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THE GLOBAL POSITIONING SYSTEM

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SYNOPSIS

GPS, the Global Positioning System, will rapidly become the most widely used radionavigation system in the world when it becomes operational later in this decade. The advantages of GPS (e.g., excellent accuracy, worldwide availability, all-weather performance, and operational simplicity) will assure its rapid acceptance, and the large market thus generated will assure many equipment choices and attractive prices.

This paper describes the current GPS development status, including an evaluation of the progress being made toward full deployment. The paper next explores the surprising number of interim GPS applications making use of the present constellation of test and evaluation Navstar satellites. Differential GPS, which can provide navigational accuracy of five meters in local areas, will be evaluated and progress toward standardization of signal formats discussed. Finally, this paper looks toward the future, projecting when GPS will be ready for widespread use and predicting some of the types of equipment which will be available.

GPS BACKGROUND

(This paper originally was prepared for the Europort Conference and was presented on 13 November 1985 in Amsterdam. This was prior to the 28 January 1986 space shuttle disaster. As of this revision (April 1986) it is still not possible to predict the full impact of this tragedy on the satellite deployment schedule. Therefore, the original artwork has not been revised, but parenthical comments have been added to the original text where appropriate).

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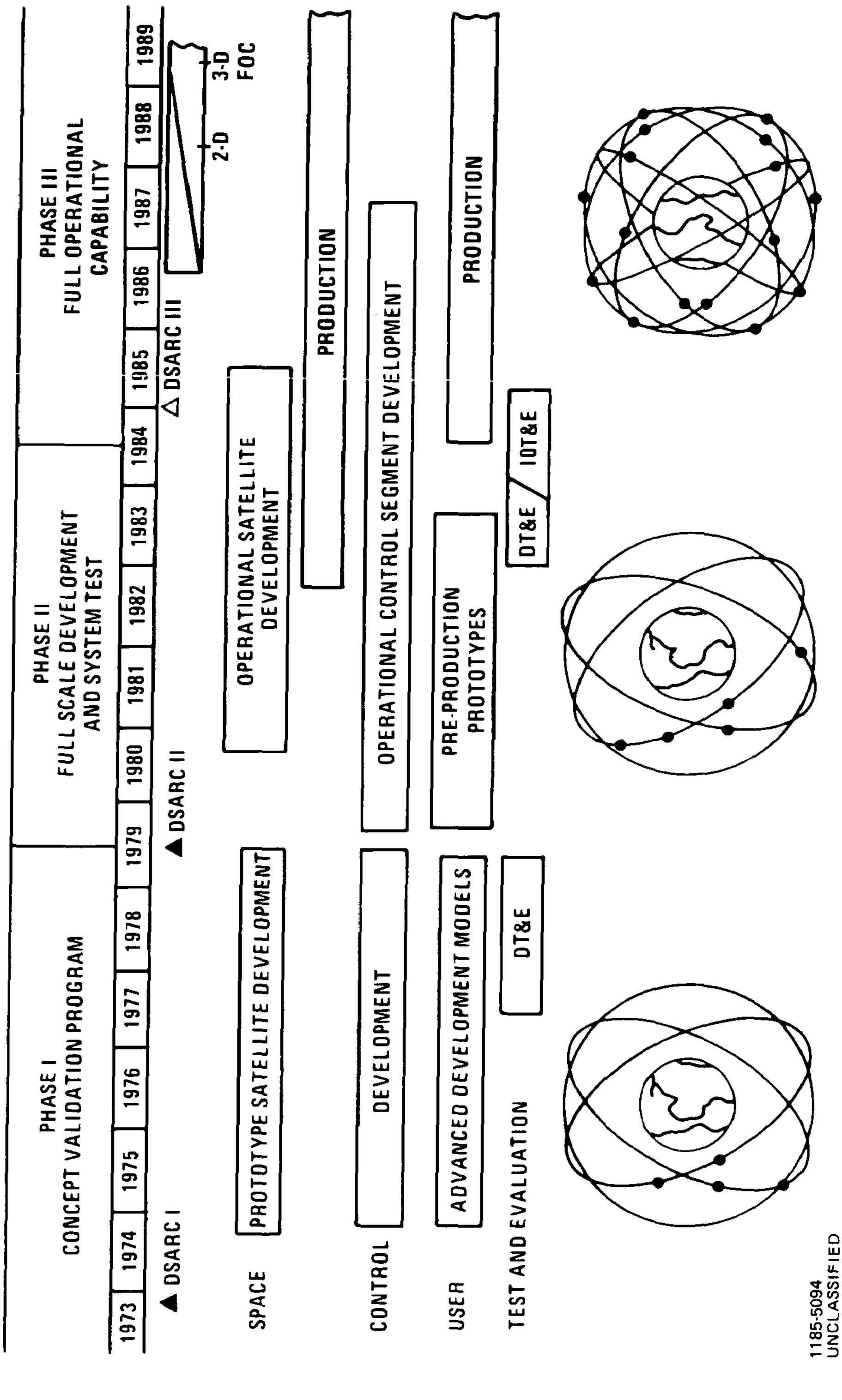

FIG. 1. — GPS program schedule.

GPS, the Global Positioning System, is being developed by the U.S. Department of Defense in order to enhance military effectiveness by providing precise, continuous, worldwide, all-weather, three-dimensional navigation for land, sea, and air applications. As shown by Figure 1, we have entered Phase III of the three-phase effort to develop and deploy GPS. If all goes well, the system should be fully operational in 1989. *(The Shuttle disaster will delay this date by a year or more).*

Although the system is being developed to serve military needs, civil users have been encouraged to consider system applications. Therefore, it is expected that, worldwide, there will be many times more civil than military users.

Seven prototype satellites now are being employed to complete the Phase II test program. Their orbits are designed to emulate full system coverage for several hours each day, which permits testing without the expense of having a full satellite constellation. As shown by Figure 2, we expect that four to seven of the prototype satellites will continue to be available for test purposes until the launch of production satellites begins late in 1986. Being larger and heavier than the prototype satellites, the production satellites will be launched from the Space Shuttle, and up to two may be launched on each flight. The curves of Figure 2 are an attempt to predict the number of satellites available in future years, with the band ranging from pessimistic on the bottom to optimistic on the top. *(Launches now cannot begin before mid-1987 and could well be later than the pessimistic curve).*

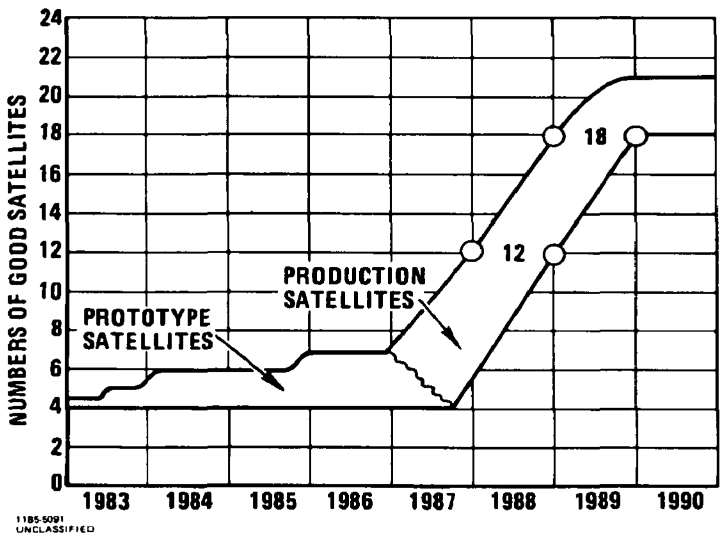

FIG. 2. — GPS satellite availability profile.

The optimistic curve shows that by the end of 1987 there could be 12 operational satellites, providing continuous, two-dimensional, worldwide navigation, which is sufficient for all marine applications. By the end of 1988 there could be 18 operational satellites in the constellation illustrated by Figure 3, permitting worldwide, continuous, three-dimensional navigation. The altitude solution is needed for optimum aircraft and land vehicle applications. In addition, the plan

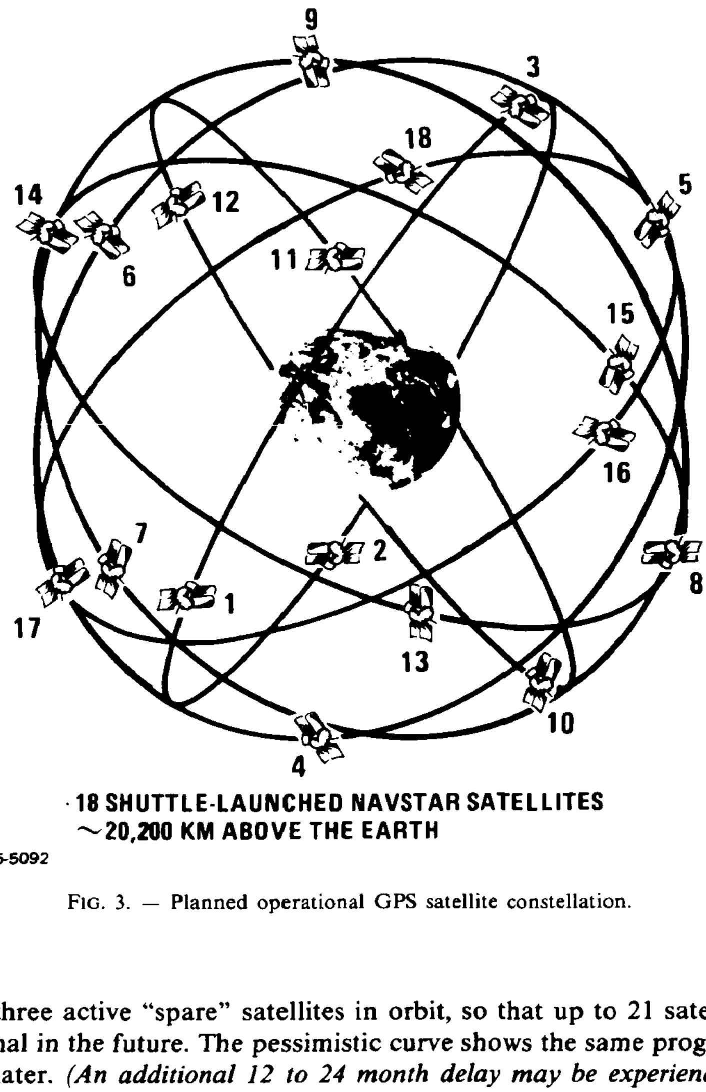

FIG. 3. — Planned operational GPS satellite constellation.

is to place three active "spare" satellites in orbit, so that up to 21 satellites could be operational in the future. The pessimistic curve shows the same progression, but 12 months later. *(An additional 12 to 24 month delay may be experienced).*

GPS satellites orbit about 20,200 kilometers above the earth. The orbit height is chosen so that it takes exactly half an earth rotation (~ 11h58m02s) for a satellite to circle the earth. There will be a minimum of three satellites evenly spaced in each of six orbit planes. With this constellation every user will be able to receive signals from four or more satellites simultaneously. By making time-of-arrival measurements on these signals, the user equipment will be able to determine four parameters: latitude, longitude, altitude, and time.

The navigation signals provided by each GPS satellite are illustrated by Figure 4. GPS satellites transmit on two frequencies in order to permit the measurement and correction of ionospheric refraction error. The two GPS frequencies are conveniently known as L_1 (1575.42 MHz) and L_2 (1227.6 MHz). The L_1 signal carries two codes, whereas the L_2 signal carries only one. The P code is a "pseudorandom" sequence of ones and zeros with a switching rate (how often a one can change to a zero or vice versa) of 10.23 MHz. The P codes run for 7 days

L_1 = 1575.42 MHz	C/A CODE AT 1.023 MHz	P-CODE AT 10.23 MHz
L_2 = 1227.6 MHz		P-CODE AT 10.23 MHz

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FIG. 4. — GPS navigation signals.

before repeating. The C/A codes switch at 1.023 MHz and repeat every millisecond (i.e. the codes are 1023 bits long). Both the L_1 P and C/A codes carry the satellite message with a data rate of 50 bits per second.

It is expected that the least expensive navigation equipment will operate on the L_1 frequency and use only the C/A codes. More expensive receivers equipped to use the P codes have three advantages. The first is access to the L_2 frequency for ionospheric refraction correction. Second is much better protection from jamming signals, which is especially important for military applications. Third is better range measurement precision, by a factor of 2.2.

Until GPS production satellites are launched it is important to note that we will have a few hours of full GPS coverage per day in most parts of the world. Figure 5 illustrates the number of satellites visible in Rotterdam and in Los Angeles throughout the day of 13 November 1985, assuming that all seven prototype satellites are operational. The figure also shows Horizontal Dilution of Precision, HDOP, which is the statistical horizontal position error in meters resulting from each meter of rms ranging error to the satellites. HDOP values of 2 to 5 are considered acceptable, but values above 10 represent quite poor satellite geometry. As you can see, there is a limited time each day during which three or four satellites are visible and the HDOP approximates what we expect to see 24 hours a day when the system becomes fully operational.

There are two key policy issues which concern potential GPS users. The first, called Anti-Spoofing (AS), is illustrated by Figure 6. The U.S. Department of Defense has announced that it intends to encrypt the P codes transmitted by the production satellites. The resultant code to be transmitted is called the Y code. This often-confirmed policy would deny P code access (and therefore L_2 access) to all but a few civilian users who can maintain crypto security and for whom use of the Y code is deemed to be in the "national security interest". This policy would seem to be an incentive for most civilian users at this time to concentrate their attention on single-frequency, C/A code equipment.

Figure 7 illustrates the second major policy issue called selective access (SA). Curve A shows the accuracy performance obtained during Phase I testing with a

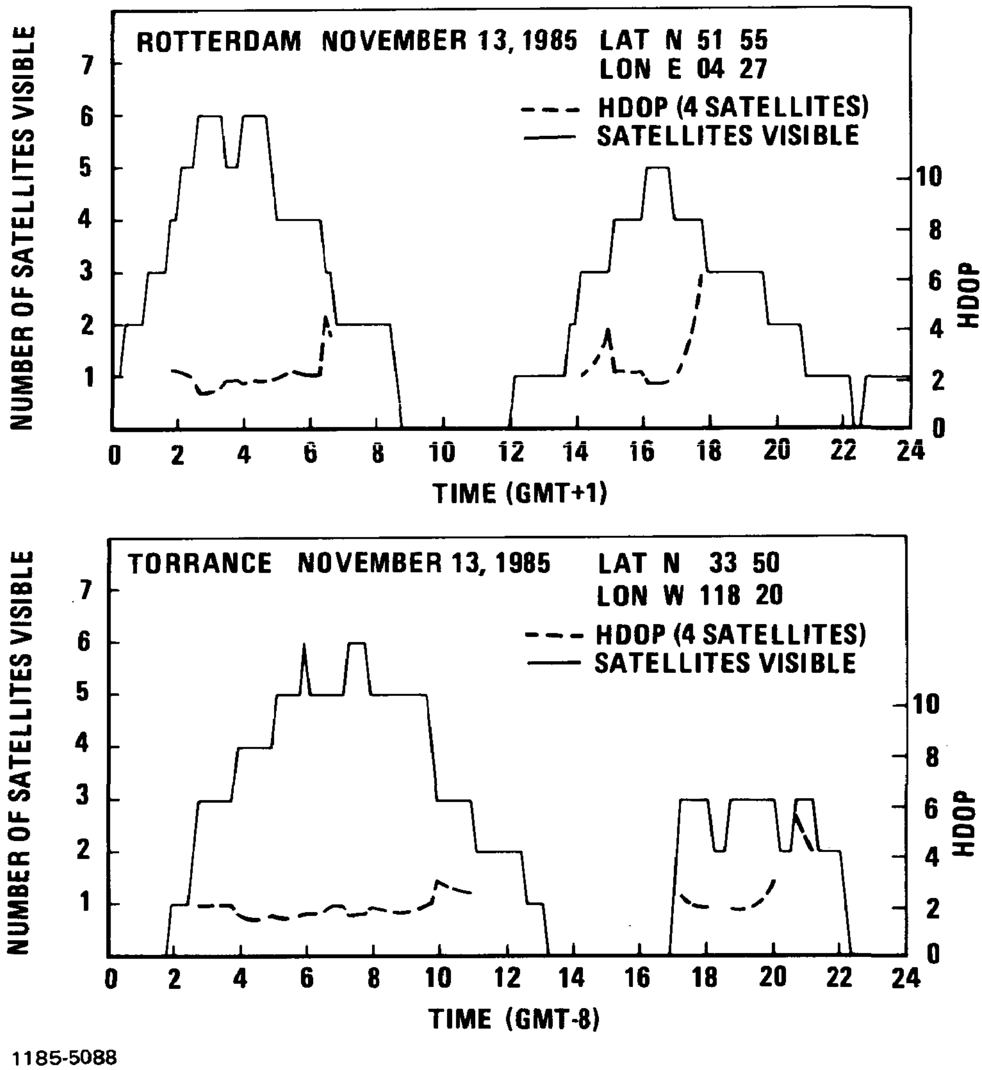

FIG. 5. — Satellite visibility profile with three-satellite HDOP.

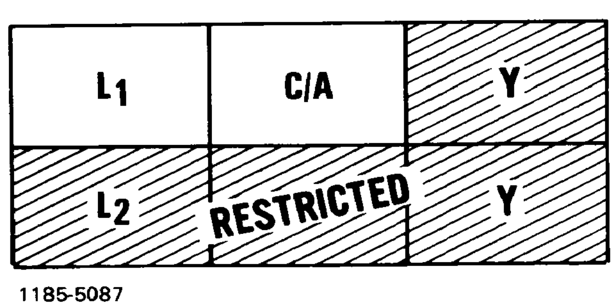

FIG. 6. — The satellites will transmit a restricted Y code.

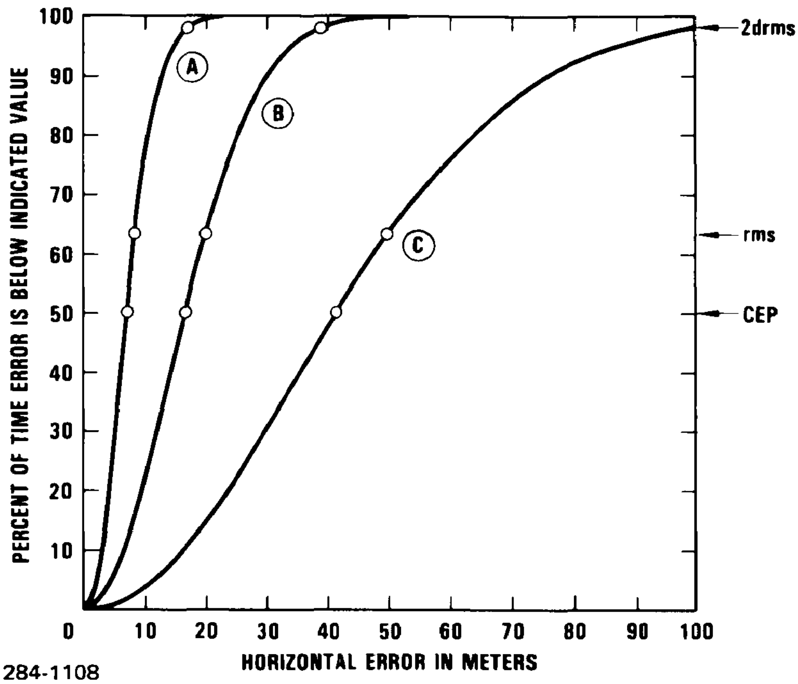

FIG. 7. — Accuracy performance.
A = multi-channel, Y code, controlled access; B = single channel, C/A code, controlled access; C = reduced accuracy, civil access.

multi-channel, two-frequency, P code receiver like the Magnavox X-Set. Curve B shows the results obtained with a single-channel, slow-sequencing, one-frequency, C/A code Magnavox Z-Set. The curve B results were surprisingly good, so a decision was reached to limit the accuracy made available to civilian users until there is no longer a national security threat. Curve C shows the planned level of SA accuracy denial of 100 meters 2 drms (95 % of the time), although future improvements could occur because of the planned annual review process. At this time, however, civilian users needing greater accuracy should direct their attention to differential GPS techniques as described later in this paper.

It is clear that low-cost GPS equipment already is being planned. The fact that the MX-1100 GPS Upgrade Kit described in the next section of this report consists of just two electronic modules, an oscillator, and an antenna unit illustrates that GPS receivers can be quite simple. The trend toward low-cost electronic navigation equipment has been underway for many years, as illustrated by Figure 8. This shows that the minimum price of a Magnavox Transit Satellite Navigator has been declining at a compound rate of about 22 % per year since 1976. Even taking into account the relative complexity of GPS versus Transit, this trend implies that $500 GPS equipment will be available before 1995. We expect GPS prices to be competitive from the moment the system becomes operational and to fall rapidly during the first several years thereafter. Those companies who wish to participate in this market surely will be required to invest millions in sophisticated research and development, manufacturing capacity and technologies, and worldwide marketing and service capabilities.

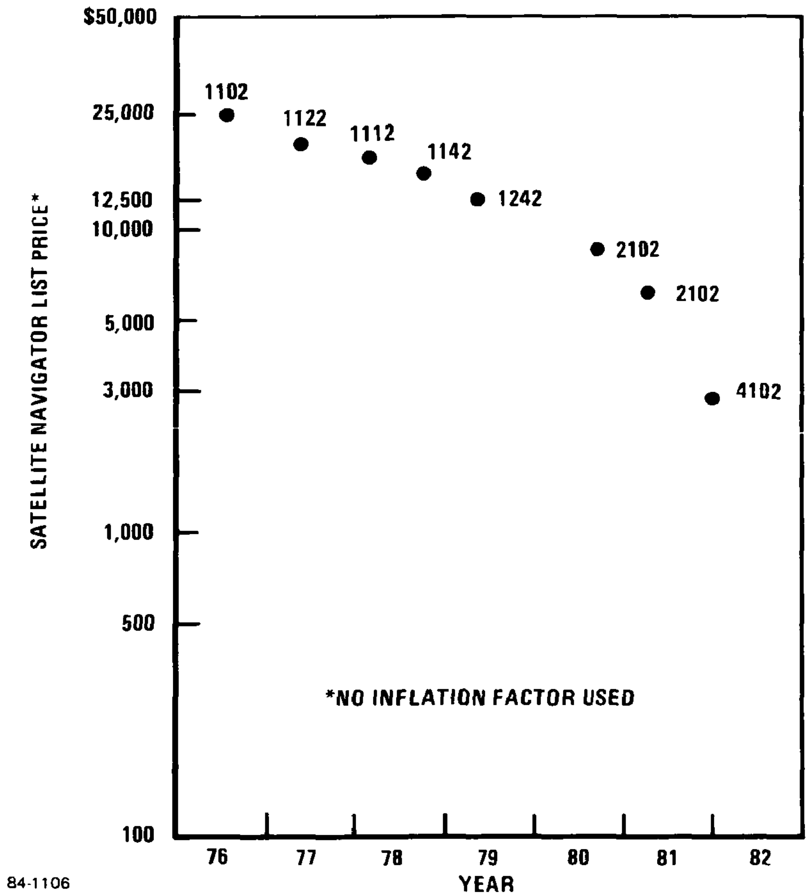

FIG. 8. — The price of Transit satellite navigation equipment has been falling faster than 22 percent per year.

Finally, it is important to mention operational simplicity, which I believe is critical to civil acceptance. GPS is easier to use and to understand than Loran-C, Transit, Omega, or any other navigation system available today. There are no concerns with calibration, lane slips, skywave interference, or notching local interfering signals. The user can turn the set on and without further adjustment begin to navigate accurately and continuously. Of course there are limitations. Terrain, including tall buildings, can obscure the signals. But wherever GPS signals are available, its operation will be truly simple.

Therefore, combining the characteristics of 24-hour, worldwide, all-weather navigation with adequate accuracy, with low cost, and with operational simplicity assures a vast potential market. Ultimately, it is reasonable to assume that there will be millions of users, so that electronic navigation by satellite will become a common experience.

INTERIM APPLICATIONS

Although GPS is not yet operational, the coverage available today permits many practical applications. As a result, several companies, including Magnavox, are selling commercial GPS navigation and positioning products. Figures 9, 10, 11 and 12 illustrate four products available from Magnavox. Figure 9 shows the T-Set which has been available since September 1984. It has been used by the U.S. Coast Guard for aircraft navigation, it is being used to evaluate land vehicle navigation, and it has been used for a wide variety of marine survey and navigation applications, including the successful search for the *Titanic* by the Woods Hole Oceanographic Institution, the navigation and positioning of several offshore drill rigs, and recovery of the Challenger wreckage off Cape Canaveral. In other words, many people are putting GPS to practical use in spite of its limited coverage and in spite of its developmental status.

FIG. 9. — T-Set GPS Navigator.

Since 1976 Magnavox has delivered nearly 6,000 of the MX-1100 navigators shown in Figure 10. Different configurations have provided both Transit and combined Transit plus Omega navigation for surface ships and for submarines. In September of 1985 Magnavox began delivery of "GPS Upgrade Kits" which add GPS to existing MX-1100 Transit Navigators. The kit consists of the GPS antenna unit (or the combined GPS and Transit antenna replacement shown in Figure 10, which avoids running an additional cable), two GPS modules which plug into available slots within the MX-1100 chassis, and another oscillator. The kit permits

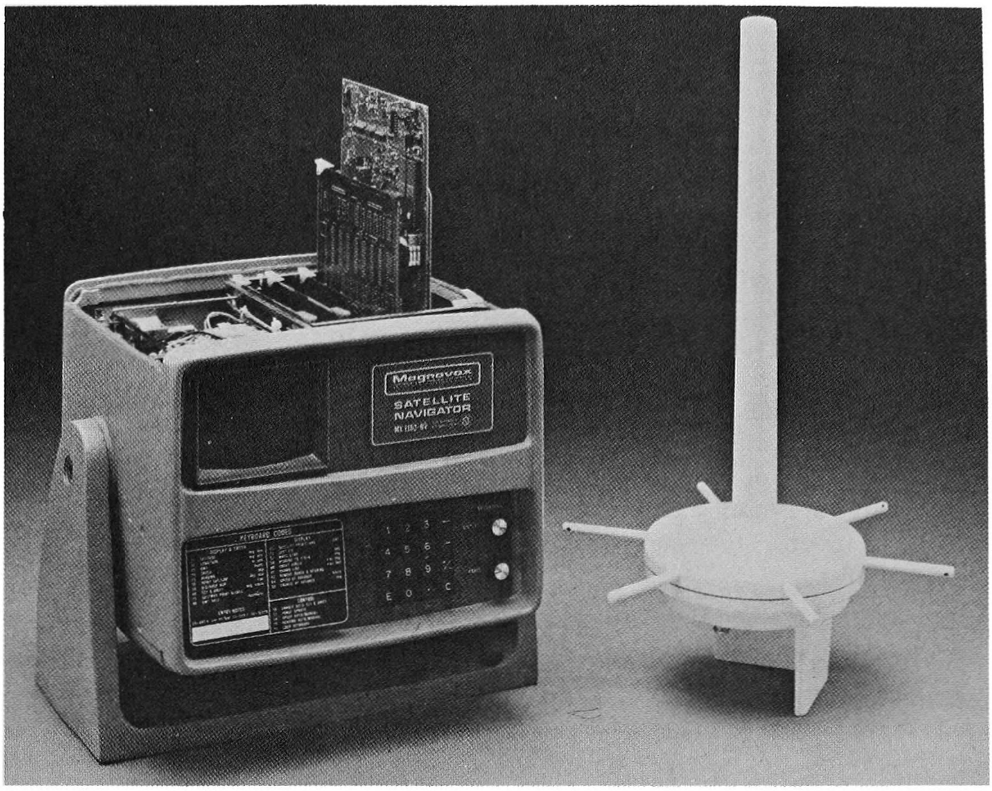

FIG. 10. — MX-1100 GPS Upgrade Kit.

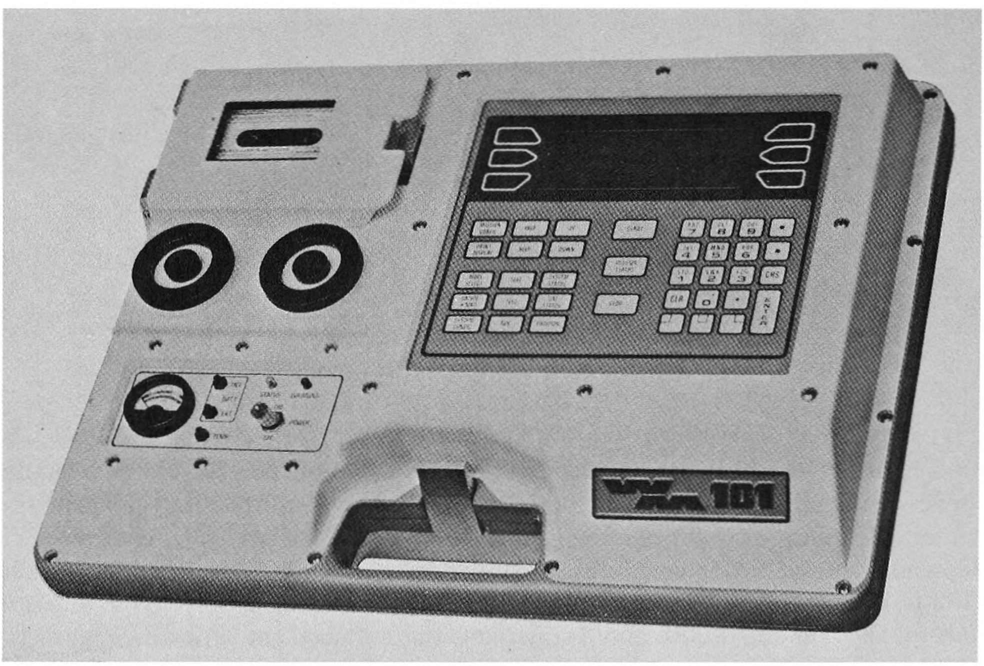

FIG. 11. — The WM-101 satellite surveying set.

GPS plus Transit plus dead reckoning navigation, and very soon it will be possible to include Omega navigation as well. Thus, a navigator is able to use GPS whenever it is available, but continue to operate with Transit and/or Omega when GPS is not available. Each system provides a check on the other, thus reducing risk in the event of a GPS ground control problem. The user experiences the benefits of GPS at the earliest possible date, and the equipment configuration allows an automatic and graceful transition from interim to full GPS availability.

Figure 11 shows the WM-101 satellite surveying equipment being developed in a joint venture with Wild Heerbrugg of Switzerland. Deliveries began in March of 1986, permitting surveyors to obtain 1 centimeter relative positioning results with this field-worthy and portable survey instrument.

FIG. 12. — MX-4400 GPS positioning and navigation system.

Figure 12 shows the MX-4400 GPS Navigator which is being introduced in May of 1986 and which will be delivered before the fourth quarter. It is a compact, low power, fully sealed product compatible with a wide range of land, sea, and air applications.

DIFFERENTIAL GPS

Differential GPS is implemented by placing a GPS monitor receiver at a precisely known location. Instead of computing a navigation fix, the monitor determines the range error to every GPS satellite it can track. These ranging errors are then transmitted to local users where they are applied as corrections before computing the navigation result. With appropriate equipment, the user can expect a real-time accuracy of 2-3 meters (5 meters at 95 % confidence) at distances of 200 kilometers or more from the monitor station. Therefore, differential techniques can be used to provide excellent accuracy in local areas whether or not the absolute navigation accuracy is being degraded as shown by Figure 7.

Differential GPS is of great interest to offshore oil industries. It provides needed accuracy over acceptable distances, and it protects the user from system errors introduced either accidentally during this test and evaluation phase of GPS or intentionally when the system becomes operational. Magnavox is preparing the equipment and the software needed to deploy operational differential GPS networks by mid-1986.

Governments also are interested in differential GPS for similar reasons. The excellent accuracy can be used effectively in harbor, harbor entrance, and river navigation applications. With differential GPS the national or local government is able to assure navigational accuracy and reliability within its own territorial waters.

It is interesting to note that the U.S. Coast Guard is planning a series of differential GPS experiments beginning in 1986. The concept being explored would add a differential GPS signal to existing marine radiobeacons operating in the 283.5 to 335 kHz band. Thus, coastal and inland users able to receive these signals also would be able to obtain the benefits of differential GPS.

Fortunately, it was recognized a few years ago that differential GPS signal standards would be needed in order to permit widespread use. In response, the RTCM (Radio Technical Commission for Maritime Services) formed Special Committee 104 to study Differential Navstar/GPS service. Participation in Special Committee 104 was extensive. Users, manufacturers, and government representatives from the United States, Canada, France, and Great Britain were involved. The work continued for over two years, and the final report will be issued by mid-1986.

The RTCM 104 report recommends transmission frequencies for various services, but — more important — it recommends a specific message format. The minimum data rate requirement is 50 bits per second. The hope is that this document will become a standard for all differential GPS services, permitting inter-operability with equipment from all manufacturers and signals from all shores.

FUTURE TRENDS

As shown by Figure 2, 12 GPS satellites should be operational at some point in 1988. *(Now this will be 1989 or 1990).* It is expected that 12 satellites, if properly spaced, could provide nearly continuous two-dimensional (latitude and longitude) navigation, thus satisfying most marine user requirements. Factors which will depress the expected enthusiasm for universal marine use at that time are : (1) the system probably will not be declared fully operational by the U.S. Government until 18 satellites can be fully assured, (2) the 12-satellite constellation probably will continue to have some coverage gaps, depending on location and time of day, and (3) many less progressive users will take a "wait and see" attitude. Nevertheless, 1988 *(now 1989 or 1990)* is the year when massive use of GPS is expected to begin.

Although there will be many variations, it is expected that there will be four general categories of GPS marine navigation equipment. First is the very low-cost, battery powered, hand-held set which will be used not only by hikers and explorers but also by small boat operators. The second category is a low-cost product designed for permanent installation aboard pleasure boats, but it will also be used for many light commercial applications. This equipment must be designed for continuous exposure to the marine environment and connection to existing power sources. The third category will be designed for heavy commercial applications requiring many years of continuous, failure-free operation. Also, the user must be able to find trained personnel and spare parts in many ports worldwide. Finally, the fourth category is the GPS sensor which forms part of an integrated navigation or positioning system.

Each manufacturer will seek to provide special features in order to increase market share. There will be interfaces to an external compass, the autopilot, and to advanced radars for map matching. Because every GPS set contains a powerful computer, computational features will abound, probably to the point of confusion.

Every indication is that a very large number of companies around the world are planning to enter the GPS user equipment market. Eventually the user will benefit from the lower prices and improved performance caused by the intense international competition. In the short run, however, we expect to see many companies enter the market only to drop out when competitive pressure becomes too intense and profit margins shrink or disappear. This certainly has been the case when one reviews the history of TRANSIT satellite navigation products, and the number of entries into and departures from the market place will be many times greater with GPS.

As with all new technologies some users will rush to employ GPS as soon as possible, and others, more conservative, will hold back. In the long term, however, the clear advantages of accuracy, reliability, coverage, and simplicity will cause even the most conservative to embrace the new system. Not even severe political differences with the United States are likely to dampen user enthusiasm for GPS, because, regardless of its source, these signals will be seen to serve the purpose of navigation and positioning better than any presently available system.

Government regulations will affect the use of GPS. It is certain that, when GPS becomes operational, the U.S. Coast Guard will accept it for navigation within U.S. waters, just as Loran-C and TRANSIT have been accepted. Eventually, international regulations may require the use of GPS or its equivalent.

The Soviet Union has announced that it is implementing a global positioning system called GLONASS. If the two superpowers vie with each other in providing the best navigation services, the user community presumably will benefit from increased accuracy and signal availability. In fact, instead of having to decide which system to use, equipment may be built to use the signals from both systems simultaneously.

CONCLUSION

GPS will be fully implemented, and it will be used extensively. Some of the remaining questions are :

(1) When will it become operational ?

(2) Will accuracy actually be degraded to 100 meters 2drms ? Part time or full time ?

(3) Will accuracy be improved in the future ? When ?
(4) Will differential GPS be needed, and will it be used extensively ?
(5) How many companies will offer a product ? What features ? What price ?

It will be interesting, even exciting, to see how these questions are answered over the next few years. Whatever the outcome, it is clear that anyone needing navigation should remain aware of the system status and be prepared to take maximum advantage of what is sure to become "the universal radionavigation system".