CHAPTER 2

Operational Theory of NAVSTAR GPS

2-1. General. This chapter provides a general overview of the basic operating principles and theory of the NAVSTAR GPS, hereafter referred to as GPS. Much of the material is synopsized from the following references: *NAVSTAR GPS User Equipment Introduction* (DoD 1996) and the *Global Positioning System Standard Positioning Service Performance Standard* (DoD 2001). These two sources, along with other references listed in Appendix A, should be consulted for more detailed coverage on all the topics covered in this chapter.

2-2. Global Positioning System (GPS) Overview. GPS is a passive, all-weather, 24-hour GNSS operated and maintained by the DoD. It consists of a nominal constellation of 24 satellites in high-altitude orbits. Its primary mission is to provide passive, real-time, 3-D positioning, navigation and velocity data for land, air, and sea-based strategic and tactical forces operating anywhere in the world. A secondary--and most predominant--application is a wide range of civil positioning and time transfer. A ground-based static or roving GPS receiver is simply a range measurement device: distances are measured between the receiver antenna and four or more satellites in view, and the position is determined from the adjusted intersections of the range vectors--equivalent to a trilateration solution in terrestrial surveying. These distances are determined in the GPS receiver by precisely measuring the time it takes a coded signal to travel from the satellites to the receiver’s antenna. The critical components in the system are the precisely synchronized atomic clocks in the satellites. In addition, many GPS receivers can also measure the phase difference of the satellite signal's carrier waves, allowing for sub-centimeter distance resolution of the range to the satellite. This phase resolution measurement process is similar to that used in conventional electronic distance measurement (EDM) land surveying equipment.

2-3. GPS Program Background. A direct product of the "space race" of the 1960's, the GPS is actually the result of the merging of two independent programs that were begun in the early 1960's: the US Navy's TIMATION Program and the US Air Force's 621B Project. Another system similar in basic concept to the current GPS was the US Navy's TRANSIT program, which was also developed in the 1960's. Currently, the entire system is maintained by the US Air Force GPS Joint Program Office (JPO), a North Atlantic Treaty Organization (NATO) multi-service type organization that was established in 1973. The DoD initially designed the GPS for military use only, providing sea, air, and ground troops of the United States and members of NATO with a unified, high-precision, all-weather, worldwide, real-time positioning system. The first US pronouncement regarding civil use of GPS came in 1983 following the downing of Korean Airlines Flight 007 after it strayed over territory belonging to the Soviet Union. As a result of this incident, in 1984, President Reagan announced the Global Positioning System would be made available for international civil use once the system became operational. In 1987, DoD formally requested the Department of Transportation (DoT) to establish and provide an office to respond to civil users’ needs and to work closely with the DoD to ensure proper implementation of GPS for civil use. Two years later, the US Coast Guard became the lead agency for this project. On December 8, 1993, the DoD and DoT formally declared Initial Operational Capability (IOC), meaning that the GPS was capable of sustaining the Standard Positioning Service (SPS). On April 27, 1995, the US Air Force Space Command formally declared GPS met the requirements for Full Operational Capability (FOC), meaning that the constellation of 24 operational satellites had successfully completed testing for military capability. Mandated by Congress, GPS is freely used by both the military and civilian public for real-time absolute/autonomous positioning of ships, aircraft, and land vehicles, as well as highly precise differential point positioning and time transferring.

2-4. GPS System Configuration. GPS consists of three distinct segments: the space segment (satellites), the control segment (ground tracking and monitoring stations), and the user segment (air, land, and sea-based receivers). See Figure 2- 1 for a representation of the basic GPS system segments.

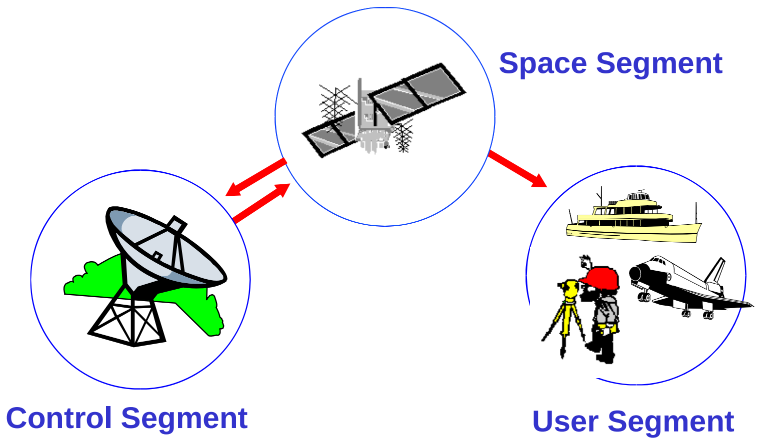

Figure 2-1. GPS System Segments

a. Space segment. The space segment consists of all GPS satellites in orbit. The initial space segment was designed with four satellites in each of six orbital planes inclined at 55 degrees to the equator. The actual number of operational satellites and their locations varies at any given time as satellites are constantly being replaced, realigned, and upgraded--see Table 2-1. The average life of a GPS satellite is approximately eight years. For example, Figure 2-2 indicates 30 healthy of the 32 functioning satellites on the date shown. The satellites are located at average altitudes of 20,200 km (10,900 nautical miles), and have 11-hour 58-minute orbital periods. They are positioned in orbit such that at least four geometrically suitable satellites will be available for navigation. The first generation of satellites launched between 1978 and 1985 were the Block I (research and development). None of these are still operational. The second series of launches (the Block II or production satellites--Figure 2-3) was begun in 1989. The GPS constellation was declared fully operational in 1995 (prior to this time, GPS positioning was intermittent due to lack of full coverage). Launching of Block IIR (R is for replenishment) satellites began in 1997 and is still underway. Future launches of a Block IIF (Follow-on) series, along with related GPS modernization initiatives (i.e. GPS III), will keep the system operational for at least the next two decades. GPS is not the only global navigation satellite system (GNSS). Russia maintains a similar global orbiting satellite navigation system (GLONASS) of nominally

24 satellites. Some high-end receivers can acquire and process both the GPS and GLONASS satellites simultaneously. This capability will be further expanded when the proposed European Union 30-satellite navigation system (GALILEO) is implemented in a decade or so. Japan and China are also considering development of their own GNSS. The Compass Navigation Satellite System (CNSS), or BeiDou 2, is China's second-generation satellite navigation system capable of providing continuous, real-time passive 3D geo-spatial positioning and speed measurement. The completed system for a global coverage will comprise 25 to 35 satellites, including 4 Geostationary Orbit (GEO) satellites (58.75° E, 80° E, 110.5° E, and 140° E). CNSS satellites are based on the DongFangHong 3 (DFH-3) satellite bus, with a designed life span of eight years (see: http://www.sinodefence.com/space/spacecraft/beidou2.asp). The ability to track more "satellites-in-view" from different GNSS enhances the accuracy and reliability of the observations.

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GPS CONSTELLATION STATUS FOR 20 DEC 2009

PLANE	SLOT	SVN	PRN	BLOCK-TYPE	CLOCK	OUTAGE DATE	NANU-TYPE	NANU-SUBJECT
A	1	39	09	IIA	CS			
A	2	52	31	IIR-M	RB			
A	3	38	08	IIA	RB			
A	4	48	07	IIR-M	RB			
A	5	25	25	IIA	RB	18 DEC 2009	UNUSUFN	2009130 - SVN25 (PRN25) UNUSABLE JDAY 352/1522 - UNTIL FURTHER NOTICE
A	6	27	27	IIA	RB			
B	1	56	16	IIR	RB			
D	2	30	30	IIA	CS			
B	3	44	28	IIR	RB			
B	4	58	12	IIR-M	RB			
B	5	40	01	IIR-M	RB			
C	1	57	29	IIR-M	RB			
C	2	33	03	II-A	CS			
C	3	59	19	II-R	RD			
C	4	53	17	IIR-M	RB			
C	5	36	06	IIA	RB			
D	1	61	02	II-R	RB			
D	2	46	11	II-R	RB			
D	3	45	21	II-R	RB			
D	4	34	04	II-A	RB			
D	5	24	24	II-A	CS	12 SEP 2009	UNUSUFN	2009066 - SVN24 (PRN24) UNUSABLE JDAY 255/2017 - UNTIL FURTHER NOTICE
E	1	51	20	II-R	RB			
E	2	47	22	II-R	RB			
E	3	50	05	IIR-M	RB			
E	4	54	18	II-R	RB			
E	5	23	32	II A	RB			
E	6	40	10	IIA	CS			
F	1	41	14	II-R	RB			
F	2	55	15	IIR M	RB			
F	3	43	13	II-R	RB			
F	4	60	23	II-R	RB			
F	5	26	26	II A	RB			

Figure 2-2. Satellite Constellation Status Report (20 December 2009)
Source: US Coast Guard Navigation Center
(http://www.navcen.uscg.gov/navinfo/Gps/ActiveNanu.aspx)

Note: Obtain current satellite constellation reports from the US Coast Guard Navigation Center web site

Figure 2-3. GPS Block IIA Satellite

b. Control segment. The GPS control segment consists of Master Control Stations and six monitoring stations located throughout the world (Figure 2-4). The Master Control Station is located at Schriever Air Force Base, Colorado with a backup station in Gaithersburg, Maryland. The information obtained from the monitoring stations that track the satellites is used in controlling the satellites and predicting their orbits. All data from the tracking stations are transmitted to the Master Control Station where it is processed and analyzed. Ephemerides, clock corrections, and other message data are then transmitted back to the monitoring stations with ground antennas for subsequent transmittal back to the satellites. The Master Control Station is also responsible for the daily management and control of the GPS satellites and the overall control segment.

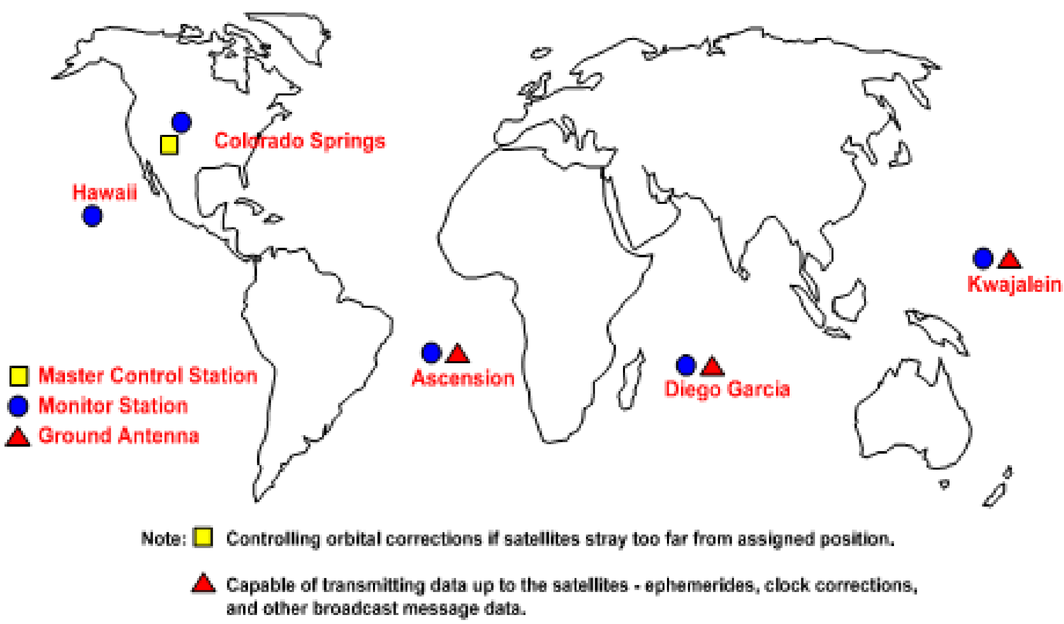

Figure 2-4. GPS Control Station Network (1994)

c. User segment. The user segment represents the ground-based GPS receiver units that process the GPS satellite signals and compute the position and/or velocity of the user. Most GPS receivers perform these functions automatically, in real-time, and often provide visual and/or verbal positional guidance information. Users consist of both military and civil activities, for an almost unlimited number of applications in a variety of air, sea, or land-based platforms. Geodetic surveying applications represent a small percentage of current and potential GPS users. Typical user receivers are shown in Figure 2-5.

Figure 2-5. Hand-held GPS receiver (Garmin Oregon 400t handheld) for general navigation and positioning (left) and a geodetic quality GPS receiver (Trimble R8 GNSS receiver with TSC2 Controller) for precise control surveying (right)

2-5. <u>GPS Broadcast Frequencies and Codes</u>. Each GPS satellite transmits ranging signals on two L-band frequencies, designated as L1 and L2. With the launch of the Block II-F and newer satellites, a third L-band frequency, designated L5, will also be available. The L5 frequency is in the aeronautical navigation band as is intended primarily for civilian and safety of life applications. The L1 carrier frequency is 1575.42 megahertz (MHz) and has a wavelength of approximately 19 centimeters (cm). The L2 carrier frequency is 1227.60 MHz and has a wavelength of approximately 24 cm. The L5 carrier frequency is 1176.45 MHz and has a wavelength of approximately 26 cm. The L1 signal is modulated with a 1.023 MHz Coarse/Acquisition Code (C/A-code) and a 10.23 MHz Precision Code (P-code). The L2 signal is modulated with the 10.23 MHz P-code. On BLOCK II-M and newer satellites, a new civilian-use code has been added to the L2 signal and is referred to as L2C. Unlike the L1 C/A code, L2C contains two distinct PRN code sequences to provide ranging information; the Civilian Moderate length code (called CM), and the Civilian Long length code (called CL). The CM code is 10,230 bits long, repeating every 20 ms. The CL code is 767,250 bits long, repeating every 1500 ms. Each signal is transmitted at 511,500 bits per second, however they are multiplexed together to form a 1,023,000 bit/s signal. The L2C signal is tasked with improving accuracy of navigation, providing an easy to track signal, and acting as a redundant signal in case of localized interference. Two PRN ranging codes are transmitted on L5 as well: the in-phase code (denoted as the I5-code); and the quadrature-phase code (denoted as the Q5-code). Both codes are 10,230 bits long and transmitted at 10.23 MHz (1ms repetition). All five codes can be used to determine the range between the user and a satellite. The P-code, however, is normally encrypted and is available only to authorized users. When encrypted, it is termed the Y-code. An immediate effect of having more than one civilian frequency transmitted is that the civilian receivers can now directly measure the ionospheric error in the same way as dual frequency P(Y)-code receivers. Table 2-1 below summarizes the carrier frequencies and codes on a Block IIR satellite. Each satellite carries precise atomic clocks to generate the timing information needed for precise positioning. A 50 Hz navigation message is also transmitted on both the P(Y)-code and C/A-code. This message contains satellite clock bias data, satellite ephemeris data, orbital information, ionospheric signal propagation correction data, health and status of satellites, satellite almanac data for the entire constellation, and other general information.

Table 2-1. Civilian GPS L band frequencies. L5 is in some current and future Block II-F and Block III Satellites.

Frequency Label	Frequency	Contents
L1	1575.42 MHz	COARSE ACQUISITION (C/A) CODE, PRECISE CODE [P(Y)], NAVIGATION MESSAGE
L2	1227.60 MHz	PRECISE CODE [P(Y)], L2C CIVIL CODE ON BLOCK II-M AND NEWER
L5	1176.45 MHz	CIVILIAN SAFETY OF LIFE (SoL-PROTECTED AERONAUTICAL, NO INTERFERENCE), BLOCK II-F AND BLOCK III

(see: http://www.ngs.noaa.gov/PUBS_LIB/NGSRealTimeUserGuidelines.v1.1.pdf)

a. Pseudo-random noise. The codes modulated on the L1, L2 and L5 carriers are referred to as pseudo-random noise (PRN). This pseudo-random noise is actually a 1023 bit code with a clock rate of 1.023 MHz that repeats every 1 millisecond on L1 and as described above on L2 and L5. The 10.23 MHz P(Y)-code PRN has a coded sequence of 267 days. This sequence of very precise time marks permits the ground receivers to compare and compute the time of transmission between the satellite and ground station. From this transmission time, the range to the satellite can be derived. This is the basis behind GPS range measurements. Each satellite has a different PRN. The L1 C/A-code pulse intervals are approximately every 293 m in range and the more accurate P-code every 29 m.

b. Pseudoranges. A pseudorange is the time delay between the satellite clock and the receiver clock, as determined from C/A, L2C, I5, Q5, or P-code pulses. This time difference equates to the range measurement but is called a "pseudorange" since at the time of the measurement, the receiver clock is not synchronized to the satellite clock. In most cases, an absolute or autonomous 3-D real-time navigation position can be obtained by observing at least four simultaneous pseudoranges. The Standard Positioning Service (SPS) uses the less precise L1 C/A-code pseudoranges for real-time GPS navigation. The new L2C signal may be used in a variety of civilian applications as it enhances performance by eliminating the unacceptable 21 dB cross-correlation performance of the C/A code, which allows a strong GPS signal to interfere with weak GPS signals. The L2C signal achieves this by having a worst-case cross-correlation performance of 45 dB (over 251 times better). Furthermore, L2C lowers the data demodulation threshold, making it possible to read the message when barely tracking the signal. As a result, L2C is likely to become the signal of choice for applications like E911 positioning inside buildings, personal navigation in wooded areas, or vehicle navigation along tree-lined roads. If this prediction comes true, embedded GPS in wireless phones will make L2C the most widely used of all GPS signals (*The Modernized L2 Civil Signal, Leaping Forward in the 21st Century* by Richard D. Fontana, Wai Cheung, and Tom Stansell). The Precise Positioning Service (PPS) is the fundamental military real-time navigation use of GPS. Pseudoranges are obtained using the higher pulse rate (i.e. higher accuracy) P-code on both frequencies (L1 and L2). P-codes are encrypted to prevent unauthorized civil or foreign use. This encryption requires a special key.

c. Carrier phase measurements. Carrier frequency tracking measures the phase differences between the Doppler shifted satellite and receiver generated frequencies. Phase measurements are resolved over the relatively short L1, L2 and L5 carrier wavelengths (19 cm, 24 cm, and 26 cm respectively). This allows phase resolution at the mm level. The phase differences are continuously changing due to the changing satellite earth geometry. However, such effects are resolved in the receiver and subsequent data post-processing. When carrier phase measurements are observed and compared between two stations (i.e. relative or differential mode), baseline vector accuracy between the stations below the centimeter level is attainable in three dimensions. Various receiver technologies and processing techniques allow carrier phase measurements to be used in real-time centimeter positioning. The implementation of L5 will be a boost to overall system reliability and may make instantaneous (one-epoch) ambiguity resolution feasible for a broad range of applications. (Note that reference to L5 as part of signal modernization should not be confused with the “L5 Wide-Lane Observable” obtained by subtracting the two phase equations, L1 minus L2.)

2-6. GPS Broadcast Messages and Ephemeris Data. Each GPS satellite periodically broadcasts data concerning clock corrections, system/satellite status, and most critically, its position or ephemerides data. There are two basic types of ephemeris data: broadcast and precise.

a. Broadcast ephemerides. The broadcast ephemerides are actually predicted satellite positions within the navigation message that are transmitted from the satellites in real-time. The ephemerides can be acquired in real-time by a receiver capable of acquiring either the C/A or P-code. The broadcast ephemerides are computed using past tracking data of the satellites. The satellites are tracked continuously by the monitor stations to obtain more recent data to be used for the orbit predictions. This data is analyzed by the Master Control Station and new parameters for the satellite orbits are transmitted back to the satellites. This upload is performed daily with new predicted orbital elements transmitted every hour by the Navigation Message. The broadcast navigation message consists of 25 frames of data, each data frame consisting of 1,500 bits. Each frame is divided into 5 sub-frames. At the 50 Hz transmission rate, it takes six seconds to receive a sub-frame, or 12.5 minutes to receive all 25 frames of data. The following information is broadcast from the satellite to the user's GPS receiver:

Satellite time-of-transmission
Satellite position
Satellite health
Satellite clock correction
Propagation delay effects
Time transfer to UTC (USNO)
Constellation status

b. Precise ephemerides. The precise ephemerides are based on actual orbital tracking data that is post-processed to obtain the more accurate satellite positions. These ephemerides are available at a later date and are more accurate than the broadcast ephemerides because they are based on actual orbital tracking data and not predicted data. The reference frame used is the International Earth Rotation Service Terrestrial Reference Frame (ITRF). NASA's International GPS Service (IGS) is the agency that coordinates the precise orbital tracking and disseminates this information to Global Data Centers for public use. In addition, an informational summary file is provided to document the computation and to convey relevant information about the observed satellites, such as maneuvers or maintenance. NOAA's National Geodetic Survey (NGS) has been designated as the Federal agency responsible for providing precise orbital ephemerides to the general public. Since the precise orbits are a combination of several orbit production centers around the globe, it does lag behind in its availability until all centers have reported in. Also, it is not made available until a full GPS week has been completed--the NGS Precise Orbits generally are available seven or eight days after the date of observation. The IGS also supplies a predicted Ultra-Rapid Orbit, which is updated twice daily, and a Rapid Orbit which is updated daily--see Table 2-2 for a summary of satellite orbital data availability. NGS provides satellite orbit positions in SP3 format every 15 minutes--in the current ITRFxx reference frame. For most USACE surveying, mapping, and navigation applications, the broadcast ephemerides are adequate to obtain the needed accuracies. For high-precision USACE control survey applications (especially vertical control densification) the final precise ephemerides should be used. Most baseline reduction software provides options for inputting precise orbital data--see Chapter 10. Details on orbital latencies, formats, and downloading instructions can be obtained at the NGS web site listed in Table 2-3 and at http://www.agc.army.mil/ndsp/links_gnss.asp.

Table 2-2. Summary of GPS Satellite Ephemerides Information (International GPS Service)

Ephemeris	Orbital Accuracy	Latency (approx)	Updates	Sample
Broadcast	260 cm	Real-time	--	daily
Predicted (Ultra-Rapid	25 cm	Real-time	twice daily	15 min/15 min
Rapid	< 5 to 10 cm	(14 to 17 hours)	daily	15 min/5 min
Final	< 5 cm	(13 days)	weekly	15 min/5 min

Sources: International GPS Service and National Geodetic Survey
http://www.ngs.noaa.gov/orbits/

2-7. GPS Status and Problem Reporting. The US Coast Guard Navigation Center (NAVCEN) provides notification of changes in constellation operational status that affect the service being provided to GPS users, or if the US Government anticipates a problem in supporting performance standards established in the *GPS Standard Positioning Service Performance Standard* (DoD 2001). Through operation of the Navigation Information Service (NIS), NAVCEN provides the public with information on the GPS status. The current mechanism for accomplishing this notification is through the Notice: Advisory to Navigation Users (NANU). NANUs are a primary input in the generation of GPS-related Notice to Airmen (NOTAM) and US Coast Guard Local Notice to Mariners (LNM). In the case of a scheduled event affecting service provided to GPS users, the NIS will issue an appropriate NANU at least 48 hours prior to the event. In the case of an unscheduled outage or problem, notification will be provided as soon as possible after the event. USACE users performing high-order GPS control surveys or DGPS-controlled dredging measurement and payment surveys should closely monitor NANUs for potential problems. The NIS may be accessed through any of the following media:

Internet: http://www.navcen.uscg.gov

E-Mail: nisws@navcen.uscg.mil

GPS Status Recording: Telephone (703) 313-5907

WWV/WWVH Radio Broadcast or Telephone (303) 499-711:
14-15 minutes past hour (WWV) and 43-44 minutes past hour (WWVH)
Frequencies: 2.5, 5, 10, 15, and 20 MHz

Write or Call: Commanding Officer (NIS)
US Coast Guard Navigation Center
7323 Telegraph Road
Alexandria, VA 22315-3998
Telephone: (703) 313-5900

A typical GPS Status Report and a NANU disseminated by the NAVCEN is shown below in Table 2-3. The NANU provides notice that a particular satellite (SVN 17) is unusable. GPS users can subscribe to automated receipt of these GPS Status Reports and NANUs (see http://cgls.uscg.mil/mailman/listinfo/nanu).

Table 2-3. GPS Status Report and NANU (30 December 2009)
Source: US Coast Guard Navigation Center (http://cgls.uscg.mil/mailman/listinfo/nanu)

30 NOV 2009
TIS-PF-NISWS TIS-PF-NISWS at uscg.mil
Mon Nov 30 10:08:08 EST 2009

- Previous message: NAVCEN PHONES RETURNED TO NORMAL
- Messages sorted by: [date] [thread] [subject] [author]

GPS OPERATIONAL ADVISORY 334
SUBJ: GPS STATUS 30 NOV 2009

1. SATELLITES, PLANES, AND CLOCKS (CS=CESIUM RB=RUBIDIUM):
A. BLOCK I : NONE
B. BLOCK II: PRNS 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
PLANE : SLOT B6, D1, C2, D4, E6, C6, A4, A3, A1, E3, D2, B4, F3, F1
CLOCK : RB, RB, CS, RB, RB, RB, RB, CS, CS, CS, RB, RB, RB, RB
BLOCK II: PRNS 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28
PLANE : SLOT F2, B1, C4, E4, C3, E1, D3, E2, F4, D5, A5, F5, A6, B3
CLOCK : RB, RB, RB, RB, RB, RB, RB, RB, RB, CS, RB, RB, CS, RB
BLOCK II: PRNS 29, 30, 31, 32
PLANE : SLOT C1, B2, A2, E5
CLOCK : RB, CS, RB, RB
2. CURRENT ADVISORIES AND FORECASTS :
A. FORECASTS: FOR SEVEN DAYS AFTER EVENT CONCLUDES.
NANU MSG DATE/TIME PRN TYPE SUMMARY (JDAY/ZULU TIME START - STOP)

NANU	MSG DATE/TIME	PRN	TYPE	SUMMARY (JDAY/ZULU TIME START - STOP)
2009112	052257Z NOV 2009	25	FCSTDV	314/1100-315/0100
2009114	061607Z NOV 2009	06	FCSTDV	316/2100-317/1200
2009115	101656Z NOV 2009	25	FCSTSUMM	314/1117-314/1649
2009116	122119Z NOV 2009	12	FCSTDV	321/1320-322/0200
2009117	130443Z NOV 2009	06	FCSTSUMM	316/2112-317/0443
2009118	171919Z NOV 2009	12	FCSTSUMM	321/1338-321/1913

B. ADVISORIES:
NANU MSG DATE/TIME PRN TYPE SUMMARY (JDAY/ZULU

TIME START - STOP)
2009066 122006Z SEP 2009 24 UNUSUFN 255/2017-/
2009111 051914Z NOV 2009 08 UNUSUFN 309/1902-/
2009119 201802Z NOV 2009 08 UNUSABLE 309/1902-324/1751
C. GENERAL:
NANU MSG DATE/TIME PRN TYPE SUMMARY (JDAY/ZULU
TIME START - STOP)

2009025 061455Z APR 2009 GENERAL /-/
2009064 122000Z SEP 2009 GENERAL /-/
2009065 121946Z SEP 2009 GENERAL /-/
3. REMARKS:
A. THE POINT OF CONTACT FOR GPS MILITARY OPERATIONAL SUPPORT IS THE GPS
OPERATIONS CENTER AT (719)567-2541 OR DSN 560-2541.
B. CIVILIAN: FOR INFORMATION, CONTACT US COAST GUARD NAVCEN AT COMMERCIAL (703)313-5900 24 HOURS DAILY AND INTERNET HTTP://WWW.NAVCEN.USCG.GOV
C. MILITARY SUPPORT WEBPAGES CAN BE FOUND AT THE FOLLOWING HTTPS://GPS.AFSPC.AF.MIL/GPS OR HTTP://GPS.AFSPC.AF.MIL/GPSOC

2-8. GPS User Operating and Tracking Modes. There are basically two general operating modes from which GPS-derived positions can be obtained: (1) or autonomous positioning, and (2) differential (or relative) positioning. Within each of these two modes, range measurements to the satellites can be performed by tracking either the phase of the satellite's carrier signal or the pseudo-random noise (PRN) codes modulated on the carrier signal. In addition, GPS positioning can be performed with the receiver operating in either a static or dynamic (kinematic) environment. This variety of operational options results in a wide range of accuracy levels that may be obtained from the GPS. These options are discussed in detail in subsequent chapters of this manual. Positional accuracies can range from 100 m down to the sub-centimeter level. Increased accuracies to the centimeter level usually require additional observing time; however, many dynamic applications can now provide this accuracy in real-time. Selection of a particular GPS operating and tracking mode (i.e. absolute or autonomous, differential, code, carrier, static, kinematic, real-time, post-processed, and/or combinations thereof) depends on the user application, accuracy requirement, and resources. Most USACE project control survey applications typically require differential positioning using carrier phase tracking. Dredge control and hydrographic survey applications typically use meter-level accuracy differential code measurements. GIS feature mapping applications may use either differential code or carrier measurements, depending on the desired accuracy. Non-differential absolute or autonomous positioning modes are adequate for lesser accuracy requirements but are rarely used for geodetic surveying applications; however, they may be used for some small-scale mapping projects. In general, the cost of a particular operating system and tracking mode will exponentially increase as a function of accuracy--e.g., a 30 m point accuracy can be obtained with a $100 GPS receiver, meter-level accuracy for $5,000 to $15,000, and sub-centimeter accuracy requires differential GPS equipment (or systems) in the $15,000 to $50,000 range.

2-9. Absolute or Autonomous GPS Positioning Techniques. The most common GPS positioning technique is "absolute or autonomous positioning." Most commercial hand-held GPS receivers provide absolute or autonomous (i.e. non-differential) positioning, with real-time horizontal or vertical accuracies in the 10 m to 30 m range, depending on the receiver quality and numerous other factors--see *Global Positioning System Standard Positioning Service Performance Standard* (DoD 2001) for a detailed analysis of GPS positional accuracies. These receivers are typically used for real-time vehicle or vessel navigation. When operating in this passive, real-time navigation mode, ranges to GPS satellites are observed by a single receiver positioned on a point for which a position is desired. This receiver may be positioned to be stationary over a point or in motion (i.e. kinematic positioning, such as on a vehicle, aircraft, missile, or backpack).

a. GPS absolute or autonomous positioning services. Two levels of absolute or autonomous positioning accuracy are obtained from the GPS. These are called the (1) Standard Positioning Service and (2) Precise Positioning Service.

(1) Standard Positioning Service (SPS). The SPS is the GPS positioning service that the DoD authorizes to civil users. This service consists of the C/A-code and navigation message on the L1 signal. The L2 signal is not part of the SPS, nor is the P(Y)-code on L1. The DoD may deliberately degrade the GPS signal for national security reasons. When it is deliberately degraded, as it was prior to 2000, horizontal accuracies were in the range of 75 to 100 m. DoD degradation of the GPS signal is referred to as "Selective Availability" or S/A. DoD also implements AntiSpoofing (A/S) which will deny the SPS user the more accurate P-code. S/A and A/S will be discussed further in Chapter 4. Since May 2000, when this degradation was suspended, horizontal accuracies down to the 10 to 30 m level or better may be achieved with a quality single frequency receiver. The SPS GPS position accuracy statistics for the combination of: a 4.0 m 1-sigma (7.8 m 95%) SIS-only (signal-in-space only) URE (user range error) value over all AODs (age of data) during normal operations, the modern single-frequency SPS receiver UEE (user equipment error) of 2.3 m 1-sigma (4.5 m 95%), and an assumed single-frequency ionospheric delay compensation error of 2.5 m 1-sigma (4.9 m 95%) under benign ionosphere conditions in the mid latitudes; or a total UERE (user equivalent range error) of 5.2 m 1-sigma (10.3 m 95%), are:

9.4 m = 95% Horizontal Position Accuracy
17.3 m = 95% Vertical Position Accuracy

Refer to *Global Positioning System Standard Positioning Service Performance Standard, 4th Edition, September 2008,* which may be accessed at http://pnt.gov/public/docs/ for more detailed information.

(2) Precise Positioning Service (PPS). Use of the PPS requires authorization by DoD to have a decryption device capable of deciphering the encrypted GPS signals. USACE is an authorized user; however, actual use of the equipment has security implications. Real-time 3-D absolute/autonomous positional accuracies of better than 10 m are attainable through use of the PPS with dual-frequency receivers.

b. Applications. Absolute or autonomous point positioning is suitable for few USACE surveying applications where SPS accuracies as described above are acceptable, e.g., rough reconnaissance work, general vessel navigation, , small-scale mapping. They are also useful for some military topographic surveying applications (e.g., artillery surveying). Typical USACE applications are summarized in Chapter 6. With certain specialized GPS receiving equipment, data processing refinements, and long-term static observations, absolute/autonomous positional coordinates may be determined to accuracy levels less than a meter. Future GPS modernizations and receiver enhancements are expected to improve positional accuracies down to the 3-meter level, a level that is now only achievable with differential observations described below. Refer to Chapter 4 for more information on absolute/autonomous GPS positioning techniques.

2-10. <u>Differential or Relative GPS Positioning Techniques</u>. Differential GPS (DGPS) positioning is simply a process of determining the relative differences in coordinates between two receiver points, each of which is simultaneously observing/measuring satellite code ranges and/or carrier phases from the GPS satellite constellation. The process actually involves the measurement of the difference in ranges between the satellites and two or more ground observing points. Typically, one GPS receiver is located at a known "reference" station and the other remote or "rover" receiver is positioned (or dynamically traverses) over an unknown point that requires georeferencing. Both receivers simultaneously acquire GPS data for later computation (post-processing), or, alternatively, the reference receiver transmits data to the rover receiver for "real-time" position computation. The range measurement is performed by a phase difference comparison, using either the carrier phase or code phase. The basic principle is that the absolute positioning errors at the two receiver points will be approximately the same for a given instant in time. The resultant accuracy of these coordinate differences is at the meter level for code phase observations and at the centimeter level for carrier phase tracking. These relative coordinate differences are usually expressed as "3-D baseline vectors," which are comparable to conventional survey azimuth/distance measurements. Differential GPS positioning can be performed in either a static or dynamic (kinematic mode). Most USACE precise control surveys are performed in a static (post-processing) mode while dredge and survey boat positioning is performed dynamically in real-time--see Chapter 6 for typical applications. Detailed information on differential GPS survey techniques can be found in Chapter 5.

2-11. <u>GPS Modernization Initiatives (2003-2014)</u>. GPS Modernization is a proposed multi-phase effort to be executed over the next 15+ years--refer to Figure 2-6. Full implementation is contingent on funding availability through the program out years. The GPS Modernization effort focuses on improving position and timing accuracy, availability, integrity monitoring support capability, and enhancement to the control system. Additional signals are being implemented (i.e., L2 C/A and L5, which are not yet fully operational) to enhance the ability of GPS to support civil users and provide a new military code. The first new signal being implemented is the C/A-code on the L2 frequency (1227.60 MHz). This feature will enable dual channel civil receivers to correct for ionospheric error. A third civil signal is being added on the L5 frequency (1176.45 MHz) for use in safety-of-life applications. L5 can serve as a redundant signal to the GPS L1 frequency (1575.42 MHz) with a goal of assurance of continuity of service potentially to provide precision approach capability for aviation users. In addition, a secure and spectrally separated Military Code (M-Code) will be broadcast on the L1 and L2 frequencies enabling the next generation of military receivers to operate more fully in an electronic jamming environment.

As these system enhancements are introduced, users will be able to continue to use existing compliant receivers, as signal backward compatibility is an absolute requirement for both the military and civil user communities. Although current GPS users will be able to operate at the same, or better, levels of performance than they enjoy today, users will need to modify existing user equipment or procure new user equipment in order to take full advantage of any new signal structure enhancements. Reference also the *2008 Federal Radio Navigation Plan* (FRP 2008).

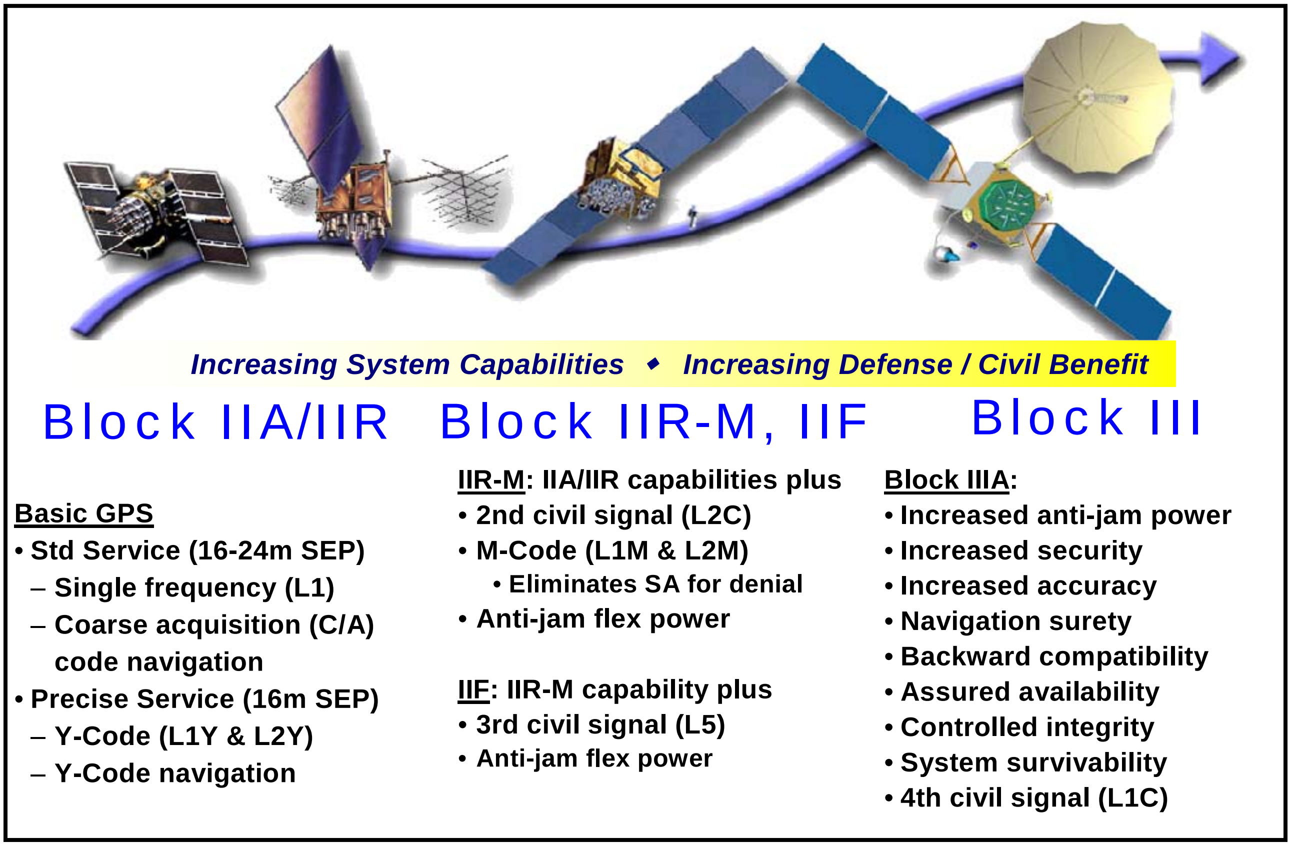

Figure 2-6. GPS Modernization