UNIT-IV EARTH STN TECHNOLOGY, SATELLITE NAVIGATION & GPS

UNIT-IV:

Earth Station Technology: Transmitters, Receivers, Antennas, Tracking systems, Terrestrial Interface, Power Test methods, Lower Orbit Considerations.

Satellite Navigation & Global Positioning Systems: Radio and Satellite Navigation, GPS Position Location principles, GPS Receivers, GPS C/A code accuracy, Differential GPS.

Earth Stations Introduction

Earth stations provide access to the space segment, interconnecting users with one another and with terrestrial networks such as the Internet and the public telephone network. In the first decades of this industry, Earth stations were large, both in physical and financial terms. Individual ownership of a satellite terminal was within the reach only of major organizations and perhaps a few wealthy individuals. By the late 1980s, low-cost TV receive-only (TVRO) terminals cost as little as $1,000; many people who lived in remote areas were pleased to be able to receive commercial television programming through this means. During the 1990s and past 2000, we have the widespread adoption of low-cost user terminals (UTs) that provide access to two-way as well as one-way services. Interestingly, the electronic complexity of the modern UT is no less than what formerly took up several equipment racks in the large Earth stations.

In this Unit, more will be said about the various Earth station architectures in relation to the types of services that are provided. Included are digital media content, data communications, and fixed and mobile telephony. A discussion is provided of the TT&C Earth station and satellite control facility, both of which are needed to implement and operate the space segment. They are not typically used for communication services, but their design and operation are no less important to meeting the technical and financial objectives of a satellite mission. Tradeoffs in design of the various types of Earth stations are also described. The terrestrial ‘‘tail’’ that connects the Earth station with the outside world is reviewed, as are considerations for implementing the building and other support facilities.

Earth Station Technology:

The earth segment of a satellite communications system consists of transmit and receive earth stations. The simplest of these are the home *TV receive-only* (TVRO) systems, and the most complex are the terminal stations used for international communications networks. Also included in the earth segment are those stations which are on ships at sea, and commercial and military land and aeronautical mobile stations.

As mentioned in earth stations that are used for logistic support of satellites, such as providing the *telemetry, tracking, and command* (TT&C) functions, are considered as part of the space segment.

Terrestrial Interface:

Earth station is a vital element in any satellite communication network. The function of an earth station is to receive information from or transmit information to, the satellite network in the most cost-effective and reliable manner while retaining the desired signal quality.

The design of earth station configuration depends upon many factors and its location. But it is fundamentally governed by its Location which are listed below,

- In land
- On a ship at sea
- Onboard aircraft The factors are
- Type of services
- Frequency bands used
- Function of the transmitter
- Function of the receiver
- Antenna characteristics

Transmitter and Receiver

Any earth station consists of four major subsystems

- Transmitter
- Receiver
- Antenna
- Tracking equipment

Two other important subsystems are

- Terrestrial interface equipment
- Power supply

The earth station performance depends on the following parameters

- Transmitter power
- Choice of frequency
- Gain of antenna
- Antenna efficiency
- Antenna pointing accuracy
- Noise temperature

The functional elements of a basic digital earth station are shown in the below figure

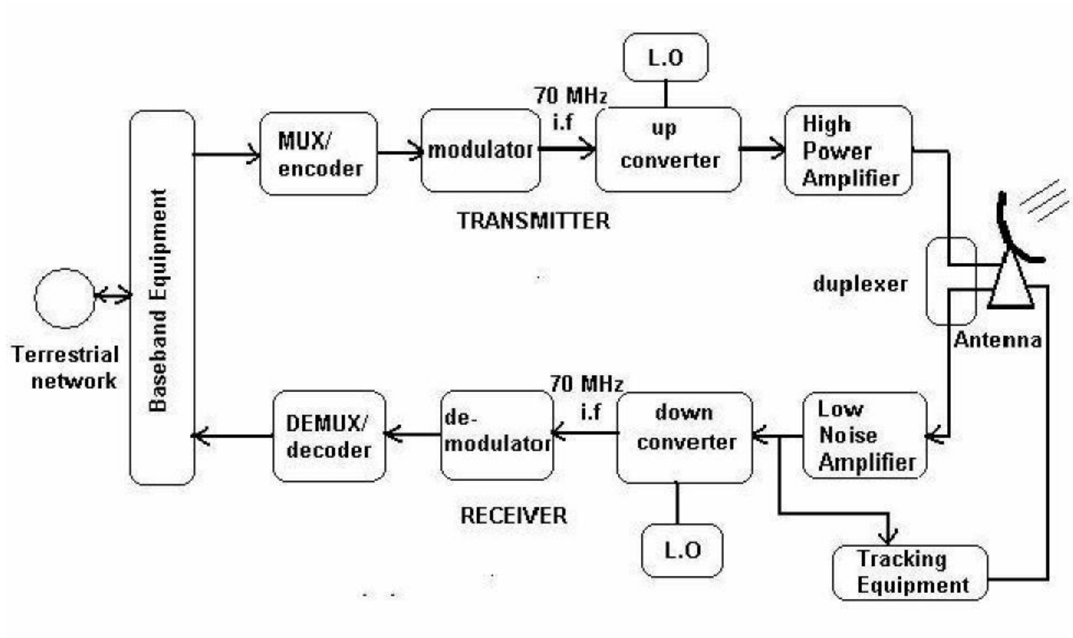


Fig 4.1: Transmitter and Receiver of Earth Station

Transmitters and Receivers

Historically, large earth stations are assembled as discrete elements. On the receive side, the antenna and feed components are connected by waveguide to the front-end, low noise amplifier LNA, behind the LNA, a mixer /down converter changes the signal from radio frequency(RF) to an intermediate frequency(IF). After filtering and amplification, the IF signal is demodulated, de-multiplexed, and decoded and the baseband signal forwarded to the user.

The transmit side is the mirror image of the receive side with the signal input at baseband and the output at RF. With the LNA receiver replaced by a high-power amplifier (HPA) transmitter. This design of the earth station is typical of a hub station used in a VSAT (Very Small Aperture Terminal) network. Much of this discrete component design has changed with the introduction of digital receivers and the need to develop cheap, mass-produced VSAT terminals.

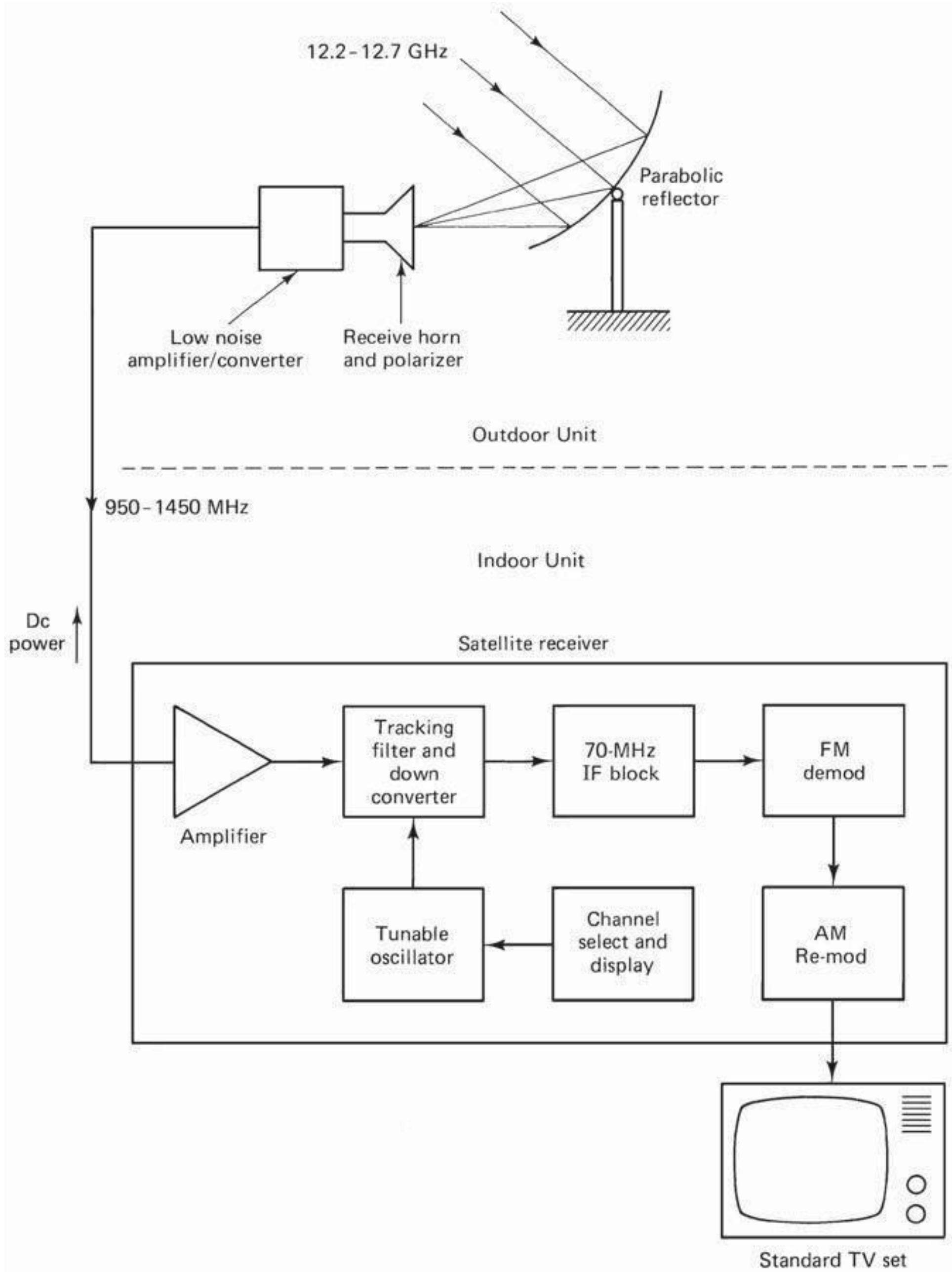
Earth Station Tracking System:

Tracking is essential when the satellite drift, as seen by an earth station antenna is a significant fraction of an earth station's antenna beam width.

An earth station's tracking system is required to perform some of the functions such as

i) Satellite acquisition
ii) Automatic tracking
iii) Manual tracking
iv) Program tracking.

Typical DTH System

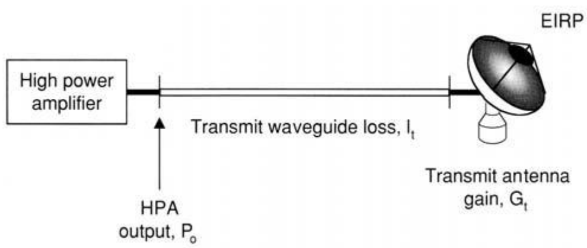


Performance Requirements

The performance requirements of the Earth station mirror those of the satellite. That is to ensure that there is a satisfactory RF link between the ground and the space segments under all expected conditions and for the range of required services. In addition, the Earth station determines the baseband quality and much of the end-to-end communication performance of the services being provided. We first consider the key parameters of EIRP and G/T as they relate to the ground.

Transmit EIRP

The Earth station EIRP simply is the value that applies to the uplink. As with the satellite (downlink) EIRP, it is obtained by multiplying the antenna gain (as a ratio) by the transmit power at the input to the antenna. In decibel terms, it is the antenna gain plus the transmit power in decibels relative to 1W (dBW). As shown in simplified block diagram in Figure 9.2, the EIRP also considers any RF loss between the HPA and the antenna. The loss factor, *lt* , is a number greater than 1, and the ratio 1/*lt* is actually the transmission factor (e.g., a gain less than 1). Major Earth stations typically are designed for reliable uplink operation with low outage due to rainfall. Therefore, the required uplink EIRP is substantially higher than that of the downlink (possibly including uplink power control). That may require the use of vacuum tube HPAs capable of transmitting several kilowatts or at least a substantial fraction of 1 kW. The antenna gain will, of course, depend on the uplink frequency and the size of the antenna. While the behemoth 30-m antennas of the early INTELSAT system no longer are being constructed, it is common to find antennas in the 7-m to 13-m class for service at C-, X-, Ku-, and Ka-bands.



$$\text{EIRP} = \frac{P_o}{l_t} G_t \quad \text{in watts}$$

$$\text{EIRP} = P_o - L_t + G_t \quad \text{in dBW}$$

Fig 9.2: Definition of Earth station transmit EIRP, indicating the primary contributors to performance.

VSAT networks are designed to not require vacuum tube HPAs at the remote sites, favouring instead lower power SSPAs. EIRP for a hand-held UT is going to be low because of low transmit power and low antenna gain. In non-GEO systems, the satellite can be literally anywhere in the sky, so the UT antenna should provide nearly uniform radiation in all directions. The expected elevation angles toward the satellites as they pass overhead, as well as the variety of physical orientations that the user might impose, must be considered.

High-power uplinks bring with them a concern about radiation hazard to humans and other living things. That is one of the reasons major Earth stations are not located in highly populated areas or are shielded from such exposure. Careful consideration must be given to that aspect of safety. Low-power uplinks in VSATs and MSS terminals may pose less of a risk but still should be considered potentially harmful to humans. Handheld UTs expose the user to direct radiation, but power is kept to levels as low as typical cell phones. This is an area of active research and is still controversial with regard to the operation of common cell phones, which transmit similar power levels. In all cases, appropriate research and testing are prudent.

Receive G/T

The figure-of-merit of overall Earth station performance in the downlink is the G/T. G/T is the ratio of the antenna gain (itself as a ratio) to the total system noise temperature (in Kelvin, which is with respect to absolute zero) of the receiving Earth station, converted to decibels per Kelvin. The contributors to G/T are indicated in Figure 9.3. Again, *lr* is a factor greater than 1, and 1/*lr* is the transmission factor (e.g., less than 1). Higher antenna gain improves sensitivity as does lower noise, hence the use of a ratio. The G/T of the station is used in link budget calculations (discussed in Chapter 4) to compute the ratio of carrier to noise. In general, Earth station downlink performance can be adequately measured and optimized
by consideration of the G/T figure.

The figure of merit (G/T in dB/K) of a C-band Earth station is plotted in Figure 9.4 as a function of antenna diameter for three common levels of LNA noise temperature: 30K, 70K, and 110K. We assume that the antenna temperature in each case is a typical value of 40K, common for parabolic reflectors at elevation angles greater than about 20 degrees. The other factors that make up G/T consist

$$\frac{G}{T} = \frac{\frac{G_r}{l_r}}{\frac{T_a}{l_r} + \left(1 - \frac{1}{l_r}\right) \cdot 290 + T_{re}}$$

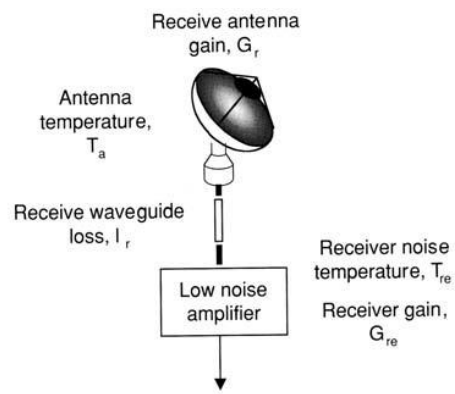


Figure 9.3 Definition of Earth station receive G/T, indicating how noise contributes to performance. Receiver gain, Gre, is sufficiently high to reduce the downstream noise (due to down conversion and so forth) to less than the equivalent of 1K.

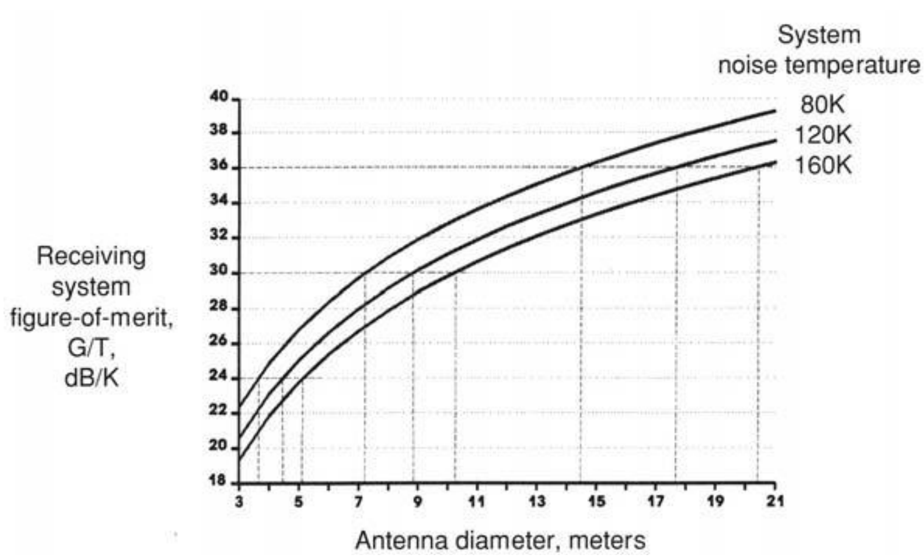


Figure 9.4 Earth station receiving figure of merit (G/T) at C-band as a function of antenna diameter and system noise temperature.

High-Power Amplifiers

The performance of an Earth station uplink is gauged by the EIRP, the same parameter that applies to the satellite downlink. As discussed earlier, the EIRP is the product of the HPA output power, the loss of the waveguide between HPA and antenna (expressed as a ratio less than 1), and the antenna gain. The result is expressed in decibels relative to 1W, so it also is convenient to add the component performances in decibel terms. For example, an EIRP of 80 dBW results from an HPA output of 30 dBW (i.e., 1,000W), a waveguide loss of 2 dB, and an antenna gain of 52 dB. Since the dimensions of an Earth station antenna are not subject to the physical constraints of the launch vehicle, the diameter and, consequently, the gain can be set at a more convenient point. That could be the optimum, which occurs where the cost of the antenna plus HPA is minimum. In VSATs and small UTs, HPA power must be held to an absolute minimum to save cost and minimize radiation, so the optimization usually is reversed to rely on the satellite G/T and EIRP to produce a satisfactory link. Antenna size or diameter may also be constrained by the location, such as the military vehicle system.

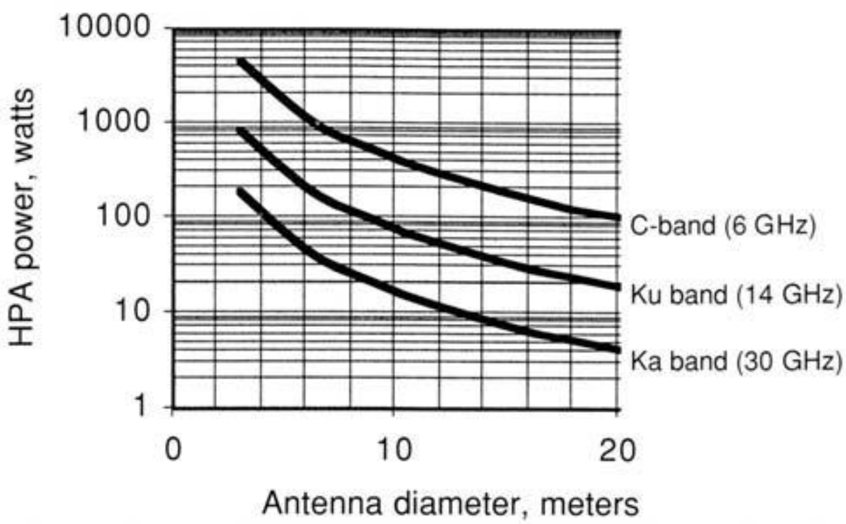


Figure 9.11 Earth station HPA power versus antenna diameter for full transponder uplinking (e.g., EIRP of 80 dBW).

Figure 9.11 presents a tradeoff curve for the design of an Earth station uplink for use in full transponder digital video service (in C-, Ku-, or Ka-band). To deliver an EIRP of 80 dBW, the curve gives the requisite antenna diameter and HPA power. An allowance of 2 dB for waveguide loss has been made in the curve. At Ku-band, relatively low HPA powers (less than 200W) are acceptable with antennas 6m in diameter or greater. To be able to employ a more compact reflector of 3m in diameter (typical for a truck-mounted transportable Earth station), the HPA must be capable of outputting 1,000W. There is an additional problem with the smaller diameter antennas, namely, the excessive power also will be radiated through the antenna sidelobes, producing unacceptable interference in the adjacent satellite. Also, these numbers do not allow for Ku- or Ka-band uplink power control (UPC) which requires up to 10 dB of HPA power margin. The discussion of HPA technology in Chapter 4 provides another perspective with which to evaluate the tradeoff in Figure 9.11. Sufficient antenna size permits the use of lower powered, less expensive HPAs. In FDMA services, it is possible to use an SSPA to achieve the required Earth station EIRP for a single carrier provided sufficient antenna gain is available. Likewise, a klystron HPA could be avoided if the power for video service is less than 600W, which is possible in the example with a 6-m Ku-band antenna. There is an important consideration for multiple carrier service in that the HPA would have to be backed off to control RF IMD. That increases the HPA power rating at saturation by between 7 and 10 dB.

Terrestrial Interface

A terrestrial interface may be needed to connect the communications Earth station to one or more remote user locations. The distance to be covered can range from a few meters to hundreds of kilo meters. In C-band satellite systems, the Earth station is often isolated from a city to reduce terrestrial interference, in which case an elaborate tail is required. On the other hand, terrestrial interference is not present in most Ku- and Ka-band systems; therefore, tails can be relatively short. An exception is the case where a large Earth station (i.e., a teleport) is shared by several users each of which must be reached by local terrestrial transmission links, often provided by local telecommunications carriers. Site diversity may be needed at Ka-band and higher to provide reception when one location is severely affected by rain. The tail link between the diverse sites can represent a considerable investment in fiber optics or microwave towers due to the requirement to transfer a large bandwidth.

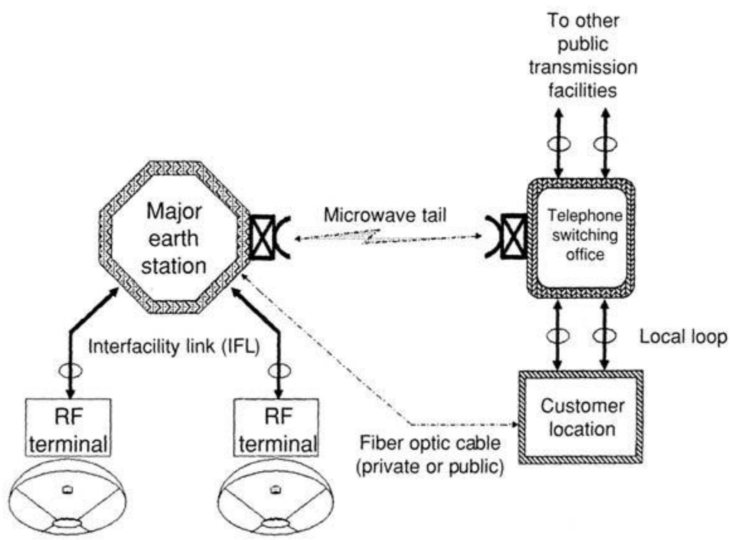


Figure 9.15 Use of terrestrial tails between Earth station facilities, switching offices, and customer locations (distances not to scale).

A few examples of the tail configuration for a major Earth station are illustrated in Figure 9.15. A cable inter facility link (IFL) connects each of two RF terminals (lower left of the figure) to the main Earth station building. A good option for this IFL is fiber optic cable terminated in optical analog transceivers, as discussed later. Within the building can be found the baseband and interface equipment appropriate for the types of services being provided. It is assumed that all the traffic is to be transported to the nearest city. These transmission requirements are met in the example with a single-hop terrestrial microwave link, equipped with sufficient receiver-transmitter units to carry the video voice, and data traffic. The customer location or locations access the first telecommunications office through either public or private fiber optic cable.

The two principal types of terrestrial tails for bulk transmission purposes are line-of-microwave and fiber optic cable. Both are effective and reliable and can be economical when applied properly. Short distances between buildings, such as for the IFL within an Earth station site or when a VSAT is connected to one or more users, are best traversed with fiber optic cable. It has become a practice in large Earth station design to rely on fiber optic cabling because of its low-noise performance and its ability to reduce radiated electromagnetic interference and conducted electrical surges. Another option for short tails is single-hop microwave communication. Available in capacities of a few megabits per second to over 1 Gbps, single-hop microwave systems are relatively inexpensive to install and operate. They, too, have the benefit of not transferring electrical surges and high levels of interference.

A fiber optic link is relatively costly per kilometer of construction, particularly in a metropolitan area. The black line of constant slope is the cost of the cable, electronics, and installation for a basic point-to-point link, assuming that the right-of-way is already available at essentially no cost. Most of the expense is for the repeater and terminal electronics and for installation, which is labour intensive. Fiber optic cable itself is a small part of the cost, so it usually is wise to facilitate future expansion and repairs by including more fiber pairs than are necessary for the current demand. The cost of putting in a high-capacity terrestrial microwave system, including receiver-transmitter units, towers, and antennas, is shown with the stair step, where the step occurs at the assumed repeater spacing of 50 km. The cost of preparing and obtaining repeater sites is not included. In comparing the two technologies, it is clear that fiber optic is attractive for relatively short tail lengths, that is, less than the extent of one microwave hop. On the other hand, the capacity of the fiber optic link can be made many times greater. That is because the cable contains extra fiber pairs that are available for expansion (and that were included in the original cable at little extra cost). In addition, transmission rates on a given fiber pair can be increased as newer optical modems and electronics are introduced. It should be kept in mind that any real-world situation should be examined in detail before the tail technology is selected. That is because installation and rightof- way costs can vary widely, as can the cost of the equipment itself.

RADIO AND SATELLITE NAVIGATION

Prior to the development of radio, navigation was by compass and landmarks on land, and by the sun. Neither technique provides high accuracy. And shipwrecks caused by inaccurate navigation and foggy weather were a common occurrence. On land, people often got lost in wilderness areas (and still do).pilots of light aircraft, relying solely on a map and landmarks, would get lost and run out of fuel before they found some where to land. With a GPS receiver and a map, it is impossible to get lost. GPS receivers are very popular with airplane pilots, owners of sea-going boats, and wilderness hikers.

The development of aircraft that could fly above the clouds, and particularly the building of large numbers of bomber aircraft in the 1930s, made radio navigation essential. Military thinking after WW I, and during WW II, placed high reliance on the ability of bomber aircraft to win a war by destroying the weapon manufacturing capability of the enemy. During WW II, the allies sent 1000 bomber aircraft at a time to targets in Germany, causing immense destruction to many cities. The philosophy of mass destruction continued after

WWII with the development of nuclear bombs, intercontinental ballistic missiles (ICBMs), and cruise missiles. However, bomber aircraft, ICBMs, and cruise missiles must find their target, so accurate navigation is an essential part of each of the weapon systems. This demand for accurate targeting of airborne weapons led to the development of GPS.

Commercial aircraft fly on federal airways using VOR (VHF Omni range) beacons. The airways are 8 miles wide to allow for the angular accuracy of VOR measurements, which is better than 4^0. GPS will eventually replace VOR navigation, allowing aircraft to fly directly from point of origin to destination, but the system of VOR beacons in the United States is likely to remain for many years as a backup to GPS.

GPS can provide a single navigation system with better accuracy and reliability than all earlier radio navigation aids. It can provide navigation of aircraft directly between airports, instead of indirectly via airways, while providing absolute position readout of latitude and longitude. Differential GPS can be used instead of ILS to provide the required straight line in the sky for an instrument approach to a runway, and can be linked to an autopilot to provide automatic landing of aircraft in zero visibility conditions. Ships can safely navigate and dock in treacherous water in bad weather by using differential GPS Eventually, GPS will replace all other means of navigation, although some may be retained as backup systems in case of failure of the GPS receiver (s) or jamming of the signals.

GPS was preceded by an earlier satellite navigation system called Transit, built for the U.S Navy for ship navigation, which achieved much lower accuracy and became obsolete when GPS was introduced. Transit satellites were in low earth orbits and the system used the Doppler shift observed at the receiver when a beacon signal was transmitted by the satellite. Because of the high velocity of LEO satellites-about 7.5 km/s their signals are significantly shifted up in frequency when the satellite appears over the horizon with a component of velocity toward the receiver. The Doppler shift falls to zero as the satellite passes the observer, and then becomes negative as the satellite files away. Observation of the Doppler shift with time .which may need to be as long as 10 min, and a knowledge of the satellite orbit, allows calculation of the receiver's position. There was never a sufficient number of transit satellite to provide continuous position data, and the long time required to obtain an accurate position fix was a disadvantage. A similar system called SARSAT, for search and rescue satellite is used to find emergency locator transmitters (ELTs) on aircraft that have crashed. Most general aviation aircraft carry an ELT, Which turns on at a frequency of 121.5 MHz when subjected to high g forces, as might be experienced if the aircraft crashes. Certain LEO satellites carry 121.5-MHz receivers. That relay the signals to earth stations at rescue coordination centers. If an aircraft LET turns on, a SARSAT satellite will eventually fly by and relay a Doppler shifted signal to the rescue station.

Analysis of the Doppler shift over the observation period provides information about the location of the ELT, but with an accuracy of only 1 or2 km. Almost 97% of ELT locations turn out to be false alarms- the ELT was dropped or accidentally turned on. It seems probable that GPS and cellular phones will eventually replace the SARSAT system.

The Elements of the GPS System

The GPS system consists of three “segments” called the Control Segment, the Space Segment, and the User Segment. Proper operation of each of these three segments results in accurate, reliable operation of the entire system.

The Control Segment is responsible for detecting satellites that are not broadcasting properly, or that are not in the proper orbit, and commanding the satellites to identify themselves as unhealthy when circumstances warrant. This allows the Control Segment to keep results obtained from using the system consistently within operating specifications.

The Space Segment is composed of a constellation of satellites orbiting approximately 20,000 km (about 12,500 miles) above the Earth.

- The full constellation is defined as 24 satellites, but there may be more or fewer active at any one time.
- The satellites are arrayed in 6 separate orbits, each inclined about 55° with respect to the equator, with 4 slots per orbit designated to hold a satellite.
- The orbit is traversed in about 12 hours.
- With a full constellation, receivers located on most spots on the Earth can see at least 6, and sometimes as many as 12 of the satellites at any one time.

The User Segment is the term given to all of the GPS receivers listening to the satellites at any time. There is no organization to the User Segment, but for any user, it consists of the receiver currently in use and its associated antenna. User receivers are passive -- they need only listen to the Space Segment and not broadcast anything, thus making the system accessible to any number of users at one time without users interfering with each other.

Principles of Operation

Broken down to the simplest terms, the satellites orbiting above the Earth simply broadcast their location and the current time. The GPS receivers listen to several satellites (how many will be discussed below), and from the broadcasts determine what time it is and where the receivers are located. The principles, of course, require much more detail, but this the essence.

Each satellite broadcasts two signals consisting of carrier waves that undergo phase changes that occur in a defined pattern at very precise rates and at exact times (see Section III below). A GPS receiver generates a copy of the phase-change pattern and moves it back and forth in time, attempting to correlate it with signals it receives. If the signal it is trying to correlate with is being received, at some point the received pattern and the internally generated pattern will match. The correlator circuit will then generate a large output. This pattern match and associated correlator output constitute lock-on to a satellite, and provides a pattern generator in the receiver that is working exactly in step with the received signal. Knowing how much this generator was shifted in time tells the receiver when the signal arrived at the receiver with respect to its own internal clock. If the receiver could determine how its clock was adjusted with respect to true GPS time, it would then know exactly how long it took the signal from the satellite to reach the receiver. When the receiver multiplies this time by the speed of light, it knows how far it is from the satellite.

In addition to transmitting a specific phase-change pattern that is unique for each satellite, additional data is also added to the signal. This data comprises the Navigation Message.

(a) It includes the current time to the nearest second,

(b) and the information needed to compute the location of the satellite at the time of transmission.

Using this information, the receiver can set its clock to the correct second, and compute the current position of the satellite. It now knows how far it is from the satellite, and where the satellite is. Using simple geometry, the receiver now knows it is somewhere on the surface of a sphere centered on that satellite with radius equal to the distance from the satellite.

Let’s look at the process in an end-to-end scenario. Several satellites are broadcasting their patterns -- each one unique -- which are arriving at the antenna of a receiver. Each pattern arrives at a different time determined by the relative distance between the receiver and the satellite sending the pattern. The receiver searches for specific satellites by generating and shifting the pattern for each satellite that might be broadcasting. Once matches are found, the receiver can compute the distance, called pseudorange, to each satellite. If the receiver’s clock is precisely coordinated to GPS time, the receiver could immediately compute its position using simple algebra.

Unfortunately, the receiver’s clock is usually not set exactly to GPS time. Thus, the pseudorange consists not only of the time it took the signal to travel to the receiver, but also an amount that represents how far the receiver clock and GPS time differ. This is called clock offset, and represents a fourth unknown (in addition to the receiver’s x, y and z position). Clock offset could be either positive or negative since the receiver clock could be either ahead of or behind GPS time. Pseudorange is measured in units of time. Because we know that the signal traveled to the receiver at the speed of light (about 300,000,000 meters per second), we can convert it to a distance simply by multiplying it by that number. Similarly, clock offset is measured in units of time and can also be converted to distance as well. This distance or time error is common to all of the pseudoranges since the receiver uses the same clock to measure all pseudoranges.

When a receiver acquires a satellite, the receiver monitors the navigation message from the satellite. Part of the data contained in the navigation message is the current GPS time, expressed in seconds. GPS time is the number of seconds since midnight between January 5 and 6, 1980. Thus, the receiver is able to set its own time indication to the exact whole second (the receiver computes fractions of a second later).

Coordinate System

Another part of the navigation message is a set of numbers called the ephemeris, that together describe the satellite's orbit in space, and where the satellite is in that orbit at a particular time. The receiver computes the exact location of the satellite in space from the ephemeris and the current time. The result is a set of **x**, **y** and **z** coordinates where the satellite was when the signal was transmitted. These values tell the position of the satellite with respect to a coordinate system defined by the World Geodetic System 1984 (referred to as WGS84). The **origin** of this coordinate system is near the Earth's mass center, and its **z** axis matches the mean spin axis of the Earth. **+z** is towards the North pole; **+x** emerges from the Earth on the Greenwich meridian at the equator (just south of Ghana, and west of Gabon, in the Atlantic Ocean). The **+y** axis emerges at the equator on the 90° East meridian (at a point in the Indian Ocean southeast of Sri Lanka and west of Sumatra), thus defining a right-hand coordinate system.

At this point the receiver has the location of each satellite, and the pseudorange to that satellite. Using appropriate math the receiver computes its position (x, y and z) and clock offset (Δt). To understand how this works, let's look at it graphically. To make it easier to visualize, we will use a two-dimensional solution. The three-dimensional solution works exactly the same, but with the added **z** factor. Refer to Figure 1. Points A, B and C are the locations of three satellites in the x, y coordinate space of the diagram. Radii d1, d2 and d3 represent the pseudoranges we measured from each satellite (here shown in the distance form). Thus, we would define our position as located on the intersection of the three circles centered on each satellite with radius equal to the respective pseudoranges. But the three circles do not meet at a point. They intersect to form a triangle with arcs for sides (in some cases, they could even miss each other entirely).

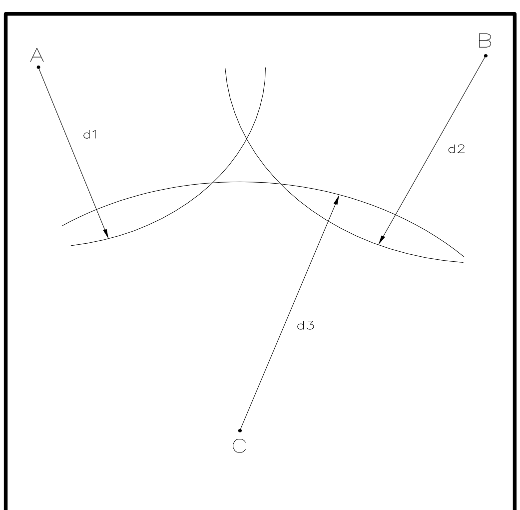


figure 1

Now refer to Figure 2. In this case we have added a small amount, t, to each pseudorange. The result is that we have adjusted each pseudorange by the same amount, **t,** causing the circles to meet at a point. The coordinates of this point represent our position, and **t** represents our clock offset. As a result of this process, we not only know our position, but we also know the correct time (fractions of a second) within the resolution of our code pattern shifter. Time resolution is typically to fractions of microseconds, resulting in a time determination that is more accurate than about any other method generally available. In fact, GPS receivers designed specifically to adjust atomic clocks yield time determinations that match UTC to within 10 nanoseconds!

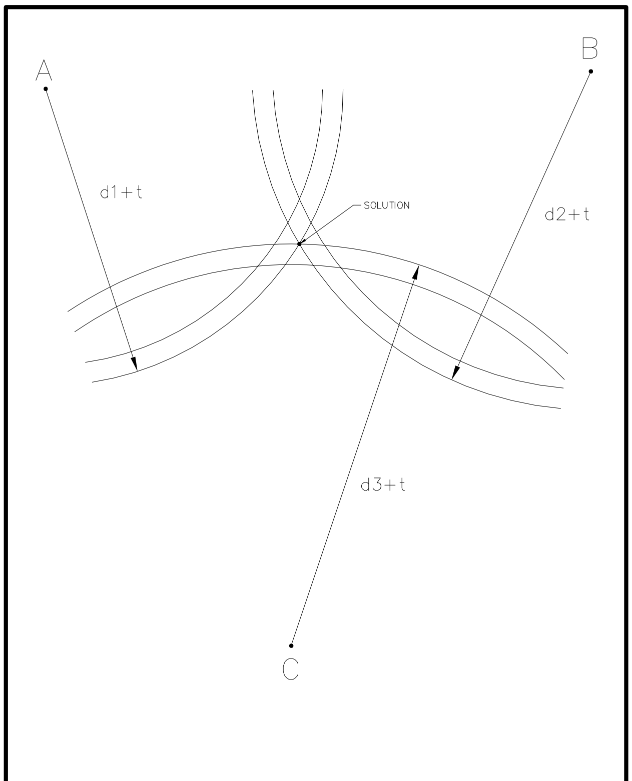


figure 2

An interesting element of the position determination process becomes apparent here. Note that if the receiver is a long distance from the antenna, the satellite signals must travel that distance inside a cable to reach the electronic circuits that measure the pseudorange. As a result, the measured pseudorange increases by the time required to travel the distance represented by the cable length. In addition, signals tend to travel slower than the speed of light inside cables (in some cables, at less than two thirds the speed of light). This factor also increases the time for the signal to reach the receiver. However, since the signals from all satellites travel this same distance, the effect is to add the same amount of time delay to all signals. Now recall that pseudorange is the sum of the time it takes the signal to travel to the receiver, and the clock offset of the receiver.

The GPS Signal

All GPS satellites broadcast on the same two frequencies.

The primary signal is broadcast on what is referred to as L1 frequency, which is 1,575.42 MHz. The signals are broadcast using spread-spectrum techniques, which allow many signals to coexist on the same frequency, and for receivers to detect and separate the different signals from each other. The L1 signal is modulated with two information signals called **C/A** (for **Coarse and Acquisition code**) and **P (for Precise code).**

In addition, the satellites also broadcast **a copy of the P code** on the second frequency called L2, which is 1,227.60 MHz.

Spread-spectrum modulation basically consists of the carrier signal being repeatedly inverted, that is, having its phase shifted 180°, in a specific pattern.
The C/A code pattern is generated by a hardware signal generator consisting of a pair of 10-bit shift registers with feedback connections in them, whose outputs are combined by an exclusive-OR gate.
The resulting digital sequence is referred to as a **Pseudo-Random Number, or PRN,** sequence. The generator produces a pattern that is exactly 1,023 bits long, which then repeats. By starting both the shift registers at a defined starting point, and by combining the resulting outputs with a phase shift between them (that is, the output of one register is delayed by some number of bits from the output of the other), several unique codes can be generated.

The GPS system defines 36 specific phase shifts to be used, resulting in 36 unique codes (called Gold Codes) that could be transmitted by satellites. Since the satellite number is represented in the navigation message by only 5 data bits, only 32 of these 36 codes are actually used. The others are reserved for other uses, such as ground transmitters. The bit rate of the generator used to modulate the carrier is referred to as the "chipping" rate, and each bit is referred to as a "chip." For GPS satellites, the C/A code chipping rate is 1.023 MHz. Since the code is 1,023 bits long before it repeats, the code repeats every 1 msec.

To receive a spread-spectrum signal, the receiver must know the desired PRN sequence. It generates its own copy of the sequence, and applies it to the output of a down-converter and detector. The receiver then shifts the pattern in time looking for a match with what appears to be noise coming from the detector. The match is made in a circuit called a correlator, which produces an output that corresponds to the degree of match between the two signals. When the receiver's code matches the received signal, there is a large rise in the magnitude of the correlator's output. To search for a transmitter, the receiver first adjusts the internally generated pattern in time, chip-by-chip, until an indication of matchup has occurred, then shifts the pattern by fractions of a chip until the correlator output is maximized. At this point the internal pattern generator is generating a code in exact step (at least to the resolution of the pattern shifter) with the received signal.

For greater precision in determining the time it takes a signal to travel to the receiver, a second signal is generated and transmitted on the same frequency. **This second carrier is 90° ahead of the carrier with the C/A code, but it is of a lower amplitude. It is modulated with a PRN sequence called the P (for Precise) code.** The P code has a chipping rate of 10.23 MHz, so it is 10 times the rate, and thus, precision, of the C/A code. In addition, the P-code sequence is much longer than the C/A code - it does not repeat over a complete week. This makes it harder to acquire without the initial time setting afforded by the C/A code being acquired first (in fact, this is why the C/A code has the term "acquisition" in its name). A feature called Anti-Spoofing (A-S) can be activated by the US DoD to prevent the intentional deception of receivers by use of a phony, or "spoofing" transmitter. The result of A-S being turned on is that the P code is hidden by an encryption scheme. The P code thus encrypted is called Y code. Figure 3 shows how the C/A code and P (or Y) code modifies the carrier sine wave. While the P-code carrier also is phase shifted 180° by its bit pattern, since it is lower in amplitude than the C/A code carrier and 90° out of phase with it, the effect of combining the two carriers is for the output signal from the satellites to appear to shift by about 70° when P-code bits change.

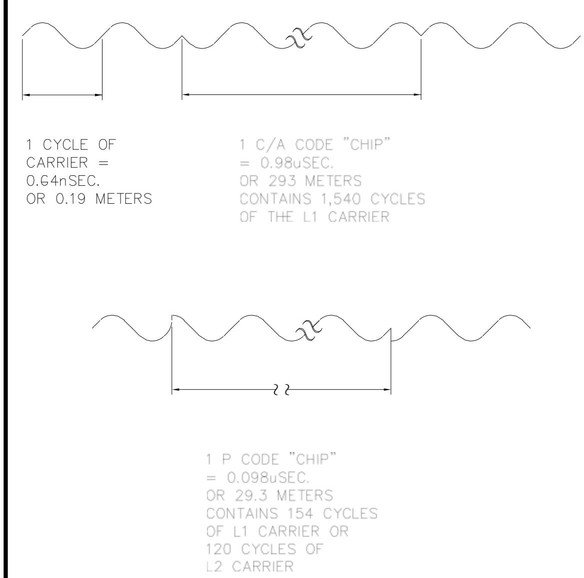


figure 3

Data being sent on the carrier is represented by either inverting or not inverting the PRN code, so that at the receiver the correlator will generate either a positive or negative correlation output. The data rate is usually much slower than the chipping rate so that it does not interfere with the integration that is done as part of the correlation process. Data on the GPS signals, called the Navigation Message, are modulated at a nominal 50 bits per second rate.

Each satellite contains multiple atomic clocks, and the carrier and modulation signals are timed precisely to the clocks. Thus, at exactly the start of a second as defined by the master GPS timing, each satellite's signal is crossing zero or passing an integral multiple of one of the phase changes, and its modulation (both C/A and P codes) are also starting bits. In fact, the L1 and L2 frequencies have been chosen so that they relate to each other and to the chipping rates in a coherent manner. The basic timing is provided by the 10.23 MHz frequency of the P code. L1 is exactly 154 times this frequency, and L2 is exactly 120 times this frequency, so a single P chip consists of 154 cycles of the L1 or 120 cycles of the L2 carrier. The C/A chip rate is composed of 10 P chips, and the actual navigation message data rate is defined as exactly 20 copies of the 1023-bit C/A pattern. Thus, a properly working satellite has all the elements of the signal locked to one reference frequency, and the phase of the carrier, the phase of the chips and the data all align with transitions occurring on 0° boundaries of the unmodulated carriers.

The coherency of the transmitted signal provides yet another method of determining pseudorange; this is referred to as carrier phase. Once a receiver has determined its own clock offset, it can determine the actual start of a second. The received signal will differ from this point in time by some integral number of carrier cycles, plus a fractional part of a cycle. Just as with the C/A code, this offset is due to the time it takes the signal to travel from the satellite to the receiver. The fractional cycle can usually be determined to about 1 part in 1000 using current technology. The integer number of cycles, however, is subject to some ambiguity, but can be determined using a process called ambiguity resolution. Since the wavelength of the carrier is about 0.19 meters, resolving this to 0.1% (one part in one thousand) yields a pseudorange measurement that has a resolution of about 0.2 mm (this is less than 8/1000"). For purposes of illustration, the P code chip length (the equivalent of wavelength) is about 29 meters, and the C/A code chip length is about 290 meters. Assuming the same 0.1% resolution on these as on the carrier waves, this implies resolution of 2.9 cm for P code (a little over 1"), and 29 cm for the C/A code (about 11").

The Navigation Message

The data modulated onto the C/A and P codes consist of several types of information. The data are packaged into 30-bit words that consist of 24 data bits and 6 parity bits. Words are grouped together into groups of 10 called a subframe. Each subframe is thus 300 bits long, of which 240 bits are data and 60 bits are parity. Subframes take 6 seconds to transmit at 50 bps. There are 5 subframes defined, numbered 1 through 5. The satellite transmits a set of all 5 subframes in 30 seconds, then begins to transmit another set.

Each subframe starts with a pair of data elements called the Telemetry Word (TLM) and the Handover Word (HOW). The TLM provides a standard bit-pattern preamble that can be used to detect the start of a subframe, plus administrative status information such as data upload status. The HOW contains the GPS system time (referred to as Z-count) that corresponds to the start of the next subframe, and an identification of which subframe number this is. The TLM and HOW together take up the first two words of every subframe. All information discussed below about the 5 subframes relates only to the remaining 8 data words.

Subframe 1 contains information that can be used to compute a correction term for the satellite's clock. Even though the satellites have multiple atomic clocks on them, the clocks do drift. This drift is monitored by the Control Segment stations, and a second-order curve fit is made to it. The coefficients of the expression describing this curve are reported in subframe 1 so that the users can compute the current modeled clock error and thus improve their own navigation.

Subframes 2 and 3 contain the ephemeris data for the satellite. The ephemeris is presented in a format called "Keplerian elements plus secular drift terms and harmonic coefficients." With these parameters, the user is able to accurately compute the satellite's location at a specific time to an error of less than 0.3 meters. The data are updated about once an hour (once every 2 hours for newer satellites), with the ephemeris data known to be valid for about four hours.

Subframes 4 and 5 are used in a different manner from subframes 1-3. Among other data, they contain what is referred to as almanac data. Almanac data consists of a truncated set of ephemeris data, reduced so that it will fit in a single subframe, with corresponding reduction in accuracy. Unlike the other subframes which repeat exactly the same data for about an hour or two, these two subframes change every time they are sent. And instead of sending data only about the transmitting satellite, these subframes contain data about all satellites in the constellation. The purpose of the almanac data is to allow a receiver locked onto one satellite to find out about all other satellites in the constellation. Subframe 5 contains the almanacs for satellites 1 through 24 (satellite numbers correspond to the specific PRN Gold Code that satellite is using as its C/A code chipping signal as described in Section III), each broadcast in sequence in successive versions (called "pages") of the subframe. After sending 24 almanacs, subframe 5 then contains a page that reports on the health of those 24 satellites. This makes 25 unique pages of subframe 5, each sent once over a 12.5 minute period, after which it repeats. Subframe 4 contains pages that contain the almanacs for satellites 25 through 32, and a health page for those satellites. In addition, there are 16 other pages defined for subframe 4 that are either used for other purposes, or reserved for later features that might be added to the GPS system. This results in 25 unique pages for subframe 4 as well. Almanac data may be used for several days, even for weeks, since the purpose is not navigation, but simply finding the satellite.

GPS Errors

The process of transmitting, receiving and detecting the GPS signal is a physical process which, like any other physical process, contains sources for errors. Some of the errors are obvious: the satellite clock is not exactly correct, even when the broadcast correction terms are used to adjust it. The location of the satellite in space is not necessarily correct since it is determined by observations made on the ground, and the ephemeris values only yield a solution accurate to about 30 cm. And the receiver computing its own position can only resolve the received signals to some specific precision determined by the wavelength of either the carrier (for carrier phase measurements) or the code bit length (for code pattern matching), and the resolution of the code or phase shifter in the receiver. Further limitations occur in the receiver based on the precision of the computations, where mathematical processes may truncate or round values rather than carrying them out to their last possible decimal place.

Some other error sources appear when we look at the physical process of a signal traveling through space to the receiver. For example, the signal is transmitted by a satellite traveling at a high rate of speed in space. Since it is unlikely that the receiver is traveling at the same direction and speed, there will be a Doppler shift of the signal that affects the effective wavelength of both the code and carrier waves. And the signal must travel through the ionosphere above the Earth, which has an effect of shifting the signal and bending its path. It also travels through the troposphere (the lower layer of the atmosphere where most weather occurs), which also affects the signal's path and speed. As the signal nears the receiver, some of it may reflect off of the ground, water, or buildings, water towers, signs, etc., located near the receiver, and reach the antenna after traveling a greater distance than the signal that arrives directly from the satellite (a phenomenon called multipath).

Finally, the receiver is also prone to errors that can be detected. The clock is unstable, causing individual ticks to occur not truly regularly, but with some "wobble" between them. Most receivers compute the pseudorange to a satellite several times per second, and average the measurements. If the clock in the receiver is "noisy," that is, not ticking at a uniform rate, the time during which each individual measurement is made can vary. This would result in each observation being made over a time span that is unique, and the resulting average could contain errors caused by this effect. In addition, all receivers detect noise along with the real signals, and that affects the received signals, further degrading them. Satellites closer to the horizon tend not only to be weaker, and thus more prone to noise, but their signals are more prone to multipath. It is for this reason that some receivers allow the user to set an elevation mask, that is, an angle below which satellites will not be tracked.

The result of all of these and other error sources is that the computed pseudorange is an estimate with a possible error whose magnitude can be computed using standard statistical methods. So when we compute our location with respect to a satellite, instead of finding ourselves on a sphere as described earlier (shown as the circular arcs in the two-dimensional model of figures 1 and 2), we really find ourselves in a space located between two concentric spheres -- one with radius equal to our pseudorange plus the error, one with radius equal to the pseudorange minus the error. This will be illustrated in two dimensions in the next figure.

The actual geometry of the satellites in the sky also has an effect on the accuracy of results. Returning to a 2-dimensional representation for ease of illustration, let's see how the geometry affects our results. Figure 5 shows a case where we are only considering two satellites. Instead of a single arc, the distance from each satellite is shown as three arcs.

The center, bolder arc is the same one we computed before -- representing the computed pseudorange. The two lighter arcs surrounding the center arc represent the magnitude of the error we estimate. Thus, the true range from the satellite is really somewhere in between the two outer arcs for each satellite, and therefore we are located somewhere inside the shaded area where these two spaces intersect. Now look at Figure 6. In this example the errors and ranges are exactly the same, but the two satellites are located closer together. Note how the geometry of the satellites causes the area where we might be located to grow. Obviously, if the two satellites were at the same point in the sky, the presence of the second satellite would not help our position determination at all!

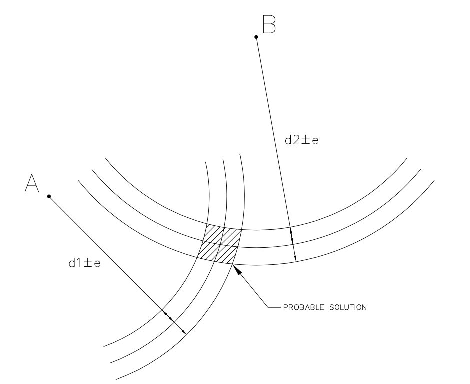


figure 5

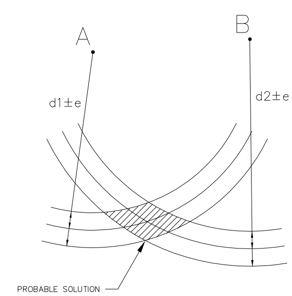


figure 6

The effect of this geometry on our overall error computation results in what is called a Dilution of Precision, or DOP. If we had such a thing as an ideal geometry, with satellites in all possible directions, we would have a DOP value of 1.0. In a more realistic situation, with 6 to 12 satellites visible, and all of them above the horizon, the DOP value rises. When true position and clock offset are computed, the error on these values and others computed from them can be determined by multiplying the composite error of the observations by the appropriate DOP.

The overall DOP term is called Geometric Dilution of Precision, or GDOP. GDOP may be broken down into two components: one related to the receiver's position (Position DOP, or PDOP) and one related to the time determination (Time DOP, or TDOP). While PDOP is related to the satellite geometry, as discussed above, TDOP is strictly dependent on the time bases in the receiver and all the satellites. Thus, it is a function only of the number of satellites being tracked. GDOP, PDOP and TDOP are related orthogonally by:

$$GDOP^2 = PDOP^2 + TDOP^2$$

The PDOP value is further found to have two components: horizontal (HDOP) and vertical (VDOP), again related to PDOP orthogonally. Here one of the limitations on the GPS system becomes apparent. The horizontal component is basically affected by how the satellites are dispersed in azimuth about the receiver. If all satellites are bunched up in a single direction, the HDOP will be larger than if the same number of satellites were evenly spaced around the horizon. But consider VDOP. It is dependent on the elevation of the satellites, as you might expect. But since satellites below the horizon cannot typically be seen by a receiver, by necessity all satellites that we use are bunched up in the space from the horizon upwards. This simple fact explains why receiver manufacturers will specify larger error values for their receivers for vertical position determinations than they will for horizontal positions. For completeness, here is how PDOP, HDOP and VDOP relate:

$$PDOP^2 = HDOP^2 + VDOP^2$$

One final error source must be noted. Since the original design of the GPS system was for the US military, there was concern that it might be used by an adversary to guide weapons. For this reason, there was a decision to put an intentional error source into the transmitted signals that would limit the availability of the system to users. This was done by such factors as altering the satellite's clock, or by altering the broadcast clock correction terms or other ephemeris terms. A user computing position using the C/A code from a fixed location would find the position solution moving over time such that the resulting position determinations would have about 100 meters 2d RMS variation. At the same time, an authorized user with access to the appropriate technology could still use the P code and navigate as accurately as before. This process is referred to as selective availability, or SA. Don't confuse it with anti-spoofing (A-S), which is the encryption of the P code into a Y code. While the SA makes real-time position determination less precise, the use of post processing with one or more reference receivers can remove most of the effects. Real-time differential GPS tracking can similarly remove these effects. Both methods are described later.

Differential GPS

Earlier we presented a discussion of some of the error sources affecting GPS measurements. To summarize, there are sources associated with the satellites, sources associated with the signal traveling from the satellite to the receiver's antenna, and sources associated with the receiver. Differential GPS was developed as a means of providing real-time correction of several of these errors.

Consider the makeup of a pseudorange measurement in a receiver. The receiver has determined the difference in time between when a signal left a satellite and when it was received by the receiver. This includes the actual time of travel of the signal, plus the effects of error such as those originating in the satellite, in the path of the signal from the satellite to the receiver, and in the receiver, as discussed earlier.

Now consider the receiver's position determination process. Recall that the receiver uses the broadcast ephemeris to determine the location of the satellite. As noted before, this value is also subject to errors; thus defining one additional error source. Therefore, even if all of the errors in measuring the pseudorange could be corrected in some manner, there would still be an error element in the resulting position.

In normal survey applications, the data from the reference receiver and from the receiver(s) that survey the points of interest, are combined in a post-processing environment, and mathematical techniques are used to remove the common errors. The result is a position that can be repeated to within as little as 1 or 2 mm. But this is only after collecting a large number of observations and performing extensive math. An alternative exists that works in real time, but with less spectacular results.

The Differential GPS (DGPS) process works using a reference receiver, as in the post-processing technique above. That receiver is placed in a location which is known very well. This might be a benchmark to be used as a starting point for a survey, the end of an airport runway or the entrance to a harbor that is critical for navigation, or some other similar location. The receiver either surveys the location, or is told the location through data entry by an operator, and it saves this position and assumes it to be true. Next, the reference receiver makes normal observations and computes pseudoranges just as any other receiver would do. It also listens to the broadcast ephemeris, and combines the current time and broadcast ephemeris to compute the satellite's location. Using the computed satellite position and its own known location, it computes the mathematical, or model, range to the satellite. If there were no errors in the broadcast ephemeris or in the satellite's location, this model range would represent what the pseudorange would be expected to be. If we compare the observed pseudorange and the model range we will nearly always find they differ, due to the errors from all the sources previously noted. The reference receiver computes this difference for each satellite, and reports all of the values as corrections over some form of data link (radio broadcast, wire connection, etc.) to any other receiver wanting to use them. The other receivers, called User receivers, or simply users, take the values and apply them to their own pseudorange observations prior to computing their own position.

The pseudoranges observed by users contain the same types of errors as those observed by the reference receiver. Of the errors, those which are introduced by the satellite are identical at both receivers. Those caused by the signal path, including ionospheric and tropospheric effects, are usually similar at both receivers, but not exactly the same. The errors caused by the receiver are of course unique to each receiver. Let's examine these errors in more detail.

(a) <u>Satellite errors, generally consisting mainly of clock error</u>, are common to any observer. Clearly, the correction reported by the reference receiver contains the effects of this error. Thus, when the user receiver applies the corrections, the effects of the satellite errors are removed from the solution.

(b) <u>Errors in the pseudorange</u> caused by the signal's passing through the ionosphere tend to be on the order of several meters to tens of meters. However, since the satellite is about 20,000 km above the Earth, and the ionosphere is also quite high above the Earth, the path of the signal through the ionosphere is generally quite similar for receivers which are no farther than a few hundred kilometers apart. As a result, while the errors due to signal path through the ionosphere differ somewhat, the corrections generally correct of these errors. The troposphere's effects are not as common between two receivers. First, the troposphere is much lower, extending from the surface of the Earth upwards. Thus, the signal's path through the troposphere differs much more as the distance between the two receivers increases. Second, the troposphere can vary more dramatically over short distances. The types of features in the troposphere that affect signals include the moisture content. The presence of a large cloud in one signal path, and the absence of that cloud in another could cause considerable difference in the effects. Fortunately, the total effect of the tropospheric variations tends to be on the order of parts of a meter to a few meters. Thus, while the corrections sent from a reference to a user receiver will contain effects of the troposphere, there is likely to be only partial accounting for these errors, with the benefit reducing as distance increases. Certainly, the effects may be quite different to the point that corrections of tropospheric effects are probably useless within some few tens of kilometers. The other major signal-path error, multipath, is quite unique. Since this error amounts to multiple copies of the same signal appearing at a single point in space, but with different times of arrival, the effect is one of signal interference. It is well known that such effects tend to vary greatly over a distance of less than a single wavelength of the signal, or less than 20 cm for the GPS L1 carrier! Obviously, multipath errors cannot be corrected for reliably by the broadcast corrections. This is mitigated by placing the reference receiver at a site with good satellite visibility to ensure a strong direct signal, and one that is protected from obvious multipath sources, such as on top of a building where other sources of reflected signals are below the antenna. Good antenna designs help greatly reduce the effects of multipath sources near the horizon and below, thus reducing the multipath error effects on the reference receiver's computed corrections.

Because corrections are more effective closer to the reference receiver, reference receivers are often located near harbor entrances or at major airports so that vehicles navigating to such locations have the least error in the most important portion of their navigation.

Errors originating within the two receivers used for a differential GPS data link include errors due to the clocks of the receivers, noise on the received signals, and limitations of the pattern shifting process. The corrections from the reference receiver will contain these errors. When the user receiver applies the corrections, this will have the effect of transferring reference-receiver errors to the user receiver. However, some of these errors tend to be common to all signals observed by the reference receiver (for example, clock offset errors), and thus will be included in all corrections. The user receiver will thus find the error to be the same as common terms such as those caused by using a longer or shorter antenna cable -- that is, they will become lumped into the clock offset portion of the solution rather than affecting the x, y and z position coordinates. It is for this reason that when a receiver is using differential corrections, it should not use a mixture of observations with corrections and observations for which there are no corrections present; use of such a mixture would preclude the reference receiver's common errors from being placed solely in the clock offset portion of the solution and would result in a position with greater error.

One interesting side effect of this process involves errors in the reference receiver's position. Such errors are directly propagated since they are not common to all satellites, but rather affect each satellite depending on the associated geometry. For example, if the reference receiver's position is assumed to be farther north than it really is, the effect on satellites to the north of the receiver will be in the opposite direction of that for satellites to the south; and satellites directly east or west of the location would have no different corrections due to such an error. As a result, the user receiver would find its position displace from "truth" by exactly the same amount and in the same direction as the error in the reference receiver. While this may be bad, in fact it could also be beneficial.

Consider that a survey is being done relative to a benchmark whose position is published, but is in error with respect to the GPS system. If the position of this benchmark were entered for the reference station, the error in the published position would be propagated to the user receivers, and the result would be that all surveyed points would be proper <u>with respect to the benchmark,</u> without any conversions being necessary! Similarly, aircraft landing at an airport or ships navigating into a harbor would find themselves computing positions that agree with the local charts regardless of the presence of any errors in those charts.

Any error associated with the broadcast ephemeris will be seen at the reference receiver only in the model range, since the observations themselves are made without regard to the broadcast position of the satellite. However, their effect will be seen in the corrections, and will be accounted for in the user receiver when the position is computed since the user receiver will at that time use the same incorrect position of the satellite to convert pseudoranges into positions. Thus, all errors originating on the satellite (including those caused intentionally by selective availability, or SA) will be removed in the DGPS process.

In practice, there are errors which differential techniques cannot correct for, and even errors which are introduced by the process (such as errors in the reference receiver's observations that are not common to all satellites). But the overall effect is quite significant. Just using the pseudorange derived from the C/A code, a stationary receiver will generally compute its position as a point which moves over time by more than 100 meters. When a nearby reference station's corrections are applied, that range of movement will generally be much less than 10 meters, and even less than 2 meters when the receivers are relatively close. This real-time process makes position determinations quite accurate in most navigation modes (but still not as accurate as post-processing for surveying applications).

The above description describes what could be referred to as code differential GPS, since the observations and associated corrections are made from pseudoranges derived from the C/A or P code on the satellite carrier. Another form of differential can be developed that looks at the carrier phase. The higher resolution of the carrier wave makes the application of such corrections yield position solutions that vary by only a few centimeters. This form of differential is referred to as Real Time Kinematic, since it allows the performance of the ambiguity resolution process used for kinematic navigation to be performed in real time with immediate results.

Applications of GPS

GPS receivers have been used in numerous applications. Most relate either to the ability of the receiver to determine the position of the antenna in space, or to the ability of the receiver to determine time to great precision.

The ability of GPS receivers to determine time to great precision makes them ideal clock drivers. In fact, several manufacturers have adapted receivers to provide precise time pulses out, or to produce the time pulses and then compare them to those from an external source such as a Cesium or Rubidium clock, and to provide output that tells how the two differ. These latter receivers can be connected into control systems that use the differences reported to steer the atomic clock until it comes into close agreement with the GPS time. Such receivers are used by time standards services in several countries around the world. The best receivers permit clock steering to within a few nanoseconds of GPS time. In addition, the US National Aeronautics and Space Administration (NASA) uses GPS receivers as part of their Deep Space Network so that precise time references are available to use to measure the signals from spacecraft traveling to other planets, thus permitting increased precision in determining their positions in outer space.

The ability to determine position is the most widely used feature of the GPS system. This can be used in several ways. Certainly a vehicle such as a truck, ship or aircraft can have a receiver that constantly keeps track of position. This is how many of the new navigation systems for automobiles -- those that show the vehicle's location on a map display -- work. Some trucking companies connect receivers into radio systems that use satellite communications to allow one master control center to track all of the trucks in the fleet anywhere they travel. And emergency vehicles have been fitted with receivers so that the dispatcher can always know which vehicle is closest to an emergency. Ships at sea and aircraft flying in bad weather can use GPS anywhere on Earth to keep track of position and speed, regardless of visibility or time of day.

Some aircraft have been equipped with two or more GPS antennae, with the signals from all antennae sent to one receiver. The receiver is thus able not only to compute position, but by measuring the difference between the signals from each of the antennae, to compute the attitude of the aircraft. When the aircraft has an inertial navigation system (INS - a navigation system using gyroscopes and accelerometers to sense changes in a vehicle's attitude and velocity) connected into the navigation package, the two systems can greatly improve overall navigation reliability. GPS is not affected by drift over time, but can exhibit some variations between individual measurements due to noise. In contrast, INS is quite precise in measurements over a short range of time, but its errors accumulate over time, resulting in larger errors as the time between external updates increases. Together, the two technologies complement each other, with INS smoothing GPS measurements, and GPS frequently updating the INS. This can result in very accurate and precise navigation.

The use of GPS systems has revolutionized the practice of surveying. Instruments and computer software to process the results have been developed specifically for various surveying applications. A review of current uses shows the broad range of applications:

- Rapid data collection is the goal of systems designed to be mounted in vehicles. Users include utility companies who survey the locations of their poles, contractors and highway departments who survey existing roads and planned routes, and governments who are converting their maps into computerized information systems. With these systems, the surveyor can drive from point to point, and by stopping for about 1 minute at each point and typing some information into the receiver, collect data for later computer processing. Data collection from several hundred locations can be done in one day, where previous systems required much longer times at each location, and teams of surveyors in order to measure between points. The resulting data can be processed into maps that have a accuracy of less than 1 meter.

- Surveyors use GPS receivers to survey locations that are located at a distance from the reference points they must use. In optical surveying methods, a direct line of sight had to be established, often by connecting points that went around or over obstructions like a mountain. Since each measurement required a team, one person at the last point and one at the next point, this could often be very time consuming and even dangerous in hazardous terrain. But with GPS, a receiver at the reference point and another at the desired end point provides precise results without regard to line of sight between them. And the precision is improved due to the elimination of several intermediate measurements.

- At the high-precision end of the surveying spectrum are the geodesists. These scientists measure the Earth to great precision for such purposes as tracking the movements of tectonic plates, or establishing major political boundaries. Geodesists often set up permanent GPS receiver sites and collect data continuously. One group that does this on a world-wide basis is the International GPS Service for Geodynamics (IGS). This group has a network of stations that include sites in North and South America, Europe, Asia, Africa, Australia and Antarctica, all of which collect data continuously. IGS collects the data and makes it available to anyone over the Internet world-wide computer network. Others have developed local clusters of stations that monitor areas of specific interest. For example, southern California contains an array of several hundred defined locations, some continuously occupied, to monitor the Earth movements that relate to the frequent earthquakes in that area. Receivers are used that are able to measure the locations with a repeatability of only a few millimeters over baselines that extend several hundred kilometers. When an earthquake occurs observations can determine which parts of the area actually moved, and in which directions and how far. This information permits the determination of where pieces of the Earth are divided, and which parts are connected together.