Post-Modernization GPS Performance Capabilities

Keith D. McDonald
Sat Tech Systems, Inc., Alexandria, VA

Christopher Hegarty
The MITRE Corporation, McLean, VA

BIOGRAPHIES

Keith McDonald is the President of Sat Tech Systems and Technical Director of Navtech Seminars. He was Scientific Director of the DoD Navigation Satellite Program during the formative stages of the Navstar GPS program. Later, with the FAA, he directed the Aeronautical Satellite Division and managed the satellite applications and technology program. He has also been active in RTCA, preparing guidelines for using satellite systems in aviation, and he received the 1989 RTCA Citation for Outstanding Service. Mr. McDonald also received the 1988 Institute of Navigation's Norman P. Hayes Award for outstanding contributions to the advancement of navigation. He served as President of the ION in 1990-91 and President of the International Association of Institutes of Navigation during 1997-2000.

Dr. Christopher Hegarty received his B.S. and M.S. from Worcester Polytechnic Institute, and his D. Sc. from The George Washington University. He has been with The MITRE Corporation since 1992, most recently as a Project Team Manager. In August 1999, he began a one-year assignment as Civil GPS Modernization Project Lead with the FAA through the Intergovernmental Personnel Act. He was a recipient of the 1998 ION Early Achievement Award, and currently serves as Editor of *Navigation*: *Journal of the Institute of Navigation* and as Co-chair of RTCA SC159 Working Group 1 addressing the 3rd Civil GPS Frequency signal structure.

ABSTRACT

For nearly a decade, recommendations for the modernization of GPS have been put forth by various panels, committees, organizations and individuals. At this time, the definition of the principal elements and characteristics of the modernization program is nearing completion. Institutional and funding arrangements for implementation of the modernization initiatives also appear to be on track. It is now possible and it appears appropriate to address in some detail the performance of GPS as it evolves from its current state into the end-state of present modernization plans. This paper attempts to accomplish this goal.

INTRODUCTION

The current GPS modernization program promises to deliver both the civil and military GPS communities numerous improvements to the core GPS services that have already enabled so many positioning, navigation, and timing applications in many unexpected ways. Civil GPS users, now enjoying a more accurate Standard Positioning Service (SPS) since Selective Availability (SA) has been discontinued, have two new civil signals to look forward to. Military users will soon have new signals as well.

Although a great amount of attention has been paid to the modernization program components, few researchers have yet focused on the performance levels that may be expected in the next two decades as the successive stages of the current modernization program are implemented. This paper attempts to address these incremental performance improvements in sufficient detail to reveal dominant components in error budgets. The paper begins by providing a brief overview of the GPS modernization program.

GPS MODERNIZATION OVERVIEW

An overview of principal activities and planned schedule for the current GPS modernization program is shown in Figure 1 [1]. Currently, the Department of Defense (DoD) is awaiting authorization to proceed (ATP) from one of four Congressional committees (the Senate Appropriations Committee [SAC]) that are required to authorize DoD's recent proposed changes to the GPS program. Figure 1 and the following short GPS program summary (divided into space and control segment discussions) assume SAC approval.

Space Segment

In 1989, Lockheed-Martin (at that time, the General Electric Astro Space Division) was awarded a contract to build 21 "replenishment" GPS satellites (Block IIR). The current GPS program includes retrofitting the last 12 IIR satellites (referred to as "IIR Mod" in Figure 1) to include the capability to broadcast the new military signal on L1 and L2, and also a C/A-code on L2.

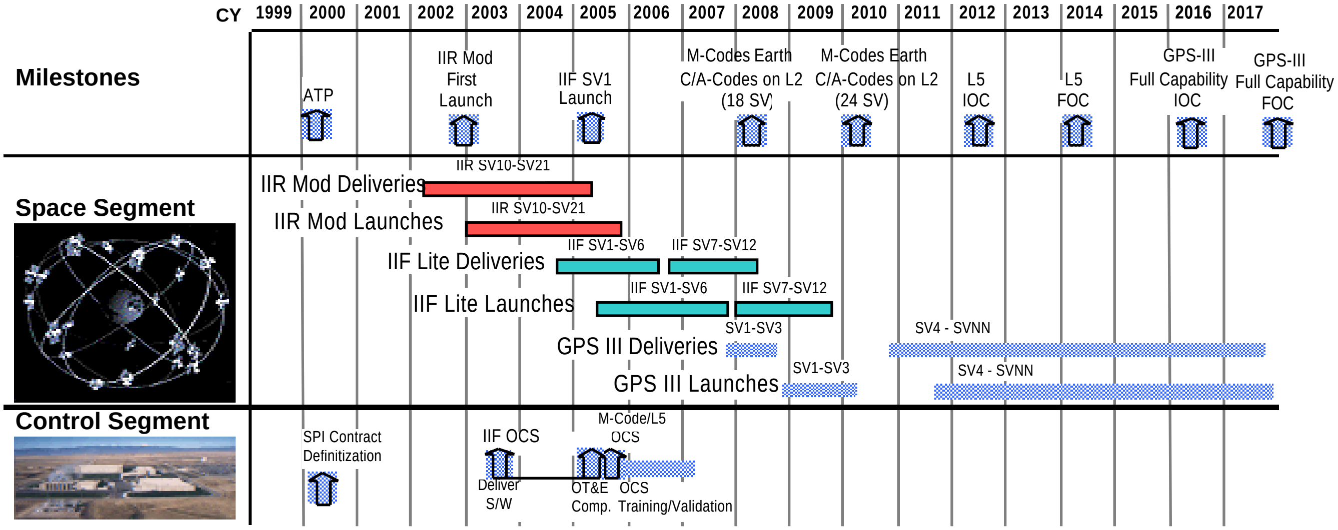


Figure 1. GPS Modernization Schedule

In 1990, Boeing North America was awarded a contract to build up to 33 "follow-on" GPS satellites (Block IIF). The initial contract provided for a purchase of 6 satellites, with options for the remaining 27. In accordance with the current GPS program, the DoD will only exercise options for a total purchase of 12 satellites. A contract change will be negotiated to modify these 12 IIF satellites to include the new military (M-code) signals on L1 and L2 (transmitted by an Earth-coverage antenna), C/A on L2, and the third GPS civil signal at 1176.45 MHz (L5). The modified IIFs are referred to as "IIF lites."

Beyond the IIR and IIF spacecraft, the current GPS program calls for the procurement of GPS III satellites, which will include all capabilities discussed so far for the Block IIFs and additionally will increase the power levels of the M-code signals to increase their anti-jam capability.

As shown in Figure 1, the nominal schedule would result in an initial operating capability (IOC) for the Earth-coverage M-code and L2 C/A code in 2008 (IOC is defined as 18 operating satellites with the new capabilities). Full operational capability (FOC) for these new signals will nominally occur in 2010 (FOC is defined as 24 satellites). IOC and FOC for L5 will nominally occur in 2012 and 2014, respectively. High-power M-code will reach IOC and FOC in 2016 and 2017, respectively. It should be noted that these nominal IOC and FOC dates are based on IIF spacecraft specified mean mission durations (MMDs) for the Block IIR and Block IIFs. Actual IOCs and FOCs may occur much later if experienced MMDs exceed those specified and used in the current planning process. This occurrence is very likely, as has already been experienced with the growth of the MMDs for the Block II/IIA spacecraft.

Control Segment

The GPS operational control segment (OCS) determines the quality of the spacecraft orbital elements and timing data. These are periodically uploaded to the GPS spacecraft memory and then continually broadcast to the users in the GPS data message. This spacecraft position and other data directly affect user accuracy. Moreover, the data is influenced by the update rate (or latency) of the uploads to the GPS space vehicles (SVs) since the data degrades with time relative to the true SV position,. Recent improvements in the OCS have been reported to provide root-mean-square (rms) signal-in-space range errors (SISREs) for Precise Positioning Service (PPS) users at the 1.5-meter level or better.

As shown in Figure 1, the GPS modernization program includes an incremental set of improvements to the OCS, to be led by a single prime contractor under the Single Prime Initiative (SPI). Each incremental step adds a new capability, such as will be necessary to operate each new class of satellite (e.g., IIR-M, IIF, and III).

The planned addition of the six (or more) ground stations of the National Imagery and Mapping Agency (NIMA) to the GPS tracking network will substantially improve the quality and timeliness of the GPS tracking measurements of the OCS as well as the related computed parameters. More frequent uploads to the GPS spacecraft are also planned. In the 2000-2010 period, it is expected that the near term sub-meter ephemeris accuracy for the GPS tracking network will improve to the decimeter range.

STAND-ALONE GPS PERFORMANCE EVOLUTION

Present Standard Positioning Service Performance

Until recently, users of the GPS Standard Positioning Service (SPS) were subject to performance limitations due to Selective Availability (SA). U.S. policy, from June 28, 1983 [2] to May 1, 2000 [3], has been to specify a limitation on GPS accuracy of 100 meters horizontal (95 percent). As SA was actually implemented, most users experienced a 95 percent horizontal accuracy closer to 60-80 m [4].

Although SA could have been realized as a combination of perturbations of the satellite clock (dither) and broadcast satellite positions (epsilon), apparently only dither was normally implemented. Ranging errors due to SA have been well characterized statistically with zero-mean and a root-mean-square (rms) value of 23 m [5], making SA the dominant error source for SPS users. An error budget for SPS with SA is shown in Table 1 (using input parameters from [6, 7]).

Table 1. SPS Horizontal Accuracy Model with Selective Availability

Parameter	Value (m)
Signal-in-space ranging error (rms)	3.1
Residual ionospheric errors (rms)	7.3
Selective availability (rms)	23.0
Residual tropospheric errors (rms)	0.2
User equipment errors due to noise and multipath (rms)	0.7
TOTAL UERE* (rms)	**24.3**
Typical HDOP**	1.2
Horizontal Accuracy (95%)	**58.3**

*UERE = User Equivalent Range Error
**HDOP = Horizontal Dilution of Precision

SPS Performance since SA Discontinuance

On May 1, 2000, the United States announced that SA would be discontinued and removed it. With SA discontinued, the dominant error source of the SPS is the residual ionospheric error after application of the single-frequency correction algorithm [4, 8]. The residual errors of the single-frequency correction algorithm have been well characterized in terms of their marginal distributions. The 95 percent ranging error for a satellite directly overhead (vertical residual delay) varies greatly, depending on the total electron content (TEC) along the signal path through the ionosphere, which in turn varies depending on factors including time of day, phase of the roughly 11-year solar cycle, and level of geomagnetic activity [8].

Assuming the residual ionospheric errors are independent from satellite to satellite (an assumption that will be analyzed), a typical horizontal error budget for the SPS is presented in the left-hand "values" column in Table 2. Although the resultant 95 percent horizontal accuracy value of 19.1 m compares well with similar tables presented in [4, 7], it does not compare well with the accuracies reported by various organizations since SA has been discontinued. Reported 95 percent values are more accurate by about a factor of three.

Contrasting the 19.1 m 95 percent horizontal positioning value from Table 2 with the sub-ten-meter 95 percent errors routinely observed by many SPS users in the past few months, it is apparent that treating the residual ionospheric errors as independent from satellite to satellite is not a very good assumption. The fact that 2 _ HDOP _ UERE is a poor estimate of the 95 percent horizontal positioning accuracy for the SPS without SA (due to correlated residual ionospheric errors) was previously noted in [9-11]. The use of a 3.1 m rms signal-in-space ranging error in Table 2 (from [6]) is also pessimistic since it is based on low-level specifications from [12] that are exceeded in reality.

The right-hand "values" column of Table 2 uses less pessimistic values for SISRE, and assumes that the correlation of the ionospheric errors provides an effective reduction to about 2.0 m for this component. As shown, this results in a horizontal accuracy of about 7 m, a value more consistent with observations.

Table 2. Typical SPS Horizontal Accuracy Model with Selective Availability Off

Parameter	Value (m)
Signal-in-space ranging error (rms)	3.1 2.0
Residual ionospheric errors (rms)	7.3 2.0
Selective Availability (rms)	0.0 0.0
Residual tropospheric errors (rms)	0.2 0.2
User equipment errors due to noise and multipath (rms)	0.7 0.7
TOTAL UERE (rms)	**8.0** **2.9**
Typical horizontal DOP	1.2 1.2
Horizontal Accuracy (95%)	**19.1** **7.0**

To further explore the correlation of residual ionospheric errors between satellites, a limited set of data from the National Geodetic Survey (NGS)'s Continuously Operating Reference Station (CORS) system was examined. Figure 3 illustrates the ionospheric contribution to delay error for a representative day (January 1, 1999) at Point Loma, California (each satellite is represented with a different color). During the evening hours, the delay is in the 5-10 m range rising during the daytime hours to the 10-20 m level, with a relatively small number of measurements extending above 20 m. It is unknown as to the extent the receiver's L1/L2 group delay bias influenced this dual-frequency "truth" source.

As shown in Figure 4, using the standard ionospheric model algorithm, the various SV residual error values vary with time after correction. The residual delay errors appear to have a 2σ distribution around their mean of about 1-2 m (after considering that most of the dispersion visible in Figure 4 is due to measurement noise of the unsmoothed L1/L2 pseudorange measurements that were used). The high correlation of the gross delays for all SV moderates considerably the overall SV error contribution at any given time.

As described in [10], positioning errors do not arise from rms residual ionospheric delay errors, but rather from the variation of the residual errors around their mean value. As illustrated in Figure 4, this variation typically has a relatively modest value (of 1-2 m), even during the ionosphere's highly active daylight hours. The net result is a considerably better 95 percent user accuracy than would be predicted from conventional analysis based on the product of the rms ranging error and twice the applicable constellation dilution of precision (DOP). The ionospheric error correlation may also explain the surprisingly good performance (2-6 m) of military single frequency (L1) Precise Lightweight GPS Receivers (PLGRs) observed during the past several years.

Based on the above considerations, an accuracy of 7 m (or better) for the SPS may be valid and reasonable. Again, it is not the gross value of the ionospheric error that degrades accuracy but the variation of the delay errors around a common mean value (the decorrelation effects). Unfortunately, a study that has considered a statistically significant quantity of residual ionospheric error data has yet to be completed. Until this is accomplished, a high-fidelity analytic model for SPS accuracy is not possible.

SPS Performance with the New Civil Signals

Dual-frequency L1/L2 C/A code users, once a sufficient number of L2 C/A-code capable satellites are in orbit, will obtain nearly as good accuracy as current PPS users. There are two reasons why L1/L2 C/A code service will remain less accurate, however. The first is that the C/A-code's multipath performance is inferior to the P(Y)-code, due to their difference in chipping rate. The second, and not so well known reason, is that C/A-code users will experience signal timing errors due to the fact that GPS time is maintained using L1/L2 P(Y)-code measurements by the OCS.

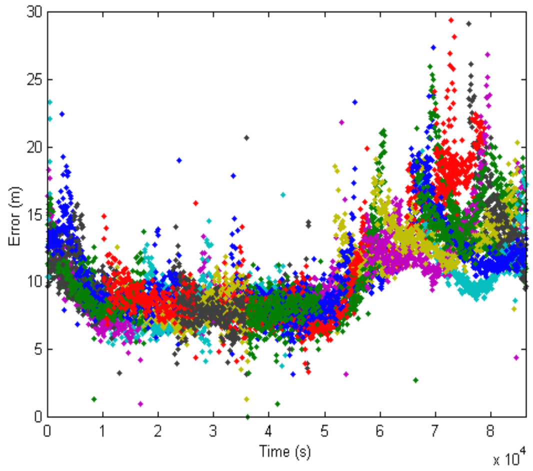


Figure 3. Slant Ionospheric Delay Errors Seen at Point Loma, California on January 1, 1999.

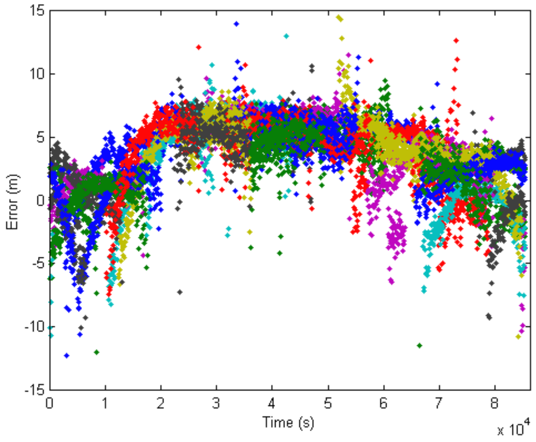


Figure 4. Residual Slant Ionospheric Delay Errors After Ionospheric Model Correction Algorithm

The group delay between the C/A-code and P(Y)-code on L1 is specified to be less than 10 ns, two-sigma [12]. It is unclear from [12] whether the L2 C/A to P(Y)-code transitions have the same specification, and furthermore whether L1 and L2 C/A-to-P(Y) delays are independent or highly correlated.

Table 3 presents a pair of estimates for the horizontal accuracy of the SPS when the C/A-codes on L2 are available. The left-hand column of values is a conservative estimate based on an SISRE of 3.7 m [6], which is dominated by group delay uncertainties (as described above). The right-hand column is a more optimistic estimate based an improved value for SISRE (assuming measures are taken to control group delay uncertainties) and other error sources, and a more realistic value for HDOP. Considering that the civil code will not be available for use until about 2010, these values are believed reasonable.

Table 3. Typical SPS Horizontal Accuracy Model for L1/L2 C/A-Code

Parameter	Value (m)	
Signal-in-space ranging error (rms)	3.7	1.2
Residual ionospheric errors (rms)	0.4	0.2
Selective availability (rms)	0.0	0.0
Residual tropospheric errors (rms)	0.2	0.2
User equipment/multipath (rms)	0.7	0.5
TOTAL UERE (rms)	**3.8**	**1.3**
Typical horizontal DOP	1.2	1.2
Horizontal Accuracy (95%)	**9.1**	**3.2**

L1 C/A-L5 and Precise Positioning Service Performance

Precise Positioning Service (PPS) users have never suffered from SA. Dual-frequency PPS users also have the ability to directly measure ionospheric delays. PPS accuracy is approximately equivalent to what is expected for L1 C/A-L5 dual-frequency users (see Table 4). The L5 signals are not to be available until about 2012-2014, and it is assumed that the values in the right hand column of Table 4 are reasonable. These values are also consistent with the reported capabilities of the military L1-L2 P/Y-code receivers today.

Table 4. SPS L1 C/A-L5 and PPS Horizontal Accuracy Model

Parameter	Value (m)	
Signal-in-space ranging error (rms)	1.5	0.8
Residual ionospheric errors (rms)	0.4	0.1
Selective availability (rms)	0.0	0.0
Residual tropospheric errors (rms)	0.2	0.2
User equipment/multipath (rms)	0.7	0.4
TOTAL UERE (rms)	**1.8**	**0.9**
Typical horizontal DOP	1.2	1.2
Horizontal Accuracy (95%)	**4.3**	**2.2**

DOMINANT ERROR SOURCES

Based on the discussion in the previous section, the following error sources are expected to be of the greatest concern for certain periods within the GPS modernization program:

- Current SPS (single-frequency) – Residual errors due to the ionosphere after application of the single-frequency ionospheric correction algorithm are the dominant error source. As pointed out earlier, although the distribution of the residual errors for a single-satellite are well understood, there is still a great deal to learn about the level of correlation of the residual errors between satellites. Only with a statistical characterization of the joint distribution of the residual errors can analytic models be developed that accurately predict actual performance levels.

- Dual-frequency SPS (L1/L2 C/A) – Theoretically, the dominant error source for L1/L2 C/A users will be due to group delay uncertainties (e.g., C/A-to-P(Y), P(Y)-to-GPS time) [6]. These uncertainties result because GPS time is based on dual-frequency P(Y)-code measurements made by the OCS. The C/A code is not at present monitored, and furthermore, even if it were, the GPS navigation message does not include fields for C/A-to-P(Y) biases. Civil GPS users and advocates are encouraged to further study group delay error sources. Possible solutions include: tighter specifications for the group delay uncertainties, and OCS C/A code monitoring combined with use of reserved fields in the navigation message (if there really are any spare bits that are not used by the military) to broadcast corrections.

- Dual-frequency SPS (L1 C/A-L5) or PPS – The dominant error source for these users will likely be due to signal-in-space ranging errors. Given that SISREs for some satellites have already been observed below 80 cm [11], there is an excellent possibility that the 1.5 m value shown in the left hand column of Table 4 may be greatly diminished. The right hand column assumes a diminished value and indicates the improvement in performance.

DIFFERENTIAL USERS

The previous sections focused on stand-alone GPS use, i.e., GPS without any augmentations. In stand-alone GPS applications, the user equipment receives and uses only the signals received from the constellation of spacecraft to determine user position, velocity, time (PVT) and related parameters. This section looks briefly at the implications of modernization on the differential user.

Over short baselines, GPS modernization improvements will hardly affect code differential GPS (DGPS) accuracy at all. Code DGPS, over short baselines, is currently limited in performance by user equipment and multipath errors, not GPS SISRE errors which are mostly common to the DGPS reference station and user. Short-baseline DGPS users will mostly benefit from the robustness provided by the new civil signals, or for military DGPS users, by the anti-jam capability provided by high-powered M-code signals.

Over longer baselines, DGPS users will benefit from the additional civil signals in that they will be able to compensate for ionospheric errors that are not common between their location and the reference station. Wide-area DGPS users will obtain similar benefits from being able to directly measure ionospheric delays. Although it has been stated in [11] that stand-alone GPS SPS without SA can meet all requirements for aviation through non-precision approach, this view is not shared by aviation experts (see, e.g., [13-14]).

Carrier-phase DGPS users interested in achieving centimeter-level accuracies or better through ambiguity resolution will be greatly assisted by the new civil signals, which will improve wide-laning performance over that currently provided using semi-codeless receivers, and enable tri-laning. Benefits will accrue mostly in terms of minimizing the time required for ambiguity resolution (including reacquisition) and maximizing the probability of correct resolution over short spans (e.g., single-epoch), especially over long baselines.

The new signals that will become available create many more classes of users employing various combinations of civil and military signals. These include C/A-, P/Y-, M, I5-, and Q5-codes and frequencies L1 and L2 for C/A-, P/Y- and M-codes, and the new civil L5 for the I5- and Q5-codes.

All civil users will benefit from the robustness against inteference provided by having multiple frequencies available to them. If interference causes the loss of a single frequency, applications may still continue with only a loss in performance, not a loss in service. For example, a usable ionospheric correction is possible using L2/L5, albeit with less accuracy.

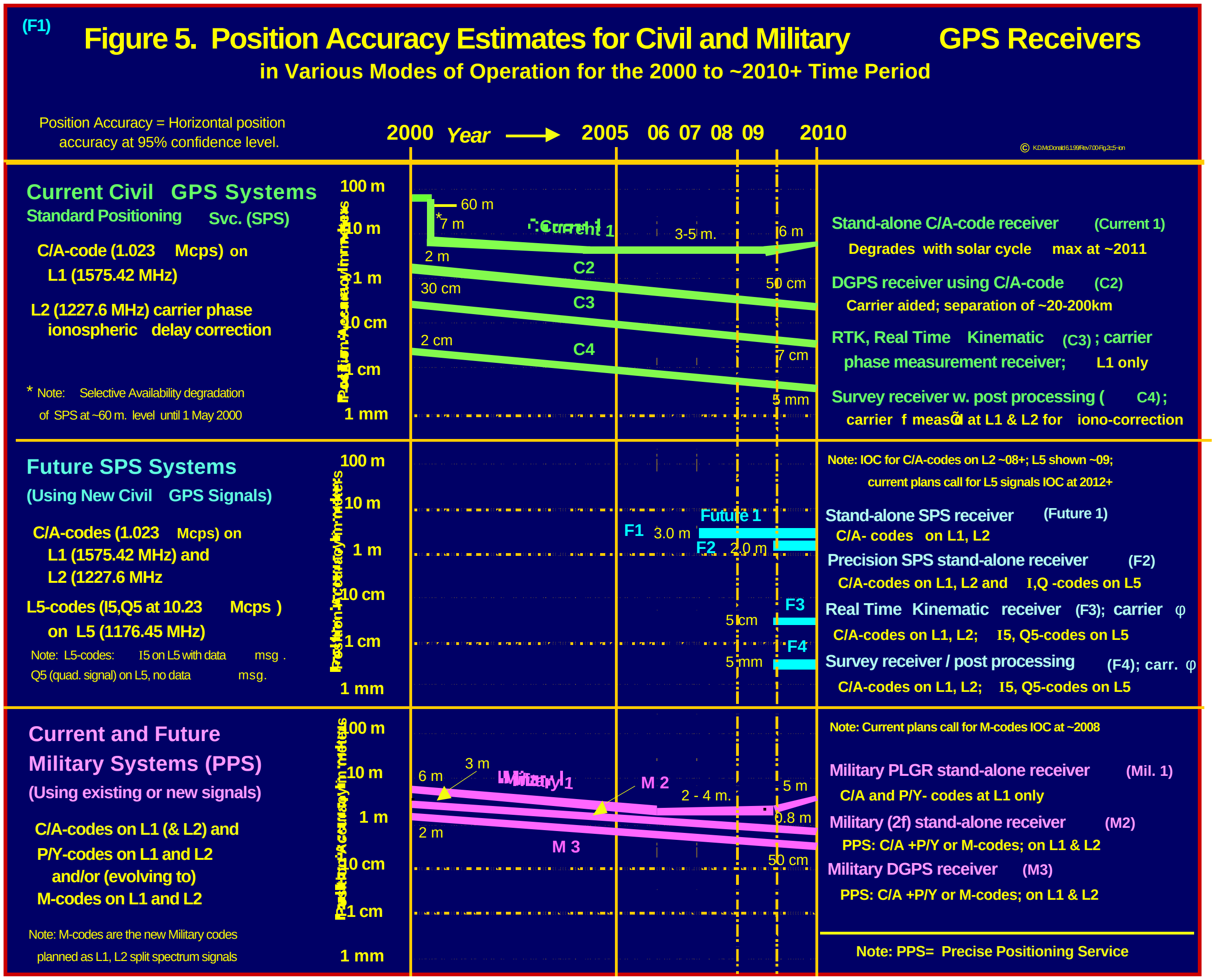
PROJECTIONS FOR THE FUTURE

Figure 5 illustrates the performance that can be expected from the various implementations of GPS receivers representing three principal categories of equipment. The top group of performance curves are for the conventional current civil SPS user equipment. This includes receivers that operate as stand-alone or differential receivers at the L1 frequency using only the C/A-code. The minor exception to this is the use of the “L2 carrier phase” capability for primarily static survey receivers. The sharp improvement in accuracy shown in the figure for the stand-alone receivers indicates the removal on May 1, 2000 of the SA degradation from the signals.

The performance values for the stand-alone SPS receiver are in the 7 m range at this time and should improve somewhat with the decline of the solar cycle during the first half of the decade. Typical DGPS receivers using the C/A-codes are typically performing at the 1-2 m level now. Kinematic receivers using carrier phase measurement methods currently provide accuracy at the 20-30 cm range and clearly will continue to improve. GPS survey equipment currently provides impressive results in the cm. range and also will continue to improve substantially from this in the future. Both kinematic and static survey equipment have improved their capabilities by more than an order of magnitude in the past decade.

The center group of performance curves indicates the future capabilities of the second civil signals placed at L2 and at L5. The use of two separated frequency signals essentially eliminates the effect of the ionospheric group delay on the receiver. Since this is now the largest error component in the GPS error budget, its removal much improves the performance capabilities of the system, as shown. The higher chipping rate (×10) of the L5 codes provides a reduction in code noise and better measurement precision. When combined with the use of the excellent precision of carrier phase measurements, the performance easily reaches the cm and mm ranges.

The lower group of curves in Figure 5 represents the expected capabilities of military receivers. Except for the single frequency (L1) PLGR receiver, current military units all use the P/Y-codes on L1 and L2, and the C/A-codes on L1 for acquisition. The new military signals (the M-codes) employ a new split spectrum signal structure that provides improved measurement precision and simultaneously displaces the signal energy away from the C/A-codes and the P/Y-codes. The new M-codes also allow military users direct access to their secure signals, a significant advantage over their current arrangement. This combination of features provides substantial performance improvements for the military signals resulting in the estimated capabilities shown.


(F1) Figure 5. Position Accuracy Estimates for Civil and Military GPS Receivers in Various Modes of Operation for the 2000 to ~2010+ Time Period

In a few cases, it may appear that an optimistic view is being taken for future GPS capabilities. However, in view of the technological advancements that continue to occur in the GPS development area, it is likely that these estimates may, in fact, be conservative. “It is difficult to make predictions, especially into the future”, as Yogi Berra has observed, but the position accuracy estimates presented are believed to be generally reasonable and based on sound rationale.

SUMMARY

This paper has reviewed the current GPS Modernization program and evaluated the accuracies anticipated for successive stages towards “full-modernization.” Current observed SPS accuracies, better than 7 m horizontal, 95 percent, can only be understood by recognizing that residual ionospheric errors after application of the single-frequency correction algorithm are highly correlated. Civil users can look forward to approximately 2-3 meters 95 percent horizontal positioning accuracy with the advent of L5, as good as PPS users currently enjoy. L1/L2 C/A code users cannot expect quite as good a level of performance, unless group delay uncertainties between

L1/L2 P(Y)-code and L1/L2 C/A code are addressed, either through a tightening of satellite specifications, or through additional corrections provided to the user via the GPS navigation message.

ACKNOWLEDGMENTS

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REFERENCES

[1] Fontana, R., and D. Latterman, “GPS Modernization and the Future,” *Proceedings of IAIN/ION Annual Meeting*, San Diego, California, June 2000.

[2] Anon., *Department of Defense Announces Revised NAVSTAR Global Positioning System Accuracy Policy*, News Release, Office of Assistant Secretary of Defense for Public Affairs, June 28, 1983.

[3] Anon., White House official press release on Selective Availability, May 1, 2000.

[4] Parkinson, B., “GPS Error Analysis,” in *Global Positioning System: Theory and Applications*, B. Parkinson and J. J. Spilker, Jr., Ed., Washington, D.C.: AIAA, Inc., 1996.

[5] van Graas, F., M. Braasch, “Selective Availability,” in *Global Positioning System: Theory and Applications*, B. Parkinson and J. J. Spilker, Jr., Ed., Washington, D.C.: AIAA, Inc., 1996.

[6] Kovach, K., “New User Equivalent Range Error (UERE) Budget for the Modernized Navstar Global Positioning System (GPS),” *Proceedings of The Institute of Navigation National Technical Meeting*, Anaheim, California, January 2000.

[7] Shaw, M., K. Sandhoo, D. Turner, “GPS Modernization,” *Proceedings of The Royal Institute of Navigation GNSS-2000*, Edinburgh, Scotland, May 2000.

[8] Klobuchar, J., “Ionospheric Effects on GPS,” in *Global Positioning System: Theory and Applications*, B. Parkinson and J. J. Spilker, Jr., Ed., Washington, D.C.: AIAA, Inc., 1996.

[9] Stephens, S., *Navigation Improvement with the GPS Single Frequency Ionospheric Time-Delay Algorithm*, Aerospace Technical Memorandum 88 (3476-02)-2, The Aerospace Corporation, El Segundo, California, March 3, 1988.

[10] Greenspan, R., A. Tetewsky, J. Donna, and J. Klobuchar, “The Effects of Ionospheric Errors on Single-Frequency GPS Users,” *Proceedings of The Institute of Navigation ION GPS-91*, September 1991.

[11] Conley, R., and J. Lavrakas, “The World After Selective Availability,” *Proceedings of The Institute of Navigation ION GPS-99*, Nashville, Tennessee, September 1999.

[12] Anon., *NAVSTAR GPS Space Segment/Navigation User Interfaces*, Interface Control Document No. ICD-GPS-200C, Department of Defense, June 2000.

[13] Van Dyke, K., “The World After SA: Benefits to GPS Integrity,” *Proceedings of The Institute of Navigation ION GPS-99*, Nashville, Tennessee, September 1999.

[14] Corrigan, T., et al., *GPS Risk Assessment Study: Final Report*, Johns Hopkins University, Baltimore, Maryland, January 1999.