

## **NAVSTAR GLOBAL POSITIONING SYSTEM**

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### **SUMMARY**

A brief description of Navstar GPS is given which includes the basic requirements and general principles of the system.

This is followed by more detailed discussion of the satellites and their orbital characteristics and sources of position disturbances. The data message transmitted by the satellites is then described with an assessment of the range error budget. The navigation equation is presented in very simple form. A brief review of the system control arrangements is given, together with satellite geometry. User equipment is briefly considered.

The overall United States programme schedule is presented and an indication of costs is given.

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The Navstar Global Positioning System is a satellite-based, world-wide radio navigation system due to become operational in the late 1980s. The system is intended to satisfy the requirement for continuous global coverage for an unlimited number of passive users and to provide the user with details of his precise position, velocity and time in a world-wide common grid. Spread spectrum L-band signals will give the system jam-resistant capabilities.

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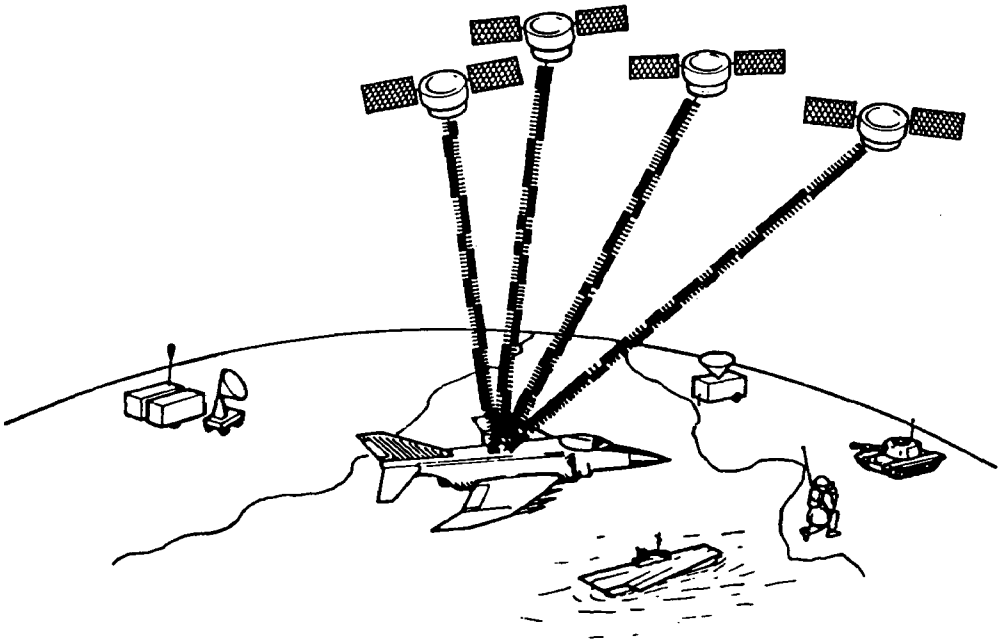


FIG. 1. - A 3-dimensional fix is obtained using signals from four satellites.

Twenty-four satellites will be placed into three, equally-spaced orbital planes; each orbital plane will contain eight satellites, also equally spaced (\*). To obtain a three-dimensional position fix, the user requires signals from four satellites together with the necessary orbital information to compute the satellite positions at the time of the fix (see fig. 1). The signals from each satellite comprise a known, pseudo-random ranging code specific to each satellite which is used to determine the range or, more correctly, the pseudo range of that satellite from the user. All satellites are synchronised to a common GPS time and, with knowledge of the time of transmission and measurement of time of arrival, the range can be calculated.

Using the most accurate signal transmission and parallel signal reception the accuracies obtainable are expected to be within 5 m in the horizontal direction and 9 m in the vertical direction; velocity will be accurate to 0.03 m/s (about 0.06 knots). All figures have a 50 per cent probability.

The satellites themselves will be injected into nominally circular orbits at a height of nearly 11 000 nautical miles. This height will give them a twelve-hour orbital period and is such that the ground track of each satellite will remain fixed. Due to the difference between solar and sidereal time, the Greenwich Mean Time at which a given satellite might be in view from a given point will be

(\*) *Editor's note* : Since this paper was presented, the number of satellites has been reduced from 24 to 18 in total and from 8 to 6 in each orbital plane. The analysis of the system which follows, however, remains valid and is considered to be a particularly clear presentation.

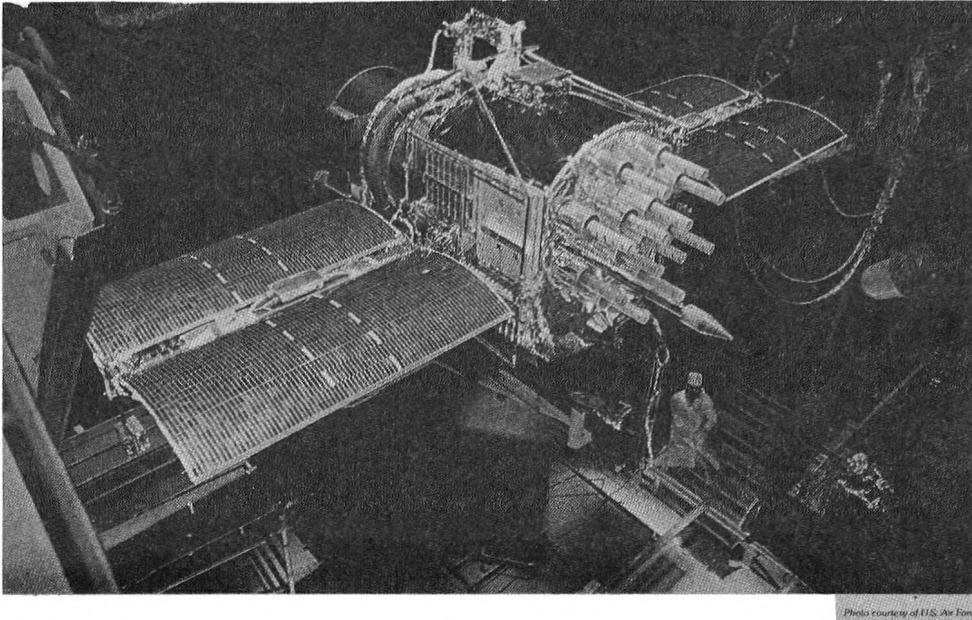


FIG. 2. - The current Navstar satellite.

about four minutes earlier each day. The four Phase I satellites which are currently in orbit for system proving have orbital planes inclined at  $63^\circ$  to the equatorial plane. All the satellites will have station-keeping properties and this will limit their life to between seven and ten years.

Figure 2 illustrates a current Navstar satellite. It shows the deployed solar panels and the beam-forming L-band antenna array, designed to give equal signal strength at the earth's surface, regardless of slant range. The control telemetry antenna is also visible as a conical log spiral. Current plans are to launch GPS satellites from the hold of the space shuttle but the delay in the shuttle programme could mean that early satellites may be launched using a conventional Atlas F rocket.

The satellites will experience various disturbances in their orbits due to the effect of astronomical bodies, gravitational irregularities of the earth and solar radiation pressure. Table 1 shows the relative sizes of these effects in metres per hour. In addition, the polar wobble of the earth has a significant magnitude if the ultimate in accuracy is to be achieved. The GPS signals transmitted down to the user suffer a relativistic frequency shift due to the difference in gravitational potential and relative velocities of satellite and user, giving a timing error of about 39 microseconds per day. This is equivalent to a range error of almost 12 km. All the effects mentioned are compensated for by the control and monitor stations or in frequency standard offsets so that they do not affect the user.

Each Navstar satellite has several clocks to allow for redundancy; the current test satellite uses three rubidium atomic clocks with a crystal clock as the final resort. In due course these will be replaced by caesium clocks and, in the

**Table 1**  
Factors affecting the orbital position of satellites

Factor	Size of effect
Relativistic shifts .....	38.7 $\mu$ s/day
Polar wobble .....	10 m
Second zonal harmonic .....	300 m
Lunar gravity .....	40 m/h
Solar gravity .....	20 m/h
Fourth zonal harmonic .....	0.6 m/h
Solar radiation pressure .....	0.6 m/h
Gravity anomalies .....	0.06 m/h
All other forces .....	0.06 m/h

future, perhaps hydrogen maser clocks will be used. All satellite clocks are nominally synchronised to Navstar GPS time.

The quality or stability of the frequency standards used in the space craft directly affect the user navigation performance. For example, an unmodelled drift of 1 in  $10^{10}$  will result in a time error of 4320 nanoseconds after 12 hours. This is equivalent to a range error of about 1300 m (4320 feet) – by no means an insignificant amount. Adequate clock-modelling and performance are therefore very important as the satellite is not in continuous view by the control and monitor stations and has to rely upon its own clock most of the time.

The user downlink frequencies are the  $L_1$  upper frequency, which is 1575.42 MHz, and the  $L_2$  lower frequency, which is 1227.6 MHz. Signal strength at the earth's surface is around 160 dBW, varying with the code and frequency. A control and telemetry link in the S-band (2 to 4 GHz) is currently used.

The user signals transmitted by the satellites are spread-spectrum signals using two direct sequence codes simultaneously to quadriphase modulate the carrier using a balanced modulator. Codes are specific to each spacecraft. The two types of code are designated P and C/A. The P, or protected, channel is intended for users requiring security and a high degree of anti-jamming protection. It uses a long sequence code, lasting about 267 days, running at 10.23 MHz per bit. In practice, each satellite does not transmit the full 267-day sequence, merely a preselected seven-day segment which it then repeats. The C/A, or clear/acquisition, code is a short code of 1023 bits lasting 1 millisecond with a bandwidth one-tenth of the P code. This code would be used by non-secure users, such as civilian marine, and by security-class users for acquisition. Both the P and C/A codes are transmitted on the upper frequency,  $L_1$ , but only the P code will be transmitted on the  $L_2$  lower frequency. The data message blocks are transmitted on  $L_1$  at 50 Hz and comprise 1500 bits, taking 30 seconds in total. The  $L_2$  frequency may have only the P code and will be used for correcting ionospheric propagation errors.

Various parameters are required by the user receiver to derive the position fix. These are listed in Table 2.

**Table 2**  
Parameters required to derive a position fix

	Number of parameters
Clock model . . . . .	3
$L_1$ - $L_2$ correction . . . . .	1
Age of data (clock) . . . . .	1
Reference GPS time . . . . .	1
Ionospheric correction . . . . .	8
Age of data (ephemeris) . . . . .	1
Orbit parameters . . . . .	15

The spacecraft clock model is required to calculate the true transmission time. The  $L_1$ - $L_2$  correction is required, together with the ionospheric correction model parameters, if the  $L_2$  channel is not available. The age-of-data parameters provide a confidence check to the user on the last update time of the clock and ephemeris data. Fifteen orbital parameters are transmitted to define the satellite position at the reference GPS time.

The 1500-bit data message frame is divided into five subframes, each subframe having ten words of 30 bits. In these ten words, each subframe has a synchronisation-and-telemetry word and a handover word (allowing handover from C/A to P code synchronisation); the remaining eight words are used for the data message. The subframes of the navigation message are used as follows :

- subframe 1 transmits the satellite clock correction, ionospheric modelling and the  $L_1$ - $L_2$  correction parameters.
- subframes 2 and 3 give the satellite's own ephemeris data.
- subframe 4 is used for special messages.
- subframe 5 is used for cyclical transmission of almanac data for up to 25 other spacecraft, covering them one at a time per message frame. These data provide an aid to satellite selection and acquisition by the user.

All the parameters comprising the navigation message are computed on the ground using data from monitor stations and are then uploaded to each satellite

**Table 3**  
Range error budget

Source	UERE 1 sigma (m)
Satellite clock and ephemeris after two hours . . . . .	1.5
Atmospheric delays . . . . .	2.4-5.2
Multipath . . . . .	1.2-2.7
Group delay in satellite equipment . . . . .	1.0
User equipment measurement accuracy . . . . .	1.5
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in turn as it passes over the upload station. The upload data therefore carry future predictions and will degrade with time. A figure of merit, called the User Equivalent Range Error (UERE), is used to describe the way the accuracy degrades. Table 3 attributes the UERE to the various sources. It is of interest to note that, for short periods after the upload, the atmospheric delays and multipath errors predominate. However, for longer times, the satellite ephemeris errors assume increasing importance. The parameters used to describe the orbit are intended to apply over the time interval from one upload to the next.

Figure 3 shows the user position-solution. For a single satellite, the geometry may be represented by three vectors – a satellite position vector,  $D$ , a user position vector,  $P$ , and a range vector,  $R$ . Consider each vector to be resolved into components  $x$ ,  $y$  and  $z$  in the reference GPS frame. The satellite predicted-position is known from the navigation message it transmits to the user. The range magnitude can be measured but requires corrections for propagation and clock effects.

The magnitude,  $R$ , of the pseudo range can therefore be written as shown below using the resolved components for satellite, suffix  $s$ , and user, suffix  $u$ . Propagation and satellite clock effects are calculated from the navigation message parameters or dual frequency reception.

$$R = [(x_s - x_u)^2 + (y_s - y_u)^2 + (z_s - z_u)^2]^{1/2} + c\Delta t_a + c(\Delta t_u - \Delta t_s)$$

where

$c$  is the speed of light

$x$ ,  $y$  and  $z$  are resolved components of  $R$  and  $D$

$\Delta t_a$  is the propagation delay

$\Delta t_u$  is the user clock delay

$\Delta t_s$  is the satellite clock delay.

The user therefore must determine three user-position vector components and a user-time error and to solve the four unknowns it is necessary to use four satellites to provide sufficient information. Filtering or smoothing of the range

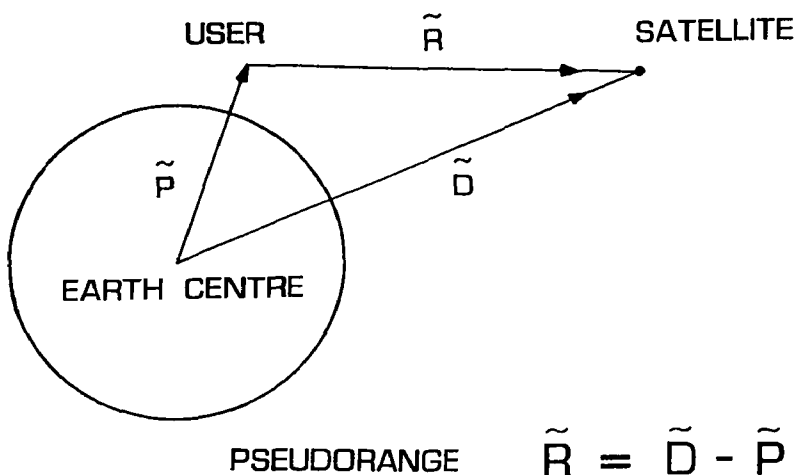


FIG. 3. - Position vector diagram.

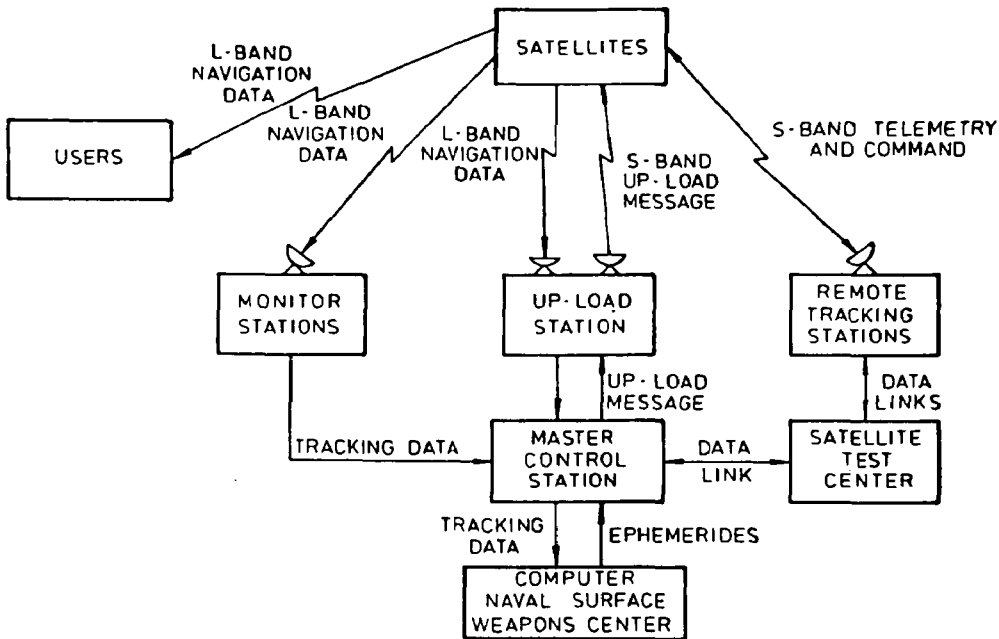


FIG. 4. - Navstar global positioning system.

information is an obvious advantage but will not be discussed here. Velocity information can be derived from doppler or range rates measured.

The overall system can be regarded as having three segments namely SPACE, USER and CONTROL. The space and user segments have already been briefly considered. The control segment is shown more fully in Fig. 4. The prime function of the control segment is to provide precise navigation data for the user. To do this, it must provide  $x_s$ ,  $y_s$ ,  $z_s$  and  $\Delta t_s$  and sufficient information to allow the user to estimate  $\Delta t_a$ .

Monitor and tracking stations situated in Guam, Alaska, Hawaii and California pass information to the Master Control Station. The tracking information, in turn, is passed to the computer at the Naval Surface Weapons Centre for calculation of ephemeris parameters. The parameters are then uploaded when the satellite is in view. Satellite status information and command control telemetry links are also used.

For the full GPS system, the number of satellites above the horizon will be between six and ten, depending upon the user position and time of day (\*). Selection of the satellites to be used will depend greatly upon their relative positions. In simple terms, the angle of cut of the range vectors will affect the quality of the fix. Generally, the best fix is obtained by maximising the volume of the tetrahedron formed by the four satellites and the user.

A figure of merit termed Geometric Dilution of Precision, GDOP, is used to describe the degradation of range error for a given configuration; it includes the

(\*) *Editor's note* : Now between 4 and 8.

variances of distance and time. If, for example, the GDOP figure averages around 2.5, a UERE of 5 m would give a position error of 12.5 m standard deviation.

To receive transmissions from four satellites, the receiver can be either a multi-channel set or a single-channel set using a sequential technique. For uses such as in high dynamic aircraft, a multi-channel, inertially-aided receiver is the optimum. For a ship, transport aircraft or land vehicle, a single channel sequential receiver might be sufficient. A trade-off between receiver complexity and user requirements is needed.

Full-scale development of the user equipment is now under way – contracts going to Magnavox and to Rockwell Collins. At present, four satellites are being used for system proving; this number is expected to increase to five or six shortly. The final Phase III spacecraft is currently in the prototype stage and is due to begin launch in 1984 to meet the 1986 date for system availability. The third and final Defence System Acquisition Review Committee decisions for the satellites and user equipments are scheduled for 1981 and 1983 respectively. The Navstar Control Centre is due to become operational in 1986.

The approximate cost of the Navstar system to the United States is :

space	: US \$ 1000 M
control	: US \$ 180 M
user	: US \$ 1500 M

The total number of user sets of different types is expected to amount to more than 30 000.

Finally, it is perhaps worth reflecting that the everyday marine user of the Navstar system, given its promised accuracy, will have to grapple with problems such as reference datums. These have been familiar ground to the surveying fraternity for many years and it is interesting to speculate on what the surveyor is going to do in order to keep one step ahead!