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Providing Time in GPS Denied Environments

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Abstract: Assured Positioning, Navigation, and Timing (APNT) is a high-level reserve for systems that utilize Global Positioning Systems (GPS) for operational use. If GPS is degraded or inaccurate, APNT provides a backup in order to maintain operations and readiness. Accurate information about APNT, with an emphasis on distributing Timing, is key to owning the battlefield and achieving tactical and operational success as communications, smart weapons, and security systems can become inoperable if Timing is out of sync. The research team set out to find an alternative technique or system to provide APNT, with an emphasis on Timing, to military, rotary aircraft. Through our analysis, the team identified the specific high-level functions and objectives, filtered possible solutions, and weighed the resulting systems to determine the best fit. Overall, the Iridium Satellite achieved the highest scores and is the best considered solution.

Keywords: GPS, APNT, Timing, IMU, Aviation, System Decision Process

1. GPS Background and Problem Statement

The Global Positioning System (GPS) is a U.S.-owned global navigation satellite system that provides users with Position, Navigation, and Timing. GPS has both the Precise Positioning Service (PPS), which is used for military and government applications, and the Standard Positioning Service (SPS), which is for all users worldwide, without charge (Kaplan, 2017, p. 3). The system is composed of three segments: space, control, and user (Dorsey et al., 2017, p. 89). The space segment is composed of a constellation of satellites that constantly transmit pseudorandom noise (PRN)-coded signals to the user (p. 89). Since the satellites only transmit signals and do not receive anything back from the user, an unlimited number of users can access the system at the same time (p. 89). The control segment is responsible for station-keeping—maintaining satellites in their proper orbital position—and monitoring satellite subsystem health and status (p. 90). The user segment is made up of the receiving equipment employed by the user. The GPS receiver process the L-band signals transmitted by the satellites to determine its position, velocity, and time in relation to the satellite (p. 137). Regardless of its type, all GPS receivers have five basic components: antenna, receiver front end, processor, input/output device, and power supply (p. 137). Technological advancements and a trend towards miniaturization have made GPS ubiquitous, deeply affecting the way we live our lives. It has, no doubt, become an extremely important capability on the battlefield.

The Army employs GPS to provide own-force position information because it provides a common and consistent reference and does not deteriorate with time or distance traveled (Yerget, 2004, p. 20). Accurate, real-time position and time data of friendly units provides increased situational awareness and provides Army leaders with the ability to more effectively monitor and control the fight. The Army's reliance on GPS has made it a prime target for our adversaries.

Although it is a highly advanced system that continues to be updated and upgraded, GPS has its drawbacks. Most of the drawbacks center on the user segment of GPS. Many of us have experienced degraded GPS capabilities in our daily lives, such as losing signal while driving on roads surrounded by mountains or while hiking in the backcountry. Losing GPS capabilities on the battlefield, however, can have graver consequences than getting lost on the way to a restaurant. There are four basic reasons for GPS deterioration: interference, signal blockage, ionospheric interference, and multipath (Kaplan, 2017, p. 549). Our project focuses on interference, both intentional and unintentional, rather than the other three because it most closely represents the "GPS-degraded" environment we are interested in exploring.

Unintentional interference mostly concerns the interference between two friendly units while intentional interference comes from a source deliberately seeking to degrade our GPS capabilities. Intentional interference happens when radio signals transmitted from a source other than the desired GPS satellite are received by the user's receiver (Kaplan, 2017, p. 550). These unwanted radio signals can be classified as noise. Jamming occurs when the signal to noise ration becomes too low and goes below an acceptable, predetermined threshold (Cunningham, 2020). Spoofing, on the other hand, occurs when the source transmission produces a false position and/or time within the victim receiver (Kaplan, 2017, p. 551). Our client has shown an interest in differentiating intentional and unintentional interference.

GPS provides more than navigation; it also provides highly accurate time to all users thanks to advanced atomic clocks mounted on GPS satellites. In terms of positioning and navigation, the loss of GPS can significantly affect the accuracy of indirect fires, reduce the speed and effectiveness of maneuver units, and result in loss/degradation of real-time situational awareness (Radspinner, 2018, p. 5). The loss of Timing will also significantly affect command and control. Frequency hopping, which provides secure radio communications between units, is negatively affected when the common time reference provided by GPS is lost (Dubois, interview, 2019).

This project focuses on exploring the challenge of deriving and distributing time across the battlefield in a GPS-degraded environment by utilizing all available platforms and network resources, with the focus on aviation platforms. The problem set allows for an exploration of technologies with mature Technology Readiness Level (TRL) of six or higher. A TRL level of six indicates that the developer has a working prototype that has been tested in a relevant environment. Following the exploration, the problem set also allows for an analysis of the alternatives.

2. Methodology

The Systems Decision Process (SDP) was utilized (Figure 1). It consists of four phases: Problem Definition, Solution Design, Decision Making, and Solution Implementation. The SDP was created and is taught by the Systems Engineering Department at USMA. In the Problem Definition phase, analysis is conducted on the stakeholders and existing research to frame the problem and develop the problem statement. Using the problem statement, high level functions and requirements of the system are created and turned into a value model with additional feedback from the stakeholders. Moving into the Solution Design phase, ideas and alternatives are generated in accordance with a cost analysis to narrow down the possible solutions. Once the alternatives have been set and screened, each one can be valued and compared in the Decision-Making phase, where tradeoff and sensitivity/risk analyses are used to highlight the best possible solution. Finally, the best system will enter the Solution Implementation phase where it will be executed into the operational environment.

Due to the nature of the project and the requirements given by the clients, the research team did not utilize the Solution Design and Solution Implementation phase. Our focus was on pre-existing systems with a technology readiness level (TRL) of six or higher to be screened and evaluated. Therefore, these phases were not within the scope of the project.

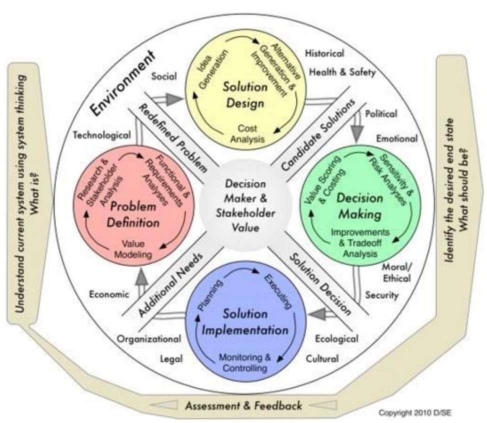

Figure 1. Systems Decision Process

3. Analysis

3.1 Problem Definition

The first step in this phase involves stakeholder and existing research analyses. From our initial problem statement given by PM Aviation, as well as the interviews conducted with staff and faculty, the 160th Special Operations Aviation Regiment, Trellisware, Viasat, Joint Vulnerabilities Assessment Branch (JVAB), and other third parties who had experience as aviators, we were able to create a Findings, Conclusion, and Recommendations (FCR) matrix. This matrix highlighted the key takeaways, or findings, that these experts wanted, expected, and hoped for in an APNT device. Based on what we found, we were able to create overarching conclusions about our system. Finally, the main recommendations that we derived from these conclusions were the necessity of dealing with jamming and spoofing separately, the inclusion of redundant Timing aspects, and the system's production in the United States.

The next step in our analysis was creating a functional hierarchy (Figure 2) in the problem definition phase of the SDP. This tool allowed us to define the overarching objective for our proposed solution as well as functions, subfunctions, objectives, and value measures for that objective. The overarching objective is to "Provide Alternate Position Navigation and Timing in a GPS Denied Environment with an Emphasis on Timing". The corresponding subfunctions were elicited from research and interviews with stakeholders and subject matter experts. The eight total functions are: detect GPS degradation, defeat enemy interference, provide alternate Timing, integrate into airframe, distribute time across the network, usability, maintainability, and producibility. We then further defined the problem by breaking the functions into 17 subfunctions. Altogether, the subfunctions have 26 total objectives with 26 corresponding value measures.

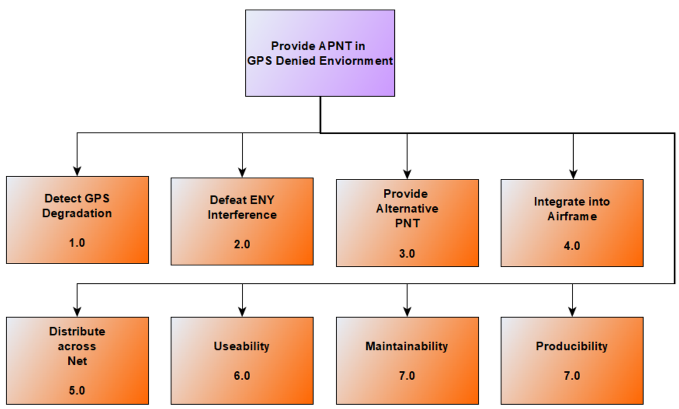

Figure 2. Functional Hierarchy

3.2 Solution Design

Since we are only exploring technologies with a TRL level of six or higher, we conducted alternative analysis for existing alternatives that have been tested in close to operational environments. Through research and stakeholder interviews, we generated a list of 11 alternatives. We then ran these alternatives through screening criteria. That is, criteria that must be included in an alternative for that system to be feasible, given the problem. Based on our screening criteria, we were able to eliminate multiple APNT devices. Specific screening criteria that denied multiple systems that are considered APNT devices was the ability to provide Timing, the ability to defeat enemy interference, and the use of the system while operating in a rotary aircraft. These aspects are critical to solving our problem and for completing aviation operations successfully. So, while devices that perform optical matching and use signals of opportunity can accurately navigate, they cannot provide the critical Timing aspect, while the devices made for ground vehicles were rendered null by their operational limitations. Finally, other devices were screened out due to the risks they posed to security, such as civilian-marketed devices and foreign networks.

After alternative analysis the final alternatives were Curtiss-Wright's DBH-672 Digital Beachhead, Orolia's Versa Sync, Raytheon's Landshield, Trellisware's TW-875 Ghost, the S65-8282-186 UHF Satcom/Iridium/GPS Antenna, and ViaSat's Link 16 BATS-E 1000.

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Curtiss Wright's Digital Beachhead is Size Weight and Power (SWaP) optimized for easy integration (Wranovics, 2018). It contains an Inertial Measurement unit and a Chip Scale Atomic Clock (CSAC) that allows for accurate Timing when GPS is denied (Wranovics, 2018).

Orolia's Versa Sync Rugged Time and Frequency Reference is a "high performance GNSS master clock and network time server that delivers accurate, software configurable time and frequency signals under all circumstances, including GNSS-denied environments" (Orolia, 2020).

Raytheon's Landshield counters GPS jamming attempts by "using steerable null technology, detecting the direction of jamming and then creating a null in the antenna's receive pattern to minimise the jamming effect" (Ebbutt, 2019). Furthermore, the Landshield antennas counter spoofing by identifying and denying false signals (Ebbutt, 2019). Timing is maintained by preventing the degradation of GPS functions.

Trellisware's Ghost is a radio relay that connects to TSM waveform and can provide accurate Timing if one node of that network is outside the denied region (Trellisware, 2019). We are analyzing this alternative under that circumstance.

Next, is the UHF Antenna that utilizes Iridium Satellites. Iridium Satellites can operate "in obstructive zones such as metropolitan areas, woodlands, foothills, valleys, as well as under jamming or spoofing attempts or amid battlefield radio frequency noise" (Walpole, 2012). So, this antenna will be able to withstand friendly, enemy, and physical interference while maintaining accurate Timing using the satellites' atomic clocks.

Finally, ViaSat's Link 16 BATS-E 1000 connects to the Link 16 network. In doing so, it can provide time through the data-link network (ViaSat, 2017), similar to the Ghost.

3.3 Decision Making

Now that we generated feasible alternatives, weights needed to be developed for the value measures in order to complete the weighted value model for alternative evaluation. Due to the large amount of value measures (26) as well as client time, we chose to determine the values' weights based on their ranking. The first method we explored used linear weights with a variable slope represented in Equation 1 (Alfares, 2004, p. 4).

$$Weight = 100 - \left(3.19514 + \frac{37.75756}{n}\right)(r-1),\ 1 \le r \le n, r \text{ and } n \text{ are integer} \tag{1}$$

where n represents the number of ranked value measures and r is the value measure's rank. However, while this technique does have a very low mean absolute percentage error (MAPE) of 3.39, this technique cannot support more than 22 functions without having negative weights (Alfares, 2004, p. 5). The model's drawback is not referenced by Alfares et al. and was found by our group. So, we chose to use another established model. This model uses linear weights with a fixed slope since it has the next lowest MAPE of 24.63 (p. 5). The fixed slope method is represented by Equation 2 below.

$$Weight = 100 * \left(\frac{n+1-r}{n}\right),\ 1 \le r \le n, r \text{ and } n \text{ are integer} \tag{2}$$

Using this method, we took the ranked value measures and gave them weights of 100 and 3.846 percent for the top and bottom ranked functions, respectively. (Note all values after this point are notional due to the need for further stakeholder deliberation and discussion.) The top five ranked values were Timing drift, compatibility interference, negative impact on airworthiness, jammer/signal ratio strength, and signal to noise ratio threshold (SNR). The bottom five ranked values are optimizing location, weight, volume, installation time, and ease of software upgrades.

Next, we divided each weight by the sum of all the weights to create the global weight where the sum of the global weights is equal to one. Then, we created value functions using subject matter experts. These functions take the feasible value measures on a range from best to worse and assigns a value to each value measure. An example of the value functions for the top two measures are below in Figure 3:

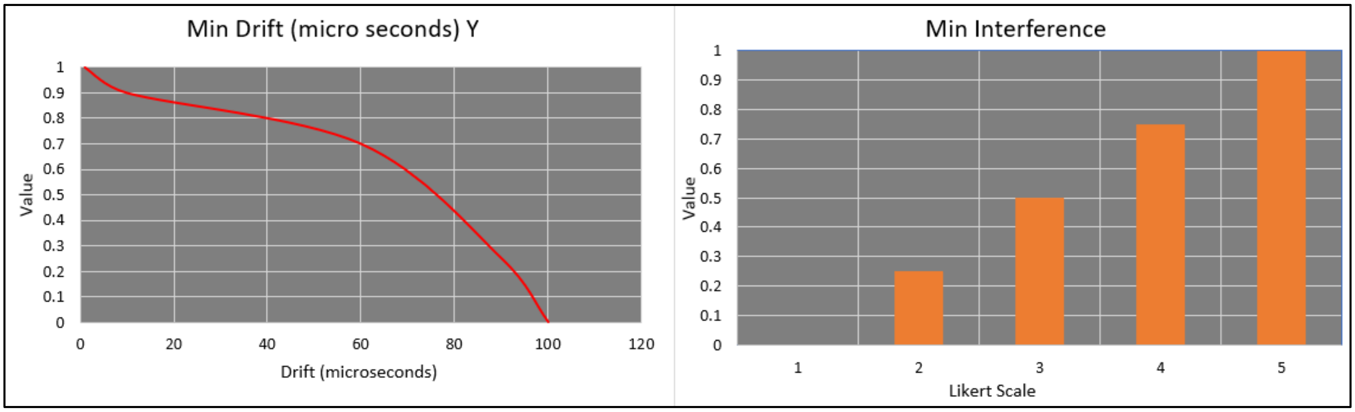

Figure 3. Value Functions

Now, we can input the values for each alternative into the created value functions for each measure. In doing so, we can compare measures with different units on the same scale. Finally, we take the sum-product of each alternatives' value with the respective measures' global weight to account for the relevant importance of each rank value measure. This creates each alternatives' total value score.

Finally, to make a proper comparison, we factor in cost by taking the final scores and graphing them versus cost, shown in Figure 4 below:

Figure 4. Value vs. Cost

4. Results

Based on Figure 4, we can tell which values are dominated. That is, which values have a higher cost and lower value than the others. In this case, Iridium Satellites dominate all other alternatives because it has the highest total value score of 91.237 and the lowest cost of $3000 per unit. If we were to not consider Iridium Satellites, then the client would have a choice between TSM Waveform, Versa Sync, and Beachhead. This is because Landshield is dominated by Beachhead since it has a

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higher value for a lower cost. The remaining choice depends on the cost the client is willing to pay since they would pay more for a better value when considering the Beachhead, Versa Sync, and TSM Waveform.

Further work will be performed to convert this deterministic value model into a stochastic model in order to consider the inherent uncertainty in values as well as lifecycle cost risk. Sensitivity analysis will also be included in this final model.

5. Conclusion

The future of warfare is contingent on the operational capabilities and efficiency of military aircraft. The model that we created will aide rotary-wing aircraft in distributing accurate Timing across the battlespace by analyzing different solutions and finding what the best fit is. According to our notional data and research, the S65-8282-186 UHF Satcom/Iridium/GPS Antenna is the best current alternative on the market. This device performs better than all other alternatives while still being the least expensive option. It can increase the lethality of combined arms by making it impossible to jam under current GPS denial technologies while saving the Army a significant amount of money. It will reliably provide APNT needs across the battlespace, furthering the combined arms effort and increasing the overall success and efficiency of the U.S. Army, as well as other combined arms combat.

The importance of a device which can distribute accurate Timing is highly sought after in the military community. Enemy anti-GPS capabilities will cause a greater need for a new technique to distribute time across the battlespace. With more data on each alternative, our model would be more accurate in determining which device is the best. Further research into other devices that have a lower technology readiness level would offer many more solutions to potential future threats.

6. References

Alfares, H. K. (2004). Alfares, Hesham K. and Dr. Salih O. Duffuaa. "DETERMINING CRITERIA WEIGHTS AS A FUNCTION OF THEIR RANKS IN MULTIPLE-CRITERIA DECISION MAKING." (2004). 1-6.

Cunningham, C. C. (2020, February 21). Special Operations Aviation Regiment Interview. (W. Bridgham, G. Lambert, A. Moe, & T. Morin, Interviewers)

Dorsey, A. J., Marquis, W. A., Betz, J. W., Hegarty, C. J., Kaplan, E. D., Ward, P. W., & Wiederholt, L. F. (2017). Global Positioning System. (E. D. Kaplan, & C. J. Hegarty, Eds.) *Understanding GPS/GNSS: Principles and Applications*, pp. 89-189.

Dubois, P. M. (2019). Aviator Interview. (W. Bridgham, G. Lambert, A. Moe, & T. Morin, Interviewers)

Ebbutt, G. &. (2019, September 13). *DSEI 2019: Raytheon reveals GPS anti-jamming antennas.* Retrieved from JANES: https://www.janes.com/article/91265/dsei-2019-raytheon-reveals-gps-anti-jamming-antennas.

Kaplan, E. D. (2017). Introduction. *Understanding GPS/GNSS: Principles and Applications*, pp. 1-18.

Orolia. (2020, Feburary 26). *VersaSync Rugged Time and Frequency Reference.* Retrieved from Orolia Corporation Web site: https://www.orolia.com/documents/versasync-rugged-gps-master-clock-datasheet/attachment

Radspinner, E. (2018). *Joint Force Operations in GPS-denied or degraded environment. Joint Military Operations Department.* Retrieved from DTIC: https://apps.dtic.mil/dtic/tr/fulltext/u2/1061997.pdf

Trellisware. (2019). *Trellisware Technologies.* Retrieved from Trellisware Technologies Web site: https://www.trellisware.com/wp-content/uploads/2019/03/TW-875-TSM-Ghost-Datasheet.pdf

ViaSat. (2017). *ViaSat Incorporated.* Retrieved from https://www.viasat.com/sites/default/files/media/documents/bats-e_1000_datasheet_015_web.pdf

Walpole, L. M. (2012). *Saved by Iridium? An Alternative to GPS.* Fort Leavenworth: School of Advanced Military Studies.

Wranovics, J. (2018, May 22). *Press Releases: Curtiss Wright Annouces Assured Position, Navigation, and Timing (A-PNT) Solution Roadmap.* Retrieved October 21, 2019, from https://www.curtisswrightds.com/news/press-release/cw-introduces-a-pnt-solution-roadmap.html.

Yerget, R. (2003). No Longer Guaranteed…Global positioning system alternative necessary. *Army Space Journal*, 20-21. Retrieved from https://apps.dtic.mil/dtic/tr/fulltext/u2/a525765.pdf

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