Global Positioning System –

The Newest Utility

The Global Positioning System (GPS) has become the high tech utility of the 20th century. It was developed by the US Department of Defense as a precise navigation reference for the military services. Although the signal available to civilian users had been purposely degraded in what is called selective availability (SA), it is one of a few technological success stories that had positive unintended consequences. Recent announcements indicate that this SA impediment has been removed. GPS currently has a huge civilian market in commercial and private aviation, ship navigation, mapping and surveying, telecommunications position determination, and recreational boating and hiking. By 2003 sales of GPS based products are expected to be $16 billion.

Introduction

In 1964 the US Navy developed a two-dimensional space-based navigation system known as Transit to accurately locate the position of their surface ships. It was also used as a reference for nuclear submarines that allowed them to accurately launch their Polaris ballistic missiles. System design was based on measurement of the Doppler shift of a radio signal transmitted from a satellite in a known orbit. The Transit system was implemented with five satellites in low, nearly circular, polar orbits (1100 Km). Since only one Transit satellite was visible at a time, it had only one degree of freedom and only position was able to be calculated.

The Air Force (AF) was facing a similar problem and proposed using a pseudorandom noise signal that would allow all satellites to broadcast on the same frequency. The AF proposal relied on a constellation of 24 satellites orbiting at 20,000 Km. This initial program was called NAVSTAR and advanced the technology by being able to provide simultaneous position, velocity and time information to an unlimited number of users. In 1973 the Department of Defense approved the AF architecture, renamed it NAVSTAR/GPS and made it a multiservice program. The first satellite was launched in 1978 and the system became fully operational in 1995. It is estimated that $10 billion was spent in creating it, and the annual maintenance cost is between $250 and $500 million.

The basis of GPS-based navigation is triangulation from satellites. The concept is somewhat similar to a two-dimensional LORAN hyperbolic navigation system. Improbable as it may seem, the whole idea behind GPS is to use satellites in space as reference points for locations here on Earth. To triangulate, a GPS receiver measures distance using the travel time of radio signals from the satellite to the user. To measure travel time, GPS needs very accurate timing that it achieves with some tricks. Indeed, the development of ultra-stable clocks and stable space platforms in predictable orbits are key technologies that made GPS possible. Along with distance, the knowledge of exactly where the satellites are in space is required. High orbits and careful monitoring are the secret. Finally, corrections are made for any delays the signal experiences as it travels down through the atmosphere.

The geometry and triangulation, which is the basis of GPS, is explained as follows: Suppose we measure our distance from a satellite and find it to be R1 kilometers. Knowing that R1 kilometers from a particular satellite narrows down all the possible locations we could be in the universe to the surface of a sphere that is centered on this satellite and has a radius of R1 kilometers. Next, we measure the distance to a second satellite and find out that it’s R2 kilometers away. Then it follows that we’re not only on the first sphere but we’re also on a sphere that’s R2 kilometers from the second satellite. In other words, we’re somewhere on the circle where these two spheres intersect. If we then make a measurement from a third satellite at distance R3, that narrows our position down even further, to the two points where the sphere with a radius of the distance to the third satellite cuts through the circle that’s the intersection of the first two spheres. So by ranging from three satellites we can narrow our position to just two points in space. To decide which one is our true location we could make a fourth measurement. But usually one of the two points is an impossible solution (either too far from Earth or
GPS geometry for triangulation
moving at an unrealistic velocity) and can be rejected without further measurement.

Perfect clocks or frequency references onboard the spacecraft are achieved by carrying a pair of cesium and rubidium atomic standard clocks. The frequency stability of these clocks is 1 part in $10^{14}$ and 1 part in $10^{15}$, respectively. The satellite clocks do drift by a very small amount every day (about $10^{-16}$ sec). This drift in the clock is corrected by a network of tracking stations, which estimate the correction parameters for each clock. If measuring the travel time of a radio signal is the key to GPS, then the local clocks have to be very good, because if their timing is off by just a thousandth of a second, at the speed of light, that translates into almost 200 miles of error! But can the receivers on the ground have such accurate clocks? Remember that both the satellite and the receiver need to be able to precisely synchronize their pseudorandom codes to make the system work. If our receivers needed atomic clocks (which cost upwards of $50K$ to $100K$) GPS would be a lame duck technology. Nobody could afford it. Luckily the designers of GPS came up with a brilliant idea that allows the use of much less accurate clocks in our receivers. This trick is one of the key elements of GPS and as an added side benefit it means that every GPS receiver is essentially an atomic-accuracy clock. The secret to perfect timing is to make an extra satellite measurement. If three perfect measurements can locate a point in 3-dimensional space, then four imperfect measurements can do the same thing. This idea is fundamental to the workings of GPS.

The GPS global navigation system is not the only system of its kind. The Russians came up with a similar concept called GLONASS with a full constellation of 24 satellites that began broadcasting in early 1996. But due to monetary problems in the Russian Federation their system had declined to 14 working satellites by August of 1997. Due to the uncertainties of the GLONASS system, it has not become very popular although a dual mode GPS-GLONASS receiver is technically feasible and would provide very high reliability.

Europe has launched an initiative for development of a new Global Navigation Satellite System (GNSS), called GALILEO, to safeguard their navigation services. GALILEO is a project of the European Tripartite Group (EU, ESA, Eurocontrol), for the development, implementation and operation of a state-of-the-art satellite navigation system. It will have varying degrees of capability, control and autonomy, and be under European civilian control. ESA, the European Community (EC) and the European organization for the safety of air navigation (Eurocontrol) will contribute to development of the two step Global Naviga-

ation Satellite System (GNSS-1 and GNSS-2) program. The first step, GNSS-1, called EGNOS, will implement a differential system to enhance position, accuracy and will interface with GPS and GLONASS similar to the US WAAS. GNSS-2, GALILEO, will deploy a 24 to 45 satellite constellation to provide navigation signals to users around the world. Most of the satellites will be in circular MEO and will be complemented by GEO satellites. The GALILEO ground infrastructure is to be composed of 24 receiving stations. If approved transmission will start in 2005 and the system will be fully operational by 2008, when it will become an integral part of the European Transport Network infrastructure.

GPS System Architecture

The architecture of the GPS system is similar to other satellite systems. There is a space segment, a ground segment (for control) and the user segment (terminals). The baseline GPS satellite constellation is composed of 24 satellites in nearly circular 26,560 Km orbits with an orbital period of nearly 12 hours. This segment is in six orbital planes of four satellites each. The ground segment provides satellite management to monitor and control GPS on-orbit operations. The US Department of Defense is responsible for both the space and ground segments. The remaining user segment, the GPS receivers and the applications, is left to the commercial sector.

With the 24 satellite constellation, a user anywhere in the world with a clear view of the sky can see at least 4 satellites, and in practice should be able to see 6-8. The satellites broadcast ranging data and navigation signals to allow the receivers to measure their pseudo-ranges and estimate their positions. The GPS terminals are receivers with a listen-only mode and cannot transmit to the GPS satellite. The first 10 GPS satellites, called Block I, were launched between 1978 and 1985 as a GPS constellation proof-of-concept (POC). These prototype satellites were followed by Block II production models with superior performance capability, longer life and reduced cost.

The US Air Force manages the ground segment portion of the system through a network of monitoring stations in Ascension Island, Diego Garcia, Hawaii, Kwajalein and Colorado Springs. To obtain a precise terrestrial frame of reference GPS uses an Earth-centered, Earth-fixed Cartesian coordinate frame. The satellite position and the user position are defined with respect to this coordinate frame. GPS time is similar to the Coordinated Universal Time (UTC). The introduction of leap seconds in the UTC are, however, not incorporated into the GPS. Not accounting for the leap seconds, the
Rockwell GPS Satellite

NAVSATR GPS Satellites
GPS time is a required to be maintained within 1 sec of the UTC as transmitted by the US Naval Observatory. In 1998 the GPS time differed from the UTC by less than 10 nsec.

GPS Code

Each GPS satellite transmits simultaneously on two L band frequencies, called L1 and L2, 1575.42 MHz and 1227.6 MHz, respectively. Each L1 signal is modulated by a pseudorandom noise (PRN) sequence called coarse acquisition code. Each coarse acquisition code is 1023 Gold code with a chip rate of 1023 Mchips/sec. The L2 signal is encrypted and primarily intended for use by the Department of Defense. Each signal, like any CDMA signal, consists of 3 parts, the carrier, the PRN spread spectrum code and data message. PRN codes are chosen for their favorable autocorrelation and crosscorrelation properties. For the coarse acquisition code, for example, the autocorrelation function is 24 dB lower for all shifts greater than one chip width.

GPS signals received on Earth are extremely weak. The specification for the minimum power level received for the users on Earth is -160 dBW. Such a weak signal is clearly vulnerable to noise and jamming and this is one of the most important GPS user concerns. Performance realized by GPS users is dynamic and changes with time and place depending on the satellite geometry and measurement errors. In safety-critical applications such as civil aviation, exceptional navigation accuracy is required. At present GPS systems do not have the ability to detect anomalies in their signals and convey it to the user. Thus, system and data integrity is largely the responsibility of the user. The FAA and ESA have been developing systems (WAAS and EGNOS) that will overcome these deficiencies. On May 1, 2000 the U.S. deactivated the civilian GPS feature, known as selective availability (SA), that intentionally skewed position and timing information for civilian use. This should improve accuracy from about 100 to better than 20 meters for the general public user.

Augmentation With Differential GPS

The quality and therefore the accuracy of the GPS derived position, velocity and time is a function of the
measurement errors at any point on Earth. It was recognized that these systemic errors are not very different for users located close to each other. In other words, these errors vary temporally and spatially and furthermore have a very slow variation with respect to time and space. The selective availability (SA) for civilian users degraded the achievable precision and was the single largest source of error in measurement and is highly correlated over a 5-10 second interval. Differential GPS solved this problem by providing measurement corrections to all users in a local area.

Differential GPS involves the cooperation of two receivers, one in a fixed location and the other in motion that is making position measurements. The stationary receiver is the key and it ties all the satellite measurements into a solid local reference. Remember that GPS receivers use timing signals from at least four satellites to establish a position. Each of those timing signals is going to have some error or delay. Since each timing signal used in the position calculation has some error, that calculation is going to compound those errors. Luckily the sheer scale of the GPS system comes to our rescue. The satellites are so far out in space that the small distances traveled here on Earth are insignificant. So if two receivers are fairly close to each other, say within a few hundred kilometers, the signals that reach both of them will have traveled through virtually the same slice of atmosphere, and so will have virtually the same errors. That’s the idea behind differential GPS: We have a fixed receiver measure the timing errors and then provide correction information to the moving receivers. That way virtually all errors can be eliminated, even the SA error that the DoD had intentionally inserted in the signal. Differential GPS can provide meter and submeter level accuracy depending on proximity of the user to a reference station. The Federal Aviation Administration has been developing a system to improve GPS accuracy and ensure safety and to meet the needs of civil aviation. The program is called the WAAS.

Europe’s EGNOS and Galileo

Europe is currently developing their own differential GPS augmentation system called the European Geostationary Navigation Overlay Service (EGNOS) as part of GNSS-1. EGNOS operates its payloads on GEO satellites with the objective of augmenting the performance of GPS and GLONASS data. Its satellites will provide 24-hour European coverage. EGNOS will provide differential positioning accuracy similar to that of the US WAAS; and alarm signals in less than 6 seconds in case a data anomaly is detected in GPS or GLONASS transmissions. In addition to European countries EGNOS will cover Africa, the Middle East, North and Central Asia (e.g. India) and Latin America. It will use two existing INMARSAT-3 satellites (one over the eastern Atlantic Ocean and the other over the Indian Ocean) and the Italian ARTEMIS satellite, positioned over Africa. Mission Control Centers will be located at Gatwick, UK; Langen, Germany; Torrejon, Spain; and Ciampino, Italy. The RIMS (Ranging and Integrity Monitoring Station) reference stations will be deployed at over 80 different sites in various European countries.

The second-generation GNSS-2 system, called Galileo, will orbit a satellite constellation similar to GPS and GLONASS to provide services to users that are under civilian operation and control.

US officials are continuing discussions with the European counterparts regarding GPS and Galileo interoperability. Compatibility between the systems would mean a more precise and robust positioning capability for all.

Commercial Applications

The large scale commercial success of the GPS is primarily due to the fact that the GPS receivers have dropped in cost from $100,000 in the mid 1980’s to about $300 today, and have become much more compact and light. Commercial applications of GPS receivers have become widespread. It has proven to be of tremendous value in high precision positioning systems, transportation - land, aeronautical and maritime - and other consumer products. Outdoor enthusiasts use GPS as a navigational safety aid. These include backpackers and hikers, pleasure boats, cruise boats, fishing boats as well as oil tankers. Since the oil spill caused by Exxon Valdez, harbors are exploring active monitoring of oil tankers. The oil tankers will transmit their location via radio links to monitoring harbor stations for control. Use of such systems will make the harbor operations much safer. A similar system is being explored for civil aviation.

The consumer market for GPS and differential GPS receivers is expected to explode in the next ten years. Automobile manufacturers may incorporate GPS in all cars. The convergence of wireless communications, the internet and GPS is considered the most important market driver. This may bring the cost of a single chip GPS receiver down to the $10 range. Such receivers could then be integrated into a wide array of consumer products such as palm tops, personal digital assistants, and security devices from cars to computers. Due to the unprecedented and unexpected success of GPS, plans are afoot to modernize the GPS system.
Perspective

Even with removal of the SA errors there continues to be a need for signal redundancy. DoD would not agree to terminate SA until technology that would protect military use had been developed and tested. Two new signals are planned to be added for civil use in addition to the one available today. The benefits to civil users, based on the new and improved services, would unfold over the next several years as much greater accuracy and robustness of service. The frequency diversity available with three signals will allay some of the concerns associated with the signal weakness or jamming.

GPS is regarded as having made an important contribution to the civil World similar to the Internet. Since the system has exceeded all expectations for its use, it has thereby created additional demands that it was not designed to meet. The modernization of the GPS constellation is expected to meet nearly all future commercial demands. When completed, accurate position determination will be as easy as accurately determining time today.

Satellite Communications –

A Continuing Revolution

Overview

Telecommunications is one of the most fascinating scientific and technological achievements of the twentieth century. In the early 1900s enormous strides were made in the field of electronics by extending telephone and telegraph networks. Today we have optical fibers that can carry terabits of data, satellites that provide broadband multimedia services and the Internet carrying voice along with the vast amounts of other data. The general public seldom considers how much satellite and electronic communications (SATCOM) systems owe to aerospace and electronic systems.

The Space Age began in October 1957 with the launch of Sputnik by the Soviet Union. Sputnik broadcast only a beacon signal and had very limited communication capability. Satellite communications (SAT-COM) has made tremendous progress since then. It has revolutionized the way people communicate across the globe, and is now a vibrant industry with worldwide revenues of about $13 billion a year. Indeed, several SATCOM systems have been operational for so long and with such high reliability that they are now considered “traditional” and are taken for granted by millions of customers. A number of emerging systems will continue the revolution by providing innovative services at affordable cost to an ever-increasing mass market in the next century. The services include personal communications for data and voice to hand-held terminals and multimedia services to desk-top or even smaller.