Chapter 2
Operational Theory of GPS

2-1. General

This chapter provides a general overview of the basic operating principles and theory of the NAVSTAR 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 global navigation satellite system (GNSS) operated and maintained by the Department of Defense (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 to ten 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 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 19 and 24 cm 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. NAVSTAR 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 NAVSTAR GPS Joint Program Office (JPO), a North Atlantic Treaty Organization (NATO) multi-service type organization that was established in 1973. 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 NAVSTAR 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 positioning of ships, aircraft, and land vehicles, as well as highly precise differential point positioning and time transferring.

2-4. NAVSTAR System Configuration

The NAVSTAR 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.

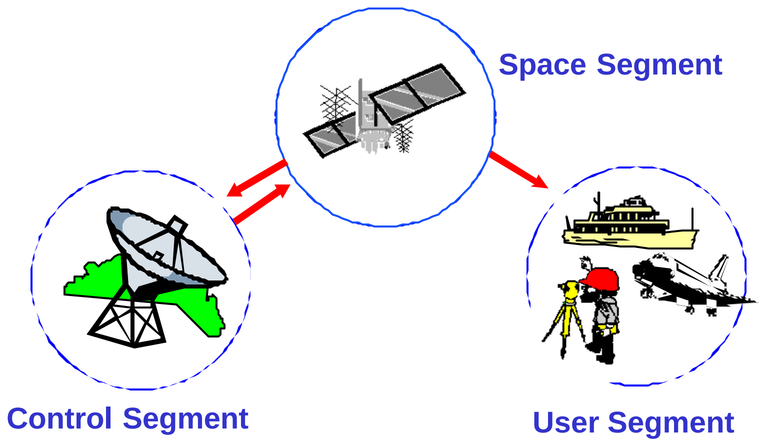

Figure 2-1. NAVSTAR GPS System Segments

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, Table 2-1 indicates 29 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 2-2) 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. NAVSTAR 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 ability to track more "satellites-in-view" from different GNSS enhances the accuracy and reliability of the observations.

Table 2-1. Satellite Constellation Status Report (5 May 2002)
Source: US Coast Guard Navigation Center (www.navcen.uscg.gov)

SVN No	PRN No	Block-Mission No	Launch Date	Slot	Operational Date	Months Operat'al	Years Operat'al	IRON No
1	4	I-1	22-Feb-78	**	29-Mar-78	21.9	1.825000	5111
2	7	I-2	13-May-78	**	14-Jul-78	25.5	2.125000	5112
3	6	I-3	06-Oct-78	**	09-Nov-78	161.3	13.441667	5113
4	8	I-4	11-Dec-78	**	08-Jan-79	93.6	7.800000	5114
5	5	I-5	09-Feb-80	**	27-Feb-80	45	3.750000	5117
6	9	I-6	26-Apr-80	**	16-May-80	126.8	10.566667	5118
7	**	I-7	18-Dec-81	**	**	0	0.000000	5115
8	11	I-8	14-Jul-83	**	10-Aug-83	116.8	9.733333	9794
9	13	I-9	13-Jun-84	**	19-Jul-84	115.2	9.600000	9521
10	12	I-10	08-Sep-84	**	03-Oct-84	133.5	11.125000	9783
11	3	I-11	09-Oct-85	**	30-Oct-85	99.9	11.783333	6374
14	14	II-1	14-Feb-89	**	14-Apr-89	141.4	11.783333	6142
13	2	II-2	10-Jun-89	B3	12-Jul-89	138.6	11.550000	2567
16	16	II-3	17-Aug-89	**	13-Sep-89	136.4	11.366667	6738
19	19	II-4	21-Oct-89	A5	14-Nov-89	134.5	11.208333	2272
17	17	II-5	11-Dec-89	D3	11-Jan-90	132.6	11.050000	4373
18	18	II-6	24-Jan-90	**	14-Feb-90	127.5	10.625000	3028
20	20	II-7	25-Mar-90	**	19-Apr-90	72.7	6.058333	3310
21	21	II-8	02-Aug-90	E2	31-Aug-90	125	10.416667	470
15	15	II-9	01-Oct-90	D5	20-Oct-90	123.3	10.275000	8639
23	23	II-10	26-Nov-90	E4	10-Dec-90	121.6	10.133333	8896
24	24	II-11	03-Jul-91	D1	30-Aug-91	113	9.416667	5681
25	25	II-12	23-Feb-92	A2	24-Mar-92	106.2	8.850000	1920
28	28	II-13	09-Apr-92	**	25-Apr-92	101.1	8.425000	2941
26	26	II-14	07-Jul-92	F2	23-Jul-92	102.2	8.516667	3055
27	27	II-15	09-Sep-92	A4	30-Sep-92	100	8.333333	2524
32	1	II-16	22-Nov-92	F4	11-Dec-92	97.6	8.133333	6809
29	29	II-17	18-Dec-92	F5	05-Jan-93	96.8	8.066667	3659
22	22	II-18	02-Feb-93	B1	04-Apr-93	93.8	7.816667	8800
31	31	II-19	30-Mar-93	C3	13-Apr-93	93.5	7.791667	4780
37	7	II-20	13-May-93	C4	12-Jun-93	91.6	7.633333	5689
39	9	II-21	26-Jun-93	A1	21-Jul-93	90.3	7.525000	9631
35	5	II-22	30-Aug-93	B4	20-Sep-93	88.3	7.358333	7948
34	4	II-23	26-Oct-93	D4	01-Dec-93	85.9	7.158333	9802
36	6	II-24	10-Mar-94	C1	28-Mar-94	82	6.833333	4715
33	3	II-25	28-Mar-96	C2	09-Apr-96	57.7	4.808333	3365
40	10	II-26	16-Jul-96	E3	15-Aug-96	53.5	4.458333	8006
30	30	II-27	12-Sep-96	B2	01-Oct-96	51.9	4.325000	3320
38	8	II-28	06-Nov-97	A3	18-Dec-97	37.4	3.116667	3722
42	12	IIR-1	17-Jan-97	**	**	0	0.000000	**
43	13	IIR-2	22-Jul-97	F3	31-Jan-98	36	3.000000	8456
46	11	IIR-3	06-Oct-99	D2	03-Jan-00	12.9	1.075000	1597
51	20	IIR-4	10-May-00	E1	01-Jun-00	7.9	0.658333	1436
44	28	IIR-5	16-Jul-00	B5	17-Aug-00	5.40	0.450000	443
41	14	IIR-6	10-Nov-00	F1	10-Dec-00	1.60	0.133333	1423
54	18	IIR-7	30-Jan-01	E4	15-Feb-01	--	---	---

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

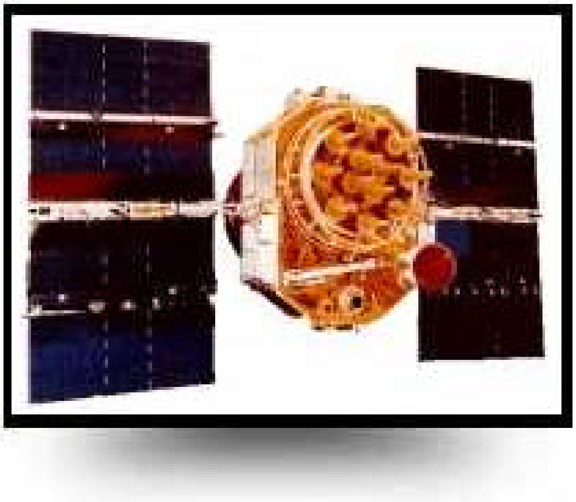

Figure 2-2. NAVSTAR GPS Block IIA Satellite

b. Control segment. The GPS control segment consists of Master Control Stations and six monitoring stations located throughout the world (Figure 2-3). 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.

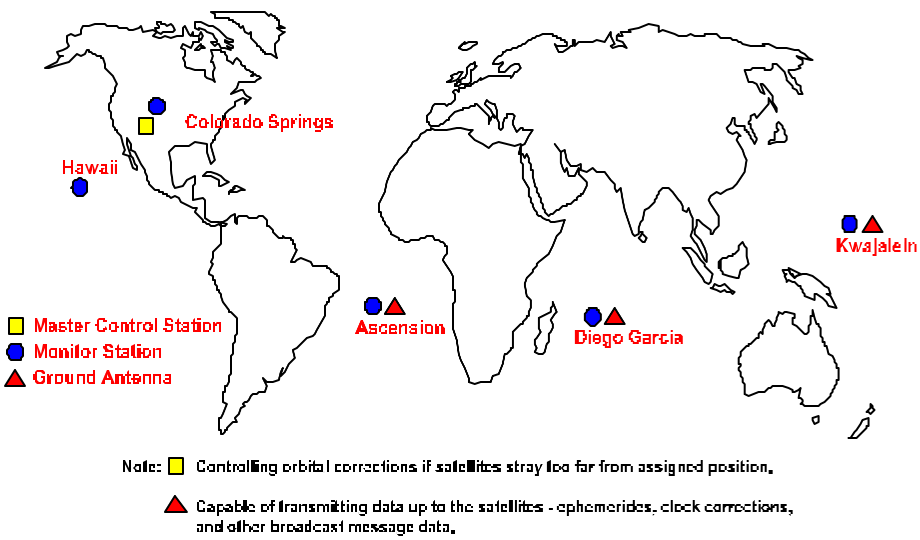

Figure 2-3. GPS Control Station Network (1994)

c. User segment. The user segment represents the ground-based GPS receiver units that process the NAVSTAR 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 2-4.

Figure 2-4. Hand-held GPS receiver (PLGR) for general navigation and positioning (left) and a geodetic quality GPS receiver for precise control surveying (right)

2-5. GPS Broadcast Frequencies and Codes

Each NAVSTAR satellite transmits ranging signals on two L-band frequencies, designated as L1 and L2. 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 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 only the 10.23 MHz P-code. Both codes can be used to determine the range between the user and a satellite. The P-code is normally encrypted and is available only to authorized users. When encrypted, it is termed the Y-code. Table 2-2 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 2-2. NAVSTAR GPS Signal Codes and Carrier Frequencies (Block IIR)

Carrier (L-Band)		Codes: Civilian C/A-Code	Codes: Military P(Y)-Code	Satellite Messages
L1	1575.42 MHz 19 cm wavelength	Present 293 m wavelength	Present 29.3 m wavelength	user messages satellite constants satellite positions
L2	1227.60 MHz 24 cm wavelength	Not Present	Present 29.3 m wavelength	

a. Pseudo-random noise. The modulated C/A-code is 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. 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 C/A-code pulse intervals are approximately every 293 m in range and the more accurate P-code every 29 m--see Table 2-2.

b. Pseudoranges. A pseudorange is the time delay between the satellite clock and the receiver clock, as determined from C/A- 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 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 L2 signal is not used in SPS positioning. 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 frequencies. Phase measurements are resolved over the relatively short L1 and L2 carrier wavelengths (19 cm and 24 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.

2-6. GPS Broadcast Messages and Ephemeris Data

Each NAVSTAR 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 2-3 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.

Table 2-3. 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 (2002) and National Geodetic Survey http://www.ngs.noaa.gov/GPS/GPS.html

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. 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.

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UNCLASSIFIED
GPS OPERATIONAL ADVISORY       281.OA1
SUBJ: GPS STATUS      08 OCT 2002

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, 13, 14, 15
   PLANE   : SLOT F4, B5, C2, D4, B4, C1, C4, A3, A1, E3, D2, F3, F1, D5
   CLOCK   :      CS, CS, CS, RB, CS, CS, RB, RB, CS, CS, RB, RB, RB, CS
   BLOCK II: PRNS 17, 18, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31
   PLANE   : SLOT D3, E4, E1, E2, B1, E5, D1, A2, F2, A4, B3, F5, B2, C3
   CLOCK   :      RB, RB, RB, CS, RB, CS, CS, CS, RB, RB, RB, RB, 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)

2002121       111648Z SEP 2002    22   FCSTMX       261/1100-261/2300
2002122       181306Z SEP 2002    22   FCSTSUMM     261/1123-261/1300
B. ADVISORIES:
NANU          MSG DATE/TIME       PRN  TYPE         SUMMARY (JDAY/ZULU TIME START - STOP)

2002123       251818Z SEP 2002    21   UNUSUFN      268/1830-/
2002124       070107Z OCT 2002    17   UNUSUFN      280/0110-/
C. GENERAL:
NANU          MSG DATE/TIME       PRN  TYPE         SUMMARY (JDAY/ZULU TIME START - STOP)

3. REMARKS:
A. THE POINT OF CONTACT FOR GPS MILITARY OPERATIONAL SUPPORT IS THE GPS
SUPPORT 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
WWW.SCHRIEVER.AF.MIL/GPS OR WWW.PETERSON.AF.MIL/USSPACE/GPS_SUPPORT
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NOTICE ADVISORY TO NAVSTAR USERS (NANU) 2002124 SUBJ: SVN17 (PRN17) UNUSABLE JDAY 280/0110 - UNTIL FURTHER NOTICE
1. NANU NUMBER: 2002124
NANU DTG: 070107Z OCT 2002
NANU Type: UNUSUFN
REFERENCE NANU: N/A
REF NANU DTG: N/A
SVN: 17
PRN: 17
START JDAY: 280
START TIME ZULU: 0110
START CALENDER DATE:Monday, October 07, 2002
STOP JDAY: UFN
STOP TIME ZULU: N/A
STOP CALENDER DATE: N/A
2. CONDITION: GPS SATELLITE SVN17 (PRN17) WILL BE UNUSABLE ON JDAY 280 (07 OCT 2002) BEGINNING 0110 ZULU UNTIL FURTHER NOTICE. 3. POC: CIVILIAN - NAVCEN AT (703)313-5900, HTTP://WWW.NAVCEN.USCG.GOV MILITARY - GPS Support Center, DSN 560-2541, COMM 719-567-6616, GPS@SCHRIEVER.AF.MIL, HTTP://WWW.SCHRIEVER.AF.MIL/GPS

2-8. GPS User Operating and Tracking Modes

There are basically two general operating modes from which GPS-derived positions can be obtained: (1) absolute 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 NAVSTAR 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, 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 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 GPS Positioning Techniques

The most common GPS positioning technique is "absolute positioning." Most commercial hand-held GPS receivers provide absolute (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 positioning services. Two levels of absolute 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. Since May 2000, when this degradation was suspended, horizontal accuracies down to the 10 to 30 m level may be achieved with a quality single frequency receiver. (DoD 2001 reports average global SPS accuracies are $\leq$ 13 m horizontal and $\leq$ 22 m vertical, with worst case accuracies $\leq$ 36 m horizontal and $\leq$ 77 m vertical). 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.

(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 positional accuracies of better than 10 m are attainable through use of the PPS with dual-frequency receivers.

b. Applications. Absolute point positioning is suitable for many USACE surveying applications where 10 to 30 m accuracy levels are acceptable, e.g., rough reconnaissance work, general vessel navigation, wetland delineation, 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 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 GPS positioning techniques.

2-10. Differential or Relative GPS Positioning Techniques

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 NAVSTAR 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. NAVSTAR GPS Modernization Initiatives (2003-2014)

GPS Modernization is a proposed multi-phase effort to be executed over the next 15+ years--refer to Figure 2-5. Full implementation is contingent on funding availability through the program outyears. 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 planned to enhance the ability of GPS to support civil users and provide a new military code. The first new signal will be 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 will be 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. At least one satellite is planned to be operational on orbit with the new C/A on L2 and M-Code capability no later than 2003. Initial operating capability (IOC) (18 satellites on orbit) is planned for 2008 and full operational capability (FOC) (24 satellites on orbit) is planned for 2010. At least one satellite is planned to be operational on orbit with the new L5 capability no later than 2005, with IOC planned for 2012 and FOC planned for 2014. 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 *2001 Federal Radio Navigation Plan* (FRP 2001).

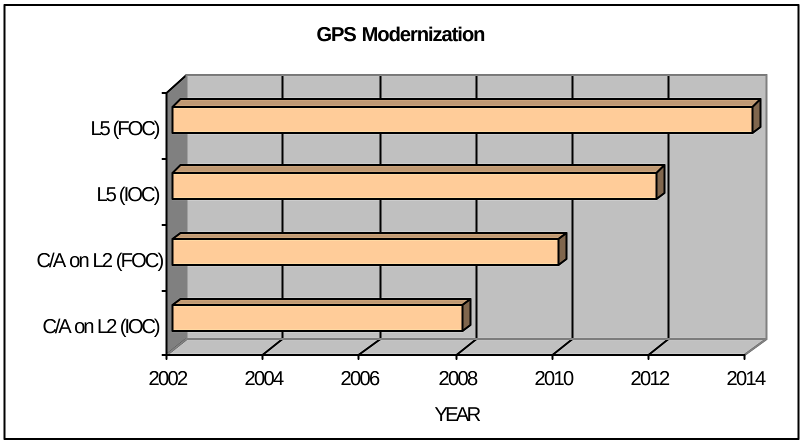

Figure 2-5. GPS Modernization Timelines