Worldwide Trends in GNSS Development and their Implications for Civil User Performance and Safety

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BIOGRAPHY

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. His current work includes the development of revised system architectures and algorithms for the next phase of LAAS to support operations up to and including Category III precision landings. He also participates in the development of the next generation of GPS, now known as "GPS III." His interests extend to the optimal design of navigation systems and engineering systems in general under significant prior uncertainty. Dr. Pullen has won several awards for his work, including the Institute of Navigation "Early Achievement Award" in 1999.

ABSTRACT

This paper examines the trends that are apparent in the worldwide development of Global Navigation Satellite Systems (GNSS) and how they will affect the growing population of civil users of satellite-positioning technologies. It reviews the development of new GNSS systems such as Galileo (Europe) and Beidou (China) as well as the growth of satellites that augment existing GNSS constellations, such as the Japanese Quasi Zenith Satellite System (QZSS). It also considers the many new and improved signals on multiple frequencies that these systems and the ongoing modernization of the U.S. Global Positioning System (GPS) will make available to near-future civil users. The additional satellites and additional signals appear to promise greatly improved civil user performance in coming years, but much thought should be given as to how best to make use of this enhanced system performance redundancy. This paper proposes several approaches to utilizing both additional satellites and frequencies without requiring that all satellites in view or all signals broadcast be received and utilized.

1.0 Introduction

Over the past twelve years since the achievement of full operational capability (FOC) of the U.S. Global Positioning System (GPS) in 1995, the number of civil users of satellite navigation has grown at a remarkable rate, and the performance that civil users can expect has also improved steadily (see [1]). The use of satellite navigation is now an accepted and unremarkable part of everyday life throughout the developed world, and this trend looks set to continue for at least the foreseeable future even if no major changes to satellite navigation capabilities were to occur. Nonetheless, major changes are set to occur. In addition to the continuing modernization of GPS, several new satellite constellations are expected to take shape in numbers over the next decade or so, and at least some of these are expected to be interoperable with GPS, creating a truly robust, world-wide, multi-component Global Navigation Satellite System (GNSS).

This paper describes the key elements comprising the new GNSS, highlights how the growing stream of civil users will be affected by this transformation, and proposes several important technical areas where additional work should be done to insure that future civil users obtain the greatest possible benefits. The most significant change is the coming of new navigation satellite constellations that will be compatible with GPS. Two forms of these exist. The first are "complete" constellations of satellites in Middle-Earth-Orbits (MEO) that could be used independently of GPS, such as the European Galileo system, the Russian GLONASS system (which has existed for many years but never reached end-state capability), and the Chinese COMPASS system. The second are smaller sets of satellites in MEO or Geosynchronous orbits (GEO) that are designed to augment another constellation, such as the GEO satellites used to augment GPS and enable Space Based Augmentation Systems (SBAS) such as the U.S. Wide Area Augmentation System (WAAS), the European EGNOS, and the Japanese MSAS systems. Another example is the Japanese Quasi-Zenith Satellite System (QZSS), which is designed specifically to augment GPS and provide additional ranging satellites visible at high elevation angles over Japan [2]. Each of these near-future satellite systems will be discussed in more detail in Section 2. Section 3 will briefly summarize the present status and future prospects of space-based and ground based augmentation systems to GNSS.

A key variable among the new satellite constellations coming on-line is the degree to which they are interoperable with the existing GPS. QZSS and SBAS augmentation satellites, which are designed to work directly with GPS, are on one side of this spectrum, while the other side (as of the time this article is written) is the Chinese "Beidou" or "Compass" system, of which little is known at this point and which may have a primarily military purpose. In the middle is the European Galileo system, which is designed for independent operations, but for which years of meetings between the U.S. and the European Union have been needed to devise signal designs, clock-offset information sharing, and other mechanisms to maximize the ability of GPS and Galileo to support combined GPS/Galileo user positioning [3]. Even without COMPASS or GLONASS, the combination of GPS, Galileo, and SBAS and/or QZSS augmentation satellites will provide far superior satellite geometry and signal availability than is available today with GPS alone. The requirements to achieve interoperability between different GNSS elements in order to achieve maximum civil user benefit will be discussed in Section 4.

To the degree that interoperability is achieved, the resulting improvements to satellite navigation will make a big difference to both present and future civil applications. But before these improvements are simply added on top of existing civil-GNSS user algorithms, we should be careful that the theoretical benefits that should result from them will actually be realized in a cost-effective manner. Section 5 examines this issue by considering some weaknesses that exist in current civil user equipment and the degree to which GNSS modernization addresses them, does not address them, or potentially makes them worse. With the potential for unforeseen negative consequences in mind, an increased focus on real-time "executive logic" in civil user algorithms is recommended as the best means to make optimal use of the many facets of the future GNSS. Two specific examples are explored in some detail in Section 5. One is the old issue of "satellite selection," meaning selection of a subset of all satellites in view as the best choice for a given navigation task. The second is the question of when multiple frequencies should be used to perform ionosphere delay removal and when this should not be done (i.e., when does the cost and risk imposed by this removal outweigh its benefit?). The larger point that this paper raises is that the potential for improved civil user performance from GNSS modernization is quite possibly greater than it appears from the individual improvements to GNSS that are now occurring.

2.0 GNSS Satellite Constellation Evolutions

2.1 The Global Positioning System (GPS)

As determined by continuing observations of GPS performance and coverage over time, the GPS constellation continues to meet and, in most cases, exceed the goals stated in the 2001 Standard Positioning System (SPS) Signal Standard [4] for civil users (see [5] for an example of the quarterly GPS performance reports prepared by the U.S. Federal Aviation Administration, or FAA). Having said this, GPS constellation maintenance represents one ongoing concern, as the constrained number of replenishment launches and satellites has left many old satellites continuing to operate well past their design lifetimes. For example, at the time of writing (7 November 2007), there were a total of 29 active and usable GPS satellites. This count does not include SVN 55/PRN 15, which was launched on 17 October 2007 and was not yet approved for use, nor does it include the very-old SVN 23/PRN 32, which had been flagged as unhealthy since 27 June 2007 [6,7]. Of these 29 satellites, 14 (almost half) had been launched more than 10 years earlier, and 10 had been launched more than 12 years earlier. Of the 24 satellites in primary orbit slots which contribute most directly to user coverage, 9 and 5 had been launched more than 10 and 12 years earlier, respectively.

The slow aging of the GPS constellation has been a concern for quite some time, and the GPS Joint Program Office has adapted well to maintaining such a system while waiting for more modernized satellites (Block IIR-M and IIF) to be launched (see [8]). As shown in [9], GPS coverage still easily exceeds the SPS goals expressed in [4] even when occasional satellite outages occur, and the overall SPS positioning accuracy of the system is, on the whole, as good as ever. The problem for most civil users is that they long ago grew to expect more from GPS SPS than SPS expects of itself according to the SPS Signal Standard [4]. Thus, the rare system failures, such as the orbit maneuver of SVN 54/PRN 18 on 10 April 2007 while the satellite was still flagged as "healthy" for navigation use (see [5] for details), and the occasional occurrence of multiple satellite maintenance actions in close proximity to one another, does affect the performance of many civil users.

As described in detail in [1], the future of GPS is very promising. The gradual replacement of today's aging Block IIA satellites with Block IIR-M, Block IIF, and (starting sometime next decade) Block III satellites will provide better across-the-board performance in addition to new capabilities, such as additional civil signals on the L2 and L5 frequencies. The improvement in GPS JPO maintenance capability projected in [1] is now complete – the NGA/NIMA monitoring sites shown in that paper have been added to the pre-existing U.S. Air Force monitoring sites to give fully-redundant visibility of each GPS satellite. Also under discussion as part of planning for GPS III is "growing" the GPS constellation to a 30-satellite standard.

Much of the motivation for this and other enhancements to GPS is the widespread recognition within the U.S. that maintaining GPS performance solely in accordance with the SPS Signal Standard is not sufficient to meet the needs of GPS users (both civil and military) at present and becomes less so as every year passes. Two counter-balancing factors apply. The first is the acceptance that other funding demands will continue to limit what can be spent on GPS modernization and operations; thus not all wished-for GPS improvements can be realized. The second is the understanding that civil users, at least, have already begun to shift toward using GPS in combination with augmentations such as SBAS and will continue to shift toward the use of new augmentations and future satellite constellations as they become available.

2.2 The Russian GLONASS System

While the Russia GLONASS satellite constellation has a history almost as long as that of GPS, GLONASS is still struggling to achieve a full constellation of satellites as successive generations of satellites increase the navigation capability and reliability of GLONASS on a per-satellite basis. According to [10], as of 21 September 2007, a total of 11 out of a planned 24 GLONASS satellites (in 3 orbit plans) were in orbit, and of these, 9 were healthy and usable for navigation. Seven of the 11 satellites in orbit were of the newer GLONASS-M type, which is being launched at present in units of three by Proton-class rockets. The relatively short design lifespan of the GLONASS-M satellites (7 years, which if achieved would be a major improvement over earlier GLONASS satellites) and setbacks such as the Proton launch failure on 6 September 2007 (carrying a Japanese communications satellite instead of GLONASS satellites but still potentially upsetting future Proton launch plans [11]) pose significant obstacles to completing the GLONASS constellation and making it fully usable for navigation.

Despite the checkered history of GLONASS, the projections shown in [10] (most likely made before the Proton launch failure) suggest that 24 GLONASS satellites will be in orbit in the 2010 – 2011 time frame, and additional plans for GLONASS modernization in the next decade suggest that Russian hopes and plans for GLONASS are as bright as ever. These plans include at least the possibility of shifting from today's FDMA system to a CDMA system like GPS and Galileo, and Russia continues to show interest in international cooperation on GLONASS [25]. One tangible symbol of Russia's motivation to rapidly proceed with GLONASS is the successful launch of three new GLONASS-M satellites on a Proton launcher on 26 October 2007, less than two months after the 6 September failure of the same launcher type as mentioned above. The next launch of three more GLONASS-M satellites is scheduled for 25 December [26].

2.3 The European Galileo System

Technical progress on the European Galileo navigation system, comprising of 30 future navigation satellites (27 active satellites in a 3-plane 27/3/1 Walker configuration plus 3 spare satellites, one per plane) in MEO orbits (see [16]), has been rapid over the past several years. Tests of the GIOVE-A prototype satellite have secured the Galileo signal frequencies and confirmed the basic operation of the satellites [12,15]. The monitoring of GIOVE-A signal broadcasts led to the decoding of the GIOVE-A signal structure by more than one party not affiliated with Galileo (e.g., see [13]), perhaps helping to motivate the early release of the Interface Control Document for the Galileo "Open Segment" (OS) signals in May 2006 [14]. The second prototype satellite, GIOVE-B, is scheduled to be launched in early 2008 [15].

The next technical step for Galileo beyond completion of GIOVE activities is known as "In Orbit Validation" or (IOV). As part of IOV, the first four operational Galileo satellites to be launched will be used with the initial set of ground monitor stations (Galileo Sensor Stations, or GSS's) and uplink antennas to test all facets of the performance of the eventual end-state Galileo system [15]. This approach to early-stage system testing mirrors (on a larger scale) the "Yuma Proving Ground" testing conducted on the original GPS Block I satellites and user equipment in the late 1970's [19]. As shown in the projected Galileo development and deployment schedule in [15], with the first launch of IOV satellites planned for early 2009, the "operational phase" of Galileo's life cycle will not begin before 2012 (2013, according to [17]), and it seems very optimistic to expect the 30-satellite constellation to be completed before 2015 even if no significant program setbacks are encountered.

While technical progress on Galileo has been steady, the political fortunes of Galileo within Europe's Byzantine political framework has been much less so. However, a major step forward appears to have been taken with the recent shift in plans toward a traditional public (governmental) procurement of Galileo as opposed to Public-Private Partnership (PPP), on which negotiations appeared to have been stalled for many months (see [17,18]). Whether the European Union

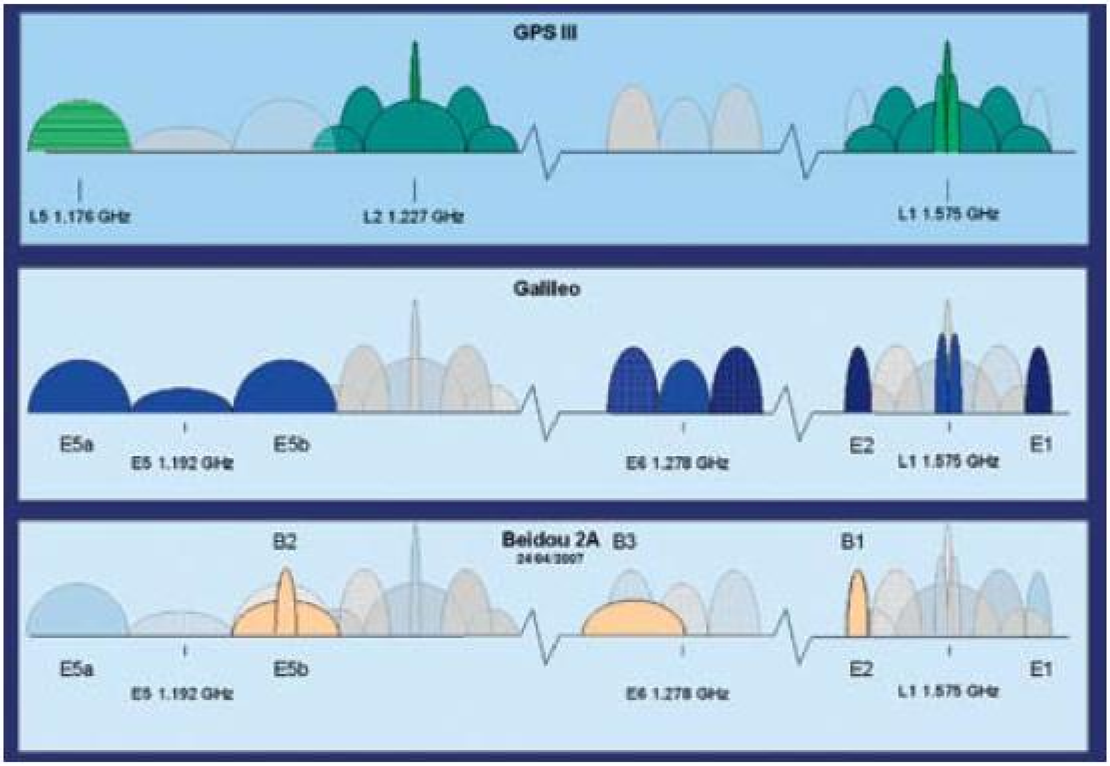

Figure 1: Comparison of Modernized GPS, Galileo, and Beidou Ranging Signals [21]

Transport Ministry will accept this change is not yet clear, but the promise of a resolution of the "PPP dilemma" in the near future would be of great benefit to both the Galileo program itself and the many equipment manufacturers and potential users waiting for more predictability from Galileo before committing major resources toward it. When Galileo finally does come to fruition, the presence of a second satellite navigation system whose scope and "Open Segment" performance is likely to at least match the performance of today's GPS SPS will no doubt change the way users worldwide see their options with respect to equipping with satellite navigation technology.

2.4 The Chinese "Beidou" or "Compass" System

In contrast to the public evolution of Galileo over the last decade from a plan to a very real concept, another satellite navigation system that perhaps started from scratch at about the same time has made similar strides in relative secrecy. This system is known in Chinese as "Beidou" (北斗) or "Compass" in English (more fully, the "Compass Navigation Satellite System" or "CNSS"). The Compass system became much better known on 14 April 2007 with the launch of its first MEO satellite, known as "Compass M-1", into an orbit with an altitude between those of GPS and the planned Galileo satellites [20]. As a MEO satellite and an apparent precursor to an independent navigation system on the scale of GPS and Galileo, this satellite marks a significant departure from the previous four GEO satellites launched by China (the first Compass GEO satellite was launched on 31 October 2000). Relatively little is known about the eventual shape of the Compass system, but it is projected to have a total of 30 MEO satellites (in 6 orbit planes) and 5 GEO satellites when completed [20,21,24].

As with the future (modernized) GPS and Galileo systems, Compass plans to broadcast CDMA-type ranging signals on multiple frequencies, suggesting that, in principle, Compass signals could be combined with GPS and Galileo signals by future civil navigation users. Figure 1 (from [21]) compares the signal spectra plans for all three systems and shows that the Compass B1, B2, and B3 signals overlap the planned Galileo E2, E5b, and E6 signals, respectively. The work performed in [20,21] was able to identify at least the I-channel components of the ranging signals broadcast by the Compass M-1 satellite on all three of these frequencies as combinations of Gold codes (identical 11-stage Gold codes on E2 and E5b, two 13-stage Gold codes on E6) with 20-bit (or 20-msec) Neuman-Hoffman secondary codes.

The fact that the Compass ranging signals identified thus far are quite similar to those used by GPS and Galileo at least supports the possibility of future use of Compass with other elements of a global GNSS. However, there is one potential technical difference: the original Compass GEO system (denoted as “Beidou-1”) is a “two-way” ranging system in which users measure “round-trip” time between their own transmissions to Compass satellites and the satellites’ return transmissions [24,25]. Not only does this approach differ from that of all other GNSS systems, it imposes major disadvantages on users, who would need very powerful (and thus bulky) transmitters to send signals to satellites. However, since the new Compass satellite (denoted as “Beidou-2”) downlink signals are similar to those of other GNSS systems, this element of Compass could be changed to increase its utility and make it more interoperable with other GNSS systems. According to [24], the intent in fielding next-generation satellites is to do just this and remove the need for two-way ranging for users of the end-state “Beidou-2” system.

2.5 The Japanese QZSS Augmentation to GPS

The Japanese Quasi Zenith Satellite System or “QZSS” (準天頂衛星 in Japanese) currently occupies a unique location within the spectrum of satellite navigation systems in that it is designed to augment another satellite navigation system (in this case, GPS) but is not limited to a “bent-pipe” transposition of ground-generated ranging signals through a GEO communications satellite. Instead, QZSS satellites will occupy inclined, eccentric MEO orbits chosen specifically for optimal high-elevation visibility for users in Japan, and they will operate more like independently-operating GPS or Galileo navigation satellites rather than in the restricted ground-controlled manner common to SBAS GEO augmentation satellites (see [2,22]). This precedent is important for the future of GNSS because, while only a very few nations or groupings of nations have the resources to build their own complete satellite navigation system on the scale of GPS, many other nations will have the capability to build GNSS augmentations on the scale of QZSS in the future, and the benefits that can be obtained for users in those nations are substantial compared to the much lower costs of QZSS-scale systems compared to GPS-scale systems.

Because the details of QZSS design and planned future operation are likely to be well-known to this audience, this paper will not delve into these areas in detail – they are well-described in [2,22,39] and other references. Within the context of this paper, the key thing to note is where and how well QZSS fits into the evolving picture of the future GNSS. As shown in [2], QZSS will broadcast civil ranging signals to match each modernized-GPS civil signal on L1, L2, and L5 plus an “L1-SAIF” signal designed for enhanced SBAS performance and a new “LEX” signal on the Galileo E6 frequency. QZSS demonstrates that the building blocks of GNSS established by global-scale systems such as GPS and Galileo are starting points for further innovation on a regional scale. One key QZSS innovation that, if successful, will likely be used in future regional GNSS systems is the remote-time-synchronization system known as RESSOX (see [39]) that will adjust the effective clock time of each QZS to match a ground-based atomic frequency standard; thus avoiding the need for atomic clocks on the QZS satellites themselves.

3.0 GNSS Augmentation System Prospects

GNSS augmentations that broadcast local-area or wide-area differential corrections provide significant performance enhancements to a significant fraction of the GNSS civil user base. For a small fraction of these users, augmentation is required to meet stringent accuracy or integrity (safety-assurance) requirements. The majority of users of differential corrections, such as those conducting surveying or precision farming, provide their own local-area differential corrections from nearby static reference stations using well-known algorithms (see [31]). Users with strict integrity requirements are much more likely to use existing or soon-to-come governmentally-provided SBAS or Ground Based Augmentation Systems (GBAS) (see [32]). Because SBAS, in the form of the U.S. WAAS (and soon the European EGNOS and the Japanese MSAS) provides freely-available corrections over very large areas via Geostationary satellite broadcast, many users without a need for SBAS performance will use SBAS corrections to improve their performance to the degree that they are available.

Among SBAS systems, WAAS was the first to be commissioned (in July 2003), and as of September 2007, it has expanded to physical maturity with a total of 38 reference stations (that make GPS measurements), 3 master stations (that compute satellite and ionosphere corrections), 2 new GEO satellites at 107^o and 133^o West longitude, 4 ground-earth stations (that uplink corrections and ranging signals to the GEO satellites), and 2 operational control centers [33]. What remains to be done in the current phase of WAAS development is to complete a sequence of software upgrades that will provide full, optimized LPV-200 precision-approach coverage to as much of North America as possible (note that WAAS reference stations have now been fielded in Alaska, Canada, and Mexico). Completion of these software upgrades is expected in 2008. Meanwhile, MSAS fielding and testing was completed between 2005 and 2007, and MSAS was commissioned for aviation use (supported by two MTSAT GEO satellites at 140^o and 145^o East longitude) on 27 September 2007 [2]. EGNOS is also close to completion and expects to complete qualification testing in 2008 and officially enter service in 2009 with 34 reference stations and 3 GEO satellites at 15.5^o West, 5^o East, and 25^o East longitude [15].

GBAS ground systems are also not far from entering service to support Category I precision approaches at airports where these systems are fielded, but no ground system meeting the RTCA LAAS or ICAO GBAS SARPS requirements has yet been approved for use. This is unfortunate because approved GBAS avionics equipment has existed for several years and now equips several types of new Boeing aircraft (GBAS-equipped Airbus aircraft should begin appearing in 2007). The SLS-4000 LAAS ground system developed by Honeywell is expected to gain FAA System Design Approval before the end of 2008 [33]. To achieve this approval, several difficult integrity threats have had to be addressed and mitigated, including anomalous ionosphere spatial gradients [34], very large ephemeris errors [35], and satellite signal deformation [36]. WAAS was able to mitigate similar threats by abandoning its intent to providing Category-I-like service (protecting a Vertical Alert Limit (VAL), or safety bound, of 10 meters) and instead only supporting first LNAV/VNAV operations (with a 50-meter VAL) and now LPV-200 operations (with a 35-meter VAL) with lower-than-planned availability. LAAS does not have that degree of freedom – it must demonstrate that it can support Category I operations with high availability to have any future. It is hoped that the initial commissioning of Category I LAAS ground stations in the U.S. and several other nations (including Australia, Germany, Spain, and Brazil) combined with new single-frequency [37] and dual-frequency [38] concepts for achieving Category II/III LAAS will provide the impetus more-active development and fielding of LAAS to replace older aviation navigation aids in the early part of the next decade.

4.0 GNSS Satellite Constellation Interoperability

As highlighted in Figure 1, the shape of the future of GNSS (with the possible exception of GLONASS) is fairly clear – multiple satellite constellations will broadcast CDMA-like ranging signals with similar modulations on similar frequencies. At first glance, this is great news for future GNSS civil users, as it suggests that user equipment tuned to receive signals on two or three specific frequencies will have multitudes of satellite signals available. However, as has been learned over the past few years of meetings between GPS JPO and Galileo experts (see [3]), interoperability is far more difficult to obtain than that. A key lesson from the GPS/Galileo process is that *interoperability is not the default result*. If it is to be obtained at a useful level at all, is the product of years of hard work and close coordination between system experts who all hope to achieve interoperability despite the many technical and programmatic obstacles that will exist.

Before proceeding further, it is important to better define "interoperability" in the context of the future of GNSS. Before defining "interoperability", we need to define the more limited concept of "compatibility". Two GNSS systems are said to be "compatible" if they can be used together or separately without interfering with each other or having one system cause non-negligible problems with the other. Two systems that do not interact with each other are "compatible" by definition as long as the emissions of one system do not degrade those of the other. For GNSS systems that broadcast signals at similar frequencies and with similar CDMA waveforms, such degradation could occur due to an undesirable increase in the noise floor at a given frequency or (worse) an unacceptably high probability of cross-correlation between the signals of different systems, making it more difficult than it should be to correctly acquire, track, and guarantee proper error bounds on desired signals [3,23]. These possibilities make it clear that signals from multiple GNSS systems of similar types at similar frequencies could do more harm than good if some degree of coordination is not in place.

"Interoperability" is much more demanding than simply avoiding mutual harm. Two systems are said to be "interoperable" if they can be used together in a manner that provides better service or performance to some class of users than would be obtained by using one system or the other by itself [3,23]. Note that interoperability includes compatibility because non-compatible systems could not be combined to produce a joint system that would be better than either system alone. However, achieving a useful degree of interoperability goes far beyond that.

Two examples of GNSS interoperability are worth noting that demonstrate the degree of effort and coordination that is required. The first is the initial Japanese proposal to augment GPS with QZSS to give specific performance advantages to users in and near Japan. Because QZSS was designed to work directly with GPS, it used the same signals as did GPS, and to gain official permission for this, it applied to the GPS JPO for permission along with getting C/A-code PRN assignments for QZSS satellites. Several years of coordination efforts have made it possible for QZSS to directly augment GPS with minimal cross-system complications. One example of this close relationship is the fact that time offsets of individual Quasi Zenith Satellites (QZS's) are expressed relative to GPS master time, thereby eliminating the need to maintain a separate QZSS master time and broadcast its offset with GPS time [22]. This level of integration with GPS goes beyond interoperability to offer the prospect of what Prof. Bradford Parkinson defines as "interchangeability", whereby satellites from multiple constellations can be mixed together in a single user's navigation solution with no loss of accuracy (compared to using only satellites from a single constellation) and no loss of redundancy (e.g., no need to use one QZS satellite to resolve time offsets or other biases between GPS and QZSS constellations) [25].

Achieving interoperability between GPS and Galileo is a much greater challenge because Galileo was intended from the start to be a system which would operate independently from GPS. In fact, one key rationale for Europe building Galileo in a world that already had free access to GPS SPS was that access to GPS could be denied by the United States at some point in the future. The U.S. had its own concerns that Galileo would overlap with future GPS military (M-code) signals such that the U.S. could not deny its adversaries the use of Galileo open signals without also denying itself the ability to use the GPS military service (known as the Precise Positioning Service, or PPS) [27]. Fortunately, both sides had the others' interests in mind, and over several stages of negotiations and information-sharing between 2000 and 2006, the GPS and Galileo programs agreed upon the best spectra and signal structures for both the modernized GPS civil signals and the new Galileo signals, whose definitions changed at least once during this process [3]. The results of these years of patience and hard work will be highly favorable for the users of both modernized GPS and Galileo.

One particularly favorable outcome of the GPS/Galileo coordination process is that the same signal definition will be used as the future L1C signal on GPS and the E1 open-service signal on Galileo [28,29]. Use of the exact same signal minimizes, if not eliminates, inter-signal biases across signals that must be calibrated out for maximum accuracy, as is done today when making dual-frequency L1-L2 measurements. This cooperative decision to eventually provide the same modernized civil signal from as many as 60 or more combined GPS and Galileo satellites makes the promise of "interoperability" and possibly even "interchangeability" a future reality.

Examining the means by which QZSS and Galileo are working to achieve interoperability with GPS makes it clear that interoperability does not come naturally. As noted before, the Chinese Compass system is developing the technical elements needed to make interoperability with GPS and Galileo possible, and the possible future shift from FDMA to CDMA technologies would open this door for GLONASS as well. With respect to Compass, however, there is reason for concern because of the degree of secrecy that has been attached to information about the details of Compass operations to date. Not only are Chinese representatives of the Compass system typically not present at international meetings (no presentation on Compass was given at the 47th CGSIC meeting in Fort Worth, Texas, USA, prior to ION GNSS 2007, unlike every other navigation system mentioned in this paper, although a very brief Compass presentation was given at a recent international meeting in Bangalore, India [30]), but Chinese working on satellite navigation appear uncomfortable even discussing the subject.

Given that the Compass briefing given in Bangalore states that "is willing to cooperate with other countries to develop the satellite navigation industry together" [30], the reason for China's reticence about discussing the details of Compass is unclear. It may simply be a product of the culture of the Chinese government in avoiding open discussion, or it may be a product of the original development of Compass by the Chinese military. The Compass briefing from Bangalore states that the oversight of Compass has shifted to the China Satellite Navigation Project Center (CSNPC), although it is not clear who oversees this body [30]. Regardless of the reason, China has not yet shown any willingness to participate in the kind of open, frank interchange that will be needed for Compass to become interoperable with other GNSS systems. Before interoperability is discussed, the U.S. and Europe already have a potential "compatibility" problem with the fact that the Compass B1 signal shown in Figure 1 overlaps with the Galileo E2 Public Regulated Service (PRS) signal.

5.0 Optimal Enhancement of Civil User Performance

The planned enhancements to GNSS between now and 2015 (not to mention 2025) are so extensive that, even if only half of them are realized, and if these improvements are simply incorporated into future user equipment with no other modifications, the performance of future civil user equipment will be far better than it is today. While that is a comforting prospect, our job as GNSS engineers is to look forward and foresee not only the obvious advantages of GNSS evolution but the problems that might follow in its wake and be prepared to address them in designing modernized user equipment. This section begins by examining deficiencies in current user equipment that reduce GNSS availability more than is necessary and provides examples of the types of "executive logic" that should be added to future user equipment to achieve optimal performance from the a future GNSS in which signals from multiple satellite navigation systems are available on multiple frequencies.

First, it is useful to divide the civil GNSS user population into two groups. The first group is the vast majority of automobile, pleasure-boat, and mobile-phone users who do not rely on GNSS for safety-critical applications and instead simply want the highest availability of a given level of accuracy that is possible. The second group is the much smaller set of aviation, railroad, commercial maritime, and other users who count on GNSS to provide safety-critical guidance. For them, the highest availability of a given level of integrity is their primary objective. The need to mitigate all possible integrity threats under worst-case conditions in SBAS and GBAS (as mentioned briefly in Section 3) leads to substantial availability loss compared to what could be achieved with less-conservative threat assessments, but availability and continuity are also lost needlessly because insufficient attention is paid to preventing detected failures of individual measurements (many of which are "false alarms") from causing service to be lost for long periods of time when only one or two temporary measurement exclusions were needed (see [40] for a description of Executive Monitoring or "EXM" for a prototype LAAS ground system that is intended to avoid such problems).

While the lack of optimal executive-monitor logic for all conditions is a concern for high-integrity users, it generally does not lead to loss of integrity (only loss of availability or continuity), and its overall impact is probably much lower than the lack of similar logic in the inexpensive equipment that supports the first group of users. As with other classes of consumer electronics, the performance-to-price ratio of inexpensive GPS receiver equipment for use in mobile phones and cars has dramatically improved in the last decade. At present, very cheap ($5 or less) GPS units exist for mobile phones, allowing wide penetration of satellite navigation into the mobile-handset market [25]. Without increasing in cost, these units will need to handle multiple satellite constellations and signals on multiple frequencies to take full advantage of the future GNSS. Instead of tracking 8 – 12 GPS L1 signals now, a future dual-frequency GPS/Galileo user might want to track as many as 48 signals (L1 and L5 signals on 24 combined GPS and Galileo satellites in view). Much of the effort in making this possible will be in exploiting "Moore's Law" to gain the factor-of-4 increase in processing power needed to track 48 signals instead of 12. But it would be foolish to stop there. By sacrificing perhaps 5% of their total processing power to executive-logic functions, the need to track all GPS and Galileo signals on both frequencies can be avoided with equal or better performance than would be obtained by using all signals.

Two specific sub-functions of executive logic (among others) would make this possible. The first is an old topic known as *satellite selection*, which was an active research area in the early 1990's as many GPS launches in rapid succession quickly created a 24-satellite constellation that overwhelmed the capabilities of the many 4 and 6-channel receivers of the time. For these receivers, some logical method for selecting which satellites M out of the visible set N would be utilized in position-fixing was highly desirable (the alternative was to be at the mercy of the lower-level acquisition and tracking procedures, which might neglect a newly-risen satellite in order to keep tracking a less-valuable setting satellite). Various methods have been used, including selecting the M satellites with the highest elevation angles, selecting the M satellites that, when used for position-fixing, give the best Dilution-of-Precision or DOP measure, and other related methods intended to find the subset with the best accuracy (see [41]) or the tightest integrity bound (see [42]).

The general problem in optimizing satellite-selection algorithms is to find the optimal tradeoff between selection performance and selection algorithm complexity (see [41]). For the case of aviation users who need both very high integrity and very high availability (and whose avionics will cost thousands of dollars per unit), more complexity is usually worth it if a performance gain can be obtained. Mobile-phone users are on the other end of the spectrum and will not have much processing power to spare to examine many permutations of possible satellite sets before selecting the optimal one. Therefore, the best satellite-selection approach for inexpensive user equipment would be one that prevents unnecessary navigation signals from being acquired in the first place.

How might such a system work? First, the navigation unit would have a "mission need" utility function for the user's current operation that could quickly be evaluated for any set of usable satellites. It would not require pseudo-inverse range-to-position transformations; instead, it would assess the positioning utility of each satellite based on its elevation angle and the presence of nearby obstructions and multipath reflectors (based on a digital map of the vicinity given an approximate position fix). Thus, the unit's executive logic could quickly determine which satellites would be useful to acquire and which would not (due to high multipath, high ionosphere error, or simply insufficient improvement to justify the processing burden). Since the unit would be able to predict some changes but not others (e.g., loss of satellite tracking as the user moves past a vehicle that partially shades the sky), it would need to re-evaluate its utility function frequently, and the utility function would need to consider the value of one or two additional satellites to provide margin against sudden unexpected loss of high-value tracked satellites.

Another function of executive logic would determine when ionosphere delay removal from pseudoranges is likely to improve positioning accuracy and when it would not. As noted above, almost all GNSS satellites to be launched from this point forward (including the GPS Block IIR-M and IIF satellites) will broadcast civil ranging signals on two or more frequencies. This provides three major advantages to users: (1) it provides another dimension of signal redundancy, in this case against unintentional radio frequency interference (RFI) on a single frequency; (2) it allows for the ionosphere delay impact on GNSS ranging measurements to be estimated and removed; and (3) it supports "widelane" and "multilane" mechanisms for converging on carrier-phase integer ambiguities for carrier-phase differential GNSS (CDGNSS) users. The second benefit (ionosphere delay removal) will significantly improve standalone (non-differential) user accuracy during most periods of the day, particularly during local daylight hours. However, using signals from two frequencies to remove ionosphere delay has the effect of combining receiver noise and multipath errors on both frequencies, thereby increasing this component of the user's error budget by a factor of 2 or more (see [38]). Therefore, when the ionosphere is very likely to be quiet (e.g., local nighttime in locations that do not normally experience enhanced ionosphere activity), better accuracy will normally be obtained by not removing ionosphere delays from user pseudoranges. However, users requiring very high integrity will normally make some ionosphere correction at all times (when possible) to limit the risk of anomalous (and unpredictable) ionosphere activity affecting them (see [38]).

6.0 Summary

This paper has outlined the progress being made around the world toward developing new satellite navigation systems and improving the ones that already exist. While these developments will evolve over the next decade, and the final shape of the systems and modernizations now being planned is far from clear, what is apparent is that future GNSS users will have more satellites to navigate from, and these satellites will be broadcasting improved navigation signals on multiple frequencies.

Today's civil GPS users have reason to hope that the multiple new satellite-navigation systems to be fielded over the next 10-15 years can be used cooperatively with GPS in real time. This would greatly increase the accuracy and availability of GNSS, particularly for users in urban areas who do not have a full view of the sky. Whether or not "interoperability" of GNSS systems is a reasonable prospect depends on the willingness of system designers from various nations to work together. Achieving interoperability is indeed a challenge – it will not happen automatically. The examples of U.S.-Japanese cooperation on QZSS and U.S.-European cooperation on GPS and Galileo show both that it is possible and that it requires years of extensive effort and commitment.

As the future of GNSS takes shape, civil user equipment will need to grow significantly in capability if it hopes to take advantage of the new capabilities that GNSS will offer. Simply increasing processing power (while keeping prices low) to be able to utilize many more satellites on multiple frequencies is challenging enough. However, taking full advantage of GNSS modernization requires adding executive logic to be able to optimize the use of the many new signals in real time, as trying to use all of them will be expensive in terms of processing power and will not, in general, give optimal accuracy. Enhanced executive logic has the additional advantage of better handling "cold-start" and "warm-start" satellite acquisition and, in rare cases where RF interference on one or more GNSS frequencies exists, to mitigate it to the degree possible.

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