A Civil User Perspective on Near-Term and Long-Term GPS Modernization

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BIOGRAPHIES

Sam Pullen is a Senior Research Engineer at Stanford University, where he is the director of the Local Area Augmentation System (LAAS) research effort. He has supported the FAA in developing LAAS and WAAS system concepts, technical requirements, integrity algorithms, and performance models. He and his group have developed a LAAS ground facility prototype that utilizes innovative algorithms for detection, exclusion, and recovery of system failures. He is now working on revised system architectures and algorithms for the next phase of both LAAS and JPALS (a military variant of LAAS) to support operations up to and including Category III precision landings. He also participates in the development of standards and technical concepts for the next generation of GPS, now known as "GPS III." Dr. Pullen has won several awards for his work, including the Institute of Navigation "Early Achievement Award" in 1999.

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ABSTRACT

This paper examines the impact of future plans for modernizing the GPS constellation and ground segment from the point of view of civil users, especially those with demanding integrity, continuity, and availability requirements. In the next few years, incremental system improvements will offer several benefits, including increased resistance to RF interference and faster response to satellite anomalies. More significant benefits will occur when a second civil frequency is made available to civil users as significant numbers of GPS Block IIR-M (supporting L2C) and IIF (supporting L5C) satellites are fielded. The conversion from today's L1 C/A code to an improved (and backward-compatible) L1C format is also likely. Beyond that, GPS Block III will likely expand the GPS constellation to 27 independent primary orbit slots and will provide greatly improved integrity to standalone civil users while easing the task of civil augmentation systems (SBAS and GBAS). The schedule for these improvements is discussed, and the need for continuous civil user input to the GPS modernization decision-making process is highlighted.

1.0 Introduction

Civil users of Global Navigation Satellite Systems (GNSS) have much to look forward to over the next 5 to 20 years. Today, civil users are now limited to a single constellation of Global Positioning System (GPS) satellites operated by the U.S. Department of Defense and several GEO satellites supporting the U.S. and European Space Based Augmentation Systems (SBAS). In the not-so-distant future, many more ranging satellites and signals will be available, including those of the European Galileo constellation, those of the Japanese Quasi-Zenith Satellite System (QZSS), and additional GEO satellites. The addition of Galileo by itself will approximately double the number of ranging satellites available to users with receivers than can use both systems (see [1,2,3]). At the same time, augmentation systems that provide real-time differential corrections and integrity information to civil users will become more and more common worldwide. Starting with the U.S. Wide Area Augmentation System, which became fully operational in July 2003, more and more of these systems will become available worldwide, including SBAS systems in Europe, Japan, China, and India, the Australian Ground-based Regional Augmentation System (GRAS), and U.S. Local Area Augmentation System to provide near-zero-visibility navigation at major airports (see [4,5,6]).

Partially in response to these new systems and partly in response to evolving U.S. military and civil user

Year	Number of Outages	Mean Outage Duration (hours)	Median Outage Duration (hours)	Outage Duration Sigma (hours)	Implied MTBUO (hours)
1999	19	96.69	1.20	249.68	12,457
2000	20	81.82	10.20	199.07	11,834
2001	16	144.62	7.40	401.79	14,793
2002	17	101.30	120.45	98.69	13,922
2003	13	171.24	71.40	198.19	18,206

Table 1: GPS Satellite Outage Statistics from 1999 to 2003

requirements, GPS will also undergo several improvements over the next two decades. This paper gives an overview of these planned GPS improvements and discusses how they will improve civil user performance, whether or not civil users also make use of augmentation systems and other ranging satellites. Section 2.0 discusses the incremental impacts of several changes that are being made now or may be made in the near term, including higher C/A-code signal power, modifications to the standard 24-satellite GPS constellation, and additions to the GPS Operational Control Segment (OCS). Section 3.0 discusses the larger impacts of new civil frequencies (L2 and L5) and the modernized L1 civil signal (L1C) that will be made available in the next 5 – 15 years. Section 4.0 discusses further improvements in standalone user accuracy and integrity that are likely to come from the next generation of GPS satellite designs, now known as "GPS III". Section 5.0 summarizes the projected schedule for these GPS enhancements and explains why these dates are highly uncertain at present. Section 6.0 summarizes the paper and discusses the need for continued civil input into the process of GPS modernization to ensure that upgrades of value to the civil community are implemented in ways that provide the greatest utility possible.

2.0 Ongoing and Near-Term GPS Improvements

While the focus of GPS modernization work at the present time is the future enhancement of GPS via the improved capabilities of the Block IIR-M, IIF, and III satellites, ongoing improvements to the existing GPS constellation and control segment are helping to significantly improve civil user performance [7,8]. This section summaries some of these activities and explains their significance for civil users.

2.1 GPS Constellation Maintenance

The performance of the GPS space segment over the first half of this decade has been very good and continues to improve gradually [9]. One area where this is most noticeable is the low rate and duration of unscheduled satellite outages. Table A-2-3 of the *GPS SPS Performance Standard* [10] released in 2001 shows that, while the Block II/IIA design-requirement Mean Time Between Failures (MTBF) was 2346.4 hours, the historical MTBF observed since 1994 was 10,749.4 hours. Observations of unscheduled satellite outages since 2001 based on the U.S. Naval Observatory archive of GPS Non-Availability Notices to Users (NANUs; see ftp://tycho.usno.navy.mil/pub/gps) show that the historical Mean Time Between Unscheduled Outages (MTBUO) continues to improve (i.e., longer intervals between outages), as shown in Table 1 (from [11]). Note that every year from 1999 onward has had a per-satellite MTBUO higher than the historical MTBF in the SPS Performance Standard, and a continuing trend of gradual improvement is evident in the data.

One reason for this improvement is an apparent change in policy regarding how long to examine failed satellites before resetting them back to "healthy." From 1999, to 2001, the median outage duration (for unscheduled outages) was less than 10 hours (the mean is much higher due to satellites that were eventually declared to be "end of life" and were retired). The outage records from those years show multiple cases where a given satellite has an unexpected failure, is returned to service within several hours (presumably after all symptoms of failure have gone away), and then fails again several days later. Keeping failed satellites unhealthy for much longer (as the table indicates was done in 2002 and 2003) and making sure that the cause of the outage has been corrected results in fewer outages and a higher MTBUO.

While the longer outage durations mean a slight loss in the per-satellite availability (or "uptime percentage") on the order of 0.25% (compared to the historical value of 99.34% reported in Table A-2-3 of [10]), there is a large and significant gain in continuity for users who cannot easily tolerate an unexpected loss of service. Civil aviation users, for example, typically have requirements on the loss-of-continuity probability on the order of 10^{-5} – 10^{-6} per exposure time interval (see [1,4]). The majority

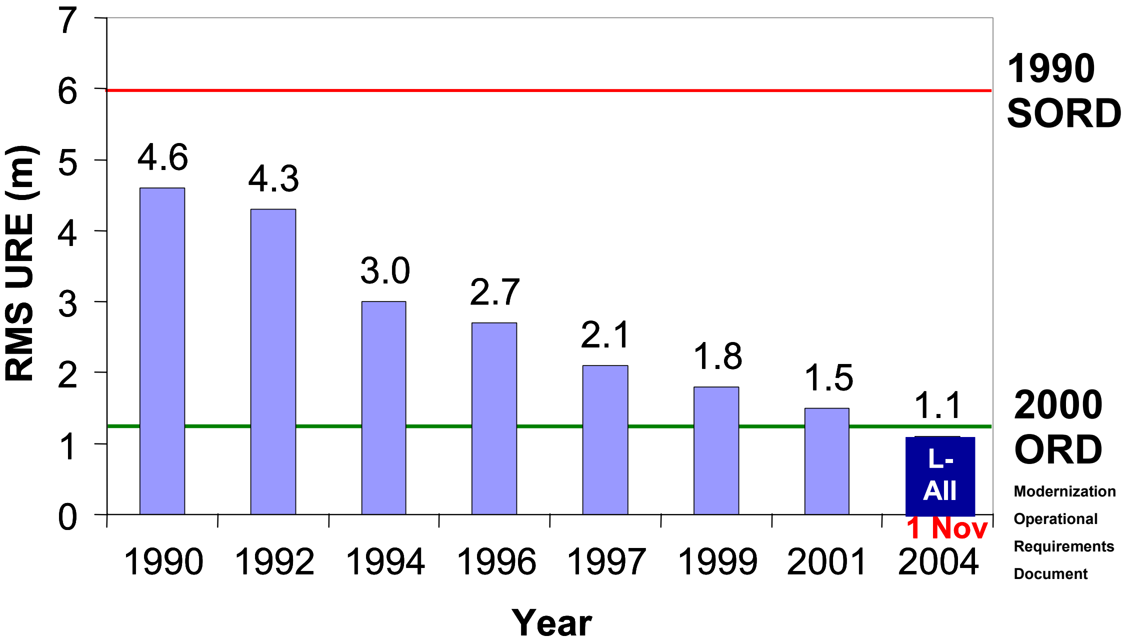

Figure 1: GPS Satellite RMS URE Improvement over Time (*Source*: M. Crews briefing [8])

of this is taken up by the unexpected satellite loss probability for satellites that are "critical" in a given user geometry, meaning that the loss of an individual satellite would weaken that user's navigation quality to the point where the operation must be aborted. A lower per-satellite failure probability means that more critical satellites can be tolerated; thus users can utilize weaker satellite geometries than they could otherwise.

The GPS Joint Program Office (JPO) goal for maintaining the orbits of the GPS constellation continues to be focused on today's 24-satellite constellation. Over the past few years, multiple active spares have also been present so that the total number of GPS satellites is 26 or more. While the existing spare satellite locations do add robustness in the case of "primary" satellite failures, a proposal has been made to modify the current constellation to make it perform more like a constellation with 27 primary satellite "slots". This proposal, reported in [12,13], splits three of the existing 24 primary slots (B1, D2, and F2) in two, placing two equally-spaced satellites on both sides of the original slot and separating them by 24 to 29 degrees. While this approach may not achieve the performance that might be obtained from an "new" constellation design optimized for 27 primary slots, it clearly outperforms the existing 24 (primary) + 3 (active spare) constellation that is loosely maintained today [13]. Another advantage is that it is straightforward to create this new constellation from the existing one [12]. While a decision to adopt this proposal has not been made, the U.S. is studying which requirements and policies need to be changed to allow a gradual transition to it as new satellites are launched.

2.2 GPS Satellite Accuracy

A major step forward in the civil adoption of GNSS was the U.S. decision to deactivate Selective Availability (intentional degradation of the clock signals driving L1 C/A code) in May of 2000, which dramatically increased the performance of "standalone" (not augmented by SBAS or GBAS) civil users [14]. Meanwhile, improvements for military standalone users have come from improved GPS satellite clock and ephemeris data that have resulted in progressively lower User Range Errors (UREs) over time. As shown in Figure 1 (from [8]; also see [21]), the RMS of GPS satellite URE has improved steadily over time and is less than half of its value when GPS was officially commissioned in 1995. Details of how this improvement is reflected in new GPS Precise Positioning Service (PPS) standards for military users are in [15].

At present, civil users cannot benefit from all of this improvement. Some of the recent improvement is due to the additional bits of data in PPS navigation messages that are not available to civil users. In addition, single-frequency users will still suffer from ionosphere errors several meters (1σ) except when the ionosphere is "quiet"; thus they will not be aided by URE reductions below the level of typical ionosphere errors. However, once dual-frequency service is widely available to standalone civil users (see Section 3.1), this ionosphere limitation will disappear, and further URE improvements will directly translate into significantly improved civil user performance.

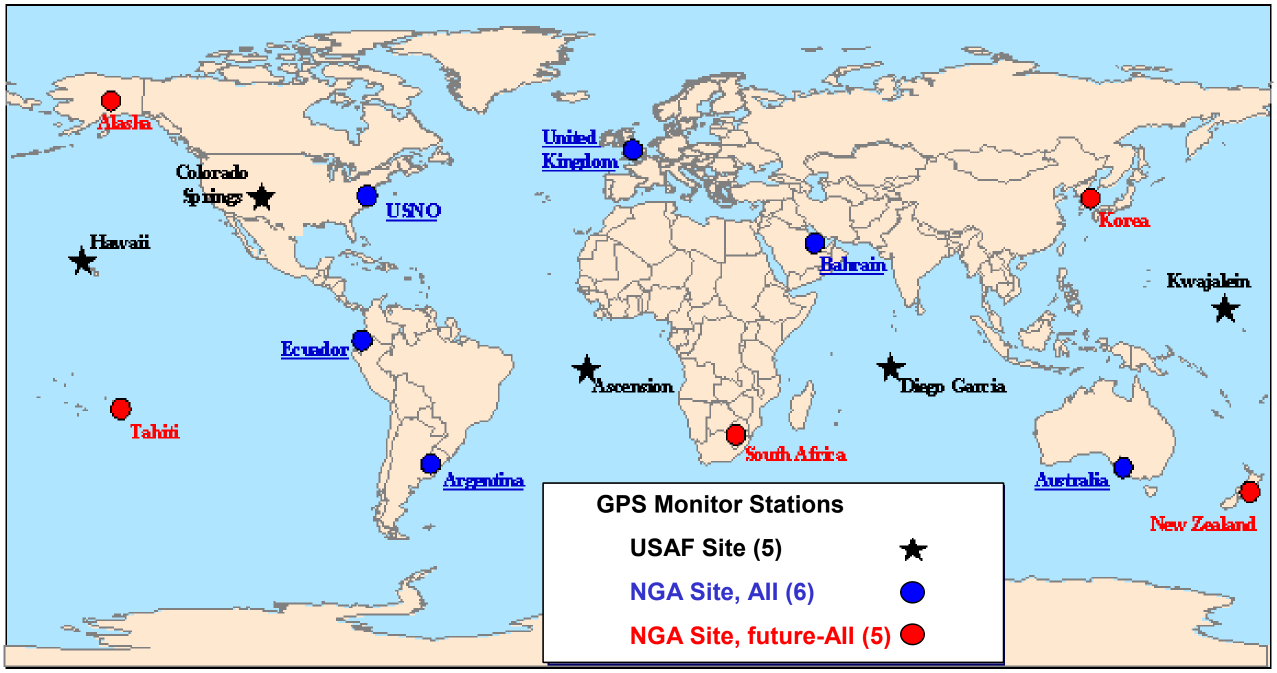

Figure 2: Existing and New OCS Monitor Stations (*Source*: M. Crews briefing [8])

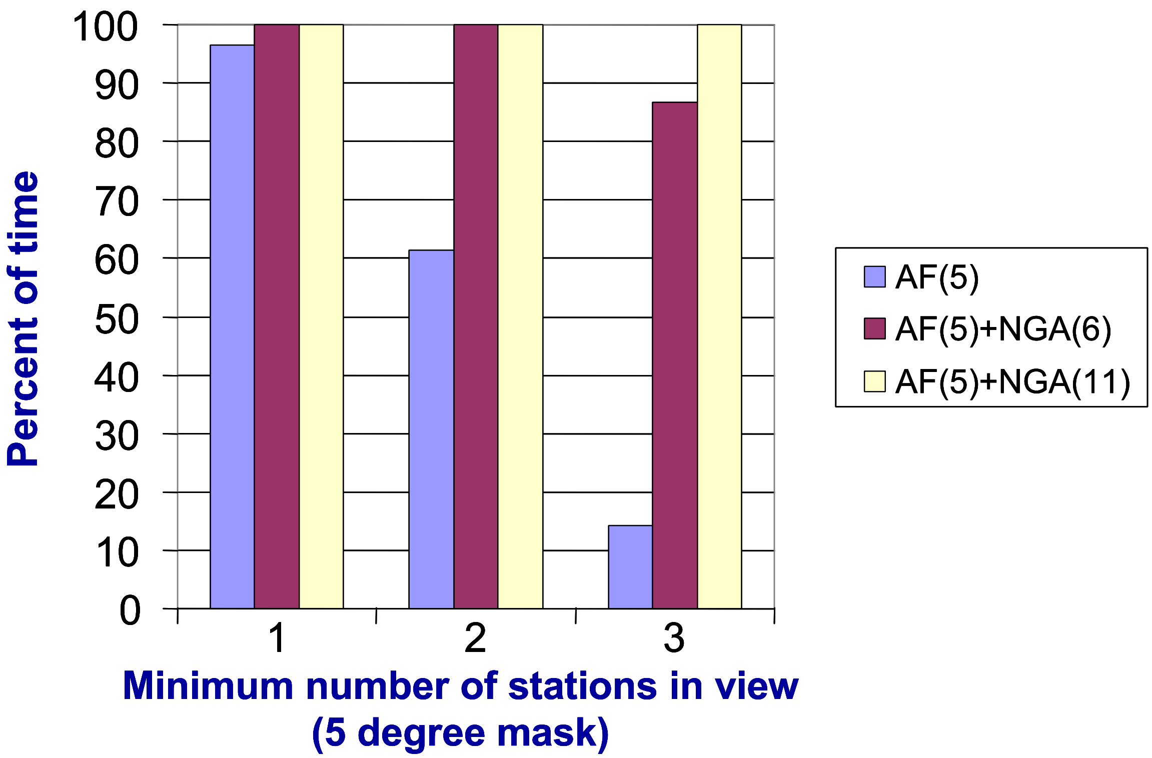

Figure 3: GPS Satellite Visibility Improvement from New OCS Monitor Stations (*Source*: M. Crews briefing [8])

2.3 GPS Control Segment Improvements

One key reason why GPS performs as well as it does is the quality of the work performed by the GPS Operational Control Segment (OCS) that continually monitors satellite performance, generates updated navigation data, and uplinks it to satellites on a regular basis (at least once per day). However, the equipment used by OCS has not been significantly modernized or expanded since GPS commissioning in 1995, and its limitations place an upper bound on what OCS can achieve. To address this, the GPS JPO is now in the process of upgrading both the hardware and software elements of the OCS. The software upgrade is known as the Version 5.2 of the Architecture Evolution Plan (AEP) and represents a major shift from a mainframe-based architecture to a system of distributed workstations [16]. Meanwhile, hardware-upgrade plans that have been on the table for several years are now coming to fruition through the Legacy Accuracy Improvements Initiative (LAII), which is the key to achieving the 1.1-meter RMS URE shown on the right-hand side of Figure 1 [8,21]. As described in [8,16], LAII will add six existing NIMA monitoring stations to the existing five U.S. Air Force monitor stations by the end of this year, and five more NIMA stations will be added before the end of 2006. Figure 2 (from [8,21]) shows the locations of these old and new stations.

Figure 3 (from [8,21]) shows the impact of LAII in the degree to which they will improve the quality of GPS monitoring. One well-known limitation in OCS monitoring today is that "visibility gaps" exist within which satellites are not visible to any of the five existing monitor stations. As Figure 3 shows, individual satellites are not visible almost 5% of the time even when all five stations are operating (and, like all hardware, these stations are occasionally offline). Some of these gaps, such as the one over the southern Pacific (see [8]), cause satellites to be invisible to monitors for as long as 1 – 2 hours. If a satellite were to fail and broadcast anomalous signals or data while in a "visibility gap," it would take that long before OCS could be made aware of the situation and take any action. The first stage of LAII will dramatically improve things by ensuring that all satellites are visible to two or more monitor stations (three or more after the second stage) if all stations are operational. The result is likely to be significantly improved OCS navigation data uploads and much faster response time to unexpected satellite anomalies.

3.0 Addition of New Civil Signals

3.1 New L2 Civil Signal

A major milestone for civil users of GPS will be the broadcast of civil signals on a second frequency. When combined with the existing L1 signal, this will allow users who track both signals to estimate and remove the impact of ionosphere delay on their range measurements (see [17,18]). A preview of this day may occur as soon as March of 2005, when the first GPS Block IIR-M satellite is currently scheduled to be launched [7,16]. The Block IIR-M satellites are equipped to broadcast coded civil signals on the L2 frequency now used by the military and used (but in codeless or semi-codeless form) by civil survey receivers and SBAS reference receivers. Once these satellites occupy the GPS constellation in sufficient numbers, and OCS equipment has been modernized so that it can monitor L2 civil signals, the benefits of dual-frequency removal of ionosphere delays that have been available to military users since the dawn of GPS will finally be available to civil users as well.

While the IIR-M satellites may initially broadcast the existing C/A code definition on L2 to ease the transition, the goal is to eventually switch to a new L2C signal. The L2C signal has the same chipping rate as L1 C/A (1.023 Mcps) but is split between a moderate-length (10,230-chip) "CM" code with data modulated on it and a much longer (767,250-chip) "CL" code without data modulation (see [19] for details). The primary advantage of the "dataless" code is that integration times for resolving the code can be much longer than the 20 ms limit that applies to the 50 bps L1 C/A code data today (this integration time must be shorter than the interval between bit transitions triggered by data bit flips). The result is that signals can be reliably tracked at weaker signal strengths, which means that signal tracking is more robust to RF interference or jamming. However, gaining this advantage means that the navigation data must be obtained in some other manner: either from L1 C/A or from an external source (e.g. over the Internet or another data network). The navigation data broadcast on the CM code will either be the existing 50 bps framework or a "CNAV" data structure at 25 bps like that adopted for L5 (see Section 3.2) [19]. Another advantage to the longer codes is much better rejection of code cross-correlation and narrowband interference (a 24-dB improvement compared to C/A code) [8].

The chief disadvantage of L2C for civil aviation users is that the L2 frequency (1227.6 MHz) is not in one of the Aeronautical Radio Navigation Service (ARNS) bands as required by FAA and International Civil Aviation Organization (ICAO) regulations for signals used to support "safety of life" navigation [20]. While the L2 frequency is in a band dedicated to satellite navigation and should have few interfering signals, the lack of ARNS protection means that, if an interfering signal did appear on or near L2, the FAA would not necessarily have the regulatory authority to shut the interferer down quickly. For this reason, L2C is not part of current upgrade planning for civil aviation users, but all other civil users that choose to equip with L2C-capable receivers will gain significant benefits from it. In fact, SBAS ground stations supporting civil aviation users that already rely on L2 semi-codeless tracking to estimate ionosphere delays will see a major improvement from coded L2 signals because they will be much easier to track and much more resitant to disturbances such as ionosphere scintillation [20,21].

3.2 New L5 Civil Signal

Once all 8 Block IIR-M satellites are launched, the U.S. Air Force will begin launching the Block IIF generation of satellites starting as early as mid-2006 [7,16]. In addition to broadcasting L2 civil signals, these satellites will be capable of broadcasting an all-new civil-only signal on the L5 frequency (1176.45 MHz). Because this

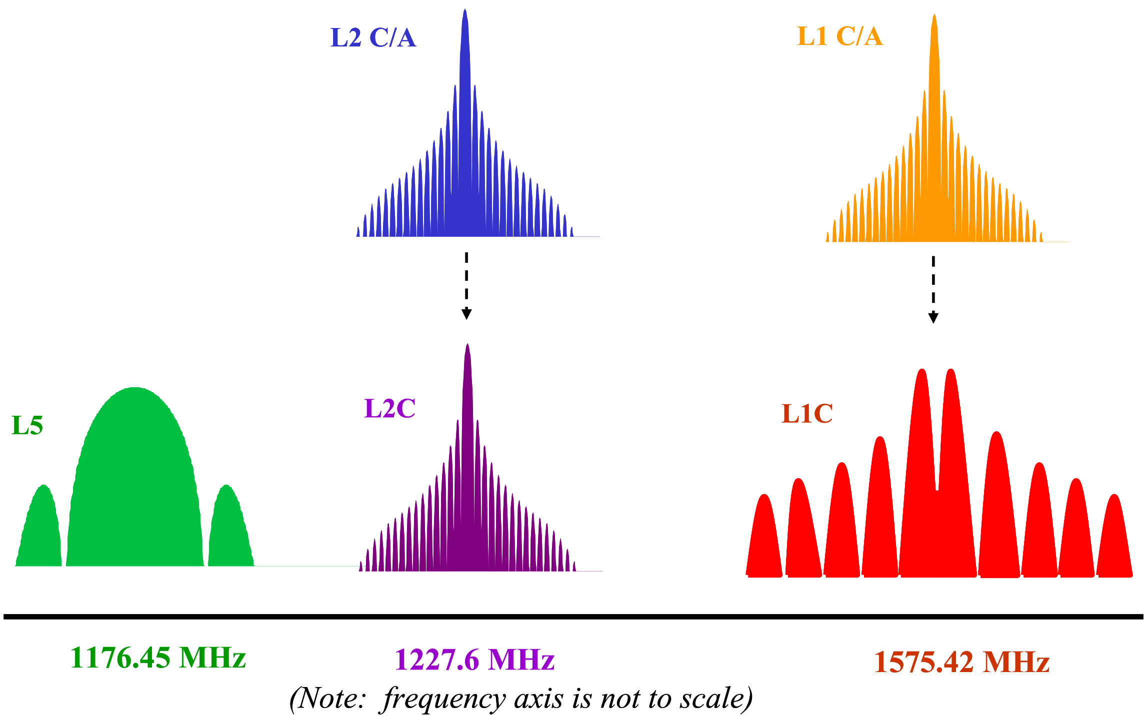

Figure 4: Overview of Civil GPS Signal Evolution [8]

frequency is in an ARNS band, it will be fully usable by civil aviation users, and the resulting dual-frequency capability will provide a major improvement to their performance and availability.

As with L2C, and for the same reasons, the new L5 civil signal will consist of one PRN code with data encoded on it and another one without data. However, the implementation is different: the data and dataless bit trains will be modulated by two similar PRN codes in phase-quadrature. Thus, the code with data modulation will be the "in-phase component (I5-code), and the code without data modulation will be the quadrature component (Q5-code) [22]. Also, fewer constraints exist on L5C because no military signals will be transmitted on L5. Thus, the L5C signal will have a chipping rate of 10.23 Mcps (equivalent to military P/Y code) while retaining the 1 msec period of C/A code, and it will occupy 24 MHz of bandwidth around L5 without overlapping military signals. This higher chipping rate and signal bandwidth will make code tracking more effective and result in significantly lower code multipath errors (see [23]). Navigation data is added to I5 via a 100-sps "data code" that will support a new navigation data message format at the same bit rate (50 bps) as L1 C/A code [22]. One other feature is the use of 10-bit and 20-bit Neumann-Hoffman codes for additional encoding of the I5 and Q5 codes, respectively (in the I5 case, this is done to the 100-sps navigation data bit pattern). This has the effect of "spreading" narrowband interference such that it cannot distort the L5 signal to the degree it can distort L1 C/A code (see [22]).

Once L5 is available on a sufficient number of satellites, dual-frequency navigation will be possible for civil-aviation users. As noted above, the benefits will be substantial. Standalone civil users will be able to reliably remove ionosphere delay errors from their range measurements, and this will remove the largest single source of error (when the ionosphere is active) for these users now that S/A has been deactivated. While almost all ionosphere delays are removed by SBAS and GBAS users when they apply differential corrections, but it is difficult for these systems to assure that unacceptable residual (differential) errors are not present during ionosphere storms in which gradients between reference stations and users are much greater than normal [24]. Because anomalous ionosphere activity cannot be completely observed by SBAS and GBAS ground stations, the range-domain error bounds broadcast by SBAS and GBAS must allow for the possibility of such errors; thus the user position-domain protection levels generated by users are much more conservative than they would need to be in the absence of this threat, and the result is lower precision-approach availability [24].

When dual-frequency measurements (and thus direct measurements of ionosphere delays) become available to users, this threat of ionosphere anomalies is no longer a concern (beyond the rare impact of scintillation in making GPS signals untrackable), and one major limitation to SBAS and GBAS will be a thing of the past. More details on the benefits of this are in [25] (for SBAS) and [18,26] (for GBAS). Signal redundancy is another major benefit: if any given frequency is rendered unusable by unintentional RF interference, other frequencies will likely remain usable.

3.3 Modernization of Existing L1 Civil Signal

Once modernized civil ranging signals are available on L2 and L5, the limitations of the existing L1 C/A code will become less and less tolerable to high-performance users. Rather than simply leaving L1 as is, GPS plans to introduce a new L1 civil signal (L1C) that will provide improvements similar to those of L2C and L5C for users with modernized receivers while still supporting legacy receivers by continuing to broadcast L1 C/A code.

Because L1C will likely not become available until the GPS Block III satellites begin to be launched, the definition of L1C need not be finalized yet. A recent Interagency GPS Executive Board (IGEB) study on the optimal design of L1C makes it clear that L1C is feasible while retaining L1 C/A and other flexibility options and that L1C will be a worthwhile improvement for civil users [27]. In addition, a clear consensus developed among the civil user experts surveyed that the best choice for an L1C signal is a BOC(1,1), or a "Binary Offset Carrier" signal with a 1 MHz code rate modulated by a 1-MHz square-wave "subcarrier" (see [28] for a detailed description of BOC signal characteristics).

There is more debate on another issue: what should the data rate of the L1C navigation message be? There is little interest in keeping it at today's 50 bps. The choices are either to gain RFI and noise resistance by reducing the data rate to 25 bps (thus along receivers to integrate the code signals twice as long between data bit transitions) or to gain room to transmit additional ephemeris, differential-correction, and integrity related data by increasing the data rate to 100 bps.

As noted in the IGEB report [27], the problem with increasing to 100 bps is that the additional bandwidth is insufficient to satisfy the many different demands that would be made on it. For example, one set of users would like high-accuracy ephemeredes good for longer periods to be broadcast to improve the time-to-first (high-accuracy) fix of future GPS receivers. Even if this is doable, it would likely require additional work for the GPS JPO that could be done just as well by civil GPS user networks (with the longer-duration ephemeredes transmitted to users by mobile-phone links that most users will have access to). Similarly, 50 extra bps are probably insufficient to transmit differential messages valid for everyone receiving the satellite in question, and it would duplicate a function that civil augmentations are already providing. Thus, while the considerations would be different for an "all-new" system such as Galileo or QZSS, this author agrees with the IGEB report [27] that 25 bps for extra signal-strength margin is the best way to go for GPS, and he feels that this does not preclude providing real-time integrity updates within the GPS data message (see Section 4.0).

4.0 GPS III: The Next Generation

The next generation of GPS satellites (to follow the Block IIF satellites) and control-segment systems are collectively known as "GPS Block III" or "GPS III". While GPS III is in the early planning stages, it is expected to introduce a new level of performance to both military and civil users. Military users will likely benefit from a high-power (+ 20 dB) "spot beam" that can concentrate additional signal power (and thus jamming resistance) into a region of the globe that needs it [7]. The modernized L1 civil signal described in Section 3.3 will likely be included in GPS III if it is not retrofitted to earlier satellites [8]. Additional URE improvements beyond what will be achieved by LAII (see Sections 2.2 and 2.3) are also planned [7].

Of particular interest to both military and civil users are the expected improvements in standalone GPS integrity, with the current requirement being to provide reasonable availability of precision approaches to CAT I minima (200 feet above the runway) without SBAS or GBAS augmentation. This requires both lower UREs and greatly improved GPS system integrity, since CAT I requires that failures that make CAT I approaches unsafe be detected within a 6-second time to alert with a probability of 2×10^{-7} per 150-second approach duration (see [33]). This is well beyond what GPS can achieve today or in the near future, as GPS satellites fail at a rate of $10^{-4} – 10^{-5}$ per hour, and OCS detection and alerting of such failures may take hours (see [10]).

Several methods have been proposed for improving GPS such that it can meet this integrity requirement. The ideal approach would be to use our past experience of GPS satellite and control segment anomalies to make GPS III satellites reliable to the level needed to support a 2×10^{-7} per 150-second integrity requirement. Since each of 12 or more satellites potentially in view could cause unsafe errors, and failures are also possible in the control segment, the failure probability that could be allocated to each satellite would probably be 10^{-9} per approach (2.4×10^{-8} per hour) or lower – in other words, three or four orders of magnitude better than today's GPS satellites (see Section 2.1). While some built-in monitoring of the most critical functions (such as the real-time AFS vs. VCXO clock monitor implemented in the Block IIR satellites [31]) could be applied, it seems very unlikely that such a requirement could be met cost-effectively solely by improving the satellite design. Thus, additional integrity monitoring outside of the satellite signal-generation functions will likely be needed.

If external integrity monitoring is required, it could be applied in several different places. One proposal is to design an "add-on" module to GPS satellites that will

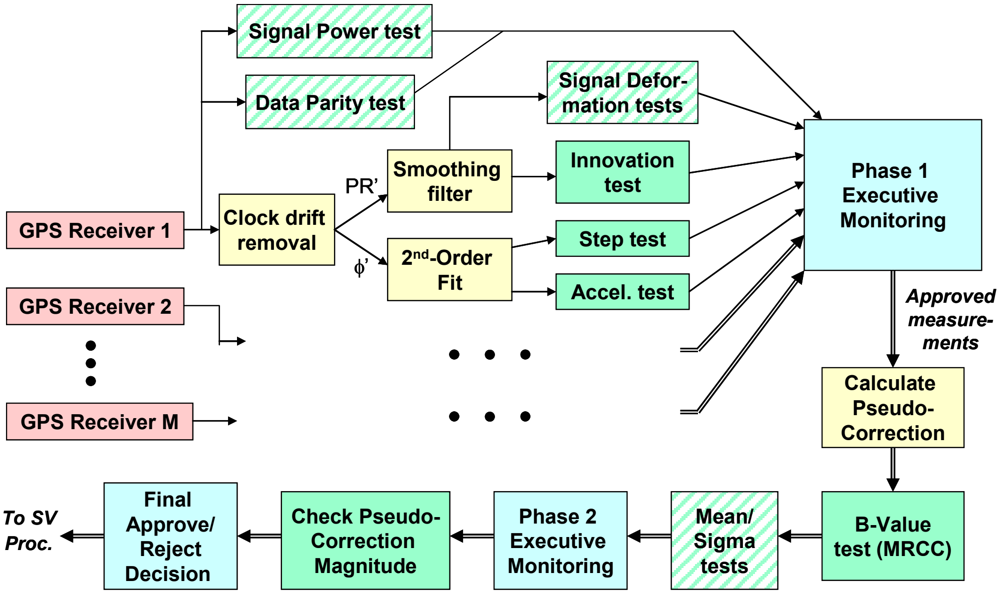

Figure 5: One Approach to Satellite Autonomous Integrity Monitoring (SAIM) Implementation [29]

perform the needed monitoring on the satellite in questions. This concept, known as "Satellite Autonomous Integrity Monitoring" or SAIM, is discussed in [29]. Figure 5 (from [29]) illustrates how SAIM might be implemented. In this concept, the SAIM "add-on" module includes multiple GPS receivers that receive and track the signals of the satellite that they are hosted on, either via a "side-lobe" antenna or a direct RF feed from the signal generator. These receivers perform a series of integrity checks on these signals in a manner similar to that of a GBAS ground system (the approach to SAIM in Figure 5 was based on the design of the Stanford University LAAS Ground Facility Prototype known as the "Integrity Monitor Testbed" or IMT – see [34]). If a fault is detected on more than one of the SAIM receivers, an alert is passed back to the satellite so that the broadcast signals can be modified right away to protect users.

While SAIM may play a key role in GPS III satellite integrity monitoring, not all failures can be detected by SAIM. Two examples of such failures are satellite ephemeris failures (i.e., bad ephemeris data is broadcast for a given satellite) and "slow" clock drifts that are too gradual to be detected within the satellite or by SAIM. One approach to these errors is to monitor the crosslink ranging signals transmitted by IIR and future satellites (see [35]). Several neighboring satellites that track the crosslink signals of a given satellite could combine their information to determine if that satellite is where it should be. Another option is to further expand and enhance the modernized OCS ground monitor network described in Section 2.3 so that it OCS can uplink alert messages back to the affected satellite quickly. While it may not be possible to detect a failure on the ground and trigger an alert on the affected satellites within 6 seconds, ground monitoring may be sufficient for errors that grow slowly. As long as an OCS alert precedes the point when a slowly-growing error becomes hazardous to users, the time-to-alert requirement would be met.

Another key consideration is how to transmit satellite warnings to users. Today's GPS satellites trigger non-standard code (NSC) when failures are detected [31]. Since NSC cannot be tracked by a GPS receiver that meets the requirements of GPS-ICD-200C [36], this is a good way of forcing all users of that satellite to stop using it. The problem with this approach is that failures threatening to, say, CAT I precision-approach users may be a non-issue for users that have less-stringent requirements. Transitioning to NSC thus makes all users pay the price to meet the requirements of the most-demanding users.

An alternative to using NSC alone is to follow the lead of SBAS and GBAS and instead broadcast real-time quality indicators for each satellite. SBAS and GBAS do this in the form of bounding error standard deviations ("sigmas") that each user can translate into his or her position domain. If GPS III satellites did this, precision-approach users would determine that a given satellite should no longer be used when they compare their position-domain "protection levels" to their tight safe-zone requirements (known as "alert limits" – see [4]), whereas other users with larger safe zones would discover that the affected satellite does not hurt them and is better used than not used. The challenge here would be to insert this real-time quality metric in the GPS navigation data such that it can be updated often enough to meet the time-to-alert requirements. One approach would be to design in an "override" quality-metric update to future civil signals while retaining NSC for L1 C/A-code legacy users.

5.0 Timeline for GPS Enhancements

The timeline for near-term GPS enhancements is reasonably well known at this point. As noted above, the first Block IIR-M satellite (with L2C capability) will likely be launched in 2005 [7,16]. L5C will be available when the first Block IIF satellite is launched, which is currently projected to occur before the end of 2006 but may be delayed depending on how long the existing GPS satellites last. When L2C and L5C will actually be available for use depends on when control-segment upgrade "Version 6.0" is complete, which will support monitoring of these new signals, and this is not projected to be operational until 2009 or later [7].

Unfortunately, the full benefits of dual-frequency will not occur until a substantial majority (say 18 or 21) GPS satellites are of the IIR-M or later (for L2C) or IIF or later (for L5C) classes. How soon this will be the case depends on how long the existing GPS satellites last. The reason that 8 Block IIR-M launches are projected to occur in 2005 and 2006 is that many older GPS satellites now in the constellation are well past their mean lifetimes and will need to be replaced soon [16]. However, this has been true for the past several years, and existing GPS satellites continue to live longer and longer past their expected lifetimes. Barring a decision to retire satellites before they completely fail, the rate at which new satellites are launched may be lower than forecast. For example, the schedule projections in [7] assume at least three satellite launches per year. However, over the last five years, only nine GPS satellite launches have occurred (3 in 2000, 1 in 2001, none in 2002, 2 in 2003, and 3 in 2004) [32] without any noticeable loss of GPS satellite geometry quality.

Thus, several uncertainties affect how long it will take for GPS modernization to benefit civil users: the resources dedicated to it, the rate at which new satellites are launched, and the speed with which OCS improvements can be developed and tested. All of these affect the prospects for GPS III. GPS III is in an early stage of development now, and the first GPS III satellite launch likely could not occur before 2012 [7]. Because of the above uncertainties, even that may be optimistic. In short, GPS modernization is coming and will eventually revolutionize the use of GPS, but patience will be required before these possibilities become real.

6.0 Summary and Conclusions

It is clear from the many aspects of GPS modernization discussed in this paper that the capabilities that GPS provides to users will continue to grow with time. This is true even for "standalone" GPS-only users who do not take advantage of the increasing availability of SBAS, GBAS, and (eventually) new satellite constellations such as Galileo and QZSS. When combined with these other enhancements, the future of civil user navigation using GNSS looks very bright indeed.

One of the keys to fulfilling this promise is to make sure that, as GPS and other GNSS modernization decisions are made, civil users keep abreast of developments and make sure that the decision makers understand how the proposed changes will affect the many different types of civil users. Because of the multiplicity of GNSS users, it is difficult for any decision maker or group of decision makers to fully understand how their decisions will affect users outside of their own areas of experience. Therefore, it is up to civil user groups to work together and make their consensus preferences known.

In addition to the IGEB study on L1C user preferences [27] reported in Section 3.3, another example of civil user work to make their requirements clearer to the GPS JPO is the work done by the U.S. Department of Transportation (including the FAA) to produce a document submitted to the Interagency Forum for Operational Requirements (IFOR) [30] that explains in detail the technical assumptions on GPS performance (e.g., nominal URE, satellite outage rates, etc.) made by existing civil transportation applications. Another example, the Integrity Failure Modes and Effects Analysis (IFMEA) effort [31], shows how civil and military users can work directly with the GPS JPO to better understand GPS weaknesses and how to correct them in future modernization efforts. Activities like these are needed throughout the GPS and GNSS modernization process to ensure that civil user benefits are as great as the effort and resources invested in modernization allow them to be.

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