INVITED PAPER

Satellite Navigation for Aviation in 2025

This paper reviews the techniques that enable satellite navigation for aircraft, the benefits of satellite navigation in aviation, and how new and modernized GNSS constellations will further expand its performance and coverage in the near future.

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ABSTRACT | Satellite navigation has been used for aircraft navigation for more than 50 years. In the last ten years, the capabilities of satellite navigation have been expanded to more demanding phases of flight, in particular vertical guidance down to 200 ft, thanks to the implementation of augmentation systems. In this paper, we attempt to predict the state of satellite navigation in the next 15 years. We will start by reviewing the challenges that must be addressed by satellite navigation for aircraft guidance. Then, we will describe the current techniques that enable satellite navigation for aviation and the level of performance they achieve today. This will be followed by a description of the upcoming changes to satellite navigation, which include the launch of new constellations and the introduction of new civil signals. Despite these developments, satellite navigation is inherently vulnerable to radio-frequency interference so that backup navigation systems are still necessary. Nonetheless, these improvements will have a great impact on the availability and level of service achieved by satellite navigation, in particular enabling worldwide coverage of vertical guidance.

KEYWORDS | Compass; Galileo; Global Positioning System (GPS); GLONASS; ground-based augmentation systems; radio-frequency interference; receiver autonomous integrity monitoring (RAIM); satellite navigation; space-based augmentation systems

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I. INTRODUCTION

Compared to the development of computers, or the Internet, or even cars, the evolution of aviation equipment appears to be very unhurried. Several factors contribute to this very gradual pace, but one of the most important is the extreme care with which any innovation affecting safety has to be examined, evaluated, analyzed, and tested. Satellite navigation equipment for aircraft is not an exception, so predicting its future for the next 20 years is relatively easy compared to predictions for other fields.

In the paragraphs below we will describe briefly the challenges that satellite navigation must solve to be a viable solution for aviation. Then, we will describe the systems that have been developed to overcome these challenges and the performance they offer today, or will offer very soon. There is currently an explosion in satellite navigation: before the end of this decade there will be over three times more satellites, offering civil signals in two distinct frequencies (as opposed to one today). These improvements are not yet being exploited for satellite navigation for aircraft, so after describing more precisely the undergoing changes, we will outline the plans to take advantage of them and their impact on performance. We will end with a note on radio-frequency interference, which constitutes the greatest challenge to satellite navigation in general.

II. CHALLENGES

Four primary challenges must be addressed to use satellite navigation for aircraft guidance. The first two challenges mostly have an impact on the integrity (i.e., safety) of the position solution, whereas the two last ones affect the availability of the service.

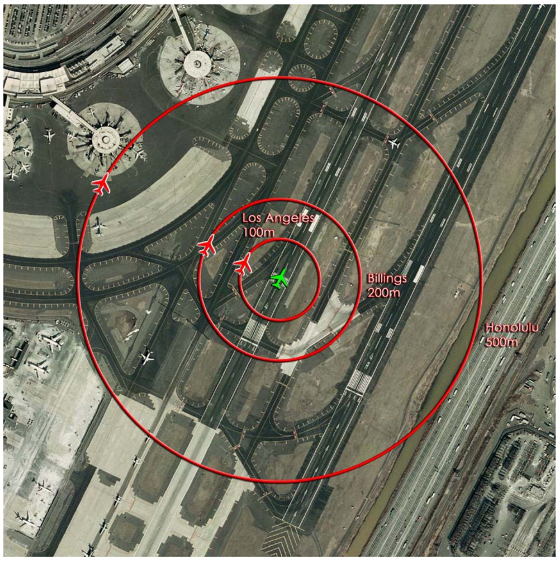

Fig. 1. ***An unflagged maneuver on April 2007 caused ephemeris errors in one GPS satellite. This ephemeris error caused location-dependent position errors of up to 500 m on receivers without detection capability. Clock runoffs cause similar errors about twice a year.***

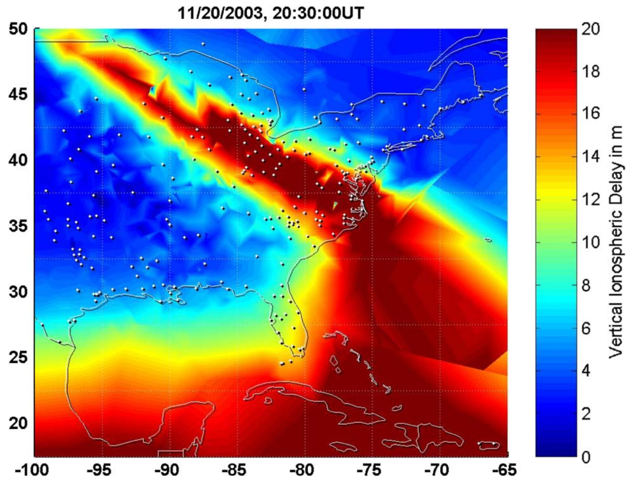

Fig. 2. ***Ionospheric storms, such as the one that occurred in November 2003, cause large pseudorange delays. Single-frequency users rely on smooth ionospheric models which cannot capture these features spatially or temporally (figure courtesy of Seebany Datta-Barua). The map above shows the vertical delay: actual range delays can be up to three times as large.***

A. Faults

Faults can arise from within a Global Navigation Satellite System (GNSS). In recent years, *major service faults* have occurred less than three times per year for the Global Positioning System (GPS). Many of these can be attributed to *clock runoff*, where the signal broadcast by a given satellite is not properly synchronized to the signals from the other satellites in the constellation. Others have been due to an upload of faulty navigation data from the GPS control segment to the GPS satellites for broadcast to the users, or from unannounced maneuvers that render the broadcast satellite position invalid. Any of these types of faults can introduce positioning errors that are hazardous to aviation users, as illustrated in Fig. 1. Moreover, in normal operation, GPS may not detect and alert these threats for several hours [4], [5], [8], [11], [13], [14], [23], [27], [34], [35], [38].

B. Space Weather Effects

Adverse space weather can generate ionospheric storms. These storms can persist for hours while introducing large pseudorange errors, which can translate into dangerous guidance errors. Fig. 2 shows the range delays that can result from an extreme ionospheric storm. Concern over the possibility of undetected ionospheric anomalies creates the largest restriction on operating regions and times for today's single-frequency users of GPS-based systems [6], [15]. In addition, the ionosphere can cause scintillation, which has an effect on the availability of the signals, especially in high latitudes and near the equator.

C. Constellation Weakness

Constellation weakness means that too few well-positioned satellites are operational in the GNSS constellation relative to the number needed to support key aircraft operations. Constellation strength means that the GNSS constellation is adequately replenished and that *all* key aircraft operations are adequately supported all of the time. In principle, GPS users only need four satellites to estimate their position. However, aircraft on approach typically need seven or more satellites to guarantee the performance needed to assure the safety of the operation. As mentioned earlier, GPS had approximately 30 operational satellites in orbit in late 2011. This constellation strength virtually guarantees that every approaching aircraft has an adequate number of satellites in view at all times. However, a spate of satellite failures in this aging constellation could weaken user geometry, and replenishment could take years to address [10]. Needless to say, similar difficulties could affect any of the GNSS constellations.

D. Radio-Frequency Interference

Radio-frequency interference (RFI), be it scheduled, accidental, or malevolent, can readily result in GNSS outages. The GNSS satellite signals originate in medium earth orbit, approximately 20 000 km from the Earth's surface. GPS signals are received below the user background thermal noise level. Hence, these signals are weak and readily overwhelmed by any of the multitude of signals emanating from terrestrial sources. RFI events can occur due to scheduled activities (e.g., U.S. Department of Defense testing). They can be accidental or unintentional, causing cochannel degradation (e.g., the use of personal privacy

Fig. 3. ***Personal privacy devices (PPDs), although illegal, have become widely available in the past year. They range in price from $30 to over $300. They radiate power of up to hundreds of milliwatts, which can have dangerous effects on satellite navigation for many miles (image courtesy of T. Kraus).***

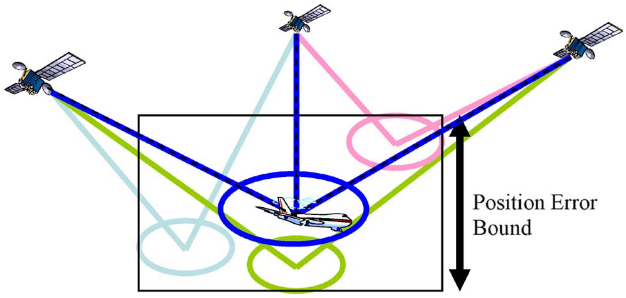

Fig. 4. ***Although it can be formulated in several ways, the basic idea of the receiver autonomous integrity monitoring (RAIM) is to compare the all-in-view solution (in blue) to the subset solutions. The subsets that need to be considered depend on the assumed prior probabilities of fault.***

devices (Fig. 3), which are only meant to jam GNSS in the immediate vicinity of an individual but that can affect all receivers within hundreds of meters [28]). Finally, these RFI events can be malevolent and intended to deny service. In the past few years, unintentional RFI incidents have been on the rise, and these have taken days or weeks to isolate and mitigate. A truly malevolent RFI event (i.e., jamming and spoofing) would be very problematic and could deny service for weeks. Finally, the plan by the mobile carrier Lightsquared to operate a broadband network in a band adjacent to GPS for terrestrial communications has put in evidence the fragility of GNSS signals with respect to RFI [20].

These challenges limit the performance of today's GPS-based systems. Any of these four challenges can lead to interruptions of service, sometimes for extended periods, and can prevent an aircraft from initiating or completing an approach procedure. Ultimately, GNSS will be fully accepted as a worldwide navigation aid for civil aircraft only when: powerful sovereign techniques exist to mitigate GNSS faults and rare normal events; the impact of weakness in any single GNSS satellite constellation is small; and RFI, even malevolent, causes only manageable disruptions to operations.

III. SATELLITE NAVIGATION FOR AVIATION TODAY

GPS is currently the sole GNSS constellation in wide spread use by aviation. GPS use for aviation today is enabled by three technologies. First, receiver autonomous integrity monitoring (RAIM) is a fault detection mechanism that is contained within the avionics. RAIM requires an abundance of satellites, because it evaluates the consistency of each satellite measurement with the other available satellite measurements. Two other technologies use aircraft-external monitors that compare GPS measurements to ground truth and broadcast error information to the airborne users in real-time: satellite-based augmentation systems (SBASs) and ground-based augmentation systems (GBASs). We introduce all three techniques in the brief sections that follow.

A. Receiver Autonomous Integrity Monitoring (RAIM)

RAIM is so named because the airborne receiver performs self-contained fault detection. RAIM compares each GPS measurement to the consensus of the other available GPS measurements. In this way, RAIM detects the presence of a faulty satellite within the current set of in-view satellites, and, under certain circumstances, isolates it (Fig. 4) [1], [3], [19]. There are variants of RAIM which include integration with baro-altimeter or inertial measurements. RAIM has been used since the mid-1990s to support supplemental navigation in the en route and terminal area phases of flight, and is also used to support lateral guidance during the approach phase of flight [in lateral navigation (LNAV) approaches] [30], [31]. However, currently, RAIM cannot support vertical navigation for at least two reasons. First, today's RAIM cannot support the vertical error bounds required for vertical guidance, and, second, it does not yet have the required design assurance level [2]. We will outline later what would be required to enable vertical navigation using RAIM.

B. Satellite-Based Augmentation System (SBAS)

Aircraft-external monitors form the basis of SBASs and GBASs. These external monitors process measurements from networks of GPS reference receivers at known locations on the ground. SBASs and GBASs provide corrections to the civil signals from GPS as well as error bounding data in real time. As such, both systems augment the GPS Standard Positioning System (SPS). Relative to RAIM, they do not require as many satellites in the GPS constellation for a given fault detection capability, because they detect faults by comparing GPS measurements to a surveyed ground truth.

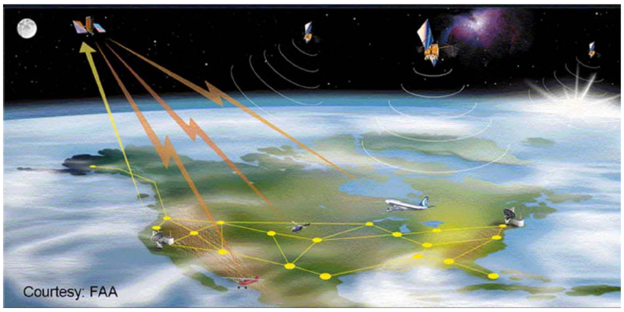

Fig. 5. *In satellite-based augmentation systems (SBASs), a network of reference stations monitors the performance of GPS satellites in real time. Corrections and error bounds on the corrections are sent via a Geostationary Earth Orbit (GEO) satellite. Anomalies are flagged to users within 6 s.*

SBAS is based on networks of strategically positioned reference receivers spread over continental areas. These reference receivers measure the GPS signal in space, and these measurements are backhauled to redundant master stations. The master stations calculate errors in the GPS signal which are used to create corrections to the GPS measurements and real-time error bounding data for these corrections (Fig. 5). The corrections and error data are both valid over the continental area spanned by the reference network, and are broadcast to using satellites in the Geostationary Earth Orbit (GEO). This GEO broadcast of SBAS data uses spread spectrum signals within the same L1 (1575.42-MHz) band used by GPS, and can provide an additional GPS-like ranging capability. The SBAS corrections improve the accuracy of GPS from approximately 4 to 1 m [36]. The error bounding data enable SBAS avionics to compute an upper bound of the positioning error in real time, and is updated often enough to support a 6-s time to alert against any potentially hazardous navigation information.

Operationally, SBAS supports en route, terminal area navigation, nonprecision approach and, in some implementations, vertically guided approaches down to a decision height of 200 ft above ground level (these approaches are called LPV-200, and are essentially equivalent to Category I approaches). In summary, SBAS: 1) improves safety by reducing controlled flight into terrain on approach [18]; 2) increases the number of runway ends that have approach procedures; and 3) supports en route area navigation for aircraft that are not capable of inertial navigation and/or flight management systems.

For the above listed reasons, the United States has operated SBAS for North America since 2003, and this system is called the Wide Area Augmentation System (WAAS). WAAS mitigates the faults and space weather effects that trouble the use of standalone GPS. With the use of ranging from the GEO satellites, it also reduces aviation's sensitivity to the strength of the GPS constellation. In the United States, more than 70 000 aircraft are currently equipped with suitable avionics, and approximately 2700 runways across the United States have LPV approach procedures based on WAAS (twice as many as there are Instrument Landing System glide slopes). In addition, WAAS has enabled the development of many missed approach procedures, and departure guidance for numerous runway ends and heliport/helipads in the National Airspace System. The European Geostationary Navigation Overlay Service (EGNOS) is an SBAS that covers Europe and was certified for aircraft navigation in March 2011. In Japan, the MTSAT Satellite Augmentation System (MSAS) has been operational since 2007 for the Japanese islands and the surrounding Asia-Pacific area [22]. SBAS is also being developed in India [33] and in Russia [17].

C. Ground-Based Augmentation System (GBAS)

As with SBAS, GBAS is based on measurements from GPS reference receivers at surveyed locations. As opposed to SBAS, GBAS utilizes a small number of reference receivers with antennas placed close together on the property of a single airport. Hence, one GBAS installation serves a single airport and the surrounding terminal area by broadcasting GPS corrections and error bounds to the aircraft via a VHF Data Broadcast (VDB) from the host airport. This VDB provides reliable coverage within 45 km of the airport (Fig. 6). The GPS corrections broadcast by GBAS improve the accuracy of GPS from approximately 4 m to better than 0.5 m. GBAS error bounds are updated every 0.5 s, and thus have the potential to meet the time-to-alert requirements for all categories of precision approach.

The air transport industry has worked diligently to develop a GBAS for the following reasons. First, the VDB data includes the path points for the GBAS landing

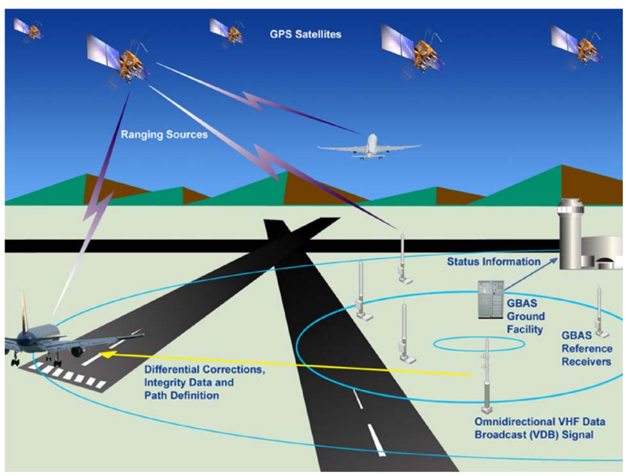

Fig. 6. *In ground-based augmentation systems (GBASs), the reference receivers are placed close to a single airport. A VHF Data Broadcast disseminates the corrections and error bounds within 45 km of the airport (image courtesy of the Federal Aviation Administration).*

procedures at the given airport. This avoids the need for a separate data base that contains the path points. In addition, GBAS is targeting support for Category II and III landings, while this capability is not currently envisioned through SBAS. For these reasons and others, Boeing and Airbus plan to install GBAS avionics in the B-737NG, B-787, B747-8, A-320, and A-380. Category II and III GBAS systems are planned to become operational within this decade [7], [24].

D. Summary of Current Capabilities Offered by Today's Systems

Today, satellite navigation supports worldwide en route, terminal, and lateral guidance during the nonprecision approach phase of flight (Fig. 7). At the moment, this is achieved by RAIM. However, this service is not always available as RAIM demands very strong satellite geometries. In contrast, SBAS-enabled receivers have 100% availability of lateral navigation down to nonprecision approach within and around the primary service regions of WAAS, EGNOS, and MSAS (which includes much of the northern hemisphere). SBAS also supports vertical guidance in North America, Europe, and in Japan. More precisely, WAAS offers vertical guidance down to 200 ft in the conterminous United States, Alaska, parts of Canada, Mexico, and the Caribbean; EGNOS in Europe is certified to allow guidance down to 250-ft decision height; and MSAS in Japan offers more limited vertical guidance availability. Both SBASs and GBASs are sensitive to space weather. Ionospheric storms include spatial gradients that may cause the SBAS and GBAS reference observations to be decorrelated from the airborne measurements. Today's SBASs and GBASs must hedge against this possibility with large error bounds and, therefore, vertical guidance is prone to lapses in availability or continuity. Fortunately, lateral navigation and nonprecision approach is virtually unaffected.

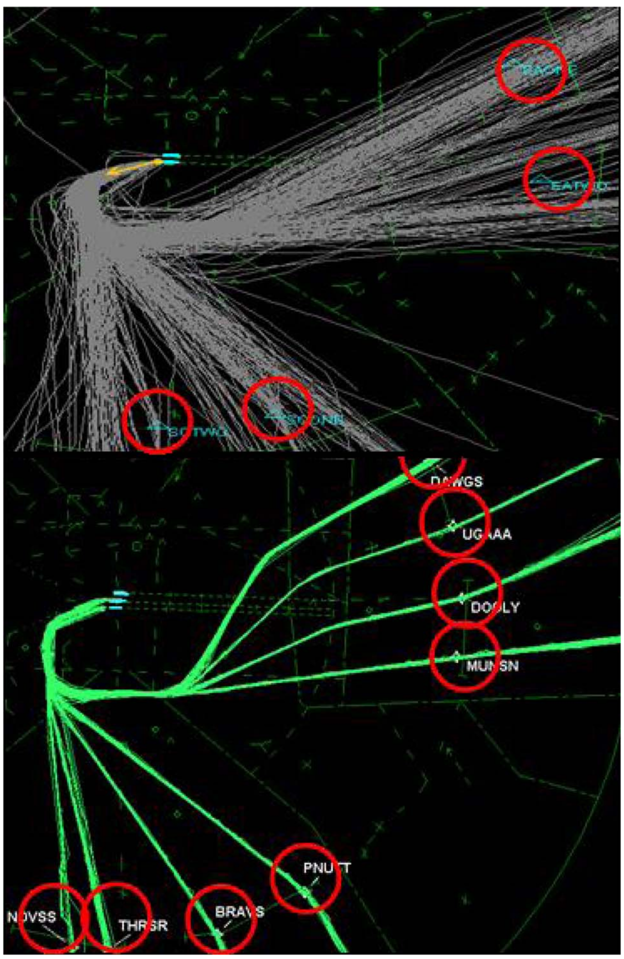

Fig. 7. ***The use of area navigation (RNAV), shown in the bottom figure, allows a twofold increase in capacity compared to radar vectors, which result in a much less efficient use of the airspace (top figure). RNAV is mostly enabled by satellite navigation. (Figure courtesy of the Federal Aviation Administration.)***

IV. UPCOMING CHANGES IN THE GNSS ENVIRONMENT

There are three important changes happening in the GNSS environment during this decade: the introduction of a new civil signal in the L5 band (1176.45 MHz), the launch of new GNSS core constellations, and the increased integrity offered by the GNSS core constellations.

A. Dual-Frequency Diversity

Since 2010, all newly launched GPS satellites have broadcast ranging signals for civil use on the L1 and L5 frequency bands. Both signals fall within the intersection of two radio bands: aeronautical radionavigation service (ARNS) and radionavigation satellite service (RNSS), which makes them suitable for aircraft navigation. This dual-frequency diversity will almost obviate the most troublesome aspect of space weather: ionospheric storms. With ranging signals in two distinct frequency bands, the avionics will autonomously remove the ionospheric delay and potential ionospheric gradients will have no effect on the GNSS range measurements.

In some regions of the globe, ionospheric scintillation may still break continuity for dual-frequency users. Scintillation causes rapid variations in the amplitude and phase of the received signal. The equatorial region is most prone to amplitude scintillation while northern latitudes exhibit phase scintillation effects. These scintillation effects may affect L1 and L5 simultaneously. However, deep amplitude fades usually only last for a fraction of a second. This brevity suggests that the impact of simultaneous effects could be considerably reduced provided that the avionics standards require the avionics to reacquire any lost signals within 1 or 2 s [32].

Dual-frequency diversity will also diminish the impact of accidental or scheduled radio-frequency interference. If either L1 or L5 is overwhelmed by RFI, then the remaining frequency will form the basis for reversionary navigation, though the level of service may be reduced. In addition, the L5 signal is intrinsically more resistant to RFI than the L1 signal [12].

B. New Global Navigation Satellite Systems

New satellite navigation systems are under development and should complement GPS in the next decade [12]. These include systems from Europe, Russia, and China. Like GPS, these three systems are based on 24–30 satellites in medium earth orbit. They will broadcast signals near the GPS L1 and L5 frequencies. These signals will fall in bands that are allocated to both ARNS and RNSS, and thus be useful to aviation users. These systems are briefly described in the next three paragraphs.

The first two in-orbit validation satellites of Galileo, the European GNSS, were launched on October 21, 2011, and two more will be launched this year. This follows the launch of two experimental satellites on December 2005 and April 2008 [29]. Galileo will offer a multiplicity of services based on four signals in the L-band of the microwave portion of the radio spectrum. Among these, the open service (OS) will be free for anyone to access and well suited for aviation augmentation, because it has signals in the same ARNS/RNSS bands used by the GPS L1 and L5 frequencies.

The Russian system, GLONASS, has recently been rejuvenated after years of decline. As of April 2012, the GLONASS system consists of 31 satellites. Of these, 24 are operational, one is being commissioned, two are in maintenance, one is being tested, and three are spares. In 2013, the Russians plan to start launching their GLONASS-K2 generation of satellites. Like GPS and Galileo, these will radiate signals in the L1 portion of the radio spectrum. Shortly thereafter, the next generation of GLONASS satellite should add signals at L5. Thus, the planned signal structure would satisfy aviation's desire for dual-frequency diversity based on signals within the ARNS/RNSS spectrum. Moreover, these new signals will be based on code-division multiple access—like GPS and Galileo—rather than the frequency-domain multiple access currently employed by GLONASS.

China is developing Compass, which is based on the same passive ranging capability as GPS, Galileo, and GLONASS. Since 2007, four GEO satellites, four inclined GEO satellites, and one Medium Earth Orbit (MEO) satellite have been launched. When completed, Compass will have 30 MEO satellites and five GEO satellites broadcasting signals in both L1 and L5.

C. Increased Integrity of the Core Constellations

In addition to the two previous major changes, the GNSS providers have all expressed a strong interest in increasing the safety-of-life utility of their basic satellite navigation systems. The United States targets the GPS III generation of satellites for initial integrity services [16]. In the case of Galileo, the European GNSS, a safety-of-life concept was an integral part of the design from the onset of the project [26]. Although the design assurance of these integrity services might not meet the stringent requirements of civil aviation, the increased integrity of accuracy of the GNSS core constellations, together with dual frequency, could enable the expansion of RAIM to vertical guidance.

V. SATELLITE NAVIGATION FOR AVIATION IN 2025

The evolutions of the GNSS core constellations outlined above will be leveraged by the providers of integrity. Dual-frequency diversity will provide a powerful mitigation of the ionospheric storms that are today's most prevalent threat to the continuity and availability of vertical guidance. The use of the L5 frequency also will provide a redundant signal and reversionary approach capability in the event of RFI. In addition, new constellations will provide geometric diversity, addressing the long-standing concern over constellation strength. Finally, the current interest from the GNSS service providers for built-in integrity could be utilized.

A. Dual-Frequency SBAS

Dual-frequency SBAS users will not suffer from errors due to space weather because the user directly measures the ionosphere-induced path delay to each GPS satellite. Thus, the user avoids the performance penalty due to spatial decorrelation inherent in the ground-based ionosphere corrections. This will make possible the expansion of SBAS-enabled vertical guidance to lower latitudes, and it will make SBAS more robust during ionospheric storms where it is already available. If dual frequency is coupled with an expansion of the ground networks to the southern hemisphere, then all land masses could have full coverage of vertical guidance down to 200-ft decision height [37]. This is illustrated in Fig. 8.

The inclusion of L5 in SBAS is not a small undertaking. Both the ground and air systems—including hardware and software—must be updated. Dual-frequency SBAS avionics will be needed, and so the associated Minimum Operational Performance Standards (MOPS) [31] will need to be updated.

B. Dual-Frequency GBAS

As mentioned earlier, GBAS supports navigation for terminal area flight, precision approach, and landing. All of these capabilities are based on GPS L1 alone. Dual-frequency operation will bring the same advantages to GBAS that it brings to SBAS. Inclusion of L5 in the ground and air systems will reduce continuity issues associated with ionospheric storms and RFI. Most importantly, the availability of Category II and III landing operations will increase significantly, as the use of two frequencies to mitigate ionospheric spatial anomalies is far superior to

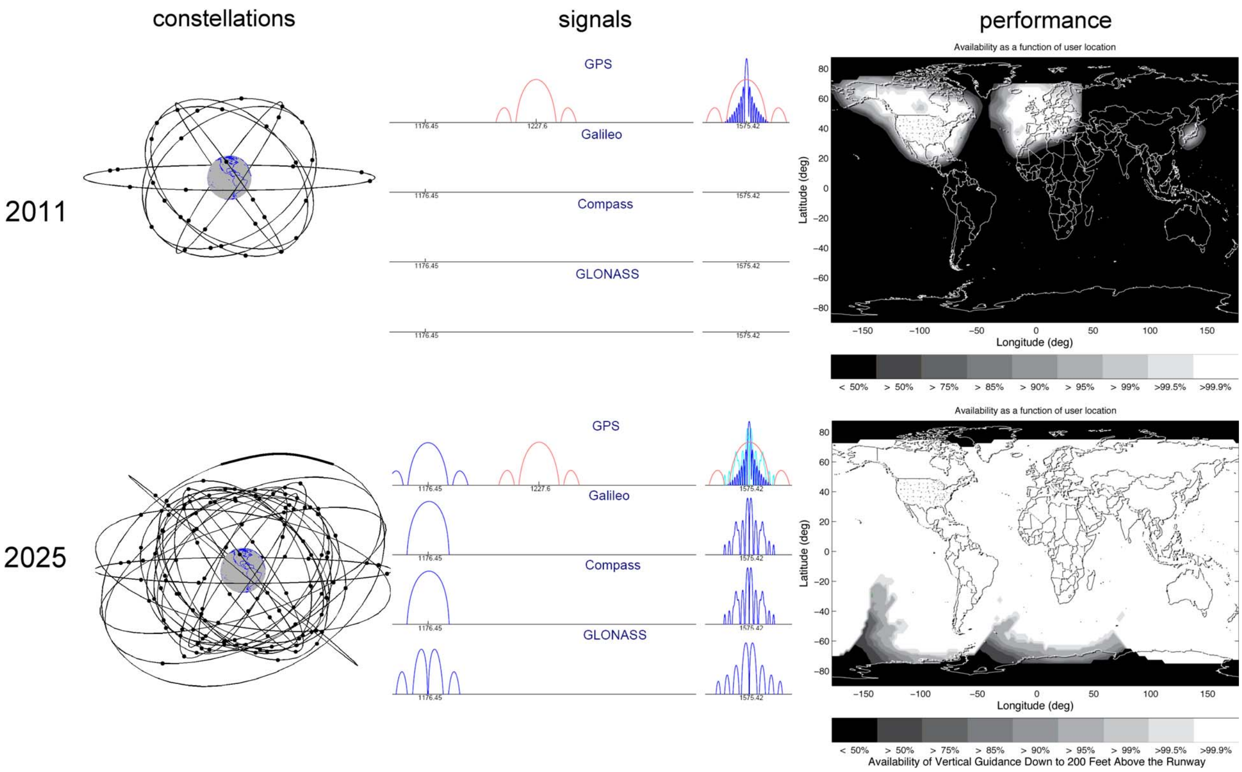

Fig. 8. ***The new constellations and signals will enable the worldwide expansion of vertical guidance based on satellite navigation. It can be achieved either by expanding satellite-based augmentation systems or with advanced RAIM.***

the methods available to single-frequency (L1-only) systems.

C. Advanced RAIM

Advanced RAIM (ARAIM) for vertical guidance is a possible extension of the single-frequency horizontal-guidance-only RAIM discussed in Section III-A [2]. ARAIM would rely on the increased number of satellites and constellations, on the increased reliability of the GNSS signals, and on the dual-frequency signals. ARAIM rests on the same principle as RAIM, but detects pseudorange faults at a much smaller level. It would accommodate multiple constellations, which would make it less sensitive to the size of any one of them. This would be especially true if three constellations or more were used.

ARAIM has generated strong interest because it could provide worldwide coverage of vertical guidance (bottom map in Fig. 8) without an expensive ground infrastructure, and without the expense of the SBAS GEOs. However, the strength of ARAIM is also its weakness: without a real-time ground truth, ARAIM relies on the performance of the core constellations and is thus much more dependent on their performance. Civil aviation authorities may be reluctant to depend on resources they neither control nor have full insight into their design and operation. Thus, in contrast with RAIM, ARAIM would still require a certain level of monitoring and a low rate broadcast mechanism. This monitoring would ensure that the assumptions used by the receivers to perform fault detection and isolation are met. These assumptions include the size of the nominal errors and the fault rate of any one satellite or group of satellites (including whole constellations). This information would constitute an integrity support message and would be broadcast to the airborne fleet through a variety of channels [2].

D. Realizing the Potential of Satellite Navigation for Aviation

Perhaps the most important evolution from here to 2025 will be the realization of the full potential of satellite navigation for aviation. It could be said that satellite navigation for aircraft is a valuable but underused utility. The airspace is still organized around navigational aids supporting point-to-point navigation, and does not take full advantage of the accuracy and integrity offered by RAIM and SBAS. Satellite navigation will enable routes that are much more efficient with respect to capacity and fuel [25]. These procedures would include curved approaches and continuous descent approaches. However, implementing such changes in the airspace goes beyond satellite navigation as a sensor and involves many stakeholders including airlines, pilots, air traffic controllers, and navigation service providers. Of course, this transition will become easier as the limitations of satellite navigation are better understood and mitigated.

VI. THE RFI MITIGATION CHALLENGE

As mentioned earlier, satellite navigation signals are weak when they reach Earth (the received power is only 10^{-16} W). They can be easily overwhelmed by earth-sourced interfering transmissions at the GPS frequency. Among the types of RFI, deliberate interference is the looming threat. A Federal Aviation Administration (FAA) investigation was sparked during the installation of GBAS at Newark International Airport, Newark, NJ. As described above, GBAS uses GPS receivers at the airport to aid GPS receivers in the approaching aircraft. The GBAS antennas were placed next to the New Jersey Turnpike, and the ground receivers suffered frequent continuity breaks during the test period. These breaks were due to so-called personal privacy devices (PPDs) carried by vehicles on the New Jersey Turnpike. In the past year, these devices have become widely available. They range in price from $30 to over $300 based on the number of frequencies under attack and the transmitted power. They radiate powers from a few milliwatts to hundreds of milliwatts. The former knock out GPS receivers for hundreds of yards, and the latter can have dangerous effects for many miles. PPDs are marketed to individuals that fear for their privacy, but they are also used by car thieves that wish to prevent on-car warning systems from reporting the GPS location of a stolen car to the authorities. In any event, a PPD can cause collateral damage much greater than any privacy protection the user may possible enjoy.

Although technical remedies can mitigate the effect of PPDs, and RFI in general, they cannot eliminate it, so legal remedies are also being investigated. For the longer term, in the United Sates, the FAA will develop an alternate position navigation and time (APNT) based on terrestrial radio navigation and inertial navigation, which will provide a backup to satellite navigation down to RNP.3 [9], [21]. Today, the aviation community continues to operate the full set of terrestrial navigation aids that predated GPS. These include VHF omnidirectional range, distance measuring equipment, and instrument landing systems (ILSs). If satellite navigation is unavailable, pilots can revert to these systems. However, this terrestrial network is expensive and does not support the navigation capabilities needed for the next-generation air traffic management system [25]. It needs to be reconfigured to reduce cost and provide area navigation rather than point-to-point navigation. To this end, the APNT effort focuses on the provision of area navigation for all en route and terminal airspace over the conterminous United States and approach navigation for all airports required for safety and commerce. APNT will be independent of GNSS and based on navigation aids that can be cost effectively retained or are planned for installation in the next decade.

VII. SUMMARY

The benefits of satellite navigation for aircraft that have been experienced in the past decade offer only a hint of the changes it will bring to the airspace. Even with current satellite navigation performance, the potential to improve the airspace is enormous. And this performance is only going to increase with the addition of new GNSS constellations and new navigation signals during this decade. The submeter accuracy and integrity of the GNSS position fix will make satellite navigation the main navigational aid for aircraft. However, since satellite navigation is inherently vulnerable to RFI, other sensors in the aircraft remain indispensable and backup navigational aids on the ground need to be maintained to provide reversionary navigation. ■

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