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INTRODUCTION

This book describes satellite-based navigation and timing (satnav), the engineering of systems that transmit radio frequency (RF) ranging signals from a constellation of satellites so that a passive receiver can determine time and its position. Satnav is an established field, yet it is poised to grow in terms of number of satellites and signals, number of receivers, number of innovations and applications based on satnav, and in the ways it affects people worldwide.

Like the Internet, cellular telephony, and aviation, satnav is technologically rich, benefitting from many innovations and innovators over the past decades. This book collects and describes the principles behind satnav and the theories that describe how well it works. A better understanding of how to engineer the systems, the signals, and the receivers is key for contributing to the advance of satnav technology; this material also enriches skills and backgrounds for making contributions in related fields like radar and communications.

The intent of this book is to provide a consistent and integrated depiction of the engineering behind satnav; this chapter provides an introduction and the basic background. Section 1.1 discusses the changing scene of satnav we are currently witnessing—what makes satnav so attractive, its current status, and its prospects. Section 1.2 outlines the principles behind satnav, including the basic architectures of satellites and receivers.

Engineering Satellite-Based Navigation and Timing: Global Navigation Satellite Systems, Signals, and Receivers, First Edition. John W. Betz.

Section 1.3 summarizes commonly employed attributes that apply to any satnav system. Section 1.4 outlines the structure of this book, and suggests how different types of readers can use it.

1.1 SATNAV REVOLUTION

Satnav is revolutionizing our concepts of positioning, navigation, and timing (PNT). Consumers expect to be able to push a button and be shown their location on a map display with accuracy of a few meters, then be guided to walk or drive to any location of interest. Professionals with more sophisticated equipment expect centimeter-level accuracies for surveying or machine control. Meanwhile, aviation worldwide is moving to satnav-guided operations for en route navigation and even airport approaches, to achieve efficiencies and to fit more flights into the increasingly congested air space. Satnav-derived timing, the less-widely recognized function of satnav, is increasingly used to synchronize communication networks and even to time stamp financial transactions. Scientists use satnav to assist with weather forecasting, environmental observations, and earthquake monitoring. Military applications include situational awareness that has substantially reduced fratricide, while highly accurate satnav-based targeting and munition guidance have enabled precision delivery of small munitions with less collateral damage and fewer civilian casualties.

The United States' Navstar Global Positioning System (GPS) has been the primary source of this revolution in what is sometimes known as space-based PNT. Since 2000, GPS modernization has been underway to provide further improved capabilities. Other systems also are contributing to the revolution. Russia's GLONASS has been revitalized in the past few years, reestablishing a full constellation and undergoing modernization. Europe is fielding Galileo to provide a worldwide system that is highly interoperable with GPS, while China has deployed a Phase 2 regional BeiDou constellation and is building out a worldwide BeiDou Phase 3 system. Meanwhile, Japan is developing a regional system called the Quasi-Zenith Satellite System (QZSS). India is fielding a regional system, and has expressed ambitions for a global system as well. Simultaneously, the international aviation community has developed standards for a Satellite-Based Augmentation System (SBAS); more and more SBASs are being fielded to augment standalone satnav systems, yielding higher integrity and higher accuracy when combined with GPS and other satnav systems.

These systems transmit signals that allow a receiver to determine time and its location. The widespread benefits of satnav come from the use of these signals, reliably present to a receiver with adequate view of the sky, by highly capable low cost receivers coupled with software for mapping, route planning, and other applications. The development of novel augmentations, combined with creative integration of satnav with existing communications infrastructure, has produced further advances in capability and user experience. The combination of GPS and these other capabilities has produced the revolution we are experiencing. The emergence of more and better satnav signals, and more satnav systems, promises to launch the next round of creative developments in receivers and application software, augmentations, and integrations with other sensors and with communications capabilities.

While the practice and applications of satnav have evolved rapidly, so have the underlying theory and principles. The original design of GPS implemented many innovations, and the designers recognized other advances that were not included then because of technology limitations in the 1970s. Some of these previously conceived advances, such as pilot components and error control coding of data messages, are now practical to implement and are widely used in new and modern signals. Theoretical advances also have been made since GPS was originally designed, spurred in some cases by the pressures of GPS modernization and the emergence of multiple satnav systems, with the resulting need for hundreds of signals to share common frequency bands. Some of these recent advances involve new techniques, while in other cases they involve a better understanding of performance and how to assess it. Furthermore, user demands for operation in challenging environments like urban canyons and indoors, where satnav operation had previously been thought impossible, and applications demanding accuracies that had not previously been considered, have led to further advances in theory and techniques, along with a better understanding of how to mitigate some of the limitations of satnav.

Satnav has been found to have important attributes that merit the interest, the investment, and the innovation. These attributes, unmatched by any other known navigation and timing technology, include:

- All-weather operation. Satnav's use of L band signals in the 1–2 GHz band makes its use for PVT calculation[1] insensitive to most weather effects, except for the heaviest rainstorms and occasional space weather events.
- Day and night utility. Satnav's use of radio frequency (RF) signals allows it to work under any conditions of light or dark.
- Worldwide utility. Global systems using satellite constellations in medium Earth orbit allow satnav to work anywhere there is an adequate view of the sky, on the surface of the Earth and even in air and space.
- Consistent performance even over featureless surfaces of the Earth.
- Absolute measurements. Measurements of position and time are made, or can be transformed into, absolute Earth-centered, Earth-fixed coordinate systems and universal coordinated time (UCT), not relative to another location or time epoch.
- Three-dimensional positioning, with accuracy of the order of meters.
- Timing accuracy to tens of nanoseconds.
- Consistent accuracy over time and location.
- Inexpensive user equipment. Receiver costs range from tens of dollars for a simple consumer device to several thousands of dollars for a professional device to tens of thousands of dollars for a certified aviation device.

[1] Some scientific applications of satnav, such as LEO satellite-based radio occultation, can be highly sensitive to weather.

- User equipment with small size, low mass, and modest power consumption.
- No or minimal user training, without requirement for expertise involved in using traditional means for navigation.
- Rapid updates, with time, position, and velocity measurements reported of the order of seconds or fractions of seconds.
- Passive operation. User equipment does not need to transmit, but only receive.
- No local infrastructure. Sparsely spaced monitoring stations and several ground control stations with antennas that transmit to the satellites are the only terrestrial infrastructure needed for satnav.
- No detailed local surveying or measurements, no need for local surveys of gravity, terrain, or magnetic fields, and no need to know building topography.

Two additional characteristics that have amplified the revolution are based on far-sighted policies rather than technological characteristics:

- No user charges. For decades, both GPS and GLONASS have provided civil signals to the world free of user charges, funded out of the United States and Russian Federation government budgets.
- Open signal descriptions. For decades, both GPS and GLONASS have provided full technical descriptions of their civil signals, with openly available documentation on how to use them.

These policies have led to worldwide acceptance and use, and to innumerable innovations that exploit satnav systems and signals in ways never conceived by their original developers. Furthermore, more recently introduced and planned systems have adopted similar policies, with some exceptions.[2]

However, satnav has limitations. Severe space weather events can cause fading, signal distortion, and loss of tracking lock in receivers, especially those operating in equatorial and high latitude regions. Satnav signals do not propagate underground or underwater, and they do not propagate well deep indoors. In urban canyons and indoors, even when receivers are able to obtain and process the signals, measurements are often distorted by shadowing and multipath, producing errors of tens or hundreds of meters. Received satnav signals have very low power, and thus are susceptible to even relatively low power interference. Many receivers in use today do not use secure designs; like first-generation computers on the Internet, many satnav receivers have been specified, designed, and tested under the implicit assumption that no one would attack them, and consequently the receivers assume that any apparently valid signal is in fact valid.

The modernization of GPS and GLONASS and the introduction of new satnav systems will help reduce these limitations of satnav with new signal designs, higher-power signals, and new generations of receivers. These receivers will use the improved

[2] For example, Galileo may charge for use of civil signals that support the Commercial Service and Public Regulated Service. See Chapter 10 for a description of these services and signals.

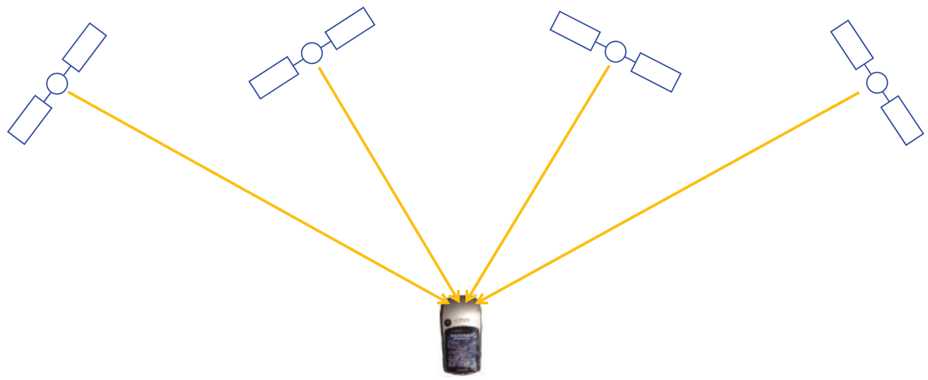

Figure 1.1. Satnav Basic Geometry

signal characteristics to obtain better performance in stressing situations, to further extend the conditions where they can operate, and to mitigate the limitations of satnav. Readers of this book will acquire the knowledge and insights needed to contribute to this next set of advances.

1.2 BASIC PRINCIPLES OF SATNAV

Satnav goes by many different names. “GPS” is sometimes used as a generic term for any satnav system or capability. Others use “Global Navigation Satellite System,” or “GNSS,” despite the fact that some systems are regional. “Radio Navigation Satellite Service,” or “RNSS,” is also used in the communities that manage spectrum use. This book adopts “satellite-based navigation and timing” and uses the abbreviation “satnav.” This is based on the widely accepted definition of navigation as going beyond merely planning and following a route, but also determining one’s position and possibly velocity. Unfortunately, timing is not mentioned explicitly in “satnav,” but is included implicitly.

The term “navigation” has varying definitions. Some sources define navigation as determining your own position and velocity, while others include the concept of guidance—planning and following a route—in the definition of navigation. The treatment of navigation in this book does not include guidance.[3] It does include determining position, velocity, and time (PVT), and uses the term PNT in spite of redundancy between positioning and navigation.

Figure 1.1 shows the basic geometry used in satnav. Each satellite continuously broadcasts one or more signals over the surface of the Earth in view of the satellite. A receiver processes signals from at least four satellites, measuring each signal’s time of arrival relative to a clock in the receiver. The receiver also uses information encoded

[3] GPS commonly is blamed for inefficient or incorrect route planning in vehicle GPS systems, even though route planning is performed by terrestrial-based software not associated with GPS, which only provides the current position and velocity of the vehicle.

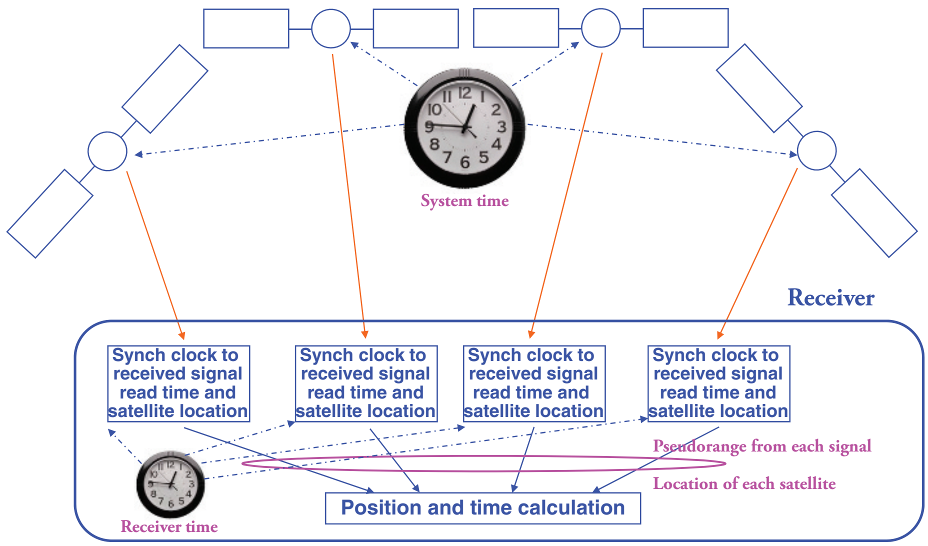

Figure 1.2. Satnav Receiver Processing Overview

in each signal to determine when that signal was transmitted by the satellite and the satellite's position at the time of transmission. To understand the underlying principle, assume initially that the receiver clock and the satellite clocks are perfectly synchronized, so that taking the difference between a signal's time of arrival and the time of transmission yields its signal's propagation delay. As long as the signals propagate at the speed of light in a straight line, the receiver can then calculate its distance from each of the satellites, and then trilaterate,[4] or calculate its location based on known distances from known locations. Clearly, in this case there is no need to calculate time, since it is assumed the receiver's clock is already synchronized to the satellite clocks.

As long as the receiver clock and satellite clocks are synchronized, trilateration can use measurements from three satellites. (The receiver is solving for three unknowns—its coordinates in three dimensions—using three independent measurements.) But attaining positioning accuracies of the order of a meter requires synchronization between the receiver clock and satellite clock of the order of several nanoseconds. Since atomic clocks that provide this type of accuracy have been large, expensive, and power-hungry, receivers would not have been compact, inexpensive, and able to operate for many hours on a small battery if this approach were used.

Instead, a variant of this approach is used, as illustrated in Figure 1.2. Here, all satellites are perfectly synchronized, as above, to system time. This synchronization could be achieved by the technique illustrated—distributing a common time to all

[4] Trilateration determines position by measuring distance from known locations. In contrast, triangulation determines position by measuring angles to known locations, and multilateration (also known as hyperbolic positioning) measures the differences in distances to known locations.

satellites, or with separate clocks on each satellite that are adjusted to maintain synchronization, or with separate clocks that drift, as long as the receiver can correct for the drift. This last approach is typically used in operational satnav systems, but the principle would be the same with any of these approaches. As depicted in Figure 1.2, the receiver has a number of channels, one dedicated to each satellite signal being tracked. Each channel contains signal processing circuitry that continuously measures the signal's time of arrival in terms of a time source at the receiver, or "receiver time." Although the signals are continuous, the receiver selects epochs, or reference times, on each signal to measure their time of arrival. Each signal is modulated with information receivers used to determine the system time and the satellite location when an epoch was transmitted. Comparing each signal's epoch time of arrival in terms of receiver time to the system time when the epoch was transmitted yields the propagation delay plus an offset, or bias, due to the difference between receiver time and system time. This bias is the same for each received signal, since receiver time is common to all the receiver channels, and system time is common to all the satellites. In satnav terminology, these biased delays are known as "pseudodelays," and dividing all the pseudodelays by the known speed of propagation yields a set of pseudoranges: the set of distances from the receiver to each satellite, each biased by a common amount. (Pseudodelays and pseudoranges are equivalent, and related by the speed of light.) The receiver then uses the set of pseudoranges and satellite positions to calculate its position and time in the same coordinate systems used by the system.

Figure 1.3 shows the satellite locations, receiver location, system time at a particular epoch, receiver time at the same epoch, and propagation delays. Locations may be defined in different coordinate systems, with the satellite locations described in an inertial reference system, the receiver location in a geodetic or Earth-centered, Earth-fixed (ECEF) coordinate system, and the receiver position sometimes reported in an east-north-up (ENU) or other relative coordinate system. System time is defined relative to a time standard such as UTC, and receiver time t_r is defined as system time t_s plus a receiver clock offset Δ_r. Known to the receiver are the satellite locations (x_k, y_k, z_k), system time at a particular epoch, receiver time, and the pseudodelays D_k corresponding

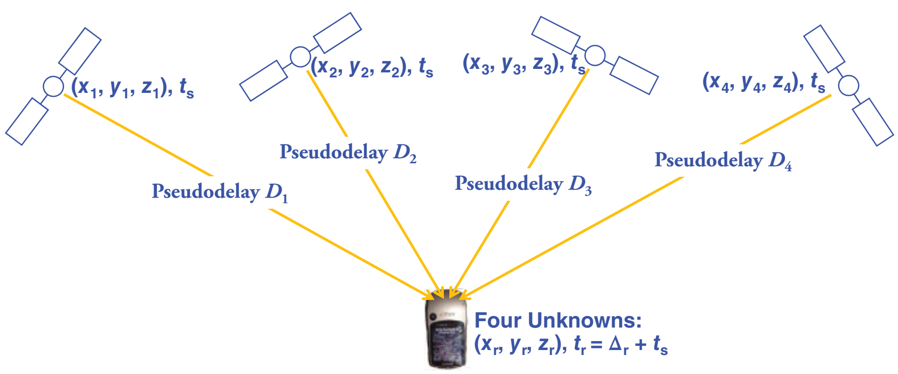

Figure 1.3. Quantities Used for Calculating Position and Time

to that epoch. Assuming the signals propagate in a straight line at the speed of light $c = 2.99792458 \times 10^8$ m/s, the pseudoranges are $D_k c$ and the true ranges are $(D_k - t_b)c$.

If there are four satellites, as shown, applying the Pythagorean theorem for each satellite yields the system of four equations in four unknowns x_r, y_r, z_r, Δ_r

$$\begin{aligned}
cD_1 &= [(x_1 - x_r)^2 + (y_1 - y_r)^2 + (z_1 - z_r)^2]^{1/2} + c\Delta_r \\
cD_2 &= [(x_2 - x_r)^2 + (y_2 - y_r)^2 + (z_2 - z_r)^2]^{1/2} + c\Delta_r \\
cD_3 &= [(x_3 - x_r)^2 + (y_3 - y_r)^2 + (z_3 - z_r)^2]^{1/2} + c\Delta_r \\
cD_4 &= [(x_4 - x_r)^2 + (y_4 - y_r)^2 + (z_4 - z_r)^2]^{1/2} + c\Delta_r
\end{aligned} \tag{1.1}$$

Numerous approaches exist for solving these equations. Some approaches yield two solutions, one of which is typically physically impossible. If there are fewer than four satellites, this approach does not yield a unique solution, although there are ways to handle that situation in some cases. If there are more than four satellites, the overdetermined system of equations can be used to advantage in different ways, including crosschecking the validity of measurements and reducing the effects of measurement errors. Chapter 20 discusses these topics in detail.

Naively applying these concepts in actual satnav would produce results with very large errors, since the preceding model is overly simplistic, with many second-order and third-order effects neglected. Satellites and receivers are not points in space, but distributed, so the positions in (1.1) actually describe the antenna phase centers. Everything is moving—satellites, receivers, and even the ECEF coordinate system, and all this motion must be taken into account in several different ways. The actual satellite locations differ from what is encoded onto the signals, the satellite clocks are not perfectly synchronized in reality, and the encoded clock corrections are not perfectly correct. The satellite speeds are high enough that relativistic effects must be taken into account. The signals do not propagate at the speed of light or in a straight line, but instead are refracted by the ionosphere and then undergo signal-specific delays in the troposphere. Reflections from nearby objects (multipath), noise, and interference contaminate the received signals, causing errors in receiver measurements. These and other details must be taken into account in order to achieve the accuracies experienced with satnav today.

Satnav engineering then consists of designing systems, signals, and receivers that provide navigation and timing capabilities, under constraints of cost and complexity. Satnav systems are generally described in terms of three segments or subsystems, portrayed in Figure 1.4. The space segment consists of the satellites that transmit the signals as electromagnetic waves. The signals are sinusoids modulated by spreading modulations and spreading codes, along with data that provides to receivers the satellite's ephemeris (location in space at different times), offset of the satellite clock relative to system time, and other system information. The user segment consists of antennas that capture the electromagnetic waves, and receivers to process the signals for measuring time of arrival, reading the data modulated onto the signal, and then calculating the receiver position, velocity, and time. While the space segment receives publicity each time a satellite is launched, and we are used to handling receivers, the relatively unknown but also essential segment is the control segment, sometimes called the ground segment. The control

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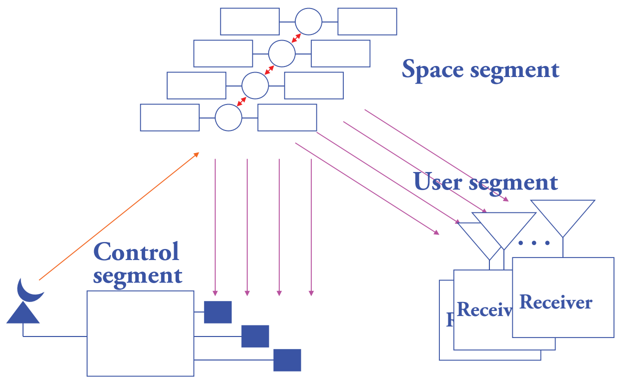

Figure 1.4. Generic Satnav System Architecture

segment makes satnav a closed-loop system by monitoring the signals from the satellites (including the same signals received by the user segment, other telemetry signals from the satellite describing health and status of its subsystems and components, and in some cases laser signals reflected from the satellites) to determine the satellites' orbits and clock alignment as well as the satellite's status. The control segment then transmits to the satellites new data message contents, with updated ephemeris and clock corrections, along with updates to other system information, to be modulated onto the signals.

Satnav signals connect the space segment to the other two segments. As explained above, these signals enable the receiver to perform two different functions:

1. Measure each signal's time of arrival (yielding pseudoranges) and frequency of arrival (yielding rate of change of the pseudorange, and from this line of sight speeds relative to the satellites),
2. Read each satellite's position and the time of transmission at a signal epoch, as well as other system information modulated onto the signal.

In this sense, satnav is much like a blend of radar, where time of arrival and frequency of arrival measurements are critical, and digital communications, involving reading digital information modulated onto the signal.

The satellite assembles the signals, including modulating the data onto the signals. An entire book could be written about satnav satellite design, describing the bus, propulsion, thermal management, power supply, communications links with ground systems, and other subsystems. The relevant focus for this book is the navigation signal generation, depicted in Figure 1.5. Key is the satellite clock, with its low phase noise and low drift rate. Satnav satellites typically transmit multiple signals at two or more different carrier frequencies; five signals are portrayed in the figure. Baseband signal generation occurs for each of these five signals, including forming data messages from information telemetered from the ground control segment and generating spreading codes to produce each baseband signal as described in Chapter 3. Multiple signals are multiplexed

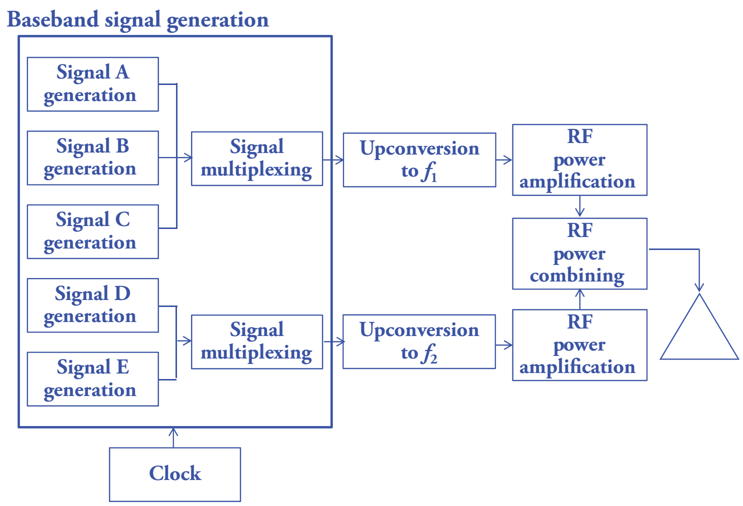

Figure 1.5. Navigation Signal Generation on a Satnav Satellite

together to be modulated onto a single carrier; in this example three signals are multiplexed being modulated onto a carrier with frequency f_1 and two signals multiplexed onto a carrier with frequency f_2, using multiplexing techniques described in Chapter 3. These low-power signals at RF are each amplified to high power (typically tens of watts of RF power for each signal) using power amplifiers tuned to each carrier frequency. The signals are then combined at high power into a single high-power signal (having effective isotropic radiated power sometimes exceeding a kilowatt) transmitted from the antenna.

Building and launching satnav satellites are both very expensive, with the cost for developing, building, and launching a satellite typically exceeding 100 million US dollars. Satellite weight is highly related to cost, and every transmitted watt of power adds to satellite weight in multiple ways, including the solar panels that supply the power to the power conversion and conditioning circuitry, power amplifiers, power combiner, antenna elements, as well as heat pipes and radiators needed to handle waste power on the satellite. The most efficient power amplifiers are highly nonlinear, operating in what is called “saturation” where the output voltage’s magnitude is constant, with only the phase changing. An important aspect of satnav signals, as discussed in Chapter 3, is for the transmitted signal to have a constant magnitude, also known as “constant envelope,” to enable use of efficient power amplifiers. The signals themselves must be designed to enable efficient transmission and effective receiver processing.

The receiver processes the signals to make the measurements and read the data. Receiver processing consists of four main functions:

- Perform initial synchronization: when the receiver is not already tracking signals, it detects the signals that are available to receive, then obtains an initial estimate of each signal’s time of arrival and received carrier frequency to initiate tracking.

- Track the signals: the receiver estimates the time-varying time of arrival and frequency of arrival of each signal, providing periodic estimates of pseudoranges and received carrier frequencies (and possibly the carrier phases).
- Read the data messages: the receiver demodulates the encoded message bits, deinterleaves the bits, decodes the channel encoding, checks for errors, synchronizes to the message structure, and then interprets the data message to obtain satellite ephemeris and clock corrections, along with other system information.
- Calculate receiver position and velocity: the receiver uses pseudoranges, system time information, and ephemerides to calculate and smooth the receiver position and velocity.

Figure 1.6 provides a simple block diagram of receiver functions. The receive antenna transforms the incident electromagnetic field to electric signals. These are conditioned (amplified and filtered) at RF, then downconverted to an intermediate frequency (IF) or baseband. Signal conditioning involves additional amplification and filtering, as well as automatic gain control in some receivers. At some point in this process the analog signals, continuous in time and in amplitude, are processed by an analog-to-digital converter that samples them, producing outputs of discrete amplitude samples represented by digital values, at discrete points in time. Signal processing operates on these digitized signals, performing initial synchronization, tracking the signals, computing values used to demodulate the data message, and reading the data message. Signal processing for acquisition and tracking relies on correlation processing between the received signals and noise and interference with a locally generated replica. Different receiver channels perform tracking on different signals being received and processed. Navigation processing uses measurements from tracking, as well as information from the data message, to produce estimates of the receive antenna's location and velocity, and of time. The receiver processing is driven by frequencies synthesized from a reference oscillator in the receiver.

This book describes the engineering of satnav systems, signals, and receivers, with emphasis on how these receiver functions are implemented, and methods to determine and predict how well they are performed.

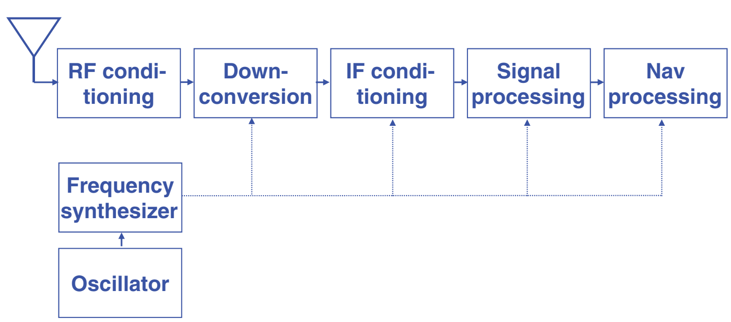

Figure 1.6. Overview of Receiver Functions

1.3 SATNAV ATTRIBUTES

The aviation community has defined four attributes that apply to any satnav system: accuracy, integrity, continuity, and availability [1]. Accuracy is defined as the degree that the navigation system's reported PVT correspond to their true values in the same reference system. Integrity indicates that the signals transmitted are valid and useful, and that their RF characteristics and data message contents are within specification and will produce valid PVT. Further, integrity indicates the system will provide timely and valid warnings when the system should not be used for the intended purpose. Any warning must be provided within a given period of time (time-to-alert) when the system should not be used. Continuity describes a navigation system's capability to perform its function without unscheduled interruptions during an intended period of operation. Availability is the fraction of time during which the service provides expected levels of accuracy, integrity, and continuity, taking into account all the reasons for the lack of service.

1.4 BOOK STRUCTURE AND HOW TO USE THIS BOOK

This book begins with a top-down view of satnav engineering. Part I describes the principles and practices of systems engineering and signal engineering for satnav, including the basic calculations that describe system operation and performance, along with the generic characteristics of satnav signals. Descriptions of satellite orbits and Kepler's laws provide insights into how ephemeris is represented and how it is used by receivers. Geometrical relationships are calculated between satellites and receivers and the resulting effects on signals propagating from satellites to receivers are derived. Concepts and terminology associated with satnav signals that link satellites to receivers are provided. The many characteristics that describe a satnav signal are discussed, with perspectives on choosing these characteristics. Mathematical representations are provided for signals and how they are processed, with definitions of terminology and concepts essential to understanding and using modern satnav signals. Link budgets are presented, showing how to calculate relationships between transmitted power and received power for space-to-Earth links used for satnav signals, how to calculate link budgets for satnav signals, and how to estimate ground-to-ground propagation loss for local interference sources, as well as how to account for additional attenuation caused by foliage and buildings. Essential descriptors of signal and interference environments and of receiver performance are introduced, along with the analytical tools to assess effects of interference on receiver performance metrics. Satnav positioning and timing error analyses are presented.

Part II then describes specific satnav systems and signals. The United States' GPS, multiple nations' SBASs, Russian Federation's GLONASS, Europe's Galileo, China's BeiDou, Japan's QZSS, and India's IRNSS are each described, with summaries of their history and characteristics. Most important from the perspective of this book, however, is the description of their signals. Using the concepts, terminology, and mathematical notation from Part I, the different chapters provide succinct yet detailed descriptions of the signal characteristics, preparing the reader to understand how to design receivers for processing these signals, as well as providing a useful introduction to each system's signal interface specifications that provide the complete set of details needed to receive the signals.

Part III describes essential aspects of receiver design and evaluating receiver processing performance, from receiver front end through position calculation. Characteristics of front-end components and various front-end architectures are described, along with associated tradeoffs. Details of analog-to-digital conversion (ADC) are described, along with models for relating ADC sampling rates and quantization to processing losses. Initial synchronization, where a receiver detects the presence of satnav signals and estimates their time of arrival and frequency of arrival, is described with focus on modern algorithms enabled by advanced digital circuitry along with associated performance. Since receiver measurements typically rely on tracking loops for estimating the time-varying carrier frequency and phase and the spreading modulation time of arrival, the theory, design, and performance of tracking loops are described using a general formulation that applies to the different types of loops in satnav receivers. The specifics of carrier tracking and code tracking are then addressed, integrated with analytical tools for assessing performance to enable design trades. Finally, position calculation techniques are introduced, along with how to account for errors introduced by the ionosphere and other phenomena. Also, variations are discussed for position calculation using signals from fewer than and more than four satellites. The material emphasizes processing of new and modern signals, using the advanced features incorporated into these new signal designs for better and more robust performance, and providing the latest results in terms of techniques and performance assessment. Numerous alternatives are described, with integrated presentation of analytical tools for predicting performance in trading off the alternatives. Along with an emphasis on modern signals, the material presented also emphasizes modern receiver processing techniques enabled by the ability to perform large and complex digital processing functions inexpensively, providing opportunities to implement techniques previously considered impractical.

Although basic receiver processing techniques are important, modern and future satnav receivers increasingly involve more advanced techniques and capabilities. Part IV introduces specialized topics that are essential for obtaining the next level of performance and enabling advanced applications. Since interference is and will be a reality, specialized techniques for dealing with interference are presented. As new and modernized multifrequency satnav systems become available, multipath and shadowing will often be the dominant source of errors, and an overview of multipath's effects and how to mitigate them is provided. Differential satnav is effective in providing submeter accuracies, and alternative architectures and approaches for differential satnav are described. Assisted satnav, another recent development that employs communications functionality to simplify and improve satnav processing, is outlined. While traditional receiver processing only uses satnav signals, and tracks each signal separately, modern satnav processing need not be limited in this way. Joint tracking of all signals is described, since its implementation is increasingly practical. In addition, other sensors are readily available at increasingly acceptable cost, size, and power consumption. Sophisticated use of information from these other sensors, combined with using satnav signals, is shown to provide important extensions and improvements in capability.

This book is structured for use as a textbook for an upper-level undergraduate course or for a graduate course in satnav engineering. For a one semester course, Part I and Part III should be emphasized, with one chapter in Part II addressed in detail—this chapter should be selected based on which satnav system is of most interest to the instructor and students. An undergraduate course would emphasize the applied problems after each chapter, while a graduate course would spend more time on the theoretical problems, helping students establish a deeper technical foundation.

For a two-semester course, much more of the book can be covered. All of Part II would be addressed so that students become familiar with the entire set of satnav systems, and there will be additional time to address details and extensions of receiver processing in Part III. Further, some or all of the specialized topics in Part IV can be addressed, and students could perform class or individual projects by accessing additional information on these topics to attain greater depth.

This book can also be a very useful supplementary text in an advanced undergraduate or graduate course, or for a short course or seminar on satnav. It is also structured to be useful for an engineer seeking to enhance his or her skills in satnav engineering, or as a reference to the practicing satnav engineer.

In addition, many of the systems engineering topics in Part I and receiver design topics in Part III apply to areas other than satnav, and the organized presentation of these topics should be of interest to students or practitioners in other RF-based technologies such as communications and sensing.

1.5 MORE TO EXPLORE

A number of books provide useful overviews of satnav, typically with emphasis on GPS. Among these are:

- *Global Positioning System: Theory and Applications*, Edited by B. W. Parkinson, J. J. Spilker, Jr., P. Axelrad, and P. Enge, American Institute of Aeronautics and Astronautics, 1996.
- P. Misra and P. Enge, *Global Positioning System: Signals, Measurements, and Performance*, Revised 2nd edition, Ganga-Jamuna Press, 2006.
- *Understanding GPS: Principles and Applications*, 2nd edition, Edited by E. D. Kaplan and C. J. Hegarty, Artech House, 2006.
- F. van Diggelen, *A-GPS: Assisted GPS, GNSS, and SBAS*, Artech House, 2009.
- *Global Navigation Satellite Systems: Signal, Theory and Applications*, Edited by S. Jin, ISBN: 978-953-307-843-4, InTech, DOI: 10.5772/29453. Available from: http://www.intechopen.com/books/global-navigation-satellite-systems-signal-theory-and-applications, accessed 25 October 2014.

A nice introduction to key aspects of satnav (although some of the specifics and numerical values are out of date), also with emphasis on GPS, is:

- R. Langley, The Mathematics of GPS, *GPS World Magazine*, July/August 1991.

For decades, a column called “Innovation” in GPS World Magazine, edited by Richard Langley, has provided excellent technical detail on focused topics. A more recent column called “GNSS Solutions” in InsideGNSS Magazine, edited by Mark Petovello, is similarly an excellent resource.
In addition, there are numerous tutorials available on the Internet that are useful but do not necessarily benefit from the same quality control as formal publications. Two examples are:

- http://en.wikipedia.org/wiki/Gps
- http://www.navipedia.net

There are also free online courses available on the Internet. For example, the Massively Online Open Course (MOOC) “GPS: An Introduction to Satellite Navigation, with an Interactive Worldwide Laboratory using Smartphones,” by Professor Per Enge and Dr. Frank van Diggelen of Stanford University can be found at:

- https://www.coursera.org/course/gpslab

REFERENCE

1. Civil Aviation Authority, CAA PAPER 2003/9, April 2004, www.caa.co.uk, accessed 24 October 2014.