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STARLINK PNT FOR SOF: HOW PROLIFERATED LOW EARTH ORBIT SATELLITE CONSTELLATIONS CAN INCREASE OPERATIONAL RESILIENCE IN GPS DEGRADED ENVIRONMENTS

by

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This research seeks to determine the capabilities and limitations of Starlink position, navigation and timing (PNT) capabilities to inform how Special Operations Forces can utilize proliferated Low Earth Orbit satellite constellations to create a more robust and resilient PNT primary, alternate, contingency, and emergency (PACE) plan. The pertinence of this research is underscored by the escalating threats to GPS integrity, which pose significant risks to military navigation systems. Key findings suggest that while Starlink PNT is less capable than GPS, especially in mobile contexts, it is operationally relevant in static contexts where GPS is denied, and position data is critical. Additionally, Starlink PNT offers cost-effective resiliency due to Starlink terminals already being deployed across the military as alternative communications systems. This thesis recommends the addition of Starlink PNT data from existing Starlink communication terminals to bolster the PNT PACE plan, providing a low-cost enhancement to operational resilience in the face of GPS vulnerabilities.

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This research seeks to determine the capabilities and limitations of Starlink position, navigation and timing (PNT) capabilities to inform how Special Operations Forces can utilize proliferated Low Earth Orbit satellite constellations to create a more robust and resilient PNT primary, alternate, contingency, and emergency (PACE) plan. The pertinence of this research is underscored by the escalating threats to GPS integrity, which pose significant risks to military navigation systems. Key findings suggest that while Starlink PNT is less capable than GPS, especially in mobile contexts, it is operationally relevant in static contexts where GPS is denied, and position data is critical. Additionally, Starlink PNT offers cost-effective resiliency due to Starlink terminals already being deployed across the military as alternative communications systems. This thesis recommends the addition of Starlink PNT data from existing Starlink communication terminals to bolster the PNT PACE plan, providing a low-cost enhancement to operational resilience in the face of GPS vulnerabilities.

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LIST OF ACRONYMS AND ABBREVIATIONS

API	Application Programming Interface
CEP	Circular Error Probable
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
pLEO	Proliferated Low Earth Orbit
PNT	Position, Navigation and Timing
SOF	Special Operations Forces
VEP	Vertical Error Probable

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EXECUTIVE SUMMARY

This thesis examines the applicability of Starlink's new position, navigation, and timing (PNT) capability for Special Operations Forces' PNT primary, alternate, contingency, emergency (PACE) plan in light of current threats to GPS with a specific focus on the positioning capabilities. The research question examined is: What are the capabilities and limitations of Starlink PNT as an alternative PNT solution for Special Operations Forces? The answer to this research question will inform how Special Operations Forces can utilize proliferated Low Earth Orbit (pLEO) satellite constellations to create a more robust and resilient PNT PACE plan.

The significance of this research stems from the acknowledged vulnerability of GPS in the modern operational environment. GPS, the cornerstone of military navigation and timing, faces escalating risks from adversarial jamming. An alternative or complementary PNT solution could prove crucial in maintaining the edge in mission-critical situations where GPS is denied. This thesis assesses Starlink PNT capabilities as a potential countermeasure to these threats.

The research adopts an empirical approach, testing the terminal and analyzing the results. The baseline performance testing consists of 500 static test iterations that captured 2492 position fixes. With this data, a variety of graphical tools were used to analyze the data to capture a nuanced understanding of the results. The operational testing consists of 4 mobile test iterations, a system integration demonstration to show a real-time position fix on navigation software, and an analysis of the terminal's transmission and reception patterns. Additionally, conclusions about operational efficacy are drawn from existing research and documentation.

The results of the research show that, while Starlink PNT is found to be less capable than GPS, particularly in mobile operational contexts, it exhibits sufficient utility in stationary applications. As an additional benefit, the cost of integrating Starlink PNT is marginal because Starlink terminals are already being fielded within the military for communication. The inherent value of Starlink PNT lies in the terminal's dual use as a communication and navigation aid, presenting a unique opportunity for resource optimization.

In light of these findings, this thesis advocates for a specific course of action: the integration of Starlink's positioning function alongside its primary use for communications. This recommendation promotes a layered PNT approach, enhancing the robustness of the SOF PNT PACE plan. From unmanned systems to night operations, such integration would provide a backup position source in case of GPS denial, increasing access to critical positioning data. Additionally, as this capability matures and other pLEO PNT providers enter the market, SOF will be well positioned to capitalize on this technology.

The results of the research are summarized in Tables 1 and 2, outlining Starlink PNT baseline performance capabilities in a static context and relevant operational capabilities. The baseline performance testing results show how the Standard Terminal performed over hundreds of tests while stationary. It shows the fix accuracy and the latency and reliability of a fix within a given accuracy threshold.

Table 1. Baseline Performance Testing

Criteria	Figure of Merit	Standard Terminal Results
Accuracy (Latitude/ Longitude)	First Fix Lat/Long Position Accuracy (CEP)	327.6 meters
	5-minute Lat/Long Position Accuracy (CEP)	215.2 meters
	20-minute Lat/Long Position Accuracy (CEP)	17.6 meters
Accuracy (Altitude)	First Fix Altitude Accuracy (VEP)	2272 meters
	5-minute Altitude Position Accuracy (VEP)	182 meters
	20-minute Altitude Position Accuracy (VEP)	31.43 meters
Latency	First Fix Acquisition Time	5.76 minutes
	25-meter Fix Acquisition Time	13.31 minutes
Reliability	First Fix Rate Success	99.8%
	25-meter Fix Rate Success	80%

The operational testing results (Table 2) show how the terminals performed during mobile tests, system integration tests and signal transmission analysis. Additionally, it shows the operational conclusions about jamming and detection drawn from published research.

Table 2. Operational Testing

Criteria	Figure of Merit	Standard Terminal Results	Flat High-Performance Terminal Results
Interoperability	Compatibility with Other Systems	Pass	Pass
	Compliance with Industry Standard (NMEA-0183)	Pass	Pass
Mobility	Accuracy at 5 MPH	Fail	Fail
Jamming	Rx Signal Strength Compared to GPS	+ 30 dB (1000x Stronger)	+ 30 dB (1000x Stronger)
Jamming/Detection	Antenna Gain Pattern	Directional ESA	Directional ESA
Detection	Rx only	Fail	Fail

This subset of empirical evidence serves as a quick-reference guide for military planners considering Starlink PNT's role in future operations. The full thesis delves into the detailed methodologies used, the extensive testing conducted, and the broader strategic implications of the findings.

This research effort is intended to provide decision-makers with a concise yet comprehensive understanding of Starlink PNT's potential role in SOF operations. It is an invitation to consider how cutting-edge civilian technology, when judiciously adopted, can meet military needs at a rapid pace, ensuring that SOF maintains its operational advantage in an increasingly contested domain.

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I. POSITION, NAVIGATION, AND TIMING FOR SPECIAL OPERATIONS FORCES

U.S. Special Operations Forces (SOF) are tasked to operate in an environment that is different from those of the past two decades in the Middle East.[1] Increasingly prevalent competition with near-peer adversaries requires SOF to change and adapt their tactics and capabilities to maintain tactical effectiveness.[2] According to the 2022 Special Operations Forces Vision and Strategy, "SOF has proven their capability as a premier CT (counterterrorism) force over the last two decades and must sustain the capability. However, current and future threats demand that SOF evolves into a force capable of creating strategic, asymmetric advantages for the nation as a key contributor of integrated deterrence."[3] Unlike the conflicts in Iraq and Afghanistan, a near-peer threat will have sophisticated military technology, professionally trained personnel, and weapons designed specifically to counter U.S. military technology. To become a meaningful contributor to integrated deterrence, SOF standard operating procedures (SOPs) and equipment must be adapted to the demands of this new environment.

Before SOF can properly adapt their force, they must first understand the threat environment. This knowledge is critical for the proper development of the tactics, techniques, and procedures (TTPs) and systems needed to operate against near-peer adversaries. One of the threats in a near-peer conflict is the manipulation of the electromagnetic spectrum for military purposes, known as Electromagnetic Warfare (EW). A broad range of operations fall under EW, but for this thesis, the discussion centers on jamming attacks against the Global Positioning System (GPS).

Jamming attacks against GPS are one form of EW that is especially concerning for the United States:

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[1] Richard Clarke and Christopher Maier, "SOF Vision and Strategy," April 11, 2022, https://www.socom.mil/Pages/SOF-Vision-and-Strategy.aspx.

[2] Richard Clarke, "Statememnt of General Richard D. Clarke, USA," April 5, 2022, https://www.armed-services.senate.gov/imo/media/doc/2022%20USSOCOM%20Posture%20-%20Clarke%20-%20SASC%20(5APR22)%20(FINAL).pdf.

[3] Clarke and Maier, "SOF Vision and Strategy."

> The U.S. Department of Homeland Security has called the GPS 'a single point of failure for critical infrastructure.' This is, in part, due to the fact that the vast majority of GPS receivers need to be very sensitive because of the weak signals coming from distant, orbiting satellites. This weakness creates many opportunities for criminals as well as state actors seeking military strategic gains.[4]

This reliance on GPS is integrated throughout the U.S. military, and adversaries have developed weapons to exploit this dependency. A report published by the American Security Project in 2020 stated that "through EW, Russia can counter some of the capabilities that make the U.S. military so effective. … it can disrupt or degrade the navigation systems used by U.S. forces to locate themselves and identify targets for precision guided munitions (PGMs)."[5] The United States' reliance on GPS is deeply woven into all warfighting domains and remains at risk of adversarial EW attacks.

There are many ways for an adversary to degrade GPS including destruction and jamming of satellites and their receivers. Compared to larger proliferated constellations like SpaceX's Starlink constellation with thousands of satellites, the GPS constellation consists of only 31 satellites. 24 satellites are required to provide the basic coverage of Earth with six backup satellites already in orbit around the Earth.[6] This small number of satellites provides critical capabilities to the United States' economy and military. A report published in 2019 on the economic benefits of GPS for the United States found "that GPS has generated roughly $1.4 trillion in economic benefits (2017$) for the private sector in the years since it was made available for civilian use in the 1980s. Most of those benefits have accrued since 2010."[7] Disrupting GPS signals would have a harmful impact on the United States' economy. In addition to the economic benefits of GPS, the "American military and civilian users depend on assured PNT information, which is essential to effective military operations and civil infrastructure. GPS is the primary source of PNT

[4] Tegg Westbrook, "The Global Positioning System and Military Jamming: Geographies of Electronic Warfare," *Journal of Strategic Security* 12, no. 2 (2019): 1–16, https://www.jstor.org/stable/26696257.

[5] Patrick Smith, "Russian Electronic Warfare: A Growing Threat to U.S. Battlefield Supremacy" (American Security Project, 2020), https://www.jstor.org/stable/resrep24679.

[6] "GPS.Gov: Space Segment," accessed February 4, 2023, https://www.gps.gov/systems/gps/space/.

[7] Alan C O'Connor et al., "Economic Benefits of the Global Positioning System (GPS)" (Research Triangle Park, NC: RTI International: National Institute of Standards and Technology, June 2019).

information for U.S. and multinational warfighters and is operated by the U.S. Space Force on behalf of the DOD."[8] With all this capability being produced by a small number of satellites with weak, jammable signals, the likelihood of GPS degradation in future conflicts is high.

Jamming attacks have been carried out in conflicts around the world. Since the Russia-Ukraine war began in 2022, EW attacks have frequently been observed on navigation systems. General Thompson, U.S. Space Force's Vice Chief of Space Operations, said "Ukraine may not be able to use GPS because there are jammers around that prevent them from receiving any usable signal. … Certainly, the Russians understand the value and importance of GPS and try to prevent others from using it."[9] The Russians understand the value of offensive jamming and use this capability to prevent their adversaries from having reliable positioning capabilities. In addition to offensive denial of GPS, Russia has used GPS denial to prevent UAVs from entering their airspace. They will conduct GPS jamming around their cities so GPS dependent systems are unable to maintain accurate position.[10] As the Russia-Ukraine war continues to demonstrate, GPS denial will be a constant threat on the modern battlefield.

Since GPS has been the primary source of PNT for SOF, loss of GPS presents a vulnerability to operational success that SOF must counter if they want to contribute to integrated deterrence. Traditional SOPs and technology used during the wars in Iraq and Afghanistan will leave SOF dangerously exposed to GPS jamming from near-peer adversaries with extensive EW capabilities. Historically, SOF relied on GPS as their principal navigational aid, supplementing it with map and compass techniques when needed; however, map and compass navigation proves impractical in numerous operational settings, such as the maritime domain, or during operations with limited visibility, like

[8] U. S. Government Accountability Office, "GPS Alternatives: DOD Is Developing Navigation Systems but Is Not Measuring Overall Progress | U.S. GAO," accessed February 5, 2023, https://www.gao.gov/products/gao-22-106010.

[9] Elizabeth Howell, "Russia Is Jamming GPS Satellite Signals in Ukraine, U.S. Space Force Says," Space.com, April 12, 2022, https://www.space.com/russia-jamming-gps-signals-ukraine.

[10] Matt Burgess, "GPS Signals Are Being Disrupted in Russian Cities," *Wired*, accessed May 1, 2023, https://www.wired.com/story/gps-jamming-interference-russia-ukraine/.

night operations or jungle warfare. These two navigation methods do not provide sufficient PNT PACE plan depth and diversity for reliable navigation in a future conflict against a near-peer adversary, especially not in a denied or degraded environment.

These are precisely the types of environments where SOF will be required to operate should the United States find itself in a conflict with a peer adversary. Since SOF has a history of innovation and adaptation and is poised to be on the leading edge of future military innovation, it is also natural to assume that these forces will be first to field and implement new and emerging battlefield technologies. According to the 2022 Special Operations Forces Vision and Strategy, "Over the next 10 years, we will modernize SOF, pioneer dynamic and unorthodox approaches (including the full toolkit associated with irregular warfare), leverage emerging technologies to mitigate adversarial activities by China and create asymmetric advantages for current and future conflict."[11] The emergence of proliferated Low Earth Orbit (pLEO) satellite constellations present a new approach to traditional GPS systems, offering enhanced resilience against the threats posed by near-peer adversaries. These new constellations, comprised of hundreds of satellites, provide a more distributed and redundant architecture, making them less susceptible to disruption or destruction. Furthermore, the proximity of Low Earth Orbit (LEO) satellites to the Earth's surface translates to stronger signal strength, which is critical for the reliability of PNT services in challenging operational environments. The advent of these systems can provide SOF with a robust layer of redundancy and can ensure uninterrupted access to position data, even in the event of GPS compromise or denial. This research seeks to determine the capabilities and limitations of Starlink PNT to inform how Special Operations Forces can utilize pLEO satellite constellations to create a more robust and resilient PNT PACE plan.

[11] Clarke and Maier, "SOF Vision and Strategy."

II. THE THREAT TO THE GPS LINK SEGMENT

To assess the vulnerabilities of the GPS link segment, this chapter delves into two critical areas: design vulnerabilities and electronic warfare vulnerabilities. Design vulnerabilities are inherent in the system's architecture and the methodologies employed for geolocation. Meanwhile, electronic warfare vulnerabilities are assessed in the context of the capabilities possessed by nations worldwide, presenting a spectrum of challenges that stem from the strategic to the tactical level. This examination offers a holistic view of the fragility of GPS and the potential risks it faces in the current geopolitical landscape.

A. GPS DESIGN VULNERABILITIES

When considering threats to space based PNT systems like GPS, most practitioners consider three main segments, or areas, of concern: the space segment, the user segment, and the control segment. All three of these segments are required for the proper functioning of GPS. Figure 1 shows the three GPS segments.

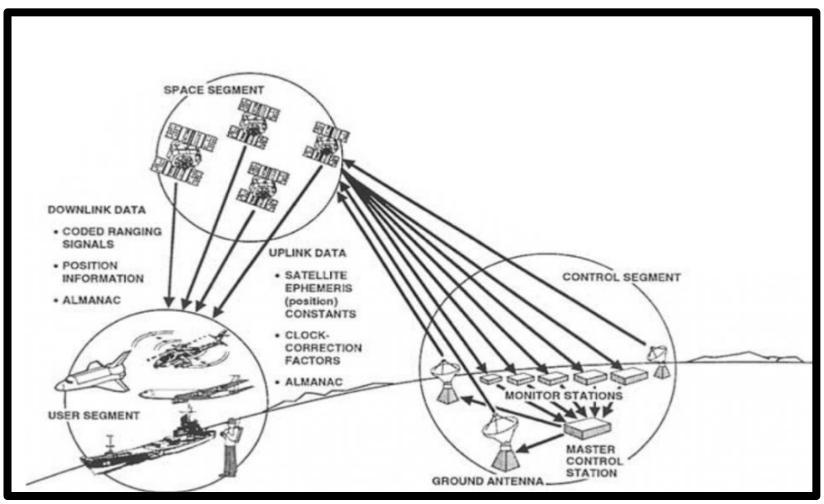

Figure 1. GPS Segments[12]

[12] Source: National Research Council (U.S.) and National Academy of Public Administration, eds., *The Global Positioning System: A Shared National Asset: Recommendations for Technical Improvements and Enhancements* (Washington, D.C.: National Academy Press, 1995), 150.

The space segment encompasses all space assets required for the system; in particular, all models of the GPS satellites. The user segment includes all receivers that depend upon the downlink data from the spacecraft. From airplanes to cell phones, GPS receivers are ubiquitous throughout the world. The control segment comprises all the ground infrastructure required to maintain, track, and update the satellite constellation.[13] Each segment presents distinct challenges in addressing threats and developing resilience for the system. For this thesis, the vulnerability considered is the link between the user segment and the space segment. This concentration is because user segment represents the most readily accessible facet for achieving immediate enhancements in system resiliency for SOF. As the commercial sector progresses in its development of innovative receivers and satellite systems, it will enable users to deploy a diverse array of receivers, each with its own distinct level of susceptibility to electronic warfare. A nuanced understanding of uplink and downlink vulnerability is crucial for informing future developments and ensuring the robustness of PNT systems against EW threats.

To understand the threat to the user segment, it is important to understand the user segment's functionality, specifically the downlink from the satellite to the receiver. For GPS, the user must receive signals from at least four of the 31 GPS satellites. GPS currently utilizes three carrier frequencies—L1 (1575.42 MHz), L2 (1227.6 MHz), and L5 (1176 MHz)—each transmitting the navigation message from the satellite. This message is encoded into a spread spectrum waveform at these carrier frequencies. Various codes for GPS, known as Pseudo-Random Noise (PRN) codes—such as C/A, P(Y), and the military M-code—are available. These codes facilitate receivers in attributing signals to specific satellites and decoding the signal. Upon signal receipt, the data message encoded in the signal is extracted and utilized to locate the receiver's position.

GPS signals contain a standardized message for each code, which includes data about the satellite's own position (x_1, y_1, z_1) and the time of transmission (T_{trans}) among other data. The basic math behind GPS' geolocation is as follows: Utilizing the location

[13] U.S. Department of Homeland Security, "Global Positioning System (GPS) Overview | Navigation Center," accessed November 17, 2023, https://www.navcen.uscg.gov/global-positioning-system-overview.

information from 4 different satellites (x_1, y_1, z_1), (x_2, y_2, z_2), (x_3, y_3, z_3), (x_4, y_4, z_4), and the speed of the signal, which is the speed of light (c), the receiver calculates the range to each satellite (R_1, R_2, R_3, R_4). With R_1, R_2, R_3 and R_4 calculated, the receiver clock bias (ΔT) and the position of the receiver (x, y, z) remain to be solved. The system of equations depicted in Figure 2 is then used to solve the remaining unknown variables. Once the receiver clock bias (ΔT) is calculated, the true time of reception (T_{rec}) at the terminal is calculated using the equation $\Delta T = T_{rec} - T_{trans}$.[14]

$$
\begin{aligned}
R_1 &= \sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2}-(\Delta T)c \\
R_2 &= \sqrt{(x-x_2)^2+(y-y_2)^2+(z-z_2)^2}-(\Delta T)c \\
R_3 &= \sqrt{(x-x_3)^2+(y-y_3)^2+(z-z_3)^2}-(\Delta T)c \\
R_4 &= \sqrt{(x-x_4)^2+(y-y_4)^2+(z-z_4)^2}-(\Delta T)c.
\end{aligned}
$$

Figure 2. The System of Equations for GPS TOA

This geolocation method, known as trilateration, is a Time of Arrival (TOA) geolocation method. TOA utilizes the time and position data encoded in the signal to solve for range, distinguishing it from other forms of geolocation, such as Time Difference of Arrival (TDOA) or Frequency Difference of Arrival (FDOA), which are typically used when the receiver lacks access to the underlying signal structure or does not have the necessary number of satellites in view for trilateration. Since GPS is designed for compliant receivers capable of decoding the signal, the simpler TOA method is employed for geolocation. This method, along with more complex corrections, can result in precision of 3 meters for the C/A code and 0.3 meters for the P code.[15]

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14 Xu Guochang, *GPS: Theory, Algorithms and Applications*, 2nd ed. (Berlin: Heidelberg: Springer-Verlag, 2007), 37, https://doi.org/10.1007/978-3-540-72715-6.

15 Guochang, 39.

To accomplish trilateration without receiver clocks being synchronized with the satellite, the receiver requires line of sight to four satellites. Due to the GPS constellation's location in Medium Earth Orbit (MEO) at an altitude of 20,200 km, global coverage is possible with 24 satellites, as compared to a constellation in LEO which would require hundreds of satellites.[16] This altitude allows the satellites to have a large section of Earth in their view, thereby reducing the total number of satellites needed for global coverage. With the limited satellite launch capacity during the development of GPS, producing, launching, and controlling hundreds of satellites was not realistic; therefore, an orbital regime in MEO made sense for the GPS system. Figure 3 represents the difference in beam coverage between a LEO satellite and a MEO satellite.

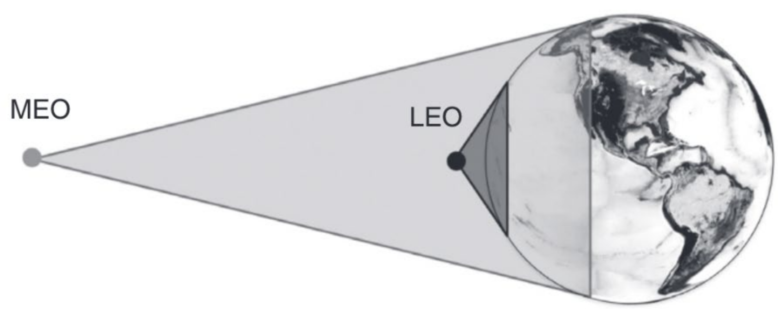

Figure 3. Satellite Signal Footprint Comparison[17]

While the MEO orbital regime offers global coverage, the GPS satellites are positioned at least 18,000 km farther from the receivers than those in LEO. This greater distance leads to an increased free space path loss (FSPL), which is defined by the erosion of power density of a signal. The FSPL equation is illustrated in Figure 4.

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[16] "Satellite Navigation – GPS – How It Works | Federal Aviation Administration," accessed August 2, 2023, https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/gps/howitworks.

[17] Source: Tyler G.R. Reid et al., "Navigation from Low Earth Orbit: Part 1: Concept, Current Capability, and Future Promise," in *Position, Navigation, and Timing Technologies in the 21st Century*, ed. Y. T. Jade Morton et al., 1st ed. (Wiley, 2020), 1359–79, https://doi.org/10.1002/9781119458555.ch43a.

$$FSPL = \left(\frac{4\pi df}{c}\right)^2$$

Figure 4. Free Space Path Loss Equation

The FSPL grows exponentially as the distance (*d*) rises linearly. This explains why the GPS signal strength received on the ground is around -125 dBm, which is substantially below the standard noise floor for most receivers.[18] Due to this weak signal, "a one-watt jammer, about twice the power of a LED night light, can prevent the continuous tracking of the military GPS signal at a distance of about two miles and can prevent the initial acquisition of that signal at about 10 miles."[19] When comparing the FSPL of a satellite in LEO with that of a satellite in MEO, the satellites in LEO experience significantly less FSPL resulting in signals that are 1000 times stronger than a comparable satellite in MEO.[20]

The architectural choices behind the GPS constellation expose the system's link segment to potential electronic warfare (EW) threats. Specifically, reliance on a modest set of satellites, coupled with the trilateration process necessitating at least four of them for accurate geolocation, creates inherent vulnerabilities for jamming. Moreover, the position of these satellites in MEO results in weak signals to the receiver, increasing the potential risk to EW. Given the global awareness of the U.S.'s heavy dependence on this critical yet susceptible service, it becomes a particularly tempting target for adversarial EW attacks.

B. ELECTRONIC WARFARE THREATS

The electronic warfare threat addressed in this thesis is a type of electromagnetic interference known as jamming. Jamming obstructs the desired signal from reaching its

[18] "Global Position System Low Noise Amplifier" (Philips, May 2009), https://www.nxp.com/docs/en/brochure/75016740.pdf.

[19] F. S. Prol et al., "Position, Navigation, and Timing (PNT) Through Low Earth Orbit (LEO) Satellites: A Survey on Current Status, Challenges, and Opportunities," *IEEE Access* 10 (2022): 83971–2, https://doi.org/10.1109/ACCESS.2022.3194050.

[20] Reid et al., "Navigation from Low Earth Orbit."

target receiver by broadcasting a more powerful signal on the same frequency.[21] A report by the Government Accountability Office for the U.S. Senate's Armed Service Committee states that "jamming is the most common and prevalent threat to GPS, largely because jammers are cheap and easily accessible."[22] Notable countries with jamming capabilities include China, Russia, Iran, and North Korea.[23] The simplicity of jamming GPS signals and the inherently weak power of these signals means that jammers can be easily crafted and distributed, offering a cost-effective way to hinder military operations with a relatively low technical barrier to entry for an adversary force.

The 2022 Russian invasion of Ukraine exposed many examples of modern applications of jamming. To comprehend the tactical employment of Russian EW, it is essential to recognize the significance of EW in the Russian military. The Russian military has invested heavily in electromagnetic warfare equipment that is capable of jamming GPS signals. According to the American Security Project report on Russian EW, "EW has occupied an important position within the broader modernization of Russia's military. Laurie Moe Buckhout, a retired U.S. Army Colonel with a specialization in electronic warfare, observed that Russia has 'redone and reengineered [its] entire EW fleet in the last 20 years.'"[24] Russia understands the importance of electromagnetic dominance on the modern battlefield and has invested in assets to become experts in EW. This investment has been on display during their war with Ukraine.

Leading up to the invasion, the Organization for Security and Cooperation in Europe (OSCE) was monitoring the Ukraine-Russian border with UAVs and experienced

[21] United States Government Accountability Office, "GPS ALTERNATIVES- DOD Is Developing Navigation Systems But Is Not Measuring Overall Progress," Report to the Committee on Armed Services, U.S. Senate (Washington, D.C.: Government Accountability Office, 8/22), https://www.gao.gov/assets/gao-22-106010.pdf.

[22] United States Government Accountability Office (GAO), 14.

[23] United States Government Accountability Office (GAO), 14.

[24] Smith, 3.

jamming on over 60% of UAV flights.[25] In addition to the OSCE UAV jamming, a long-range UAV experienced GPS interference the day before the invasion.[26] It is assessed that this jamming came from a Russian anti-UAV system called the Krasukha-4 that is specifically designed to jam GPS and GNSS receivers onboard the UAVs.[27] Following the invasion, there were many civilian reports of GNSS jamming and by March 2022, the European Union Aviation Safety Agency (EASA) released a warning for aviators that said, "In the current context of the Russian invasion of Ukraine, the issue of Global Navigation Satellite Systems (GNSS) jamming and/or possible spoofing has intensified in geographical areas surrounding the conflict zone and other areas."[28] The pervasive use of Russian jamming tactics in the war with Ukraine, particularly targeting GNSS systems, underscores the strategic emphasis Russia places on electronic warfare in its operations.

Although the war in Ukraine exposed more examples of GNSS jamming by Russia, this is not a Ukraine specific threat; Russia and the prior Soviet Union have a long history of jamming. Leaders in the Soviet military believed that electronic warfare was important to the future of war and that it could control modern warfare.[29] This interest in electronic warfare, and specifically jamming, resulted in advanced Soviet EW ground stations, aircraft, ships and even satellites that were designed to negate adversary radio capabilities.[30] After the collapse of the Soviet Union, the importance placed on EW in the Russian military remained.

[25] Kari A. Bingen, Kaitlyn Johnson, and Makena Young, "Space Threat Assessment 2023" (Center For Strategic & International Studies), accessed August 1, 2023, 18, https://csis-website-prod.s3.amazonaws.com/s3fs-public/2023-04/230414_Bingen_Space_Assessment.pdf?VersionId=oMsUS8MupLbZi3BISPrqPCKd5jDejZnJ.

[26] Bingen, Johnson, and Young, 18.

[27] Bingen, Johnson, and Young, 18.

[28] Tom Bateman, "Russia Jammed Passenger Plane GPS Signal, French Official Says," euronews, April 1, 2022, para 14, https://www.euronews.com/next/2022/04/01/russia-responsible-for-gps-jamming-in-europe-french-air-safety-official-claims.

[29] Guy Thomas, "Soviet Radio Electronic Combat and the U.S. Navy," *Naval War College Review* 35, no. 4 (1982): 16–24, https://www.jstor.org/stable/44636175.

[30] Thomas.

More recently, Russia utilized GPS jamming in Syria. In 2018, retired General Raymond Thomas, former commander of U.S. Special Operations Command, said that Syria is “the most aggressive EW environment on the planet.”[31] Russia used EW to jam manned aircraft and UAVs with sophisticated encryption and anti-jam receivers.[32] Although it is not clear how the aircraft were jammed, it was noted by Buckhout that “they may have taken the much easier route of interfering with PNT or their communications gear, making it more difficult to fly the aircraft since crews would have had to rely on maps, line of sight, and other techniques.”[33] Russia’s investment in EW and their use of jamming in Syria and Ukraine demonstrates that EW remains a threat for any nation in conflict with Russia.

Beyond offensive battlefield jamming, Russia also uses EW techniques to create safe zones to protect their cities. They have installed GPS jammers on infrastructure such as cell-towers to create a bubble where GPS dependent systems are degraded.[34] According to GPSjam, an open-source software that uses public aircraft data to display reports of GPS jamming, a higher number of jamming reports (> 10%) have been reported over Russian cities such as Moscow (Krasnogorsk), Saint Petersburg, and Volgograd.[35] Figure 5 shows the prevalence of jamming around these cities. Systems dependent on a reliable GPS signal will struggle to be effective if operating in these cities and other GPS degraded environments.

[31] Colin Clark, “Russia Widens EW War, ‘Disabling’ EC-130s OR AC-130s In Syria,” Breaking Defense, April 24, 2018, para. 1, https://breakingdefense.sites.breakingmedia.com/2018/04/russia-widens-ew-war-disabling-ec-130s-in-syria/.

[32] Smith, “Russian Electronic Warfare,” 5.

[33] Clark, para. 6.

[34] Bingen, Johnson, and Young, “Space Threat Assessment 2023,” 19.

[35] “GPSJAM GPS/GNSS Interference Map,” accessed November 17, 2023, https://gpsjam.org/.

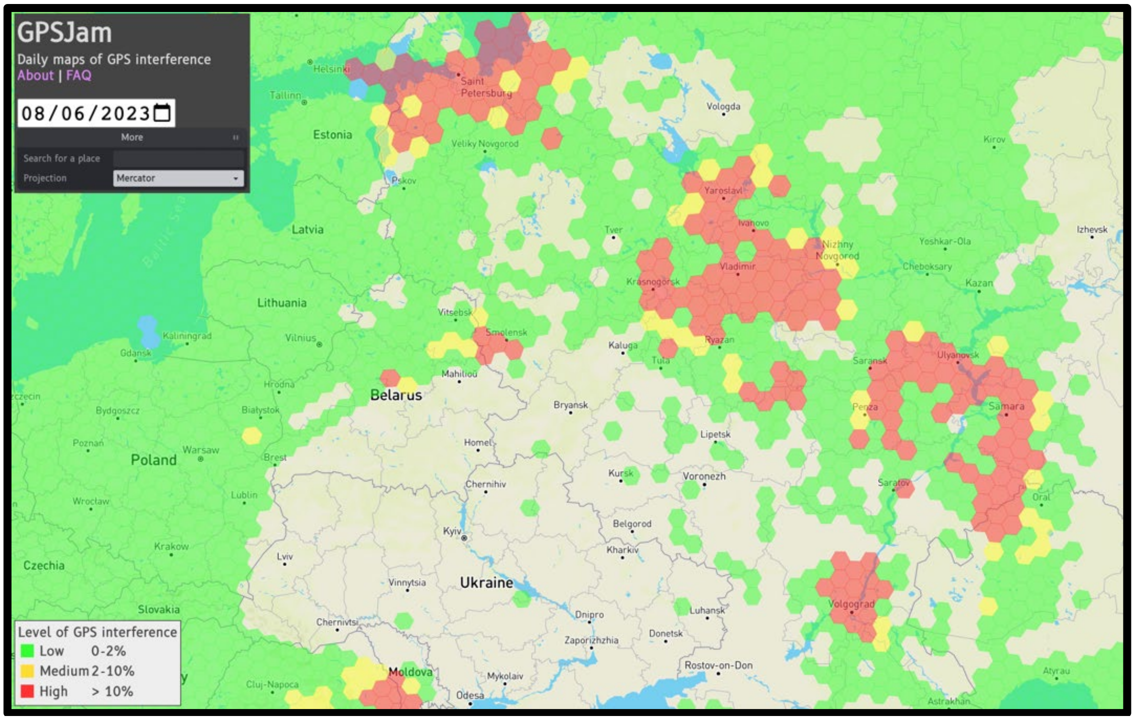

Figure 5. GPS Jamming Reports on 8/6/2023[36]

As demonstrated in the Russia-Ukraine war and their operations in Syria, Russia has heavily integrated jamming capabilities into their military strategy and in defense of their cities. Based on the persistent and consistent integration of these capabilities across Russian military and civilian infrastructure, it is likely that any future engagement between the United States and Russia will be marked by EW offensive and defensive employment.

Although jamming is a major component of Russian war strategy, jamming GNSS receivers is not specific to Russia. Militaries across the world have developed their own jamming capabilities that will likely be employed in a conflict with the United States. For example, China has invested in jamming capabilities and has reorganized its military to better leverage electronic warfare which they consider to be critical for modern warfare.[37] In 2015, China created the Strategic Support Force (SSF) responsible for "the coordinated

[36] Source: "GPSJAM GPS/GNSS Interference Map," accessed August 6, 2023, https://gpsjam.org/.

[37] Department of Defense, "Military and Security Developments Involving the People's Republic of China," Annual Report to Congress (Department of Defense, 2023), 102, https://media.defense.gov/2023/Oct/19/2003323409/-1/-1/1/2023-MILITARY-AND-SECURITY-DEVELOPMENTS-INVOLVING-THE-PEOPLES-REPUBLIC-OF-CHINA.PDF.

employment of space, cyber, and electronic warfare to 'paralyze the enemy's operational system-of-systems' and 'sabotage the enemy's war command system-of-systems' in the initial stages of conflict."[38] Contributing to this effort, the People's Liberation Army (PLA) "routinely incorporates in its exercises jamming and anti-jamming techniques that probably are intended to deny multiple types of space-based communications, radar systems, and GPS navigation support to military movement and precision-guided munitions employment."[39] The deliberate enhancement of electronic warfare capabilities through structural reforms and dedicated training within the PLA highlights a focus on the implementation of electronic warfare into the Chinese military strategy.

The Chinese have also invested in jamming capabilities that project this capability beyond their borders. Mobile EW systems have been observed on different reefs in the South China Sea with commercial satellite imagery.[40] The isolated location of these reefs makes them "ideal for collecting discrete electromagnetic signals or generating electromagnetic interference"[41] Additionally, EW systems have been established on Hainan Island, in the South China Sea, at the Mumian facility. According to the Center for Strategic & International Studies, "imagery from November 21, 2021, reveals the recent construction of several key new assets … at least four tall tower antennas suitable for communications or EW. An older northern facility in the area has an array of three tower antennas, likely for use in EW."[42] Figure 6 shows the Mumian Facility on Hanian Island.

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[38] John Costello and Joe McReynolds, "China's Strategic Support Force: A Force for a New Era," *Institute for National Strategic Studies*, China Strategic Perspectives, 13 (n.d.), 2, https://ndupress.ndu.edu/Portals/68/Documents/stratperspective/china/china-perspectives_13.pdf.

[39] Defense Intelligence Agency, *Challenges to Security in Space: Space Reliance in an Era of Competition and Expansion*, [Second edition] (Washington, D.C.: Department of Defense, 2022), 17, https://www.dia.mil/Portals/110/Documents/News/Military_Power_Publications/Challenges_Security_Space_2022.pdf.

[40] J Michael Dahm, "Electronic Warfare and Signals Intelligence," *John Hopkins Applied Physics Laboratory*, South China Sea Military Capability Series, n.d.

[41] Dahm, 5.

[42] Matthew P. Funaiole, Joseph S. Bermudez, and Brian Hart, "China Is Ramping Up Its Electronic Warfare and Communications Capabilities near the South China Sea," December 17, 2021, https://www.csis.org/analysis/china-ramping-its-electronic-warfare-and-communications-capabilities-near-south-china-sea.

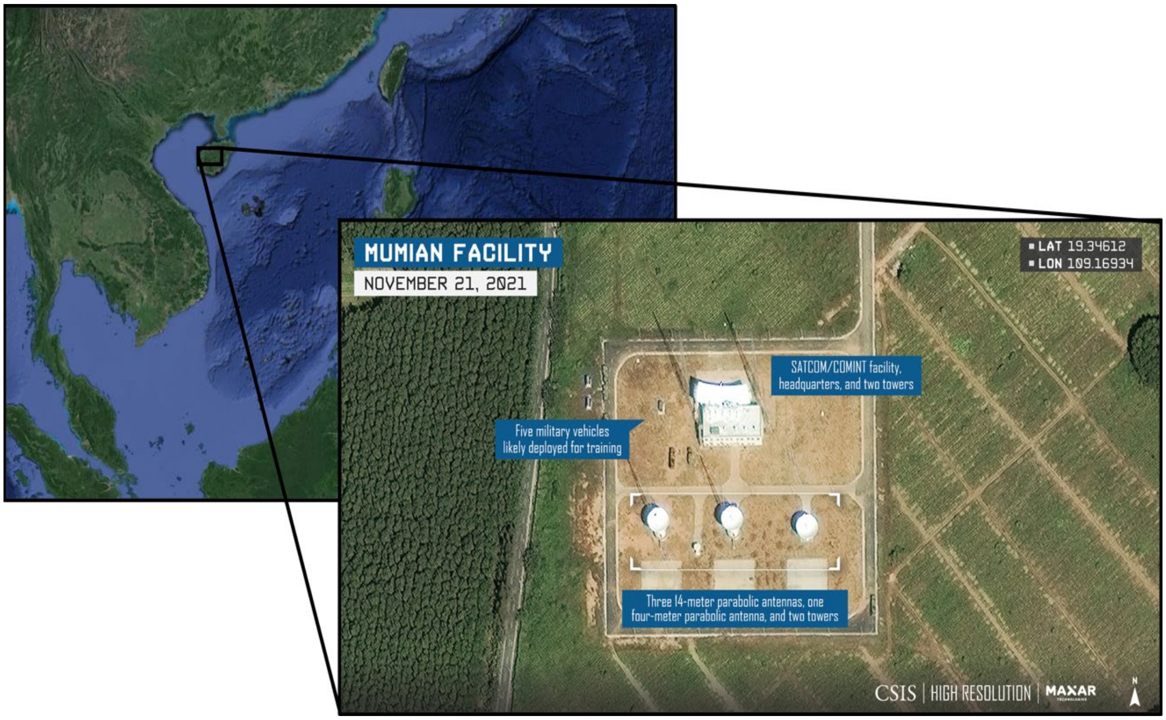

Figure 6. Mumian Facility in the South China Sea[43]

Although these facilities can conduct EW beyond China's continental borders, they are limited by their line of sight. To reach beyond the horizon and project power beyond their land bases, the PLA is also fielding EW aircraft. Aircraft such as the Y-8G, Y-9 or the carrier-based J-15D with EW wing pods all increase the range of PLA jamming abilities.[44,45] This airborne EW capability can extend the ability to jam receivers on the surface of Earth from tens of nautical miles to hundreds of nautical miles. While the ground-based facilities typically target air-borne and space-borne assets, Chinese aircraft can target ground-based and maritime-based assets. By integrating ground-based EW systems with airborne platforms, China is enhancing its electronic warfare reach, thereby broadening the spectrum of its strategic influence and the capability to disrupt adversarial systems across multiple domains.

43 Source: Funaiole, Bermudez, and Hart.

44 Dahm, "Electronic Warfare and Signals Intelligence."

45 Department of Defense, "Military and Security Developments Involving the People's Republic of China."

Electronic warfare is also a part of the military strategy of Iran and North Korea. By targeting the space-based navigation systems upon which the U.S. military heavily relies, these nations could significantly degrade the operational effectiveness of U.S. forces. According to the Defense Intelligence Agency, "Iran recognizes the strategic value of space and counterspace capabilities and will attempt to deny an adversary use of space during a conflict. Tehran has publicly acknowledged it has developed capabilities to jam space-based communications and GPS signals."[46] The ability to jam GPS signals not only undermines the tactical effectiveness of expensive U.S. equipment but also poses a significant threat to the safety of civilian aviation and maritime activities in their regions. North Korea has a continued reputation of jamming GPS capabilities against civilian ships and aircraft. According to the South Korean government, since 2010, 58 planes and 52 ships have been affected.[47] Electronic warfare gives nations like Iran and North Korea an asymmetric advantage against U.S. systems and has the potential to defeat expensive U.S. equipment or disrupt military operations for fractions of the cost.

The strategic deployment of GPS jamming and broader EW tactics by nations such as Russia, China, Iran, and North Korea underscores a crucial shift in modern conflict dynamics. These nations have not only invested in EW but have also integrated it into their military doctrine and training, showcasing its use in regions like Ukraine, Syria, and the South China Sea. The ability of EW to compromise navigation systems represents a significant threat to operations, highlighting the vulnerability of U.S. forces over-reliant on GPS. Without reliable navigation, military effectiveness is compromised, emphasizing the need for diversified navigational capabilities and a robust response to EW threats. This evolution in warfare demonstrates EW's role in disrupting military operations and shaping strategic outcomes, making it a pivotal element in contemporary and future conflicts.

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[46] Defense Intelligence Agency, *Challenges to Security in Space,* 31.

[47] "North Korea 'jamming GPS Signals' near South Border," *BBC News*, April 1, 2016, sec. Asia, para. 10, https://www.bbc.com/news/world-asia-35940542.

III. STARLINK POSITIONING TESTING METHODOLOGY

In the face of escalating electronic warfare challenges, particularly threats to navigation systems, alternative PNT solutions are being prioritized by the U.S. military.[48] As the satellite launch capacity increases in the United States, large constellations of hundreds of satellites are being deployed, reshaping satellite architecture possibilities.[49] This shift paves the way for novel communication, reconnaissance, and positioning systems. Starlink, currently at the forefront of the pLEO development with its impressive constellation of over 4,000 satellites, provides commercial communications using the Ku-band to locations across the globe.[50] In addition to the communications service, Starlink began providing a positioning service to each terminal in 2023 by using a proprietary geolocation method. Notably, Starlink terminals have aided Ukraine and the U.S. in communications, but the potential of these terminals as positioning alternatives remains under-explored.[51] By integrating Starlink's positioning capabilities, Starlink terminals could increase resilience and operational effectiveness in electromagnetic conflict; however, a deep dive into its capabilities and constraints is crucial. For this purpose, the subsequent testing methodology was adopted:

A. DEFINING CRITERIA

To evaluate the capabilities of the Starlink positioning system, specific criteria must be established. These criteria outline the performance characteristics of the system, facilitating comparisons with other systems, such as GPS. Key factors to consider include accuracy, latency, reliability, interoperability, mobility, jamming and detection. These

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[48] United States Government Accountability Office, "GPS ALTERNATIVES- DOD Is Developing Navigation Systems But Is Not Measuring Overall Progress," 6.

[49] Alexandra Witze, "2022 Was a Record Year for Space Launches," *Nature* 613, no. 7944 (January 11, 2023): 426–426, https://doi.org/10.1038/d41586-023-00048-7.

[50] Todd E. Humphreys et al., "Signal Structure of the Starlink Ku-Band Downlink," *IEEE Transactions on Aerospace and Electronic Systems*, 2023, 1–16, https://doi.org/10.1109/TAES.2023.3268610.

[51] Walter Isaacson, *Elon Musk* (Simon & Schuster, n.d.), 428.

elements are essential for the functionality and operational efficacy of any positioning system and therefore form the criterion for testing and evaluation.

B. DEFINING FIGURES OF MERIT

Establishing a metric to evaluate each criterion is crucial. Referred to as figures of merit (FoM), these metrics are employed to either quantitatively or qualitatively assess performance for each criterion.

1. Accuracy

The figure of merit for accuracy will be a measurement in meters from the predicted terminal position using Starlink's PNT data, to the terminal's true position, determined by multiple GPS receivers and Google Earth. This will assess the accuracy of both latitude and longitude coordinates, with a separate evaluation for altitude accuracy. The accuracy will be evaluated based on five-minute time intervals and the circular error probable (CEP) of the fixes. For the final evaluation, the CEP of the first fix, 5-minute fix and 20-minute fix will be recorded.

A similar methodology will be used for altitude accuracy. The accuracy will be evaluated based on five-minute time intervals and the vertical error probable (VEP) of the fixes. For the final evaluation, the VEP of the first fix, 5-minute fix and 20-minute fix will be recorded.

2. Latency

Latency evaluates the duration the system requires to deliver the necessary information to the user. The figure of merit for latency will be a time measurement in minutes that measures the time it takes to acquire a fix within a given accuracy threshold. For final evaluation, latency of the first fix is recorded, and latency of a 25-meter accuracy threshold is recorded.

3. Reliability

Reliability measures the frequency with which the system operates as anticipated. The figure of merit for reliability will be the ratio of successful tests to the total number of tests. For one FoM, a successful test is any test that achieves a fix during the 20-minute fix interval. For the other FoM, a successful test is any test that reaches the 25-meter accuracy threshold within the 20-minute interval.

4. Interoperability

Interoperability assesses the system's ability to integrate with existing software. The figure of merit for this criterion will be successful demonstrations of the Starlink position integrating with current systems as well as compliance with the PNT industry standard NMEA-0183 data format.

5. Mobility

Mobility assesses the system's ability to be used in a mobile context. The figure of merit that will be used for this criterion will be the average distance error over a given route. This will be measured at 5 MPH, 20 MPH and 65 MPH.

6. Jamming

Jamming evaluates the system's resilience against EW. This criterion will be assessed based on the system's antenna gain patterns and the signal strength.

7. Detection

Detection evaluates the system's resilience direction finding. This criterion will be assessed based on the system's antenna gain patterns and if it requires a two-way communication between satellite and terminal.

C. TEST DESIGN

The evaluation of Starlink positioning was divided into two tests concepts: baseline performance testing and operational testing. Baseline performance testing involves many test iterations to get an accurate understanding of the consistent performance in terms of accuracy, latency and reliability. Operational testing involves using the terminal in various operational contexts and examining its capabilities and limitations in terms of interoperability, mobility, jamming and detection. This methodology enables comparison between performance in a static test environment and performance in an operational environment. Tables 1 and 2 will be used for recording the performance results.

Table 1. Baseline Performance Criteria and Figure of Merit

Baseline Performance Testing			
Criteria	**Figure of Merit**	**Standard Terminal Results**	**Flat High Performance Terminal Results**
Accuracy (Latitude/ Longitude)	First Fix Lat/Long Position Accuracy	Meters	Meters
	5-minute Lat/Long Position Accuracy	Meters	Meters
	20-minute Lat/Long Position Accuracy	Meters	Meters
Accuracy (Altitude)	First Fix Altitude Accuracy	Meters	Meters
	5-minute Altitude Position Accuracy	Meters	Meters
	20-minute Altitude Position Accuracy	Meters	Meters
Latency	First Fix Acquisition Time	Minutes	Minutes
	25-meter Fix Acquisition Time	Minutes	Minutes
Reliability	First Fix Rate Success	Percent	Percent
	25-meter Fix Rate Success	Percent	Percent

Table 2. Operational Testing Criteria and Figure of Merit

Operational Testing			
Criteria	**Figure of Merit**	**Standard Terminal Results**	**Flat High Performance Terminal Results**
Interoperability	Compatibility With Other Systems	Pass/Fail	Pass/Fail
	Compliance With Industry Standard	Pass/Fail	Pass/Fail
Mobility	Accuracy at 5 MPH	Meters	Meters
	Accuracy at 20 MPH	Meters	Meters
	Accuracy at 65 MPH	Meters	Meters
Jamming	Rx Signal Strength Compared to GPS	Decibel	Decibel
Jamming/ Detection	Antenna Gain Pattern	Pattern Type	Pattern Type
Detection	Rx only	Pass/Fail	Pass/Fail

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IV. BASELINE PERFORMANCE TESTING

To gauge the capabilities of the Starlink positioning system in an operational context, establishing a baseline performance was essential. The baseline performance testing, conducted over 500 iterations, was designed to measure the terminal's static efficacy. This chapter provides a detailed account of the testing methodology and an analysis of the results, laying the groundwork for understanding the system's operational potential.

A. TEST SETUP

To obtain position data from the Starlink system, several essential pieces of equipment are required. These include a Starlink terminal, a Starlink router, a power supply, a service plan, and a computer to record the data. For the tests conducted, Starlink's Standard and Flat High-Performance Terminals were employed. Figure 7 shows the specifications for both terminals. Additionally, a subscription to the Mobile Priority service plan was established. The service plans are required to gain access to the Starlink network, similar to a cell phone plan. Compared to other Starlink service plans, the Mobile Priority service plan grants the user the ability to transition the terminal between different Starlink coverage regions, known as roaming, and use the network while moving.

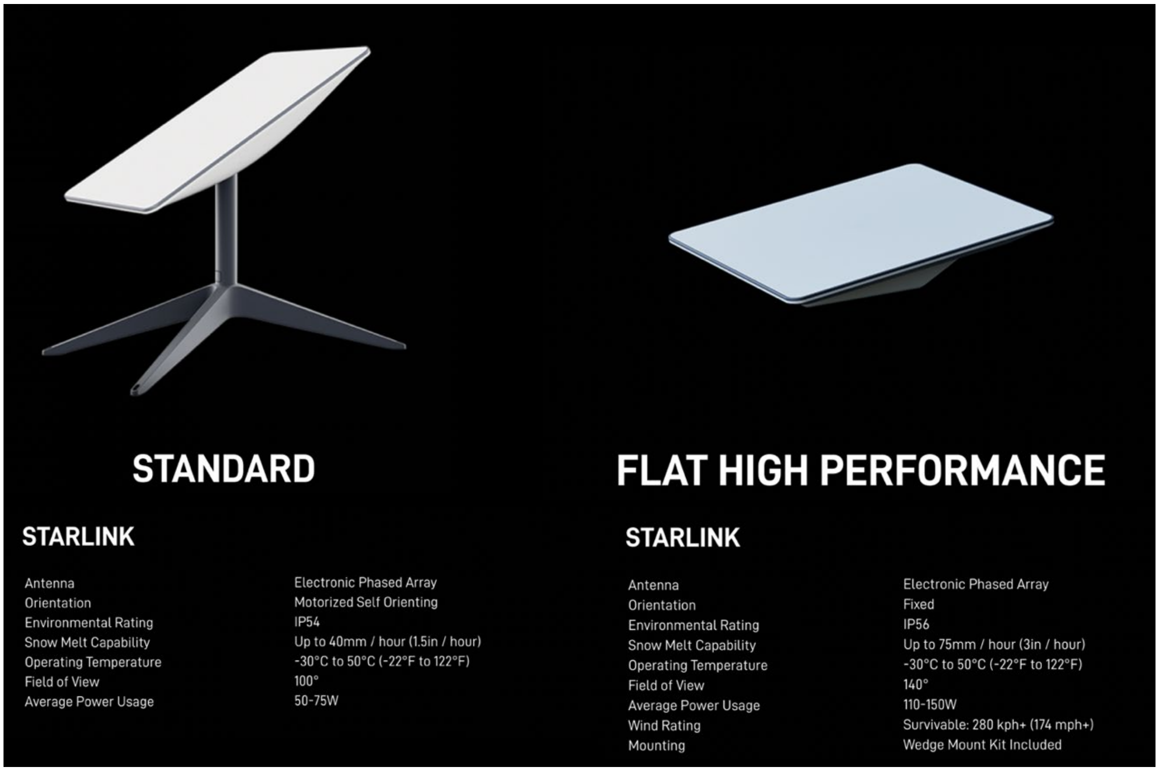

Figure 7. Starlink Terminal Specifications[52]

The setup depicted in Figure 8 represents the configuration for the baseline performance evaluation using the Standard Terminal. The entire setup was contained within a single 1660 Pelican case and had an unobstructed view of the sky. The Flat High-Performance Terminal was tested in the same location; however, due to complications in disabling the GPS, it was unable to be used during the baseline performance testing. This is explained further in the following section.

52 Source: "Hardware Options," Starlink Business & Enterprise Guide, accessed November 7, 2023, https://starlink-enterprise-guide.readme.io/docs.

Figure 8. Standard Terminal Setup

B. DISABLING GPS

The first step in assessing the capabilities of the Starlink positioning service involved the deliberate disruption of the GPS receiver onboard the terminal. While it is possible to adjust the settings within the Starlink application to "exclusively use Starlink Positioning," the terminal defaults to GPS when the power is cycled. To ensure consistent reliance on Starlink positioning service for determining the terminal's location, the GPS receiver was obstructed. For the Standard Terminal, aluminum foil was placed around the base as depicted in Figure 8. This obstruction prevented the onboard GPS receiver from obtaining a connection to the GPS satellites. In Figure 9, the Starlink application confirms that the terminal is no longer connected to GPS and the Starlink debugging data confirms that the terminal has acquired zero GPS satellites. With the confirmation that the Standard Terminal is no longer using GPS, the Starlink positioning service could be exclusively tested for its positioning capabilities.

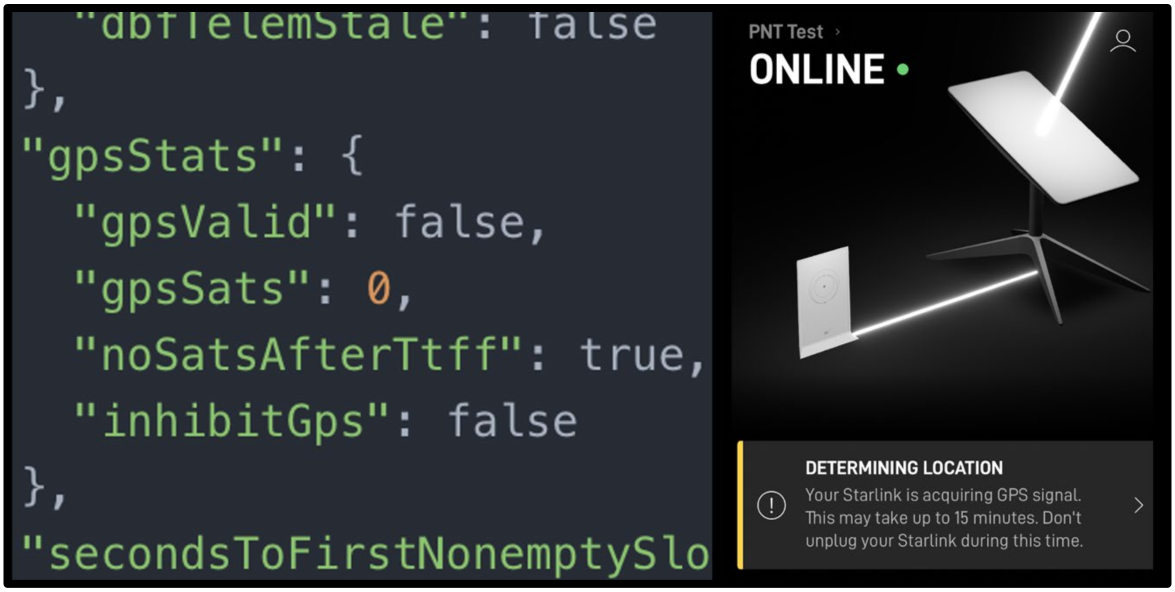

Figure 9. Confirmation of No GPS

This same method for blocking the GPS receiver was unsuccessfully attempted on the Flat High-Performance Terminal. The next attempt to block the GPS receivers used a Faraday fabric that is designed to block radio frequencies. This fabric was placed on the terminal in various configurations. The GPS receivers were blocked when the terminal was completely covered by the fabric, but exposing even the slightest amount of the terminal's electronic phased array would cause it to acquire GPS satellites. After attempting numerous fabrics and configurations, it was determined that the terminal's GPS could not be blocked by using an exogenous material. This prevented baseline performance testing on the Flat High-Performance Terminal. The Flat High-Performance Terminal is designed with enhanced GPS capabilities for mobile applications.[53] It is unknown how many GPS receivers are on this terminal or how it maintains this robust connectivity to GPS satellites. Follow-on research with approved GPS jamming capabilities is necessary to provide large data collections of this terminal's performance independent of GPS. For the rest of the baseline performance testing, the Standard Terminal was utilized.

53 "Starlink," Starlink, accessed November 10, 2023, https://www.starlink.com.

C. SOFTWARE DEVELOPMENT

The next step necessary for the testing process involved software access to the terminal's data for collection and integration with other software applications. Instead of manually recording position data through the iPhone Starlink application, an API was used to extract data directly from the terminal. This API, known as Starlink gRPC Tools, is hosted on GitHub and is written in Python.[54] It provides access to the "starlink_grpc" Python library, which offers multiple functions that access terminal data. Among these, the "get_location()" function played a pivotal role, as it returned data containing latitude, longitude, and altitude information. The code depicted in Figure 10 enabled the collection of this data, which could then be stored in an Excel spreadsheet using the "openpyxl" Python library.[55] Additionally, the data could be seamlessly streamed into plotting software such as Plotly for further analysis and visualization.[56] Appendix A shows StaticTest.py which is the code used to collect during static tests. Appendix B shows MobileTest.py which is the code used during mobile tests. Appendix C shows WriteToNetwork.py which is the used to display the terminal's active position in a third-party application.

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54 sparky8512, "Starlink-Grpc-Tools," Python, October 20, 2023, https://github.com/sparky8512/starlink-grpc-tools.

55 "Openpyxl – A Python Library to Read/Write Excel 2010 Xlsx/Xlsm Files — Openpyxl 3.1.2 Documentation," accessed October 20, 2023, https://openpyxl.readthedocs.io/en/stable/.

56 "Plotly," accessed October 20, 2023, https://plotly.com/python/.

```python
#Retrieve the current latitude
lat = starlink_grpc.get_location().lla.lat
#Retrieve the current longitude
lon = starlink_grpc.get_location().lla.lon
#Retrieve the current altitude
alt = starlink_grpc.get_location().lla.alt
```

Figure 10. Python Code for Accessing Terminal Data[57]

D. DATA COLLECTION AND ANALYSIS

With the ability to collect this data using the Starlink gRPC API, a test with 500 iterations was executed to obtain accuracy, latency, and reliability performance metrics for Starlink's positioning service. The test involved leaving the Standard Terminal powered on for 20 minutes to evaluate the refinement of the fix accuracy. Every time the position data was updated by the terminal, the data would be recorded. At the end of the 20-minute interval, the terminal would be power cycled, and another test iteration would begin. After 500 test iterations—totaling 2492 position fixes—a variety of analyses were conducted to investigate different performance abilities of the system.

1. Latitude and Longitude Accuracy

The initial analysis was aimed at understanding the evolution of the terminal's predicted location accuracy over time by examining individual iterations of the test. For this purpose, a step plot was employed. Figure 11 is a step plot of 10 randomly selected test iterations. It shows various patterns of position refinement observed during testing. Test number 446 is an example where an initial fix was acquired, but no further refinement took place over a 20-minute span. Test number 36 is an iteration where the initial fix was several kilometers away from the actual position, yet it managed to refine its location to within 20 meters of the true terminal position. Conversely, test number 44 demonstrates a

[57] Source: sparky8512, "Starlink-Grpc-Tools."

scenario where the subsequent fix was less precise than the initial one, with no refinement observed during the 20-minute window.

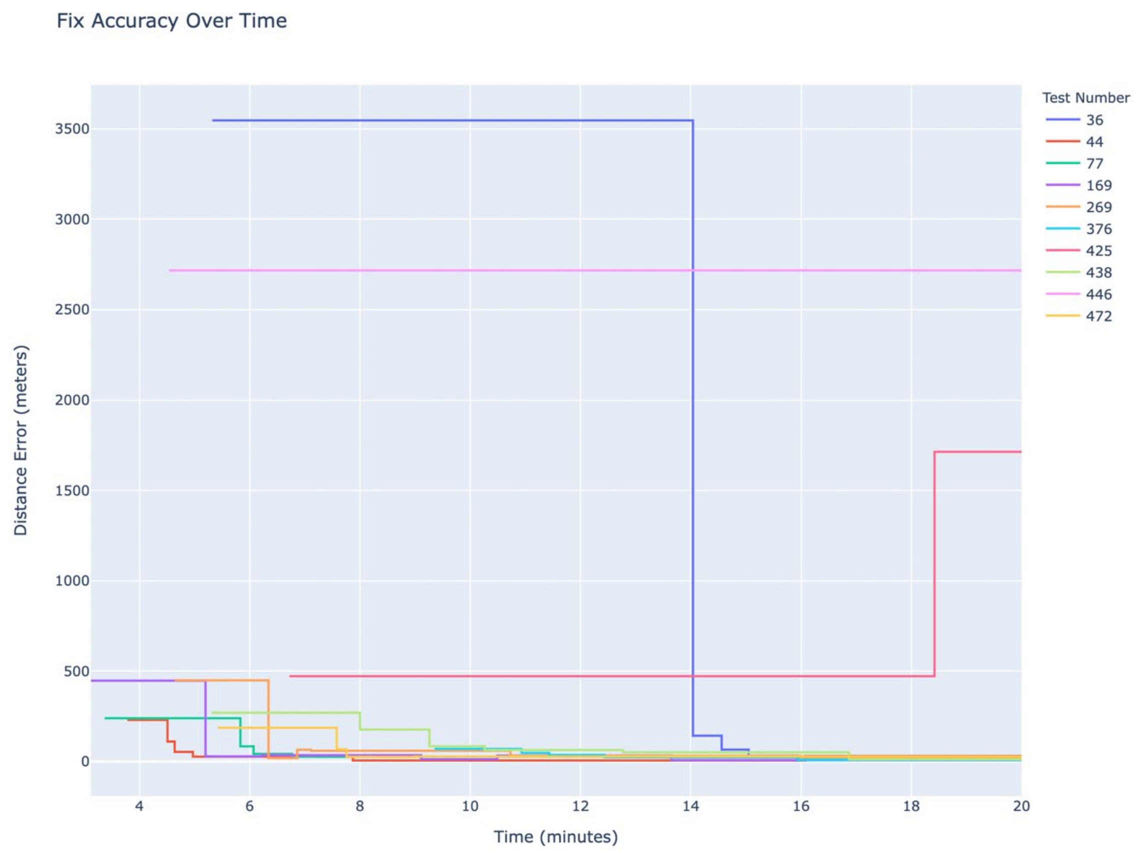


Figure 11. Fix Refinement 3800m Scale

The tests resulting in below 500 meters of distance error are challenging to observe in Figure 11. Figure 12 presents the same data as Figure 11 but rescaled to emphasize errors within 100 meters. At this scale, more patterns emerge. In test number 169, the accuracy fluctuates, moving closer to and farther from the actual position. Test number 376 illustrates a more consistent refinement over time, with each subsequent fix being closer to the true position than the last. Finally, this graph reveals that six out of the ten test iterations achieved an accuracy within 100 meters by the 10-minute mark and 6 out of the 10 iterations achieved an accuracy of 25 meters by the end of the 20-minute window, giving early indicators of the latency and reliability of the system.

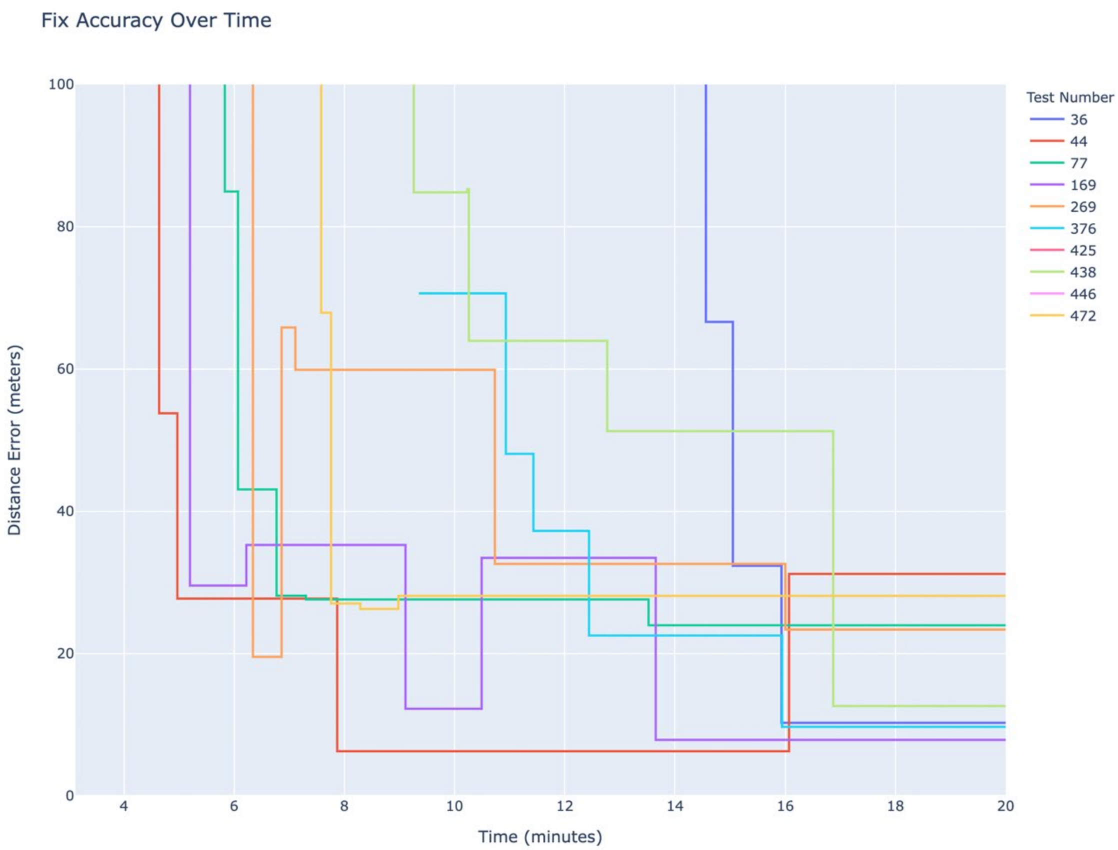


Figure 12. Fix Refinement 100m Scale

The subsequent analysis aimed to visualize how the fixes clustered when overlaid on a map. For this analysis, the data was examined at four five-minute intervals rather than on a continuous time scale. Figure 13 represents the four-time intervals and the fixes at each interval. In this figure are all the fixes obtained at each interval with the possibility of points overlapping. The orange triangle indicates the terminal's true position. Although it seems that the fixes from the 5-minute interval are less accurate than those from the 10-minute interval, this observation is misleading for two reasons. First, the 5-minute interval has 227 plotted fixes, while the 10-minute interval has 442. These additional fixes make the map more cluttered with data points. Additionally, as the fixes refine, they tend to overlap near the terminal's true position, which at a 2000-meter scale, becomes difficult to distinguish.

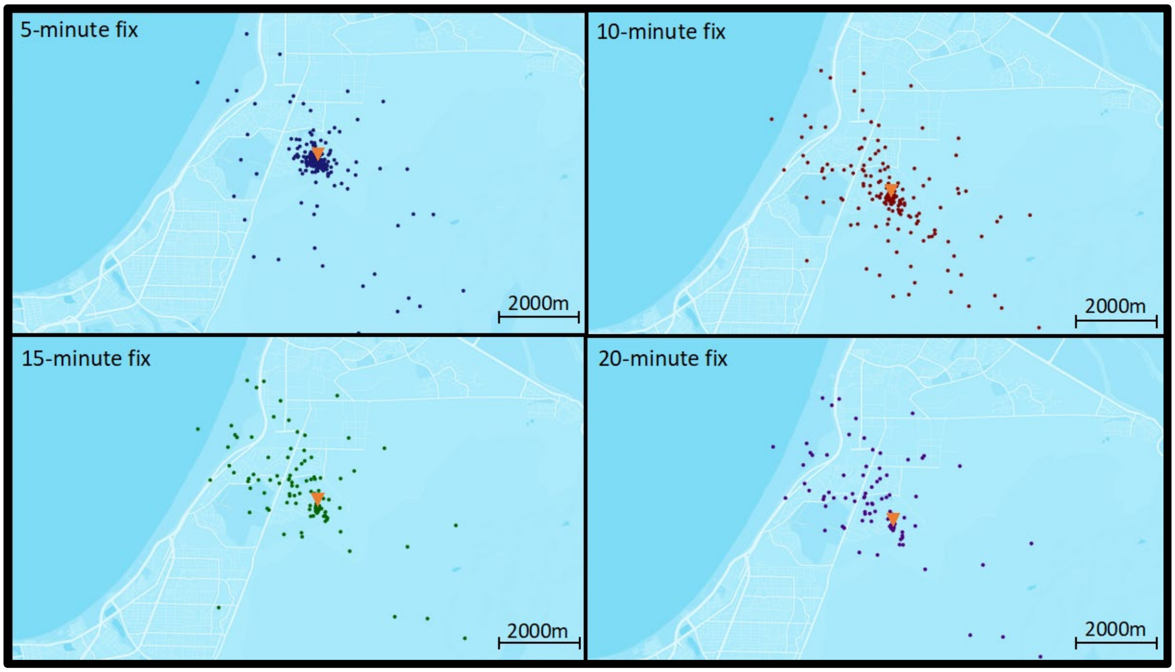


Figure 13. Fix Accuracy 2000m Scale

From the five-minute to the 20-minute interval, the points increasingly cluster around the terminal's actual position, making it seem as though there are fewer points when there are 499 fixes by the 20-minute interval. For a clearer view of the area around the terminal's true position, where the points are densely packed, Figure 14 was rescaled to a 100m scale. In this figure, it is evident that the 10-minute segment offers greater accuracy than the 5-minute segment; but this fidelity is not apparent in Figure 13. Table 3 captures the average fix accuracy during each time interval.

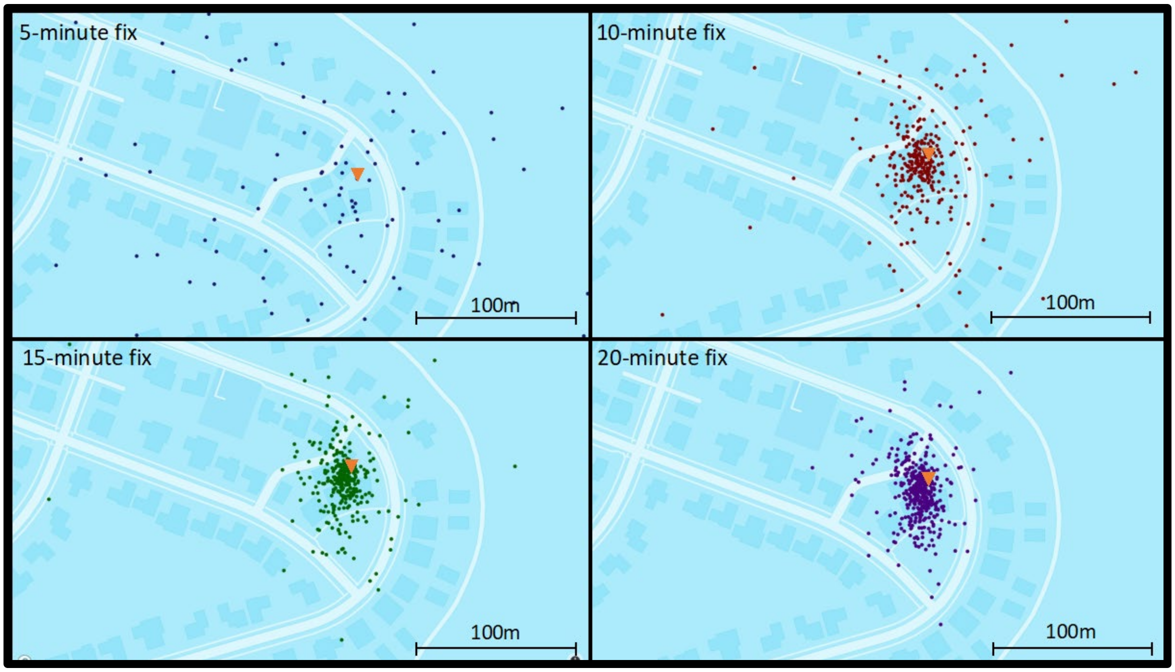


Figure 14. Fix Accuracy 100m Scale

Table 3. Average Fix Accuracy

Time Interval	Average Distance Error
First Fix (499 Fixes)	803.7 meters
5-minute (227 Fixes)	620 meters
10-minute (443 Fixes)	519 meters
15-minute (481 Fixes)	401.7 meters
20-minute (499 Fixes)	330 meters

While the average distance error falls within the range of several hundred meters, it is crucial to account for the outliers that can distort this data. Even though they are infrequent, some fixes deviate by more than a kilometer with no refinement over the 20-minute interval. Figure 15 is a histogram illustrating the error distances at the conclusion of the 20-minute test period. From the graph, it is evident that the majority of the fixes fall within a 100-meter range for distance error.

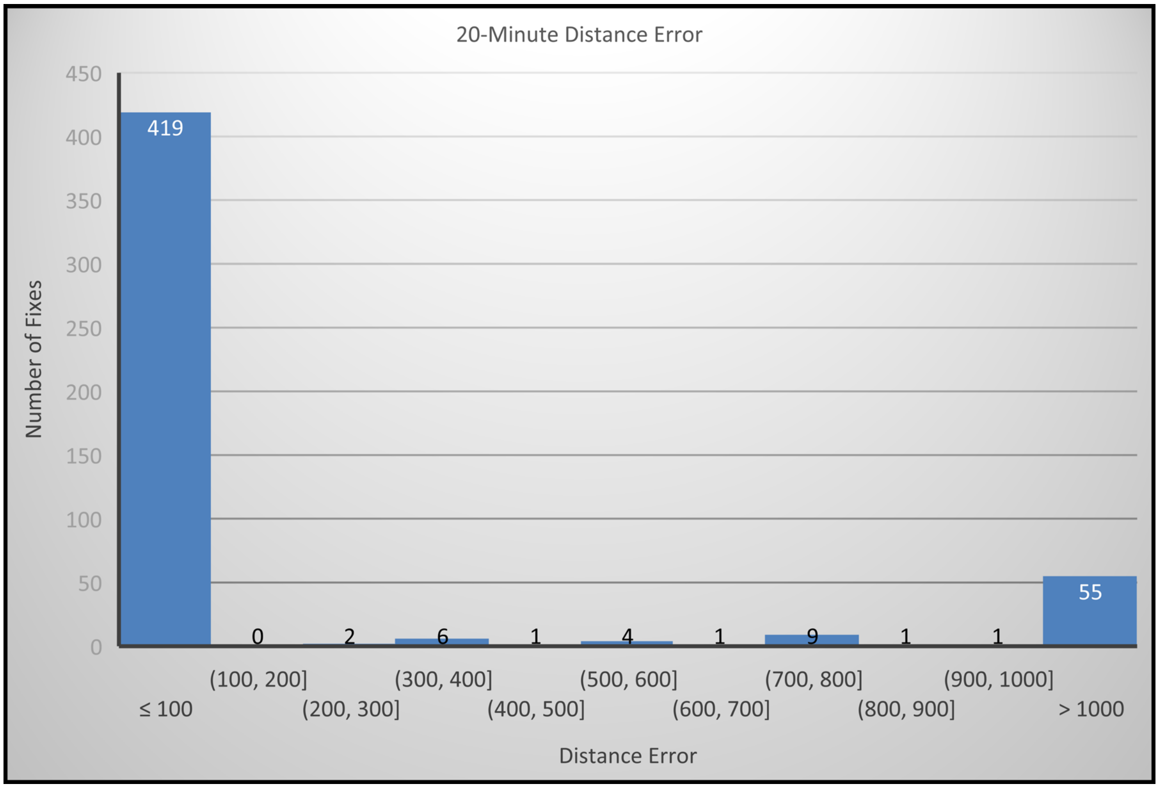


Figure 15. Distance Error Histogram

The average accuracy of the test can be adjusted depending on how the user defines outliers and how much confidence they want to put on the accuracy of the fix. One standard for fix accuracy is using the circular error probable (CEP) which is defined as the circle centered on the true position where a fix has a 50% chance of being within that circle.[58] Assuming a normal distribution of fixes around the terminal position, the Excel function PERCENTILE() was utilized to find the 50th percentile of the distance error. Table 4 shows the CEPs for each of the intervals.

58 National Research Council (U.S.) and National Academy of Public Administration, eds., *The Global Positioning System: A Shared National Asset: Recommendations for Technical Improvements and Enhancements* (Washington, D.C.: National Academy Press, 1995), 177.

Table 4. CEP Over Various Time Intervals

Time Interval	CEP
First Fix (499 Fixes)	327.6 meters
5-minute (227 Fixes)	215.2 meters
10-minute (443 Fixes)	34.9 meters
15-minute (481 Fixes)	20.2 meters
20-minute (499 Fixes)	17.6 meters

The majority of the accuracy refinement happens between the 5-minute and 10-minute iteration. By the end of the 20-minute test window, 50% of the fixes fall within a 17.6-meter radius of the true terminal position.

2. Altitude Accuracy

In addition to analyzing the accuracy of the latitude and longitude data, the altitude accuracy of the terminal was also analyzed. The terminal's true altitude was 132 meters above sea level, as determined by GPS and verified using Google Earth. Altitude data was documented concurrently with position data. This data was subsequently plotted at 5-minute intervals in the same manner as the latitude and longitude analysis. Figure 16 and Table 5 display the results of all 500 test iterations. Dense sections of the graph with a higher color saturation indicate overlapping data points.

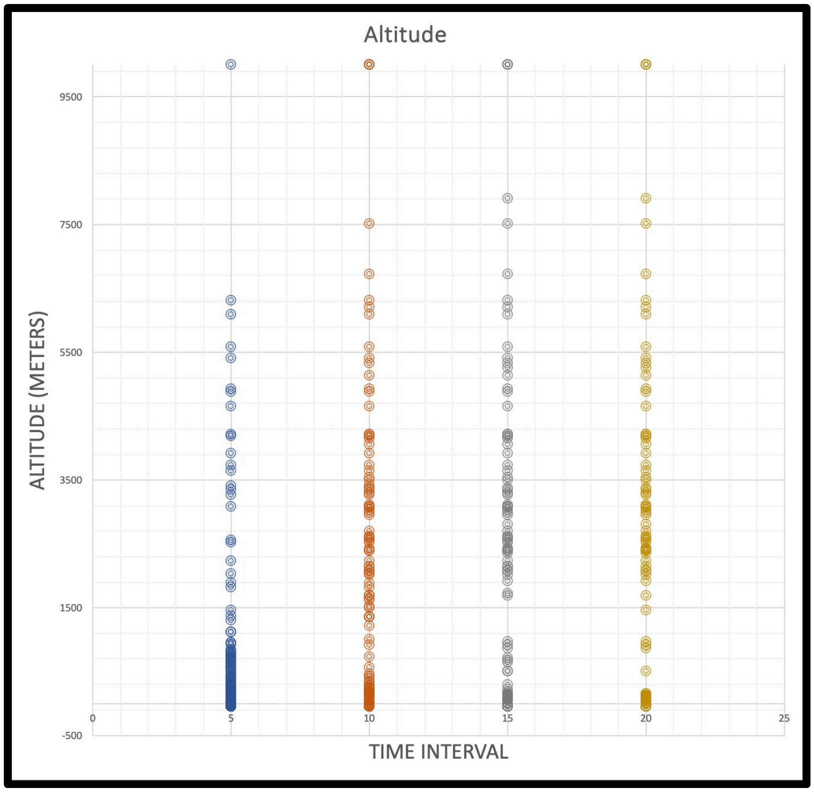


Figure 16. Altitude Readings 10,000-meter Scale

Table 5. Altitude Results

Time Interval	Average Altitude	Average Altitude Error
First Fix (499 Fixes)	776.9 meters	773.0 meters
5-minute (227 Fixes)	570.7 meters	568.0 meters
10-minute (443 Fixes)	604.1 meters	561.1 meters
15-minute (481 Fixes)	602 meters	539.2 meters
20-minute (499 Fixes)	559.0 meters	491.4 meters

Similar to the latitude and longitude data, these results are skewed due to outliers. Figure 17 illustrates the distribution of altitude error values. The altitude error data is heavily concentrated within 100 meters, with sparsely distributed results extending to a max error of 9869 meters. Although the average altitude error is more than 400 meters throughout the 20-minute testing window, more than 80% of the tests (420 out of the 500) fall within 100 meters of the true terminal altitude.

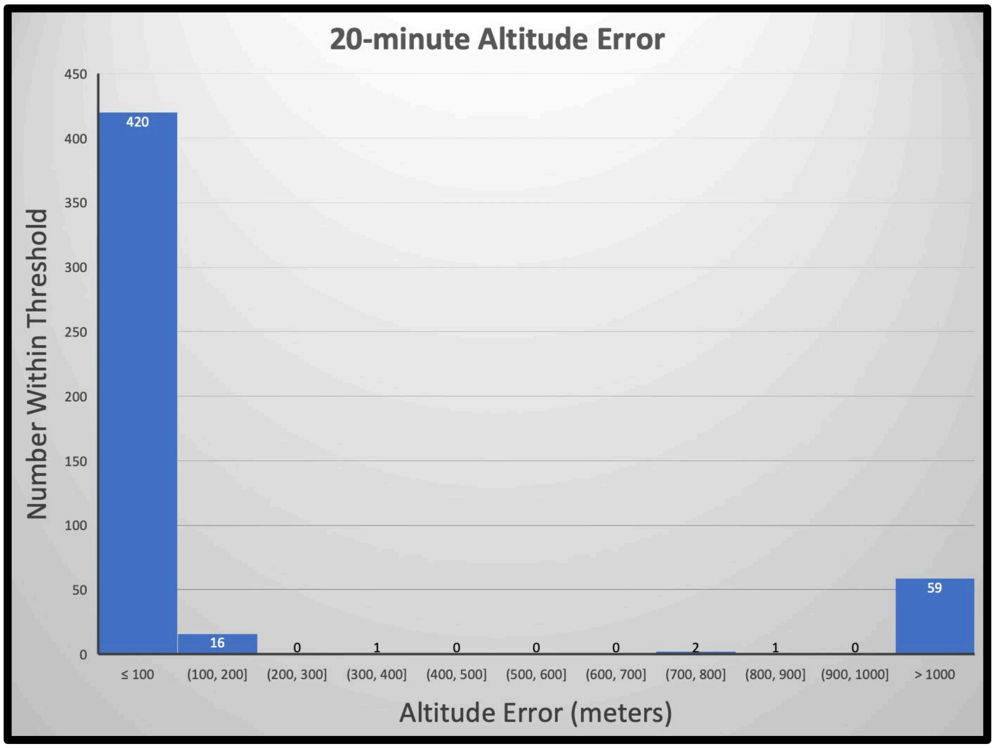


Figure 17. Altitude Error Distribution

To gain a more accurate understanding of the data, the vertical error probable (VEP) was used. VEP is comparable to CEP, but it is applied to 1-dimensional data, in this case, altitude. The VEP is the range from the terminal's true altitude that contains 50% of the data points. To compute VEP, the same PERCENTILE() excel function from the CEP calculation was used. Figure 18 represents the same data as Figure 16, only rescaled to better highlight the clustering around the terminal's altitude. Table 6 presents the average altitude and altitude error VEP values for the first fix and across each 5-minute interval. While the mean value remained relatively consistent across the intervals, the altitude error VEP showed increasing accuracy over time; however, the VEP seemed to approach 31 meters of altitude error rather than zero meters of error. The reason behind the consistent

31-meter discrepancy from the terminal's actual altitude of 132 meters remains undetermined.

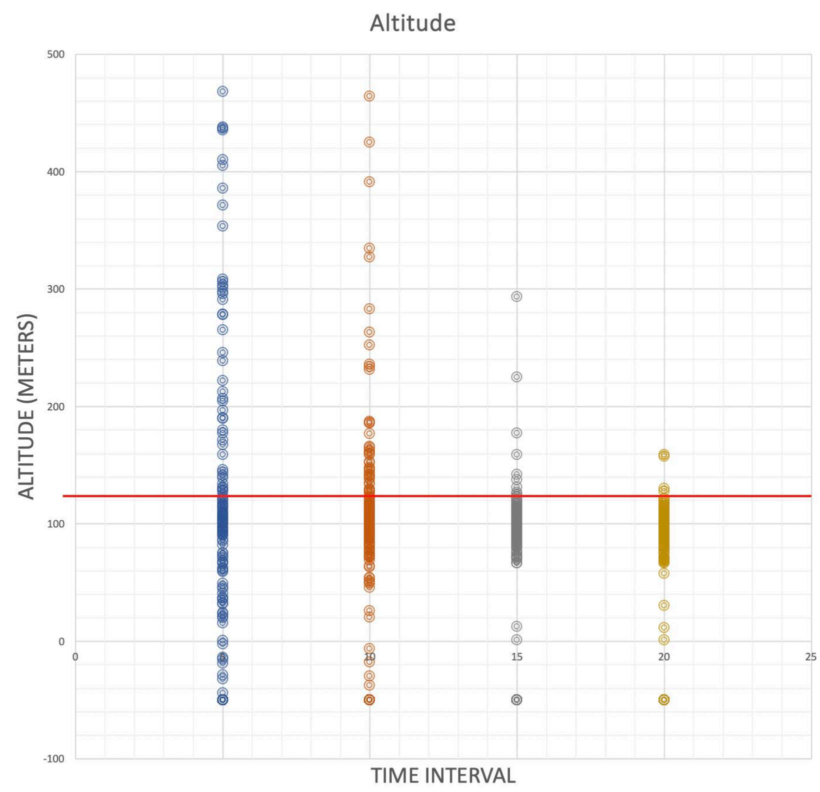


Figure 18. Altitude Readings 500-meter Scale

Table 6. Altitude Median and VEP

Time Interval	Altitude Error VEP
First Fix (499 Fixes)	2272 meters
5-minute (227 Fixes)	182 meters
10-minute (443 Fixes)	35.45 meters
15-minute (481 Fixes)	31.18 meters
20-minute (499 Fixes)	31.43 meters

3. Latency and Reliability

The following analysis aimed to determine the time needed for the terminal to achieve latitude and longitude accuracy within a specified proximity to the terminal's true position. In contrast to the prior analyses, this evaluation designates accuracy as the independent variable and time as the dependent variable. The defined accuracy thresholds are 1000 meters, 100 meters, 25 meters, and 10 meters. These thresholds were chosen because of their common usage in the Military Grid Reference System (MGRS). Figure 19 illustrates the average duration required for an iteration to meet the threshold for latitude and longitude accuracy, as well as the percentage of successful fixes that achieved the threshold within the 20-minute iteration timeframe.

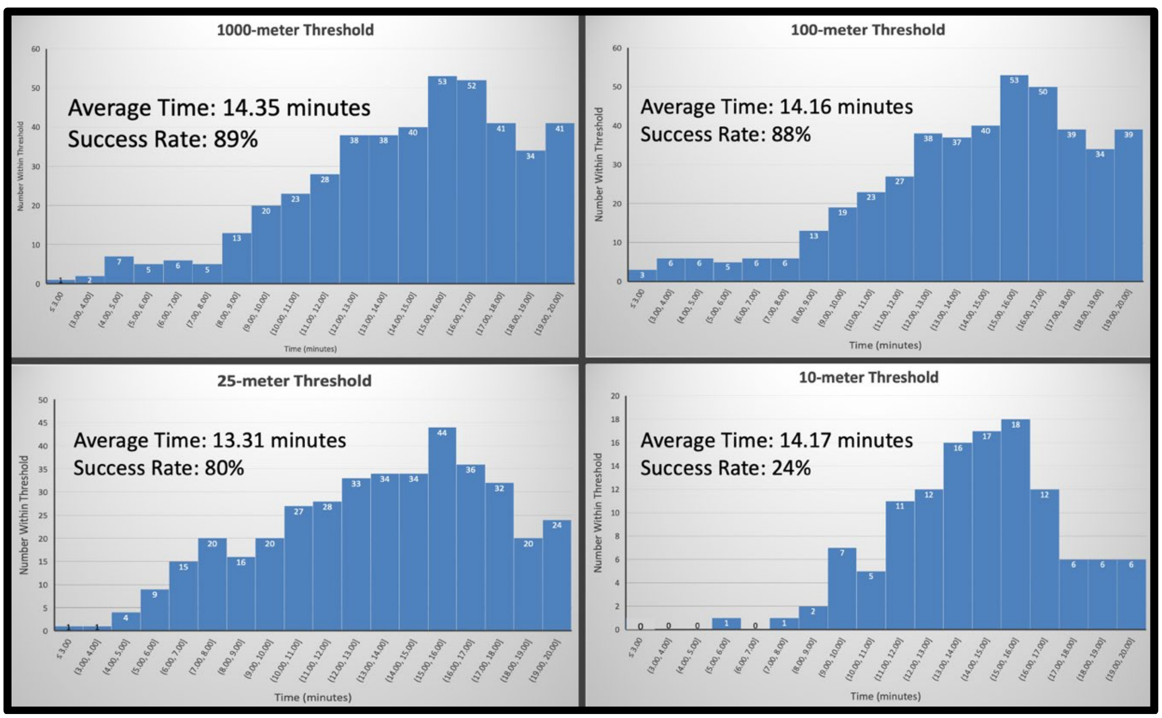


Figure 19. Speed Test Results

All accuracy thresholds were exceeded in an average time of 13–15 minutes, highlighting that accuracy improves rapidly rather than gradually. This aligns with the observations from Figures 11 and 12, which depict the fixes either quickly enhancing their accuracy or remaining stagnant. Notably, fixes rarely achieved their threshold within the first 3 minutes, likely due to the terminal's startup, orientation, and satellite acquisition processes. When considering the first fix latency (accuracy independent) and 25-meter threshold for the test's figures of merit, the terminal exhibits a first fix latency of 5.76 minutes and an average 25-meter latency of 13.31 minutes.

While success rates remained relatively consistent from the 1000-meter to the 25-meter thresholds, a significant drop is evident at the 10-meter threshold. This can be attributed to the system's CEP at 20 minutes being 17.6 meters, implying that fewer than half of the fixes will ever reach the 10-meter threshold within the 20-minute timeframe. Yet, with the 25-meter threshold, the system boasts a reliability rate of 80%. Table 7 shows the latency and reliability results for the system at each threshold.

Table 7. System Latency and Reliability

Distance Threshold	Latency	Reliability
First Fix (accuracy independent)	5.76 minutes	99.8%
1000 meters	14.35 minutes	89%
100 meters	14.16 minutes	88%
25 meters	13.31 minutes	80%
10 meters	14.17 minutes	24%

The testing of Starlink's positioning service provided insights into its performance capabilities. By conducting 500 iterations and using different visualization tools, including step plots, overlays on maps, and histograms, nuanced interpretations of the data were exposed. Most prominently, most position fixes converged to the terminal's actual position during the 20-minute interval; however, altitude accuracy presented an intriguing pattern: there was a consistent underestimation by about 31 meters. Regarding latency and reliability, the system's performance demonstrated a rapid increase in accuracy from 3-minutes to 20-minutes rather than a gradual refinement. The consistent 3-minute latency can be partly attributed to startup processes intrinsic to the terminal. As the threshold of accuracy tightens, a dip in reliability was observed, particularly at the 10-meter mark. Yet, at the higher 25-meter threshold, Starlink's system maintained an 80% reliability rate.

Table 8 shows a summary of the baseline performance results in terms of the testing figures of merit.

Table 8. Baseline Performance Results

Baseline Performance Testing		
Criteria	**Figure of Merit**	**Standard Terminal Results**
Accuracy (Latitude/ Longitude)	First Fix Lat/Long Position Accuracy (CEP)	327.6 meters
	5-minute Lat/Long Position Accuracy (CEP)	215.2 meters
	20-minute Lat/Long Position Accuracy (CEP)	17.6 meters
Accuracy (Altitude)	First Fix Altitude Accuracy (VEP)	2272 meters
	5-minute Altitude Position Accuracy (VEP)	182 meters
	20-minute Altitude Position Accuracy (VEP)	31.43 meters
Latency	First Fix Acquisition Time	5.76 minutes
	25-meter Fix Acquisition Time	13.31 minutes
Reliability	First Fix Rate Success	99.8%
	25-meter Fix Rate Success	80%

In sum, Starlink's positioning service presents promising results with areas of potential improvement. The baseline performance testing gives insight into the Standard Terminal's performance when in a static context. While follow-on testing is required to better understand the Flat High-Performance Terminal's baseline performance, the patterns and nuances unearthed through this assessment will undoubtedly serve as vital feedback for operational testing.

V. OPERATIONAL TESTING

Building upon the baseline performance metrics established in Chapter IV, the subsequent phase of operational testing encompassed a comprehensive assessment of system integration, mobility, and the system's resilience to jamming and interception. This testing offers a detailed exploration of the Starlink system's operational efficacy.

A. NMEA-0183 STANDARD

To ensure ease of integration, the terminal position data needed to comply with industry standards. Many navigation systems use the NMEA-0183 data message standard. NMEA-0183 is the most common GPS messaging standard.[59] Table 9 illustrates the required standard formatting for NMEA-0183 messages with example data. To transform the Starlink data into an NMEA-0183 message, a Python function was developed named "generate_nmea_gga()," taking the latitude, longitude, and altitude of the terminal as arguments to the function. The NMEA standard is designed for GNSS' and therefore has requirements that do not make sense for Starlink navigation. For example, in the "message identifier" GPGGA, GP means that GPS was used. There is currently no two-letter code for Starlink positioning data in the NMEA-0183 standard. To get around these issues, the generate_nmea_gga() function crafted the message as if it was a GPS message. In Table 9, the blue rows represent data that was supplied from the terminal's data, the red rows represent dummy inputs and black rows are left empty. Subsequently, with the properly formatted message, the navigation data could be written to a network socket connected to a navigation system that uses the NMEA-0183 standard.

[59] "GPS NMEA 0183 Messaging Protocol 101 | Arduino Documentation," accessed October 31, 2023, https://docs.arduino.cc/learn/communication/gps-nmea-data-101.

Table 9. NMEA-0183 Message Standard

Field Number	Field Name	Example Data	Description
1	**Message ID**	**$GPGGA**	**The type of the message, GPGGA in this case.**
2	**UTC Time**	**123519**	**Time of fix, HHMMSS format.**
3	**Latitude**	**4807.038,N**	**Latitude in degrees and minutes, N/S indicator.**
4	**Longitude**	**01131.000,E**	**Longitude in degrees and minutes, E/W indicator.**
5	**Fix Quality**	**1**	**Fix quality (0 = invalid, 1 = GPS fix, 2 = DGPS).**
6	**Number of Satellites**	**13**	**Number of satellites being tracked.**
7	Horizontal Dilution of Precision (HDOP)	(empty)	Measure of precision.
8	**Altitude**	**545.4,M**	**Altitude above mean sea level, in meters.**
9	Height of Geoid	(empty)	Height of geoid (mean sea level) above WGS84 ellipsoid.
10	Time since last DGPS update	(empty)	Time in seconds since last DGPS update, if available.
11	DGPS Station ID	(empty)	DGPS station ID number.
12	**Checksum**	**40**	**Used to check data integrity.**

B. NAVIGATION SYSTEM INTEGRATION

In order to test the navigation message's ability to integrate into existing software, OpenCPN was utilized. OpenCPN is an open-source chart plotting navigation system that allows for real-time position, track, and navigation information using maritime charts. To connect the data stream from the terminal to OpenCPN, a Python script was developed to establish a network connection and to write the NMEA-0183 message to port 10110 on the localhost (127.0.0.1) via a UDP socket. Figure 20 shows the schematic for connecting the Starlink terminal to OpenCPN.

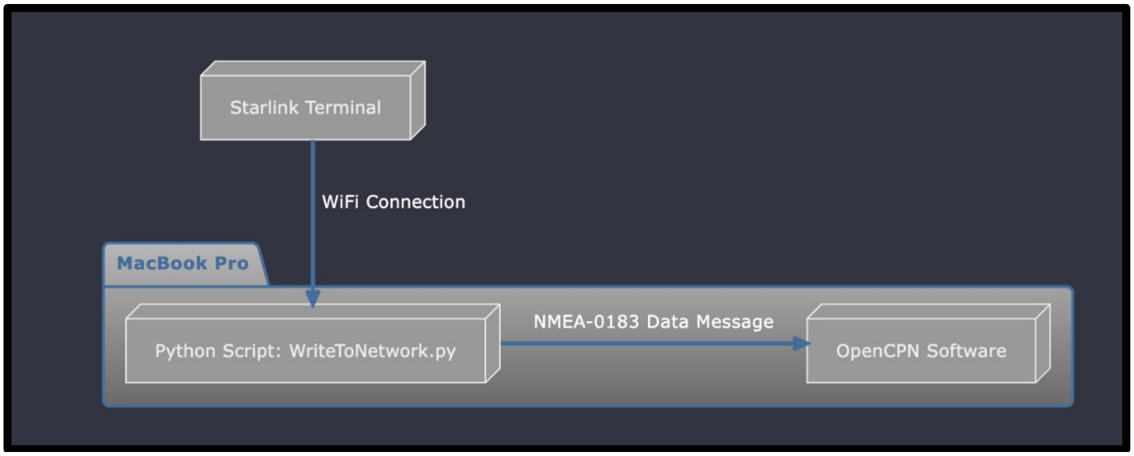


Figure 20. Schematic For OpenCPN Data Connection

Once a connection between the Starlink terminal and OpenCPN was established, OpenCPN would render the real-time latitude and longitude fix on downloaded maritime navigation charts. Figure 21 shows OpenCPN with the real-time position of the terminal. The red vessel is the predicted real-time fix of the terminal. The yellow and red circle was manually placed on the chart to show the true location of the terminal. In this example, the predicted location of the terminal was within 25 meters of the terminal's true position.

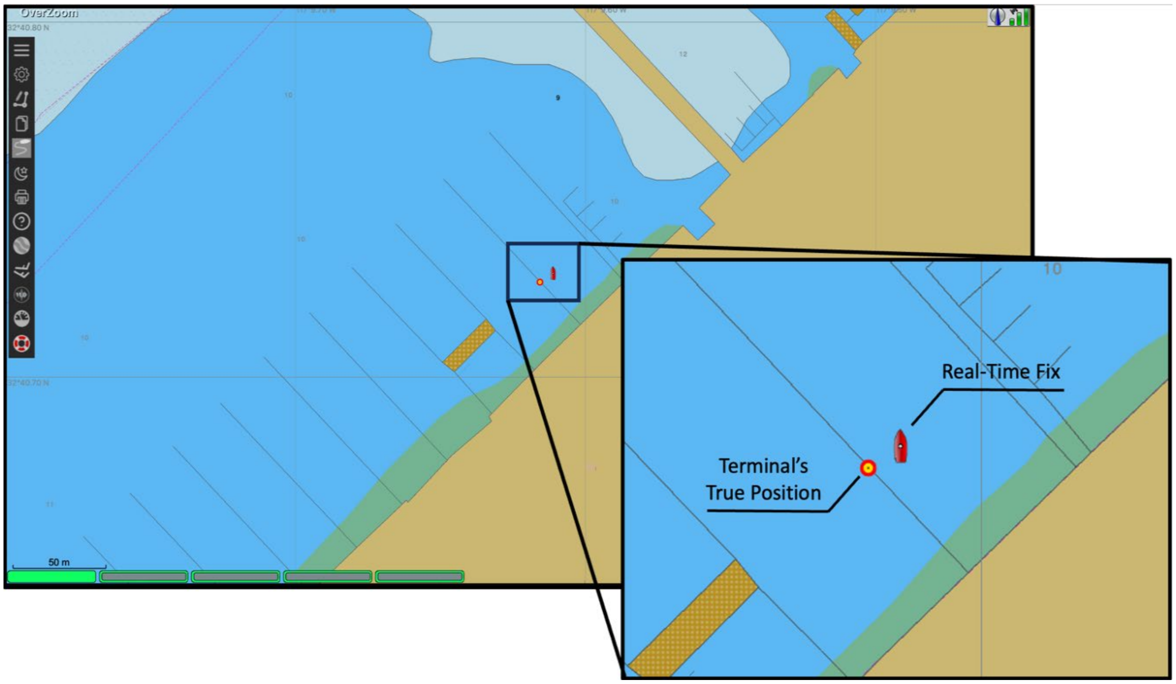


Figure 21. OpenCPN Real-Time Position

Integration of Starlink data into military systems' existing navigation software is potentially facilitated by using a standard data format such as NMEA-0183. According to a RAND report on leveraging commercial space services, "DOD's current ground and user segments for PNT and satellite communications (SATCOM) need to be modernized to enable broader access to commercial services. For example, PNT signals might need to be accommodated and integrated into user equipment that uses only GPS today."[60] The ability for integration is critical for future adoption. To get the benefits of spectrum diversity, a PNT system operating outside of the L-band would require a new antenna from existing systems. Since the military is already adopting Starlink receivers as an alternative SATCOM, the terminals can double as both a SATCOM and PNT receiver. Rather than changing an existing military system and buying PNT specific hardware, an additional data input from the Starlink terminal adds operational redundancy that comes at a lower cost

60 RAND Corporation, "Leveraging Commercial Space Services: Opportunities and Risks for the Department of the Air Force" (RAND Corporation, 2023), vi, https://doi.org/10.7249/RRA1724-1.

than changing the existing navigation system and integrating new antenna hardware which would require additional time and resources for acquisition, integration, and testing.

C. MOBILITY TEST

The subsequent phase in evaluating the operational efficacy of the Starlink positioning system involved testing the terminals' capability to retain a fix while in motion. Both the Standard Terminal and the Flat High-Performance Terminal underwent assessment.

Upon deactivating GPS in the Starlink settings, an advisory message was displayed, cautioning that reliance solely on Starlink for PNT will diminish service quality and functionality during movement. Figure 22 illustrates this notification within the Starlink application interface. Despite prior awareness of this message, it remained unclear whether the warning pertained to a potential decrease in communication service quality or specifically to the degradation of positioning features. There was also uncertainty as to whether this limitation was applicable to all terminals, particularly the Flat High-Performance Terminal, which is engineered for mobility.

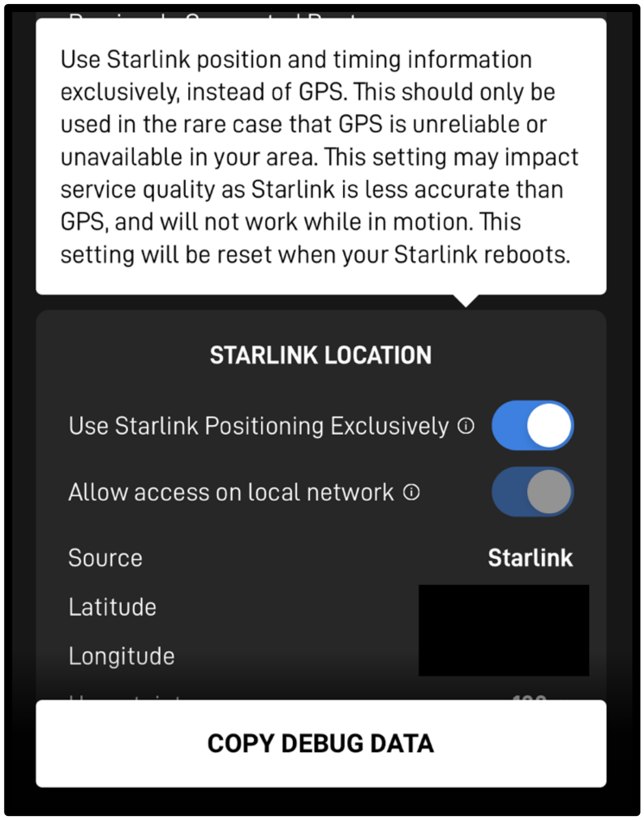


Figure 22. Use Starlink Positioning Exclusively Warning

Bearing the advisory in mind, the experiment was structured to evaluate the functionality of Starlink's PNT while moving. The mobile test setup involved mounting the terminal on top of a vehicle and supplying power either through the vehicle's 100-watt outlet or using a portable battery pack. Additionally, a GPS puck receiver, serving as the benchmark for the terminal's actual location, was situated adjacent to the terminal. This GPS receiver was connected to a laptop via USB, while the terminal maintained a Wi-Fi connection with the computer. Figure 23 depicts the arrangement for the 5 MPH Mobile Test utilizing the Flat High-Performance Terminal. The setup for testing the Standard Terminal mirrored this setup, with the sole distinction being the replacement of the terminal on the vehicle with the Standard Terminal.

Figure 23. Starlink Mobile Test Setup

To gather the necessary data, a Python script was created to log information from both the terminal and the GPS puck receiver. The script captured latitude, longitude, and altitude from the terminal, as well as latitude, longitude, speed, and direction from the GPS puck receiver. Data collection occurred in one-second intervals, during which the script calculated the discrepancy between the terminal's predicted coordinates and the GPS puck's readings. Each data point was then time-stamped and documented in a spreadsheet, with this procedure being replicated for each iteration of the 5 MPH test. Figure 24 shows the schematic for the 5 MPH tests.

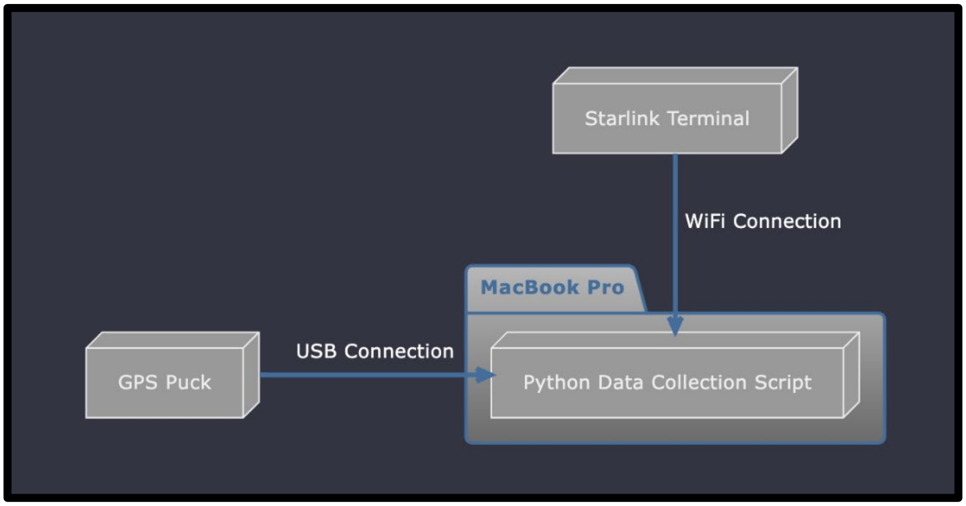
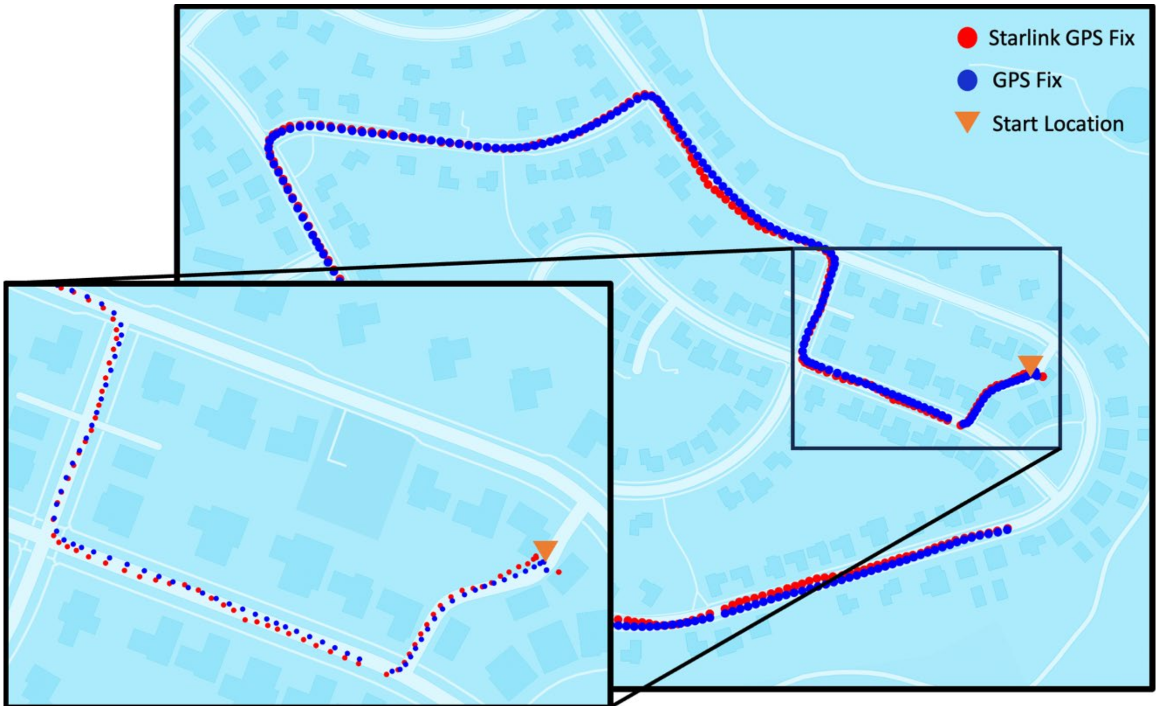


Figure 24. Schematic for 5 MPH Test

1. 5 MPH Test Standard Terminal

For the test, the Standard Terminal was positioned atop the vehicle, adjacent to a GPS puck receiver. The vehicle traveled a predetermined route while the data was recorded. For the first iteration of the test, the Starlink terminal maintained activation of its onboard GPS receiver, thereby demonstrating the terminal's positioning capabilities with GPS during normal operations. Figure 25 shows the outcomes of this iteration.

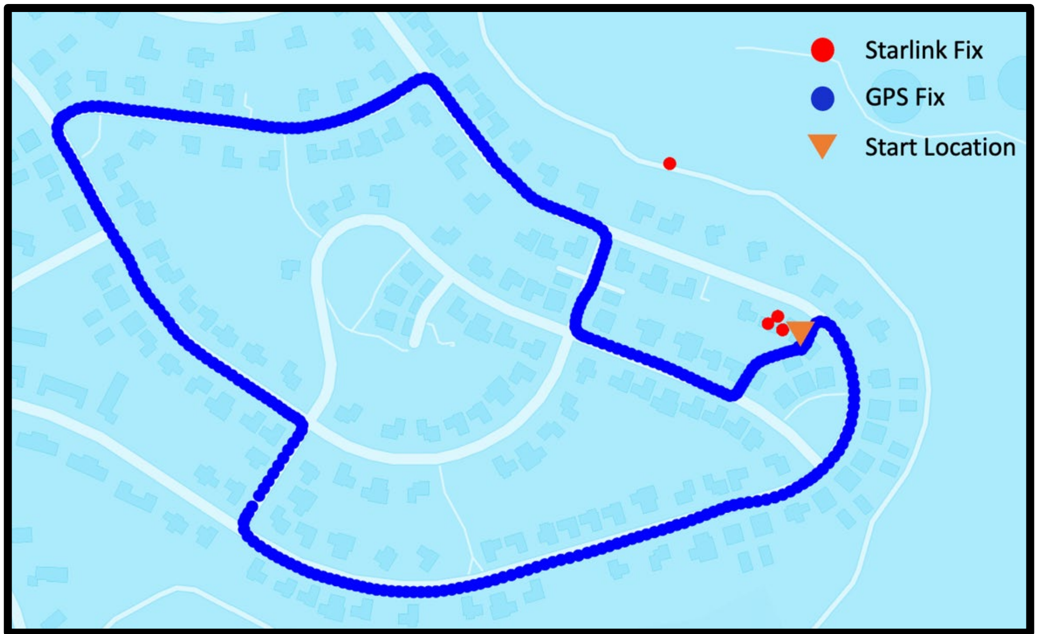


Average Speed	6.17 MPH
Average Distance between Starlink and GPS Puck	2.26 m

Figure 25. 5 MPH Test Starlink GPS Enabled Standard Terminal

The terminal successfully maintained a fix that closely aligned with the GPS puck's latitude and longitude readings. The mean distance between the terminal's fix and the puck's fix was recorded at 2.26 meters.

With this benchmark performance established, the subsequent iteration entailed deactivating the terminal's GPS receiver, forcing the terminal to rely solely on Starlink's positioning capabilities. To achieve this, the same method was used as the baseline performance test where aluminum foil was used to shield the onboard receiver, preventing it from capturing GPS signals. The first iteration of the 5 MPH Test commenced once the terminal had sufficient time to refine its fix to within 30 meters of the starting point. The findings of this test are depicted in Figure 26.



Average Speed	4.78 MPH
Average Distance Between Starlink and GPS	281 m

Figure 26. 5 MPH Test with Standard Terminal

Upon initial position refinement, the terminal ceased to update its position for the remainder of the iteration. Consequently, the average discrepancy between the Starlink fix and the GPS fix measured 281 meters; however, the significance of this result is minimal since the terminal's position fix remained static while the variation arose from the GPS puck moving away from the initial start point. Given the unsuccessful outcome at 5 MPH, further testing of the terminal at higher speeds was not pursued.

In conclusion, the mobile test revealed that the Standard Terminal was incapable of providing updated positional data while in motion. This limitation likely stems from the Standard Terminal's design, which is intended for stationary use, negating the need for continual position updates. The exact cause of this update failure—whether due to hardware constraints, software limitations, or the geolocation methodology employed—remains undetermined.

2. 5 MPH Test Flat High-Performance Terminal

The subsequent mobility test utilized the Flat High-Performance Terminal, which is engineered specifically for mobile applications. As stated on Starlink's website, this terminal is equipped with advanced GPS features and is "currently the only designated dish for in-motion use." [61] For this test, the terminal was positioned on the vehicle's roof next to the GPS puck receiver. The first iteration of the test maintained the terminal's onboard GPS receiver in an active state during the route to gauge the standard positioning capabilities of the terminal in a similar manner as the Standard Terminal's initial test. The outcomes of this iteration are depicted in Figure 27.

Average Speed	6.35 MPH
Average Distance between Starlink and GPS	1.22 m

Figure 27. 5 MPH Test Starlink GPS Enabled Flat High-Performance Terminal

61 "Hardware Options."

As with the Standard Terminal, the GPS integrated into the Flat High-Performance Terminal tracked closely with the GPS puck receiver mounted beside the terminal. The average distance between the terminal's GPS fix and the GPS puck was 1.22 meters.

With the initial iteration complete, the second iteration of the test involved disabling the GPS receiver onboard the terminal to force the terminal to rely on Starlink positioning. Unlike the Standard Terminal, the Flat High-Performance Terminal did not have any physical obstruction to the onboard GPS receiver because all attempts to manually block the onboard GPS receiver were ineffective. To isolate the source of PNT to only use Starlink positioning, the GPS was disabled using the Starlink application's settings which allows the user to manually disable the GPS. With the GPS disabled, the test began once the terminal's position was within 30-meters of the true position. Figure 28 shows the results of the test.

Average Speed	6.04 MPH
Average Distance between Starlink and GPS	291 m

Figure 28. 5 MPH Test Flat High-Performance Terminal

Like the Standard Terminal 5 MPH test, the Flat High-Performance Terminal was unable to maintain a fix as the vehicle moved along the test route. The terminal started with a fix on the initial position and then updated three times throughout the route. Each update was off-course and delayed.

In conclusion, when the onboard GPS is disabled, the Flat High-Performance Terminal was not capable of providing updated position data while in motion, either. This restriction suggests that despite its design for mobile use, the terminal's mobile PNT capability is reliant upon its onboard GPS. The inability to update its position without GPS input points to a possible dependency on integrated GPS functionality for accurate mobile positioning. This finding highlights a critical limitation for operational scenarios where GPS access is compromised.

D. JAMMING AND DETECTION

The final aspect to consider in operational testing is assessing the advantages and constraints of Starlink's signal design in terms of jamming and detection. In evaluating Starlink's potential for PNT applications, several critical questions arise with respect to the resilience of the system's terminals and satellites against potential jamming and whether the terminal transmits during PNT usage. To address these unknowns, both an examination of the system's design and an analysis of Starlink data transmission were conducted.

1. Constellation Design

The Starlink constellation, comprising thousands of satellites in LEO, expanded to 4,519 satellites by July 2023.[62] Figure 29 illustrates the configuration of the Starlink constellation as of November 2023.

62 "Starlink Satellites: Facts, Tracking and Impact on Astronomy | Space," accessed November 10, 2023, para. 4, https://www.space.com/spacex-starlink-satellites.html.

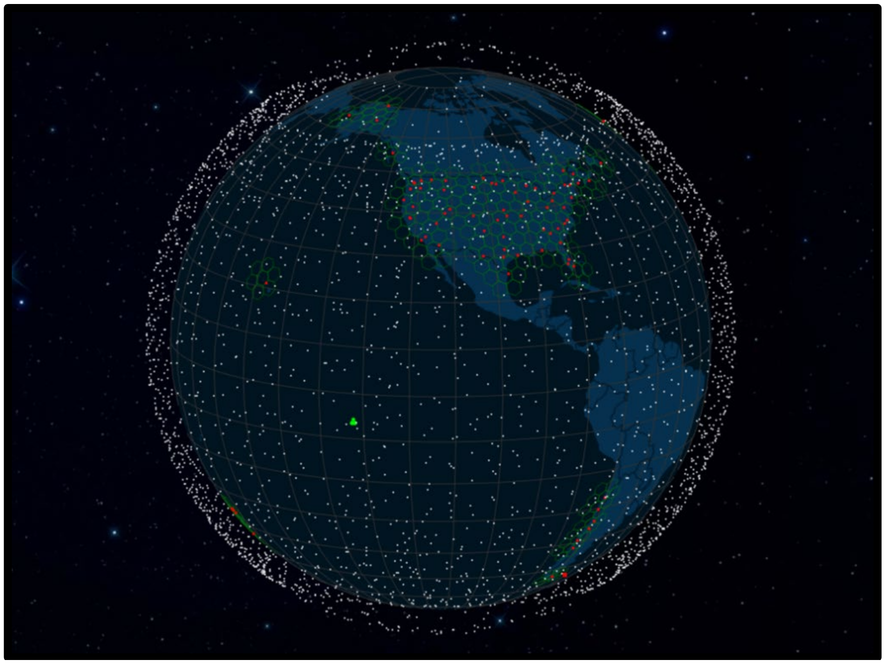


Figure 29. Starlink Constellation[63]

Due to the density of the constellation, there are always multiple satellites present overhead. The Starlink system is engineered to establish communication with a satellite as it traverses the sky. When a satellite moves beyond the terminal's field of view, the system transitions to the next available satellite. While the constellation does not utilize all overhead satellites for PNT purposes like the GPS system does, this configuration does afford the flexibility to switch communication links if a satellite becomes jammed or is otherwise rendered inoperative. Figure 30 illustrates the terminal having 14 satellites within its line of sight during testing.

[63] Source: "Starlink Satellite Tracker," Starlink satellite tracker, accessed November 17, 2023, https://satellitemap.space.

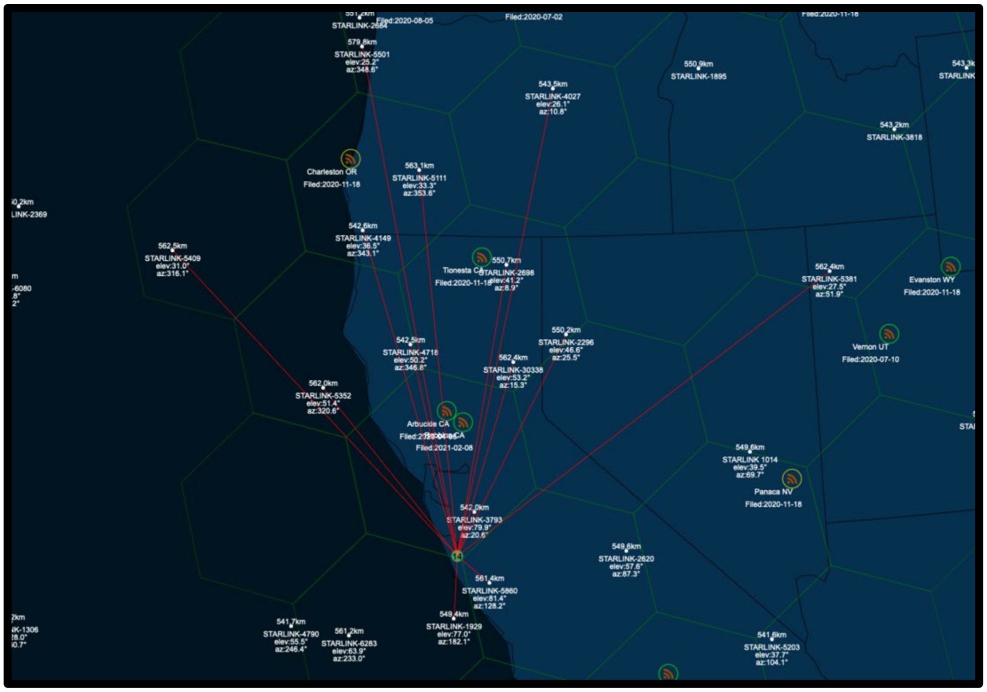


Figure 30. Starlink Satellites in View[64]

2. Signal Strength

As explored in Chapter II, Low Earth Orbit satellites experience less free space path loss, which typically results in higher signal strength for space-to-ground communications. The Starlink constellation operates at altitudes between 540 km and 570 km above the Earth, significantly closer than the GPS satellites orbiting at 20,200 km.[65] According to research conducted by Stanford University, "LEO has the advantage of being closer to Earth than core constellations in MEO, experiencing less path loss and delivering signals 1,000 times (30 dB) stronger. This makes them more resilient to jamming and more capable in deep attenuation environments such as in urban canyons and indoors."[66] This robust signal strength inherently makes it more difficult to jam the terminals, as a jammer would require sufficient power to override these stronger PNT signals. Although jammers can still

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[64] Source: "Starlink Satellite Tracker."

[65] "SpaceX Delivers 52 More Starlink Satellites into Orbit – Spaceflight Now," accessed November 10, 2023, para. 8, https://spaceflightnow.com/2023/05/31/spacex-delivers-52-more-starlink-satellites-into-orbit/.

[66] Reid et al., "Navigation from Low Earth Orbit," 1376.

overpower LEO PNT signals, the effective range of the jammer is reduced without additional transmit power. While the exact link budget of the Starlink system is not publicly disclosed, it is reasonable to infer based on prior research regarding LEO based signal strength, that the signal strength surpasses that of conventional GPS signals with around a 1,000-fold (30 dB) increase.[67]

3. Terminal Gain Pattern

When evaluating the jamming resilience of a PNT system, the receiver's gain pattern is a crucial factor. GPS receivers are typically omnidirectional, designed to capture signals from every direction from the requisite number of GPS satellites for positioning; however, this also renders them vulnerable to interference. In contrast, Starlink terminals utilize an electronically steered array (ESA) with a directional antenna gain pattern. According to a patent filing for an ESA design by SpaceX,

> a phased array antenna can be formed from a set of antenna elements to simulate a large directional antenna. An advantage of the phased array antenna is its ability to transmit and/or receive signals in a preferred direction (i.e., the antenna's beamforming ability) without physically repositioning or reorienting the system… while having a high ratio of the main lobe power to the side lobe power.[68]

Figure 31 shows an example ESA gain pattern presented in a Starlink patent for their terminal design. Although Figure 31 is labeled as radiated power, this pattern also represents that of the received signal due to the principle of antenna reciprocity.[69]

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[67] Reid et al., 1359.

[68] Alireza Mahanfar, Uni-dimensional steering of phased array antennas, United States US10770790B1, filed February 28, 2018, and issued September 8, 2020, https://patents.google.com/patent/US10770790B1/en.

[69] Peter Delos, Bob Broughton, and Jon Kraft, "Phased Array Antenna Patterns—Part 1: Linear Array Beam Characteristics and Array Factor | Analog Devices," accessed November 10, 2023, https://www.analog.com/en/analog-dialogue/articles/phased-array-antenna-patterns-part1.html.

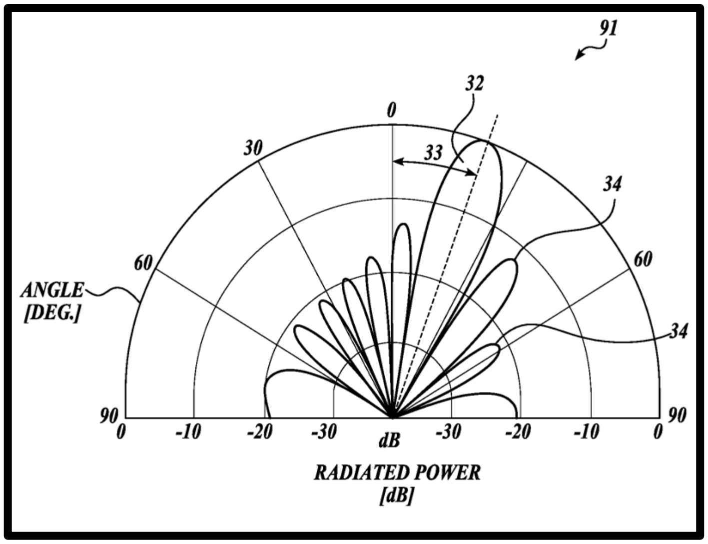

Figure 31. Starlink Terminal Gain Pattern[70]

In addition to the terminal's antenna gain pattern, Starlink satellites leverage beamforming to precisely transmit signals to specific geographic areas, known as cells. Using the ESAs on the satellites, the signal direction is manipulated towards the intended cell. By carefully coordinating the timing and power applied to each antenna element in the array, Starlink can form beams that are highly directional and focused. These beams are dynamically adjusted to effectively 'steer' them to maintain continuous communication with the ground-based terminals within the designated cells.[71] This focused approach not only enhances signal strength and quality within the target areas but also minimizes interference and signal spillover to adjacent regions, ensuring efficient and reliable connectivity.

Starlink's use of beamforming reduces its vulnerability to jamming. The ability to create highly focused beams directed toward specific geographic cells means that the power of the signal is concentrated where it is intended. This concentration makes it more difficult for jammers to interfere with communications because the signal strength in the

[70] Source: Mahanfar, Uni-dimensional steering of phased array antennas.

[71] Mohammad Neinavaie and Zaher M. Kassas, "Unveiling Beamforming Strategies of Starlink LEO Satellites" (35th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2022), Denver, Colorado, 2022), 2525–31, https://doi.org/10.33012/2022.18580.

direction of the intended receiver is significantly enhanced. The tight control over where the beams are pointed limits the exposure of the signals to potential jammers, as areas outside the main beam path receive much weaker signals, if at all. This directed beam approach, compared to the broad coverage of traditional antennas, makes Starlink's signal transmission and reception inherently more resistant to jamming efforts, bolstering the reliability and security of its satellite communication network.

Lastly, LEO satellites offer an advantage against jamming, due to their limited time in view of the user. Unlike geostationary satellites that maintain a fixed position relative to the Earth's surface, LEO satellites move rapidly across the sky. This constant motion means that a potential jammer must continuously adjust their equipment to target a specific satellite or have enough power to jam a wide field of view, both of which are complex and resource intensive.

4. Two-Way Communication

An essential operational aspect to consider in PNT discussions is one-way communication. GPS systems are designed for one-way signal broadcast, requiring no response from the receiver.[72] In contrast, the Starlink constellation, aimed at providing global high-speed internet, is not inherently set up for one-way PNT communication.[73]A Starlink terminal, upon being powered on, links to the network through the satellite constellation; this process involves two-way communication, with the terminal transmitting signals back to the satellite. Additionally, the terminal can be accessed via the Starlink network by external systems, which implies that it remains in communication with the network, independent of user data transmission intentions. Terminal statistics, as shown in Figure 32, can be retrieved from a traditional internet connection on Starlink's website within the user's Starlink dashboard.

[72] "GPS.Gov: Space Segment."

[73] "Starlink."

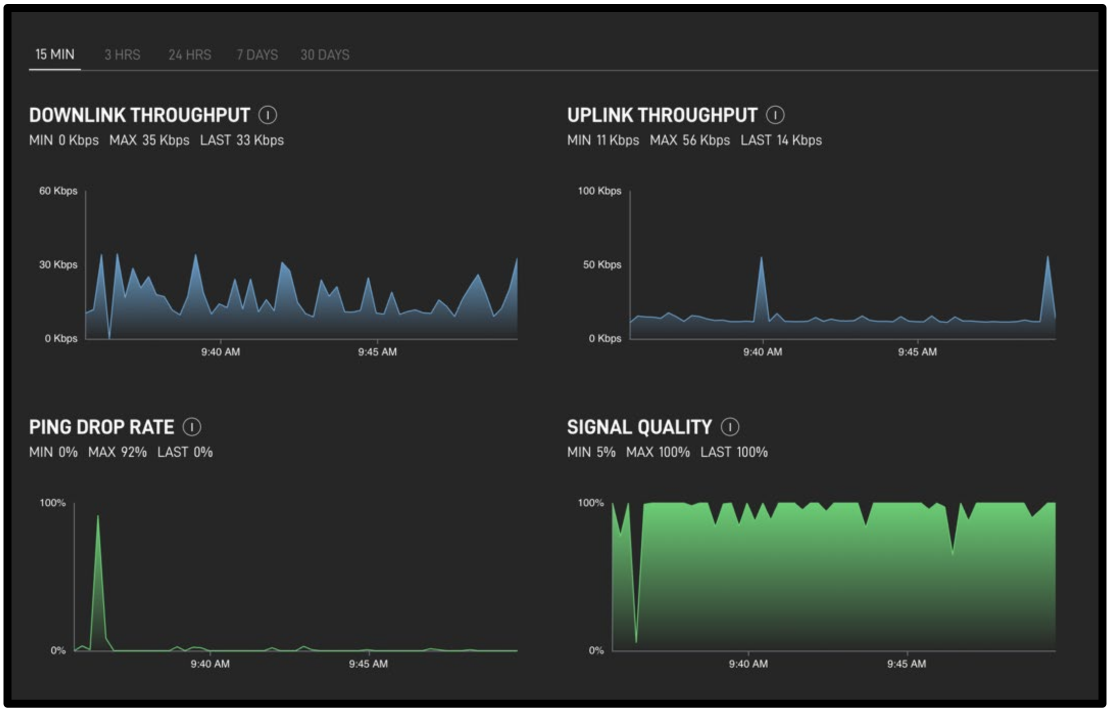

Figure 32. Starlink Terminal Statistics[74]

During the monitored period, no devices were connected to the terminal, yet it continued to send transmit data, indicating active transmission independent of the user's need to send data. This test confirmed that the Starlink terminal engages in two-way communication, even if the user's intention is solely to receive PNT information. Of note, access to a Starlink terminal remotely requires secure credentials, and location data from the terminal cannot be accessed without a direct connection to the terminal, either via Wi-Fi or an ethernet cable.

Operational testing has revealed that Starlink's positioning system presents several strengths for modern navigation needs. The system's successful integration with existing navigation software via the NMEA-0183 standard demonstrates its potential to enhance and complement traditional GPS services. This capability facilitates the use of Starlink data for latitude, longitude, and altitude inputs, ensuring compatibility with current systems and promising a smoother transition for military applications. Moreover, the robust design of

[74] Source: "Starlink."

Starlink's terminals, featuring beamforming and a directional gain pattern through electronically steered arrays, significantly bolsters the system's resilience against jamming. These features provide a strong, focused signal, lessening the likelihood of interference and enhancing the reliability of the system.

Conversely, the system's limitations became evident in mobility tests; both the Standard Terminal and the Flat High-Performance Terminal showed a heavy reliance on GPS to maintain positional accuracy when in motion, indicating that independent positioning without GPS is not yet viable. This reliance poses challenges in environments where GPS signals are compromised. Additionally, the terminals' design for two-way communication may introduce operational security concerns. The terminals' constant data transmission could potentially reveal the user's location, a critical factor for military operations. Table 10 summarizes the results of the Operational Test.

Table 10. Operational Testing Results

Criteria	Figure of Merit	Standard Terminal Results	Flat High-Performance Terminal Results
Interoperability	Compatibility with Other Systems	Pass	Pass
	Compliance with Industry Standard (NMEA-0183)	Pass	Pass
Mobility	Accuracy at 5 MPH	Fail	Fail
	Accuracy while driving 20 MPH	Fail	Fail
	Accuracy while driving 65 MPH	Fail	Fail
Jamming	Rx Signal Strength Compared to GPS	+ 30 dB	+ 30 dB
Jamming/ Detection	Antenna Gain Pattern	Directional ESA	Directional ESA
Detection	Rx only	Fail	Fail

The operational evaluation has highlighted both the strengths and weaknesses of the Starlink PNT system. Its seamless integration with current equipment and adherence to standard data protocols positions Starlink as a hassle-free supplemental PNT solution. The system's robust signal strength, a product of its constellation architecture and terminal design, suggests that incorporating Starlink into the SOF PNT PACE plan could significantly enhance resilience. Nevertheless, the system's limitations in mobility and its inherent two-way communication present considerable drawbacks compared to traditional GPS. While Starlink PNT has viable static applications, addressing these limitations is imperative to fully unlock its potential for SOF operations.

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VI. CONCLUSION

Starlink PNT presents a potentially transformative addition to the PNT PACE plan for Special Operations Forces. Its constellation of Low Earth Orbit satellites offers a complementary layer of resilience to the existing GPS framework. This chapter aims to encapsulate the findings of the extensive testing and analysis conducted, drawing conclusions on the operational viability of Starlink as a supplementary PNT source for SOF, while also highlighting areas that necessitate further exploration.

The performance evaluations and operational testing of the Starlink system have demonstrated its potential as a backup positioning source. In scenarios where GPS availability is compromised, whether due to natural phenomena, adversarial jamming, or other forms of disruption, Starlink's architecture could serve as an additional redundant solution; however, it is imperative to acknowledge that while Starlink shows promise, it is currently less capable than the established GPS system.

GPS has been the cornerstone of global navigation systems, offering unparalleled accuracy and stability. Starlink positioning, in its current iteration, does not match the exacting standards set by GPS. The baseline performance test indicated that while Starlink can provide location data with reasonable accuracy, it falls short of the high precision to which military service members are accustomed. The latency and reliability metrics, although improving rapidly after the initial startup phase, do not yet rival the consistent performance delivered by GPS. Nevertheless, the value of Starlink may not lie in its ability to replace GPS but in its capacity to augment it. In the event of GPS being disrupted, Starlink could ensure that SOF units retain positioning capabilities, albeit with a reduced level of accuracy. This redundancy could prove invaluable in contested environments where position data is a critical component of operational success.

The operational testing results also highlighted the need for further investigation into the Flat High-Performance Terminal's baseline performance characteristics. The testing encountered challenges, particularly with blocking the GPS signals with external material to isolate Starlink's positioning service to allow for large data collection. These challenges prevented a thorough assessment of the terminal's capabilities. As such, a comprehensive understanding of the terminal's performance in a controlled environment remains unknown. Future research should aim to overcome these obstacles to evaluate the terminal's true potential as a PNT source for SOF.

Another intriguing aspect that warrants additional research is the consistent altitude error observed during the baseline performance testing. The error, which manifested as a systematic underestimation of altitude, raises questions about the underlying algorithms or the sensor calibration within the Starlink system. Determining the cause of this discrepancy is crucial, as altitude data is a vital component of three-dimensional PNT information. Further technical investigation into the system's altitude determination process is necessary to identify and rectify the source of this error.

Lastly, during mobility testing, both the Standard Terminal and the Flat High-Performance Terminal demonstrated the ability to accurately track movement when their onboard GPS was enabled; however, a stark contrast in performance was observed when these terminals were tested using the Starlink positioning capabilities, independent of GPS. In the absence of GPS input, neither terminal could maintain an accurate positional fix while in motion. This suggests that while the terminals are well-equipped to function in tandem with GPS technology, their standalone positioning functionality is not yet adept at handling the complexities of movement. It is unknown if this limitation is due to hardware, software, or inherent limitations of the geolocation method utilized. Further investigation into this major disadvantage is critical for future adoption of Starlink PNT.

As we look to the future, the integration of Starlink into SOF's PNT PACE plan holds potential; however, this integration must be approached with a clear-eyed understanding of the system's current limitations and a commitment to rigorous ongoing evaluation. The path forward should include a structured program of research and development, aimed at ensuring seamless interoperability with existing GPS systems should GPS fail. In the short term as Starlink terminals are being integrated into SOF units, operators should be familiar with this capability and how to access this PNT data.

Starlink PNT can offer an alternative positioning data source to SOF should GPS become unavailable.

This thesis discussed Starlink PNT, but the landscape of satellite navigation is rapidly evolving with the proliferation of LEO satellites and the decreasing cost of entering the satellite market. Alongside Starlink, new constellations are emerging with dedicated missions to provide PNT services. Companies like Satelles, TrustPoint, and Xona Space are at the forefront of this emergent PNT market, focusing on LEO-based PNT systems. Satelles is leveraging the existing Iridium constellation to field PNT capabilities that augment the traditional GPS system and are currently providing PNT solutions to customers.[75] TrustPoint and Xona, on the other hand, are in the process of developing their own satellites aimed at delivering centimeter-level positioning accuracy, with Xona having already launched a demonstration satellite in 2022 that confirmed their high-precision claims.[76] TrustPoint followed suit with a demonstration satellite launched in 2023.[77] Although these companies are in the nascent stages of development, their efforts along with Starlink PNT, underscore the expanding involvement of private entities in the PNT market leading to new potential capabilities and PNT solutions for SOF.

In conclusion, Starlink offers an alternative for diversifying PNT sources for Special Operations Forces. Its ease of integration with existing systems and the enhanced signal strength derived from its sophisticated constellation and terminal design are significant advantages. The inclusion of a Ku-band signal within the PNT PACE plan introduces a beneficial layer of signal diversity, particularly useful in scenarios of GPS L-band compromise; however, Starlink's limitations are apparent, with performance dips in accuracy, latency, and reliability when benchmarked against GPS. The system's current constraints in mobile applications and the inherent risks associated

[75] "STL Provides Global Coverage for Timing Synchronization," Satelles, Inc., accessed November 11, 2023, https://satelles.com/technology/stl-provides-global-coverage-timing-synchronization/.

[76] "Xona Broadcasts Demo PNT Signals From Low Earth Orbit," Xona Space Systems, accessed November 11, 2023, https://www.xonaspace.com/xonademospntsignals.

[77] Debra Werner, "TrustPoint Launches PNT Cubesat," *SpaceNews* (blog), April 15, 2023, https://spacenews.com/trustpoint-launches-pnt-cubesat/.

with mandatory two-way communication highlight areas for refinement. Despite these shortcomings, Starlink PNT has the potential to bolster SOF PNT resilience. With a history of pioneering and quickly integrating new technologies, SOF is well-positioned to harness these emerging capabilities, enhancing their PNT resilience to maintain their operational effectiveness on the modern battlefield.

APPENDIX A. STATICTEST.PY

```
import starlink_grpc
import argparse
import time
import logging
import os
import sys
import geopy.distance
import gspread
import openpyxl
from oauth2client.service_account import ServiceAccountCredentials

#IF USING EXCEL
workbook = openpyxl.load_workbook('PATHNAME') #Replace with path to excel file

#global variables
coords_2 = (12.345678, -123.456789) #Replace with terminal true coordinates
group = 1 #This is the iteration number
oldLat = 0
oldLon = 0
MaxTime = 1200 #seconds  #If more than this much time has elapsed, start next iteration
MaxDistError = 1 #meters #If within this distance error, start next iteration
startTime = time.time()

#This function writes the collected data to the excel spreasheet
def writeDataToSheet(group, lat, lon, alt, dist, time, fixNum):

    worksheet = workbook.active
    new_row_data = [group, lat, lon, alt, dist, time, fixNum]
    worksheet.append(new_row_data)
    workbook.save('PATHNAME')

# Function to get the terminal info (lat, long, alt) and calculate true terminal distance
# returns True if fix not withing MaxDistError
# returns False if the fix is within MaxDistError
def fixCheck():
    global oldLat
    global oldLon
```

```
    global group
    global fixNum
    global MaxDistError

    try:
        #gather the starlink terminal informaiton
        lat = starlink_grpc.get_location().lla.lat
        lon = starlink_grpc.get_location().lla.lon
        alt = starlink_grpc.get_location().lla.alt
        coords_1 = (lat, lon)
        dist = geopy.distance.geodesic(coords_1, coords_2).m
        endTime = time.time()
        updateTime = endTime - startTime
        print(lat, lon, alt, dist)
        print(oldLat, oldLon)

        #if within MaxDistError of target, record data
        if dist < MaxDistError:
            writeDataToSheet(group, lat, lon, alt, dist, str(updateTime), fixNum)
            print("Final Fix", lat, lon)
            return False

        #If the fix was updated, then record it
        if oldLat != lat or oldLon != lon:
            writeDataToSheet(group, lat, lon, alt, dist, str(updateTime), fixNum)
            print("Updated Fix", lat, lon)
            fixNum = fixNum + 1
            oldLat = lat
            oldLon = lon
            return True

        #if neither if statement is satesfied
        print("nothing new...")
        return True
    except Exception as e:
        print("An exception occurred:", e)
        return True

# Function to check how much time is spent refining this group of fixes
```

```
# returns True if the total time for trying to refine the group of fixes is less than the
MaxTime
# rturns False is the time trying to refine the group of fixes is more than MaxTime
def timeCheck(startTime):
    testtime = time.time() - startTime
    if testtime > MaxTime:
        print("Group failed to meet criteria. Rebooting Terminal", group)
        return False
    return True

#Initialization
starlink_grpc.reboot()
time.sleep(30)

#Main loop
while True:

    #start with the first fix of the group
    fixNum = 1

    # while the fix is not within MaxDistError and still under the MaxTime,
    # keep refining the position by calling fixCheck()
    while fixCheck() and timeCheck(startTime):
        print("Fixing Group", group)
        time.sleep(1)

    #Clean and update to next group
    starlink_grpc.reboot()
    print("Data recorded")
    print("Rebooting System")
    time.sleep(30)
    startTime = time.time()
    group = group + 1
```

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APPENDIX B. MOBILETEST.PY

```
import starlink_grpc
import argparse
import time
import logging
import os
import sys
import geopy.distance
import gspread
import openpyxl
import serial
import pynmea2

# Load excel workbook using openpyxl
Mobileworkbook = openpyxl.load_workbook('’PATHNAME’) #Replace with pathname
for excel document

#global variables
# Replace '/dev/ttyUSB0' with your GPS device's serial port
gps_device = '/dev/ttyUSB0
# Set the baud rate according to your device's specifications
baud_rate = 9600

# This function writes the terminal's and GPS' data to the excel workbook
def writeDataToSheet():

    # Open the serial port for the GPS device
    with serial.Serial(gps_device, baud_rate, timeout=1) as ser:
        try:
            #Read NMEA data from GPS receiver
            line = ser.readline().decode('ascii', errors='replace').strip()
            # NMEA sentence from GPS receiver starts with $GPRMC
            if line.startswith('$GPRMC'):
                try:
                    #parse the message for lat, long, speed and course
                    msg = pynmea2.parse(line)
                    GPSlat = msg.latitude
                    GPSlon = msg.longitude
```

```
                GPSspeed = msg.spd_over_grnd
                GPScourse = msg.true_course

            except pynmea2.ParseError as e:
                print(f"Parse error: {e}")

        except KeyboardInterrupt:
            print("Stopped by the user")

    #After GPS data is collected, Collect the Starlink data
    try:
        #gather the starlink terminal informaiton
        Starlat = starlink_grpc.get_location().lla.lat
        Starlon = starlink_grpc.get_location().lla.lon
        Staralt = starlink_grpc.get_location().lla.alt
        Starcoords = (Starlat, Starlon)
        GPScoords = (GPSlat, GPSlon)
        #determine distance between GPS and Terminal
        dist = geopy.distance.geodesic(Starcoords, GPScoords).m
    except Exception as e:
        print("An exception occurred:", e)
        return True

    #With the data from the GPS and Terminal, write it to the excel document
    Mobileworksheet = Mobileworkbook.active
    new_row_data = [Starlat, Starlon, Staralt, '' , GPSlat, GPSlon, GPSspeed, GPScourse,'',
dist, time.ctime()]
    Mobileworksheet.append(new_row_data)
    Mobileworkbook.save('PATHNAME')

#This function checks to see if the starlink terminal is on and receiving location data
#Return True if an error occurs (likely due to terminal not powered on)
#Return False if the terminal has a location and no error thrown
def firstfixCheck():
    try:
        #gather the starlink terminal informaiton
        lat = starlink_grpc.get_location().lla.lat
        lon = starlink_grpc.get_location().lla.lon
        alt = starlink_grpc.get_location().lla.alt
        return False
```

```
    except Exception as e:
        print("An exception occurred:", e)
        return True

#START OF MAIN LOOP#

#Reboot terminal to begin the test
starlink_grpc.reboot()
time.sleep(30)

#Do not begin movement until the terminal is booted
while firstfixCheck():
    print("Hold Position. No fix yet")
    time.sleep(1)

print("Continue with test. Begin movement")

#Main loop
while True:

    #record starlink terminal lat long altitude
    writeDataToSheet()

    #Clean and update to next group
    print("Data recorded")
    time.sleep(1)
```

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APPENDIX C. WRITETONETWORK.PY

```
import socket
import starlink_grpc
import time
import datetime

#Function that writes the nmea_sentence to the destination
def write_nmea_to_dataport(nmea_sentence):

    # Change these values to match your network configuration
    host = '127.0.0.1'    # Replace with the IP address or hostname of the destination server
    port = 10110       # The port number you want to use
    try:
            # Create a UDP socket
            sock = socket.socket(socket.AF_INET, socket.SOCK_DGRAM)
            # Send Data to destination
            sock.sendto(nmea_sentence.encode('utf-8'), (host, port))
            # Close the socket
            sock.close()
        print("NMEA sentence sent successfully!")
    except Exception as e:
            print("Error occurred while sending NMEA sentence:", e)


#Function to output a string in the NMEA-0183 standard
def generate_nmea_gga(latitude, longitude, altitude, fix_quality = 1, num_satellites =
13):

    #convert to positive numbers
    lat_abs = abs(latitude)
    lon_abs = abs(longitude)

    #Split into degrees and minutes
    #latitude
    lat_deg = int(lat_abs)
    lat_min = (lat_abs - lat_deg)
    lat_min = lat_min * 60/100

    #longitude
    lon_deg = int(lon_abs)
    lon_min = (lon_abs - lon_deg)
    lon_min = lon_min * 60/100
```

```
    #Move decimal place for proper NMEA formatting
    lat = (lat_deg + lat_min) * 100
    lon = (lon_deg + lon_min) * 100
    timeNow = str(time.localtime())

    # Create the GGA sentence
    gga_message = f"$GPGGA,{time},{lat},{'N' if latitude >= 0 else 'S'},{lon},{'E' if
longitude >= 0 else 'W'},{fix_quality},{num_satellites},, 1{altitude:.2f},M,,"

    # Calculate and append the checksum
    checksum = 0
    for char in gga_message[1:]:
        checksum ^= ord(char)
    gga_message += "{:02X}\r\n".format(checksum)

    return gga_message

# Main Loop
# First gathers lat, long and alt data from terminal
# Second generates NMEA sentence
# Third Writes NMEA to dataport
while True:
    try:
        lat = starlink_grpc.get_location().lla.lat
        lon = starlink_grpc.get_location().lla.lon
        alt = starlink_grpc.get_location().lla.alt

        # Call the function to generate the NMEA sentence
        nmea_data = generate_nmea_gga(lat, lon, alt)
        # Call the function to send the NMEA sentence
        write_nmea_to_dataport(nmea_data)
        except Exception as e:
            print("no signal yet", e)
            time.sleep(10)
```

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