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A Design Approach for a GPS User Segment for Aerospace Vehicles

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Abstract

As new applications for the use of the Global Positioning System (GPS) on aerospace vehicles emerge, more attention is being paid to the design of the user segment, which comprises the hardware and software employed by the user to obtain navigation information from GPS. The complexity of the design of the user segment, as well as the performance demanded of the components (such as the antenna), depends on user requirements such as total navigation accuracy. Other factors, for instance the expected satellite/vehicle geometry or the accuracy of an accompanying inertial navigation system, can also affect the user segment design. The interaction between these effects, the user requirements, and the user segment design is studied. Design curves are developed which allow quick trade studies to be performed.

I. Introduction

GPS is a satellite navigation system developed and maintained by the United States Department of Defense [1]. Because of the versatility provided by the global availability and the passive nature of the user segment, GPS is being used in a wide range of aerospace applications. Among these are on-board navigators and trajectory references for range safety and for testing inertial navigation systems.

GPS user segment designs can be broadly classified into two categories: receiver- and translator-based designs. A GPS receiver processes GPS signals to estimate its own position and velocity. This information can be used directly, or can be combined with other navigation estimates (from an inertial navigation system, for instance) to get a best-estimate of the vehicle position and velocity. A GPS receiver must compensate for known measurement errors in real time [2]. A GPS translator, on the other hand, is a relatively simple device whose function is to frequency shift ("translate") the GPS signals from one frequency band to another, such as a telemetry band. The translated signal is then retransmitted to a ground receiving station, where it is time-tagged and processed or recorded for later processing.

Oftentimes an application will require the use of a receiver-based user segment. For instance, using GPS for on-board navigation usually demands a receiver. On the other hand, when using a GPS user segment as a navigation reference for testing inertial navigation systems, a translator-based segment offers several advantages, including low cost, weight, and power consumption and high reliability. Furthermore, ground post-processing of the signals allows for the use of highly accurate satellite orbital information not available in real-time and highly detailed corrections.

This paper considers the performance factors which affect the design of a GPS user segment. Although the results apply to various other applications, GPS used as a navigation reference for testing inertial navigation systems is considered as a specific example [3].

II. User Requirements and the GPS User Segment

A. Contributors To System Performance

The ability to meet application-specific performance requirements depends on the design of the GPS user segment as well as other factors relating to the system performance. This relationship is illustrated in Figure 1. Each box represents either a measure of performance or a factor affecting performance; boxes higher in the figure depend on boxes connected to them from below.

At the top of the figure is the user's requirement on the performance of the whole system. For GPS/inertial navigation system hybrids, the user's requirement would typically be on the total navigation accuracy [4]. For an autonomous GPS navigation system, the user requirement would be on the GPS navigation accuracy. For the case of GPS used as a trajectory reference for flight testing inertial navigation systems, the user requirement would be on measures such as estimation uncertainties.

The three-dimensional measurement accuracy of the GPS user segment can be determined independently of other components in the user's system, as illustrated in the second level of Figure 1. It depends on the satellite geometry [5], the vehicle flight path, and the one-dimensional GPS measurement accuracy. The measurement accuracy depends on the receiver or translator design, the antenna design, the accuracy of the satellite ephemeris data, relativity and atmospheric effects, and fixed characteristics of GPS. The data used in this study are based on the literature [6][7] and flight test experience.

Receivers and translators can be designed to process the L_1 (1575.42 MHz) or L_2 (1227.60 MHz) signals or both. Processing two frequencies allows for better ionospheric refraction corrections. In addition, receivers and translators can be designed to process one or both of the GPS codes. The GPS L_1 signal is quadrature modulated by two pseudorandom codes, a 1.023 Mbit/s coarse acquisition (C/A) code and a 10.23 Mbit/s precision (P) code [2]. The type of code used determines the range precision which can be achieved.

The design and calibration of the antenna affects the accuracy of the phase-derived delta range measurement. The antenna phase induces a delta range error through three mechanisms: error in the phase calibration, vehicle attitude error coupled with the antenna phase slope, and ionospheric refraction correction error. The accuracy of the phase center calibration also affects the calculation of vehicle reference point to phase center lever arm, effectively introducing measurement errors.

The GPS satellite ephemerides are obtained either in real time from the GPS navigation message [8] or from satellite tracking data spanning a period of several days both before and after the time of interest.

Two different data correction schemes are considered. The coarser correction scheme adjusts the GPS measurements for satellite clock phase and frequency, drift in the translator carrier frequency, and changes in the signal path length due to ionospheric and tropospheric refraction. A coarse correction for relativistic effects is also built into the GPS clock frequency. A finer approach does the coarse corrections plus precise corrections for general and special relativistic effects due to the vehicle motion and higher accuracy tropospheric refraction corrections based on weather data.

B. GPS Error Model

The various contributors to GPS measurement errors were modeled and then simulated to assess their impact on the user segment performance. Although this model applies to a translator-based user segment, it can be used for receivers by taking the receive time and location to be coincident with the translation time and location.

The GPS range measurement is modeled as

$$\begin{aligned} R^i(t_k) = {} & r^i(t_k) + \underline{S}^i(t_k^{*})^T C_{RH}^i(t_k^{**})\, \underline{X}_P^i \\ & + (t_k^{**} - t_o)\, \underline{S}^i(t_k^{*})^T C_{RH}^i(t_k^{**})\, \underline{X}_V^i \\ & + (t_k^{**} - t_o)\, X_{CF}^i + c/10^9\, X_{CP}^i + B^i(t_k)\, X_{TSF}^i(t_k) \\ & + X_{RAI}^i(t_k) + \underline{S}^i(t_k^{*})^T C_{RB}(t_k^{*})\, \underline{X}_{LA} + v_R^i(t_k) \end{aligned}$$

where

R^i is the measured range from the i^{th} satellite to the vehicle to the ground;

r^i is the true range;

t_k is the ground receive time;

t_k^{*} is the vehicle translation time;

t_k^{**} is the satellite transmission time;

t_o is the reference time;

$\underline{S}^i$ is the unit vector from the vehicle to the i^{th} satellite;

C_{RH}^i is the direction cosine matrix from the HLC frame for the i^{th} satellite to the reference frame;

C_{RB} is the direction cosine matrix from the vehicle body frame to the reference frame;

c is the speed of light;

B^i is the tropospheric refraction correction for the i^{th} satellite;

$\underline{X}_P^i$, $\underline{X}_V^i$, X_{CF}^i, X_{CP}^i, X_{TSF}^i, and X_{RAI}^i are per-satellite GPS errors;

$\underline{X}_{LA}$ are global GPS errors;

v_R^i is the range measurement noise for the i^{th} satellite.

The GPS delta range measurement is modeled as follows:

$$\begin{aligned} D^i(t_k) = {} & d^i(t_k) \\ & + [\underline{S}^i(t_k^{*})^T C_{RH}^i(t_k^{**}) - \underline{S}^i(t_{k-1}^{*})^T C_{RH}^i(t_{k-1}^{**})]\, \underline{X}_P^i \\ & + [(t_k^{**} - t_o)\, \underline{S}^i(t_k^{*})^T C_{RH}^i(t_k^{**}) \\ & \qquad - (t_{k-1}^{**} - t_o)\, \underline{S}^i(t_{k-1}^{*})^T C_{RH}^i(t_{k-1}^{**})]\, \underline{X}_V^i \\ & + (t_k^{**} - t_{k-1}^{**})\, X_{CF}^i \\ & + B^i(t_k)\, X_{TSF}^i(t_k) - B^i(t_{k-1})\, X_{TSF}^i(t_{k-1}) \\ & + X_{DRI}^i(t_k) - X_{DRI}^i(t_{k-1}) + X_{DRA}^i(t_k) - X_{DRA}^i(t_{k-1}) \\ & + [\underline{S}^i(t_k^{*})^T C_{RB}(t_k^{*}) - \underline{S}^i(t_{k-1}^{*})^T C_{RB}(t_{k-1}^{*})]\, \underline{X}_{LA} \\ & + X_{GR}^i(t_k) + X_{SR}^i(t_k) + v_{AC}^i(t_k) - v_{AC}^i(t_{k-1}) \end{aligned}$$

where

$D^i(t_k)$ is the measured delta range from the ith satellite to the vehicle to the ground over the interval $(t_{k-1},t_k]$;

$d^i(t_k)$ is the true delta range;

X_{DRI}^i and X_{DRA}^i are per-satellite GPS errors;

X_{GR}^i and X_{SR}^i are residual general and special relativity effects;

$v_{AC}^i(t_k) - v_{AC}^i(t_{k-1})$ is the one-step anticorrelated delta range measurement noise for the ith satellite; $v_{AC}^i(t_k)$ is white and Gaussian.

The GPS errors X_n^i and X_n (where n=TSF, LA, etc.) are assumed to be constants, random constants, or random variables from a first-order Gauss-Markov process.

C. Flight Testing Inertial Navigation Systems

To estimate inertial navigation system (INS) errors the INS telemetry is processed with the GPS measurement data to generate observations that are functions of the INS errors and the GPS errors. Specifically, the corrected GPS range and delta range are differenced with the equivalent quantities as indicated by the INS under test. These INS-indicated ranges and delta ranges are determined by using integrated accelerometer data and the satellite ephemerides. The GPS minus INS-indicated ranges and delta ranges are used as the observations for a Kalman filter. The Kalman filter state vector contains an element for each modeled INS and GPS error.

III. GPS User Segment Performance Measures

A. General Performance Measures

The performance of a GPS user segment, including its ability to achieve user objectives, can be quantified using various measures. Measures of the ability to meet user requirements are application-specific. On the other hand, measures of performance at lower levels in the system design can be defined without reference to the specific application.

The GPS three-dimensional measurement accuracy can be quantified by a six by six position/velocity error covariance matrix. Here, position and velocity measurements are assumed to be independent, and therefore this accuracy can be expressed instead as two smaller matrices, each three by three. These GPS position and velocity error covariance matrices P_{POS} and P_{VEL} are calculated by propagating the GPS error variances into position/velocity space.

Because P_{POS} and P_{VEL} are matrices and therefore rather unwieldy, a scalar representation of measurement accuracy derived from them, known as the spherical error probable (SEP), is used instead. The SEP is defined as the 50th percentile probability radius. One SEP each can be calculated from the position and velocity covariance matrices; smaller SEPs indicate better GPS performance.

The GPS one-dimensional measurement accuracy can be expressed as two (scalar) standard deviations, one each for range and delta range. These one-dimensional accuracies are calculated by propagating GPS error variances into range and delta range space. Smaller numbers represent better performance.

The GPS satellite geometry is usually quantified by the Geometric Dilution of Precision. Because the completion of the GPS constellation will mean uniformly good geometry, this study did not vary the assumed satellite geometry; a full constellation was used in the simulations.

B. Performance Measures for INS Flight Testing

Several different measures can be used to quantify the ability to estimate INS errors given the GPS data. One important measure is the total estimation uncertainty. This information is produced by the filter in the form of a large covariance matrix, a square matrix with a side dimension equal to that of the filter state. Because the uncertainty in this form is very unwieldy, a preferable measure is a circular error probable (CEP) based on it. This scalar is produced by propagating the state space error covariance matrix into impact space and then calculating a 50th percentile radius.

IV. GPS User Segment Design Analysis

An analysis of a GPS user segment was performed to determine the effects on performance of the design parameters described in Section II; the results of the analysis are presented in this section. These results can be used to determine the basic design parameters for a GPS user segment needed to achieve a desired performance.

Four fundamental design parameters were varied in the analysis: the code type (C/A or P), the number of frequencies (single or dual), the measurement correction scheme (coarse or fine), and the antenna phase calibration error standard deviation (from 20 to 80 degrees in ten degree increments). Four user segment configurations, representing various combinations of code type, frequency usage, and measurement correction scheme, were studied. Furthermore, the antenna phase calibration error was varied for one of the configurations. Figures 2 through 6 show the results of the analysis.

The one-dimensional results (Figures 2 and 4) do not depend on either the vehicle motion or the specific user application, other than the assumption that conditions permit the user segment to produce useful measurements. The three-dimensional results (Figures 3, 5, and 6) depend on the relative motion between the vehicle and the GPS satellites. The analysis considered a missile on a 4000 mile trajectory and nominal satellite coverage. Figure 6 is for the specific case of GPS as a trajectory reference for evaluating inertial navigation system errors.

Figures 2 and 3 contain the one- and three-dimensional position accuracies for the four configurations. Figures 4 and 5 present the one-dimensional range rate accuracies and the three-dimensional velocity accuracies. The largest effects on GPS measurement accuracy are the code type, which establishes the range resolution, and whether a second frequency is used for ionospheric corrections. Range rate measurements with coarse corrections also contain large residual refraction errors during the first 100 seconds of flight, within the troposphere. As seen in Figure 5, the antenna phase calibration error also has a significant effect on range rate for the dual frequency configurations; otherwise, its contribution gets swamped by the ionospheric refraction error. Note that the antenna phase error does not affect the range measurement (see Section II.B).

Figure 6 shows the effects of the user segment configuration on the ability to estimate the total INS navigation error. Refraction errors (ionospheric for the L_1 only configuration, tropospheric for the coarse correction case) are seen to degrade the ability to estimate the total error due to the INS. On the other hand, the antenna phase error is important only if the measurements are derived from dual frequency P code using fine corrections.

V. Summary

The performance required of a GPS user segment depends on the application-dependent objectives. The performance is achieved by appropriate design of the measurement calculation scheme, the antenna, and the receiver or translator. Performance measures can be defined at various levels; each level takes into account various components of the overall application. The top level measures presented here are peculiar to the specific application of GPS as a navigation reference for testing INSs, but the other measures are not. Therefore, the one- and three-dimensional accuracy data presented here can be used to design GPS user segments for a wide variety of applications.

The results of this study indicate that the ability to track P code on two different frequencies is the most critical aspect of GPS user segment design. In addition, the extra effort required to perform fine data corrections, especially tropospheric refraction corrections, results in a significant improvement in GPS accuracy. Antenna phase calibration is critical only if dual frequency tracking is used.

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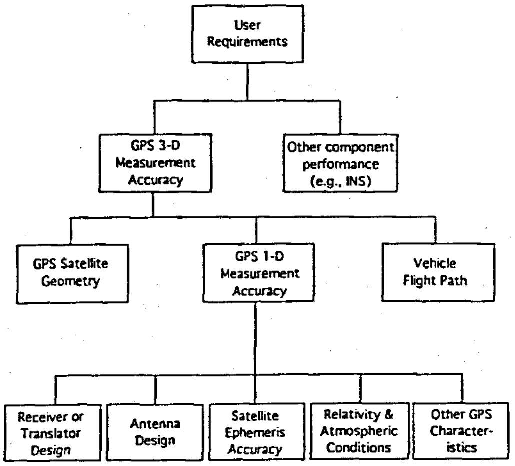

Figure 1 - User Segment Design

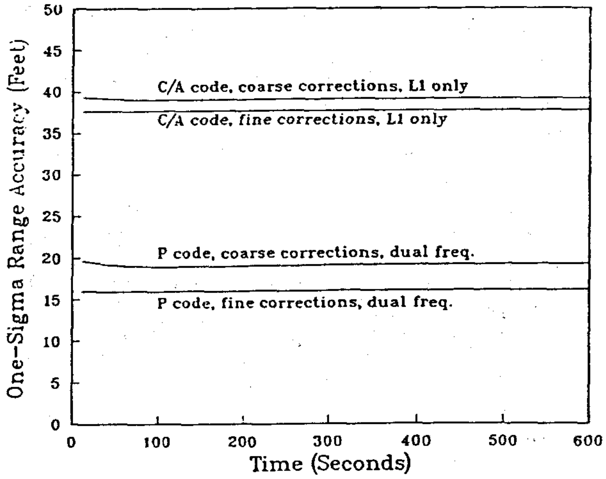

Figure 2 - GPS Range Measurement Accuracy

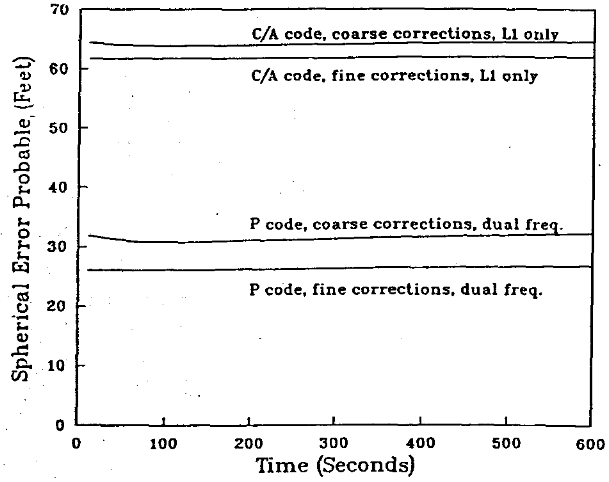

Figure 3 - GPS Position Spherical Error Probable

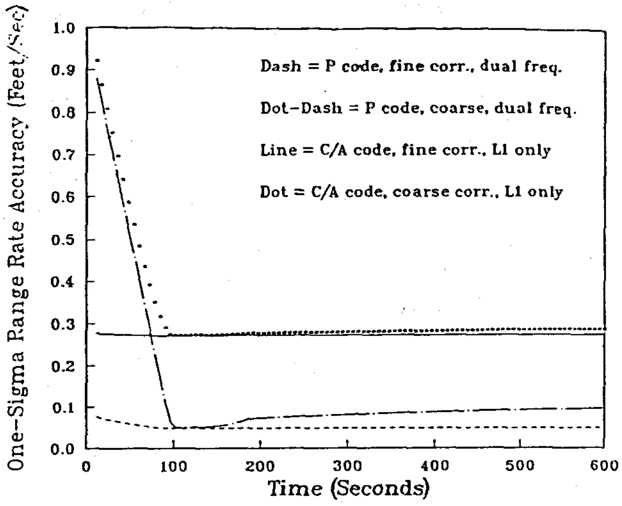

Figure 4 - GPS Range Rate Measurement Accuracy

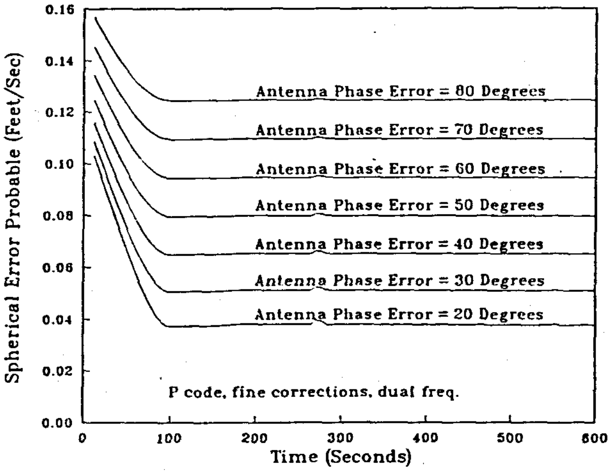

Figure 5 - GPS Velocity Spherical Error Probable

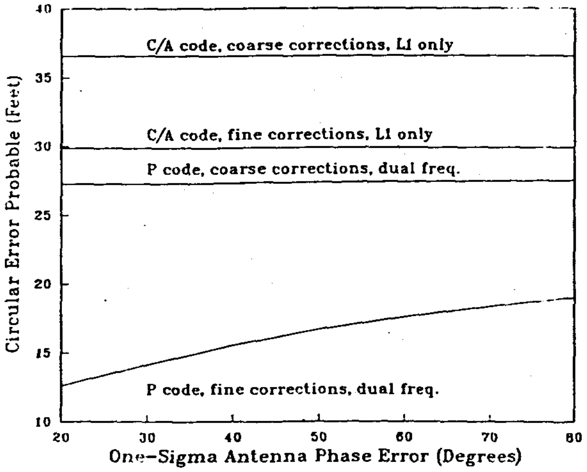

Figure 6 - Total INS Estimation Error