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GPS in Ten Years

Karl L. Kovach, *ARINC*
Karen L. Van Dyke, *DOT/Volpe Center*

BIOGRAPHIES

Karl L. Kovach is a Senior Principal Engineer with ARINC, Inc. in El Segundo, CA. Karl has over 19 years in various aspects of the GPS program, including 3 years as the Air Force Officer-in-Charge of the GPS Control Segment when it was at Vandenberg AFB, CA (1983-1986). He received his BS degree in Mechanical Engineering from the University of California at Los Angeles.

Karen L. Van Dyke is a member of the technical staff with the Center for Navigation at the U.S. Department of Transportation Volpe Center in Cambridge, MA. Karen is currently conducting GPS integrity studies for the FAA in support of RTCA SC-159. She received her BS and MS degrees in Electrical Engineering from the University of Massachusetts at Lowell.

ABSTRACT

What will GPS look like in ten years? This paper discusses improvements to the overall GPS system planned over the next ten years and examines their impact on system performance for several applications. The Presidential Decision Directive (PDD) released in March 1996 states that Selective Availability (SA) will be turned off within ten years. Efforts have been ongoing over the past year to place a second civilian frequency on the Block IIF satellites. In addition, a program known as the GPS Modernization Effort, or GPS-III, is underway to identify additional enhancements to GPS for the future. Finally, the Air Force is in the process of upgrading the Control Segment, which includes the Accuracy Improvement Initiative (AII).

These enhancements to GPS, combined with improved user equipment expected to be developed over the next ten years, will significantly improve the accuracy, integrity, and availability of the system. For example, removal of SA not only improves the GPS positioning accuracy, but will allow a significant increase in the availability performance of integrity monitoring algorithms such as Receiver Autonomous Integrity Monitoring (RAIM) and Fault Detection and Exclusion (FDE). Upgrades to the Control Segment also will improve the overall integrity of the GPS system.

Will these improvement make GPS good enough in ten years time to be a "stand-alone" Global Navigation Satellite System (GNSS)? For many applications, the answer to this question is a definite "yes". For other more demanding applications, GPS will still need augmentations, but this paper shows these augmentations can be much simpler and less costly than often envisioned.

INTRODUCTION

Think back 10 years ago for GPS. Way back to 1987... It was two years since the final Block I satellite had been launched and still two years until the first Block II satellite would be placed in orbit. There generally were not enough visible satellites to form a position solution and when four or more satellites were visible to the user, it was only for a short period of time. These "visibility windows" opened and closed four minutes earlier each day. The "old timers" will remember waking up at 2 AM to catch the start of the window at 3 AM. Of course, one advantage they had was that these satellites did not have SA on them.

There was not much in the way of a user population. A small number of military receivers and some surveying systems were in existence, along with a few commercial manufacturers with grand ideas for the future. GPS was envisioned for oceanic aviation use and possibly nonprecision approach operations, but certainly never for precision approach!

Between 1987 and 1997, GPS blossomed into a system which has been referred to as the "next utility". Twenty-six Block II/IIA satellites were launched successfully, while many of the Block I satellites significantly outlived their design life of five years, providing the opportunity for users to gain operational experience with the system. In July 1997, the first launch of the Block IIR satellite to replenish the GPS constellation occurred, after losing a IIR to a launch failure earlier in the year.

During this time frame, GPS use has exploded into applications previously unimaginable, ranging from recreational use (hiking, sailing, golfing) to all modes of transportation and more transparent applications such as synchronization of communication networks. Although the military has made great use of the system, most notable during Operation Desert Storm, civilian use has dominated the market.

The problem of not having four or more visible satellites became a rare occurrence, rather than the norm. However, as applications began to push this technology to the limit, new problems arose. Users required more accuracy, integrity, continuity, and availability from the system. For example, receiver autonomous integrity monitoring (RAIM) requires a minimum of five visible satellites for fault detection and six satellites for fault detection and exclusion. This requirement leads to "holes" in the coverage which become significant, lasting an hour or more, for more stringent phases of flight.

In March 1990 SA was turned on, significantly degrading the accuracy of GPS, which angered civilian users of the system and has been a sore spot with them ever since. As a result, differential GPS systems began sprouting up not only to defeat SA, but to provide even greater accuracy by removing ionospheric errors.

The past few years has seen increased civilian input into the operation of GPS and its future capabilities. During 1997, the GPS Modernization program began which is a combined DoD/DoT effort to define near, medium, and long term requirements for GPS. Those providing input on this activity were encouraged to think "outside the box" and not be restricted to the current system's operational characteristics.

What will happen from now until 2007? Of course this is difficult to predict precisely (crystal balls are notoriously prone to give whatever answer is wanted, rather than the truth). Just try to imagine predicting GPS as it exists today, based on its status in 1987. INTEGRITY WARNING: Authors' Opinions may show up at any time!

BASIC PARADIGMS

The Presidential Decision Directive (PDD), issued in the spring of 1996, is a good framework to operate from in examining where GPS will be ten years from now [1]. The basic GPS constellation will still be operated by the DoD and the service will be available free of any direct user charges. The PDD is elaborated on in the 1996 Federal Radionavigation Plan (FRP), spelling out the roles for the DoD, DOT, and Dept. of State (DOS) [2].

By 2007, there will be a combination of GPS regional satellite-based augmentations (SBAS), local area ground-based augmentation systems (GBAS), and special application augmentation systems, as indicated in Table 1. The SBAS systems will consist of the FAA Wide Area Augmentation System (WAAS), the European Geostationary Overlay Service (EGNOS), and the Japanese Multifunction Satellite Augmentation System (MSAS). The SBAS systems are primarily deigned for aviation use, although they may serve other user communities as well.

For aircraft precision approach, local area augmentation systems (LAAS) will be installed, which may include airport pseudolites (APLs). Also, government-provided differential GPS networks will be available to serve the land and marine community with RTCM SC-104 correction data and commercial services, such as broadcasts using the FM subcarrier. These systems already exist today and will most likely be expanded in the future. Other differential networks also are and will be available for special application projects.

Table 1 Regional/Local/Special Augmentations

REGIONAL (SBAS)	LOCAL (GBAS)	SPECIAL APPLICATIONS
WAAS	LAAS & APLs	Geodynamics
EGNOS	RTCM SC-104	Local Survey Nets
MSAS	Commercial Services	Special Kinematic (<1 cm)

There also will be non-GPS based augmentations, such as the Russian GLONASS system and inertial navigation systems. However, complementary U.S. radionavigation systems may not be available. According to the 1996 FRP, Loran will be turned off at the end of 2000, and VOR and ILS will begin to be phased out starting in 2005. This leads to a situation of strong reliance on GPS and essentially placing all of our eggs in the "GPS basket". However, given the strong reluctance of the user community to turn off navigation aids, as witnessed by the recent user conference on Loran, and the demand for back-up systems, it is difficult to imagine that these systems will be phased out without more operational experience with GPS for safety critical functions.

IMPORTANT CHANGES COMING

There are some important changes in the works for GPS. These changes should make GPS better for everyone by 2007. We say "should make GPS better" rather than "will make GPS better" in acknowledgment that our anticipation of these GPS changes is still fundamentally a prediction of the future. No matter how solid the plans for these system changes may seem today, tomorrow is another day and anything can happen.

We can foresee two major possibilities that might derail the anticipated GPS system changes. Realistically, we do not think that either one will come to pass, but both situations are possible. Either or both *could* happen. In keeping with our optimistic outlook for the future, however, we make the following assumptions about the two possibilities *not* happening.

1. We assume the U.S. Congress will continue to fully fund GPS. GPS has to be operated and maintained. GPS satellites eventually will fail and must be replaced. Cutting back to only 18 satellites could save the taxpayers a lot of money (i.e., GP$). This sort of a cutback has happened before. GPS was originally designed as a 24-satellite constellation, but was cut back to 18 satellites plus 3 operating spares in the early 1980's for budgetary reasons (recall "18+3" was the GPS baseline back in 1987). Although cutting GPS back might save GP$, the total economic impact on the taxpayers would surely be a net loss due to additional money that would have to be spent elsewhere (e.g., more robust augmentations).

2. We assume the world will stay at peace (at least suffer no greater level of conflict than at present). We must not let ourselves forget that GPS is still a military system. The PDD [1] reminds us of the fact that "GPS was designed as a dual-use system with the *primary purpose of enhancing the effectiveness of U.S. and allied military forces*". GPS will remain responsive to the U.S. National Command Authorities (NCA). If a hostile force were to use GPS to drop bombs on Washington D.C. (or on Pearl Harbor), then we would certainly expect that GPS characteristics and signals formats might change per NCA direction such that GPS would cease operating for the hostile force. We hope (and explicitly assume) that these sorts of scenarios will remain as nothing more than plots for Hollywood movies. Peacetime GPS operations should be normal GPS operations.

THE FIVE IMPORTANT CHANGES

If we are lucky and the two assumptions in the preceding section hold true (i.e., that bad things will not happen), then our crystal ball leads us to predict that five important changes will take place over the next ten years for GPS. These five important changes are listed in Table 2 and are discussed at greater length below.

Table 2 Five Important Changes

I.	No more SA (SA set to zero)
II.	Second civil frequency
III.	24 SVs plus spares
IV.	30 dB more anti-jam for the military
V.	Better accuracy for everyone (2.5 m SIS URE)

I. SA Set to Zero. This is a very important change, but not a very bold prediction. This change is actually spelled out in the PDD [1] which reads: "It is our intention to discontinue the use of GPS SA within a decade...". Given a 1996 date for the PDD, this means SA will be set to zero no later than 2006. The PDD also calls for an annual determination by the President on the continued use of SA beginning in 2000, thus setting the no-earlier-than date for setting SA to zero.

For civilian GPS users, this change will substantially improve the signal-in-space (SIS) accuracy by instantly eliminating the approximately 24.2 meters worth of pseudorange (PR) error induced by SA (note that 24.2 m is the root-sum-square difference between the SPS SIS accuracy value of 24.6 m 1-sigma and the PPS SIS accuracy value of 4.3 m 1-sigma reported in [3]). For military PPS users, this change offers no benefits.

OPINION: The authors think the setting of SA to zero will occur sooner rather than later, particularly if the world stays at peace.

II. Second Civil Frequency. The addition of a second civil frequency to the next generation of satellites (i.e., Block IIF) is another very important change whose coming is predicted by official Government documents (e.g., [4] and [5]). This second civil frequency will carry a C/A-code signal and navigation message data such that it can serve as a full function backup or alternative to the current L1 C/A-code signal. The exact carrier frequency is not yet known, but should be decided upon by March 1998. Until the second civil frequency C/A-code signal is available, civil access to the L2 Y(P)-code signal using "codeless" techniques has been guaranteed. By 2007, roughly half to two-thirds of the on-orbit satellites should be broadcasting this second civil frequency C/A-code signal.

For civilian GPS users, this change will provide the capability to directly compensate for the PR errors caused by ionospheric delays using dual-frequency measurements. These PR errors are typically the second largest contributor to the SPS accuracy budget after SA. The ability to directly compensate for them will thus substantially improve the received SPS accuracy. For military PPS users, this change provides no improvement since PPS receivers have always been able to track the Y(P)-code signals on L1 and L2 for their dual-frequency ionospheric delay compensation. (Note, however, that some PPS receivers are limited to just L1 operation for cost reasons.)

> *OPINION:* The authors believe that the only suitable second civil frequency for a new C/A-code signal is at L2.

III. 24 SVs Plus Spares. This is perhaps less of a change than an important recognition of the way that GPS constellation sustainment strategy has evolved. The Air Force has committed to maintaining a 24-satellite GPS constellation [6]. To fulfill this commitment, the sustainment strategy has become "launch on expected failure" rather than "launch on need" or "launch on schedule". Under this strategy, replacement satellites are launched before they are actually needed so as to prevent "holes in the coverage" from occurring when the expected satellite failure finally happens. This typically results in there being more than 24 satellites operating in the constellation at any one time.

As an example of this launch-on-expected-failure strategy in action, Table 3 has the "nominal" probabilities of various numbers of satellites operating in the constellation for a launch-on-need strategy alongside the "actual" probabilities of various numbers of satellites, based on the current implementation of the launch-on-expected-failure strategy. The "actual" probabilities in Table 3 are taken from the actual observed on-orbit performance of the GPS constellation over the 750 day period from the internal declaration of Full Operational Capability (FOC) on 27 April 95 until 15 May 1997 (roughly 50 total satellite-years). The probabilities shown in Table 3 only include "bona fide" operating time, where the satellite was both operating normally and there was no "Notice Advisory to Navstar Users" (NANUs) indicating any scheduled satellite downtime.

Anticipatory NANUs tend to be conservative, indicating a larger scheduled satellite downtime than actually ends up being used. To maintain this conservativeness, the scoring for Table 3 counts all "scheduled-down-but-still-up" times as downtime. For reference, the results in Table 3 correspond to an unscheduled outage rate of 1.2 events per satellite-year with a mean duration of 35.0 hours per event, plus a scheduled outage rate of 2.2 events per satellite-year with a mean duration of 13.8 hours per event.

Table 3 "Nominal" versus "Actual" Satellite Constellation Number Probabilities

"Nominal" Satellite Number Probabilities	"Actual" Satellite Number Probabilities
0.00 % probability of 26 SVs	3.94 % probability of 26 SVs
0.00 % probability of 25 SVs	31.81 % probability of 25 SVs
72.00 % probability of 24 SVs	53.10 % probability of 24 SVs
17.00 % probability of 23 SVs	10.79 % probability of 23 SVs
6.40 % probability of 22 SVs	0.36 % probability of 22 SVs
2.60 % probability of 21 SVs	0.00 % probability of 21 SVs
1.20 % probability of 20 SVs	0.00 % probability of 20 SVs
0.60 % probability of 19 SVs	0.00 % probability of 19 SVs
0.20 % probability of ≤18 SVs	0.00 % probability of ≤18 SVs

For both civilian and military GPS users, this "change" dramatically improves availability by reducing the occurrence of SIS coverage holes. The holes are far less frequent and, when they do occur, they are much less severe.

> *OPINION:* The authors feel this increased reliance on GPS for safety of navigation will lead to further reductions in the occurrence of SIS coverage holes by earlier replacement launches and a possibly increased nominal constellation size.

IV. 30 dB More AntiJam. Unlike the other important changes taking place over the next ten years, this 30 dB increase in antijam (AJ) change is focused almost exclusively on military GPS users and is subject to much less certainty as to how the change will be implemented. There are several avenues being explored as possible routes for this change, ranging from fancy antennas and advanced signal processing techniques for military GPS receivers to some potentially major modifications to the GPS SIS itself ([7], [8], [9]). The efforts to bring about this change are a large part of the "GPS Modernization Program" being pursued by the GPS Joint Program Office (JPO) [10].

For military GPS users, this change will help ensure survival of their GPS satellite navigation (SATNAV) capability on future battlefields. There is nothing "magical" about the 30 dB value for this change; it is not enough to guarantee survival of the user's GPS SATNAV capability in the future, but it does go a very long way towards helping ensure that survival. For civilian SPS users, this change has no benefits. At worst, it may instead impose some drawbacks if any SIS changes are not 100% backwards compatible. Although no incompatibilities are anticipated, [11] describes a concept for bandwidth limiting the SPS to ±4 MHz which may or may not be innocuous.

> *OPINION:* To the authors, it seems likely that the 30 dB goal for military PPS users will be achieved – and surpassed -- without undue drawbacks for civilian SPS users.

V. 2.5 m SIS URE. This change is the result of a number of different efforts associated with the GPS Operational Control System (OCS). These efforts are lumped together under the name of the "Accuracy Improvement Initiative" (AII) [12]. These "AII efforts" span a broad spectrum of activities. At one end is a long term project to incorporate up to ten National Imagery and Mapping Agency (NIMA) PPS reference stations into the OCS to improve the real-time observability of the on-orbit satellite performance. At the other end are the never-ending attempts at the OCS to work smarter, not harder. The success of these "AII efforts" over the long term is clearly demonstrated by the gradual reduction of the PPS SIS user range error (URE) from a value of 4.3 m 1-sigma as reported by [3] in 1992 to a value of 1.9 m 1-sigma as reported by [13] in 1997. (Note that the recent 1.9 m SIS URE number is indeed already less than the predicted 2.5 m SIS URE change -- this just shows that predictions can come true even as those predictions are being made.)

For military GPS users, the improved accuracy resulting from this 2.5 m SIS URE change is immediately useful and available. For civilian GPS users, this improvement currently is "lost in the noise" compared to the inaccuracies caused by SA and single-frequency ionospheric delay compensation. Once these two error sources "go away" however (see Changes I and II above), the SPS SIS URE and the PPS SIS URE will then basically be the same and civilian GPS users will thus be able to benefit from the 2.5 m SIS URE change as well.

> *OPINION:* The authors predict that the SIS URE will continue to improve over time; by 2007, it will be sub-meter.

IMPACT OF THESE FIVE IMPORTANT CHANGES

By 2007, the basic GPS (i.e., the baseline GPS of 1997 plus the five important changes described in the previous section) ought to provide very good service for all users. But will that GPS (PPS/SPS) service be good enough to use without additional augmentation? If the answer is yes, then perhaps the scope of those augmentations -- especially the Government provided ones -- can be scaled back to save the taxpayer some money. If the answer is no, then perhaps GPS could be cut back and the GP$ thus saved could be spent on more robust augmentations.

To explore this GPS vs. augmentation trade space, a worthy place to start is by considering the requirements for a GNSS to support en route aircraft navigation. The GNSS requirements for such an application, expressed in terms of the Required Navigation Performance (RNP), are becoming fairly mature with broad international consensus being reached through the auspices of the International Civil Aviation Organization (ICAO). Although the ICAO concept of RNP is focused on aviation, its rigorous definitions and categorizations of navigation characteristics is widely applicable to non-aviation applications as well. The specific question to be dealt with in exploring this one small section of the total GPS vs. augmentation trade space is therefore to determine whether GPS (baseline+changes) will satisfy the selected RNP characteristics.

RNP Characteristics. The RNP characteristics for GNSS currently are provided in draft form by the ICAO GNSS Standards and Recommended Practices (SARPS) [14]. These RNP characteristics come in two forms, one for the GNSS navigation system (i.e., the system on-board each aircraft) and one for the GNSS SIS (i.e., the signals shared in common by every aircraft in a region). For simplicity, the example used herein is limited to the GNSS SIS RNP characteristics for the "RNP-1" en route phase of flight. For this phase of flight, there are four necessary RNP characteristics: accuracy, integrity, continuity, and availability. The current draft values for these four RNP characteristics are given in Table 4.

Table 4 GNSS RNP Characteristics (Draft Values)

RNP Characteristic	Example En Route (RNP-1) Values
Accuracy	1.0 nautical mile, 95%, lateral
Integrity	$1\text{-}10^{-7}$/hr, unalerted hazardously misleading information (UHMI)
Continuity	$1\text{-}10^{-6}$/hr, unanticipated loss of RNP service type
Availability	0.9999, applies to the entire set of the above RNP characteristics

Baseline+Changes Performance Examination. The performance of the future GPS (baseline+changes) can now be examined with respect to the four necessary RNP characteristics. Because the RNP characteristics build upon each other, this examination must be performed in the order which follows. The summary correlation matrix between the five important changes and the four RNP characteristics they impact is given in Table 5.

1. Accuracy. The combination of the improved SIS URE provided by the "SA set to zero", "L2 C/A-code", and "2.5 m SIS URE" changes, along with the generally improved horizontal dilution of precision (HDOP) values afforded by the "24+ satellites" change, will allow the future GPS (baseline+changes) to satisfy the 1.0 nm, 95% RNP accuracy characteristic with an even greater margin than the current GPS (this is not a difficult value to meet). Of course, there are still times when the HDOP is so poor that the RNP accuracy value cannot be met even with a 2.5 m SIS URE. However, these occasions are rare enough that they can be defined as "unavailability events" and simply be "charged off" against the RNP availability number. Therefore, we can unequivocally predict that the future GPS will satisfy the 1.0 nm, 95% value for RNP accuracy.

2. Integrity. Similar to accuracy, GPS integrity (in the RAIM/FDE sense) also reaps major benefits from the improved SIS URE provided by the "SA set to zero", "L2 C/A-code", and "2.5 m SIS URE" changes. The first two reduce the "background noise" level that the SPS receiver RAIM algorithms must contend with to roughly the same level as for the current PPS SIS URE. The performance of RAIM algorithms with the current PPS SIS background noise level has been found acceptable [15] whenever there are sufficient satellites (or, optionally, sufficient satellites plus a barometric altimeter) in view with adequate fault detection geometry. Acceptable SPS RAIM algorithm performance has also been shown with just the "SA set to zero" change [16]. The combined benefit of all three SIS URE related changes is more than enough to allow to GPS receivers with RAIM algorithms (PPS or SPS) to satisfy RNP integrity even under very poor fault detection geometry. Of course, the limiting factor here is how poor the fault detection geometry can be while still allowing the GPS receiver to satisfy RNP integrity. The limits on the adequacy of the fault detection geometry are analogous to a cut-off threshold for a binary "available/unavailable" switch: fault detection geometries better than the cut-off threshold mean RNP integrity are available, fault detection geometries worse than the cut-off threshold mean RNP integrity are unavailable. Since there is a separate RNP characteristic for availability (see item number "4" below) where the accounting for inadequate fault detection geometries belongs, we can unequivocally predict that the future GPS will satisfy the $1\text{-}10^{-7}$/hr probability of UHMI value for RNP integrity provided RNP availability exists.

3. Continuity. Continuity is the RNP characteristic that deals with unexpected ("surprise") losses of availability. In common usage, "availability" can mean either "availability of accuracy" (i.e., "availability of navigation") or "availability of integrity" (i.e., "availability of fault detection"). These two availabilities, and the corresponding continuities, are typically different, as illustrated in the following example. Say there are five satellites in view with good HDOP (i.e., good accuracy geometry) and with good fault detection geometry. Hence both "accuracy is available" and "integrity is available". If one of those five satellites should suffer a surprise hard failure, then there would be a surprise loss of integrity (i.e., the "continuity of fault detection" would be impacted), whereas the remaining four satellites could still have a good enough HDOP such that there would be no loss of accuracy (i.e., no impact to the "continuity of navigation").

Although the distinction between these two types of continuity exists, the limiting case for GPS turns out to be when there are five satellites in view with good fault detection geometry and one of those satellites suffers a surprise soft failure (i.e., when the potential for HMI occurs).

Table 5 Five Important Changes/RNP Characteristics Correlation Matrix

	ACCURACY	INTEGRITY	CONTINUITY	AVAILABILITY
SA set to Zero	Major	Major	Minor	Minor
L2 C/A-Code	Major	Major	Minor	Minor
24+ Satellites	Minor	Minor*	Minor*	Major
30 dB AJ	--	--	Minor	Minor
2.5 m SIS URE	Major	Major	--	Minor

* Impact is primarily through availability of continuity

In this case, assume the GPS receiver RAIM algorithm detects the failure and issues a "do not use" alert. This "do not use" alert condition does not really represent a loss of integrity/fault detection since adequate fault detection geometry exists and the RNP integrity characteristic is still satisfied. Similarly, the "do not use" alert condition does not really represent a loss of accuracy/navigation since there is still an available combination of four satellites that satisfies the RNP accuracy characteristic. Instead, this limiting case condition is said to constitute a "surprise loss of service" which, in turn, impacts the "continuity of service" (COS, sometimes also called "continuity of function" or COF).

For the future GPS, the predicted COS for the limiting case of five satellites is really not much different from that for the current GPS: roughly $1\text{-}10^{-5}$/hr. Since this is approximately an order of magnitude less than the RNP continuity characteristic in Table 4, the minimum acceptable case for RNP operation is thus six satellites in view (or five satellites plus barometric altimeter) with the geometry available to support both fault detection *and* fault exclusion. Following the precedent for RNP integrity by counting inadequate FDE geometries against the RNP characteristic for availability, we can predict that the future GPS will satisfy the $1\text{-}10^{-6}$/hr probability of COS value for RNP continuity provided GPS is available.

4. Availability. Availability is the final "capstone" RNP characteristic. It is the one that suffers all of the degradations that result from the need to have adequate geometry for accuracy, adequate fault detection geometry for integrity, and adequate FDE geometry for continuity. If GPS is available in the RNP characteristic sense, then the RNP continuity, integrity, and accuracy values will all be satisfied. If any one of the lower-tier RNP characteristics cannot be met, then neither can RNP availability. This is where the "24+ satellites" change really proves its worth. If the 24-satellite constellation is maintained as predicted, then the future GPS can meet the 0.9999 value for RNP SIS availability. To accommodate this satisfaction of RNP SIS availability, however, the GPS receivers that are trying to meet the RNP characteristics must participate in the solution. Those GPS receivers must either be capable of tracking GPS satellites down close to the horizon when absolutely necessary for FDE or be able to use a barometric altimeter when necessary for FDE. Neither of these requirements is particularly onerous [OPINION WARNING]; the first is already recommended in the FAA primary means oceanic approval [17] while the second one is in Technical Standard Order for supplemental GPS navigation [18]. Given such GPS receiver participation and assuming the "24+ satellites" change comes to full fruition, we can predict that the future GPS will satisfy the 0.9999 value for RNP availability.

Baseline+Changes Performance Results. The results of the future GPS (baseline+changes) performance examination are summarized in Table 6 with respect to the RNP-1 characteristics. The accuracy, integrity, and continuity RNP characteristics are unequivocally predicted to be satisfied. The availability RNP characteristic is predicted to be satisfied based on two reasonable assumptions: 1) GPS receiver participation through the ability to track low elevation angle satellites and/or the use of barometric altimeters, and 2) the "24+ satellites" change.

Table 6 Future GPS (Baseline+Changes) Performance Predictions

RNP Characteristic	Draft En Route (RNP-1) Values	Satisfied by Future GPS (Baseline+ Changes)
Accuracy	1.0 nautical mile, 95%, lateral	Yes
Integrity	$1\text{-}10^{-7}$/hr, UHMI	Yes
Continuity	$1\text{-}10^{-6}$/hr, COS	Yes
Availability	0.9999, for accuracy, integrity,and continuity	Yes*

* Assuming GPS receiver participation and the "24+ satellites" change

BENEFITS TO AUGMENTATIONS

Over the next ten years, the five important changes described in this paper will make the basic GPS a much better system. And since it will be a much better system, it will also be much easier to augment. For example, DGPS augmentations will have a much easier task keeping up with the naturally occurring error growth over time (e.g., a rate of maybe 0.0001 m/sec) than they do trying to keep up with the SA error growth over time (i.e., a rate of up to 2.0 m/sec per [19]). Users will be able to perform their own high-accuracy ionospheric delay compensation using dual-frequency measurements, thereby simplifying wide area augmentation system implementation. For applications such as Category III precision approach which need extremely high accuracy, direct access to L1 and L2 might make wide lane ambiguity resolution reliable enough for operational use. 24+ satellites will improve the availability substantially, perhaps enough such that ranging source augmentations may no longer be needed in many cases. If the SIS URE continues to improve and ends up being much lower than 2.5 m, then some DGPS augmentations may be able to shift their focus to monitoring integrity rather than improving accuracy and thereby free up some transmission bandwidth for additional value-added services such as broadcasting weather information or GPS NANUs.

CONCLUSIONS

In ten years time, GPS will be extremely good all by itself. Assuming GPS receivers continue to improve and the predicted changes to the system described in this paper occur, GPS will be good enough to use as a stand-alone GNSS for applications such as en route navigation at the RNP-1 or higher levels. Augmentation systems will still be required though for more demanding RNP levels, such as those required for precision approach.

Even though we are both strong believers in the current GPS and have what some might call an "extremely rosy outlook" for the future of GPS and its augmentations, we are still not completely comfortable with the notion of *"putting all of our navigation eggs in one basket"*. As described earlier in this paper, there are at least two major possibilities that might derail the future GPS. We are sure there are many minor possibilities as well. It does not seem a prudent course of action to intentionally rely exclusively on any one system, regardless of whether that system is GPS, an augmented GPS, or some other single-string GNSS. There are a number of existing radionavigation systems described in [2], all of which are currently slated for termination. With the initial investments in these systems already paid for, it may be wise to consider keeping one or two of them as a back up just in case. [FINAL OPINION WARNING]

REFERENCES

1. President of the United States of America; *Presidential Decision Directive NSTC-6, Subject: U.S. Global Positioning System Policy*; 28 Mar 96.

2. 1996 *Federal Radionavigation Plan*; U.S. Department of Defense and U.S. Department of Transportation, DOT-VNTSC-RSPA-97-2/DOD-4650.5, Jul 97.

3. Malys, S., and Holm, S., *PPS and SPS Integrity Monitoring with an Independent Global Tracking Network*; Proceedings of the Fifth International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GPS-92), Albuquerque, NM, 16-18 Sep 92.

4. White House Commission on Aviation Safety and Security; *Final Report to President Clinton*; 12 Feb 97.

5. *DOT and DOD Assure GPS Access for Civil Users*; U.S. Department of Transportation (DOT) Press Release 21-97; 27 Feb 97.

6. *President Opens Door to Commercial GPS Markets: Move Could Add 100,000 New Jobs to Economy by Year*; White House Press Release, 29 Mar 96.

7. National Research Council; *The Global Positioning System, A Shared National Asset*; National Academy Press; 1995.

8. Ragahavan, S., Holmes, J., Lazar, S, and Bottjer, M.; *Tricode Hexaphase Modulation for GPS*; Proceedings of the 10th International Technical Meeting of the Satellite Division (ION GPS-97), the Institute of Navigation, Kansas City, MO, 16-19 Sep 97.

9. Anderson, Capt J., and Lazar, S., *Lm and Lc: How the Military and Civil Users of GPS Can Reuse Our Existing Spectrum*; Proceedings of the 10th International Technical Meeting of the Satellite Division (ION GPS-97), the Institute of Navigation, Kansas City, MO, 16-19 Sep 97.

10. Global Positioning System Joint Program Office; *Special Notice: Global Positioning System, Request for Information on a New GPS Signal in Space*; Commerce Business Daily; 26 Jun 97.

11. Armor, Col J., *GPS: A Joint Program Office Perspective*; Proceedings of the 53rd Annual Meeting of the Institute of Navigation, Albuquerque, NM, 30 Jun - 2 Jul 97.

12. Malys, S., *The GPS Accuracy Improvement Initiative*; Proceedings of the 10th International Technical Meeting of the Satellite Division (ION GPS-97), the Institute of Navigation, Kansas City, MO, 16-19 Sep 97.

13. Conley, R., *Results of the GPS JPO's GPS Performance Analysis Baseline Analysis: The GOSPAR Project*; Proceedings of the 10th International Technical Meeting of the Satellite Division (ION GPS-97), the Institute of Navigation, Kansas City, MO, 16-19 Sep 97.

14. *Standards and Recommended Practices (SARPS) for Global Satellite Navigation System (GNSS)*; Draft, International Civil Aviation Organization (ICAO), Summer 97 version.

15. Kovach, K., Maquet, H., and Davis, D., *PPS RAIM Algorithms and Their Performance*; NAVIGATION, Journal of the Institute of Navigation, Vol. 42, No. 3, Fall 1995.

16. Van Dyke, K., *Removal of SA: Benefits to GPS Integrity*; Proceedings of the 9th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GPS-96), Kansas City, MO, 17-20 Sep 96.

17. *Notice (N) 8110.60, Subject: GPS as a Primary Means of Navigation for Oceanic/Remote Operations*; U.S. Department of Transportation, Federal Aviation Administration, 4 Dec 95.

18. *Technical Standard Order (TSO) C129, Subject: Airborne Supplemental Navigation Equipment Using the Global Positioning System (GPS)*; U.S. Department of Transportation, Federal Aviation Administration, 10 Dec 92.

19. Global Positioning System Standard Positioning Service Signal Specification, 2nd Edition; U.S. Department of Defense, 2 Jun 95.