# 1

# INTRODUCTION

There are five basic forms of navigation:

1. *Pilotage*, which essentially relies on recognizing landmarks to know where you are and how you are oriented. It is older than humankind.
2. *Dead reckoning*, which relies on knowing where you started from, plus some form of heading information and some estimate of speed.
3. *Celestial navigation*, using time and the angles between local vertical and known celestial objects (e.g., sun, moon, planets, stars) to estimate orientation, latitude, and longitude [186].
4. *Radio navigation*, which relies on radiofrequency sources with known locations (including global navigation satellite systems satellites).
5. *Inertial navigation*, which relies on knowing your initial position, velocity, and attitude and thereafter measuring your attitude rates and accelerations. It is the only form of navigation that does not rely on external references.

These forms of navigation can be used in combination as well [18, 26, 214]. The subject of this book is a combination of the fourth and fifth forms of navigation using Kalman filtering.

## 1.1 GNSS/INS INTEGRATION OVERVIEW

Kalman filtering exploits a powerful synergism between the *global navigation satellite systems* (GNSSs) and an *inertial navigation system* (INS). This synergism is possible, in part, because the INS and GNSS have very complementary

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error characteristics. Short-term position errors from the INS are relatively small, but they degrade without bound over time. GNSS position errors, on the other hand, are not as good over the short term, but they do not degrade with time. The Kalman filter is able to take advantage of these characteristics to provide a common, integrated navigation implementation with performance superior to that of either subsystem (GNSS or INS). By using statistical information about the errors in both systems, it is able to combine a system with tens of meters position uncertainty (GNSS) with another system whose position uncertainty degrades at kilometers per hour (INS) and achieve bounded position uncertainties in the order of centimeters [with differential GNSS (DGNSS)] to meters.

A key function performed by the Kalman filter is the statistical combination of GNSS and INS information to track drifting parameters of the sensors in the INS. As a result, the INS can provide enhanced inertial navigation accuracy during periods when GNSS signals may be lost, and the improved position and velocity estimates from the INS can then be used to cause GNSS signal reacquisition to occur much sooner when the GNSS signal becomes available again.

This level of integration necessarily penetrates deeply into each of these subsystems, in that it makes use of partial results that are not ordinarily accessible to users. To take full advantage of the offered integration potential, we must delve into technical details of the designs of both types of systems.

## 1.2 GNSS OVERVIEW

There are currently three global navigation satellite systems (GNSSs) operating or being developed.

### 1.2.1 GPS

The Global Positioning System (GPS) is part of a satellite-based navigation system developed by the U.S. Department of Defense under its NAVSTAR satellite program [82, 84, 89–94, 151–153].

***1.2.1.1 GPS Orbits*** The fully operational GPS includes 24 or more (28 in March 2006) active satellites approximately uniformly dispersed around six circular orbits with four or more satellites each. The orbits are inclined at an angle of $55^\circ$ relative to the equator and are separated from each other by multiples of $60^\circ$ right ascension. The orbits are nongeostationary and approximately circular, with radii of 26,560 km and orbital periods of one-half sidereal day ($\approx$11.967 h). Theoretically, three or more GPS satellites will always be visible from most points on the earth's surface, and four or more GPS satellites can be used to determine an observer's position anywhere on the earth's surface 24 h per day.

***1.2.1.2 GPS Signals*** Each GPS satellite carries a cesium and/or rubidium atomic clock to provide timing information for the signals transmitted by the satellites. Internal clock correction is provided for each satellite clock. Each GPS satellite transmits two spread spectrum, L-band carrier signals—an $L_1$ signal with carrier frequency $f_1 = 1575.42$ MHz and an $L_2$ signal with carrier frequency $f_2 = 1227.6$

MHz. These two frequencies are integral multiples $f_1 = 1540 f_0$ and $f_2 = 1200 f_0$ of a base frequency $f_0 = 1.023$ MHz. The $L_1$ signal from each satellite uses *binary phase-shift keying* (BPSK), modulated by two *pseudorandom noise* (PRN) codes in phase quadrature, designated as the C/A-code and P-code. The $L_2$ signal from each satellite is BPSK modulated by only the P-code. A brief description of the nature of these PRN codes follows, with greater detail given in Chapter 3.

*Compensating for Propagation Delays* This is one motivation for use of two different carrier signals, $L_1$ and $L_2$. Because delay varies approximately as the inverse square of signal frequency $f$ (delay $\propto f^{-2}$), the measurable differential delay between the two carrier frequencies can be used to compensate for the delay in each carrier (see Ref. 128 for details).

*Code-Division Multiplexing* Knowledge of the PRN codes allows users independent access to multiple GPS satellite signals on the same carrier frequency. The signal transmitted by a particular GPS signal can be selected by generating and matching, or correlating, the PRN code for that particular satellite. All PRN codes are known and are generated or stored in GPS satellite signal receivers carried by ground observers. A first PRN code for each GPS satellite, sometimes referred to as a *precision code* or *P-code*, is a relatively long, fine-grained code having an associated clock or chip rate of $10 f_0 = 10.23$ MHz. A second PRN code for each GPS satellite, sometimes referred to as a *clear* or *coarse acquisition code* or *C/A-code*, is intended to facilitate rapid satellite signal acquisition and handover to the P-code. It is a relatively short, coarser-grained code having an associated clock or chip rate $f_0 = 1.023$ MHz. The C/A-code for any GPS satellite has a length of 1023 chips or time increments before it repeats. The full P-code has a length of 259 days, during which each satellite transmits a unique portion of the full P-code. The portion of P-code used for a given GPS satellite has a length of precisely one week (7.000 days) before this code portion repeats. Accepted methods for generating the C/A-code and P-code were established by the satellite developer[1] in 1991 [61, 97].

*Navigation Signal* The GPS satellite bit stream includes navigational information on the ephemeris of the transmitting GPS satellite and an almanac for all GPS satellites, with parameters providing approximate corrections for ionospheric signal propagation delays suitable for single-frequency receivers and for an offset time between satellite clock time and true GPS time. The navigational information is transmitted at a rate of 50 baud. Further discussion of the GPS and techniques for obtaining position information from satellite signals can be found in Chapter 3 (below) and in Ref. 125, pp. 1–90.

***1.2.1.3 Selective Availability*** Selective availability (SA) is a combination of methods available to the U.S. Department of Defense to deliberately derating the accuracy of GPS for "nonauthorized" (i.e., non-U.S. military) users during

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[1] Satellite Systems Division of Rockwell International Corporation, now part of the Boeing Company.

periods of perceived threat. Measures may include pseudorandom time dithering and truncation of the transmitted ephemerides. The initial satellite configuration used SA with pseudorandom dithering of the onboard time reference [212] only, but this was discontinued on May 1, 2000.

*Precise Positioning Service* Formal, proprietary service Precise Positioning Service (PPS) is the full-accuracy, single-receiver GPS positioning service provided to the United States and its allied military organizations and other selected agencies. This service includes access to the unencrypted P-code and the removal of any SA effects.

*Standard Positioning Service without SA* Standard Positioning Service (SPS) provides GPS single-receiver (standalone) positioning service to any user on a continuous, worldwide basis. SPS is intended to provide access only to the C/A-code and the $L_1$ carrier.

*Standard Positioning Service with SA* The horizontal-position accuracy, as degraded by SA, currently is advertised as 100 m, the vertical-position accuracy as 156 m, and time accuracy as 334 ns—all at the 95% probability level. SPS also guarantees the user-specified levels of coverage, availability, and reliability.

### 1.2.2 GLONASS

A second configuration for global positioning is the Global Orbiting Navigation Satellite System (GLONASS), placed in orbit by the former Soviet Union, and now maintained by the Russian Republic [108, 123].

***1.2.2.1 GLONASS Orbits*** GLONASS also uses 24 satellites, but these are distributed approximately uniformly in three orbital planes (as opposed to six for GPS) of eight satellites each (four for GPS). Each orbital plane has a nominal inclination of 64.8° relative to the equator, and the three orbital planes are separated from each other by multiples of 120° right ascension. GLONASS orbits have smaller radii than GPS orbits, about 25,510 km, and a satellite period of revolution of approximately $\frac{8}{17}$ of a sidereal day. A GLONASS satellite and a GPS satellite will complete 17 and 16 revolutions, respectively, around the earth every 8 days.

***1.2.2.2 GLONASS Signals*** The GLONASS system uses frequency-division multiplexing of independent satellite signals. Its two carrier signals corresponding to $L_1$ and $L_2$ have frequencies $f_1 = (1.602 + 9k/16)$ GHz and $f_2 = (1.246 + 7k/16)$ GHz, where $k = 0, 1, 2, \ldots, 23$ is the satellite number. These frequencies lie in two bands at 1.597–1.617 GHz ($L_1$) and 1240–1260 GHz ($L_2$). The $L_1$ code is modulated by a C/A-code (chip rate = 0.511 MHz) and by a P-code (chip rate = 5.11 MHz). The $L_2$ code is presently modulated only by the P-code. The GLONASS satellites also transmit navigational data at a rate of 50 baud. Because the satellite frequencies are distinguishable from each other, the P-code and the C/A-code are the same for each satellite. The methods for receiving and analyzing GLONASS signals are similar to the methods used for GPS signals. Further details can be found in the patent by Janky [97].

GLONASS does not use any form of SA.

### 1.2.3 Galileo

The Galileo system is the third satellite-based navigation system currently under development. Its frequency structure and signal design is being developed by the European Commission's Galileo Signal Task Force (STF), which was established by the European Commission (EC) in March 2001. The STF consists of experts nominated by the European Union (EU) member states, official representatives of the national frequency authorities, and experts from the European Space Agency (ESA).

***1.2.3.1 Galileo Navigation Services*** The EU intends the Galileo system to provide the following four navigation services plus one search and rescue (SAR) service.

*Open Service (OS)* The OS provides signals for positioning and timing, free of direct user charge, and is accessible to any user equipped with a suitable receiver, with no authorization required. In this respect it is similar to the current GPS $L_1$ C/A-code signal. However, the OS will be of higher quality, consisting of six different navigation signals on three carrier frequencies. OS performance will be at least equal to that of the modernized Block IIF GPS satellites, which began launching in 2005, and the future GPS III system architecture currently being investigated. OS applications will include the use of a combination of Galileo and GPS signals, thereby improving performance in severe environments such as urban canyons and heavy vegetation.

*Safety of Life Service (SOL)* The SOL service is intended to increase public safety by providing certified positioning performance, including the use of certified navigation receivers. Typical users of SOL will be airlines and transoceanic maritime companies. The EGNOS regional European enhancement of the GPS system will be optimally integrated with the Galileo SOL service to have independent and complementary integrity information (with no common mode of failure) on the GPS and GLONASS constellations. To benefit from the required level of protection, SOL operates in the $L_1$ and $E_5$ frequency bands reserved for the Aeronautical Radionavigation Services.

*Commercial Service (CS)* The CS service is intended for applications requiring performance higher than that offered by the OS. Users of this service pay a fee for the added value. CS is implemented by adding two additional signals to the OS signal suite. The additional signals are protected by commercial encryption and access protection keys are used in the receiver to decrypt the signals. Typical value-added services include service guarantees, precise timing, ionospheric delay models, local differential correction signals for very high-accuracy positioning applications, and other specialized requirements. These services will be developed by service providers, which will buy the right to use the two commercial signals from the Galileo operator.

*Public Regulated Service (PRS)* The PRS is an access-controlled service for government-authorized applications. It will be used by groups such as police, coast guards, and customs. The signals will be encrypted, and access by region or user group will follow the security policy rules applicable in Europe. The PRS will be operational at all times and in all circumstances, including periods of crisis. A major feature of PRS is the robustness of its signal, which protects it against jamming and spoofing.

*Search and Rescue (SAR)* The SAR service is Europe's contribution to the international cooperative effort on humanitarian search and rescue. It will feature near real-time reception of distress messages from anywhere on Earth, precise location of alerts (within a few meters), multiple satellite detection to overcome terrain blockage, and augmentation by the four low earth orbit (LEO) satellites and the three geostationary satellites in the current COSPAS-SARSAT system.

***1.2.3.2 Galileo Signal Characteristics*** Galileo will provide 10 right-hand circularly polarized navigation signals in three frequency bands. The various signals fall into four categories: F/Nav, I/Nav, C/Nav, and G/Nav. The F/Nav and I/Nav signals are used by the Open Service (OS), Commercial Service (CS) and Safety of Life (SOL) service. The I/Nav signals contain integrity information, while the F/Nav signals do not. The C/Nav signals are used by the Commercial Service (CS), and the G/Nav signals are used by the Public Regulated Service (PRS). At the time of this writing not all of the signal characteristics described below have been finalized.

$E_{5a}$– $E_{5b}$ *Band* This band, which spans the frequency range from 1164 to 1214 MHz, contains two signals, denoted $\mathrm{E}_{5a}$ and $\mathrm{E}_{5b}$, which are respectively centered at 1176.45 and 1207.140 MHz. Each signal has an in-phase component and a quadrature component. Both components use spreading codes with chipping rate of 10 Mcps (million chips per second). However, the in-phase components are modulated by navigation data, while the quadrature components, called *pilot signals*, are data-free. The data-free pilot signals permit arbitrarily long coherent processing, thereby greatly improving detection and tracking sensitivity. A major feature of the $\mathrm{E}_{5a}$ and $\mathrm{E}_{5b}$ signals is that they can be treated as either separate signals or a single wide-band signal. Low-cost receivers can use either signal, but the $\mathrm{E}_{5a}$ signal might be preferred, since it is centered at the same frequency as the modernized GPS $\mathrm{L}_5$ signal and would enable the simultaneous reception of $\mathrm{E}_{5a}$ and $\mathrm{L}_5$ signals by a relatively simple receiver without the need for reception on two separate frequencies. Receivers with sufficient bandwidth to receive the combined $\mathrm{E}_{5a}$ and $\mathrm{E}_{5b}$ signals would have the advantage of greater ranging accuracy and better multipath performance.

Even though the $\mathrm{E}_{5a}$ and $\mathrm{E}_{5b}$ signals can be received separately, they actually are two spectral components produced by a single modulation called *alternate binary offset carrier* (altBOC) modulation. This form of modulation retains the simplicity of standard BOC modulation (used in the modernized GPS M-code military signals) and has a constant envelope while permitting receivers to differentiate the two spectral lobes. The current modulation choice is altBOC(15,10), but this may be subject to change.

The in-phase component of the $E_{5a}$ signal is modulated with 50 symbols per second (sps) navigation data without integrity information, and the in-phase component of the $E_{5b}$ signal is modulated with 250 sps (symbols per second) data with integrity information. Both the $E_{5a}$ and E5b signals are available to the Open Service (OS), CS, and SOL services.

*$E_6$ Band* This band spans the frequency range from 1260 to 1300 MHz and contains a C/Nav signal and a G/Nav signal, each centered at 1278.75 MHz. The C/Nav signal is used by the CS service and has both an in-phase and quadrature pilot component using a BPSK spreading code modulation of 5 Mcps. The in-phase component contains 1000 sps data modulation, and the pilot component is data-free. The G/Nav signal is used by the PRS service and has only an in-phase component modulated by a BOC(10,5) spreading code and data modulation with a symbol rate that is to be determined.

*$E_2$–$L_1$–$E_1$ Band* The $E_2$–$L_1$–$E_1$ band (sometimes denoted as $L_1$ for convenience) spans the frequency range from 1559 to 1591 MHz and contains a G/Nav signal used by the PRS service and an I/Nav signal used by the OS, CS, and SOL services. The G/Nav signal has only an in-phase component with a BOC spreading code and data modulation; the characteristics of both are still being decided. The I/Nav signal has an in-phase and quadrature component. The in-phase component will contain 250 sps data modulation and will likely use BOC(1,1) spreading code, but this has not been finalized. The quadrature component is data-free.

## 1.3 DIFFERENTIAL AND AUGMENTED GPS

### 1.3.1 Differential GPS (DGPS)

Differential GPS (DGPS) is a technique for reducing the error in GPS-derived positions by using additional data from a reference GPS receiver at a known position. The most common form of DGPS involves determining the combined effects of navigation message ephemeris, conospheric and satellite clock errors (including the effects of SA) at a reference station and transmitting pseudorange corrections, in real time, to a user's receiver, which applies the corrections in the process of determining its position [94, 151, 153].

### 1.3.2 Local-Area Differential GPS

Local-area differential GPS (LAGPS) is a form of DGPS in which the user's GPS receiver also receives real-time pseudorange and, possibly, carrier phase corrections from a local reference receiver generally located within the line of sight. The corrections account for the combined effects of navigation message ephemeris and satellite clock errors (including the effects of SA) and, usually, propagation delay errors at the reference station. With the assumption that these errors are also common to the measurements made by the user's receiver, the application of the corrections will result in more accurate coordinates.

### 1.3.3 Wide-Area Differential GPS

Wide-area DGPS (WADGPS) is a form of DGPS in which the user's GPS receiver receives corrections determined from a network of reference stations distributed over a wide geographic area. Separate corrections are usually determined for specific error sources—such as satellite clock, ionospheric propagation delay, and ephemeris. The corrections are applied in the user's receiver or attached computer in computing the receiver's coordinates. The corrections are typically supplied in real time by way of a geostationary communications satellite or through a network of ground-based transmitters. Corrections may also be provided at a later date for postprocessing collected data [94].

### 1.3.4 Wide-Area Augmentation System

The WAAS enhances the GPS SPS over a wide geographic area. The U.S. Federal Aviation Administration (FAA), in cooperation with other agencies, is developing WAAS to provide WADGPS corrections, additional ranging signals from geostationary earth orbit (GEO) satellites, and integrity data on the GPS and GEO satellites.

## 1.4 SPACE-BASED AUGMENTATION SYSTEMS (SBASS)

Four space-based augmentation systems (SBASs) were under development at the beginning of the third millennium. These are the Wide-Area Augmentation System (WAAS), European Geostationary Navigation Overlay System (EGNOS), Multifunctional Transport Satellite (MTSAT)–based Augmentation System (MSAS), and GPS & GEO Augmented Navigation (GAGAN) by India.

### 1.4.1 Historical Background

Although GPS is inherently a very accurate system for positioning and time transfer, some applications require accuracies unobtainable without some form of performance augmentation, such as differential GPS (DGPS), in which position relative to a base (or reference) station can be established very accurately (in some cases within millimeters). A typical DGPS system employs an additional GPS receiver at the base station to measure the GPS signals. Because the coordinates of the base station are precisely known, errors in the received GPS signals can be calculated. These errors, which include satellite clock and position error, as well as tropospheric and ionospheric error, are very nearly the same for users at a sufficiently small distance from the base station. In DGPS the error values determined by the base station are transmitted to the user and applied as corrections to the user's measurements.

However, DGPS has a fundamental limitation in that the broadcast corrections are good only for users in a limited area surrounding the base station. Outside this area the errors tend to be decorrelated, rendering the corrections less accurate. An obvious technical solution to this problem would be to use a network of base stations, each with its own communication link to serve its geographic area. However, this would require a huge number of base stations and their associated communication links.

Early on it was recognized that a better solution would be to use a space-based augmentation system (SBAS) in which a few satellites can broadcast the correction data over a very large area. Such a system can also perform sophisticated computations to optimally interpolate the errors observed from relatively few ground stations so that they can be applied at greater distances from each station.

A major motivation for SBAS has been the need for precision aircraft landing approaches without requiring separate systems, such as the existing instrument landing systems (ILSs) at each airport. An increasing number of countries are currently developing their own versions of SBAS, including the United States (WAAS), Europe (EGNOS), Japan (NSAS), Canada (CWAAS), China (SNAS), and India (GAGAN).

### 1.4.2 Wide-Area Augmentation System (WAAS)

In 1995 the United States began development of the Wide Area Augmentation System (WAAS) under the auspices of the Federal Aviation Administration (FAA) and the Department of Transportation (DOT), to provide precision approach capability for aircraft. Without WAAS, ionospheric disturbances, satellite clock drift, and satellite orbit errors cause too much error in the GPS signal for aircraft to perform a precision landing approach. Additionally, signal integrity information as broadcast by the satellites is insufficient for the demanding needs of public safety in aviation. WAAS provides additional integrity messages to aircraft to meet these needs.

WAAS includes a core of approximately 25 wide-area ground reference stations (WRSs) positioned throughout the United States that have precisely surveyed coordinates. These stations compare the GPS signal measurements with the measurements that should be obtained at the known coordinates. The WRS send their findings to a WAAS master station (WMS) using a land-based communications network, and the WMS calculates correction algorithms and assesses the integrity of the system. The WMS then sends correction messages via a ground uplink system (GUS) to geostationary (GEO) WAAS satellites covering the United States. The satellites in turn broadcast the corrections on a per-GPS satellite basis at the same $L_1$ 1575.42 MHz frequency as GPS. WAAS-enabled GPS receivers receive the corrections and use them to derive corrected GPS signals, which enable highly accurate positioning.

On July 10, 2003, Phase 1 of the WAAS system was activated for general aviation, covering 95% of the conterminous United States and portions of Alaska.

In September 2003, improvements enabled WAAS-enabled aircraft to approach runways to within 250 ft altitude before requiring visual control.

Currently there are two Inmarsat III GEO satellites serving the WAAS area: the Pacific Ocean Region (POR) satellite and the West Atlantic Ocean Region (AOR-W) satellite.

In March 2005 two additional WAAS GEO satellites were launched (PanAmSat Galaxy XV and Telesat Anik F1R), and are now operational. These satellites plus the two existing satellites will improve coverage of North America and all except the northwest part of Alaska. The four GEO satellites will be positioned at 54°, 107°, and 133° west longitude, and at 178° east longitude.

WAAS is currently available over 99% of the time, and its coverage will include the full continental United States and most of Alaska. Although primarily intended for aviation applications, WAAS will be useful for improving the accuracy of any WAAS-enabled GPS receiver. Such receivers are already available in low-cost handheld versions for consumer use.

Positioning accuracy using WAAS is currently quoted at less than 2 m of lateral error and less than 3 m of vertical error, which meets the aviation Category I precision approach requirement of 16 m lateral error and 4 m vertical error.

Further details of the WAAS system can be found in Chapter 6.

### 1.4.3 European Geostationary Navigation Overlay System (EGNOS)

The European Geostationary Navigation Overlay System (EGNOS) is Europe's first venture into satellite navigation. It is a joint project of the European Space Agency (ESA), the European Commission (EC), and Eurocontrol, the European organization for the safety of air navigation. Inasmuch as Europe does not yet have its own standalone satellite navigation system, initially EGNOS is intended to augment both the United States GPS and the Russian GLONASS systems, providing differential accuracy and integrity monitoring for safety-critical applications such as aircraft landing approaches and ship navigation through narrow channels.

EGNOS has functional similarity to WAAS, and consists of four segments: space, ground, user, and support facilities segments.

***1.4.3.1 Space Segment*** The space segment consists of three geostationary (GEO) satellites, the Inmarsat-3 AOR-E, Inmarsat-3 AOR-W, and the ESA Artemis, which transmit wide-area differential corrections and integrity information throughout Europe. Unlike the GPS and GLONASS satellites, these satellites will not have signal generators aboard, but will be transponders relaying uplinked signals generated on the ground.

***1.4.3.2 Ground Segment*** The EGNOS ground segment includes 34 Ranging and Integrity Monitoring Stations (RIMSs), four Mission/Master Control Centers

(MCCs), six Navigation Land Earth Stations (NLESs), and an EGNOS Wide-Area Network (EWAN).

The RIMS stations monitor the GPS and GLONASS signals. Each station contains a GPS/GLONASS/EGNOS receiver, an atomic clock, and network communications equipment. The RIMS tasks are to perform pseudorange measurements, demodulate navigation data, mitigate multipath and interference, verify signal integrity, and to packetize and transmit data to the MCC centers.

The MCC centers monitor and control the three EGNOS GEO satellites, as well as perform real-time software processing. The MCC tasks include integrity determination, calculation of pseudorange corrections for each satellite, determination of ionospheric delay, and generation of EGNOS satellite ephemeris data. The MCC then sends all the data to the NLES stations. Every MCC has a backup station that can take over in the event of failure.

The NLES stations receive the data from the MCC centers and generate the signals to be sent to the GEO satellites. These include a GPS-like signal, an integrity channel, and a wide-area differential (WAD) signal. The NLES send this data on an uplink to the GEO satellites.

The EWAN links all EGNOS ground-based components.

***1.4.3.3 User Segment*** This segment consists of the user receivers. Although EGNOS has been designed primarily for aviation applications, it can also be used with land or marine EGNOS-compatible receivers, including low-cost handheld units.

***1.4.3.4 Support Facilities Segment*** Support for development, operations, and verifications is provided by this segment.

The EGNOS system is currently operational. Positioning accuracy obtainable from use of EGNOS is approximately 5 m, as compared to 10–20 m with unaided GPS. There is the possibility that this can be improved with further technical development.

### 1.4.4 Japan's MTSAT Satellite-Based Augmentation System (MSAS)

The Japanese MSAS system, currently under development by Japan Space Agency and the Japan Civil Aviation Bureau, will improve the accuracy, integrity, continuity, and availability of GPS satellite signals throughout the Japanese Flight Information Region (FIR) by relaying augmentation information to user aircraft via Japan's Multifunctional Transport Satellite (MTSAT) geostationary satellites. The system consists of a network of Ground Monitoring Stations (GMS) in Japan, Monitoring and Ranging Stations (MRSs) outside of Japan, Master Control Stations (MCSs) in Japan with satellite uplinks, and two MTSAT geostationary satellites.

MSAS will serve the Asia–Pacific region with capabilities similar to the United States WAAS system. MSAS and WAAS will be interoperable and are compliant with the International Civil Aviation Organization (ICAO) Standards and Recommended Practices (SARP) for SBAS systems.

### 1.4.5 Canadian Wide-Area Augmentation System (CWAAS)

The Canadian CWAAS system is basically a plan to extend the U.S. WAAS coverage into Canada. Although the WAAS GEO satellites can be received in much of Canada, additional ground reference station sites are needed to achieve valid correctional data outside the United States. At least 11 such sites, spread over Canada, have been evaluated. The Canadian reference stations are to be linked to the U.S. WAAS system.

### 1.4.6 China's Satellite Navigation Augmentation System (SNAS)

China is moving forward with its own version of a SBAS. Although information on their system is incomplete, at least 11 reference sites have been installed in and around Beijing in Phase I of the program, and further expansion is anticipated. Receivers manufactured by Novatel, Inc. of Canada have been delivered for Phase II.

### 1.4.7 Indian GPS and GEO Augmented Navigation System (GAGAN)

In August 2001 the Airports Authority of India and the Indian Space Research Organization signed a memorandum of understanding for jointly establishing the GAGAN system. The system is not yet fully operational, but by 2007 a GSAT-4 satellite should be in orbit, carrying a transponder for broadcasting correction signals. On the ground, eight reference stations are planned for receiving signals from GPS and GLONASS satellites. A Mission Control Center, as well as an uplink station, will be located in Bangalore.

Once GAGAN is operational, it should materially improve air safety over India. There are 449 airports and airstrips in the country, but only 34 have instrument landing systems (ILSs) installed. With GAGAN, aircraft will be able to make precision approaches to any airport in the coverage area. There will undoubtedly be other uses for GAGAN, such as tracking of trains so that warnings can be issued if two trains appear likely to collide.

### 1.4.8 Ground-Based Augmentation Systems (GBASs)

Ground-based augmentation systems (GBASs) differ from the SBAS in that backup, aiding, and/or correction information is broadcast from ground stations instead of from satellites. Three major GBAS are LAAS, JPALS, and LORAN-C.

***1.4.8.1 Local-Area Augmentation System (LAAS)*** LAAS is an augmentation to GPS that services airport areas approximately 20–30 mi in radius, and has been developed under the auspices of the Federal Aviation Administration (FAA). It broadcasts GPS correction data via a very high-frequency (VHF) radio data link from a ground-based transmitter, yielding extremely high accuracy, availability, and integrity deemed necessary for aviation Categories I, II, and III precision landing approaches. LAAS also provides the ability for flexible, curved aircraft approach trajectories. Its demonstrated accuracy is less than 1 m in both the horizontal and vertical directions.

A typical LAAS system, which is designed to support an aircraft's transition from en route airspace into and throughout terminal area airspace, consists of ground equipment and avionics. The ground equipment consists of four GPS reference receivers, a LAAS ground facility, and a VHF radio data transmitter. The avionics equipment includes a GPS receiver, a VHF radio data receiver, and computer hardware and software.

The GPS reference receivers and the LAAS ground facility work together to measure errors in GPS position that are common to the reference receiver and aircraft locations. The LAAS ground facility then produces a LAAS correction message based on the difference between the actual and GPS-calculated positions of the reference receivers. The correction message includes integrity parameters and approach-path information. The LAAS correction message is sent to a VHF data broadcast transmitter, which broadcasts a signal containing the correction/integrity data throughout the local LAAS coverage area, where it is received by incoming aircraft.

The LAAS equipment in the aircraft uses the corrections for position, velocity, and time to generate instrument landing system (ILS) lookalike guidance as low as 200 ft above touchdown. It is anticipated that further technical improvements will eventually result in vertical accuracy below 1 m, enabling ILS guidance all the way down to the runway surface, even in zero visibility (Category III landings).

A major advantage of LAAS is that a single installation at a major airport can be used for multiple precision approaches within its local service area. For example, if an airport has 12 runway ends, each with a separate ILS, all 12 ILS facilities can be replaced with a single LAAS installation. Furthermore, it is generally agreed that the Category III level of accuracy anticipated for LAAS cannot be supported by WAAS.

***1.4.8.2 Joint Precision Approach and Landing System (JPALS)*** JPALS is basically a military version of LAAS that supports fixed-base, tactical, special-mission, and shipboard landing environments. It will allow the military to overcome problems of age and obsolescence of ILS equipment, and also will afford greater interoperability, both among systems used by the various services and between military and civilian systems.

The main distinction between LAAS and JPALS is that the latter can be quickly deployed almost anywhere and makes full use of military GPS functionality, which includes the use of the encrypted M-codes not available for civilian use. The requirement for deployment in a variety of locations not optimized for good GPS reception places great demands on the ability of JPALS equipment to handle poor signal environments and multipath. Such problems are not as severe for LAAS installations, where there is more freedom in site selection for best GPS performance of the reference receivers. Additionally, JPALS GPS receivers must be designed to foil frequent attempts by the enemy to jam the received GPS signals.

***1.4.8.3 Long-Range Navigation (LORAN-C)*** LORAN-C is a low-frequency ground-based radionavigation and time reference system that uses stable 100 kHz transmissions to provide an accurate regional positioning service. Unlike LAAS and JPALS, LORAN-C is an independent, standalone system that does not provide corrections to GPS signals, but instead uses time difference of arrival (TDOA) to establish position.

LORAN-C transmitters are organized into chains of 3–5 stations. Within a chain one station is designated as the master (M) and the other secondary stations (slaves) are identified by the letters W, X, Y, and Z. The sequence of signal transmissions consists of a pulse group from the master station followed at precise time intervals by pulse groups from the secondary stations. All LORAN-C stations operate on the same frequency of 100 kHz, and all stations within a given chain use the same group repetition interval (GRI) to uniquely identify the chain. Within a chain, each of the slave stations transmits its pulse group with a different delay relative to the master station in such a way that the sequence of the pulse groups from the slaves is always received in the same order, independent of the location of the user. This permits identification of the individual slave station transmissions.

The basic measurements made by LORAN-C receivers are TDOAs between the master station signal pulses and the signal pulses from each of the secondary stations in a chain. Each time delay is measured to a precision of about 0.1 μs or better. LORAN-C stations maintain integrity by constantly monitoring their transmissions to detect signal abnormalities that would render the system unusable for navigation. If a signal abnormality is detected, the transmitted pulse groups “blink” on and off to notify the user that the transmitted signal does not comply with the system specifications.

LORAN-C, with an accuracy approaching approximately 30 m in regions with good geometry, is not as precise as GPS. However, it has good repeatability, and positioning errors tend to be stable over time. A major advantage of using LORAN-C as an augmentation to GPS is that it provides a backup system completely independent of GPS. A failure of GPS that would render LAAS or JPALS inoperable does not affect positioning using LORAN-C. On the other hand, LORAN-C is only a regional and not a truly global navigation system, covering significant portions, but not all, of North America, Canada, and Europe, as well as some other areas.

### 1.4.9 Inmarsat Civil Navigation

The Inmarsat overlay is an implementation of a wide-area differential service. Inmarsat is the International Mobile Satellite Organization (IMSO), an 80-nation international consortium, originally created in 1979 to provide maritime[2] mobile services on a global basis but now offering a much wider range of mobile satellite services. Inmarsat launched four geostationary satellites that provide complete

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[2] The “mar” in the name originally stood for “maritime.”

coverage of the globe from ±70° latitude. The data broadcast by the satellites are applicable to users in regions having a corresponding ground station network. The U.S. region is the continental U.S. (CONUS) and uses Atlantic Ocean Region West (AOR-W) and Pacific Ocean Region (POR) geostationary satellites. This is called the WAAS and is being developed by the FAA. The ground station network is operated by the service provider, that is, the FAA, whereas Inmarsat is responsible for operation of the space segment. Inmarsat affiliates operate the uplink Earth stations (e.g., COMSAT in the United States). WAAS is discussed further in Chapter 6.

### 1.4.10 Satellite Overlay

The Inmarsat Civil Navigation Geostationary Satellite Overlay extends and complements the GPS and GLONASS satellite systems. The overlay navigation signals are generated at ground-based facilities. For example, for WAAS, two signals are generated from Santa Paula, California—one for AOR-W and one for POR. The backup signal for POR is generated from Brewster, Washington. The backup signal for AOR-W is generated from Clarksburg, Maryland. Signals are uplinked to Inmarsat-3 satellites such as AOR-W and POR. These satellites contain special satellite repeater channels for rebroadcasting the navigation signals to users. The use of satellite repeater channels differs from the navigation signal broadcast techniques employed by GLONASS and GPS. GLONASS and GPS satellites carry their own navigation payloads that generate their respective navigation signals.

### 1.4.11 Future Satellite Systems

In Europe, activities supported by the European Tripartite Group [European Space Agency (ESA), European Commission (EC), EUROCONTROL] are underway to specify, install, and operate a future civil global navigation satellite system (GNSS) (GNSS-2 or Galileo).

Based on the expectation that GNSS-2 will be developed through an evolutionary process as well as long-term augmentations [e.g., EGNOS], short to midterm augmentation systems (e.g., differential systems) are being targeted.

The first steps toward GNSS-2 will be made by the Tripartite Group. The augmentations will be designed such that the individual elements will be suitable for inclusion in GNSS-2 at a later date. This design process will provide the user with maximum continuity in the upcoming transitions.

In Japan, the Japanese Commercial Aviation Board (JCAB) is currently developing the MSAS.

## 1.5 APPLICATIONS

Both GPS and GLONASS have evolved from dedicated military systems into true dual-use systems. Satellite navigation technology is utilized in numerous civil and military applications, ranging from golf and leisure hiking to spacecraft navigation. Further discussion on applications can be found in Chapters 6 and 7.

### 1.5.1 Aviation

The aviation community has propelled the use of GNSS and various augmentations (e.g., WAAS, EGNOS, GAGAN, MSAS). These systems provide guidance for en route through precision approach phases of flight. Incorporation of a data link with a GNSS receiver enables the transmission of aircraft location to other aircraft and/or to air traffic control (ATC). This function is called automatic dependent surveillance (ADS) and is in use in the POR. Key benefits are ATC monitoring for collision avoidance and optimized routing to reduce travel time and fuel consumption [153].

### 1.5.2 Spacecraft Guidance

The Space Shuttle utilizes GPS for guidance in all phases of its operation (e.g., ground launch, on-orbit and reentry, and landing). NASA's small satellite programs use and plan to use GPS, as does the military on SBIRLEO (space-based infrared low earth orbit) and GBI (ground-based interceptor) kill vehicles.

### 1.5.3 Maritime

GNSS has been used by both commercial and recreational maritime communities. Navigation is enhanced on all bodies of water, from oceanic travel to riverways, especially in inclement weather.

### 1.5.4 Land

The surveying community depends heavily on DGPS to achieve measurement accuracies in the millimeter range. Similar techniques are used in farming, surface mining, and grading for real-time control of vehicles and in the railroad community to obtain train locations with respect to adjacent tracks. GNSS is a key component in intelligent transport systems (ITSs). In vehicle applications, GNSS is used for route guidance, tracking, and fleet management. Combining a cellular phone or data link function with this system enables vehicle tracing and/or emergency messaging.

### 1.5.5 Geographic Information Systems (GISs), Mapping, and Agriculture

Applications include utility and asset mapping and automated airborne mapping, with remote sensing and photogrammetry. Recently, GIS, GPS, and remote sensing have matured enough to be used in agriculture. GIS companies such as the Environmental System Research Institute (Redlands, California) have developed software applications that enable growers to assess field conditions and their relationship to yield. Real time kinematic and differential GNSS applications for precision farming are being developed. This includes soil sampling, yield monitoring, chemical, and fertilizer applications. Some GPS analysts are predicting precision site-specific farming to become "the wave of the future."

## PROBLEMS

**1.1** How many satellites and orbit planes exist for GPS, GLONASS, and Galileo? What are the respective orbit plane inclinations?

**1.2** List the differences in signal characteristics between GPS, GLONASS, and Galileo.