International Hydrographic Review, Monaco, LXI (2), July 1984

PRINCIPLES AND PRESENT STATUS OF NAVSTAR GPS

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This paper was presented at an Ordinary Meeting of the Royal Institute of Navigation held in London on 16 February 1983. It was also published in the September 1983 issue (Vol. 36, No. 3) of The Journal of Navigation *and is reproduced here with the kind permission of the Royal Institute of Navigation, U.K., and the Procurement Executive, Ministry of Defence, Royal Aircraft Establishment, Farnborough, Hants, U.K. (the original is subject to British Crown copyright).*

1. INTRODUCTION

The Navstar Global Positioning System (GPS) is a satellite-based passive radio-navigation system under development by the U.S. Department of Defense (DOD) and due for operational deployment in the late 1980s. Each satellite carries an atomic frequency standard and transmits L-band spread-spectrum signals whose carrier frequencies and code epochs are synchronized with the satellite clocks. A suitably equipped user may measure the arrival time and frequency of the signals from at least four satellites to obtain accurate three-dimensional position and velocity information and, as a by-product, an accurate 'system' time.

The Navstar system was intended to comprise 24 satellites in circular inclined orbits, which would have provided continuous global coverage with more than six satellites in view at any one location. However, pressure to reduce the overall system cost has forced the DOD to develop a restructured programme. As a result the system is now planned to become operational in 1988 with an 18-satellite constellation. The reduction in the number of satellites is a significant departure from earlier plans and causes a reduction in system capability. Even so, Navstar should still be able to provide high accuracy in a world-wide common grid for long periods, and should still be much more accurate than any other externally referenced navigation aid currently available.

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2. EVOLUTION

Navstar was authorized for development by DOD in December 1973. It is a multi-service programme, the USAF being the executive agency with the Joint Program Office located at HQ Space Division (AFSC), Los Angeles.

Phase I of the GPS programme extended from December 1973 to June 1979 and was intended to validate the system concept, to identify preferred designs of user equipment, to define system costs and to demonstrate the military value of the system. During this phase eight satellites were procured; Navstar satellites 1 to 4 were launched into two orbit planes and provided suitable geometry for system testing over limited periods at certain geographic locations.

In June 1979 the Defense Systems Acquisition Review Council (DSARC II) reviewed the results of concept validation undertaken during Phase I. Based on this review and recommendations by the DSARC, the US Secretary of Defense approved transition into full-scale engineering development (Phase II) on 24 August 1979. The programme plan recommended to the DSARC was to provide an initial operational capability with 18 satellites by 1986. This capability was to be expanded to the full 24-satellite system by 1987. As already noted, however, pressure to reduce the overall system cost has forced DOD to develop a restructured programme which will limit the operational system to 18 satellites, although this is stated not to preclude expansion to 24 satellites at a later date.

Navstar 5 and 6 were launched in 1980, while Navstar 7 was lost in December 1981 due to a launch vehicle failure. During Phase II, which is currently scheduled to extend until May 1984, three replenishment spacecraft are being procured and will be launched to maintain a 5-satellite constellation to support development and initial operational test and evaluation. A block buy of 28 satellites for the operational system was authorized recently.

3. SYSTEM DESCRIPTION

The Navstar system can be divided into three parts which are usually referred to as the control segment, the space segment and the user segment. The control segment [1] comprises a Master Control Station (MCS) and a Ground Control Station (GCS), both situated at Vandenberg AFB, and a number of widely separated Monitor Stations (MS). At present there are four MS, located at Guam, Alaska, Hawaii and Vandenberg, but additional MS are expected to be installed as the system becomes operational. Each MS is equipped with a Navstar receiver, augmented by a caesium clock, and an antenna providing upper hemisphere coverage, and each one passively tracks all satellites in view to obtain one-way range observations from the navigation signals. The observations are combined with environmental data and transmitted to the MCS, where they are processed and used for orbit determination and for estimation of clock biases. The resulting orbit is used to generate an ephemeris, represented by a modified set of Keplerian elements. The MCS maintains GPS system time with a set of caesium clocks, and is capable of adjusting the time phase and frequency of the satellite clocks, if required. The GCS transmits to each satellite once per day an up-load message consisting of ephemerides, clock drifts and propagation delay data supplied by the MCS. These data are loaded into the satellite's memory, to replace the previous information, and modulated on to the navigation signals radiated by each satellite, as explained later.

When the system becomes operational in 1988, 18 satellites will be deployed in 12-hour circular orbits at a height of 20,183 km and inclined at 55° to the equator. The selected constellation will have 3 satellites evenly spaced in each of 6 planes with 40° phase differences between the planes. This pattern provides a minimum of 4 satellites visible at elevations above about 9.5° and 5 satellites almost always visible above the horizon [2].

The operational satellites will have a design life of 7.5 years. Electrical power is provided by two single-degree-of-freedom solar arrays, which are backed up by nickel-cadmium batteries for eclipse operations. When on-station, the satellites operate in an Earth-pointing, 3-axis stabilized mode. The navigation antenna is a shaped-beam array of 12 helical elements, which is used to transmit continuously two right-hand circular polarised navigation signals.

4. NAVIGATION SIGNALS [3]

The signal generation process is illustrated in Fig. 1. The basic reference frequency is 10.23 MHz, which is derived from the atomic standard and drives the clock and code generators. The P (precision) code is a fast (10.23 MHz) long-period pseudo-random binary sequence, which provides an accurate range and time measurement capability; each satellite is assigned a unique code, which is reset every Saturday midnight GMT. Additionally, each satellite is assigned a shorter code at a chip rate of 1.023 MHz to assist acquisition of the P signal and also to provide a lower ranging accuracy. This C/A (coarse/acquisition) code has a length of 1023 bits and a period of 1 ms. The C/A code epochs are used to provide a 50 Hz clock for the 1500-bit navigation message transmitted by each satellite. This message [4] provides information on system status, system time, ionospheric data, and accurate orbital data for the particular satellite. An almanac of nominal orbits is also provided.

The data format is illustrated in Fig. 2. Each 1500-bit frame is divided into 5 subframes of 300 bits, which are further subdivided into ten 30-bit words. Each word comprises 24 information bits and 6 parity bits.

The first word of each subframe is a synchronization/telemetry (TLM) word, and comprises a fixed 8-bit preamble for synchronization, followed by information on the message status. The second word of each subframe is a handover word (HOW) which gives system time in terms of the number of 1.5 s units since the start of the week (the Z count). Users with a P-code generator may use the Z count to determine the approximate phase of the P-code, and may then measure range and

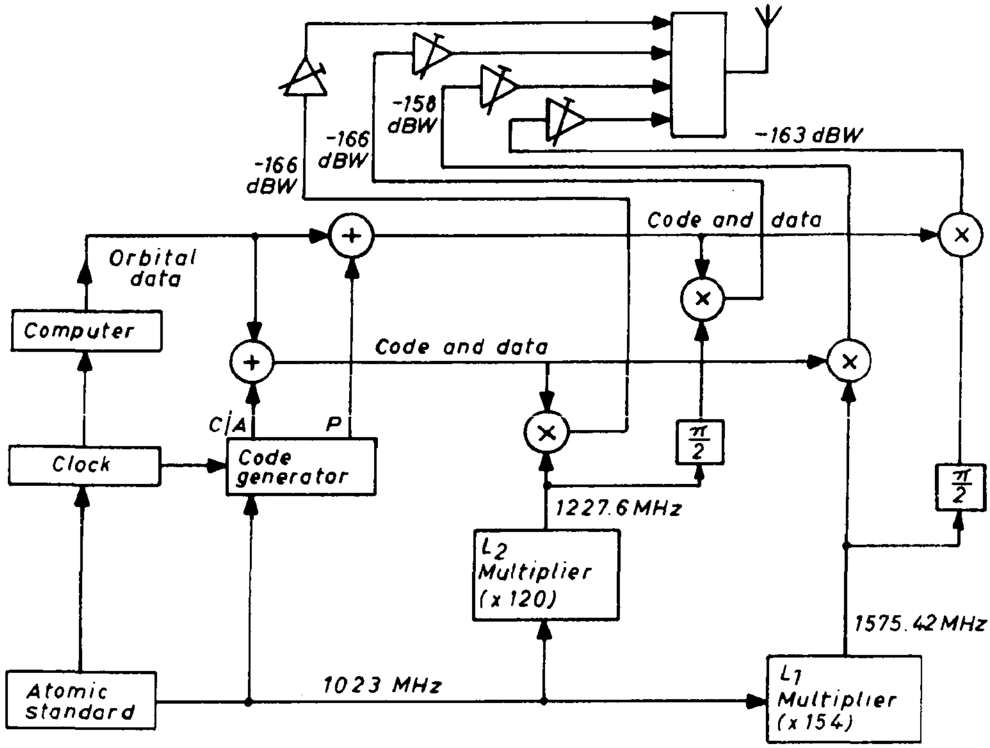

FIG. 1. — Schematic satellite signal generation.

time to better than one P-code chip length (97.75 ns) by correlation with the received satellite P signal. Other users may use the Z count in conjunction with the data bit transitions and the 1 ms C/A code epochs to determine system time to within 1 ms. Greater precision, to within one C/A-code chip length (977.5 ns) is then obtainable by correlation with the received satellite C/A signal.

The data structure for Phase I will now be described. The remaining eight words in the first subframe convey data which include ionospheric coefficients, the satellite delay calibration and the time correction coefficients. The second and third subframes contain the ephemeris data. The fourth subframe is for special messages, providing space for 192 bits every 30 s. Larger messages can be transmitted by cycling pages of 192 bits. The fifth subframe contains cyclically one page of a 25-page almanac, which provides 25 sets of Kepler elements to assist in the selection of other satellites and the acquisition of their signals. The Phase III navigation message has the same basic structure, but there will be differences in detail in individual subframes.

Each satellite transmits two coherent L-band carriers, L_1 at 1575.42 MHz and L_2 at 1227.60 MHz. The P and C/A codes are modulo-2 added to the navigation message and biphase modulated, in quadrature, on each carrier to give a spread-spectrum signal. A variety of modes of operation is possible, but the normal mode is to transmit C/A and P signals on L_1 and P only on L_2. Use of both frequencies

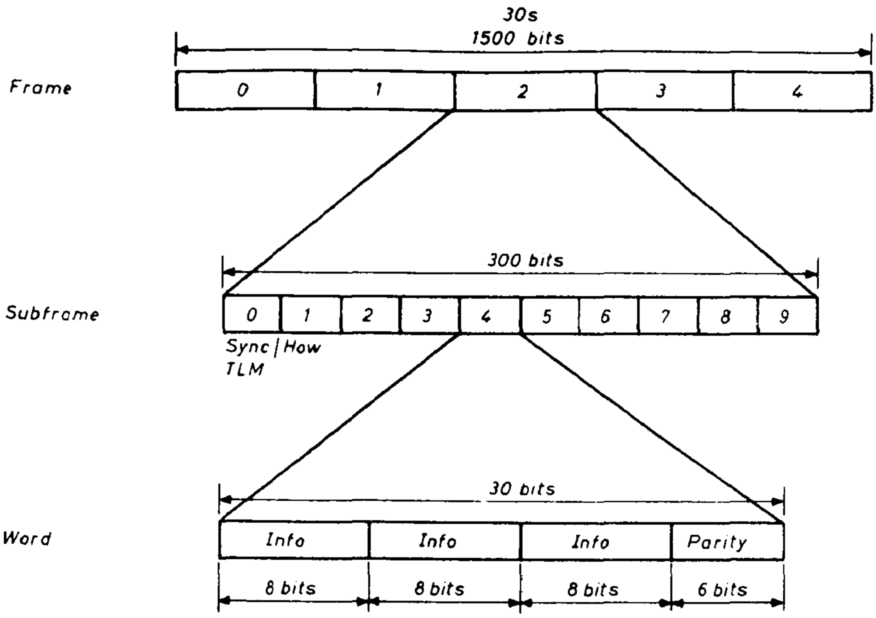

FIG. 2. — Navigation message format.

enables corrections to be made for the ionospheric propagation delay. The satellite signal powers expected from a 0 dB receiving antenna on the Earth are shown in Fig. 1.

5. RECEIVER DESIGN

A Navstar receiver (Fig. 3) has to perform a number of functions. Initially the processor must determine the set of four satellites which will provide the most accurate position fix. Then, for each satellite, it must select the appropriate L-band signal frequency from the synthesizer and acquire and maintain synchronism with the received C/A or P code using a code tracking loop, while a phase-lock loop is used to track the carrier frequency. The latter must cater for frequency shifts occasioned by vehicle motion. Next, the arrival times and Doppler frequency shift of the signals from a number of satellites must be accurately measured, either simultaneously using separate tracking loops for each satellite, or sequentially and repetitively, using the same circuitry for each satellite. The latter approach would be suitable for a relatively slow-moving vehicle.

At the next level, the receiver must provide facilities to demodulate the satellite navigation messages, to format them into subframes, and to assemble complete messages, correcting them using inbuilt parity checks.

Once the satellite ephemerides have been decoded, and the signal timings determined, the next stage is to compute the satellite positions and velocities using

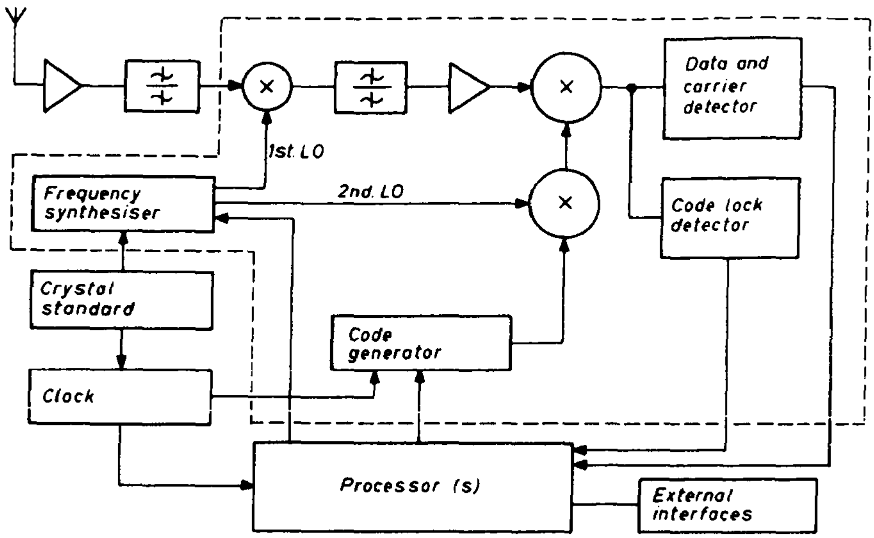

FIG. 3. — Typical Navstar receiver.

the coefficient from the navigation messages. Finally, the satellite positions and velocities and the measured arrival times and Doppler shift must be combined to yield the user's position and velocity, and the biases in the time and frequency of his clock. Times of arrival from four satellites are required to solve for three position coordinates and the receiver clock error. Direct solution (by iteration) of the range equations is possible, but more often a linearized model is used which is accurate in a region about an assumed user position. Linearizing the model also provides the opportunity to use stochastic filtering methods (Kalman or otherwise) to weight the individual measurements and so derive a best estimate of position. The receiver must also provide facilities for displaying the results of the fixes, accepting user inputs and calculating signal frequencies and code phases prior to acquisition. Additionally, the receiver may be required to incorporate inputs from other navigation sensors.

The wide variety of functions needed in the receiver permits many possible approaches to the design. The number and complexity of the mathematical operations to be performed requires at least the flexibility and performance of a general-purpose microprocessor. Depending upon the precision and frequency with which fixes are required, it may be necessary to use a fast minicomputer. Other receiver functions, such as code and carrier tracking, acquisition, etc., may be implemented by analog or digital techniques.

A range of receiver performances are possible. To provide a high-performance aircraft with good accuracy, particularly in the presence of interference, it is necessary to track four satellites simultaneously, so that four receiver channels are required. A fifth channel is required to track L_2 signals so that ionospheric corrections can be made and to acquire new satellites. At the other end of the range, a civil marine user could probably obtain adequate performance from a single-channel receiver making measurements sequentially using only the C/A code. An important parameter is the time to first fix, which can vary from tens of seconds to several minutes depending on the sophistication of the receiver.

The performance of Navstar user equipment aboard a vehicle will depend critically on the quality of the antenna design and installation. Take a medium-performance aircraft as an example. All-round cover could be provided using two elements on the fuselage. Quadrature semi-disc patches provide a wider azimuth plane beamwidth and a narrower elevation plane beamwidth than a single disc and can meet the roll-plane coverage requirements when mounted on each shoulder of the fuselage. RAE (Royal Aircraft Establishment) is experimenting at present with an alternative form of element for top mounting to provide better low-angle coverage than the current disc-type element. Where high performance is required, particularly when interfering sources are present, an adaptive antenna system may be used.

6. SYSTEM ACCURACY

The accuracy of a position fix depends on the magnitude of the ranging errors and the geometry of the selected satellites. The most suitable index of performance for a satellite navigation system is the geometrical dilution of precision (GDOP), defined as the ratio of the square root of the trace of the position covariance matrix to the pseudo-range standard deviation σ_p. Using a local coordinate frame with the x-axis pointing east, the y-axis north and the z-axis vertically upwards, we may define the following performance indexes for the dilution of precision :

a) Geometrical

$$\mathrm{GDOP} = (\sigma_x^2 + \sigma_y^2 + \sigma_z^2 + c^2\,\sigma_t^2)^{\frac{1}{2}}/\sigma_p$$

c being the velocity of light and σ_i the standard deviations of the position components and time;

b) Position

$$\mathrm{PDOP} = (\sigma_x^2 + \sigma_y^2 + \sigma_z^2)^{\frac{1}{2}}/\sigma_p$$

The value of σ_p is expected to be of order 7 m for the precision code user, being obtained as the root-sum square of errors due to satellite clock and navigation subsystem stability, ephemeris and clock prediction, ionospheric and tropospheric delay compensation, receiver noise and quantization, and multipath.

For the 18-satellite constellation elected [5], there is a probability of 0.995 that PDOP $\leqslant$ 6.0, which corresponds to a three-dimensional position error of 42 m r.m.s. This value was computed by sampling points uniformly distributed on the Earth over a 24-hour period. Another measure of performance is the spherical error probable (SEP). This has values of about 15, 17 and 22 m for elevation limits of 5°, 10° and 15°. There are small areas where a user relying solely on Navstar will experience short periods of poor satellite geometry; during these periods, PDOP normally only exceeds 6 for about 10 min, although the time can be as long as 30 min.

7. RECEIVER INTEGRATION WITH OTHER SENSORS

For some applications, for example the high-performance military aircraft, the combination of Navstar and a dead-reckoning system offers particular advantages. For example, due to their complementary features, Navstar and an INS are ideal sensors for an integrated navigation system. An INS can provide accurate information on short-term vehicle motion and its velocity outputs may be used to rate-aid the code and carrier-tracking loops of the receiver. This allows very narrow tracking-loop bandwidths to be used, so that the receiver can continue to operate at low signal-to-noise ratios and provide a higher level of AJ protection. On the other hand, under conditions of gentle motion and good signal-to-noise ratio the Navstar receiver can provide position and velocity, or possibly pseudo-range and range-rate measurements, to assist in alignment and calibration of the INS. The errors in an INS produce a long-term drift, which may readily be estimated using frequent measurements from a Navstar receiver. The result is that the navigation performance of the integrated system is considerably better than either system alone. When the signal-to-noise ratio is so low that tracking of one or more of the satellite signals is lost, the calibrated INS can provide accurate navigation. When the signals improve, so that tracking can be resumed, the INS provides position and velocity information to enable rapid re-acquisition.

The navigation filter of an unaided Navstar receiver must model vehicle motion. This means that, for a highly manœuvrable aircraft, new measurements must be included very frequently, at a rate of order 5 Hz, if any semblance of accuracy is to be achieved.

Significantly better navigation accuracy can be obtained by supplying time-tagged pseudo-range and range-rate measurements, IMU (Inertial Measurement Unit) output and other sensor data to an integrated navigation filter, as shown in Fig. 4. This filter would be of fairly high order and provide optimal estimates for a combined set of error parameters. The actual number of error states included in the filter would depend upon the processing power available and the required update rate (which is closely related to accuracy). As an example, a set of error parameters [6] suitable for a 16-state filter would be three positions, three velocities, clock error, frequency offset, altimeter bias, altimeter scale factor, three misalignments of the inertial reference frame and three gyro drift rates. These estimates can be made at a relatively low rate and used to supply infrequent updates to the INS navigation processor. The latter would provide frequent estimates of position and velocity using information from the IMU. Since the IMU errors grow only slowly, the cycle time of the Navstar/IMU filter can be much longer than that for the filter of an unaided receiver while still providing much greater accuracy, particularly in velocity. Simulations suggest that, for an update rate of 1 Hz and 11 states, IN-aiding can reduce the position error by a factor of about 2 and the velocity error by over an order of magnitude.

The integrated system's navigation filter could be implemented in the navigation processor of either the Navstar receiver or the INS. Alternatively, all navigation computations could be performed in a single processor. In the interest

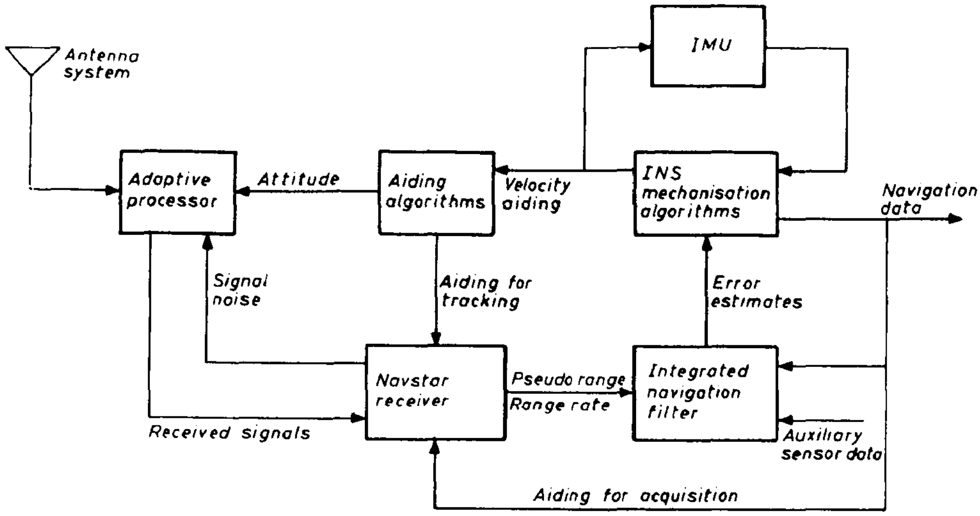

FIG. 4. — Integrated navigation system (Navstar/INS).

of reliability and to provide reversionary modes, there is a strong case for distributed processing, with multiple filters taking inputs from a subset of sensors, so that any navigation system aboard the vehicle may operate in a stand-alone mode if necessary.

8. PRESENT STATUS

Phase I testing of Navstar GPS confirmed that the system has the potential to provide a highly accurate navigation system and thereby to improve certain weapon delivery and coordinated operations. Numerous test missions conducted at the U.S. Army Yuma Proving Ground off the Californian coast using a variety of vehicles have demonstrated position errors of the order of 15 m SEP (Standard Error Position), while velocities have been measured to within 0.12 m/s, provided that GDOP was within the range expected from the system as originally planned.

On the present programme plan, the operational satellites are scheduled for launch so that the full 18-satellite constellation will have been deployed by 1988, when accurate three-dimensional position should be available continuously to users equipped to receive the precision code (the so-called Precise Positioning Service or PPS). It is claimed that the PPS will provide position accuracies of 18.1 m (2 d.r.m.s.) horizontally and 29.7 m (2 s.d.) vertically and relative accuracies of 10 m (2 d.r.m.s. [root mean square error]) horizontally and 16.4 m (2 s.d. [standard deviation]) vertically. It is expected that a two-dimensional capability will be available some 12 to 18 months before full deployment.

The objective of the programme is to provide precise positions to military users. However, it is U.S. Government policy to make Navstar available on an international basis for civil and commercial use, but only at the highest level of accuracy consistent with national security interests, due to the system's possible benefit to potential adversaries. At present, it is projected that a predictable and repeatable position accuracy of 500 m (2 d.r.m.s.) horizontally and 820 m (2 s.d.) vertically will be made available from the C/A code (Standard Positioning Service or SPS) during the first full year of operation, with possible accuracy improvements as time passes. These statements are based on the second edition of the U.S. Federal Radionavigation Plan issued [7] by DOD and DOT in March 1982. It is possible that pressure from manufacturers and potential users will cause some easing of the restrictions on accuracy.

Another significant issue is that Congress has directed DOD "to develop a comprehensive plan for recouping from other Federal government and civil users as much of the development, acquisition and operating costs of the Navstar system as is deemed feasible". The method of cost recovery and the level of user charges have not been finalized, but are the subject of an on-going DOD study.

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