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COMPUTER SIMULATION AND THE PERFORMANCE CAPABILITIES OF THE NAVSTAR SPACE-BASED NAVIGATION SYSTEM

by

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ABSTRACT

Six Navstar navigation satellites are presently traveling through space 10,898 nautical miles above the earth. By 1987, the operational constellation, which will consist of at least 18 larger and more advanced satellites, will be providing continuous navigation coverage to a worldwide class of civilian and military users. The Navstar satellite constellation will yield routine accuracies nearly 20 times better than any other global navigation system. This paper explores some of the computer modeling methods used by the Navstar system itself and by researchers who have been simulating the military and civilian benefits to be derived from its use.

1. INTRODUCTION

The Navstar Global Positioning System (GPS) is a satellite-based radio navigation system that uses dual frequency L-band transmissions to provide continuous global navigation coverage to an unlimited number of users who are equipped with one of several user sets capable of processing the signals broadcast by the satellites.

The satellites, which are being launched into 12-hour, 10,898-nautical-mile orbits, are designed for military use, but their signals are also available to suitably equipped civilian users. Six Block I satellites are presently in orbit. They provide global (but intermittent) three-dimensional navigation coverage ranging from 1 to 4 hours per day, depending on the user's geographic location. Five additional Block I satellites will be launched into orbit by 1983. Thereafter, the Block II launches will begin. By late 1987, a full constellation consisting of at least 18 Block II satellites is scheduled to be in place. These satellites will provide continuous 24-hour, worldwide coverage, with an average accuracy of at least 50 feet. Extremely precise on-board clocks (which gain or lose only about one second every 36,000 years) and specially designed software routines have made possible this unprecedented accuracy in global navigation.

2. NAVIGATION PROCEDURES

The Navstar GPS is a radio navigation system that uses triangulation procedures in which baselines are established by picking up precisely timed pulses broadcast by radio transmitters at known locations. Fig. 1 illustrates how a simple radio navigation system could be used to establish the longitude and latitude of any properly equipped ship. The two transmitters send out precisely tuned pulses that are intercepted by the radio receiver on board the ship, which is equipped with a clock in accurate synchronization with the transmitters' clocks. The navigator on the ship establishes the distance to each transmitter by subtracting the arrival time of each pulse from the time it was transmitted. The range of each transmitter then equals the signal travel time multiplied by the speed of light (about 186,000 miles a second). He can then determine his location by drawing two circles of radii R_1 and R_2 on his nautical charts. As Fig. 1 shows, the ship lies at one of the two intersections of these two circular arcs.

Theoretically, the timing pulses from three transmitters could establish the user's position at the intersection of three spheres of radii R_1, R_2, and R_3 in a three-dimensional analogy of the procedure just described. However, this approach would require an extremely accurate user-set

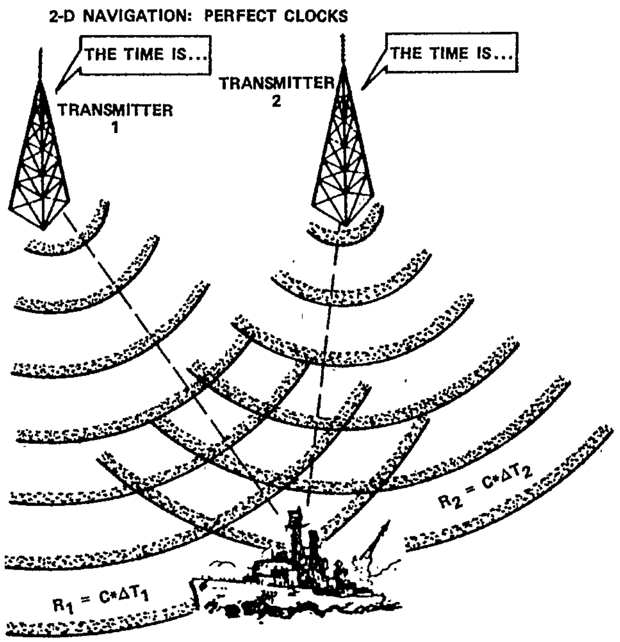


Fig. 1 Electronic Navigation

clock synchronized precisely with the clocks located at the transmitters. Such an approach would be expensive and difficult to implement. Instead, the GPS user sets are equipped with small, inexpensive quartz crystal oscillators roughly 10,000 times less stable than the atomic clocks carried by the satellites. The user sets pick up signals from four satellites rather than only three to achieve three-dimensional navigation capabilities. The extra signal is used to eliminate the effect of any timing errors in the user sets' crystal oscillators. Fig. 2 presents the four GPS navigation equations that are solved iteratively to obtain the three user position coordinates U_x, U_y, and U_z, and the clock error C_B.

The method employed by a user set in establishing the signal travel time t is outlined in Fig. 3. Basically, the satellite transmits a prearranged pseudorandom pulse train consisting of a string of binary 1's and 0's, which is duplicated in real time by the user set electronics. An automatic feedback control loop then brings the two pseudorandom sequences into correspondence via the autocorrelation function:

$$\text{Autocorrelation} = \frac{1}{N}\int_0^N S(t) \times S(t+j)\,dt,$$

where $S(t)$ is the amplitude of the signal at time t, and $S(t+j)$ is its amplitude j seconds later. Since the prearranged sequence of pulses is pseudorandom, the autocorrelation function yields a value close to zero for all values of j except when there is an exact correspondence between the two binary sequences. When this correspondence has been achieved, the value of the autocorrelation function immediately jumps to 1.

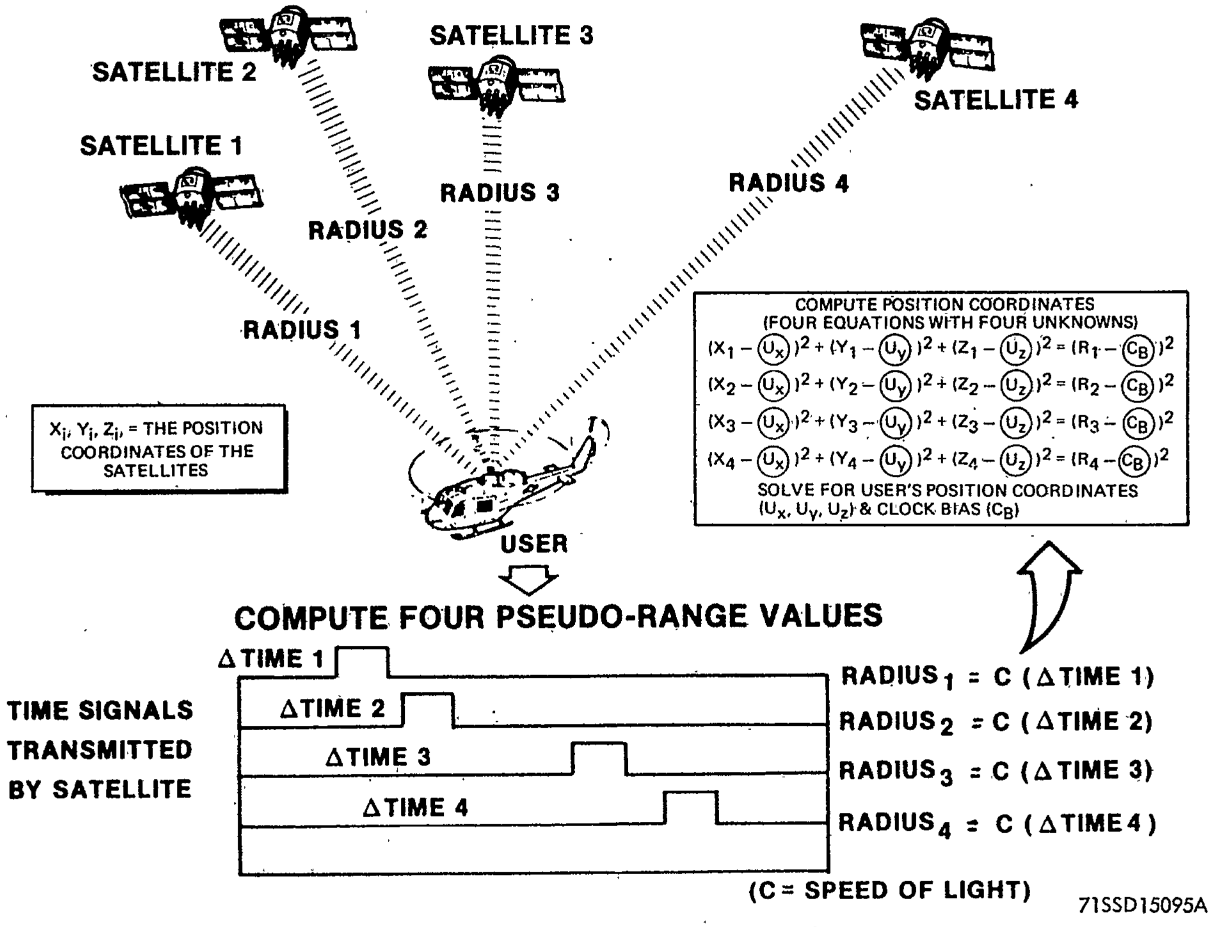


Fig. 2 Navigating With the GPS.

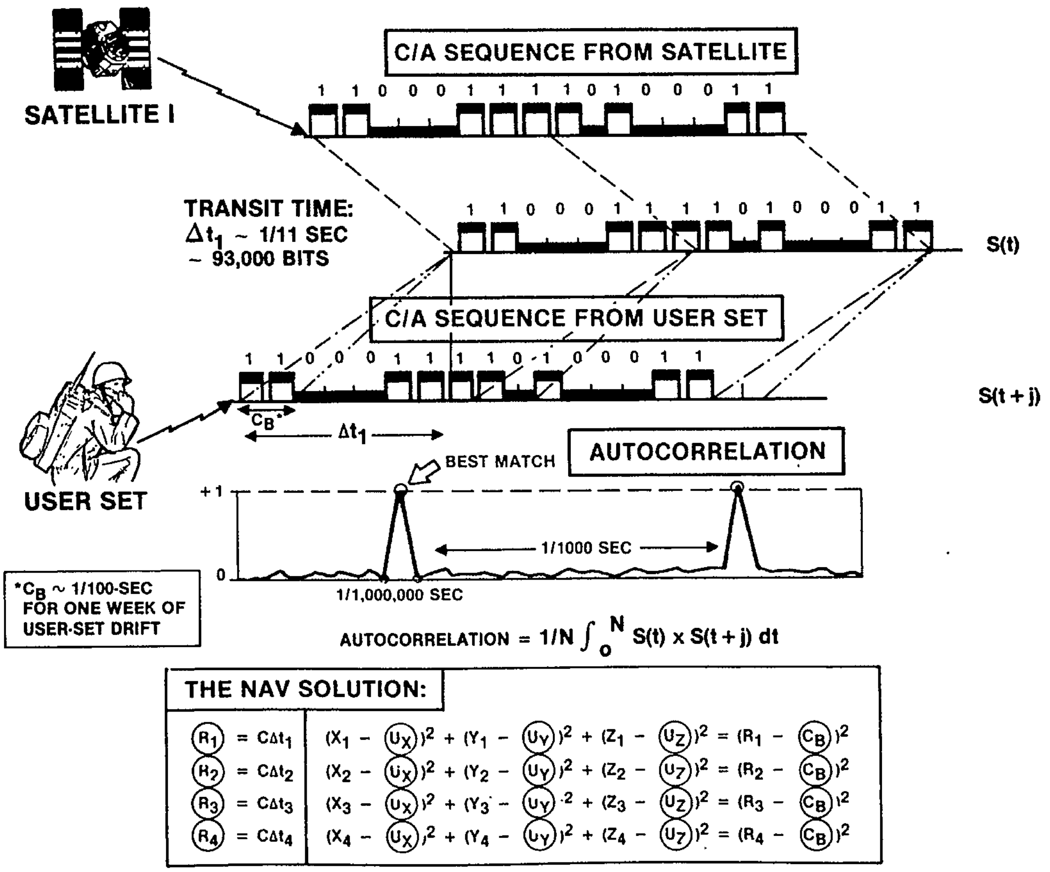


Fig. 3 Acquiring the C/A Signal

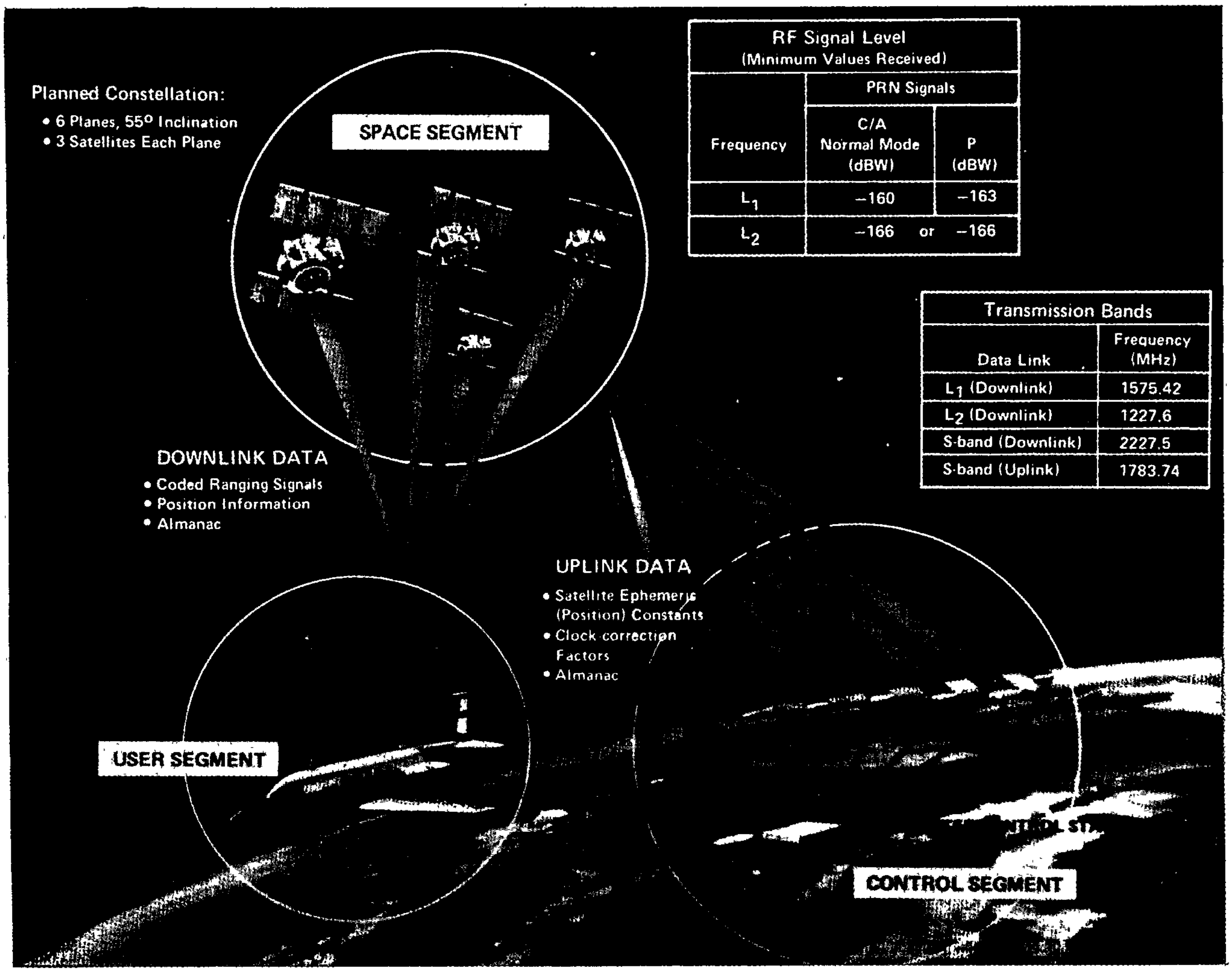
If no background information about the geometry of situation is available, the time shift j needed to bring the two pseudorandom sequences into correspondence equals the signal travel time (about 1/11 of a second) plus the clock bias factor C_B, which is typically on the order of 1/100 of a second or less. Actually, background information is available, and much less searching is required.

The signal acquisition methods just described hold only for the simple, inexpensive user sets. The more sophisticated units follow more precise and elaborate procedures. First, they lock onto the so-called C/A (Clear Acquisition) signal, as described. Then they decode the message it contains to find a timing key that allows them to lock onto another pseudorandom sequence called the P-code (Precision Code). The chipping rate of the P-code (10 million bits per second) is ten times higher than that of the C/A code, and hence navigation sets using the P-code are more accurate and jam-resistant.

In addition to the three-dimensional position coordinates, the GPS user sets also provide velocity components in three dimensions with an average accuracy of about 0.3 feet a second. The users' three velocity components U_x, U_y, and U_z are determined in a manner that is conceptually similar to the procedure used to determine the position coordinates U_x, U_y, and U_z. The satellites transmit their signals superimposed upon two carrier waves that have oscillation rates of 1575.42 and 1227.6 megahertz (million oscillations per second). The user sets generate duplicate carrier waves and match them with the waves arriving from the satellite. They then count beats to determine the frequency difference $\Delta \phi$ between the carrier and satellite waves. Most of the frequency difference arises from the fact that the user sets and the satellites are moving with respect to one another. This creates an effect known as the "Doppler shift," a systematic variation in frequency similar to the one that is observed when the whistle of a moving locomotive is heard by a waiting passenger standing beside the tracks.

In order to maintain the full accuracy of the GPS, the satellites will be updated at least once per day. These updates, determined by the Control Segment, will provide fresh and accurate clock correction factors, satellite ephemeris constants (orbital elements), and information on the current status of the earth's ionosphere.

Four monitor stations at widely separated locations (see Fig. 4) pick up the pseudorandom signals from the satellites one by one. These measurements are then transmitted via communication links to the Master Control Station, where they are filtered and computer-processed to establish the orbital elements of the satellites and their current clock errors. The results of these rather elaborate computer modeling procedures are transmitted to each satellite at least once per day.



RF Signal Level (Minimum Values Received)

Frequency	PRN Signals C/A Normal Mode (dBW)	PRN Signals P (dBW)
L_1	−160	−163
L_2	−166 or	−166

Transmission Bands

Data Link	Frequency (MHz)
L_1 (Downlink)	1575.42
L_2 (Downlink)	1227.6
S-band (Downlink)	2227.5
S-band (Uplink)	1783.74

Fig. 4 The Major Segments of the GPS System

Additional corrections to the navigation algorithms must be made because the propagation speed of a radio signal changes when it passes through the earth's ionosphere and troposphere. Less accurate user sets make use of mathematical models to eliminate both ionospheric and tropospheric effects. High-accuracy sets model the troposphere but process the dual frequency L-band transmissions from the satellites to eliminate the ionospheric effects. This is possible because the propagation velocity of a radio signal passing through the ionosphere is inversely proportional to the square of its frequency.

Corrections are also made for relativistic effects in accordance with Einstein's special and general theories of relativity. The observed chipping rates of a satellite clock and a user set clock are slightly different because of the relative motion between them and because the user set clock is affected by stronger gravity than is experienced by the clocks on board the satellites. These effects are reduced dramatically by complex mathematical modeling procedures.

Additional refinements include the use of Kalman filtering in both the Master Control Station and in the user sets to achieve improved accuracies. A Kalman filter uses the entire time history of the event being modeled to account for model uncertainties, historical evolution, and errors in the measurements in a nearly optimal manner.

3. NAVIGATION ACCURACY

The navigation accuracy that can be achieved by a particular user depends primarily on two factors:

1. The average error in the range measurement from the user set to each satellite

2. The instantaneous geometry of the satellites as seen from the user's location on earth

The range error from user to satellite is denoted by a quantity called the User Equivalent Range Error (UERE). As shown in Fig. 5, the component parts of the UERE arise from various kinds of errors in the space segment, the control segment, and the user segment. The biggest space segment errors are caused by clock instabilities and space perturbations (mostly unmodeled solar radiation pressure and lunar-solar gravitational forces). The largest control segment errors arise from difficulties in modeling the satellite ephemeris coordinates (orbital elements). The

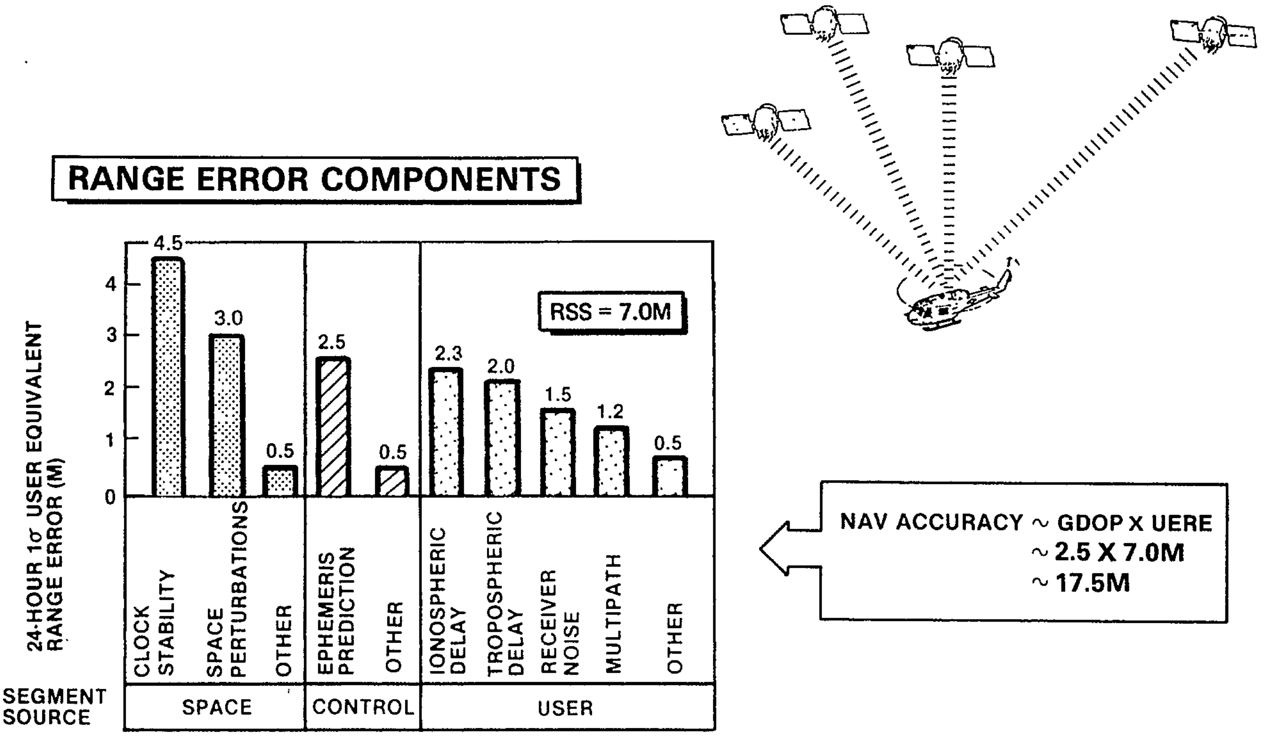


Fig. 5 Navigation Accuracy Calculations

biggest errors in the user segment arise from difficulties in modeling the delays experienced by the signals when they pass through the earth's ionosphere and its troposphere. Surprisingly, the UERE arising from all of these sources combined amounts to only about 7 meters per day.

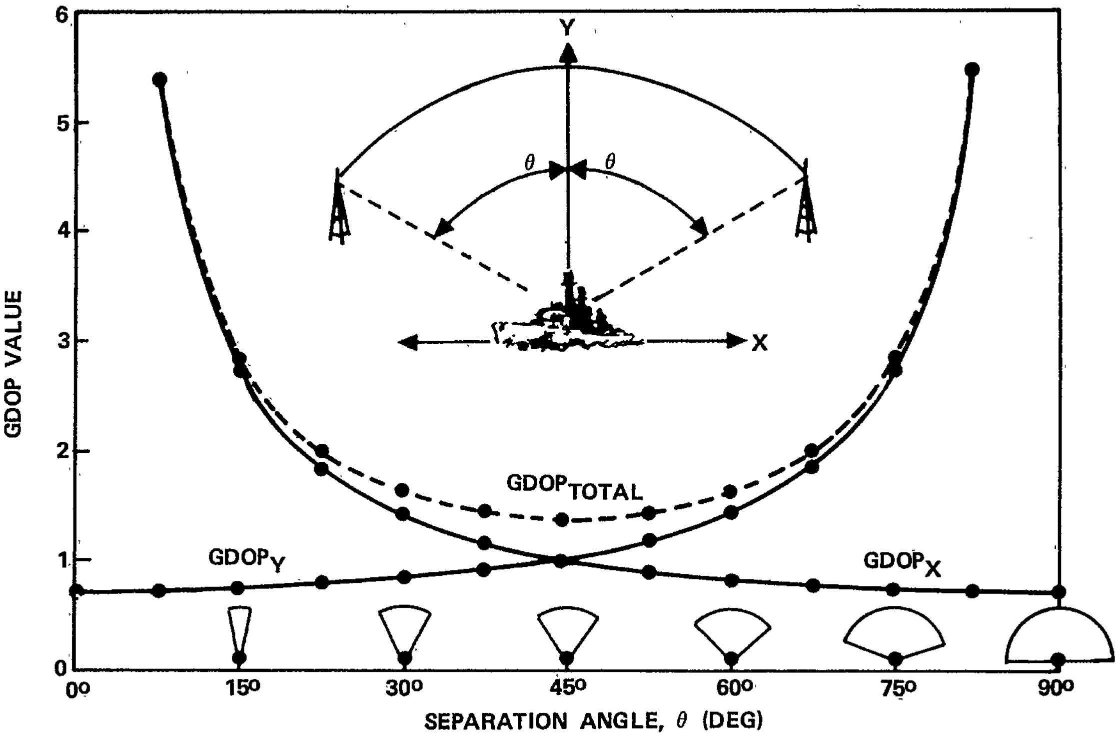
As Fig. 5 shows, the navigation error experienced by any given user is obtained by multiplying the UERE by a quantity called the Geometrical Dilution of Precision (GDOP). The value of the GDOP depends upon the locations of the four satellites relative to the user set, which automatically selects those four satellites most favorably located to minimize its navigation error. On the average, the resulting navigation error amounts to 16 or 17 meters, assuming that daily updates are made.

Fig. 6 illustrates the manner in which the GDOP values vary with changing geometry for a simple case of two-dimensional navigation with perfect clock synchronization. In this case, the quantities $GDOP_x$ and $GDOP_y$ represent the GDOP values in the x and y directions, respectively. Note that when the two transmitters both lie along the Y-axis ($\theta = 0°$), the $GDOP_x$ value is infinite. This means that the satellites are so unfavorably located that no useful information concerning the value of the x coordinate can be obtained by the user. On the other hand, if both transmitters lie along the X-axis (on opposite horizons), the $GDOP_y$ value will be infinite, and no useful information can be obtained concerning the user's y coordinate.

The overall GDOP value, $GDOP_{total}$, equals the room-sum-square of $GDOP_x$ and $GDOP_y$. It constitutes an overall average value for the GDOP in two dimensions. As Fig. 6 shows, $GDOP_{total}$ reaches its minimum value when θ equals 45° (i.e., when the angle between the two transmitters is 90°, as seen from the user's location).

The Navstar system provides navigation readings in three dimensions, as well as an accurate estimate of the current time. Hence it uses various GDOP quantities, each providing a different measure of average accuracy. One of the most useful variations is the perpendicular dilution of precision (PDOP). It represents a measure of the overall navigation accuracy in the three mutually perpendicular user coordinates U_x, U_y, and U_z.

Computer simulation procedures coded at Rockwell International and elsewhere have been run hundreds of times to determine the various GDOP values and the corresponding navigation accuracies at various times and locations with different satellite constellations. These simulations, along with other considerations (such as system survivability, redundancy, and satellite replacement strategies), have led to the conclusion that the best 18-satellite constellation consists of six orbital rings containing three satellites each. Within each ring, the satellites are evenly spaced. The equatorial crossings (ascending nodes) of the six rings are equally spaced around the equator and



$$\mathrm{GDOP}_X = \frac{1}{\sqrt{2}\ \mathrm{SIN}\ \theta}$$

$$\mathrm{GDOP}_Y = \frac{1}{\sqrt{2}\ \mathrm{COS}\ \theta}$$

$$\mathrm{GDOP}_{TOTAL} = \frac{1}{\sqrt{2}\ \mathrm{SIN}\ \theta\ \mathrm{COS}\ \theta}$$

Fig. 6 GDOP Values for a Simple 2-D Configuration

are inclined at an angle of 55°. An artist's conception of the operational constellation is shown in Fig. 7. All the elements in this figure are drawn to scale except the satellites themselves, which are oversized.

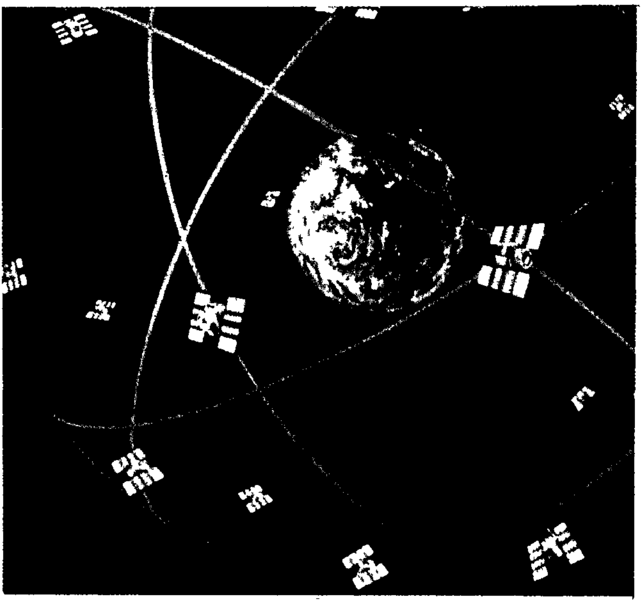
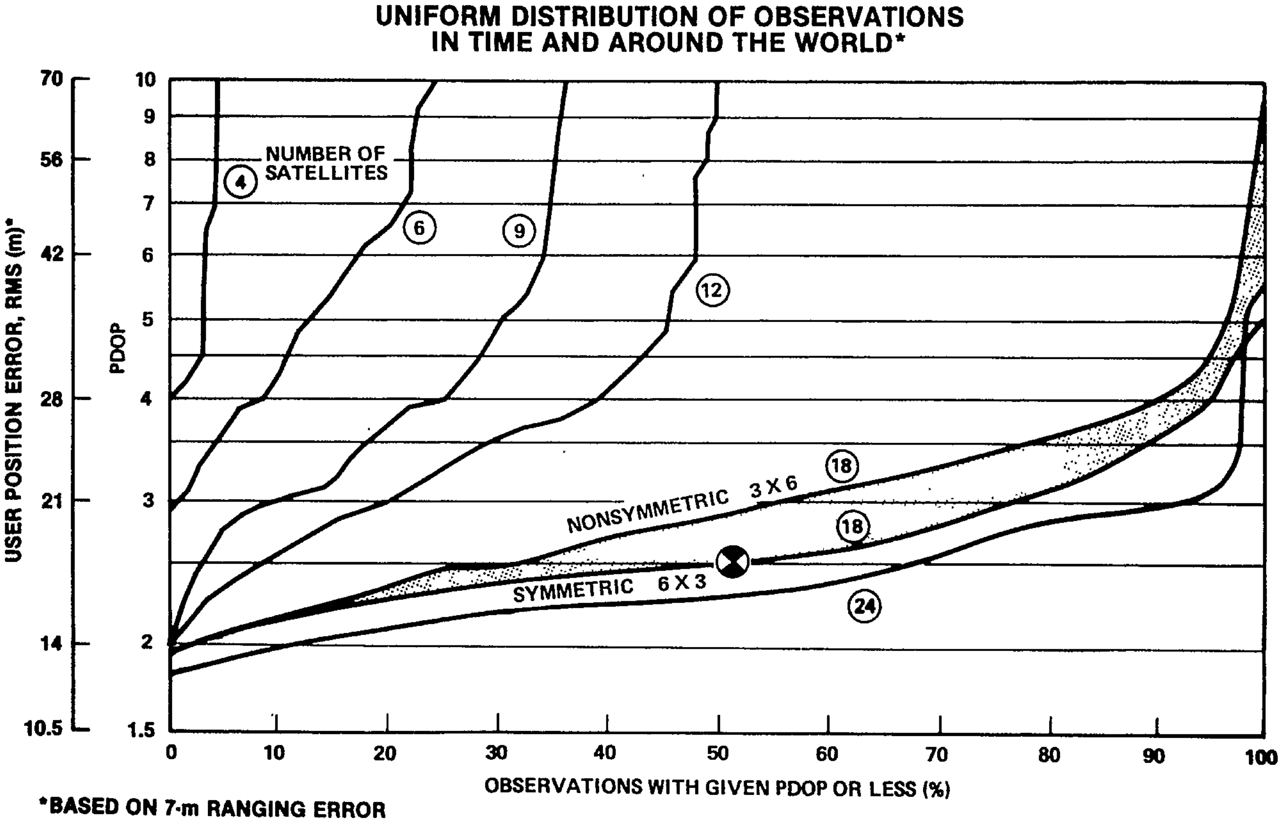


Fig. 7 The Operational Navstar GPS Constellation

Global time-averaged PDOP values for the operational constellation and a number of other constellations are presented in Fig. 8. As this figure shows, the present six-satellite constellation provides a three-dimensional PDOP value of six or less roughly 20 percent of the time. This means that if the UERE can be maintained at 12 feet, a global time-averaged navigation error of 72 feet or less can be achieved at least one-fifth of the time. The same figure shows that the operational six-plane, 18-satellite constellation will provide a PDOP of 2.5 or less 50 percent of the time. Given a UERE value of 7 meters, this implies a navigation error of 17.5 meters or less at least 50 percent of the time.

The Navstar system can provide even greater accuracies if it is used in the relative or differential navigation mode. In this specialized mode, two user sets receive signals from the same satellites and communicate with each other over a radio link to exchange the readings they are receiving. Most of the components making up the UERE are virtually eliminated by this technique because they are common to both navigation solutions. The few errors that are not common (uncorrelated) are relatively small. Studies show that, in some cases, relative navigation errors of 5 feet or less can be anticipated for the operational constellation.



*BASED ON 7-m RANGING ERROR

Fig. 8 Accuracy for Various Satellite Constellations

4. NAVIGATION COMPARISONS

Comparisons between the coverages and the 2σ navigation accuracies of the GPS system and eight other popular navigation systems are presented in Fig. 9. An operating range equal to half the circumference of the earth (about 11,000 nautical miles) has been arbitrarily selected for those systems with global navigation capabilities. Note that, among the global systems, the GPS is nearly 20 times more accurate than its nearest competitor, the Transit Navigation Satellite--which, incidentally, provides only intermittent navigation fixes every 30 to 120 minutes under normal conditions. The other two global systems, Inertial Navigation and Omega, are even less accurate when operated over intercontinental ranges.

Even in comparison with short-range navigation systems, the GPS is generally superior. Only the Instrument Landing System (ILS) achieves a smaller navigation error. Of course, the ILS is used for a very specialized purpose: to aid in terminal maneuvers for landings at major airports. The other data values presented in Fig. 9 are largely self-explanatory, but if more details are desired, they can be found in Satellite Based Navigation Systems, by Logsdon and Helms (see Bibliography).

5. FIELD TEST RESULTS

To date, more than 700 field tests have been conducted at Yuma, Arizona, and other locations using the GPS satellites now in orbit. In virtually all of these tests, the GPS has exceeded specifications. In particular, the system has been extensively tested for signal strength, navigation capabilities, and clock accuracy. In addition, it has been used in connection with such realistic military operations as aerial rendezvous, blind bombing, and marine navigation.

The results of some of the navigation accuracy tests are summarized in Fig. 10. For those cases in which the upload occurred within two hours of the test, the 1σ UERE was 5.5 meters. When the upload took place at some time within the previous day, the UERE was 11.5 meters. This latter value, which is slightly larger than those anticipated for the operational constellation, is well within the spec values for Block I.

The results of four other types of military field tests are summarized in Fig. 11. Specific versions of these tests resulted in:

1. Average static positioning errors of 23 feet
2. Harbor navigation well within the accuracy of the visual calibration systems
3. Maximum aerial rendezvous errors of 30 feet
4. Maximum blind bombing errors of 56 feet.

Of the tests that have been conducted at this writing, only a few have produced errors substantially larger than those obtained from computer simulations of the same kinds of military operations.

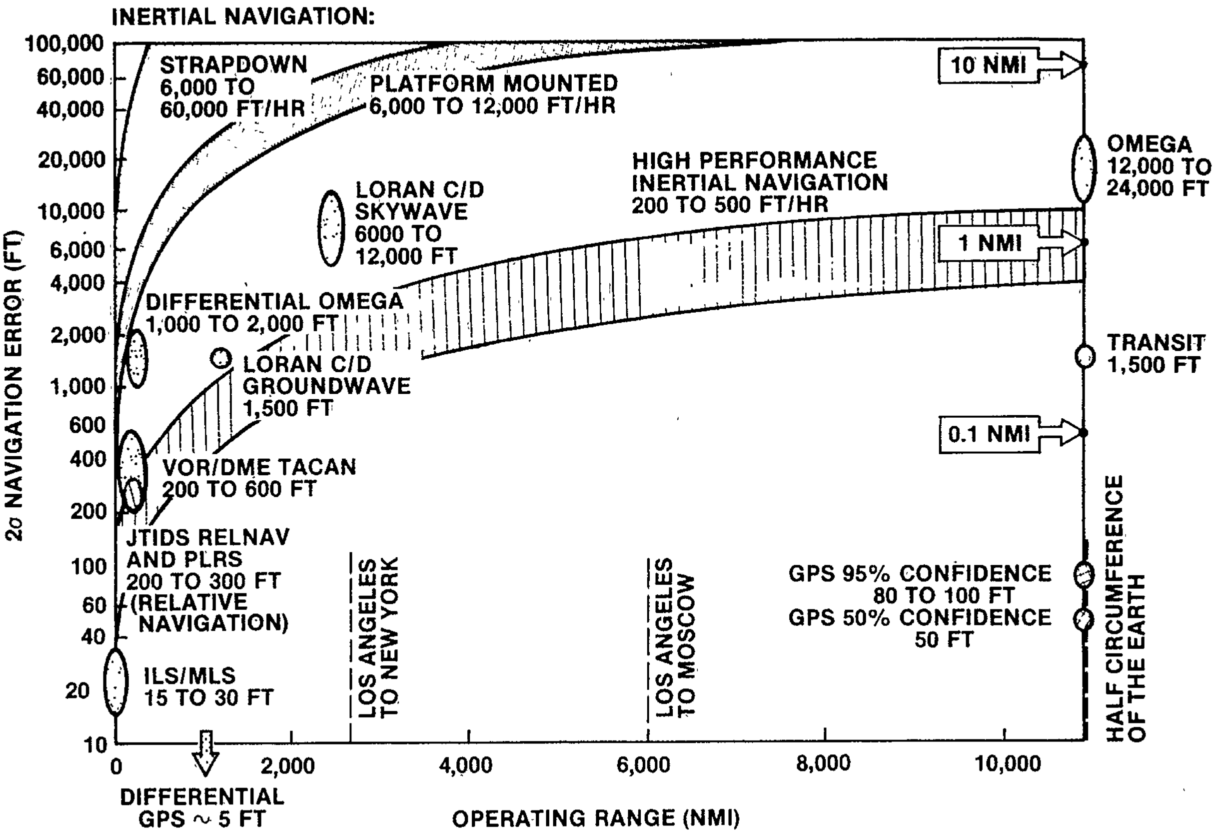
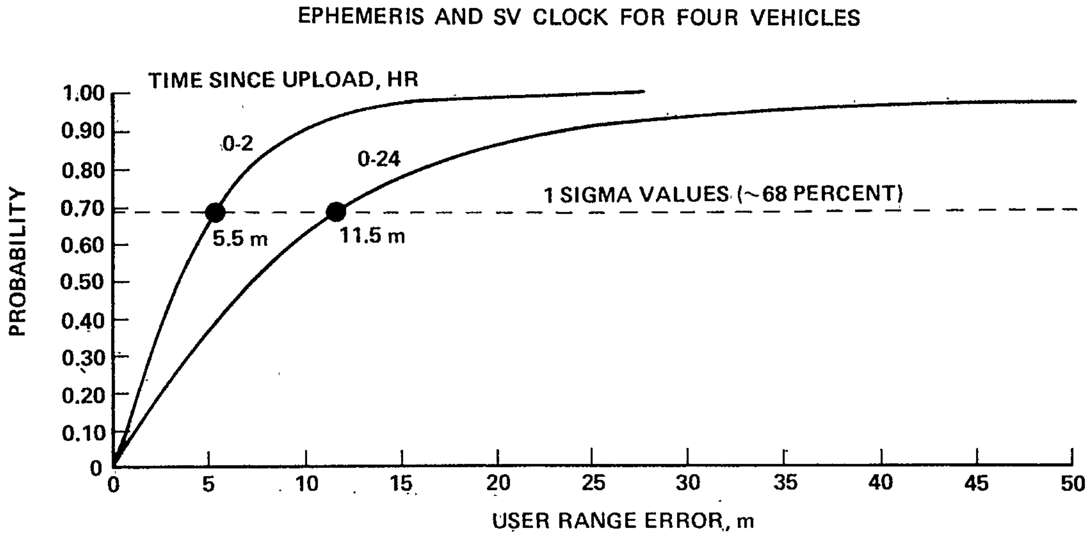


Fig. 9 Range and Accuracy Comparisons for Various Navigation Systems



1σ PROBABILITY	TIME SINCE UPLOAD (HR)	USER RANGE ERROR (UERE)—METERS FOUR VEHICLE CUMULATIVE SUMMARY				
		NAV 1	NAV 2	NAV 3	NAV 4	ALL (RMS)
68 PERCENT	0-2	5 m	6 m	4 m	7.5 m	5.5 m (18 FEET)
68 PERCENT	0-24	11.5 m	27 m	12 m	6 m	11.5 m (38 FEET)

NOTE: NAV 2 SATELLITE HAD A CLOCK INSTABILITY (FREQUENCY EXCURSIONS) PROBLEM

Fig. 10 Cumulative Error Distribution

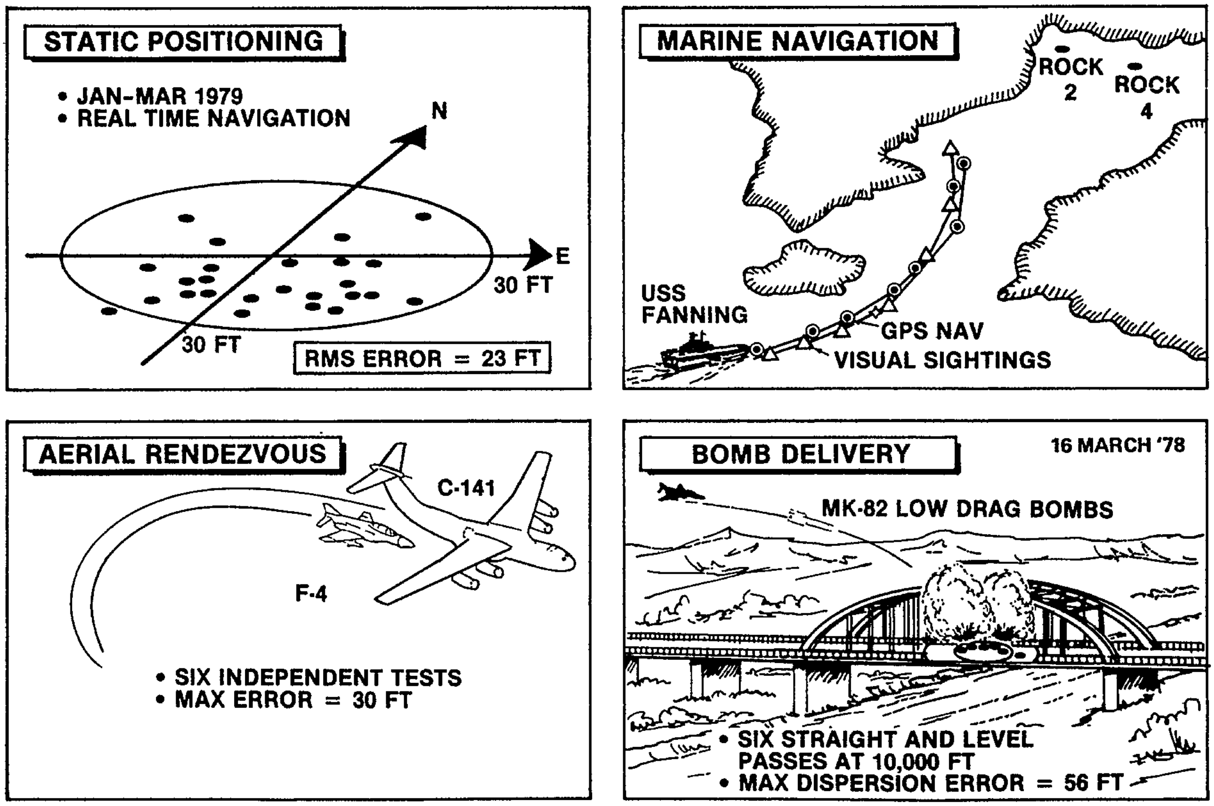


Fig. 11 GPS Field Test Results

6. SIMULATED BATTLEFIELD BENEFITS

Fig. 12 presents the results obtained from a series of computer simulations in which the effectiveness of GPS-equipped military forces was compared with that of conventionally equipped forces. These simulations demonstrated that:

1. Minesweeping operations can be accelerated by a factor of 23 over conventional approaches if the minesweepers and navy ships subsequently traversing the swept channel are equipped with GPS user sets.

2. Artillery batteries operating against the ZSU-23 radar-controlled antiaircraft gun require approximately 10 percent as many rounds as those using conventional map coordinates.

3. Precision interdiction missions against SAM sites, ammo dumps, and radar installations can increase enemy kills by a factor of four to six when the attacking airplanes use GPS precision bombing techniques.

4. Close air support missions adjacent to the front lines can produce kill probabilities against enemy targets from 300 to 400 percent higher if the GPS is used.

Thus, it can be seen that the Navstar GPS will probably turn out to be a highly beneficial addition to the support hardware manufactured for American military forces and their allies. It will also greatly increase the navigation capabilities of nonmilitary users. Oil exploration vessels, commercial airlines, fishing fleets, astronomers, and surveyors, among others, can greatly benefit from the innovative engineering and well designed computer simulation techniques that have made the Navstar GPS so practical and effective.

7. CONCLUSIONS

The operational Navstar GPS will permit users equipped with relatively small and inexpensive user sets to determine their positions in real time to an average accuracy of 50 feet anywhere on or near the surface of the earth. This is accomplished through radio navigation techniques in which precise binary pulse trains with chipping rates of 1 and 10 million bits per second are sent out by a constellation of 18 satellites in 12-hour orbits 10,898 nautical miles above the earth. The pulse trains emitted by the satellites are matched against with their identical counterparts, which are generated by the user sets. A successful match yields the travel time of the signal, which is proportional to the distance separating the satellite and the user set. Given the ranges of four satellites, the user set can automatically determine its three position coordinates U_x, U_y, and U_z, as well as the error C_b in its clock.

In order to maintain acceptable accuracy, corrections must be made for delays experienced when the binary pulse trains traverse the earth's troposphere and ionosphere. Additional adjustments are necessary because of the relativistic effects caused by the relative motion between the satellites and user sets and

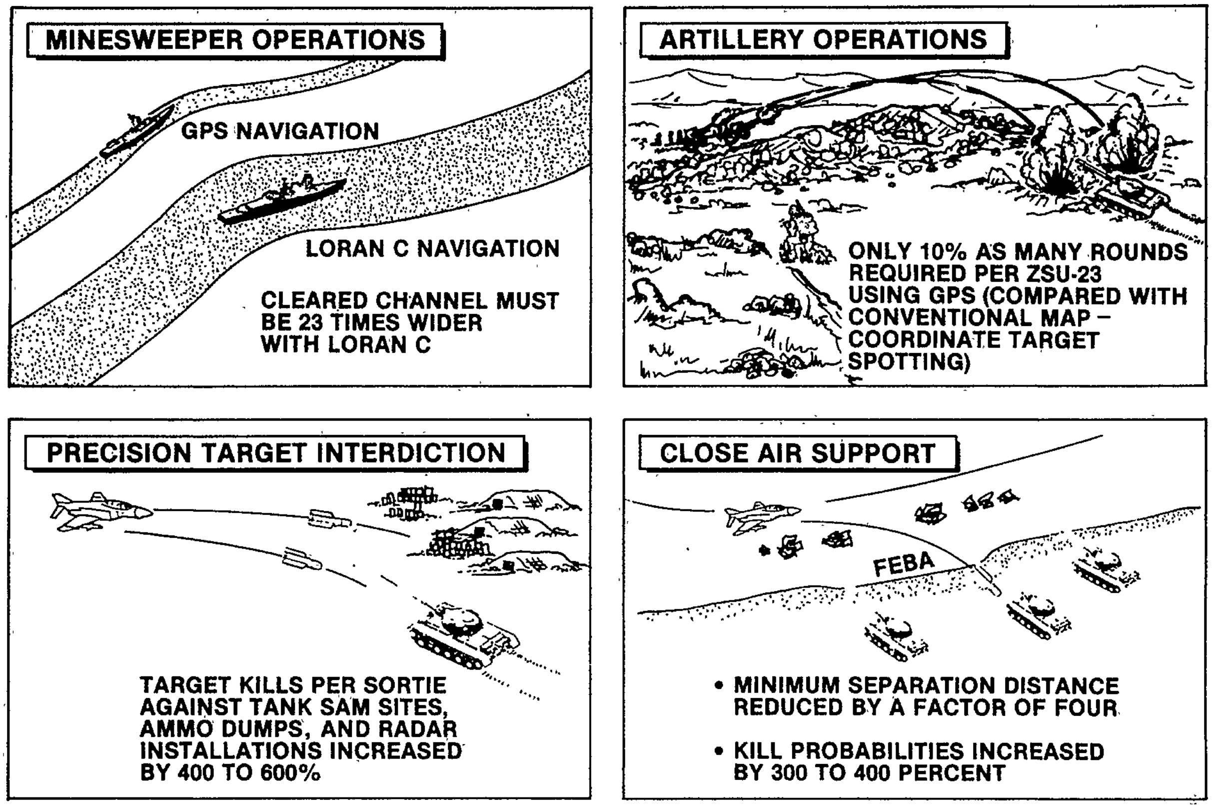


Fig. 12 Projected Battlefield Benefits

the variations in the earth's gravitational field. A final refinement made for the sake of accuracy consists of using Kalman filtering techniques in which the user set computers automatically account for uncertainties in measurements and models, as well as in the historical evolution of the measurements being analyzed.

Comparisons between the Navstar GPS system and various other navigation techniques indicate that it is nearly 20 times more accurate than any other global system. The GPS is also superior to most short-range systems, both civilian and military.

More than 700 tests conducted at various locations indicate that the GPS meets or exceeds virtually all of its design specifications. Particular attention has been paid to navigation accuracy, signal strength, and clock stability. When these and other test results are extrapolated via computer simulation techniques to realistic battlefield conditions, it is found that important benefits will definitely result.

The Navstar system, which is being financed jointly by the various branches of the military, will also be widely utilized by civilian users. These will probably include astronomers, fishing vessel and airline navigators, oil exploration experts, and a variety of others.

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