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Navigation Satellites: Their Future Potential [and Discussion]

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Navigation satellites: their future potential

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The United States Department of Defense is developing a new generation of navigation satellites known as the Navstar Global Positioning System or GPS. When the full system of 18 satellites is deployed in the late 1980s, highly accurate information on position, velocity, and time will be available continuously to users anywhere in the world. This capability has already been demonstrated by the existing constellation of five prototype satellites.

The original impetus for Navstar was the need for highly accurate positioning information by military aircraft, ships, and ground units. But Navstar also has potential for a variety of civilian uses, which include precision navigation, surveying and accurate time transfer. Moreover, the projected sharp decline in the cost of GPS user equipment will make the system available to a wide class of users.

Introduction

Improved navigation upon the Earth's surface has been one important benefit to man's venture into space. First launched in the 1960s, navigation satellites now provide accurate navigation information to thousands of ships and other users. A second generation of satellites is now under development by the U.S. Department of Defense. When fully deployed in the 1980s, these new satellites will be a true global positioning system that will provide continuous, highly accurate position, time, and velocity data to users worldwide. The potential for applications of this capability is immense, as the user community is just beginning to realize. This paper describes the existing and planned navigation satellites and then discusses their potential applications.

Today: transit

The concept for the first navigation satellite dates back to the launch of Sputnik I in 1957. While monitoring the famous 'beeps' of the passing satellite, scientists at the Applied Physics Laboratory of Johns Hopkins University noticed that their frequency shifted as the satellite traversed the field of view. Later, they demonstrated that all orbital parameters of the satellite could be determined from this doppler shift. Similarly, if the orbit of the satellite was known, a plot of the doppler shift against time could be used to determine the receiver's position on Earth.

The U.S. Navy was receptive to development of a satellite navigation system because of the need to supply submarines with precise navigation fixes worldwide. The first prototype satellite, launched in April 1960, demonstrated the potential of navigation satellites to meet the Navy's requirements. Continuous operation of navigation satellites began on 12 January 1965. The system, called Transit, represented the first routine use of space technology in direct support of the fleet.

Six operational Transit satellites are now orbiting the Earth in polar orbits at an altitude of 600 nautical miles (1111 km). The system provides a 2σ accuracy of about 460 m when a satellite is in the field of view, which occurs at intervals of 30–120 min. Over 10000 Transit

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receivers are now in use, of which about 90 % are operated by civilian users. The rapid growth in Transit users has been accompanied by a steady drop in the cost of user equipment (see figure 1), making satellite navigation economically attractive for more and more users.

The principal commercial use of Transit has been for routine navigation by ocean-going vessels. Transit is also opening new doors in oceanography and offshore oil exploitation by enabling ships to establish a position and return to within a few hundred metres of it.

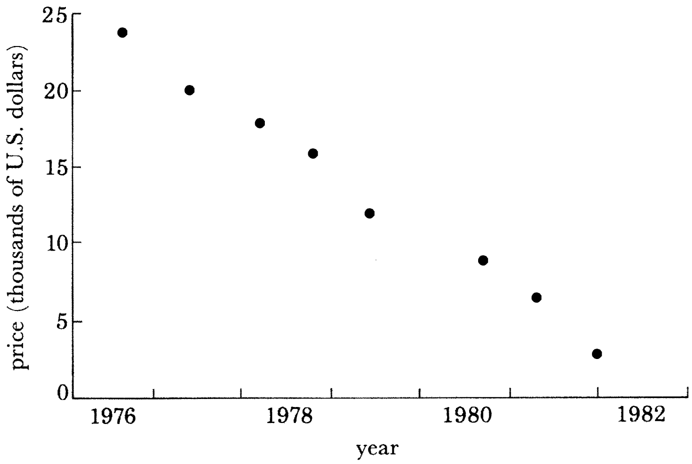

Figure 1. Trend in the list price for Transit receivers.

Tomorrow: Navstar

Although it represents a major advance in navigation, Transit is not a true global positioning system. Its coverage is intermittent; it gives position information only in two dimensions; its accuracy is insufficient for many potential applications; and its performance is degraded if the user is moving rapidly, as would be so for aircraft in flight. To overcome these limitations, the U.S. Department of Defense is developing a second generation navigation satellite system, known as the Navstar Global Positioning System (GPS).

How Navstar works

The basic concept for Navstar differs considerably from that of Transit. The latter uses the doppler shift of the signal from a single satellite, measured over several minutes, to estimate the user's position of the surface of the Earth. Navstar uses measurements of signals from multiple satellites to establish the user's position in three dimensions (including altitude), the user's velocity and the exact time. In theory, the user's set sould determine its three position coordinates from only three satellites, but that would require the set to have an extremely accurate, expensive clock. Instead, Navstar employes signals from four satellites, which allows the set to function with a small, inexpensive quartz crystal oscillator.

Given precisely timed pulses from four satellites, the user set automatically solves four simultaneous equations for its three position coordinates and the error in its clock (see figure 2). A similar system of equations that use doppler shift measurements from the same four satellites yields the user's velocity (both magnitude and heading). This procedure gives three-dimensional position worldwide with a median error of 16 m (over ten times more accurate than Transit), three-dimensional velocity to within 0.03 m s^{-1}, and time to within 50 ns.

The space segment of Navstar will consist of 18 satellites arranged in six inclined orbits with an orbital period of 12 h at an altitude of 11000 nautical miles (20372 km). Six prototype satellites are currently in orbit, providing one to four hours coverage per day worldwide. A full constellation of 18 production satellites will be in orbit in 1988. (The first production satellites will be launched from the Space Shuttle in 1986.) The ground control segment of Navstar will also be fully operational in 1988, and user equipment will be available from several manufacturers.

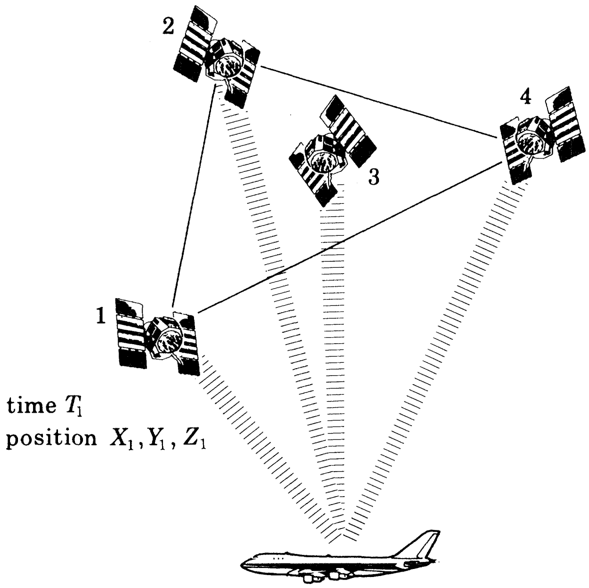

FIGURE 2. Determination of the user's position and the time from four Navstar satellites. The distance from the user to each satellite can be computed from

$$\{(X_i - X_u)^2 + (Y_i - Y_u)^2 + (Z_i - Z_u)^2\}^{\frac{1}{2}} = c \quad (T_i - T_u - E),$$

where c is the speed of light and E is the error in the user's clock; the resulting four equations can be solved for the four unknowns X_u, Y_u, Z_u, and E.

The Department of Defense is fully committed to Navstar. The three armed services plan to purchase over 20000 user sets to equip most ships and aircraft, many vehicles, and some man-portable units. The total cost to develop and produce the system and launch it into space will be over two billion dollars. In addition, the Department of Defense plans to spend over one billion dollars on development and production of user equipment.

Test experience

A variety of controlled and operational tests have been conducted with the six prototype satellites and developmental user sets. In general, performance has met or exceeded specifications for all sources of error, including clock errors, ionospheric propagation, multipath effects, and receiver noise. Figure 3 shows the result of a controlled test of a five-channel user set carried by a C-141 aircraft at the Yuma Proving Grounds on 4 February 1983. A laser ranging system was used to determine the actual position of the aircraft and the error in the

Navstar position. The horizontal error averaged between 8 and 10 m, and the total error averaged between 15 and 20 m.

Another controlled test was made on 10 October 1983 with a low-cost, single-channel commercial user set rather than the five-channel set. The results are shown in figure 4. The figure also illustrates how the geometric arrangement of the satellites affects accuracy. For the first portion of the test, before about 13h23, the set was tracking four satellites that were bunched relatively close together. The error in position ranged up to 60 m during this period.

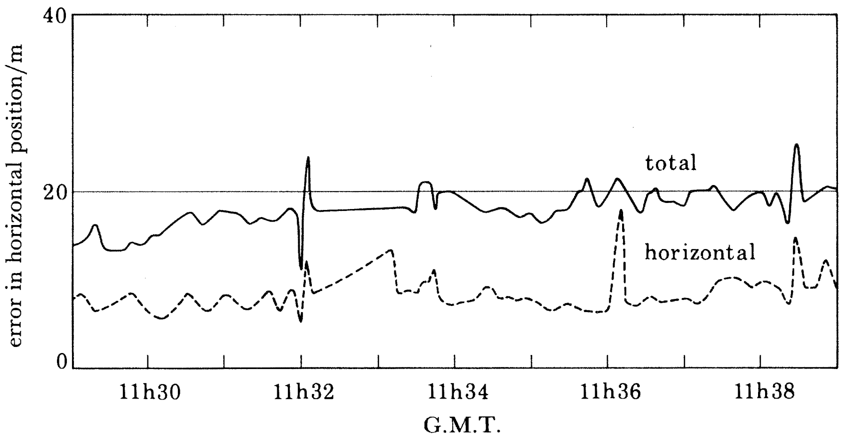

Figure 3. Accuracy of the Navstar system in test with a five-channel user set in a C-141 aircraft.

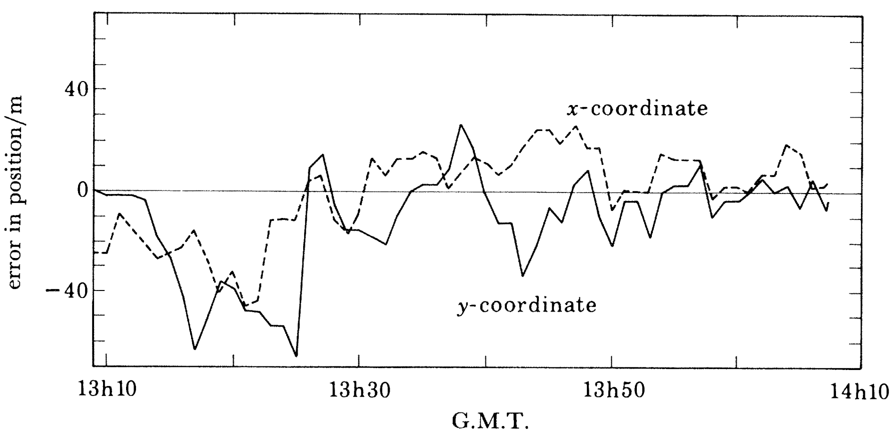

Figure 4. Accuracy of the Navstar system with a low-cost user set.

At 13h23 another satellite entered the field of view and increased the geometric dispersion. As the data shows, the accuracy then improved to better than 30 m for the remainder of the test.

A variety of operational tests have also been conducted. In one series of tests tactical aircraft used Navstar to rendezvous with an airborne tanker. The maximum horizontal error during these tests was 9 m. Equally impressive was the recent flight of a Sabreliner business jet from Cedar Rapids, Iowa, to Paris, by navigating solely with Navstar. The flight was made in five segments, timed to match the availability of the existing Navstar satellites. After touchdown at Le Bourget airport, the Sabreliner crew used Navstar to taxi to a targeted parking location without visual cues from ground personnel. The plane stopped just 7.73 m from the pre-designated spot.

Military uses

The Department of Defense developed Navstar, of course, primarily for its military applications. Navstar will be the primary navigation system for military aircraft and ships, allowing the Department of Defense to cut back or terminate operations of existing navigation systems. The most visible action will be the phasing out of Transit, which is scheduled to cease operations in 1992. The Department of Defense also plans to discontinue, in whole or in part, the use of Loran, Omega and Tacan.

The accuracy of Navstar will improve the efficiency of many operations and enable units to conduct some operations that were not possible before Navstar. Military aircraft will be able to land at any airfield, whether or not an instrument landing system is available, under virtually any weather conditions. Operations requiring coordination in position and time, such as the aerial rendezvous for refuelling mentioned above, will be more practical. Coordinated fleet air defence is another example. The lack of accurate position data is currently a serious limitation on coordinated operations by air-defense ships. Navstar will solve this problem, and will also improve the management of air-defence aircraft.

Navstar will greatly improve the efficiency of minesweeping operations. A minesweeper that knows exactly where it is and where it has been will be able to sweep a given area more quickly. Also, the area that must be swept will be smaller because ships with Navstar can navigate a narrower channel. A variety of other military operations will benefit from Navstar.

Potential civilian uses

The Department of Defense does not plan to actively market Navstar in the civil sector; the system's capabilities will have to speak for themselves. But the department will do everything it reasonably can to make the revolutionary capabilities of Navstar available to the widest possible base of civilian users. No doubt Navstar will have a variety of civilian applications, including innovative uses that are not yet envisioned.

Perhaps the most obvious civilian use of the basic Navstar system is for navigation. Navstar would be ideal for cross-country and trans-oceanic navigation by commercial aircraft. Undoubtedly it could have prevented the Korean airliner incident, where the aeroplane flew over Soviet airspace and was shot down in September 1983, and similar instances of navigation errors. Moreover, the relatively low cost of user equipment should make Navstar available to private as well as commercial aircraft. Based on the experience with user equipment for Transit (see figure 1), a basic Navstar user set should cost as little as $500 by the year 2000. Even more complex multichannel sets with computer software for route planning, multiple waypoints, etc. will probably cost just a few thousand dollars.

Maritime navigation is another obvious application for Navstar, not only on oceanic voyages but also in coastal and inland waterways and in approaches to harbours. Navstar would also be a boon to oceanography and to exploration for offshore resources. Transit has already been a major help to these activities. The greater accuracy and continuous availability of Navstar will enable ships, in effect, to draw an X on the ocean to return quickly to precisely the same spot.

Navigation for land vehicles – trucks, cars, and taxis – is also a promising application for

Navstar, particularly if it were integrated with a map display system to show the position of the vehicle. U.S. and Japanese automobile manufacturers are already experimenting with such a system. In the future, a voice synthesizer might even be added to inform the driver of present lccation, of streets ahead, or a recommended turn.

The application of Navstar to navigation extends into space. The U.S. National Aeronautics and Space Agency is planning to include Navstar equipment on the Space Shuttle to provide navigation information on orbit and during re-entry and landing. Meanwhile, down on Earth, Navstar should provide information on position to individual consumers: private aircraft, pleasure boats, recreational vehicles, even hikers, campers, and hunters.

Other applications of Navstar will depend on additions and refinements to the basic system. One refinement, known as differential positioning, could play an important role in certain civilian applications. Some error sources in Navstar, such as uncertainty in propagation through the ionosphere, are nearly constant over a fairly wide area. A calibrated receiver located at a fixed, surveyed site can determine corrections for these errors and transmit them to local users. With these error corrections the user equipment could achieve an accuracy of about five metres.

With differential positioning, Navstar could be used at thousands of airports around the world to extend the period of safe operation even under poor weather conditions. Differential positioning would not replace instrument landing systems (i.l.s.) at major airports. (Microwave landing systems, the next generation of i.l.s., will be able to guide an aircraft on to the runway automatically.) But differential positioning would be a relatively inexpensive way to improve safety and increase operation hours for the many airports and aircraft not equipped with a microwave landing system. The modest cost projected for Navstar user equipment should allow even general aviation to take advantage of Navstar's capabilities.

'Report-back' is another capability that could be combined with Navstar to produce a system with considerable potential. The idea would be for aircraft, ships, or vehicles to automatically report their position, as indicated by their Navstar user equipment, to a central dispatcher. Tracking trans-oceanic air traffic would be one such application, conceivably by using existing h.f. communications circuits for reporting back. For other applications of report-back, new communications circuits may be necessary.

Static positioning with great accuracy is another important application possible with refinements to Navstar. The first step to greater accuracy is differential positioning. By averaging the resulting readings over time, extreme accuracies can be achieved. For example, Navstar survey equipment has already demonstrated relative positioning accuracy better than one centimetre within one hour on site. Such accuracy could be achieved within tens of kilometres of the reference point. Surveying equipment incorporating Navstar could vastly improve both the accuracy and efficiency of many survey tasks.

Navstar can facilitate accurate transfer of time as well as distance. Its 100 ns accuracy is even superior to that of the portable atomic clock currently used for highly accurate synchronization between distance sources. Navstar will provide an inexpensive way to synchronize computer networks, data encryption systems, communication networks and other navigation systems.

SUMMARY

Navigation satellites were one of the first practical applications of space systems. The second generation of navigation satellites now under development will provide a truly global positioning system, which will provide opportunities for many new and important applications; some of these have been mentioned. No doubt other innovative uses will emerge when Navstar is fully developed and its capabilities and costs become known to potential users.

Discussion

J. R. PAGE (*Kingsland Road, Alton, Hampshire GU*34 1*LA*, *U.K.*). Given the potential accuracy of the GPS navigation system, will this lead to the replacement of inertial navigation systems for terminal guidance? Should the military conceive a need for a new navigation system in the future, would the American government guarantee the continuation of the system for civilian uses?

W. E. RAMSEY. It is not intended that the Navstar Global Positioning System (GPS) will replace inertial navigation systems. Instead, it is envisioned that GPS will be used to update inertials and that inertials will be employed as the primary navigation system for terminal guidance.

The current U.S. Department of Defense policy provides for worldwide access to GPS Standard Positioning Service signals at an accuracy level of 100 m by the time the system becomes operational in 1988. Considering the large military investment in GPS and the system's potential for improved accuracy through differential applications, it seems likely that GPS will remain operational well into the twenty-first century. Speculation about development of a new navigation system appears premature at this time.

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