National Defence Défense nationale

Canadian Forces College

Collège des Forces Canadiennes

ORIENTING IN FREE FALL: REALIZING GPS CAPABILITIES IN DEEP SPACE DOMAINS

Major Aaron Hines

JCSP 50

Service Paper

Disclaimer

Opinions expressed remain those of the author and do not represent Department of National Defence or Canadian Forces policy. This paper may not be used without written permission.

PCEMI n° 50

Étude militaire

Avertissement

Les opinons exprimées n'engagent que leurs auteurs et ne reflètent aucunement des politiques du Ministère de la Défense nationale ou des Forces canadiennes. Ce papier ne peut être reproduit sans autorisation écrite.

Canada

CANADIAN FORCES COLLEGE - COLLÈGE DES FORCES CANADIENNES

JCSP 50 - PCEMI n° 50
2023 - 2024

Service Paper – Étude militaire

ORIENTING IN FREE FALL: REALIZING GPS CAPABILITIES IN DEEP SPACE DOMAINS

Major Aaron Hines

ORIENTING IN FREE FALL:
REALIZING GPS CAPABILITES IN DEEP SPACE DOMAINS

AIM

The aim of this paper is to demonstrate the foundational importance of achieving knowledge of one's own spacecraft within the space domain, to highlight operational limitations facing USSF owner operators in doing so in tactically relevant timelines, and to propose a technological breakthrough, by means of a modification to future GPS systems, necessary to correct current shortfalls while also staging for future successes even further from the surface of the Earth.

INTRODUCTION

The primary motivation behind this paper comes from the author's experiences in performing rendezvous and proximity operations (RPO), and the difficulties experienced in carrying out these missions with respect to relying on incomplete or non-timely positional information. The author is concerned that such shortfalls will lead to operational failure in the event of a near-peer conflict, but offers a solution based upon currently available solutions that need only modification to correct major operational deficiencies.

This paper will discuss the realities of positional understanding on the Earth's surface as compared to the space environment, current solutions for USSF personnel, define an operational timeline in space, and discuss both China's preferred method for solving the problem as well as propose an alternate U.S. method which may be more fruitful.

DISCUSSION

1. On the surface of the Earth, knowledge of one's own position is fairly assured. This is because of the position, navigation, and timing (PNT) capabilities provided by the Global Positioning System (GPS). At any given time, one can expect at least four of these spacecraft overheard, and through a process called trilateration, whereby each satellite is constantly emitting its own position with a time stamp, at the speed of light, any user possessing a GPS receiver will attain a knowledge of one's own position down to approximately three feet accuracy.

2. This system was designed with military uses in mind, and it was first employed during the First Iraq war to deliver on the promise of air-land battle. Not only did fielded forces have greater situational awareness because of this new capability, but weapons ordinances were fitted with GPS receivers, which were in turn tied in to control mechanisms. This enhancement made these munitions orders of magnitude more accurate than before, and as such, uniquely effective in laying waist to armored and hardened targets.

3. Over the past thirty years, the GPS fleet has been modernized and upgraded to become even more of an accurate purveyor of position. Now, operators in Colorado

monitor the emissions of all thirty-one operational satellites from control segments across the globe, and he or she can update or refine the accuracy of a particular spacecraft by cross-linking signals from one satellite to another even when the latter is not in view of a ground station. While it may be said that the constellation has been optimized to provide support across the globe, the same can not be said about the reality of navigating an object through space.

4. Knowledge of position in space is a far more precarious proposition. Broadly speaking spacecraft can be said to operate in four primary regimes. These are Low Earth Orbit (LEO), Middle Earth Orbit (MEO), Geosynchronous Orbit (GEO), and Super-Geosynchronous Orbit (Super-GEO). The tools available for tracking spacecraft across each of the regimes differs in terms of weight of emphasis, but each leverages a combination of phased array radars, mechanical radars, ground-based electro-optical (EO) observation sites and space-based EO capabilities.

5. Combining these capabilities, a knowledgeable party creates a mathematically-derived probability bubble known as a vector covariance matrix (VCM) which depicts the probable location of a spacecraft at a given point in time. This process is not equal across each of these domains. In LEO it is common for knowledge of a space object to be within two to three feet of error, but out at GEO and super-GEO this knowledge can often degrade to the point one possesses only a tertiary understanding of position inside a covariance bubble 20 km high by 20 km wide by 40 km long (20x20x40). The primary reason for this is the difficulty in transmitting radar into deep space and receiving a recognizable return signal.

6. One technological solution to this problem has been the integration of GPS receivers into spacecraft design. For those spacecraft operating in LEO, between the MEO-based GPS constellation and the surface of the Earth, the same benefits are achieved as those realized by ground users, just by being in the path of the signal. Unfortunately, as mentioned earlier, this is the orbital regime in which state knowledge is already most easily attained. Beyond MEO, out at GEO where many of the nation’s most vital space assets reside, those of the protected SATCOM and Overhead Persistent Infrared (OPIR) detection variety, utilization of GPS is more complicated.

7. Today, there are satellites which leverage GPS out at GEO and super-GEO. This is possible because of a phenomenology known as ‘side lobes’. The simple explanation of this is that by sheer laws of physics, some of the signal from the GPS spacecraft extends around the edges of the Earth, and even though it gets weaker as it travels further through space, it still makes it to the GEO-based spacecraft at the opposite edge of the domain. The downside of this process is that none of the GPS satellites between the GEO-based satellite and Earth contribute to the former’s ability to solve for its location, and most of those on the opposite side are blocked from contributing by the Earth itself. This means that only a third, roughly ten of thirty-one, are of use, and as such these spacecraft often require multiple hours of receiving GPS signals before a state is achieved.

8. During the era in which space was uncontested, this shortcoming was operationally insignificant. Space is large, and the probability of collision the further one

travels from the Earth, the less likely collision becomes. This has changed over the past ten years. Both Russia and China have introduced experimental spacecraft, which operate in close proximity to other objects, to the domain.[1] Slowly but surely space is becoming a contested domain in which one must prepare for both offensive and defensive operations.

9. There are many kill chain models. Over time ATGK, acquire-target-guide-kill, and F2T2EA, find-fix-track-target-engage-assess, have come into and fallen out of vogue. But perhaps in this instance, it is appropriate to align space dogfighting terminology to that of the original master of one on one airpower competition, John Boyd, when he simplified combat to the widely publicized model of Observe-Orient-Decide-Act, or the OODA loop. He opined that whoever could effectively cycle through this sequence of actions could not help but be victorious in a head to head competition. Unfortunately, half-baked students of Boyd have often misapplied his model and concluded that fast repetitive decision and action is the key to victory. Instead, the crux of Boyd's model lies in the ability to orient, and to disadvantage your adversary from doing likewise.

10. Boyd's ideas are as true in space as they are in the air. Though the physics are different, and the methods for orientation are dissimilar, knowing one's own position remains a foundational requirement in determining what to do next. Taking action without orientation is equally as fruitless and full of risk as it would to execute basic fighter fundamentals without first taking stock as to where one's adversary is before maneuvering. The problem is not that the U.S. has no means to orient, as has been shown to this point. It is just that the current solutions are too slow. How does one quantify 'too slow'? It is by walking through a notional orbital engagement, that this can be demonstrated.

11. In geosynchronous orbit, one degree of east-to-west travel is 726 km of straight-line travel. Satellites orbit the Earth at a speed of 3 km/s, thus matching the rotation of the Earth. Under current space norms, a degree of separation is considered quite benign, and one nation would be considered quite ridiculous if it flagged another country's spacecraft as acting irresponsibly for maintaining a one degree standoff distance. At this distance, if a spacecraft performed a 50 meter-per-second maneuver to begin ingress against another, it would close the distance to kinetic impact in about 4 hours and 1 minute. Most spacecraft maneuver planning, given ideal circumstances, can be accomplished in 2-3 hours. Assuming the maneuver was detected, and the warning was passed from the operational control hubs in California and Colorado, it is reasonable to think the aggression could be thwarted. This is except for one key problem.

12. In order to move, the owner operators of the spacecraft need to first determine where they are at, and because only a small percentage of GPS satellites are supporting this, it is likely that they are not armed with this information at any given moment. Most systems will target 1-2 optimal opportunities a day, when the most GPS satellites are in

[1] Thomas Roberts, Unusual Behavior in GEO: SJ-17, Center for Strategic and International Studies, September 1 2022, https://aerospace.csis.org/data/unusual-behavior-in-geo-sj-17/.

view, to turn on their receivers and update their state. If, out of the blue, they are warned of a hostile act, before they can begin maneuver planning, they will have to activate their receivers and add those hours to the timeline of their response. This factor alone breaks the four-hour timeline.

13. There are two possible material fixes to this problem. The first method is that which was chosen by China. Yes, China is ahead of the U.S. in this regard. As of June 2020, China completed Phase 3 of their BeiDou project. Phase 3 included the deployment of 3 BeiDou PNT satellites to geosynchronous orbit, thus giving them a persistent capability within the domain.[2] This solution works particularly well for the Chinese as they have, as of yet, confined their space operations to the regions within direct view of the mainland; at GEO this is roughly 45 degrees east to about 200 degrees east. Within this region, China has effectively achieved a constant state of positional knowledge, and as such has an advantage in a confrontation with U.S. capabilities.

14. This solution is imminently achievable for the U.S. and yet it would not be the recommended way forward for two reasons. First, as compared to China, who seeks first to establish a regional hegemony, the U.S. sustains both its terrestrial military and its space capabilities across the globe. Rather than the deployment of 3 GPS satellites to a specific region, the U.S. would have to deploy 3-4 times this amount across the entire expanse of GEO to enable the effect across over 261,000 kilometers of linear distance. Both the AEHF/MILSTAR (communications) and SBIRS (OPIR) constellations have been spread across GEO in stationary orbits. The problem lies not in the capability to do this, but the practicality of the solution. This leads to the second and more pertinent point.

15. Secondly, this solution is limited in utility. Implementing it would only solve the problem for GEO, but the same problem would once again arise as further regions of space are colonized for military and civilian use. There is no point in solving today's problem, only for the same problem to crop up again in a decade. Already, the service has expressed significant interest in the LaGrange points between the Earth and the moon as the next strategic high ground. Additionally, talks have begun regarding the potential military benefit of establishing a permanent presence on the southern pole of the moon, and placing objects into a continuous lunar transfer orbit. Instead of focusing on a short-term fix, investment should be made in a solution that will work not only for today, but also for tomorrow.

16. On a spacecraft, the communications payload, where the owner operators send command to the satellite and receive telemetry indicating what the vehicle is doing, is located on the nadir, or Earth-facing, face of the vehicle. It is standard practice to place an additional antenna on the zenith, or anti-Earth-facing, face of the vehicle to aid in anomaly recovery. In the case of GPS vehicles, these communications antenna exist on both faces, and the payload antenna which transmits the GPS signal towards the Earth

---

[2] Tracy Cozzens, China Completes BeiDou-3 Worldwide Navigation Constellation, North Coast Media LLC, June 22 2020, https://www.gpsworld.com/china-completes-beidou-3-worldwide-navigation-constellation/.

exists also on the nadir face. With a degree of engineering modification, it would be entirely possible to update future GPS vehicles with an additional GSP payload antenna oriented on the zenith face, which would allow the vehicle to simultaneously transmit towards the Earth and out into space.

17. Implementing this change requires no significant deviation from operational requirements. GPS satellites have design life of 12 years, and as of February 2024, 15 of 31 vehicles have exceeded their originally expected period of utility.[3] As recently as last year a new vehicle was placed into orbit, and another is set to launch of June of this year. The most modern variant of GPS is known as Block IIIF, and within the contract it already has identified points known as 'technology insertion points'. The next of these will occur in June of 2028, which is both ideal for researching and engineering a zenith facing antenna solution and problematic for a short-term conflict with China[4]. The current plan for 2028 already includes an upgraded buss (physical structure of the vehicle), increased power, and on-orbit servicing amongst other capabilities. It does not, however, call for what is being proposed here. That is a mistake.

18. There are those who would argue that this feature is not needed. The principle argument is that increasing the numbers of optical telescopes and deep-space-capable mechanical radars would achieve the same effect, with the added benefit of tracking adversary capabilities simultaneously. It is not an argument without merit, as those capabilities would bring an added benefit to the general goal of effective orientation. Still, it is an incomplete perspective. Even with those additions, those observations from those systems are not fed directly to the tactical unit. Instead, they route into operational control hubs, who then conduct their own analysis before furnishing their results to the tactical level. This is an added layer of delay which is acceptable for routine operations, but not tactical employment of combat capabilities. Furthermore, as the number of space objects continues to grow at an almost exponential rate, solutions should not be seen as an 'either/or' type of calculus, but an amalgamation of all available options so long as the resources exist to enable them.

CONCLUSION

19. The world of space operations is changing, that much is certain. And just as the invention of radar was a necessary breakthrough shortly following the advent of airplanes, and their subsequent utilization in a combat capacity, so too now is a revolution needed in space. The solution for GEO and super-GEO already exists, and it has been exploited to its maximum capacity as currently constructed. That solution remains insufficient for the tactical timelines which will likely be presented in the event of conflict, and that insufficiency will most likely undermine chances for success. Failure

---

[3] GPS Fact Sheet, United Space Force Website, Current as of October 2020, https://www.spaceforce.mil/About-Us/Fact-Sheets/Article/2197765/global-positioning-system/.

[4] Department of Defense Fiscal Year (FY) 2023 Budget Estimates, April 2022, https://www.saffm.hq.af.mil/Portals/84/documents/FY23/PROCUREMENT_/FY23%20Space%20Force%20Procurement.pdf?ver=vMyfar1xW31ifPHFc-mz6A%3D%3D#page=67.

here will place strategic assets at risk, and endanger the lives of terrestrial forces. Instead, the service needs to champion a technological reform which will expand the utility of the current GPS constellation, and give U.S. forces the upper hand in any eventual conflict. The mechanism to do so already exists within the modernization schedule for the GPS fleet, and this change needs only to be championed at the strategic level.

RECOMMENDATION

20. Engage with the PNT mission area team (MAT) and GPS program office to conduct a viability assessment regarding placing a payload transmitter on the Zenith face of the GPS IIIF satellites as part of the 2028 technology update.

BIBLIOGRAPHY

Cozzens, Tracy. China Completes BeiDou-3 Worldwide Navigation Constellation. North Coast Media LLC. Retrieved from https://www.gpsworld.com/china-completes-beidou-3-worldwide-navigation-constellation/.

Department of Defense Fiscal Year (FY) 2023 Budget Estimates. Department of the Air Force. April 2022. Retrieved from https://www.saffm.hq.af.mil/Portals/84/documents/FY23/PROCUREMENT_/FY23%20Space%20Force%20Procurement.pdf

GPS Fact Sheet. Official United States Space Force Website. Current as of October 2020. Retrieved from https://www.spaceforce.mil/About-Us/Fact-Sheets/Article/2197765/global-positioning-system/.

Roberts, Thomas. Unusual Behavior in Geo: SJ-17. Center for Strategic and International Studies. September 1, 2022. Retrieved from https://aerospace.csis.org/data/unusual-behavior-in-geo-sj-17/.