Application of GPS to Hybrid Integrated Ranges and Simulations

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ABSTRACT

GPS user equipment has matured and is now available to support the use of live players in integrated ranges and simulations. P-code GPS provides true WGS-84 based coordinate information anywhere in the world at any time and to accuracies at the 5 ft $(1s)$ level (demonstrated in high dynamic aircraft using differential P-code GPS). C/A code GPS shows lower accuracy and is especially vulnerable to multipath degradation over water.

In supporting networked ranges with simulations, GPS is directly applicable to the dead reckoning requirements of the Distributed Interactive Simulation (DIS) community. DIS dead reckoning provides the capability of much reduced data rates in recovering TSPI information from platforms. The on-board state vector for an integrated GPS/Inertial Reference Unit provides accurate position, velocity and acceleration as well as attitude and attitude rate information so that dead reckoning thresholds can be both position and attitude driven. A simplified analysis is presented in the paper to derive dead reckoning update rates from the G loading levels of various player dynamics. Also, information is provided which results in word length requirements for GPS-based state vector information for transmission over minimum word length DIS Field Instrumentation Protocol Data Units (PDUs, which are the data block formats). The coordinate frame problem in use of GPS-based state vector information from fixed ranges is also addressed, showing that the use of a local geodetic frame is preferable to the use of an earth centered earth fixed frame, in that it is more efficient of network PDU word length.

KEY WORDS

GPS, Global Positioning System, Ranges, Distributed Interactive Simulation, Protocol Data Units, PDU

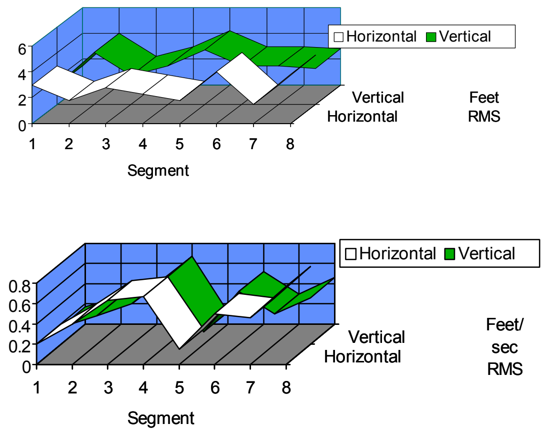
INTRODUCTION

The Global Positioning System (GPS), which is now operational, consists of a network of 24 satellites which provide true WGS-84 based three-dimensional position and time on a continuous basis with world-wide coverage [1,2,3]. Although the overall and usually quoted GPS position accuracy is 16 meters (52.5 feet) SEP (Spherical Error Probable), experience in most applications has been considerably better than this. During the Desert Storm operation from 15 January to 3 March 1991, long term averages over 11,000 navigation solutions showed the average SEP to be 8.3 meters [3] (27.2 feet), rather than the 16 meter specification. With differential GPS [4], which uses a ground reference receiver to remove common mode errors between the reference station and the user (such as satellite orbit and clock errors, and the common mode portion of ionospheric errors), errors of 2 meters or less are routinely achieved.

GPS therefore provides an invaluable tool in instrumenting live platforms on ranges. In addition to the high accuracies, operation is achieved on high dynamic platforms at G loads to 8 Gs. For high dynamic platforms, the GPS receiver is best integrated with an inertial reference unit. GPS and inertial systems are highly synergistic; the GPS removes the troublesome biases of low cost/low quality inertial systems, and the inertial system carries the GPS receiver through high dynamic maneuvers and temporary signal blockages caused by shadowing of the antennas.

Typical accuracies of P-Code differential GPS in a high dynamic platform using differential method one [4], which is by far the best because it accounts for rapid satellite switching in high dynamic maneuvers, are shown in figure 1, which shows horizontal and vertical position and velocity errors in both F-15 and F-16 flight tests [5]. These particular flight tests were conducted by the Tri-Service GPS Range Applications Joint Program Office (RAJPO) on the High Dynamic Instrumentation Set (HDIS) developed for that program by Interstate Electronics Corporation.

Absolute accuracy test results of P-Code GPS are shown in figure 2. The dynamics in these tests covered the full range up to 8 Gs in the various maneuvers used with intermittent satellite visibility caused by antenna shadowing. Ground truth was provided to 2 ft. accuracy at Eglin Air Force Base by a truth system consisting of cinetheodolites, laser ranging, FPS-16 radars and aircraft inertial navigation systems.



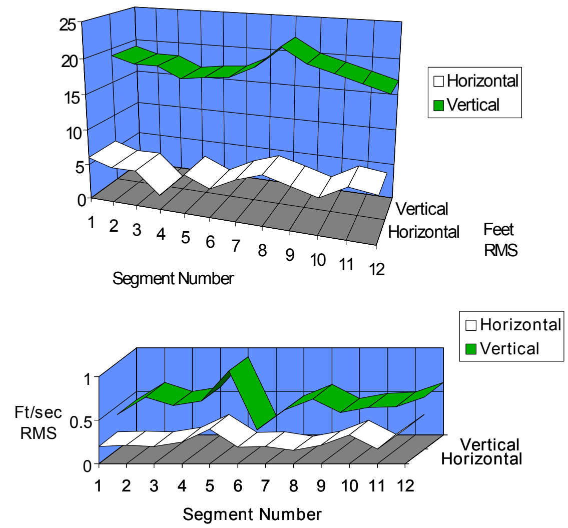
SEGMENT KEY

1. STRAIGHT & LEVEL
2. FIGURE EIGHT CW
3. TWO CIRCLES CW
4. CUBAN EIGHT
5. STRAIGHT & LEVEL
6. CLIMB & DIVE
7. FOUR POINT ROLLS
8. RACE TRACK

ERROR SPECIFICATIONS

HORIZ POS - 6 FEET RMS   HORIZ VEL - 1.6 F/S RMS
VERT POS - 12 FEET RMS   VERT VEL - 2.7 F/S RMS

Figure 1. Flight Test Results [5] for P-Code differential GPS with inertial aiding



SEGMENT KEY

1. STRAIGHT & LEVEL
2. FIGURE EIGHT CW
3. TWO CIRCLES CW
4. STRAIGHT & LEVEL
5. RACETRACK CCW
6. STRAIGHT & LEVEL
7. FIGURE EIGHT CW
8. TWO CIRCLES CCW
9. STRAIGHT & LEVEL
10. STRAIGHT & LEVEL
11. FIGURE EIGHT
12. TWO CIRCLES CW

ERROR SPECIFICATIONS

HORIZ POS - 21 FEET   HORIZ VEL - 1.6 F/S
VERT POS - 35 FEET   VERT VEL - 2.7 F/S

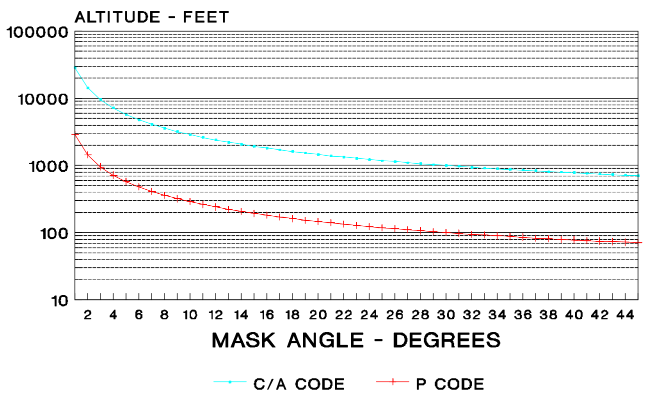
Figure 2. Flight Test Results [5] for P-Code absolute GPS with inertial aiding

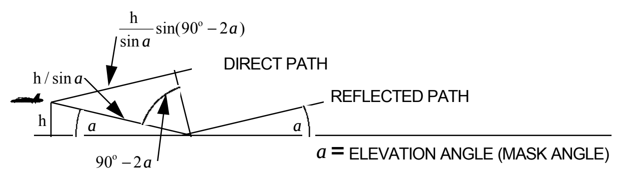
A very high accuracy differential GPS technique that is being developed for commercial aviation use is kinematic GPS, which relies on double-differenced carrier-phase differential measurements and achieves even higher accuracy than the code-phase differential GPS results shown above. To date, flight tests of this technique have been applied to low dynamic aircraft during landing. Application of the technique to range use has yet to be done.

APPLICATION TO INTEGRATED RANGE AND SIMULATION SYSTEMS

The above test results are all for P-code GPS. C/A code GPS has lower accuracy, because of the 10 times longer code chip duration, selective availability, lack of a two frequency ionospheric correction, and because of multipath. In the case of multipath, which is especially a problem in low altitude operations over water, C/A code suffers from multipath within the correlation peak for satellites with significantly high elevation angles. Figure 3 shows an analysis and plot of altitude vs. elevation angle limits at which multipath occurs within the code chip for both

C/A and P-code GPS. This shows that multipath can be a severe problem for low altitude operations, especially over water. For instance at 1000 feet altitude, multipath occurs within the main correlation peak up to 30 degrees elevation for C/A code, and only up to 3 degrees elevation at P-code. The mask angle for P-code can therefore be safely set much lower and still avoid multipath. This is also important at high latitudes where satellite elevation angles are low.





• Path Length Difference $= \frac{h}{\sin a} - \frac{h}{\sin a}\sin(90^\circ - 2a) = \frac{h}{\sin a}\left[1 - \sin(90^\circ - 2a)\right]$

• To determine h & a vs chip length, set

$$\text{Chip Length} = \frac{h}{\sin a}\left[1 - \sin(90^\circ - 2a)\right]$$

$$h = \frac{(\text{Chip Length})\ \sin a}{\left[1 - \sin(90^\circ - 2a)\right]}$$

• For Altitude less than this, multipath occurs within code chip

Figure 3. Multipath for C/A Code extends to higher elevation angle and altitude

The way in which GPS will be used in large-scale integrated range and simulation systems is currently being defined by key programs such as JTCTS and MAIS. An effort to develop standards for these applications is being carried on by the Field Instrumentation Working Group which is a part of the Distributed Interactive Simulation (DIS) standards development activity. Currently, a draft standard for field instrumentation use has been prepared and is in review. The key driver in developing these standards is minimizing the data that needs to be sent on the data link, since the data link has proven to be the main bottleneck in instrumenting large training exercises.

DIS Dead Reckoning Algorithms

A key part of the DIS standards is a technique which is very useful with regard to efficiently loading a data link with time-space-position information (TSPI). This algorithm is shown in the block diagram of figure 4. The GPS receiver output, integrated with an inertial reference unit so it periodically measures both position and attitude, is compared with the output of a "dead reckoning model". This model is a time extrapolation of previous outputs of the GPS receiver $(x = x_o + v_o t + a_o t^2)$.

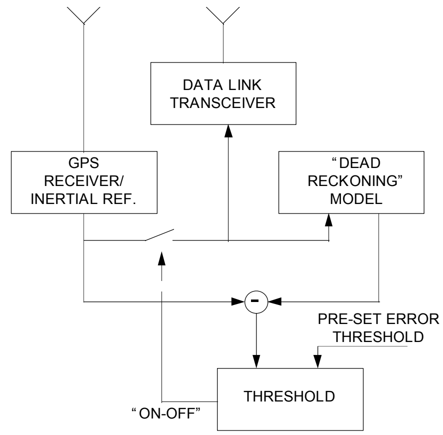


Figure 4. Dead Reckoning Algorithm for efficiently loading a data link with TSPI

When the error between the GPS -measured position (and attitude) and the extrapolated position (and attitude) exceeds some threshold level (like 10 feet or 0.02 radians), the GPS measured state is input to both the data link and the dead reckoning model. At the distant data link receiver terminal, a similar dead reckoning model is also updated with a new state vector. The two dead reckoning model errors are thereby corrected and they can then run for a while at acceptable error levels until again updated. The algorithm thus provides a means of minimizing data link loading, according to the activity level of the aircraft. When the aircraft is flying with minimal acceleration, the extrapolation can run much longer than when it is going through high-dynamic maneuvers. It therefore provides a means of taking advantage of the fact that most of the aircraft in an exercise are not maneuvering, and can be sampled at a low rate, and those that are in high dynamic maneuvers are automatically sampled at a high rate.

This algorithm is ideal for weapon scoring systems because it allows supporting very high fidelity weapon simulations by closing down the error threshold for certain exercises requiring high precision such as no-drop-bomb-scoring (NDBS). It is even possible to close some portions of the error down more than others, such as closing down the vertical error more than others for NDBS, since NDBS is particularly sensitive to vertical error. The possibility also exists of closing the error threshold down only when required, such as during weapon launch, and when the aircraft is paired as a target.

One of the key questions with regard to the use of this algorithm in a large scale system is how fast it will update vs. platform dynamics and threshold level settings. The answer to this question heavily influences data link requirements, and also affects instrumentation accuracy levels. In order to provide an easily analyzable case to demonstrate results and to provide some upper bounds on update time or "rules of thumb" as a guide for system design, the aircraft (or other platform) can be assumed to be flying in circular turns at a constant G loading. Sections of circular turns are common in aerobatic maneuvers. Even though a complete circle is not flown, small sections of circles are representative of sections of aerobatic maneuvers, since aircraft are constrained by the laws of physics to fly in a circular path constrained by G loading. More complex maneuvers can be considered as being made up of sections of circular turns. Other platforms, such as ships, also commonly make circular turns. By using this simple maneuver as a basis for analysis, it is possible to easily derive the upper bounds for update times for various dead reckoning models versus their G loading and threshold values. In the case of aircraft (and ships), the roll angle is ignored in this analysis, and only pitch and yaw angles are considered. Also, angle-of-attack and angle-of-sideslip are assumed constant, such as would occur in a steady-state circular turn. Although these assumptions may appear to limit the validity of the analysis, they allow arriving at first-order approximations which have been shown to be consistent with flight simulator test results, although somewhat optimistic, since they are more in the nature of bounds.

Using this approach, these update times were calculated as outlined in appendix A and are presented in figure 5 for various G loadings, position thresholds and attitude thresholds.

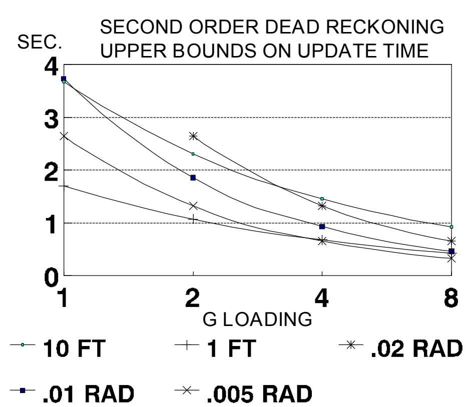


Figure 5. TSPI Update Time Bounds for Position and Attitude Threshold
Second Order Dead Reckoning

An interesting comparison of these results can be made with data from the Northrop Corporation Flight Simulation Laboratory [6]. Using thresholds of 9.1 feet in position, 3 degrees in attitude, and second order dead reckoning, they obtained an average of about 1.2 updates per second for second order dead reckoning in high dynamic air combat scenarios, and an average of 2.42 updates per second for the same scenarios with first order dead reckoning.

It would be beneficial to the range community if further similar studies were done by organizations doing dead reckoning in large scale simulations. This would allow further refinement of these bounding update time levels.

TSPI Word Length Requirements

Considerable effort has been expended by the Field Instrumentation Working Group of the DIS in the past two years in attempting to reduce the PDU (Protocol Data Unit) sizes for field instrumentation. The standard DIS PDUs are much too large to be feasible for range data link use. For example, the standard DIS entity state PDU, which defines the state vector of a platform, contains 64 bit position and velocity words. In this regard, the requirements of integrated GPS/Inertial systems for word length should be taken into account, because these are the TSPI sensors that will be used for the indefinite future in these systems. As shown in the above test data, instrumentation accuracies of close to 1 foot in position and close to 0.1 ft/sec in velocity are achievable. There is then no point in much more word length in the PDUs than that which will support 1 foot instrumentation. Attitude accuracies of 0.1 to 0.2 degrees are achieved by these same instrumentation systems, which should set the resolution of the attitude information in the DIS PDUs. Assuming maximum values such as would be required for a training system such as JTCTS, the word lengths shown in table 1 result from these instrumentation accuracy levels. It should be noted that these word lengths are much less than those in the current DIS standard.

Table 1. TSPI Word Length Requirements for a typical range application

Full Scale Values	Resolution of LSB	Word Length Required
X,Y - 2761 nmi. =16777216 ft.	1 foot	24 bits
Height - 65536 ft.	1 foot	16 bits
Velocity - +/-3277 ft/sec	0.1 ft/sec	16 bits
Acceleration - +/- 10 Gs	300 uG ~ .01 ft/sec2	16 bits
Attitude - 360 degrees	0.05 degree	13 bits

The Field Instrumentation Working Group of the DIS has proposed a flexible format of "Profiles" for the field instrumentation PDUs [7] which would have the flexibility to support variations in applications dictated by various ranges. This would be implemented by table-driven software where the profiles for each application provide the control for parsing the PDU data. With this approach, the use of word lengths no longer than the instrumentation will support should be possible.

Coordinate Frames for TSPI

The choice of coordinate frame for use in the field instrumentation PDUs also affects the number of bits required in the PDUs. For a purely surface-based exercise, there is no need to send height information, since the position coordinates provide all of the required information. Even for aircraft, fewer bits are required for instrumenting height above a range than the horizontal dimensions of the range, as seen in table 1. In comparing the use of ECEF coordinates with geodetic coordinates, studies have shown[8] that for a hypothetical 155 x 155 NM x 65000 ft range considered, 55 bits are required (for 4 ft resolution) for the three coordinates of position for translated ECEF coordinates, regardless of whether 2-dimensional or 3-dimensional information is required. For translated geodetic coordinates, 51 bits are required for the three position coordinates if height information is required (3-dimensional case), and only 37 bits are required if height information is not required (2-dimensional case). In the 2-dimensional case, velocity and acceleration state bit requirements are also significantly reduced when geodetic coordinates are used, since no height terms are necessary. This is not to say that ECEF or some other coordinate frame is not used internally for computation. ECEF coordinates are simply not the most efficient frame to use for data transmission.

CONCLUSIONS

The GPS satellites are now in place, the user equipment is available, and the DIS is proceeding to define the Field Instrumentation PDUs. The pieces are coming together for the next generation of integrated range and simulation systems. With coordination of efforts in the communications arena and open architecture real-time programmable processing, the glue of GPS and DIS provide the path to common range instrumentation. Once instrumentation is common, ranges can become multi-functional and provide tremendous cost and time savings. Transits from one range to another could be reduced. There is even potential for common test and training exercises.

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APPENDIX A
TSPI UPDATE TIME BOUNDS FOR DEAD RECKONING

To derive the update times for the dead reckoning algorithm, the aircraft is assumed to be flying at a constant airspeed, and to be making turns having various G loadings. In these circular turns, assume the position of the aircraft to be described by the vector

$$\bar{\mathrm{r}} = \mathrm{R}(\cos wt\,\bar{\mathrm{i}} + \sin wt\,\bar{\mathrm{j}}) = \mathrm{R}\bar{r}$$

where $\bar{\mathrm{r}} =$ aircraft position vector
$\bar{r} =$ unit radius vector
$\bar{\mathrm{i}}, \bar{\mathrm{j}} =$ unit x and y vectors
$\mathrm{R} =$ turning radius
$w =$ rate of turn (radians/sec)

The velocity vector is the derivative of this, or

$$\bar{u} = w\mathrm{R}(-\sin wt\,\bar{\mathrm{i}} + \cos wt\,\bar{\mathrm{j}}) = \mathrm{V}\bar{n}$$

where $\bar{n} =$ unit velocity vector
$\mathrm{V} = w\mathrm{R}$

The acceleration is, by differentiating again,

$$\begin{aligned}\bar{a} &= -w^2\mathrm{R}(\cos wt\,\bar{\mathrm{i}} + \sin wt\,\bar{\mathrm{j}}) \\ &= -w^2\mathrm{R}\bar{r} = -\mathrm{A}\bar{r}\end{aligned}$$

where $\mathrm{A} = w^2\mathrm{R} = \mathrm{V}^2 / \mathrm{R}$

The jerk or next derivative is needed, because it is the lowest order rate which is not measured, and therefore contributes the most error. It is

$$\begin{aligned}\bar{V} &= w^3\mathrm{R}(\sin wt\,\bar{\mathrm{i}} - \cos wt\,\bar{\mathrm{j}}) \\ &= \frac{-\mathrm{A}^2\bar{n}}{\mathrm{V}} = -\mathrm{J}\,\bar{n}\end{aligned}$$

The position error due to the jerk will then be

$$e = \frac{\mathrm{J}}{6}\Delta\mathrm{t}^3 = \frac{\mathrm{A}^2}{6\mathrm{V}}\Delta\mathrm{t}^3$$

We can then calculate the update time that the TSPI algorithm will operate at as a result of the position error to be approximately (setting the threshold equal to the position error)

$$\Delta t = \sqrt[3]{\frac{6eV}{A^2}}$$

The algorithm of figure 4 also can operate on an attitude error threshold. In the DIS dead reckoning approach, a combined position and attitude error threshold is used. If either position or attitude error exceeds thresholds, the dead reckoning model is updated.

The attitude of the aircraft is constantly changing in the turn and is represented as the unit velocity vector

$$\bar{n} = -\sin wt\ \bar{i} + \cos wt\ \bar{j}$$

The attitude rate is the derivative of this, or

$$\bar{y} = -w(\cos wt\ \bar{i} + \sin wt\ \bar{j})$$

The second derivative of attitude is then

$$\bar{m} = w^2(\sin wt\ \bar{i} - \cos wt\ \bar{j}) = -\frac{A^2}{V^2}\bar{n}$$

If the attitude threshold is then q_t,

$$q_t = \frac{1}{2}\frac{A^2}{V^2}\Delta t^2$$

the update time that the TSPI algorithm will operate at as a result of the attitude error will be approximately (setting the threshold equal to the attitude error)

$$\Delta t = \sqrt{\frac{2q_t V^2}{A^2}}$$

The update time for the combined position and attitude error threshold criteria will then be the smaller of the two or

$$\Delta t = Min\left[\sqrt[3]{\frac{6\varepsilon V}{A^2}}, \sqrt{\frac{2\theta_t V^2}{A^2}}\right]$$

These update times are calculated and plotted in figure 5 for various G loadings, position thresholds and attitude thresholds.

The use of circular turns at constant G loading provides a simple and convenient analysis tool for dead reckoning models. Update time bounds for specific G loads can be analytically determined, and can be verified by simulation or flight test. With this, the improvement of the second order dead reckoning model can be demonstrated analytically.