation is due to the U.S. Navstar Global Positioning System (GPS), which is being imitated by other satellite-based navigation and timing (SATNAV) systems developed by other nations around the world. GPS is unmatched by any other known technology for providing PVT. GPS offers:

- **Accuracy.** Absolute (not relative) position and time in global reference frames, 3-D positioning with accuracy on the order of a few meters, and timing accuracy to tens of nanoseconds.
- **Availability.** All-weather, day/night, worldwide, and in-space coverage, functioning over any part of the Earth including over water and featureless terrain, serving a limitless number of users.
- **Trust.** Signals are transmitted by the U.S. Air Force with high quality, integrity, and availability, including provision of encrypted military signals.
- **Ease of use.** GPS requires no local infrastructure, no surveying areas of operation. It offers low-cost, size, weight, and power user equipment (although infrastructure costs are borne by U.S. taxpayers) and passive receivers, and minimal training and skills are required for use.

"Today, almost every weapon we drop is a GPS guided weapon. Almost our entire force structure is built on GPS guidance. Our dropping of logistics off aircraft are GPS guided, the timing systems for weapons systems are GPS dependent, artillery and GMLRS are GPS guided, Navy Systems are GPS guided. In the future, we have to look at positioning, navigation, and timing as a mission, and build resilience into that architecture, as well as defending GPS on orbit."

—Gen. John Hyten,
USSTRATCOM Commander

"I hate GPS."

—Dr. Ashton Carter,
25th Secretary of Defense

With no overall strategy or even oversight concerning how PVT was to be obtained and used, thousands of individual and independent decisions have been made concerning how GPS-quality PVT could make various defense systems and applications more cost-effective. These decisions accrued over time, and were often made based on efficiency and expediency rather than robustness and resilience.

Widespread Dependence on Current GPS Is a Serious Problem

The consequence is widespread and often embedded use of GPS, with little oversight or insight into the way the system is employed and relied upon. This creates a number of serious concerns:

- GPS is a single system, making it a single point of failure for users and the host systems that rely upon it.
- GPS's weak signals make receivers susceptible to interference and jamming—threats that are increasingly widespread.
- GPS relies upon line-of-sight radio frequency (RF) propagation between satellites and receivers, so it does not work underground, underwater, or deep indoors.
- GPS requires signal reception from multiple satellites at diverse angles. Therefore, it exhibits degraded performance when lacking a clear view of the sky (such as in urban areas and challenging terrain), or when anti-jam antennas null out angular regions.
- Naively designed and operated GPS user equipment can malfunction or be susceptible to various attacks or anomalous conditions, sometimes producing erroneous outputs that can be more troubling than mere denial of service.
- Like any space system, GPS is potentially susceptible to space weather effects, as well as to attacks on the satellites and the ground segment.

These limitations are exacerbated by delays in GPS modernization. Today, we have an overly fragile and predominantly 20th century system facing 21st century threats that continue to evolve and emerge.

Because of its capabilities, attributes, and widespread adoption, GPS will remain essential for decades to come. No known technology can match its attributes, which are widely relied upon and will be increasingly needed with new technologies, such as autonomy.

As exhibited by the quotes above, the Department of Defense (DoD) has a love-hate relationship with GPS, and the DoD needs a strategy to move past these conflicting perspectives.

We are now approaching a crisis situation. Due to this combination of reliance on GPS, lack of an adequate substitute, fragility, and rising threats, users can no longer assume today's GPS will work for them when and where needed. Action must be taken now to address this emerging crisis in navigation and timing.

The question is, What strategy should the United States follow so that users and systems have the assured PVT they need in the 2020-to-2040 time frame? This document summarizes MITRE's look into this problem.

Three Rs

For many years, MITRE has advocated moving toward assured PVT through the three Rs portrayed in Figure 1. Three complementary steps are involved:

- Making satellite-based navigation and timing more **robust**, so that it can better withstand stresses without failure
- Adding **redundant** and diverse sources of PVT, so that GPS is not a single point of failure
- **Removing** threats to reduce their effectiveness

Taken together, these steps will result in the navigation and timing capability needed for future military operations.

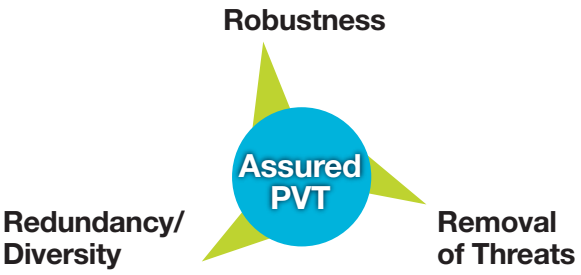

Figure 1. Three Rs for Assured Position, Velocity, and Time

Implementing the Three Rs

A comprehensive strategy for achieving robust and resilient navigation and timing is described in MITRE Technical Report MTR 170204, and the key steps are summarized here. The strategy employs proven techniques and does not require "technology miracles." Yet it also accommodates new technologies as they become cost-effective and useful. Five complementary tenets, pursued in parallel, are needed.

1. Enhance SATNAV Infrastructure

"SATNAV infrastructure" describes the integrated collection of satellites, ground segments, signals, and augmentations associated with a SATNAV system. Therefore, this infrastructure excludes user equipment.

Most important is staying the course on the GPS programs of record for space and control segments, executing the current acquisition programs on schedule and within cost. The more secure control segment that results will operate GPS III satellites broadcasting the modernized military signal—the M-signal—at higher power than previous satellites.

Also critical is development of follow-on GPS IIIF satellites, maintaining requirements and funding for their Regional Military Protection (RMP) capability. RMP concentrates even higher M-code signal power in a region of operations—allowing receivers to operate more than 10 times closer to a jammer than with the military signals operational today—while also enhancing resistance to spoofing.

Technical work and policy work should be coordinated to seek opportunities for foreign or commercial satellite systems to host signals similar to the GPS M-signal, providing trusted U.S.-controlled military signals independent of the GPS space segment and ground segment.

Assisted military SATNAV should be explored to enhance use of SATNAV signals from GPS and perhaps other SATNAV systems. Assistance can provide benefits like those that users experience with assisted GPS in consumer mobile devices, speeding signal acquisition and first fixes, enhancing robustness of SATNAV use, and possibly providing information from monitoring of broadcast SATNAV signals for improved assurance.

2. Transform SATNAV user equipment

Since SATNAV is too widely embedded and uniquely capable to be abandoned, receivers need to better use existing and planned signals, exploiting the tens of billions of dollars being invested in SATNAV infrastructure around the world.

The most important user equipment recommendation is to focus on enhanced M-signal processing robustness (better anti-jam and anti-spoof) in next generation

military user equipment. Military user equipment should be specified and built to provide increased resistance to jamming of all types, exploiting Moore's Law and the anti-jam features of the M-signal. More robust processing for signal acquisition and tracking can allow receivers to tolerate a factor of three to 10 greater jamming at the input of the receiver, for the same received signal power, relative to existing receivers.

Maintaining this anti-jam capability over the full expected range of signal powers, while adding other techniques such as heterogeneous power exploitation—using higher power signals to improve robustness of tracking weaker signals—can accelerate anti-jam capability and provide earlier benefits from higher power signals. Spoofing resistance can also be improved, particularly for use of M-signals**.**

Signal processing that excises and blocks jamming and spoofing should be selectively added to receivers, including already-fielded receivers. Such defenses can be beneficial near-term steps when they are carefully matched to user equipment characteristics and functions. They are not replacements for more robust signal processing, but can complement it.

Military receivers should be designed to avoid use of the original GPS signals (P(Y) and C/A), and instead should use the M-signal whenever possible. If they need to use civil GPS signals, they should use modernized GPS civil signals. With multiple other global and regional SATNAV systems, it is potentially attractive to implement in military user equipment the capability to use selected signals from other SATNAV systems. Using the right additional signals in the right way potentially provides multiple types of benefits (system diversity, national diversity, geometric diversity, frequency diversity, information diversity), with modest impact on user equipment and its integration and installation. However, significant work is needed to mature and demonstrate that such use can be cost-effective and safe before any decision is made to insert such capability into a major program. See the discussion of PVT Assurance in the next section.

3. Transition to Assured Navigation and Timing User Equipment

A measured approach is needed to move from today's fragile reliance on GPS to assured use of a broader set of PVT sources. A gradual transition to this broader set of PVT sources is recommended, recognizing that it will take time and funding to move away from currently integrated GPS receivers, and that technology development is needed to mature other PVT sources. In particular, other PVT sources should be thoroughly evaluated and "red teamed" to understand their capabilities, limitations, and vulnerabilities before making investments in them. It is not sufficient that these other PVT sources be resistant to attacks on GPS; they must be able to resist attacks that capable, well-resourced, and motivated adversaries could develop if the United States uses these other PVT sources.

The United States needs to develop user equipment architectures that adopt "The Flip"—moving the core PVT source from GPS to precision clocks and inertial sensors. These should be disciplined by GPS and other PVT sources. Since precision clocks and inertial sensors can be almost immune to jamming and spoofing attacks, The Flip can dramatically improve robustness and resilience.

Properly architected, The Flip also can provide a smooth on-ramp for the incorporation of diverse PVT sources. Timing receivers are the natural application for first adoption of The Flip, and there are ways to implement The Flip with existing timing receivers.

Since lack of PVT Assurance is a potential showstopper, it must be comprehensively addressed. PVT Assurance involves protecting the user equipment and its outputs from faulty (accidental or intentional) inputs and being able to measure the trustworthiness of PVT outputs. PVT Assurance is still technically immature, even in GPS. The uncertainties, unknowns, and risks associated with use of other SATNAV and other PVT sources make it even more immature for reception of these other sources. A significant, focused research and development effort is needed to mature the technologies of PVT Assurance and to then inform policymakers and lawmakers concerning the capabilities and residual risks of various PVT sources.

4. Recognize and Remove Threats

To complement steps that improve robustness and resilience against jamming and spoofing threats, these threats must be put at risk, eliminating the need for perfect defenses. As adversaries take steps to counter the recommendations in Tenets 1 through 3, their enhanced jamming and spoofing threats will become more vulnerable to recognition and removal by the United States and partners.

The first step is situational awareness within user equipment, at critical locations, and over wide areas. User equipment must recognize RF threats and report their presence and characteristics to users and host systems. Data logging is also needed to support investigations, forensics, and countermeasure development.

Wide area surveillance capabilities are needed to characterize threat environments, providing results to mission planners and platforms. Knowledge of threat systems' RF characteristics and tactics should then be used to assess their impact on different U.S. and partner systems, informing mission planning concerning employment of different systems and tactics. In addition, such knowledge should be used to determine when threats should be removed, rather than merely tolerated.

Munitions and non-kinetic capabilities must be developed to hold jammers and spoofers at risk. These weapons and tools should be integrated with an end-to-end kill chain that Finds, Fixes, Tracks, Targets, Engages, and Assesses items of interest. This enhanced kill chain/threat removal capability must be made operational, trained with, and utilized in exercises. While removing threats to military and Intelligence Community applications may not always be needed or possible, battlefield commanders should have this capability available when needed. As adversaries become aware of this capability, they will be motivated to change their threat characteristics and operations in ways that reduce their jamming and spoofing effectiveness.

5. Take Complementary Non-Materiel Steps

While Tenets 1 through 4 identify key materiel steps that must be taken, these steps must be enabled and complemented by non-materiel steps that affect organization, acquisition, policies, doctrine, and training.

DoD must organize to implement this PVT strategy, as current Department and Service organizations have contributed to the current situation. More efficient and effective governance is needed to address overall PVT issues, rather than merely dealing with issues at the individual program level.

Acquisition program deficiencies must be addressed. One specific example is the development of modernized military receivers.

This endeavor has been ongoing since studies began in 2004, without yet delivering any operational user equipment.

As the program for the next generation of user equipment (known as Modernized GPS User Equipment Increment 2) is being defined currently, there is an opportunity to streamline the requirements (e.g., focus exclusively on processing the new military signal—the M-signal—and one civil signal), to incentivize contractors that provide accelerated performance, and even to downselect contractors whose performance (technical or schedule) falls behind.

Policies must be revamped to enable and implement this strategy. Currently applicable policies date to 2004 or even earlier, but many things—from the global situation to individual technologies—have changed in the meantime. While some policies have been updated, they still may not be current, and they may not be consistent with each other or with current realities. In some cases, technical work is needed to inform policies.

Doctrine and training must be updated to account for stressed environments. One likely reason for military requirements failing to result in robust and resilient navigation and timing is that users do not fully experience the impact of stresses during training and exercises with their current equipment. This does not mean the equipment performs adequately, just that it is not realistically stressed.

Also, those who develop doctrine may not have enough opportunity in stressed conditions to appreciate the impact and to fully develop appropriate doctrine and tactics.

Recognizing and Overcoming Myths

The five tenets described in the previous section are widely accepted as obvious, constructive, and effective. Yet their implementation is hindered by three myths, which threaten to derail this strategy.

Myth 1. The current GPS programs are on the verge of providing everything needed. The first increment of modernized military receivers capable of processing the M-signal (MGUE Increment 1), combined with modern anti-jam antenna systems and signals from GPS III satellites, all monitored and controlled by the new GPS ground segment OCX, will meet future needs for robustness and resilience.

Myth 2. Most systems do not need the accuracy of GPS and can get adequate PVT through alternate technologies like sextants, maps, compasses, data link ranging, and other procedural measures.

Myth 3. New technologies that can replace GPS are imminent.

Like most myths, each of these statements contains elements of truth. While the current GPS programs will provide improvements over today's operational system, repeated studies and analyses show they will not be sufficient for the future.

It is true that many current operational systems have modes where other existing PVT sources may be adequate, but end-to-end operational concepts and kill chains need the capabilities of GPS to avoid inefficiencies, losses, and other unacceptable negative consequences.

No new technologies have been identified and shown to cost-effectively provide the capabilities and robustness of GPS. Some new technologies can provide useful niche or fallback capabilities, but GPS will remain the foundational source of PVT for decades.

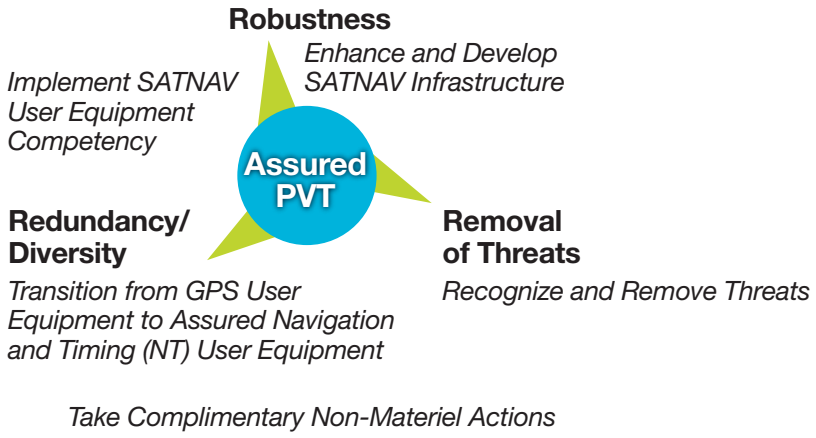

Figure 2. The Five *Strategy Tenets* Implement the Three **Rs**

A Call to Action

No longer can the tremendous benefits (in dollars and in lives) of accurate PVT from GPS be taken for granted. Unless significant steps are taken, starting now, adversaries will increasingly eliminate these benefits when we need them most.

As illustrated in Figure 2, the five tenets of this strategy lead to the three Rs that produce Assured PVT for warfighters. There is no single solution, no magic wand to wave, no quick fix.

However, embarking now on implementing all five tenets will yield the navigation and timing capability needed for future military operations, and contribute to the PVT superiority that is key to warfighting success.

Implementing the strategy will take sustained effort. Success requires commitment, funding, focus, and follow-through—none of which are easy to find.

Implementation must start with DoD giving an organization or individual the responsibility and authority to ensure that future military operations have the Assured PVT essential to their success. When that organization or individual is established and empowered, we will know that the first step has been taken on the road to robust and resilient navigation and timing for the Department.

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