The Application of GPS Technology to the Future Spacelift Range System (SLRS)

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ABSTRACT

The Spacelift Range infrastructure of the United States Air Force will, over the next decade, experience a major modernization and upgrade. The goal of the Range Standardization and Automation (RSA) Program is to meet the requirements of range users and range safety in a more cost effective manner than is currently possible.

One approach that will be considered in best achieving these goals is the further application of GPS technology to both the Eastern and Western Spacelift Ranges. Such an application can have a profound impact on the instrumentation segment of each range. Included within the instrumentation segment and clearly impacted, are both the metric tracking and telemetry subsystems.

This paper considers the SLRS requirements that can be supported with GPS technology; the advantages and shortcomings of both GPS technology and alternative techniques; and provides suggestions as to an appropriate application of GPS technology to the SLRS.

INTRODUCTION

The Spacelift Range infrastructure of the United States Air Force will, over the next decade, experience a major modernization and upgrade. The goal of the Range Standardization and Automation (RSA) Program is to meet the requirements of range users and range safety in a more cost effective manner than is currently possible. Perhaps the principal requirement that must be fulfilled in order to satisfy both range safety and range users is the provision of accurate metric data for the space and ballistic vehicles launched on the range. One of several approaches that can be utilized to support the fulfillment of this important requirement is the application of GPS technology. In this paper, the key requirements, technical issues and alternatives are addressed from which an approach for the appropriate application of GPS technology to the future SLRS can be formulated.

The paper has been organized into five sections. Following this introductory section, Section Two addresses the SLRS metric requirements and the necessity for the future SLRS to deliver capabilities with a significantly lower cost structure than is possible today. Section Three provides a brief summary background of the Global Positioning Satellite system. Included is an overview of the fundamental GPS concept, the signal structure, the factors that impact metric accuracy and approaches for accuracy enhancement. Following this, Section Four considers alternatives to GPS with respect to providing metric data and compares the pros and cons of each alternative. The paper concludes with Section Five which proposes, based on the material presented in the three preceding sections, how GPS technology might best be applied in the future SLRS.

SPACELIFT RANGE SYSTEM REQUIREMENTS

The principal requirements placed on the Spacelift Range System are to ensure range safety and to provide data to users whose vehicles are launched on the range. The range users are comprised of those attempting space launches, or testing and evaluating ballistic missiles, guided missiles or high performance aircraft. In addition to these principal requirements, the range must be capable of supporting the Space Surveillance Network.

Fundamental to supporting all these requirements is the need to generate metric data for the vehicles launched on the range. Certainly metric data for the vehicles is at the heart of the range safety issue. The vehicle’s position and velocity must be known throughout powered flight in order to determine its potential impact point if thrust was terminated. Additionally however, metric data is perhaps the most important category of data required by the range user in support and evaluation of his operation.

The two key performance measures for the metric data that must be provided by the SLRS are timeliness and accuracy. With respect to timeliness there are real time metric data requirements and post mission metric data requirements. The principal real time metric data requirement is obviously range safety. Other real time metric data requirements include the provision of designation data for downrange metric systems; data for cooperative missions that may be utilizing the space launch or ballistic missile test for other work; and for certain testing, operational data such as support for interceptor targeting. The principal post mission metric data requirements are those of the range user in order to evaluate the performance of the mission whether it is a space launch or the test of a vehicle. Additionally, the range itself has a need for post mission metric data to support the calibration and evaluation of the ranges' metric data sensors.

With respect to the accuracy of the metric data there are three important derived requirements. One is the metric accuracy of the individual sensors that provide real time data. These requirements will depend both on the geographic location of the sensor and the technology employed by the sensor. A second derived requirement is the accuracy of the process that fuses the results of all sensors and produces a real time estimate of vehicle position and velocity. Finally a third requirement is the accuracy of the post mission process that creates a non real time, best estimate of trajectory.

Overlaying these technical requirements is, as noted above, the necessity to meet these requirements with a far less expensive system (in terms of life cycle costs) than is currently in place. This in turn results in the need for standardization, commonality and automation in all aspects of the SLRS, including those subsystems that support the gathering of the metric data.

GLOBAL POSITIONING SATELLITE SYSTEM

The GPS system consists of a constellation of 24 satellites that transmit signals which allow a GPS receiver equipped user to accurately determine his position irrespective of his location. The concept is for the GPS user to listen to the transmissions from at least four satellites. Basically each satellite provides the user with accurate estimates of the satellite position and the time at which the satellite initiates portions of its transmission. By noting the instant in time that it receives the signal from a satellite the user can determine a sphere on whose surface the user is located. Furthermore, the center of the sphere is at the known position of the satellite and the radius of the sphere is equal to the pseudorange between the user and the satellite. The pseudorange is merely the range between the user and the satellite plus the speed of light multiplied by the time offset between the receiver and satellite clocks. The fact that the receivers clock offset is unknown results in the need for the user to make pseudorange measurements to at least four satellites in order to determine its' position. The four measurements are used to establish equations (1) to (4) below and can be solved for the coordinates of the user receiver (x_r, y_r, z_r) and the user clock time t_r.

$$PR_1 = \sqrt{(x_1 - x_r)^2 + (y_1 - y_r)^2 + (z_1 - z_r)^2 - c^2\,(t_1 - t_r)^2} \quad (1)$$

$$PR_2 = \sqrt{(x_2 - x_r)^2 + (y_2 - y_r)^2 + (z_2 - z_r)^2 - c^2\,(t_2 - t_r)^2} \quad (2)$$

$$PR_3 = \sqrt{(x_3 - x_r)^2 + (y_3 - y_r)^2 + (z_3 - z_r)^2 - c^2\,(t_3 - t_r)^2} \quad (3)$$

$$PR_4 = \sqrt{(x_4 - x_r)^2 + (y_4 - y_r)^2 + (z_4 - z_r)^2 - c^2\,(t_4 - t_r)^2} \quad (4)$$

In the above equations, PR_1, PR_2, PR_3, and PR_4 are the pseudorange measurements the GPS receiver makes to respectively, satellites one, two, three, and four. The terms (x_1, y_1, z_1), (x_2, y_2, z_2), (x_3, y_3, z_3), and (x_4, y_4, z_4) are the locations of satellites 1 through 4 provided to the GPS receiver by the satellites themselves. Finally t_1, t_2, t_3, t_4 are the satellite clock times for each of the four satellites, likewise provided to the GPS receiver by the respective satellite.

Signal Structure

Each GPS satellite transmits two carrier frequencies; L_1 = 1575.42 MHz and L_2 = 1227.60 MHz The standard positioning service (SPS) coarse acquisition (C/A) code modulates the quadrature component of the L_1 carrier frequency. The C/A code is a 1.023 mchip/sec rate code that has 1023 code states and therefore has a duration of 1 msec. The precise positioning service (PPS) precise (P) code modulates both, the in phase component of the L_1 carrier frequency and the L_2 carrier frequency. The P code is clocked at a 10.23 mchip/sec rate. Also modulating both carriers is a 50 BPS, 1500 bit long data message. It is this data message which provides the user's GPS receiver with the satellites accurate position and time offset. While the data message provides the GPS receiver with key information necessary to convert the pseudorange measurements it makes to a position fix, it is the pseudorandom C/A and P codes that are of principal importance. The codes allow pseudorange measurements to be made and also are fundamental in enabling the receiver to simultaneously make pseudorange measurements to multiple satellites all of whose transmissions are at the same frequency.

As can be inferred by its name the P code has an inherently greater accuracy than does the C/A code in the determination of position. As a result, and in order to both deny its capability to unauthorized users and to ensure that authorized users of this precise positioning capability can count on its use when necessary, the P code is typically encrypted. This is accomplished on the satellites by modulo 2 adding a 50 chip/second encrypted W code to the P code yielding an encrypted 10.23 mchip/sec output code referred to as the Y code. Thus, when encrypted, only authorized users (those with the crypto key) can utilize the precise positioning service and furthermore those users are ensured that when using the PPS they are never mistakenly depending on some adversary's bogus transmission.

Factors Impacting Metric Accuracy

By considering the measurements and calculations made by a user receiver in order to achieve a position fix, the factors impacting the accuracy of that position fix become apparent. There are essentially four categories of factors that impact metric accuracy.

One category is the degree of accuracy with which the signal arrival time at the user receiver can be measured. This is a S/N and bandwidth issue and is the reason the P code which is clocked at a rate ten times greater than the C/A code has an inherent range accuracy that is an order of magnitude greater.

A second category is the degree to which the time delay between satellite and GPS user accurately represents a measure of satellite to user range. The issues here are ionospheric delay which reduces the velocity at which energy propagates and tropospheric effects which can result in a longer than strictly line of sight propagation path. As an example, an uncorrected ionospheric delay can result in as much as a 16 meter error in the user position estimates.

A third category is the degree of accuracy with which the user receiver knows the satellite position and time offset. By far the most important issue here is that of selective availability. Selective availability is the intentional dithering of the satellite clock to degrade the positional accuracy of the standard positioning service to a worst case 100 meter accuracy.

The fourth and final factor impacting accuracy is the geometric dilution of precision (GDOP) which is determined by the geometry of the satellites utilized for the position fix. The further the angular separation of the satellites with respect to the user the greater the accuracy in the position fix.

Error Mitigation (or Accuracy Enhancement)

Mitigation techniques exist for several of the factors that can degrade the accuracy of GPS metric data.

The GDOP factor can be mitigated with the use of ground based transmitters known as pseudolites which transmit signals identical to the GPS satellites. The concept is to provide a GPS receiver with an increased number of transmissions from which to select those to utilize for a position fix and therefore improve the "satellite geometry" and accuracy of the position fix.

Ionospheric delay can be accurately estimated by a GPS receiver that can receive both the L_1 and L_2 channels. This is done by noting the relative carrier frequency shifts of the two transmissions. Since this information can be derived without knowledge of the P (or Y) code, a two channel unauthorized user can accurately estimate ionospheric delay. For single channel receivers, a supplementary system transmission can provide receivers with up to date ionospheric delay estimates or a model based on historical data can be included in the receiver.

In general the key error source that must be addressed for C/A code users is the above mentioned selective availability. The principal mitigation approach is the utilization of a differential GPS technique. Basically the differential GPS (DGPS) techniques can, with the right implementation, address all inaccuracies that result from propagation phenomena or lack of exact satellite information. The technique is based on a surveyed GPS receiver comparing its calculated position with its known position and generating a pseudorange correction for each satellite that reconciles the calculated and actual positions. These pseudorange corrections are then transmitted to users in order to support a navigation function or are applied to pseudorange corrections provided by users to support a surveillance function. Naturally the accuracy enhancement of the technique depends on the users and surveyed receiver experiencing the same errors. This assumption degrades with increasing distance between user and reference station. As a result two different DGPS implementations are employed. A local DGPS system operating just as described above is typically utilized for applications where the users are no more than a few hundred kilometers from the reference receiver. A wide area DGPS implementation is utilized for significantly larger separations. In the wide area DGPS implementation the pseudorange correction must be broken down into components resulting from satellite clock error, satellite ephemeris error, and propagation error. Thus a vector of corrections is provided to users in the wide area DGPS system rather than the scalar correction provided in the local area DGPS system. The user receiver for its part must be capable of separately applying each of these component corrections to its position calculation based on its nominal location.

COMPARISON OF GPS WITH OTHER METRIC TECHNIQUES

There are four different technologies that can be employed to support the generation of metric data for the SLRS. Furthermore, each of these technologies can be applied in alternative implementations. The four technologies are radar, optics, GPS and inertial guidance data.

Radar can be employed in a skin tracking mode for any target and in a beacon mode for cooperative targets. It can provide metric data for targets at substantial distances as long as the target is in geometrical line of sight to the radar. The accuracy of the metric data, however, degrades with increasing distance. This is true even for a received signal to noise ratio that is held constant with increasing distance. Under such circumstances, the degradation in accuracy results not from increasing range inaccuracy or from increasing angular inaccuracy, but merely from the fact that positional uncertainty increases with the square of the range for a fixed set of angular pointing errors. A radar multilateration approach with good geometry can be employed to substantially reduce this portion of the uncertainty but naturally that results in a proliferation of the number of required radars.

Optical techniques can be employed in either a passive mode, along with multilateration techniques, or in an active mode. Such approaches can provide extremely accurate metric data for all targets, but atmospherics substantially limit the distance (between sensor and target) at which data can be provided.

The GPS technology, as described above, can provide accurate metric data on a worldwide basis. Unlike radar and optics, the availability or accuracy of the data does not, in general, depend on the location of the vehicle relative to that of a ground sensor. Alternative GPS implementations, with varying degrees of accuracy, include

C/A code vs. P code, single channel vs. dual channel and conventional GPS vs. differential GPS. Additionally, a code tracking or carrier tracking approach may be used, as well as alternative implementations such as a receiver or a translator on the vehicle. The technology is only applicable, however, for cooperative targets.

Inertial guidance data is a fourth technology capable of providing metric data for the SLRS. Like the GPS technology, the use of an inertial navigation system (INS) to provide the SLRS with metric data, can only be applied to cooperative targets. While the INS approach is more responsive, than say GPS, to sudden changes in thrust and direction, the approach does suffer, unlike GPS again, from accuracy that degrades with time, and with the inability to make absolute measurements.

It is clear that the four techniques delineated above each have particular strengths and weaknesses with respect to performance. However, based on the SLRS requirements discussed earlier, any comparison of the techniques must address cost as well as performance. From a cost point-of-view, an accurate assessment must include the costs associated with the ground infrastructure and the costs associated with necessary cooperative electronics on board the vehicle. For radar and optics, which are basically surveillance techniques, the costs are principally centered in the ground infrastructure. For inertial guidance and GPS, which are basically navigation techniques, the costs are more evenly distributed between ground infrastructure costs and the cost of cooperative electronics onboard the vehicle.

Navigation techniques provide the vehicle with its own position and for a surveillance requirement such as the SLRS's this information must be routed to a control center. Telemetry links are the mechanism for delivering the position information (or in the case of a GPS translator approach, the raw signals on which the position can be calculated) from the vehicle to the ground. Surveillance approaches, on the other hand, do not require onboard vehicle electronics (with the exception of a beacon transponder) or telemetry links to provide metric data to the SLRS. In comparing the SLRS's costs for both the surveillance techniques and the navigation techniques, great care must be taken. Clearly if a range user is burdened with costs for vehicle electronics in order to launch on the range, these costs must be included in the total costs of the particular metric approach. However, if the SLRS can merely capitalize on a vehicle's existing navigation capability, the costs of the metric technique should be limited to the ground infrastructure.

It is the general perception that the utilization of GPS by the range may reduce the ground infrastructure costs but increase the vehicle costs. This may or may not be true. With respect to reducing ground infrastructure costs there is a cogent argument to support that point of view. The argument is based on the worldwide availability of accurate metric data in the GPS approach with only the necessity of ground receivers to support that availability. In either a radar or optics based approach this can only be achieved with groups of sensors placed in all locations where accurate metric data is required. The cost advantage for ground infrastructure clearly goes to the GPS technology. Furthermore, the advantage is significant as long as the cost of the GPS constellation is not amortized across range operations through some type of user fee.

It is less clear that the utilization of GPS technology by the range substantially increases vehicle costs. The key consideration is whether or not the onboard GPS equipment is supporting the SLRS surveillance function only, or is also supporting a vehicle navigation function as well. The latter is a distinct possibility. It has been argued that integrating a GPS function with an INS function can result in a superior navigation capability. GPS provides an absolute reference and the accuracy of GPS derived data does not degrade with time. These are definite benefits, but they must be assessed on a mission by mission basis.

Thus for example, the implementation of an onboard GPS receiver may serve an important navigation function and therefore the only vehicle costs attributable to the range would be the costs of interfacing the GPS receiver with the telemetry downlink. On the other hand, the onboard implementation of a GPS translator must be considered a range utilization cost since even though it supports the SLRS surveillance function, it does not, in anyway, support vehicle navigation.

SUMMARY AND CONCLUSIONS

It can be surmised that GPS technology can enhance the cost effectiveness of a future SLRS. The systems’ global capability will provide accurate metric data over a wider area more cost effectively than any other technique. On the other hand, an SLRS dependent solely on GPS technology for its metric data is an impossibility if only for the need to provide metric data for non-cooperative targets as well as cooperative targets. The worldwide GPS capability can certainly provide a significant increase in flexibility with respect to providing downrange metric data. Additionally, the utilization of non real time GPS carrier tracking techniques can enhance post mission metric analysis. It is also arguable that an integrated GPS/INS navigation approach where the two techniques each compensate for the others shortcomings can enhance the range safety metric data function. The GPS implementation for the range that appears most appropriate would be a differential GPS surveillance approach that includes the ability to assess the health of the GPS satellites.