

## **Aviation Benefits from Satellite Navigation**

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The Global Navigation Satellite Systems (GNSS) benefit aviation by enabling aircraft to fly direct from departure to destination using the most fuel-efficient routes or to avoid complicated terrain at low altitude. Satellite navigation provides the flexibility to design new procedures that enable aircraft to fly closer together to increase the arrival and departure rates and fly continuous climb and descent operations to minimize fuel consumption, noise, and carbon emissions. GNSS enables performance-based navigation (PBN), which consists of area navigation (RNAV) and required navigation performance (RNP). Both RNAV and RNP enable unrestricted point-to-point flight paths. RNP differs from RNAV, because it also provides a monitoring and alerting function to warn the pilot when a correction is required, which enables aircraft to fly tighter flight paths. GNSS is the only navigation source approved for RNP operations.

### **1 Introduction**

The Global Navigation Satellite System (GNSS) serves an enormous breadth of users in the air, on the ground, at sea, and in space. These widespread users enjoy five-meter location accuracy worldwide, 24 hours per day, in all weather. If better accuracy is required, differential techniques are available to provide decimeter or even centimeter accuracy.

Figures 1 and 2 show the satellites that enable this global utility. Specifically, Figure 1 shows the satellites from the Global Positioning System (GPS) that are on orbit in mid-2014. The GPS satellites are in medium earth orbit (MEO), and seven satellites in geostationary orbit (GEO) augment this core constellation by broadcasting safety information for aviation. GPS has been the mainstay of GNSS, but new constellations are being deployed by China and Europe, and Russia has rejuvenated their GLONASS system. Figure 2 shows *all* of the GNSS satellites that are on orbit in mid-2014. As shown, this superset occupies medium earth orbit (MEO), geostationary orbits (GEO), and inclined geosynchronous orbits (IGSO).

GNSS is passive; the signal travels from the satellites to the users, while the user does not radiate any signals. These satellite signals are in the L band of the radio spectrum (1.0 to 2.0 GHz), and are carefully crafted to enable very accurate time-of-arrival (ToA) measurements by the user. With four such ToA measurements, users can estimate their latitude, longitude, altitude, and time offset from the satellite system time. In short, four (or more) equations are used to estimate the four unknowns. Since, GNSS solves for the user time offset relative to the GNSS system time, which in turn is connected to the Coordinated Universal Time (UTC). For this reason, GNSS is called a space-based position navigation and time (PNT) system.

Figure 1: GPS Satellites on Orbit in May of 2014. Today, GPS has approximately 32 satellites in medium earth orbit. Also shown, seven satellites in geostationary orbit augment GPS; they broadcast real time error bounds to support aviation use. (Courtesy of Tyler Reid)

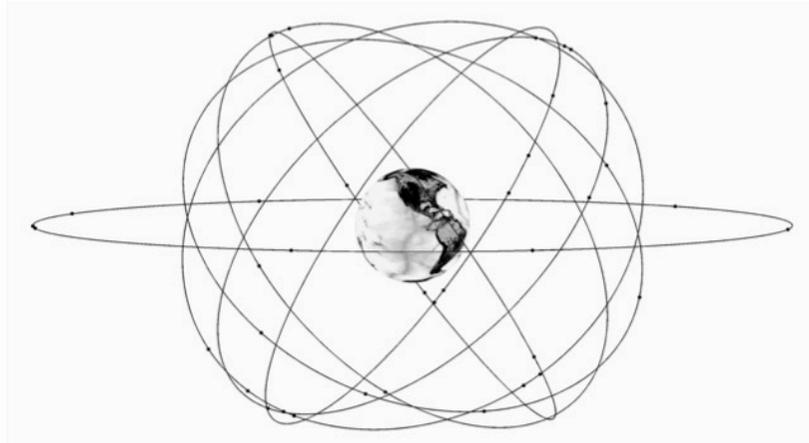


Figure 2: GNSS Satellites on Orbit in May of 2014. This figure includes satellites from GPS, GLONASS (Russia), Beidou (China), Galileo (Europe), Quasi-zenith Satellite System (QZSS, Japan), and the Indian Regional Navigation Satellite System (IRNSS). As shown, these constellations include satellites in medium earth orbit (MEO), geostationary orbits (GEO) and inclined geosynchronous orbits (IGSO). (Courtesy of Tyler Reid)

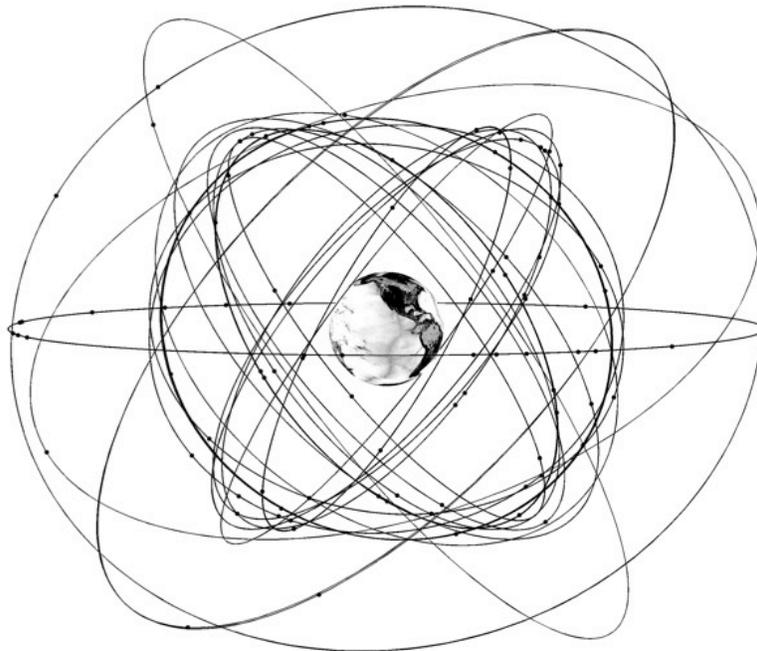


Figure 3 shows the basic operation associated with one of the GNSS satellites. Each satellite broadcasts a carefully crafted signal that enables precise ranging measurements by the receiving equipment. The signal from each GNSS satellite has two ingredients.

First, each satellite sends a unique code that creates sharp radio marks that the receiver can readily distinguish from background noise and the signals from other satellites. This code has special correlation properties that enable the user equipment to measure its time-of-arrival to within a few billionths of a second. Second, each satellite superposes needed data on top of the codes using a so-called navigation message. This data includes the satellite location and the signal time-of-transmission. Together, these two ingredients allow the receiver to precisely measure the arrival time of the signal from a few GNSS satellites.

The Global Positioning System (GPS) is presently the most-used satellite constellation within the Global Navigation Satellite System. GPS was originally developed by the U.S. Department of Defense in the 1970's. At that time, the planners predicted that GPS would serve a total of 40,000 military users with some ancillary civil use. Today, the civil community has shipped over three billion GPS receivers. The civilian tail now wags the GPS dog, and the civil aviation community has already benefited from a growing set of GPS applications that are directed at increasing efficiency, saving fuel, and reducing the environmental impact of aviation.

As mentioned earlier, GPS is not alone. Russia has rejuvenated their satellite navigation system, called GLONASS, which has 24 satellites as of December 2016. Europe has launched 16 satellites for their Galileo system that will eventually have 24 satellites. China is expanding their regional system, BeiDou, to include global coverage. Japan and India have also launched satellites for regional systems. Figure 2 depicts the current *mélange* of satellites in this system of systems. In time, these national constellations will comprise a mighty Global Navigation Satellite System (GNSS) with over 100 satellites.

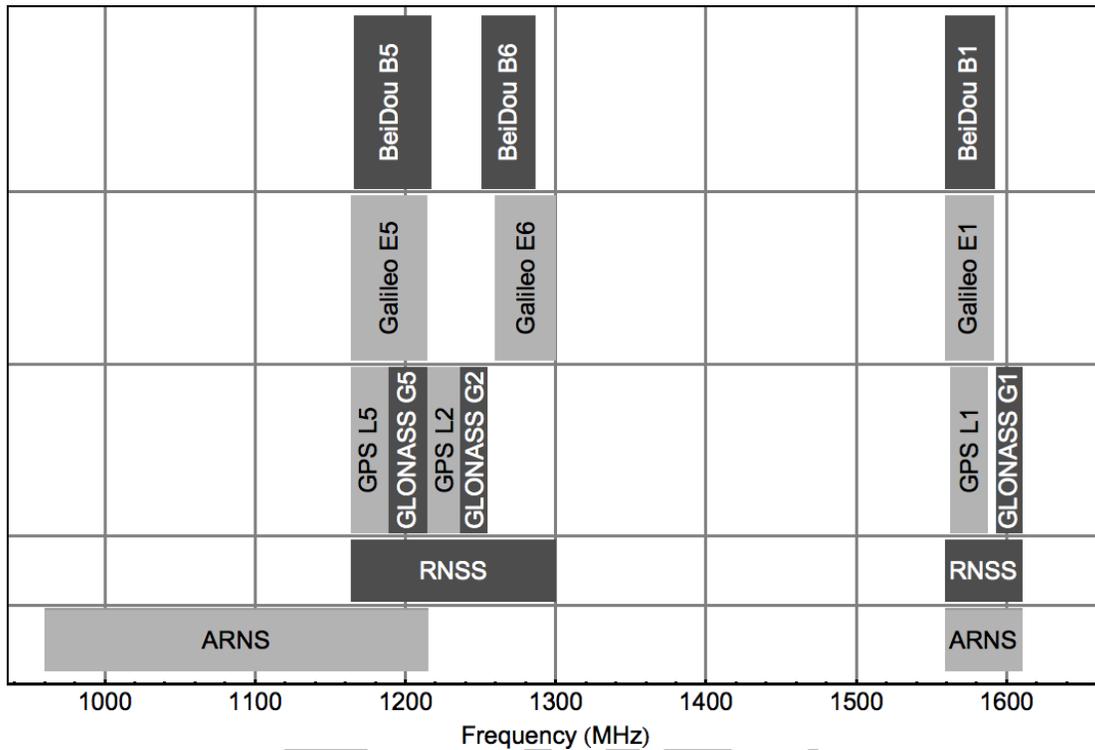
The multiplicity of satellites described above will provide *geometric diversity* with signals coming from almost every overhead direction. Importantly, the new satellites will also provide *frequency diversity* for civil users. Each new satellite will radiate civil signals at three frequencies rather than the single civil frequency offered prior to 2010.

Figure 4 shows the spectrum for the new GNSS signals that are coming on line in the next ten years. All of these signals reside in portions of the radio spectrum that have been set aside for radio navigation satellite systems (RNSS). Some also reside in bands that have been allocated for aeronautical radio navigation systems (ARNS). As shown, the GPS satellites broadcast at three civil frequencies called L1 (1575.42 MHz), L2 (1227.60 MHz) and L5 (1176.45 MHz). L1 is home to the so-called clear access (C/A) signal; this GPS signal is the basis for the vast majority of civil applications to date. This C/A signal overlays military signals in the same band. L2 also carries a civil signal on the seven most recent GPS satellites. L5 is the home for the third civil signal, and has been included on the four most recent GPS satellites. L5 has a broader spectrum than the civil signals at L1 and L2, and so it is the most robust civil signal (Misra and Enge, 2006; Spilker and Van Dierendonck, 2001; Betz, 2001).

Taken together, L1, L2, and L5 provide redundancy to combat accidental radio frequency interference (RFI) and a means to remove the dispersive delay due to the ionosphere. Both features are important. RFI is becoming more prevalent in the GPS bands, and the ionosphere is the largest natural source of error. These two challenges will be further described later in this paper. L1 and L5 are particularly important to aviation, because they both fall in Aeronautical Radio Navigation System (ARNS) portions of the radio spectrum. Thus they have greater aviation utility, because they enjoy greater institutional protection than L2.

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Figure 4: Signal Spectra for GPS, Galileo, BeiDou, and GLONASS. From the left, new GPS satellites radiate at L5 (1176.45 MHz), L2 (1227.60 MHz) and L1 (1575.42 MHz).



The signals for GLONASS, Galileo, and BeiDou are also shown in Figure 4. As illustrated, they are not placed at exactly the same places as the GPS signals. However, they share the main features: triple frequency diversity with at least two signals in the ARNS bands surrounding L1 and L5.

As mentioned earlier, GPS user equipment serves a multitude of applications. For example, every new Boeing or Airbus aircraft carries a GPS receiver for navigation in the enroute and terminal area airspace. GPS is also used to guide aircraft while approaching airports. In some cases, it provides the most critical vertical dimension of location down to altitudes of 200 feet. GPS receivers for aviation are expensive, due to the cost associated with the design and testing for such a critical safety application.

At the other cost extreme, most new mobile phones carry GPS/GLONASS receivers that have a bill of materials around \$1. These receivers are used to guide our walking and driving lives. They also provide our location automatically to emergency services when we make such a call.

We are now well prepared to engage the body of this chapter. Section 2 focuses on the efficiency and environmental benefits to aviation from GNSS, describing four aviation operations where GNSS enables fuel savings. These operations are based on the area

navigation (RNAV) capability of GNSS. Section 3 focuses on the safety of air navigation based on GNSS. More specifically, it describes the Required Navigation Performance (RNP), and discusses the technology needed to ensure that man-made faults, space weather, and bad actors (jammers and spoofers) do not endanger aircraft using GNSS for navigation. Section 4 is a brief summary of this paper.

## 2 Efficiency and Environmental Benefits

As mentioned earlier, satellite navigation will save aviation fuel and reduce the environmental impact of flight. To tell this tale, we begin by discussing a parallel development: the eco-routing of automobiles. Following this ground-based discussion, we turn our attention to the air. In subsection 2.2, we discuss one of the earliest applications of GNSS to the navigation of passenger-carrying aircraft: the departure and approach to the airport in Juneau, Alaska. We also discuss the mountainous approach to Jackson Hole, Wyoming. In subsection 2.3, we continue our discussion of approach procedures by describing optimized profile descents (OPDs) which can save fuel and reduce noise pollution. Subsection 2.4 broadens our interest to the terminal area that surrounds a metropolitan airport (e.g. the New York multiplex or the San Francisco Bay Area with its three major airports.) Section 2.5 extends our discussion to oceanic paths that adapt to weather conditions on a seasonal, daily, or even hourly basis.

### 2.1 Eco-Routing for Automobiles

Recently, Ford and Hyundai, in partnership with TeleNav and Navtech, have been working to improve the efficiency of automobiles by deploying so-called “Eco-Routing” or “Green GPS” navigation systems in their cars. Like other automotive navigation systems, these systems use distance and average speed to calculate the “shortest” route and “fastest” route from point A to point B. However, they *also* consider additional factors in order to provide the “greenest” or most fuel-efficient route. Some of these eco-factors are:

- Stoplights and stop signs: avoid stopping
- Traffic: avoid stop-and-go, idling, and very low speed
- Curves: avoid deceleration and re-acceleration
- Hills: avoid hill-climbing

A study of one such eco-routing navigation system found that taking the greenest route resulted in an average of 10 percent fuel savings (Ganti et al., 2010). This estimate is conservative, as these savings are as compared to the existing “fastest route” provided by standard navigation systems, which is already significantly more fuel-efficient than the average route taken without using a navigation system.

Given that highway CO<sub>2</sub> emissions account for 26% of the U.S. total from all sources (ORNL, 2013), eco-routing for all U.S. road trips has the potential to reduce total U.S. CO<sub>2</sub> emissions by 2.6 percent, an impressive impact for such a simple solution.

By coincidence, while highway eco-routing has the potential to save 2.6 percent of U.S. CO<sub>2</sub> emissions, U.S. aviation accounts for only 2.6 percent of total U.S. CO<sub>2</sub> emissions to begin with (ORNL, 2013). Even so, aviation will be one of the most difficult sectors in which to reduce emissions. This intransience is due to aviation's requirement for fuels with the greatest energy density (joules/kilogram and joules/volume). Thus, as total emissions decline in the future, aviation's contribution will loom larger. As the relative impact of aviation increases, so will the importance of finding effective methods of reducing its growing fraction of global CO<sub>2</sub> emissions.

In the recent history of aviation, innovations in airframe design and propulsion systems have resulted in significant reductions in aircraft fuel consumption. Between 1960 and 2008, the average fuel-burn of new aircraft decreased by more than half (Rutherford & Zeinali, 2009), thanks to improvements in engine efficiency and aerodynamics, and more efficiently utilized capacity (Lee et al., 2001). With the recent introduction of the Boeing 787, designed to be 20% more efficient than similar aircraft (Boeing, 2013), this hopeful trend will continue.

This book does not further consider aerodynamics and propulsion; rather it focuses on the use of navigation technology to enable more efficient aircraft routes and procedures. In this chapter, we will introduce several of these operational improvements, each of which has been enabled by advanced air navigation systems, primarily global navigation satellite systems (GNSS). It is important to note, however, that the efficiency improvements due to navigation, and those due to airframe design and propulsion, are additive.

## 2.2 Juneau, Alaska and Jackson Hole, Wyoming

Alaska Airlines was the first airline to routinely employ GPS guidance when approaching airports. Severe weather and landscape increase the need for navigation when approaching or departing from an Alaskan airport. GPS is vital in Alaska, because it provides navigation signals that surround the entire airport enabling unrestricted RNAV. RNAV enables aircraft to fly direct between any two points rather than flying the less efficient conventional routes between two radio navigation stations on the ground. For example, Alaska Air initiated the use of GPS when flying into the state capital, Juneau. This city is only accessible by air and water, and the air routes require several turns and appreciable consideration of safety.

Figure 5 shows a fuel-efficient path for aircraft departing from or approaching Juneau airport. As shown, this path follows the Gastineau Channel and the aircraft flies northwest to approach Runway 26 at Juneau airport. Cliffs define both sides of this

channel, and the Alaskan weather frequently blocks the view of these boundaries. Fortunately, Alaskan Airlines was able to work with the Federal Aviation Administration and The Boeing Company to define the path shown in Figure 5. GPS precise positioning with receiver autonomous integrity monitoring (RAIM), which we will discuss in Section 3, enabled Alaska Airlines to navigate the channel in low visibility. Prior to this capability, aircraft were compelled to avoid Juneau if the weather ceiling was below 1000 feet or the along-track visibility was less than 2 miles. With GPS-based navigation of the Gastineau Channel, the tolerable weather ceiling was dropped to 337 feet and the along-track visibility shortened to 1 mile.

Figure 5: Departures and Arrivals From Juneau Airport (JNU) Using the Gastineau Channel. The left-turn at the far end of the channel, close to the airport, requires an area navigation (RNAV) capability. Such a path bend cannot be supported with a line-of-sight radio beam from the ground. (Courtesy of BridgeNet International)



In 1996, Alaska Airlines began to use the Gastineau Channel in earnest. By 2011, Alaska Airlines flew 5,683 arrivals through the narrow Gastineau Channel with the assistance of GPS navigation. Of these flights, 831 were *saves*, or flights that would have been canceled or diverted due to weather if they had not been equipped with GPS. Each year, Alaska Airlines attributes a savings of approximately \$1 million to this GPS-based capability in Juneau.

Today, Alaska Airlines uses GPS to support navigation into 30 airports in Alaska and in the continental U.S. They operate a fleet of 117 Boeing 737s equipped with this capability, and their sister airline Horizon Air operates similarly capable Bombardier Q400 turboprops. According to Alaska Air, the airline flew 12,700 approach and departure procedures in 2011, avoiding the diversion of 1545 flights through the use of GPS navigation. In that year, the airline used GPS to help reduce fuel use by 210,000 gallons and save more than \$15 to \$19 million across their entire fleet and operations.

Jackson Hole, Wyoming also has a unique airport that benefits from GPS. Figure 6 shows the approach path from above. The airport (JAC) is located at the bottom left of the figure. As shown, the conventional landing route requires two straight-line segments based on the limitations of conventional ground-based radio navigation systems. The first segment flies westward, then the second segment flies southward to the airport. The new path uses RNAV waypoints for a curved path that avoids the sharp turn and the noise sensitive area near Grand Teton National Park. This new path is shorter by fourteen miles and three minutes of flight time.

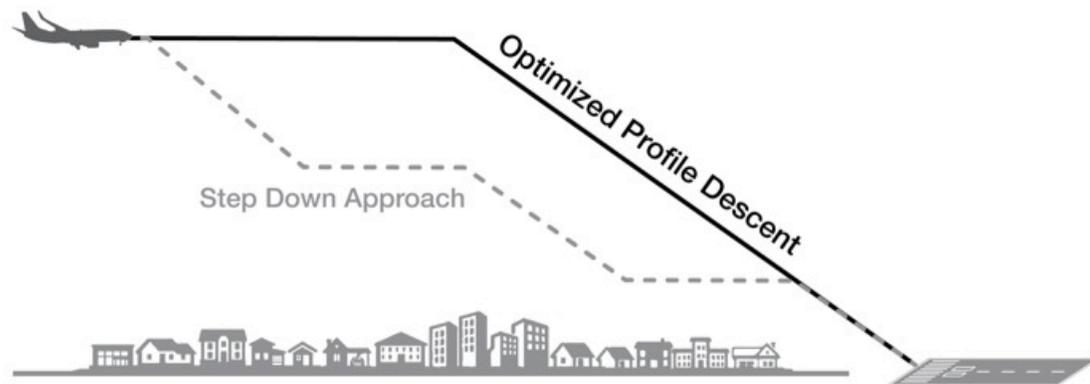
Figure 6: Arrival to Jackson Hole (JAC) Airport Using GPS-Enabled Area Navigation (RNAV). The RNAV path is curved, shorter, and avoids the main attractions of the Grand Teton National Park. (Courtesy of BridgeNet International)



### 2.3 Optimized Profile Descent (OPD)

In the cases of Juneau and Jackson Hole, the approach designers optimized the horizontal ground track. However, it is also possible to fly more efficient vertical profiles using an optimized profile descent (OPD), enabling qualified aircraft to reduce fuel, noise, and carbon emissions. Currently, standard terminal arrivals (STAR) use a series of mandatory altitudes along the arrival route that gradually step the aircraft down to the airport. The advantage of this step down design is that it is easy to standardize and minimizes the volume of protected airspace around the airport. In terms of fuel efficiency, time, and noise pollution, however, the step down approach is not ideal because aircraft use higher power settings to maintain level flight.

Figure 7: Optimized Profile Descents (OPD) in Contrast to Step-Down Approaches (Drive and Dive). OPD offers a close approximation to the optimal idle-thrust glide slope and can save hundreds of kilograms of fuel per flight. (Courtesy of BridgeNet International)



An ideal OPD is a continuous descent operation (CDO), where the aircraft descends all the way from cruise altitude to the runway in a smooth glide trajectory using low power, saving time and fuel and reducing noise and emissions. Some of these descending aircraft may be idling, but some may need slightly more power to enable anti-icing. These OPDs are published procedures so the controller can clear the aircraft to fly the OPD. When cleared, an aircraft can descend safely from near cruise altitude to near the runway, at near idle thrust.

The first OPD flight tests were conducted roughly a decade ago at Louisville International Airport (SDF). The SDF descent resulted in average fuel savings of approximately 200 kg per approach of the B737-300 test aircraft. Peak noise levels were also significantly reduced (Clarke et al., 2004).

In December 2007, Los Angeles International Airport (LAX) implemented the first publicly charted OPD. Across the LAX fleet, each aircraft using this fully operational OPD saves an average of 25 gal (76 kg), and 200 kg of CO<sub>2</sub> emissions per approach. Overall, the OPD at LAX saves approximately 2 million gallons (6 million kg) of fuel each year, and reduces annual CO<sub>2</sub> emissions by 19 million kg. The OPD also saves time, shaving 44 seconds off the average flight time, and has decreased the ground noise around LAX (Clarke et al., 2013).

Significant fuel savings have been demonstrated in flight trials at other airports as well. For example, OPD flight tests with B757s and B737-800s into Miami International Airport (MIA) showed an average savings of 49 gallons (150 kg) of fuel per approach, and tests of B767s into Hartsfield-Jackson Atlanta International Airport (ATL) demonstrated an average savings of 37 gallons (113 kg) per flight (Sprong et al., 2008).

OPD savings depend on: the efficiency of the OPD trajectory, the inefficiency of the conventional approach, the type of aircraft, and the weather. At present, the FAA is developing new merging & spacing tools for the controllers to sequence the aircraft on to the OPDs. These improved tools will enable controllers to meter aircraft hundreds of miles away from the aircraft and in the terminal area.

## 2.4 Tailored Arrivals

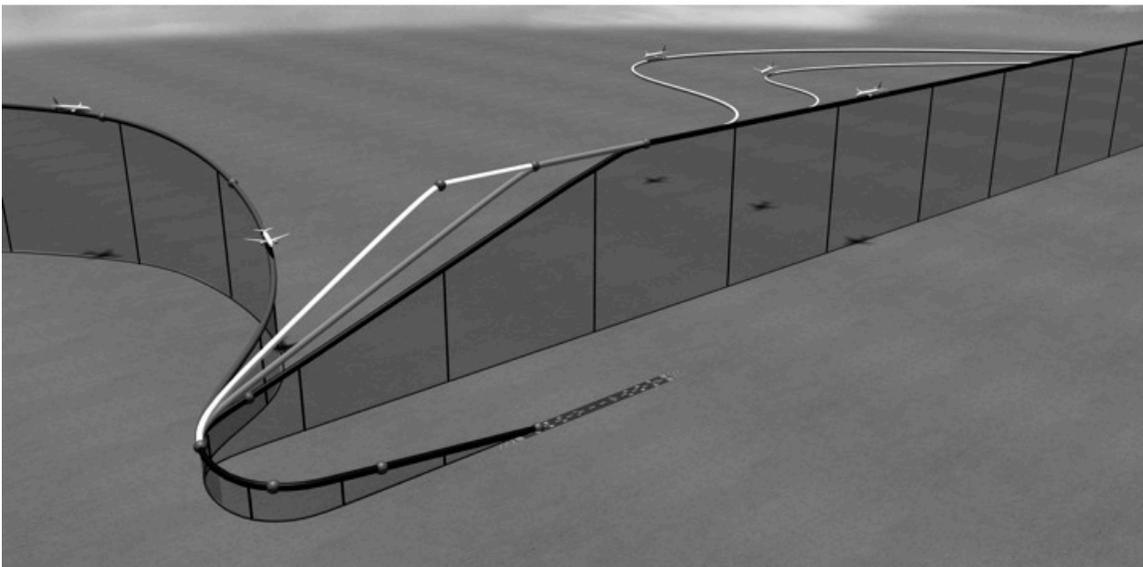
If you have a smartphone or tablet, you may have played Flight Control, the surprisingly addictive game where the goal is to direct planes to their assigned runways while avoiding potential conflicts. It starts out easy, with one plane and then two, and in these low traffic conditions, you're free to choose any path you want. But as the game progresses, and the number of planes on the screen increases, your choice of flight paths becomes much more restricted. If your strategy for the game is similar to ours, when the difficulty increases, you end up playing it safe, creating an orderly queue of aircraft for each runway, and directing each new plane to the back of the line, even if that means tracing out a much longer path than you might have otherwise.

While the job of real-world air traffic controllers requires much more skill than this simple game, the basic strategy is similar. When the sky is clear, fuel-efficient flight paths are great. When there's traffic in the sky, avoiding conflicts becomes the number one priority, to the detriment of fuel efficiency. Of course, these priorities are exactly as they should be: safety trumps fuel efficiency.

Unfortunately, this means that the potential benefits of optimized routing often go unrealized in real-world circumstances. Fortunately, fuel efficiency and safety needn't always be in opposition. Using *tailored arrivals*, we can simultaneously increase fuel efficiency while decreasing air traffic controller workload and improving safety.

Tailored arrivals allow for customized arrival pathways for individual flights based on real-time air traffic conditions. The basic concept is this: accurately measure the position and velocity of each aircraft continuously. Use that information, along with real-time weather data, to accurately predict where each aircraft will be in the future. Optimize all of the arrival (and departure) paths together, simultaneously reducing fuel consumption and flight time for each flight while maintaining separation and avoiding conflicts. An example is depicted in Figure 8.

Figure 8: Tailored Arrivals. These aircraft are engaging in advanced terminal arrival procedures. The aircraft arriving from the right each use glide slope angles that minimize fuel use for their aircraft. Also, the aircraft arriving from the left joins the approach pattern shared with the first three aircraft, which have left an opening in the pattern in anticipation. (Courtesy of BridgeNet International)



Here's how it plays out in practice: the incoming aircraft downlinks its data to air traffic control, who use a computer program such as NASA's En Route Descent Advisor (EDA) to generate an optimal descent trajectory. This computed trajectory considers the state of the aircraft, the predicted trajectories of other aircraft in the airspace, and the weather. This optimal approach pathway is then uplinked to the aircraft and loaded into the flight management system (FMS). While the technological capabilities to design and fly these tailored arrivals are not yet widely operational (on the ground or in the air), there have been several promising tests of the concept.

In 2006, United collaborated with the FAA to test the concept on 40 flights from Honolulu (HNL) to San Francisco (SFO) in various traffic conditions. Under light-traffic conditions, the tailored arrival with an OPD approach into SFO resulted in average fuel savings of 110 kg, similar to the standard OPD trials described above. Under heavy-

traffic conditions, average fuel savings rose to 1,460 kg per approach.<sup>1</sup> This dramatic increase in savings can be explained by the inefficiencies of the conventional heavy-traffic approach into SFO, which includes a 30 nm path-stretch at low altitude (Coppenbarger et al., 2009). Traditionally, during heavy traffic, any given flight is looped around to the back of the line. Tailored arrivals allow the flight to be feathered right into the middle of the queue as the aircraft continues to travel along its own most efficient approach trajectory. In summary, the SFO trials demonstrate that tailored arrivals can save more fuel in heavy traffic, because conventional heavy-traffic approaches are often much less efficient than the low-traffic approaches.

In a later phase of testing at SFO, four airlines testing tailored arrivals at SFO saved more than 500,000 kg of fuel over the course of a year (Chong et al., 2009). Tests of tailored arrivals in Melbourne (MLB) and Sydney (SYD) found an average savings of 100 to 200 kg of fuel per approach (Chong et al., 2009), and later trials in Brisbane (BNE) saved 200,000 kg of fuel and 650,000 kg of CO<sub>2</sub> emissions over the course of a year (Airservices Australia, 2008).

## 2.5 Optimized Enroute Flight

GNSS also enables advanced procedures for aircraft in enroute or oceanic flight by considering distance, winds, and convective weather. While eco-routing on the road is limited to choosing the best route using existing highways, eco-routing in the air can go one step further, choosing efficient routes which break free from the traditional highways in the sky. Assisted by GNSS, aircraft can now safely fly routes that deviate from the fixed air traffic service (ATS) routes, realizing significant fuel savings and emissions reductions, while simultaneously saving time and reducing conflicts. Figure 9 shows a hierarchy of such capabilities.

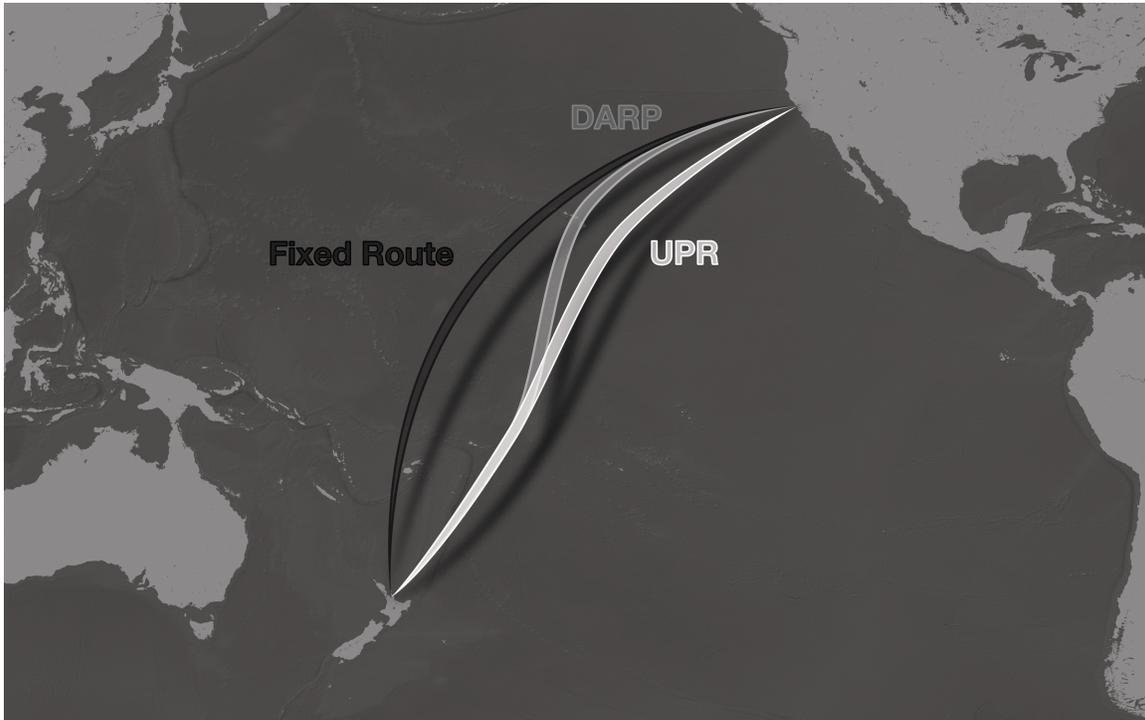
**Flexible Track Systems (FTS):** The simplest form of optimized routing in the sky is the *flexible track system*. Operators design and fly an optimized track between a pair of cities, a route that is predicted to be more efficient than the traditional ATS route based on general meteorological forecasts and a representative aircraft performance model. This optimized track becomes the route for all flights between the paired cities, and is updated seasonally.

Demonstrating the potential inefficiency of the old fixed tracks, and the potential savings that can be realized by switching to flexible track systems, a trial of 592 Emirates Airlines flights between Dubai and Melbourne/Sydney resulted in an average fuel savings of 1,000 kg per flight, and an average of 6 minutes saved per flight (INSPIRE, 2012).

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<sup>1</sup> This is after a 25% penalty based on the assumption that in heavy-traffic conditions, some upstream path-stretching will still be required to adequately coordinate arrival times. The actual savings of a truly ideal approach compared to a conventional heavy-traffic approach were 1,896 kg.

Figure 9: Three Enroute Track Protocols: 1) Fixed Tracks, 2) User Preferred Routes (UPR) and 3) Dynamic Airborne Re-Route Procedures (DARP). (Courtesy of BridgeNet International)



**User-Preferred Routes (UPRs):** User-preferred routes are similar to flexible track systems, but they are updated for individual flights based on *short-term*, specific forecasting. They consider: the specifications of the particular aircraft that will be flying (e.g., B737, A380), and the most up-to-date information about the wind and convective weather for the specific date and time the aircraft will be flying (e.g., October 17, 2013 at 09:25 PST). UPRs optimize the track for a single flight, which can be significantly different than the optimal track for the same flight flown by a different aircraft at a different time on the same day.

As a result of this flight-specific optimization, UPRs have even greater fuel saving potential compared to flexible-track systems. In UPR flight tests between New Zealand, and Japan and China, Air New Zealand obtained a savings of 616 kg of fuel savings per flight, adding up to savings of 1.09 million kg of fuel and 3.44 million kg of CO<sub>2</sub> per year (ASPIRE 2012). In a model of 15 million flights over the course of a year in the United States national airspace, optimizing for wind resulted in an average fuel savings of 95 kg per flight, and an estimated time saving of 2.7 minutes per flight. In addition, there was an estimated 29% reduction in conflicts as a result of route diversification, meaning that UPRs could potentially improve safety in addition to fuel economy (Palopo et al., 2010).

**Dynamic Airborne Re-Route Procedure (DARP):** Dynamic airborne re-route procedures are similar to FTS and UPR, but they can be updated *during the flight*, based on short-term, specific forecasting. DARP flights begin with a UPR route, but update this route en-route based on the current weather. Based on its DARP flight tests between Auckland (AKL) and San Francisco (SFO), Air New Zealand reports that 58% of their AKL-SFO flights have the potential to benefit from DARP, and that for AKL-SFO flights utilizing DARP, the average fuel savings is 450 kg (ASPIRE 2012). For comparison, the entire fuel burn for a 737-800 flying from Auckland to San Francisco is approximately 35,000 kg. Hence these fuel savings are between 2 and 3% of the entire burn.

### 3 Safety

As described above, satellite navigation holds much promise for improving flight efficiency and reducing fuel use and greenhouse gases. GNSS does this by providing an area navigation (RNAV) capability. No longer will aircraft be constrained to fly point-to-point paths defined by ground-based navigation aids or overly restrictive air traffic zones. Aircraft will not need to dive-and-drive when approaching airports; they will descend continuously toward the airport maximizing aerodynamic efficiency. In the fullness of time, aircraft will also be able to make carefully timed turns to join the queue of aircraft approaching an airport. They will adapt their speed while enroute to synchronize this coordinated merge with their flying colleagues. Their enroute flight will also be optimized based on the likely or current weather.

#### 3.1 Required Navigation Performance (RNP)

Satellite navigation supports RNAV, but this is not sufficient. For full benefit, GNSS must also provide required navigation performance (RNP). RNP comprises four tightly woven requirements on the safety of flight:

- *Accuracy* describes the day-to-day or nominal error performance of the system. As described below, it is measured at the 95% level, and has two components: navigation sensor error (NSE) and flight technical error (FTE). NSE measures the performance of the navigation sensor and FTE measures the performance of the human pilot or automatic pilot.
- *Performance monitoring* protects the navigation sensor from rare events. In contrast to accuracy, it is measured at the  $10^{-5}$ ,  $10^{-7}$ , or  $10^{-9}$  level. In the case of GNSS, NSE monitoring must detect man-made faults, space weather, and bad actors. All of these are described in the sections that follow, along with the augmentation systems that detect these events and broadcast worst-case error information in real time.
- *Reliability* of the aircraft equipment measures the ability of the navigation system to provide navigation without interruptions. Air navigation systems must be reliable; the mean-time-between-failure (MTBF) of the airborne hardware shall be greater than 100,000 hours. Such reliability is difficult to achieve with a

single string of electronics, so GNSS avionics are duplicated, triplicated, or even arranged in a dual-dual configuration. The avionics manufacturer and the airframers are responsible for the resulting reliability of the airborne equipment.

- *Signal-in-space* refers to the signals from the core GNSS constellations and the augmentation signals sent as part of performance monitoring. The Constellation Service Providers (i.e. Europe for Galileo, China for Beidou, United States for GPS, and Russian for GLONASS) are responsible for the quality of the GNSS signals. The Air Navigation Service Providers (ANSP) are responsible for the integrity of the augmentation signals. As an example, the ANSP in the United States is the Federal Aviation Administration (FAA).

As mentioned above, accuracy is based on two error components: navigation sensor error (NSE) and flight technical error (FTE). NSE is the difference between true aircraft location and the location indicated by the navigation system. FTE is the difference between the desired location as commanded by the navigation system and the position flown by the pilot or autopilot. In other words, the FTE measures the ability of the airplane (hand-flown or auto-pilot) to fly the route indicated by the navigation system. NSE and FTE are both important, and the total system error (TSE) is their statistical sum as follows.

$$TSE = \sqrt{NSE^2 + FTE^2}$$

Safe flight requires control over TSE and this requirement is defined by the *TSE limit*, which depends on the flight operation. For example, RNP 10 is often used over oceans, and means that the total system error shall not exceed 10 nautical miles (nm) more than 5% of the time (i.e. probability less than 0.05). Importantly, it has an additional meaning: the TSE shall not exceed twice the TSE limit, 20 nm, with probability greater than  $10^{-5}$ . RNP 4 is frequently used when the aircraft is enroute over continental areas. RNP 1 is used for an aircraft arriving at its destination and traversing the busy terminal area that surrounds the airport (e.g. New York or London). RNP 0.3 is often used when the aircraft is on final approach to the airport. It requires that the TSE shall not exceed 0.3 and 0.6 nm with probabilities of 0.05 and  $10^{-5}$  respectively. Clearly, the TSE limit is smaller for more demanding flight operations.

RNP does not specify how the navigation performance is met. Rather, RNP is a top-level characterization of the aircraft's capability; this capability determines whether the measured aircraft can fly a prescribed operation. Incidentally, RNAV also has this attribute where the performance level for the operation is defined that needs to be met, but not specific to any one sensor.

As mentioned above, RNP requires the TSE limit to be enforced at two probability levels: the 0.05 probability measures nominal or day-to-day performance, while the  $10^{-5}$  level measures performance in extremis (i.e. inclusive of extreme events). These

requirements on the TSE limit dictate control of both FTE and NSE. Of these, FTE is regarded as being reasonably constant for a given flight mode (auto-pilot approach, hand-flown across the terminal area, etc.). Moreover, the FTE is directly observable in the aircraft as the difference between the desired track to be flown and the actual track that is measured by the navigation system. In contrast, NSE is not directly observable, and it varies with natural conditions, faults, and other challenges to the navigation system. For these reasons, the GNSS aviation community has focused on NSE performance monitoring. This chapter introduces those efforts, and the remainder of this book expands on this important and interesting engineering effort.

## 3.2 Safety Augmentations that Monitor GNSS Performance

To cope with potential risks, civil aviation has augmented GPS to detect faults that may affect positioning accuracy. The probability of a man-made fault in the GPS system is approximately  $10^{-5}$ /hour per satellite. The target level of safety for an aircraft navigation system is approximately  $10^{-7}$  per hour, or one hundred times smaller than the observed failure rate. Similarly, the ionosphere can introduce location errors that may be potentially hazardous to the aircraft safety. Severe ionospheric disturbances can occur several times per year, creating threats that are many times greater than the target level of safety for aviation.

For these reasons, the civil aviation community has augmented GPS with systems that detect and remove such errors. Three such augmentation strategies exist, and are now described. The ground based augmentation system (GBAS) is described in the next section and provides integrity by comparing GNSS measurements to the known locations of three or four reference receivers located on the airport property. The satellite based augmentation system (SBAS) compares GNSS measurements to the known locations of dozens of reference receivers spread over continental areas. Receiver autonomous integrity monitoring (RAIM) does not use ground truth; it compares every GNSS range measurement to the consensus of the other satellite in view. All integrity techniques are based on a *comparison*, but GBAS and SBAS compare to ground truth, while RAIM compares to the other satellites in view of the aircraft.

### 3.2.1 Ground Based Augmentation

As shown in Figure 10, ground based augmentation systems (GBAS) are located at the airport to be served. Reference receivers monitor the GPS (or GNSS) signals. Since the reference receivers are at known locations, they can generate corrections to remove the nominal GPS errors. They also contribute to performance monitoring, generating alerts to flag satellites that cannot be reasonably corrected. GBAS also provides data that allows the aircraft to continuously estimate a *protection level* that should always be greater than the actual NSE. We say that the protection level *overbounds* the true position error.

All the GBAS reference receivers are on the airport property. Thus, the corrections and alarms are valid within 40 kilometers or so around the airport. They serve aircraft that are landing, approaching or departing from the airport. GBAS is also capable of supporting aircraft that are maneuvering in the terminal airspace that surrounds the airport. Given this range of applicability, GBAS uses a line-of-sight radio to broadcast the performance monitoring information to the airborne fleet. This radio broadcast operates in the very high frequency (VHF) portion of the radio spectrum and is called a VHF Data Broadcast (VDB).

### 3.2.2 Satellite Based Augmentation

Satellite based augmentation systems (SBAS) spread their reference receivers across continental areas. As shown in Figure 11, some 38 stations are used to cover North America, and a similar number are used to serve the European airspace. As shown in the figure, these receivers send their GPS measurement data to master stations that generate corrections and error bounding data that is valid over the area spanned by the reference network. Since the data is valid over continental areas, SBAS uses geostationary satellites to broadcast this navigation safety data to its users.

The Wide Area Augmentation System (WAAS) is the SBAS for North America. Similar systems are operating in Europe, Japan, and India; and are under development in Russia and South Korea.

Figure 10: Ground Based Augmentation System (GBAS). (Courtesy of BridgeNet International)

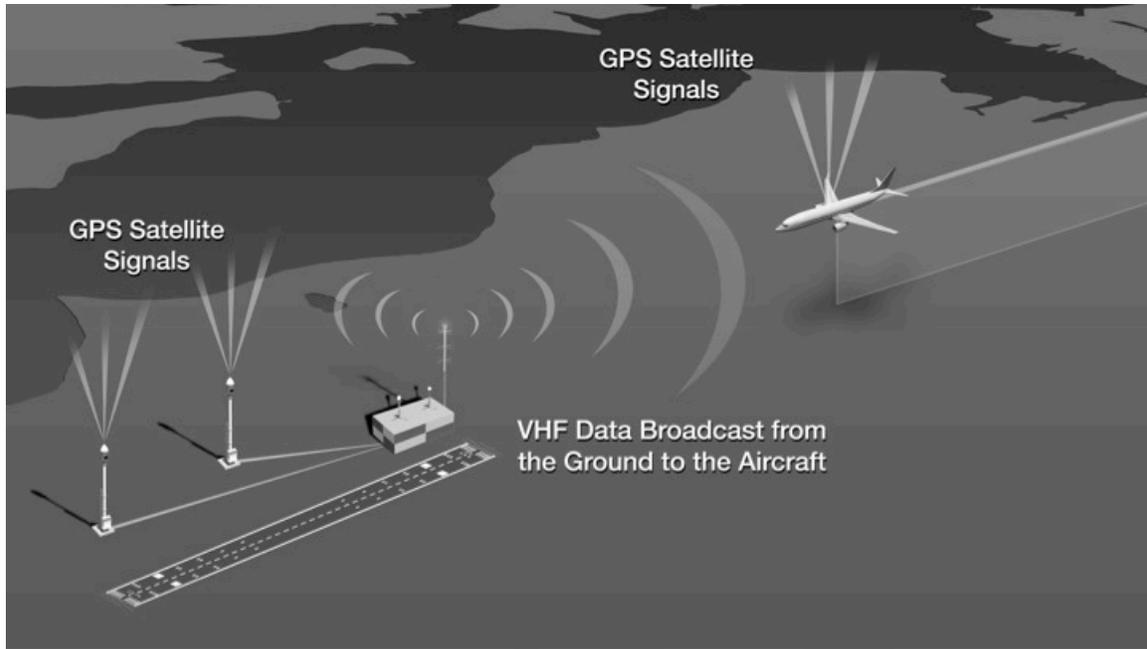


Figure 11: Wide Area Augmentation System (WAAS) Showing the Connections Between the Reference Receivers and the WAAS Master Station on the East Coast. (Courtesy of BridgeNet International)



### 3.2.3 Receiver Autonomous Integrity Monitoring

In contrast to SBAS and GBAS, receiver autonomous integrity monitoring (RAIM) is self-contained. In fact, RAIM belongs to a larger family of fault detection techniques that are known as aircraft based augmentation systems (ABAS). As mentioned earlier, SBAS and GBAS detect faults by comparing the GPS measurements to ground truth. RAIM compares the GNSS measurement from each individual satellite to the consensus of the other satellites in view (subsets). Mathematically, RAIM is based on the residuals of the individual GNSS measurements relative to the least-squares navigation solution based on all satellites in view.

RAIM is attractive because it does not need a separate ground reference network or a real-time broadcast from that ground network to the aircraft. However, RAIM fault detection is intrinsically weaker than the SBAS or GBAS capability, because the navigation solution must be over-specified and the geometries of the underlying subset solutions must be strong. In principal, SBAS and GBAS can provide integrity even for an aircraft with only four satellites in view. In contrast, RAIM needs at least five satellites, because the navigation solution must be over-determined. In addition, the five subsets created by deleting one satellite at a time must all have a strong geometry, so that the sub-fixes will have reasonably good accuracy. This means that RAIM fault detection frequently requires six or more satellites in view.

For this reason, RAIM has not yet been used for vertical guidance. However, it has been approved for lateral guidance, and approximately 200,000 aircraft carry RAIM worldwide to enable lateral guidance in the enroute, terminal area, and non-precision approach phases of flight.

As mentioned earlier, GNSS will eventually contain a multiplicity of full constellations: GPS, GLONASS, Galileo, and Beidou. With the advent of these new constellations, RAIM may be able to support vertical navigation. After all, the geometric diversity from two or more constellations will mean that all navigation solutions will be over-specified and that the subset geometries will be stronger. The air navigation community is researching this possibility, and has developed a concept known as advanced RAIM or ARAIM (Blanch, et al., 2013).

To provide vertical guidance, ARAIM includes a set of requirements on the core GNSS constellations. These requirements must be met and verified periodically if the core constellation is to be included in the suite of measurements used by the avionics to support vertical navigation. If ARAIM can be proven to be safe, then it may be able to support navigation down to altitudes of only two hundred feet over the airport surface. Since ARAIM would be a multi-constellation capability, it would be independent of the health of any one of the core GNSS constellations.

### 3.3 Bad Actors: Jammers and Spoofers

All of the GNSS satellites are placed in medium earth orbit (MEO), and so the signals must travel 20,000 to 24,000 km before they reach the surface of the Earth. Thus, these signals are extremely weak when they reach the earth's surface; their received power is approximately  $10^{-16}$  Watts. In principal, navigation satellites could be placed closer to Earth to strengthen the received power, but these closer constellations would need many more satellites to guarantee that four (or more) satellites are in view of every user.

Radio signals with terrestrial origin can easily overwhelm the weak GNSS signals. If malevolent signals are sent to deny the GNSS service, then they are called *jammers*. If these signals are counterfeits of the GNSS signal, they are called *spoofers*. The latter is more pernicious than the former, because spoofers are designed to introduce a hazardous position error without detection. Taken together, jammers and spoofers are the bad actors of GNSS.

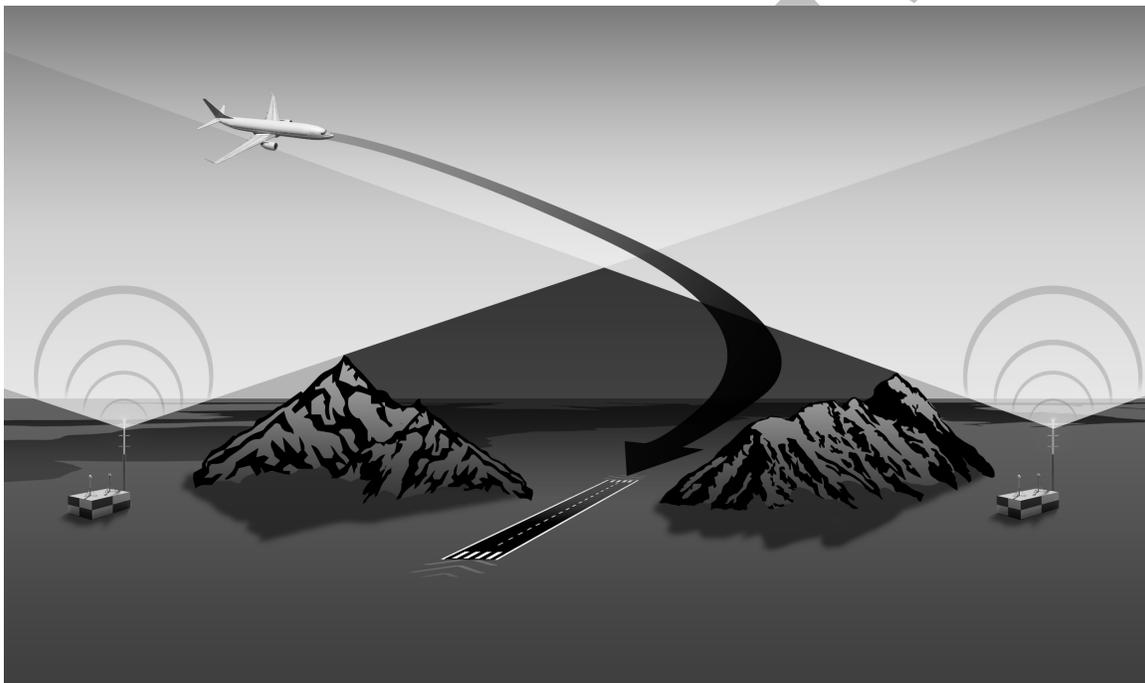
In recent years, the GNSS community has been particularly dismayed by the prevalence of *personal jammers*. These devices intentionally emit a signal in the GNSS portion of the frequency spectrum. They are designed to jam GNSS tracking devices placed surreptitiously on automobiles to secretly track the location of the driver. These personal jammers certainly serve their purpose, but they also jam *all* GNSS use in the immediate neighborhood of the automobile under surveillance. Personal jammers were particularly problematic at Newark International Airport. A GBAS prototype was placed at this airport with its antennas and reference receivers all within a few hundred meters of the New Jersey Turnpike. Unfortunately, vehicles travelling on that highway carry personal jammers and would occasionally jam the GPS receivers at Newark; the GBAS test system was collateral damage.

Today, the overall operational impact of GNSS jamming on aviation is limited by the continued presence of the navigation aids that preceded GNSS. These systems include VHF Omnidirectional Range (VOR), Distance Measuring Equipment (DME) and the Instrument Landing System (ILS). These are all terrestrial radio systems and they are still in operation (Enge, et al., 1995). VOR and DME support navigation for aircraft operating in domestic en route and terminal airspace and for non-precision approaches at airports. ILS is used to guide aircraft as they approach and land at airports. Together, these systems support all current conventional navigation operations and are discussed in detail in the next chapter.

In addition to maintaining and improving some terrestrial nav aids, the aviation community is developing a suite of techniques to specifically combat jamming and spoofing. For example, new GNSS satellites broadcast on two aviation frequencies (e.g. L1 and L5 for GPS). In other words, the new GNSS signals offer frequency diversity; and the aviation community is developing dual frequency avionics to make use of L1 and L5.

With a second frequency, airborne users of GNSS would be much less vulnerable to accidental RFI, because they would have a backup frequency. In addition, the L5 signal is intrinsically more resistant to RFI, because it uses a broader spectrum, and so it provides some protection against intentional attacks. (Spilker and Van Dierendonck, 2001).

Figure 12: Role of Inertial Sensors in Alternative Position Navigation and Time (APNT). As the aircraft descends, terrestrial signals are obstructed and APNT would use inertial sensors to sustain lateral navigation as the aircraft descends from strong radio coverage into weak radio coverage. (Courtesy of BridgeNet International)



In addition, the community is developing techniques to detect spoofing. Some of these are based on receiver autonomous tests and others could be network based. For example, the GNSS receiver could periodically compare the GNSS and APNT position fixes to fend off spoofers.

## 4 Summary

This book teaches the fundamentals and the details of satellite navigation for aviation. Hopefully, this introductory chapter has sketched the air operations that can save fuel and reduce the environmental impact of aviation. These benefits stem from the area navigation (RNAV) capability of GNSS. This first chapter has also strived to introduce the basics of safety for air navigation based on GNSS. This safety is described by required navigation performance (RNP).

Chapter 2 discusses the history of aviation navigation leading up to GNSS. Chapter 3 includes a historical perspective; it teaches the fundamentals of the navigation

techniques that have been developed before and in parallel with GNSS. It also gives an overview of the intricate standards community that permeates aviation. Chapter 2 provides the mathematics of satellite navigation, and describes the three main components of any GNSS (space, ground, and air).

Chapters 4 and 5 detail the signals sent from the GNSS satellite to serve the airborne community. These electromagnetic whispers are well worth our attention, and Chapter 4 describes the signals that are launched from space in the Aeronautical Radio Navigation System bands (L1 and L5), while Chapter 5 describes the propagation path from the satellite to the aircraft.

Chapters 6 through 9 describe the GNSS receiver that is carried by the aircraft. They follow the signal path, so Chapter 6 focuses on the antenna and radio frequency of the receivers. Chapter 7 describes the basics of signal processing and Chapter 8 focuses on the signal processing that is aviation-specific. Chapter 9 describes the so-called position engine. In other words, it focuses on the estimation of latitude, longitude, altitude, and the time offset of the receiver relative to GNSS system time. Chapter 9 also gives performance results.

Chapter 10 gives a deep discussion of the requirements that are in force when satellite navigation is used for aviation. It focuses on the safety requirements that were introduced in the present chapter. It also sets the stage for Chapters 12 through 15 that detail the augmentation systems mentioned earlier in this chapter. Specifically, these chapters explore: receiver autonomous integrity monitoring (RAIM); advanced RAIM; the integration of GNSS with inertial navigation; space based augmentation (SBAS); and ground based augmentation (GBAS).

Chapter 16 returns to our original thesis and discusses the operational use of GNSS to save fuel, reduce flight time, and minimize the environmental impact of aviation. It pays particular attention to the approach procedures that were briefly introduced in this chapter.

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