GPS: SURVEYING TECHNIQUES AND APPLICATIONS

P. Done
Department of Land Surveying
The University of the West Indies
St. Augustine,
Republic of Trinidad & Tobago.

Summary

The Global Positioning System (GPS) is an all-weather satellite positioning system which can give results of high accuracy. Its characteristics are such that it will change the way in which many survey tasks are carried out. The aims of this paper are to summarise GPS technology and to assess its impact on surveying methodology.

1. INTRODUCTION

For over 15 years the TRANSIT system has been a universal all-weather high accuracy positioning system, and will continue as such until at least 1992. However, by the end of the present decade the NAVSTAR Global Positioning System will be fully operational; although it was designed as a military navigation aid, it is the natural successor to the TRANSIT system for surveying. GPS will permit determination of positions with higher accuracy at lower cost in less time than TRANSIT.

In section 2 the GPS concept is described. The three basic types of instrumentation are reviewed in section 3 and the likely impact of GPS technology on surveying is discussed in section 4. This is followed, in section 5, by a Summary

2. THE GPS CONCEPT

2.1 The NAVSTAR Global Positioning System was designed as an accurate military navigation system. When the GPS system becomes fully operational at the end of this decade there will be a total of 18 satellites, three in each of six evenly spaced orbital planes. The satellites will be maintained in near-circular, 55° inclination orbits at approximately 20 200km altitude and have periods of 12 hours. This configuration ensures that 4 to 7 satellites will be visible from any point on the earth at all times. Operational satellites will be launched beginning in 1986; full-time three-dimensional coverage is expected by 1989. Meanwhile five or six prototype satellites are providing part time coverage for testing purposes.

2.2 The GPS ground component comprises four monitoring stations located in Guam, Alaska, Hawaii and California. Each station gathers tracking data on the satellites, collects metereological data and transmits all this information to the Master Control Station where the satellite orbits are determined and spacecraft clock errors calculated. The orbital details, satellite clock errors, ionospheric correction, are placed into a navigation message which is regularly transmitted to the respective satellites, in the same way that the "broadcast ephemeris" message is updated in the TRANSIT satellites.

2.3 Each satellite transmits a unique navigational signal centred on two L—Band frequencies: L1 at 1575 MHz (equivalent to a wavelength of 19cm) and L2 at 1227.60 MHz (equivalent to a wavelength of 24cm). The satellite signals consist of the L—band carrier wave modulated with a "precision", or P code, a "clear acquisition", or C/A code and the navigation message. The primary function of the P and C/A codes is to permit the signal transit time from satellite to receiver to be determined. The transit time when multiplied by the velocity of light gives the range. This contrasts with the TRANSIT satellite surveying system in which the basic observable is the Doppler shift of the transmitted carrier waves. At present the L1 carrier is modulated with both P and C/A codes, whereas the L2 carrier is only modulated with the P code. Both carries contain the navigation message. Although both codes have the characteristics of random noise, they are in fact binary codes generated by a mathematical algorithm and are therefore referred to as "pseudo-random noise". The codes give accurate time marks which, in addition, give details of the time of signal emissions. The signal transit time is essentially the phase shift between identical code sequences (P or C/A) generated by frequency oscillators in the satellite and in the user's receiver, each synchronised with its own clock. All the satellite clocks are synchronised, via the Master Control Station, to the GPS time system. If the receiver were equipped with an accurate clock, synchronised perfectly with this GPS time satellites, the user's position would be defined by the intersection of three spheres of known radii, centred at each satellite. This is in effect, the well-known resection by distance, where the rôle of control is played by the orbiting satellites. Normally receivers will be equipped with a less expensive crystal clock that would not necessarily keep the same time as the more stable satellite clocks. Consequently, this range is "contaminated" by the receiver clock error, and is referred to as "pseudo-range". The user is therefore required to track four satellites and solve four equations in the four unknowns: the 3—D position components and the receiver-clock offset.

2.4 The P code is generated at the GPS clock frequency of 10.23 MHz. One element in the code sequence therefore corresponds to a time interval of about 100 nano-second, which is approximately equivalent to 30m in range. The resolution can be improved to the submetre level by interpolation. The P code does not repeat itself for 267 days. This 267 day sequence is subdivided so that each satellite is assigned a unique one week portion of the code that does not overlap with that assigned to any other satellite.

2.5 By comparison the C/A code is not as complex. It is a code sequence of frequency 1.023 MHz, corresponding to a coarse range resolution of the order of 300m, which can also be improved upon by interpolation. The C/A code repeats itself every milli-second, which implies that range measurements have an ambiguity of integer multiples of 300km. The standard observing procedure is to initially "lock-on" to the C/A code, decode the navigation message and use the "handover" synchronisation data contained therein to switch from the C/A Code to the P Code for precise pseudo-range measurement. This procedure is repeated on the L2 signal to correct for ionospheric refraction in real time.

2.6 It was originally intended that the P code would provide instantaneous (navigational) positioning at the 10m level to authorised users, whilst the C/A code should satisfy requirements of a less precise character at the 100m level. Positional accuracies obtainable with GPS depend on a number of factors:

(1) range precision, estimated to be a few decimetres for P code ranging and 2—5m for C/A code ranging;
(2) atmospheric propagation effects;
(3) ephemeris and satellite clock accuracy;
(4) geometry of the observed satellites relative to the ground receiver.

In initial tests GPS has in fact exceeded expectations; ranging with either P or C/A codes has produced instantaneous point positioning accuracies of about 10m.

As with TRANSIT therefore much higher accuracies are obtained from observations made simultaneously at two observing stations. This is the so called "translocation" mode in which a number of dominant errors produce nearly equal shifts in the estimated positions of both stations, so leaving the interstation vector relatively unaffected. If one of the stations is a control station, the coordinates of the other are relatively accurately determined. Translocation is generally to be preferred to point positioning because of the reduced sensitivity to errors due to timing, faulty ephemeris and refraction.

3. OPERATING PRINCIPLES AND INSTRUMENTATION

At the present time there are three principal techniques for obtaining survey accuracies from the GPS satellite [1]; pseudo-ranging, radio interferometry and reconstructed code modulation.

3.1 The pseudo-range observations are those for which the system was designed and are made for the military by their geodetic receiver TI 4100. This receiver decrypts the coded signal broadcast by the satellite to recover the satellite clock and ephemeris message, which gives details of satellite position. The position and local clock offset are then computed by processing signals from four satellites. This technique is the most simple principle, but access to or knowledge of the precise P code is necessary. This may be denied to non-military users.

The equipment is portable, the receiver together with antenna weighs 27kg. It is a dual frequency receiver, receiving both L1 and L2; theoretically it should be more accurate than single frequency instruments, but due to a lack of published results, this has not been clearly demonstrated. The navigational solution available in real time is quoted as ±30m; the limited published translocation results indicate that submetre accuracies can be achieved by averaging data over a 15 hour period for distances greater than 50km. These results are not significantly different from the present capabilities of the TRANSIT system, but improvements are expected, particularly in a reduction of observing time, when more satellites become available.

3.2 In the interferometric "delay time" measurement method, which is based on the Very Long Baseline Interferometry (VLBI) technique used in radio astronomy, the satellites are regarded as sources of "white" (random) noise many times stronger than the random radio signals received from distant galaxies. Large parabolic radio antennae are not required; the equipment (e.g. the Macrometer) is comparatively small and transportable. Two such instruments are set up, one on a co-ordinated control point. The satellite signals, recorded on cassettes at each station, are processed at base to yield the delay time from wihch the interstation vector is determined, as is VLBI.

This is a relative positioning technique; since the satellite signal is regarded as "white" noise, knowledge of the P and C/A codes is not required. However, ephemeris data is needed, and currently three different sources are available:

(a) directly from Defence Mapping Agency through contacts in that agency;
(b) through a service provided by Litton Aero Service, the organisation that has bought the manufacturing and marketing rights for Macrometer; and
(c) from the broadcast ephemeris as collected by a separate coded receiver.

For relative positioning, the relative accuracy of position fixation is dependent on the accuracies of the orbits of the satellites. For relative positioning, the rule of thumb for determining accuracies is:

$$\frac{\text{Accuracy of Orbit}}{\text{Height of Satellite}} = \frac{\text{Relative Accuracy}}{\text{Distance between stations}}$$

(This assumes all other factors affecting accuracy are negligible).

The Macrometer V—1000 has been on the market for several years. It is a single frequency receiver with reliability and accuracy proven over two years of operation; it is vehicle mounted, and requires a generator supply of 110 volt AC, 350 watt power. Centimeter — level accuracy in three-dimensional relative positioning is achieved in all weathers over distances of several tens of kilometers with observing times of 2—3 hours. Official tests have indicated that the instruments are capable of accuracies of $1:10^6$ [2]. The ionospheric refraction effect is the limiting factor: the Macrometer V—1000 observes the GPS satellite broadcast on L1 only. A dual channel receiver is expected to be available by early 1986 and its producer, Litton Aero Service, expect it to be capable of accuracies better than 1ppm over long distances.

3.3 SERIES (Satellite Emission Radio Interferometric, or Range Inferred, Earth Surveying) is a third technique and is one also based on interferometry. With the GPS signals again being treated as "white noise", no knowledge of the P and C/A codes is required.

Recently, ISTAC, Inc., announced the avaliability of a book-sized antenna/receiver which employs the SERIES technique. This receiver uses a postage-stamp size microstrip antenna and state-of-the art electronics to achieve its light weight (81lbs) and small size. GEOHYDRO, Inc., has recently announced the availability of a back-packable surveying instrument which uses this receiver. This system, named the GPS Land Surveyor Model 1991, consists of a book-sized receiver/antenna, a briefcase-size clock unit, and a sewing machine-sized recording unit, all of which operate on internal batteries. This equipment in effect collapses the broadband GPS coded signals by a "delay and multiply" technique so that a simple sinewave is recovered. The P and CA codes of all satellites in "view" are compressed into audio bandpasses and spectrally analyzed to extract their various amplitudes, frequencies, and phases. This instrument avoids having a computer in each receiver by simply converting the received analogue spectrum into digital data and recording it on cassette magnetic tape for later processing. The main recording unit is a commercially available digital recorder which has been used in the field for several years, so its reliability is well proven.

A major difference between the GPS Land Surveyor and the Macrometer instrument is that the Macrometer requires satellite position (ephemeris) data to be loaded into each unit for each occupation. This requires that a survey be pre-planned and conducted without deviation from the plan. The GPS Land Surveyor however does not require any prior satellite data and it can be used to survey any point desired without having to rigidly preplan the operation.

Observing times depending on accuracies required. The manufacturers claim that second order accuracy (NOAA classification) over lines of 5km and first order accuracy over lines of 10km and longer are obtainable from a maximum of 30 minutes observation (which may take over an hour to process); positioning can be achieved in as little as 3 minutes observing time. It is currently seen as a "several-centimeter" rather than millimeter accuracy instrument, which can perform surveys quickly at a low cost per point; the Macrometer is needed for "millimeter" accuracies.

3.4 Other instrumentation expected to become available in the next year or so includes a WILD–MAGNAVOX product, WM 101, of briefcase size, a TRIMBLE receiver for shipboard rack mounting, a LITTON AEROSPACE Model LTN 700 and the French TR5S SERCEL. The range of such equipment can clearly be expected to widen significantly in the near future and costs will presumably be reduced as competition intensifies, technology becomes more developed and production runs lengthen.

4. THE IMPACT OF GPS TECHNOLOGY ON SURVEYING

4.1 The NAVSTAR GPS system represents a major advance in the science of navigation. At present navigators obtain information about their position either from the stars, dead reckoning, inertial navigation equipment, ground based radio beacons, or the TRANSIT satellite navigation system. There are five TRANSIT spacecraft, in low orbits, and these provide navigators with only intermittent fixes. The other systems offer relatively low accuracy and may be expensive to use and maintain. During the next ten years GPS satellite navigation capability should be installed in most civilian aircraft and ships; thus accurate (± 10m), four dimensional (three coordinates plus time) all weather, real time fixing will be available. No other present or planned navigation system has these attributes and its impact on hydrography, marine geodetic fixing and maritime boundary delimitation can be expected to be great.

4.2 Although GPS was conceived, has been designed and will be operated as a navigational system, much effort has been investigated in developing ways of utilising the system for surveying. Table 1 summarises four broad categories of potential users of GPS, which range from those satisfied with 1 part in 10^4 accuracies to those engaged in ultra-high precision crustal movement surveys which required accuracies of 1 part in 10^7 or better [3].

Table 1: Classification of Prospective GPS Users

Category	Average Accuracy Requirement	Extent of survey (KM)	Relative positioning Accuracy (m)
1. Exploratory/Geophysical	1 : 10^4	10 — 500	1 — 50
2. Large Scale Engineering Projects and Mapping	1 : 10^5	50 — 500	0.5 — 5
3. Geodesy	1 : 10^6	$\geqslant 100$	$\geqslant 0.1$
4. Geodynamics	1 : 10^7	$\leqslant 300$	$\leqslant 0.03$

GPS awareness in the surveying community comprises mainly those surveyors in government agencies, in academia and those users in private industry who are familiar with TRANSIT; they consider GPS as a replacement for TRANSIT for high precision applications. These TRANSIT users will therefore become the GPS users of tomorrow. The majority fall within category 3 (Table 1), while the remainder lie somewhere between categories 2 and 3. Interest in GPS has also been aroused for geodynamic applications (category 4) by virtue of the unique combination of high accuracy, low receiver cost, low operating expenses and high efficiency. Nevertheless all these groups are, to varying extents, familiar with satellite technology. However they will probably represent only a small proportion of all potential GPS users. Most surveyors have never used TRANSIT but are likely to be most impressed by the speed and efficiency with which surveys will be performed using GPS once the system has moved into operational phase. It may be estimated (Rizos et al, 1984) that over 90% of all civilian GPS surveys will probably be carried out by category 1 and 2 users engaged in a wide variety of activities, for example, geophysical surveys, engineering surveys, large scale and rural cadastral surveys and surveys for providing map control, to name only a few. Accuracies of 1 in 10^4 to 1 in 10^5 are involved here. The majority of these users will have had no previous experience with satellite surveying. Therefore the introduction of GPS to surveying practice will be mainly influenced by economic considerations, that is, reservations concerning this new technology will be overcome only if the surveyor is convinced that GPS could perform the positioning function, to the required accuracy, in a shorter time and with greater ease, and hence less cost, than any of the conventional tenchniques. For this to happen, the surveyor would have to satisfy himself that GPS positioning technology is superior to the conventional EDM and theodolite procedures for most tasks.

4.3 As the GPS system becomes fully operational it is likely that the basic code-dependent receivers capable of pseudo-ranging will fall from their present high levels of US$ 100,000 — 300,000 so that they might become comparable in terms of cost with total stations. (The latter, due to short production runs and the fact that combinations of precision mechanical, optical and electronic components are involved, have not undergone, and are not expected to experience, the dramatic price reductions characteristic of the microelectronic market). However for translocation a minimum of two receivers is needed, so doubling the outlay.

For those surveys conventionally carried out by EDM traversing (e.g. the coordination of distinct and unrelated points such as control stations for aerial mapping, establishment of networks of coordinated points to support, for example, — geophysical surveys, monitoring of construction activity, surveying land boundaries or control densification and subsequent detail survey) the natural advantage of GPS in not requiring lines of sight and intermediate setups is eroded if there is a need to have many control points close together. EDM — theodolite, or total station techniques then have the edge in competitiveness. However, there probably will be a critical station-separation above which GPS would be the superior technique. Initially, interstation distances of 30km or more are likely to be most efficiently bridged using GPS; this could drop to 10km. An additional factor to be considered is that GPS gives height information as well. However this height is not the orthometric elevation and must therefore be "corrected" by subtracting the geoid height value.

4.4 For first order control surveys, where accuracies of 1 part in 10^6 are required, the precedent for using satellite techniques has already been set with the widespread use of TRANSIT, which will be replaced by faster and substantially more accurate GPS techniques. A significant fact is that the accuracy of positions determined with GPS is essentially independent of network geometry. Moreover, in contrast to traversing and trilateration, control networks established with GPS are not bound by constraints such as station intervisibility and network shape. With its ability to span distances of greater than 100km, the spacing between control stations in unsurveyed regions can be increased. The increased flexibility of GPS also permits control stations to be established where they are needed in easily assessible places, rather than being confined to hilltops as has hitherto been the case.

For crustal movement studies requiring accuracies of 1 point in 10^7 or better, terrestial methods are the only geodetic methods to have provided sound results. The requirement for these geodynamic studies is distinctly different from mapping requirements in that the objective is not one of establishing absolute coordinates, but of measuring changes in position, displacement or strain; the need is for repetition of measurements under as nearly as identical set of circumstances as possible. GPS should give accuracies of 1cm horizontally and 2cm vertically over 100km baselines from observing times of several hours, and as such will constitute the most powerful observational tool.

4.5 For heighting, the vertical accuracy, while less than that attainable in the horizontal coordinates, will have a major impact on geodynamic studies. The cost will be much less than for precise levelling for distances greater than a few kilometres, and the accuracy will be higher over longer distances or for paths involving large vertical relief. Elevation differences will be obtainable with much greater ease, by smaller teams, and in less time than those required for first-order levelling. Levelling across bodies of water will be much easier. Another important aspect of vertical deformation studies is the ability of GPS receivers to operate without intervisibility between benchmarks. Precise GPS vertical control lines across rugged terrain should be obtainable with comparative ease by teams of two surveyors.

5. CONCLUSION

There are three district groups of surveying measuring techniques, which have evolved to meet particular surveying requirements. The first is conventional terrestrial surveying using line-of-sight direction and distance measurement, the second is inertial surveying, and the third is satellite surveying with TRANSIT. Each has advantages and disadvantages.

Traditional surveying with EDM and theodolite produces relative positioning of, on average, 1 part in 10^5 for distances ranging up to a few tens of kilometres, which is generally adequate for most needs. Equipment costs are relatively low, but a serious limitation is the requirement for station intervisibility. Inertial surveying methods are much faster than the traditional techniques and have the added advantages that stations need not be intervisible. However, a drawback, as far as the average surveyor is concerned, is the large bulk and cost of the equipment. TRANSIT surveying techniques can produce relative positioning accuracies of a few decimetres for station separations of several hundred kilometres. The equipment is compact, easy to operate and inexpensive relative to inertial technology, but observing periods of two or more days are required to achieve the desired accuracy.

GPS Satellite surveying will replace the TRANSIT satellite surveying system for large scale geodetic applications such as control network maintenance and extension. For high precision geodynamics GPS also provides a much needed technique to bridge the gap between terrestrial methods and VLBI. Traditional EDM-theodolite procedures will probably be retained for distances less than 10km or so, while the more established space technique of VLBI remains better suited for measurement of distances greater than approximately 300km. Furthermore, for densification of primary control, GPS will probably displace conventional traversing and trilateration with EDM and theodolites; inertial surveying technology also will share in this field.

6. REFERENCES

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