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Global Positioning System Applications

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ABSTRACT

The space-based Navstar Global Positioning System (GPS), which is scheduled to achieve full operational status by late 1988, will consist of 18 active satellites placed around six orbital rings at 10,898 nautical miles above the earth. Every other ring will contain an extra satellite that will function as an active on-orbit spare. This regular and precise constellation of GPS satellites will provide continuous, three-dimensional global navigation coverage to users worldwide. Average positioning accuracies of 15 meters or less are anticipated by the military. This extraordinary precision has been demonstrated repeatedly under field-test conditions in both the United States and Western Europe. Other tests indicate that relative (differential) navigation, which employs user sets rigged to communicate their navigation solution to one another, can achieve substantially better results. Relative errors of only 1 or 2 meters have been demonstrated with existing equipment under realistic field-test conditions.

Both military and civilian users are expected to find broad-ranging applications for the accurate and reliable navigation provided by the GPS. Various branches of the military intend to purchase more than 20,000 user sets in this century, and the Wall Street Journal projects an additional 250,000 will be purchased by civilian users. The final sections of this technical paper discuss the operational characteristics and practical benefits of the following specific civil uses of the Navstar system: (1) air traffic control, (2) time synchronization, (3) offshore oil exploration, (4) iceberg tracking, and (5) dinosaur hunting.

THE NAVSTAR GPS

The Navstar GPS is a space-based radio-navigation system that employs dual-frequency L-band transmissions to provide continuous,

worldwide navigation coverage to an unlimited number of users who are equipped with receivers capable of processing the signals broadcast by the satellites.

Ten Block I GPS satellites have been launched into 12-hour orbits at 10,898 nautical miles above the earth. They provide global (but intermittent) three-dimensional navigation coverage ranging from 1 to 5 hours per day, depending on the user's geographic location. Launches of the updated Block II satellites will begin in 1987. By late 1988, a full constellation of 18 satellites (a mixture of Block I's and some Block II's) should reach operational status. These satellites will provide continuous 24-hour coverage with military accuracy of 15 meters (see Figure 1). Extremely precise atomic clocks carried on board the satellites and extensive software routines in the user sets provide this unprecedented global navigation accuracy. The system also yields extremely precise velocity measurements and the exact time.

Operating Principles

The Navstar GPS uses triangulation procedures in which baselines are established by picking up precisely timed pulse sequences broadcast by radio transmitters positioned at known locations in space. In theory, each user set could establish its three-dimensional position coordinates by picking up the timed pulses broadcast by three space-based transmitters. This approach, however, would require an extremely accurate user-set clock precisely synchronized with the clocks carried on board the satellites. The approach that was used requires more satellites, but is less expensive to implement. The GPS user sets are equipped with quartz crystal oscillators that are small, compact, and inexpensive (but roughly 10,000 times less stable than the satellite clocks). The user set picks up the signals from four satellites (either simultaneously or sequentially) to determine its

location in three-dimensional space. The signal from the extra satellite is used to eliminate timing errors in the user set's quartz crystal oscillator. Figure 2 presents the four navigation equations that are solved in determining the three position coordinates of the receiver (U_x , U_y , U_z) and the time offset (C_B) in its imprecise clock.

The GPS user sets also determine their velocity to an average accuracy of 0.1 miles per second. The mathematical solution for velocity makes use of the Doppler shift of the signals from the same four satellites used in user positioning. The Doppler shift is a systematic variation in frequency of the signals arriving at the receiver. This frequency shift is caused by the relative motion between the user set and satellites.

In order to maintain the full accuracy of the system, the Navstar satellites are provided with fresh updates at least once per day. The information contained in these updates is provided by the control segment, which is made up of monitor stations, computer processing facilities, and ground antennas positioned around the world. The updated information transmitted to the satellites includes accurate clock correction factors, satellite ephemeris constants (orbital elements), and current information on the altitude and density of the earth's ionosphere.

The updated Block II versions of the satellites, which will weigh approximately 1,800 pounds on-orbit, are roughly 80 percent heavier than their Block I predecessors. Although each satellite involves 65,000 separate parts, it is designed to operate 7.5 years without servicing. The major navigation-related subsystems of the Block II space vehicle are listed in Figure 3. The 12-element helical antenna array transmits a cone of constant-intensity radio energy to users on or near the earth's surface. Autonomous feedback control loops always orient the two flat solar arrays toward the sun and the 12 navigation antennas on the lower edge of the spacecraft always toward the earth. Pointing accuracies of a small fraction of a degree are routinely achieved.

On-board atomic clocks (two cesium and two rubidium) generate the precise timing pulses that are broadcast toward the earth, which subtends a 28-degree angle as seen from the satellite's high-altitude vantage point in space. The atomic clocks have a fractional frequency stability of about 2×10^{-13} . Thus, if the clocks could be made to operate that long, they would lose or gain only about 1 second every 300,000 years. However, since a timing error of one-billionth of a second results in a 1- or 2-ft navigation error, the clocks on board the satellites must be mutually synchronized to within 13-billionths of a second (10) at all times. This, in part,

is the reason daily updates must be provided by the control segment.

Schedules and Milestones

Rockwell is presently working under a firm fixed-price contract to design and build 28 Block II satellites that will be launched into orbit aboard the Space Shuttle at a peak rate of eight satellites per year. Each Shuttle could carry as many as three satellites in a single launch. A total of 12 Navstar satellites (some Block I and some Block II) should be available to provide two-dimensional global coverage by 1987. Three-dimensional coverage (18 functioning satellites on-orbit) will follow by the end of 1988.

Figure 4 summarizes the current schedules for the three major segments of the Navstar project. IBM is responsible for the operational control segment, whereas the military receivers are being produced by Rockwell's Government Avionics Division (Collins). At least a dozen private companies make or plan to make receivers for the civilian market place.

Test Results

To date, more than 700 tests of the Navstar system have been conducted, mostly at Yuma, Arizona, and in or near San Diego harbor. The system has met or exceeded all its performance specifications, sometimes by a wide margin. In particular, the signals have been considerably stronger, and the atomic clocks are two to five times more stable than anticipated. Navigation errors have also been smaller than published specifications. All ten of the satellites that have reached orbit have functioned properly, and seven of them are still operational.

Accuracy Comparisons

A chart summarizing the operating ranges and the accuracy levels of several of today's radionavigation systems is presented in Figure 5. The Navstar GPS, which is depicted in the lower right-hand corner of the figure, is a global system providing a military accuracy of 50 ft at the 50-percent probability level and 80 to 100 ft at the 20 probability level. This is about 15 to 20 times better than its nearest global, but intermittent competitor, the transit navigation satellite. It is also two orders of magnitude more accurate than the global Omega system.

The GPS is surprisingly competitive in comparison with short-range navigation techniques such as VOR/DME Tacan and Loran C9. It is about two to six times more accurate than VOR/DME Tacan and at least 15 times more accurate than the Loran C skywave. And of course, these systems operate over ranges of only a

few hundred miles and cover, at most, only a few percent of the globe.

The only widely used radionavigation method with an accuracy comparable to the global Navstar system is the ILS/MLS, which provides short-range accuracies of 15 to 30 ft near domestic airports. Even in this case, however, the Navstar GPS may be competitive in the relative (differential) navigation mode. Relative navigation is accomplished by installing a cooperative GPS user set at a known location (e.g., near the end of an airport runway) and having it communicate its navigation solution to the other user sets in the area. Simulations show that, under normal conditions, this approach can result in relative navigation errors as small as 5 ft or less.

MILITARY APPLICATIONS

The navy is using the GPS satellites to study the accuracy of its Trident submarine-launched missile, which carries Navstar receivers to measure their impact points in the Pacific. Hundreds of other military uses are envisioned as more of the GPS satellites go into operation. Computer simulations indicate substantial improvements in a variety of missions including mine-sweeper operations, aerial rendezvous, amphibious landings, and close air support.

CIVIL APPLICATIONS

The civilian potential for the Navstar satellites has not been overlooked by alert entrepreneurs. Ocean-going vessels, space vehicles, and surveying teams are all enthusiastic about the promising civilian uses of Navstar, but dozens of other applications are expected to materialize as the constellation grows and matures. Several of the more promising applications are examined in the following paragraphs.

Air Traffic Control

The major commercial airlines in the United States operate approximately 2,000 aircraft, each of which completes several flights per day. In addition, more than 300,000 smaller business planes and civil aircraft (general aviation) are making many more flights. A variety of navigation aids guide these airplanes to their destinations. For instance, more than 700 domestic ILS facilities serve 120,000 users and 900 VOR/DME transmitters broadcast signals to 250,000 receiver-equipped aircrafts. These domestic services are supplemented by 34 Loran C transmitters giving nearly continuous coverage to 10 percent of the globe and eight Omega transmitters that provide much lower accuracy navigation over a broader region.

The Navstar GPS can make substantial contributions to various phases of flight including takeoff, enroute navigation, landing, and perhaps even taxiing to terminal areas. In June 1983, a pilot employed by Rockwell's Collins Division, flew a Saberliner business jet from Cedar Rapids, Iowa, to the Paris Air Show using the navigation signals broadcast by the Navstar satellites. When he landed his plane at LeBourget Field, the pilot, who employed no visual clues, taxied to within 25 ft of a predesignated point on the parking apron of the runway. (see Aviation Week, page 45, July 25, 1983).

Time Synchronization

Accurate time synchronization helps individuals and machines coordinate their activities. Timing aids of various types, such as wrist watches, quartz crystal oscillators, telephone synchronization services, and precision atomic clocks are in current use. Several years ago, the National Bureau of Standards conducted a broad-ranging study that concluded that \$4 billion per year was being spent to synchronize the activities of man and machine. The relative accuracies of several synchronization techniques are shown in Figure 6.

Radio-telephone synchronization and the transit navigation satellite are about three orders of magnitude less precise than the synchronization services provided by the GPS. Atomic clock trips are more competitive, but involve expensive jet travel by teams of technicians who carry a reference atomic clock from one site to another, usually aboard a commercial airliner. Once the technicians have synchronized the atomic clock at their destination, they return to the original site where they recheck the accuracy of their portable atomic clock. This technique is expensive and time consuming.

The navigation signals transmitted by the GPS satellites can be used to synchronize two distant atomic clocks 10 to 100 times more accurately than competing techniques. Moreover, the synchronization can be automatic and continuous. Consequently, in a few years the needs of some users that now rely upon expensive atomic clocks may be served by simpler quartz crystal oscillators adjusted every second or so by the signals emanating from the GPS satellites. A number of practical applications of this simple and precise technique will likely emerge.

Offshore Oil Exploration

Successful offshore oil exploration depends on the accurate reconstruction of three-dimensional subterranean geological structures. These reconstructions are made by triggering a series of seismic pulses that send sound waves through the water and into

the earth below. When the technicians interpret the data, they must determine the position of the exploration vessel to a high-degree of precision each time it triggered a pulse. When shore-based navigation beacons are visible, this requirement can be met with relative ease; it becomes much more difficult when the ship is below the horizon. Because accurate positioning is so important to their mission, oil exploration ships are usually equipped with integrated navigation and positioning systems costing several hundred thousand dollars each. At least one oil exploration company is already using GPS experimentally, and, as additional satellites are launched, other outfits seem sure to copy their technique. Elastic tethers as long as 300 ft are used to anchor transmitting buoys to the continental shelf. This keeps them from shifting from side to side when they are washed by tides and waves. Each buoy transmits precise positioning pulses so that the oil exploration ship conducting the seismic survey can fix its relative position with acceptable accuracy. These navigation data are recorded directly on the magnetic tapes for later analysis by computer. Signals from the GPS satellites help reposition the buoys at each new location. Studies conducted by Chappel and Wesson at Magnavox (Refence 3) indicate that this technique increases data collection efficiencies by as much as 200 percent compared with conventional integrated navigation. When the full GPS constellation is in place, much simpler navigation procedures seem likely to provide at least equivalent results.

Iceberg Tracking

In 1912, the unsinkable British luxury liner Titanic sank when it collided with an arctic iceberg. But that is just the best known of many tragic incidents involving sea ice and maritime vessels.

Each year, 10,000 icebergs form in the Northern Hemisphere. About 5,000 reach the open ocean and, on average, 300 pass below 48-degrees north latitude where they can become a major hazard to North Atlantic shipping. During the iceberg season, which lasts roughly five months, some shipping routes are lengthened as much as 30 percent to avoid the worst concentrations of floating ice. Oil drilling platforms in northern waters are also at hazard and, on occasion, they have to be abandoned when large icebergs move into their vicinity. Of course, no region in the North Atlantic and no portion of the year is entirely free from iceberg hazards. Consequently, arctic icebergs are tracked to minimize the probability of damaging collisions. This work is carried out by the International Ice Patrol, which is financed by the United States Coast Guard but financed by contributions from the various maritime nations operating in the

North Atlantic. The International Ice Patrol sends special ships and airplanes into the arctic in an effort to locate as many icebergs as possible. Sightings are also gathered from commercial and military vessels. Six radio stations broadcast warnings twice a day so that ships in the area can track their movements relative to known icebergs.

Because of its high degree of accuracy and its continuous availability, the GPS could provide an unusually attractive method for tracking icebergs. A special user set would be dropped onto the iceberg to broadcast its position coordinates to any nearby maritime vessels. Similar space-based systems have already been tested in this manner.

Dinosaur Hunting

In October 1981, two American researchers, Roy P. Mackel of the University of California and Herman Regusters of the jet Propulsion Laboratory devised a unique application of the navigation capabilities of the GPS. They developed a plan for searching out Mokele-Mbembes, large dinosaur-like creatures that had been reported repeatedly by natives in the Congo. Mackel and Regusters planned to combine the GPS data with high-resolution images produced by the Landsat earth-resources satellites. This, they believed, would help ensure that they were searching in regions of the Congo that were conducive to the support of such large amphibious animals. Unfortunately, no GPS user sets were available for loan at the time Mackel and Regusters planned their expedition. They went anyway, but did not locate any dinosaur-like creatures.

CONCLUSION

The 18-satellite GPS constellation, which is slated to reach full operational status by the end of 1988, will provide instantaneous reliable navigation to users worldwide. Projections indicate that, by the end of this century, 20,000 military receivers and as many as 250,000 civilian receivers will be in routine use. Important civil applications may include reliable and precise air traffic control, time synchronization, and offshore oil exploration. Novel applications, such as iceberg tracking and dinosaur hunting, may also be practiced in the 21st century.

Based on the research and analysis efforts discussed in the main body of this paper, the following conclusions can be derived:

- The GPS satellites will be accurate enough to support navigation and landing operations for civil aviation.
- The synchronization of noncollocated atomic clocks appears to be the most

promising short-term application of the Navstar GPS. GPS synchronization of high-precision quartz crystal oscillators provides greater average accuracy than cesium atomic clocks synchronized with portable clock trips. This approach is also simpler and more cost-effective.

- Industry studies indicate the efficiency of offshore oil exploration projects can be doubled by using the present constellation of GPS satellites with a network of transmitting buoys attached to the continental shelf with elastic tethers.
- The GPS signals offer a number of potential advantages over present experimental methods for tracking hazardous icebergs in the North Atlantic. These include continuous real-time observations, more accurate positioning, and direct reporting to nearby maritime vessels.

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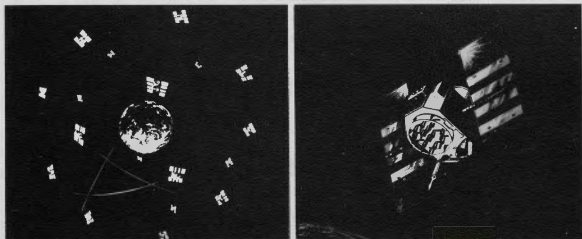


Figure 1. The Navstar Constellation

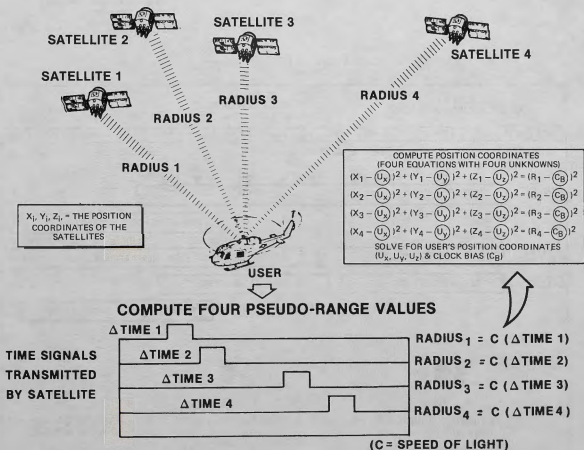


Figure 2. Navigating with the GPS

SHUTTLE LAUNCH

- PAM-DI BASELINE
- 1 TO 3 GPS/SHUTTLE

SURVIVABILITY

- LASER
- 0.015 JCS

LIFE

- 6-YEAR MMD
- 7.5-YEAR DESIGN GOAL

NAVIGATION PAYLOAD

- HARDENED NAV DATA UNIT
- 14 DAY NAV DATA STORAGE
- ANTISPOOF
- SELECTIVE AVAILABILITY
- IGS DATA DENIAL
- FREQ SYNTH/DISTR UNIT
- 2 σ_{p} +2 σ_{c} STANDARDS

L-BAND

- SIGNAL GENERATION/TRANSMISSION
- RADIO ASTRONOMY BAND PROTECTION
- USER RECEIVED L-BAND SIGNALS
- SPREAD
 - L1: -160.0 dBw C/A & -163.0 dBw P(Y)
 - L2: -166.0 dBw C/A OR P(Y)

AVCS

- ALL-YEAR ΔV & 330 DAY LAUNCH OPPORTUNITY
- PAM-DII DEPLOYMENT MODE
- 2.5-YEAR SPIN ON-ORBIT STORAGE MODE
- ACTIVE NUTATION CONTROL
- AUTOMATIC MAGNETIC MOMENTUM DUMPING

TCS

- FREQUENCY STANDARD
- TEMPERATURE CONTROLLERS
- 18 ft^2 LOUVERS
- MULTILAYER INSULATION
- COATINGS & FINISHES

STRUCTURE

- INTEGRAL BOX STRUCTURE
- THRUST CONE/CYLINDER
- 21 ft^2 RADIATING AREA

ELECTRICAL POWER

- 7-1/2 YEAR 60L 700 W SOLAR ARRAY
- 3 35-AH Ni-Cd BATTERIES
- SHUTTLE/PAM-DII POWER INTERFACE

REACTION CONTROL

- X, Y, & Z AXES ΔV THRUSTERS
- MINIMIZED PLUME IMPINGEMENT
- > 10-YEAR CONSUMABLES

ORBIT INSERTION

- STAR 37X SRM
- MECH S&A
- 26.5° ORBIT PLANE CHANGE CAPABILITY

TT&C

- S-BAND SGLS UPLINK/DOWNLINK
- SIGNAL ENCRYPTION
- 0.5 & 4K DATA RATES
- SHUTTLE INTERFACE

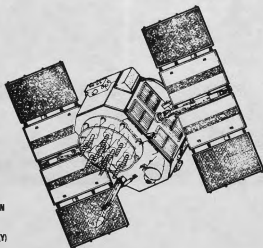


Figure 3. Significant Block II Subsystem Features

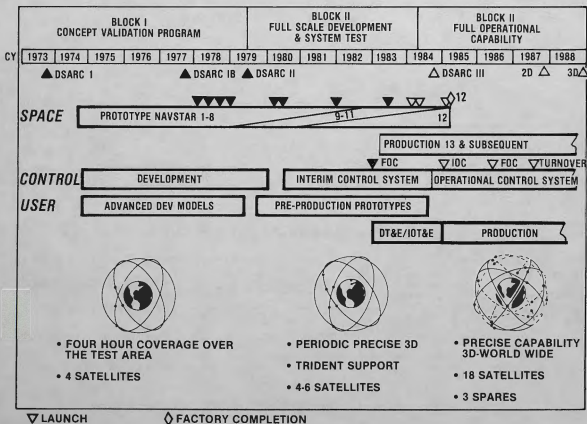


Figure 4. Navstar Program Evolution

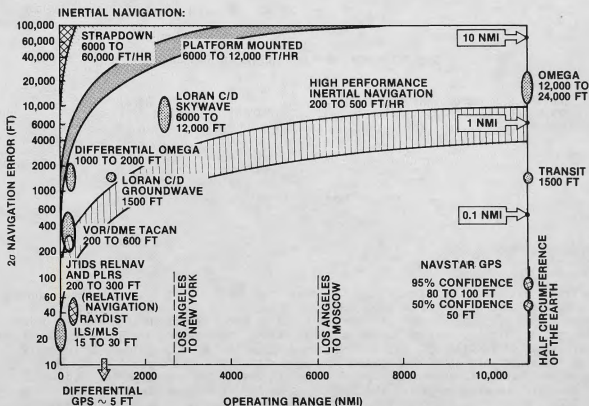


Figure 5. Range and Accuracy Comparison

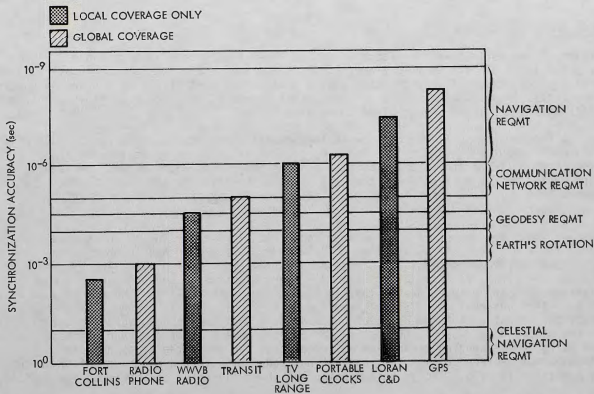


Figure 6. Time Synchronization of Various Systems