GLOBAL POSITIONING SYSTEM (GPS): USE AND INTERPRETATION

M. Nabil Aly Shoukry
Transportation Engineering Department, Faculty of Engineering,
Alexandria University, Alexandria, Egypt.

ABSTRACT

The great strides in space technology have provided vast scope for the ultimate objective of locating three-dimensional terrestrial positions to within 10 cm and even 1 cm. Satellite systems producing the accurate geographical charts needed for engineering works and contributing to enhanced knowledge of planet Earth and to various applications, have indeed become quite indispensable for cartographic institutions and engineering consultancy firms. The acquisition of adequate data, and the inherent accuracy of these systems and their global, isotropic coverage makes them the ideal tool for base mapping operations and identifying geophysical movements in the centimetre range. A comprehensive insight into satellite geodesy is presented. A special reference to the relative merits and interpretative use of the up-to-date GPS, which represents a quantum leap in modern technology, is thoroughly discussed. The system, techniques, error sources, applications and comparisons are illustratively presented in an attempt to assess the impact of the system on geodetic surveying. Recommendations are accompanied for the introduction and implementation of GPS technology in Egypt to ultimately benefit from its intermodal applications.

INTRODUCTION

The methods of satellite geodesy afford great possibilities for the determination of the form and dimension of the terrestrial body and of the external gravitational field of the Earth, for the geodetic coordination of very remote points of the Earth, e.g. across oceans, for the provision of a uniform system, etc. Developed sophisticated systems are now eminently suitable for remote monitoring applications, thus making it possible to make continuous remote measurements of tectonic movements, and to observe variations in the thickness of the polar ice caps, ground slippage, and movements of civil engineering structures.

Projects of world-wide geodetic enterprises are materialized by several space agencies, of which the Smithsonian Astrophysical Observations, the U.S. Coast and Geodetic Survey, NASA and the French Centre National d'Etudes Spatiales are the most distinguished. The results of observations are intended for the solution of problems of geometric as well as dynamic geodesy. These observations are normally performed by differently equipped stations with photographic satellite-observation cameras, laser equipment for the artificial illumination of the satellite, laser telemeters, as well as precision radars.

SATELLITE GEODESY

Satellite and Conventional Geodetic Triangulation

The advent of space technology provides an urgent impedus for establishing a precise world reference system. The purposes of a consistent world co-ordinate system are manifold, both practical and scientific. The establishment of such a precise and consistent reference system that embraces the entire world and linking the earth's land masses, is one of the fundamental aims of geodesy. Such a system consists of the geometric and dynamic elements, the former specifying the relative positions of any points in the system, i.e. describing the spatial and the temporal variations in the topography of the earth's surface; while the latter which everywhere define the direction and magnitude of gravity, i.e. developing a mathematical model for the gravitational field associated with the earth's mass. These two groups of elements are theoretically independent, but, in their derivation and application, the distinction is not so. For example, the achievement of terrestrial triangulation can be performed, theoretically at least, without any direct or implied reference to the direction of gravity if vertical angles between stations are accurately measured. This approach however, breaks down in practice for obvious reasons and dynamic quantities must be introduced instead if the co-ordinate system is to be adequately established. It is therefore necessary to express both elements in terms of a single frame of co-ordinates (i.e. they must be used in conjunction and to complement each other), also to establish an unambiguous relation to the astronomical right ascension-declination system.

The major shortcomings of classical geodesy are evident from the following considerations. 1. Conventional geodetic measurements cannot be applied for the bridging of oceans and the linking of land masses. 2. For physical reasons (refraction), it is necessary to circumnavigate the three-dimensional character of the earth's geometry by executing separately the determination of points and heights. 3. It is necessary to introduce locally biased reference surfaces to which the field data collected on the physical surface must be reduced, necessitating the acceptance of certain hypothetical assumptions. 4. Triangulation schemes suffer from the handicap of being subject to irregularities in the direction of the vertical at the observing stations. Inaccuracies of gravity and vertical angle measurements make the relations of these directions of dubious practical value. The influence of the irregular character of the direction of local verticals is superimposed on the long, gentle slopes of the geoid. 5. Gravity measurements, while avoiding the disadvantages caused by plumb-line anomalies, still demand the acceptance of an undesirable amount of hypotheses during the reduction of the corresponding field data. 6. The physical measurement of determining the third coordinate (height) by leveling, can be reduced to a geometric length only by making some certain assumptions about the mass distribution along the route of leveling. 7. Finally, unfavourable error propagation may arise for very large areas due to earth curvature and to the limitation of the side lengths of triangulations, thus causing systematic errors. In accordance, the accurate relative positions of distant points are uncertainly defined. Here again, hypothetical assumptions are necessary in order to reduce control measurements to a suitable form for incorporation into the basic triangulation.

The foregoing presents some of the problems confronting classic geodesy. Results of conventional geodetic methods are derived by a cycle of iterations, where the field data are made compatible within themselves and with certain hypothesis which are accepted a priori. The geodetic information obtained in a specific area is significant in terms of a specific datum only, and it is undesirable to amalgamate these different datums established by conventional methods into a world datum. Such a task can be accomplished by traditional geodetic methods only with the aid of gravitational measurements. The corresponding results would still however, suffer from the uneven distribution of gravity measurements (particularly the lack of data over ocean areas).

In the course of the last decennium, photographic observations of the Earth carried out by artificial satellites have resulted in an increased precision of the geodetic constants of the terrestrial body. When evaluating the results, an abundance of geodetic and geophysical knowledge of great scientific and practical importance has been achieved [1], and the systematic errors in classic geodetic datum parameters are discovered. Precise satellite tracking is required in order to correlate measurements with position and orientation in space, and accordingly, a detailed knowledge of the tracking station positions and of the earth's gravity field extended outward into space is demanded.

The application of geometric satellite triangulation allows the determination of the three-dimensional positions of ground stations without reference to any geophysical hypotheses, specifically without reference to either the direction or magnitude of the force of gravity. The process of three-dimensional satellite triangulation necessitates the determination of a triple of orthogonal coordinates for each point included in the triangulation scheme (ground station and satellite points) in an arbitrary but uniquely defined cartesian reference frame. This coordinate system is related unambiguously to intertial space, represented by the right ascension and declination system, connecting terrestrial, celestial, and orbital systems.

Geodetic results from spatial triangulation can be obtained by redundant and simultaneous measuring of either the directions from at least two, or the ranges from at least four, ground stations to a specific satellite.

The previous does not infer that the classic existing and established methods of geodesy are invaluable and should be supplanted by satellite geodesy, but rather to imply that artificial earth satellites offer perpetual developed approaches to solving the basic problem of geodesy and are continuously providing new tools for the establishment of precise applications. Reformatory developments in geodesy do not constitute any significant departure from classic concepts.

The two satellite independent, yet complementary methods provide the geometric reference system and the dynamic one.

The Geometric Method

In the geometric method the satellite orbit is considered as completely unknown. Due to its considerable altitude, the satellite can be used purely as an elevated point in space observed simultaneously from different ground stations. The three-dimensional cartesian coordinates of the satellite positions are determined from the coordinates of the known ground stations by intersection. From these computed satellite positions the coordinates of the unknown ground stations are determined by resection.

The Dynamic Method

Contrary to the geometric method, where the satellite orbit is unknown, the dynamic method involves the shape of the satellite's orbit and its motion within the orbit itself. After the initial and free flight release, only natural forces acting on the satellite influence its orbital track and force it to move around the earth into an orbit. Of these natural forces, gravitation is the most important. Considering the earth as a point-mass and applying Newton's law of mass attraction (to earth and satellite) and Keplin's law of motion, the information of the earth's gravity field can be used to determine the satellite ellipsoidal orbit in space, i.e the three-dimensional cartesian coordinates of the satellite are known at any time during the satellite observing period. Thus, observations to the satellite can be taken from unknown ground stations and their coordinates are determined by involving just the resection process.

Other perturbing natural forces however, which may be of a specular nature and others periodic, affect the satellite trajectory and presume it as not being a fixed ellipse. Atmospheric resistance, electrostatic and electromagnetic fields, and the sun's radiation pressure are such forces. Also effective, is the unsymmetrical sphericity of the earth's gravitational force field due to geoid undulations, equatorial bulge and polar flattening.

Observations for Determining Satellite Positions

The observed quantities determining the satellite positions w.r.t the tracking stations are directions, ranges and range rates; the first two are of utmost importance for the geometric method, and a combination of the three for the dynamic solution. In addition, a high degree of accuracy of an order of less than a millisecond is required for the instant of observation.

1. Directions

Direction observations are made either optically or electronically. The former means utilize precision photogrammetric reduction techniques [2], [3] that give accuracies of geodetic significance and directions that refer to a consistent stellar framework rather than a local reference system. To date, cameras of extremely advanced technology are employed to furnish a photographic record of the satellite trail segmented by a rotating shutter, a number of star images which provide the reference points and the time records at which the satellite trails have been interrupted and at which the star exposures have been made. This intensive information thus determines the satellite position in the astronomical system at a known time instant, namely, the declination and right ascension of the satellite at the instant of observation.

The chief sources of uncertainty influencing direction observations are errors introduced by time measurements, turbulent atmospheric refraction, plate measuring errors and uncertainties in the reference star catalogues used. Improving the accuracy of a direction in space is possible by curve fitting and interpolation techniques. A polynomial fitted through the positions of a sequence of satellite image recorded at short intervals and, by interpolating for an arbitrary instant, a fictitious satellite position of higher accuracy than the individual observations can be computed. Particular methods of interpolation vary, such as the Smithsonian Astrophysical Observatory which uses a modified plate constant method, or the Coast and Geodetic Survey which uses strictly photogrammetric techniques. Other establishments employ both approaches. Satellite photography is a major breakthrough in resources surveys. It offers great advantages to less developed countries like Egypt, which are in general poorly mapped and greatly in need of resources surveys.

2. Laser pulse ranging

Range measurements to satellites independent of celestial optics, employ either microwave or optical frequencies; the latter in the form of pulsed lasers which is of the most developed techniques for measuring the positions of satellites and which affords another essential increase in accuracy. Of these, is the Secor system [4] used by the U.S. Army Corps of Engineers and which is essentially a method of space trilateration. The transit time of high-energy emitted pulses of ruby lasers is measured, i.e. the distance observer-satellite-observer. Using the exactly determined value of light velocity, the distance satellite-observer may be ascertained. At least six of these values are necessary for the determination of the orbit [5]. During the periods of transmission, over 1000 distance measurements a minute can be accomplished by each ground station and, as the satellite is within range for some six or more minutes of observation, a vast amount of observed data can accumulate. The provision of so much data can be seen as a major advantage of satellite geodesy. The much more intensive energy contained in a single laser pulse and the more refined collimation of the beam makes lasers advantageous over conventional radar.

The application of high-efficient lasers, optical systems and improved laser techniques (double Q-switching and other frequency doublings) have greatly overcome the basic limitation problem of the measuring accuracy which was previously falsified by a number of influences that are of incidental or systematic nature, namely, the disknowledge of the exact light velocities, frequency error of the standard, fluctuations of the optical path length in the atmosphere [6], [7], finite resolution of the counter employed and finite time extension of the transmitter pulse including pulse distortion by the receiving electronics and the finitely extended retro-reflector.

Developed frequency doubling techniques have made it possible to reduce the pulse width to less than 1 ns, so that measuring errors of less than 0.15 ns are now easily attained. Without considering the error caused by insufficient knowledge of the light velocity, the above elaborations yielded overall measuring errors of approximately 2m, however, technical advance now yield measuring errors of approximately 10 mm or less. With a distance of the satellite of 1 Mm, this corresponds to a remarkable relative measuring accuracy of 1.10^{-8}.

It is obvious however, that the combination of both, the direction and ranging methods, yields dependable results for the execution of geometric satellite triangulation. The great penetration power of laser pulses is employed to illuminate satellites when in the earth's shadow, and to determine the directions and ranges simultaneously by photographing the momentarily illuminated conspicuous satellite against the star background as well as measuring the time interval of the pulse travel.

A main objective of laser pulse ranging is to monitor lithospheric mobility over medium to large distances by repeated precise geodetic network surveys, thus contributing to earthquake research. The Wegener (NASA) program found interest in the tectonically complex earthquake-prone area of the Mediterranean for proposed crustal movement research. The tectonic pattern expected to prevail in the Eastern Mediterranean was considered [8], in an attempt to design a network (in which Egypt was amongst) optimally for verifying and detailing the alleged motion, which was not to exceed 4 cm/year anywhere in the area. The final deployment plan was unfortunately constrained by funding levels, logistic considerations, measurement strategy, etc. Evidently, the revival of such a program with Egyptian participation will certainly achieve great benefits for investigations of lithospheric motion in relation to earthquake research.

Concerning microwave measurements, the principal uncertainties are due to ionospheric refraction [9] and the calibration of the system. The significant distinction however, between laser and micro-wave methods of ranging lies in the nature of their error. For the former, error sources tend to be random from one measurement to another, while the latter observations are seriously subjected to systematic errors which may persist for the entire satellite pass.

TRANSIT DOPPLER SYSTEM

The Doppler effect is the frequency shift associated with the motion of a moving source. If a source of a constant frequency is moving at constant subsonic speed through a homogeneous medium, wave crests emerge from the source, each spreads out from its point of origin as a sphere with radius growing with a certain speed. The successively generated spheres are closer together ahead of the source, but farther apart behind the source. The number of crests passing a stationary observer per unit time determines the frequency associated with the disturbance, and in essence, the frequency received is higher ahead of the source but lower behind it. A common instance of this Doppler shift is the drop in frequency of a whistle speeding by.

The Transit system developed by the U.S. Navy, is based on the Doppler effect. The satellite emits a continuous signal to the receiver, and the time delay of the signal due to its travel through the atmosphere is accounted for. Because of the relative movement of the satellite w.r.t. the receiver, the emitted constant frequency is Doppler shifted to a continuously variable frequency [10]. The receiver counts the number of cycles received and which is performed in terms of the "Beat-frequency", which is defined as the difference between a constant reference frequency and the received Doppler shifted signal. From this operation, the "integrated Doppler count" N is obtained. Performing the individual integrations separately, and with the essentiality that the number of cycles received (receiver time) must be equal to the number transmitted (satellite time), then the basic Doppler count equation may be defined, and which incorporates the range rate or distance difference as an unknown.

Before generating the observation equation to the individual Doppler counts, these are corrected for the refraction effects through the ionosphere and the troposphere, and for the effects of instrumental errors. The use of two-frequencies [10] enables the effect of ionospheric refraction to be computed and eliminated. As for tropospheric refraction which tends to lengthen the observed range to the satellite, there are several models [11] for correction. Finally, the elimination of instrumental errors [11], of which the most significant are antenna phase errors, receiver phase errors, receiver time delay variations, and clock and oscillator errors, can be performed through improved instrument design.

The Doppler mathematical model expresses the relation between the corrected range difference, the known satellite cartesian coordinates and the unknown ground station coordinates. In this technique, since the orbit is completely known, simultaneous observations from known and unknown ground stations is not required as in the case with satellite triangulation and trilateration. Here, observations are directly only from unknown ground station to several satellite positions. Having three unknown coordinates of the tracking station, at least four satellite positions are needed, providing three successive range difference measurements, making three mathematical models necessary for solution [12].

Doppler in Egypt

Geodetic operations employing the Doppler satellite positioning technique with precise ephemeris were first introduced in Egypt in 1977 by a British surveying group in an effort to strengthen and improve the Egyptian datum by computing new coordinates for a total of 24 existing stations of the Egyptian geodetic network. Twelve of these were interlying stations on the first-order geodetic network, while the other twelve were of second and third order. The work was completed in a period of approximately eight months, and the results indicated an average accuracy of the position solutions for the 24 points of about 1.5 ms (it is worthwhile to mention here, that this precision is independent of the length of the measured lines, i.e. whether short or long lines [13]).

A second major Doppler satellite positioning operation was undertaken later in 1979, by the Canadian Geodetic Survey in a mission considered, on a national level, to be of great significance. A special group from the Doppler section was assigned to establish a first-order network for six stations in the Delta region. Observations were taken over a period of two months, with the aim of establishing a basis for auxiliary networks of lower order and traverses, all to be subjected as control stations and monitoring points for checking up the sedimentation and corrosion actions of the river Nile in the rich Delta region.

Two modes of observations were performed. The point positioning mode in which observations of at least 30 passes were taken at each station throughout three days for accurate measurements of coordinates. The second was the relative positioning mode in which a translocation technique was used. The Tora master station was continuously observing until all observations in the rest of the other five stations were completed. The computer tape of each slave station was compared with that of the master station in order to sort out satellite passes that were observed from both, master and slave stations. The translocation solution was then performed between these two stations to determine the relative position of the slave station w.r.t. the master station. The results of both modes, point positioning and relative positioning were compared and adjusted to obtain final position solution of the five stations.

Aside from geodetic operations, Transit Doppler satellite observations have been also utilized in Egypt for seek of resource purposes as oil and mineral explorations.

GLOBAL POSITIONING SYSTEM (GPS)

Configuration and Concept

Methods of obtaining dependable results are in active development and are constantly being influenced by technical refinements. For this reason, it is inevitable that there must always be a certain amount of latitude in future investigations.

The Navigation Satellite Timing and Ranging Global Positioning System (Navstar GPS) is an all weather, high accuracy, rapidly developing positioning system. Over the past two decades, the Transit Doppler system has continuously been a high accuracy positioning system. However, the full deployment of the Navstar GPS now allows suitably equipped users to instantaneously determine their positions and velocity, and to determine absolute point positions and relative positions with greater accuracy, at lower cost, and in less time than any other method available.

With the full configuration of the GPS system, a total of 18 satellites, three in each of six evenly spaced orbital planes, are maintained at an approximate altitude of 20,200 Km (12-hour revolution period). The orbits are near-circular with an inclination of 55^{o} to the equatorial plane, optimizing worldwise coverage. This configuration ensures the visibility of four to seven satellites from any point on the earth at all times, permitting continuous three-dimensional positioning and navigation [14]. A 24 hour positioning service at any point on the globe is being provided.

The GPS satellite technique, as with the Transit satellite Doppler positioning system, permit either absolute point positioning of ground stations relative to the known satellite positions, or relative positioning of two or more ground stations which observe common satellites simultaneously.

Each of the monitoring stations comprised in the GPS ground component, gathers tracking data on the satellites, collects meteorological data and transmits all this information to the Master Control Station where the satellite orbits are determined and spacecraft clock errors calculated. A navigation message which includes the orbits, satellite clock errors, ionospheric correction, etc. is regularly transmitted to the respective satellites.Every GPS satellite transmits a unique navigational signal and timing using cesium and rubidium atomic clocks. The satellite continuously radiates wide-band pseudorandom noise signals centred at two L-band frequencies, L_1 at 1575.42 MHz and L_2 at 1227.60 MHz (19 and 24 cm wavelengths). These carriers are modulated by a message signal transmitting satellite timing and positioning information; the modulating codes are a "precision" (or protected) P code and a "clear acquisition" C/A code. These codes permit the determination of the signal transit time from satellite to receiver [14]. Multiplying the transit time by the velocity of light gives the range.

The L_1 carrier is modulated with both P and C/A codes, whereas the L_2 carrier is only modulated with the P code. Both carriers contain the navigation message. Only P code ranging on the two frequencies allows the ionospheric refraction correction to be determined. The intentional absence of a C/A code on L_2 is one of the accuracy limitations imposed on non-authorized users of the system due to military restrictions.

The codes are accurate time marks that tell us when the satellite signal is emitted. The signal transit time is essentially the phase shift between identical code sequences (P or C/A) generated by frequency oscillator in the satellite and in the user's receiver, each synchronised with it's own clock. By ranging simultaneously to three satellites, the user's position is defined by the intersection of three spheres of known radii at each satellite. This range is contaminated by the receiver clock errors (difference between receiver crystal clock and the more stable satellite clocks). This quantity referred to as the pseudo-range, requires the user to track four satellites and solve four equations in the four unknowns, the 3-D position components and the receiver-clock offset.

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 L_2 signal to correct for ionospheric refraction. All this is accomplished in real-time. Pseudo-ranging with codes was the manner in which the GPS system was designed to function for real-time navigation. The P code facility is restricted to authorised users, while the C/A code facility is freely available.

As far as surveying applications are concerned, the techniques for obtaining the highest precision from GPS are based on measurement of the phase of the L-band carrier waves and are thus independent of the operation of pseudo-ranging with codes [15]. Although some instrument designs require a knowledge of the C/A code in order to perform measurements on L_1 carrier wave, there is no need for surveyors to have access to the restricted special P code. In some instruments, and in order to satisfy the highest precision requirements (better than 1 part per million) the P code is needed for carrier phase measurement on both L_1 and L_2 frequencies to permit the determination of the ionospheric refraction.

GPS Measurement Techniques

Several modern observation modes and processing techniques are used in GPS measurements, such as the carrier or the code. The principle of the carrier phase measurements is to monitor the change of carrier phase over a given interval after removing the P and C/A modulations. The L_1 or (L_2) carrier frequency is 154 times (or 120 times) higher than the P code frequency of 10.23 MHz and hence allows for a much higher resolution in measurement. A second method based on the continuously integrated Doppler count method determines the range rates in dynamic positioning (receiver to satellite over a given interval of time). This measurement of range difference is obtained from the change of the code phase over this time interval, and is equivalent to a change in pseudo-range.

Carrier phase measurements provide the breakthrough in accuracy for geodetic applications. The carrier cycle, compared with a 100 ns P code resolution and 1 microsec C/A code, permits measurement resolution which are better than 0.6 ns. Interpolation yields an equivalent linear measurement of subcentimetre precision. Carrier phase measurements can be performed in two manners. In the "reconstructed" carrier phase approach, replica P and C/A codes generated within the receiver are used to clear the incoming signal of the modulations leaving the two carrier frequencies L_1 and L_2. A second approach is to make carrier phase measurements on the received satellite signals directly. GPS receivers based on this principle do not presuppose a knowledge of the P and C/A codes for their operation, and are therefore attractive prepositions for surveying and geodesy.

Carrier measurements are subject to ionospheric phase delay, and code measurements to ionospheric group delay, which are of the same magnitude but opposite sign [16]. The former depends on electron content and affecting the carrier signals, while the latter depends on dispersion in the ionosphere as well, and affects signal modulation.

The differential or translocation mode provides the highest accuracy for relative positioning. In the interferometric technique, and based on the principles of Very Long Baseline Interferometry (VLBI), the GPS satellites are treated as sources of random noise, and the measurements sampled at intervals and recorded an tape. The data from two stations are then cross-correlated to determine the time delay, i.e. the difference in the ranges from the two stations to the same satellite. Receivers specifically designed to operate in this mode do not require knowledge of the GPS codes. The accuracies which can be achieved by (VLBI) are unprecedented. Polar motion, which optical methods could determine to no better than 0.5 to 1.0 m at best, are determined to 1 cm in each component. The lengths of vectors between stations separated by thousands of kilometers are obtained to 1 to 5 cm. Most amazing, is that these accuracies can be easily achieved during a very short observing period. Observations can be made day or night in all weather conditions, thereby assuring highly successful, simultaneous observations from all participating stations.

GPS Receiver Instrumentation

All GPS receivers intended for surveying and geodesy potentially satisfy the highest positional accuracy requirements, provided that high precision ephemerides are available. A capsule description of some developed receivers, whether code-dependent or codeless, is given below.

The TI4100 Geostar GPS receiver built by Texas Instruments, Inc., is highly suitable for all positioning requirements, from navigation to precise geodetic applications. Being sponsored by the DMA, NGS and the U.S. Geological Survey, it is referred to as the triagency receiver. This device can observe up to four GPS satellites on both L_1 and L_2 frequencies in P code and on the L_1 frequency in C/A code. It is a single channel receiver that uses time-sharing of the single channel to allow continuous tracking of the four satellites while also reading the navigation message from all satellites. Simultaneous pseudo-ranging to four satellites yields the instantaneous receiver position with a centimetre precision. Knowledge of the codes provides the user with alternative measurement options for the use of geodetic requirements.

The Macrometer V-1000 Interferometric Surveyor, manufactured by Macrometrics, Inc., Massa., U.S.A., was the first GPS receiver specifically designed to exploit the advantages of GPS while minimising the disadvantages. A considerable advantage and a major feature of the Macrometer is its capability of tracking the phases of signals of as many as six satellites simultaneously without requiring a knowledge of the codes. The fundamental measurement made by the V-1000 is the difference between the phase of the carrier signal transmitted by the satellite and the phase of a reference signal generated within the receiver. The measurement precision thus obtained is of the order of a few millimetres in range units.

In normal operations, two receivers are developed at two stations, and the phases measured simultaneously by them are differenced. The obtained quantities are "single-differenced" (receiver clock errors), "double-differenced" (cycle slips), or " triple-differenced" which is simply the change in double-difference from one observation to the next. The different merits of different processing techniques and the method of analysing the data [17], vary according to the above-mentioned observables.

Point positioning with the Macrometer is more precise and efficient than with Transit, due to better GPS orbits, expanded GPS constellation, dual-frequency observation, longer data spans and optimal data sampling. Dual-frequency receivers are the main candidates for high precision geodetic applications. Baseline accuracies of 1 part in 10^7 are achieved, demonstrating the revolutionary capability of the GPS system, thus satisfying all user requirements. GPS tracking and orbit determination facilities are being established all over the world to support all types of GPS surveying activities.

Another codeless example of receivers is the Series, built by the Jet Propulsion Laboratory. Developed techniques track the carrier waves and generate two signals with the same frequency as the basic element of the digital codes. Phase measurements are then made on these waves as is done on the carrier waves; three classes of phase measurements, each with an ambiguity, are thus obtained. The cycle ambiguities are systematically resolved and precise pseudoranging is performed. The Series instrument was intended for crustal motion studies of a centimetre level accuracy for distance measurements of widely separated points; an accuracy of 1 part per million has been achieved.

The Istac receiver is a development of the Series receiver. It is more compact, more efficient and less expensive, and is used in a multitude of applications on land, sea and air. Like the Macrometer, it does not extract the satellite navigation message, can track several GPS satellites simultaneously and can be operated in the relative or point positioning mode. The Istac is a codeless receiver.

Sources and Nature of Errors

The errors affecting GPS measurements can be divided into three groups: 1) errors originating at the satellite (ephemeris, satellite timing, oscillator stability), 2) propagation errors (ionospheric and atmospheric), 3) errors originating in the receiver (receiver delays, noise oscillator stability).

The satellite positions involved, whether predicted or computed, represent the main error sources, and sizeable biases as well as random errors are present [18]. As for refraction effects, ionospheric refraction which is frequency-dependent, can be accounted for from the behaviour of the two emitted carrier frequencies. Models for tropospheric retardation of systematic behaviour will depend on the meteorological structure of the troposphere; the dry component using observed values and the much smaller wet component. These two effects are relatively constant over extended regions of about 100 Km [18]. Accurate water vapour data obtained from water vapour radiometers, along with data from surface meteorological equipment, allows the calculation of the path delay resulting from tropospheric water vapour. Finally, w.r.t. the third group of error sources, some applications require long term oscillator stability, others need short term stability. In accordance, the performance of the satellite and ground oscillators (used for timing) is quite critical. Also, the various methods of timing the signals are associated with different kinds of errors. The minimization of these errors is a major goal in the continuous GPS research. There may also be systematic errors in the point determination from time delays experienced with the satellite receiver.

GPS Survey Structure

Different optional strategies are possible for survey planning. Each network mark may be occupied during three separate observing sessions, or only twice in a more economical survey. Also a network loop configuration or an areal configuration may be considered. No two marks are jointly occupied for more than one observing session [19], efficient networks being thus produced. The maximum number of distinct, directly observed lines for the given number of receivers and observing sessions is thus yielded. Also survey economy by reducing travel time between observing sessions is favoured by observing over those lines connecting marks near one another.

The three vector components connecting the occupied marks are obtained through the observations of the simultaneously received signals, of two or more receivers, from the same set of satellites. The productivity per observing session will increase as the number of receivers increase, irrespective of the number of separate vectors or the number of independent vectors. The structure of GPS surveys and total productivity, are also dependent on the receiver deployment efficiency from observing session to another.

Triple occupation of marks provides greater survey reliability than economically-favoured double occupation, since each mark would be positioned relative to the remainder of the network on three separate occasions. Also triple occupation generates 1.5 times as many independent observations as double occupation [19], resulting in greater precision of determining the coordinate differences between marks.

GPS Ephemeris

An important limitation on the precision of GPS surveys is the accuracy of the ephemerides available for the data reduction. A given error in the satellite ephemeris introduces an error in a baseline reduced by the ratio of the baseline length to the satellite's altitude (20000 Km for GPS), i.e. a 20 m orbit error will result in an error of 1 cm in a 10 Km baseline.

For a country of small geographic extent like Egypt, the quality of GPS orbits computed from tracking data acquired over a large area of the globe would be superior to those based upon strictly local tracking . In the case of the U.S.A. - Western Europe GPS consortium, survey organisations can operate in the Middle East and North Africa with minimum additional effort and expense. On the basis of geographic considerations alone, a truly global tracking network must include a station or more located in the Egyptian region. Bilateral co-ordination agreements in operating a global tracking network and in return gaining unvetted access to the computed GPS ephemerides is certainly a very attractive option. The introduction of such GPS positioning technology into Egypt requires an option which grants the greatest degree of independence and the maximum investment of Egyptian resources.

Besides the above-mentioned global tracking network consortium, which involves an external ephemeris facility, other ephemeris service options would be a: regional, national, state level, or private GPS ephemeris facility. The relative merits and drawbacks of these facility schemes are based on considerations such as cost to establish and maintain an ephemeris generating facility, the level of ephemeris accuracy possible, ephemeris dissemination problems and the long-term reliability of such a service. Each option has its advantage and disadvantage when these factors are all considered.

An ideal option would be an ephemeris service based on a global tracking network with Egyptian participation, where the costs are spread evenly and the final orbital information is freely available to all users, thus avoiding annoying conditions which may be placed on civil access to computed ephemerides.

GPS Against Transit, EDM-theodolite Total Station and VLBI

A good majority of GPS surveys will, in time, be carried out by civilian users engaged in various activities such as geophysical and engineering surveys, ground-based relative positioning for crustal movements, large scale as well as rural cadastral surveys and finally surveys for adequate map control. The appreciation of the superiority of GPS positioning technology over other procedures is obvious when regarding economy considerations, required accuracy, shorter duration, greater ease and less cost.

The continuous fall in cost of GPS instruments has made them comparable to those of total-station sets, and has broadened the range of tasks for which they are used. Where ease of operation is concerned, GPS is as easy to use as medium or long range EDM. Furthermore, GPS observations and reduction procedures do not require a high degree of operator training; for instantaneous positioning, the solution software resident in the receiver require the minimum of operator input. As for the efficiency of the system with regard to time spent, GPS affords an instantaneous point positioning accuracy at the centimetre level, with either C/A or P code pseudo-ranging.

The productivity of GPS may also be shown when regarding station-separations, as example, the establishment of a network of coordinated points to support a geophysical survey or control densification, the monitoring of construction activity and surveying rural land boundaries. Great interstation distances are most efficiently bridged using GPS.

Besides the relative competitiveness between GPS and EDM-theodolite procedures, GPS can also compete with Transit Doppler and other conventional methods. Unlike Doppler, the Navstar GPS gives higher accuracies over extended distances of tens of kilometres, and is much faster in point fixations. The system offers better satellite oscillator stability, reduced ionospheric refraction effects due to the higher frequencies of transmitted signals (1227.60 and 1575.42 MHz for GPS against 150 and 400 MHz for Transit). Individual satellite receiver contact times for GPS is tenfold that of the Transit, due to the 20,200 Km orbital altitude for GPS against 1000 Km for Transit. Also, GPS orbits present a constant ground track, resulting in identical receiver-to-satellite pass geometry each day, whereas that of the Transit changes with each pass. In addition, and of a great importance, is the extraordinary GPS configuration which incorporates 18 satellites (6 for Transit), and which enables the permanent visibility of at least four satellites with 20° or higher elevation angles from any point on the earth's surface [14].

As for conventional methods, and in contrast to traversing and trilateration, GPS control networks are not bound by classical constraints such as station intervisibility and network shape. The spacing between trig stations in unsurveyed regions can be increased with its ability to span distances of great lengths. Also the system's increased flexibility permits the establishment of control stations in easily accessible places rather than being confined to hilltops as has hitherto been the case.

The space measurement technique using (VLBI) is a highly efficient method for monitoring global plate movements and large scale deformation within the plates. However, the required equipment and personnel costs discourage the deployment of such a system in the density necessary to study crustal deformation mechanisms at short baseline lengths that are of interest in most seismic zones. In contrast, the cost of making differential measurements using GPS receivers is low enough to consider their use for large numbers of crustal movement measurements with short baseline lengths. The GPS receivers are inexpensive compared to (VLBI) equipment and the personnel requirement is only one operator per receiver.

Clearly, GPS can ultimately be applied to many of the geophysical problems presently studied using ground techniques over short baselines. The use of the system however, for long baselines, is most advantageous. Accuracy-wise, GPS is competitive to the two-colour laser geodimeter, and is also a factor of two more accurate than the single-wavelength geodimeter, let alone its technical superiority.

Specifications Required

Developed specifications and guidelines for the establishment and use of a validation network for GPS surveys are essentially required, particularly specifications for achieving urban second-order relative positional accuracy. GPS observation accuracies are dependent on the geometrical strength of the satellite configuration and observational errors, both systematic and random. Systematic errors affect the results significantly, while the effect of accidental random errors is almost negligible. Thus, the proposed specifications and guidelines should be directed to enforce some basic procedures for the elimination of these systematic biases. Also, a serious impediment to the proper validation of GPS results concerns the lack of realistic covariance matrices for the adjustment results, thus leading to incorrect conclusions. The generation of reliable and compatible GPS covariance matrices is inevitable.

The trend for furnishing GPS urban specifications is the great emphasis on the contractor qualification concept [20], rather than the strict specification of procedures. Potential contractors should be required to qualify for GPS surveys before being allowed to bid on any survey, demonstrating their ability to meet specific accuracy level (involving equipment, field procedures and software).

A developed specification document [21] should involve various elements, starting with the survey design (higher-order GPS control network to provide a framework for homogeneous densification, three-dimensional control points, proper checking of blunders, orientation of baselines for improved scale and orientation, and the number of receivers for relative positioning). Secondly, a log for field survey procedures should be made recording every detailed information. Thirdly, data processing must be performed in the coordinate system defined by the GPS satellite ephemerides, and to account for realistic covariance matrices. A fourth specification would be the survey report which involves survey description, *field* procedures, office procedures, results and their archiving in standard file. Finally, an evaluation of the internal accuracy and external compatibility of the GPS survey results is made to determine whether they meet second-order standards.

GPS is a new technology, and any specifications at the present time are preliminary in nature. Further refinement is expected as technological advances in urban GPS surveying increase.

The Impact of GPS

From the previous text, one can be familiar with the problems facing geodesists and the shortcomings of the available methodology and instrumentation, in order to appreciate fully the expected impact of GPS on geodesy. Besides the establishment of GPS satellite navigation capability in civilian transport means, GPS has also made a significant contribution to surveying and geodesy. Once the system had moved into the operational phase, with a unique combination of high accuracy, low receiver cost, low operating expenses, speed and high efficiency, surveying performance has drastically changed and has now attained its extreme nourishment and optimization.

Both simulations and operational tests have provided evidence in support of predictions of the accuracy and the efficiency of GPS. Insurmountable problems are being resolved by the continuous development of the technique. Relative accuracies of a few centimetres over baselines greater than 100 Kms in very short observation periods, is routine. The drop in equipment costs and its automaticity will offer minimum required operator training, with a one-man crew per receiver. The production of network control point positions has increased as much as 20 times per person compared to terrestrial survey methods. Network densification for specific purposes can also be accomplished by GPS.

The vertical accuracy has a major impact on geodynamic studies. Elevation differences and heights are obtainable with greater ease, less crew and relatively little expenditure of time, compared to the effort and large team for first-order precise levelling. Important aspects of vertical deformation studies are levelling across water bodies, relating the ellipsoidal heights of islands and the ability of GPS receivers to operate in areas with no intervisibility between benchmarks.

GPS, together with VLBI, manage the unification of the control point networks of the world into a homogeneous world system. The networks are no longer treated as a static system for lack of the ability to detect and keep track of crustal movements. The speed, accuracy, economy and capability to span long distances without recourse to intermediate points, enable to resurvey worldwide networks of monitoring points at short intervals of time. Acquiring the full benefits from GPS will, in the near future, make the terms first-, second-, and third-order geodetic networks no longer apply in the same sense, being a reflection of the capabilities and limitations to classical geodetic surveying. GPS technology still has a lot up its sleeve, and its capabilities will spawn requirements for applications which yet cannot be envisioned.

The DORIS System

Recently, in 1990, the most up-to-date advanced satellite system was launched [22]; the DORIS integrated satellite-based orbit determination and radio positioning system, designed and developed by CNES (Centre National d'Etudes Spatiales), the GRGS (Groupe de Recherche de Géodésie Spatiale) and the IGN (The French National Geographic Institute). Its development meets new needs in precision orbit determination and high-accuracy beacon location. A network of 50 installed orbit-determination beacons (ODB) at precisely known locations evenly distributed around the world is used to determine the satellite's orbit to within 10 cm. In addition, the results of high-precision orbit determination is used for the high-accuracy location of unknown ground location beacons (GLB). The ODBs and GLBs are an integral part of the DORIS concept, incorporating transmitters, oscillators, microprocessor, meteorological sensors, etc.

The potential for location determination to within a few centimetres enables a wealth of other significant applications to be performed, such as the monitoring of various natural phenomena including seismic, volcanic or intense tectonic activity, continental drift, and monitoring of major construction sites of dams, tunnels, etc.

The topography of the sea surface which is not perfectly flat at rest, results from geophysical and oceanic factors. Accurate knowledge of the mean sea-level and its variations is a major requirement in both internal geophysics and climatology, since the ocean circulation plays a major role in ocean-climate interactions. As the satellite scans the entire terrestrial surface in a few days, the sea-surface topography can be measured accurately and repeatedly by satellite altimetry. The trajectory of the satellite-borne radar altimeter is known to an accuracy of 10 cm (equivalent to that of the satellite itself).

Also, the ease of implementation and relatively low cost of the GLBs make the system a prime candidate for general surface monitoring of hydroelectric dam sites and their environs, and for the study of ground movements during major civil engineering projects, building of tunnels, highways, etc., and tying offshore drilling platforms into coastlines.

In geodesy, the absolute location accuracy of the system will be of great benefit in improving the accuracy of existing geodetic networks, tying regional geodetic datums into a worldwide geodetic reference system, demarcating maritime frontiers in a single reference system for applications with significant economic impact (oil fields, mining resources), and for cartography.

The initial results of DORIS already confirm the expected system performance, and in early 1991 it has reached a capability of providing a complete range of services. The DORIS system produces 150 passes a day, compared with an average of 15 daily passes for satellite laser tracking. The results obtained using semi-dynamic techniques, where both the orbit and beacon locations are calculated, show that the system can provide location accuracy on the order of a centimetre in relative mode over short distances, and better than 10cm over several thousands of kilometers.

CONCLUSIONS AND RECOMMENDATIONS

The ultimate benefit of satellite surveying is the provision of a world-wide sound reference net essential for all geodetic, geographic and topographic purposes in the development of the earth sciences. An improved knowledge of the size, shape, gravitational and magnetic fields of the earth are gained, and which cannot be easily obtained by traditional survey methods.

The distinctly different measuring techniques evolved to satisfy surveying requirements are conventional terrestrial surveying, Transit Doppler and GPS satellite surveying. The former produces an average of 1 part in 10^5 relative positioning for very short distances, with a limitation of requirement for station intervisibility. The Doppler technique yields a relative positioning accuracy of less than 0.5m for distances up to 250 Km with a minimum of 30 passes. Results obtained by optical methods and by Doppler methods are not always in agreement. This stresses the care that must be taken when combining data from the two observation systems into a single solution. As for the newly developed GPS system which measures thousands of kilometres in no time, and producing a relative positioning accuracy of 1 cm level, it provides the means for achieving the perennial goal of geodesists, a unified world-wide geodetic control point network tied to an inertial reference system.

GPS provides a wide coverage area, ensures the permanent visibility of four to seven satellites from any point on the earth, yields accurate point positioning and relative positioning, and reduces the ionospheric refraction (high transmitting frequencies).

GPS satellites are routinely tracked by a network of receivers, the tracking network being of a global or regional extent. Various global networks of tracking stations have been established to support the GPS activities. Of these, is the U.S. Defence Mapping Agency (DMA), the U.S. National Geodetic Survey (NGS) and NASA.

A cornerstone for the successful phasing in of GPS in a small nation like Egypt, is entering into cooperative arrangements to establish regional frameworks from which GPS ephemerides of adequate accuracy could be obtained on a regular and assured basis. The incorporation of Egypt in a global tracking network consortium with bilateral coordination agreements, will permit the gaining of unvetted access to a GPS ephemeris service facility, which is indeed an attractive option. Also, Egyptian participation in the Eastern Mediterranean Wegener (NASA) program for investigations of lithospheric motion is certainly of a great benefit.

The estimated accuracy of the existing network control is influenced by unrealistic covariance matrices. The conversion of the Egyptian national framework and integration of other control to the North American Datum (NAD 83) will make full covariance matrices available for all control points, thus facilitating the proper integration of the GPS solutions into the existing control.

To establish a regional tracking network and orbit determination facility, two stages may be suggested. The first stage for testing and evaluating the GPS system, would involve a configuration of two stations instrumented with dual-frequency receivers and atomic clocks. The second stage would incorporate an upgraded network of 2 to 3 stations, also equipped with atomic clocks. The two stages would be completed with the establishment of a central computer facility, upgraded software, improved tracking station coordinates, data transmission and dissemination of the ephemerides to the user. At this stage Egypt would enter the operational phase of GPS for surveying and geodesy.

Aside the advanced GPS technology in geodetic and geodynamic applications, the system also has its impact and potential on routine surveying tasks. The speed of GPS performance, more accuracy and fall of instrumentation costs, make the system a dominant one, whether for short 10 to 30 Km distances over rugged to flat terrain, or large scale distances over 300 Km. GPS is unlikely to displace EDM and the theodolite, but is definitely, competitive. The field of geodesy is currently witnessing the GPS replacement of all present techniques used for positioning of points separated by short or great distances.

By implementing GPS technology in Egypt, where there is still considerable need for control densification and maximum investment of Egyptian resources, among other applications, there are likely to be substantial savings.

The infancy stage of GPS satellite geodesy was characterized by instrumental experimentation and computing techniques, and most results obtained have been of a provisional nature. Today, many and as a matter of fact most, of these problems have been overcome and GPS satellite geodesy is considered operational. In the few years to come, and in the sphere of geodesy, we should expect a harvesting of refined results towards a provision of an efficient assessment and management of the earth's resources.

REFERENCES

[1] W.H. Hunter, "Satellite Geodesy", *The Australian Surveyor*, Vol. 7, No. 22, 1969.

[2] Hermann Deker, "The Application of Photogrammetry to Satellite Geodesy", *Survey Review*, Vol. XIX, No. 150, Oct. 1968.

[3] Hermann Deker, "The Application of Photogrammetry to Satellite Geodesy", *Survey Review*, Vol. XX, No. 153, July 1969.

[4] A.J. Flatman, "Surveying by Satellite", *The Canadian Surveyor*, Vol. XXI, No.4, Sept. 1967.

[5] M.L. Baker and M.W. Makemson, *An Introduction to Astrodynamics*, 2 Ed., New York, London, Academic Press, 1967.

[6] C.G. Lehr, "Satellite Tracking With a Laser", *Res. Space Sci. SAO Spec.*, Rept. No. 215, Cambridge, Mass., 1966.

[7] C.G. Lehr and M.R. Pearlman, "Laser Ranging to Satellites", *Space Res. X*, Amsterdam, Holland, Publ. Co. 1970.

[8] B.H. Van Gelder and L. Aaerdoom, "Plate Tectonic Behaviour in the East Mediterranean Region to be Detected by Baseline Variations From Satellite Laser Ranging", Delft Univ. Tech., Rep. Dept., Geodesy, Math. and Physics Geod., No. 82:1, 1982.

[9] G.C. Weiffenbach, "Tropospheric and Ionospheric Propagation Effects on Satellite Radio-Doppler Geodesy", *Oxford Symp.*, 1965.

[10] H. Seeger, "Possibilities and Limitations of Doppler Positioning in Geodynamics", *Proc. of the 2nd Intern. Symp. on Doppler Satellite Positioning*, Munchen, 1979.

[11] J. Kouba, "A Review of Geodetic and Geodynamic Satellite Doppler Positioning", *Review of Geophysical and Space Physics*, Vol. 21, No. 1, 1983.

[12] M.M. Nassar, *Advanced Geometric Geodesy*, Dept. of Public Works, Fac. of Eng., Ain Shams Univ., Cairo, Egypt.

[13] E.J. Krakiwsky, "Geodetic Control From Doppler Satellite Observations for Lines under 200 Km", *The Canadian Surveyor*, Vol. 27, No.2, June 1973.

[14] C. Rizos, A. Stolz, E.G. Masters, "Surveying and Geodesy in Australia With GPS", *The Australian Surveyor*, Vol. 32, No.3, Sept. 1984.

[15] L.D. Hothem, G.E. Williams, "Factor to be Considered in Development of Specifications for Geodetic Surveys Using Relative Positioning GPS Technique", *Proc. of the First Intern. Symp. on Precise Positioning With GPS*, Vol. II, 1985.

[16] D. Paradissis, "GPS Standarization-Status and Problems", *Symp. on Space Technique for Geodynamics*, Hungary, 1984.

[17] C.C. Goad, B.W. Remondi, "Initiative Relative Positioning Results Using GPS", XVIII Gen. Assembly of IUGG, *IAG Symp.*, Hamburg, W. Germany, Aug. 1983.

[18] D.E. Wells, P. Vanicek, D. Delikaraoglou, "Application of Navstar/GPS to Geodesy in Canada. Pilot Study", Dept. of Surveying Eng., Tech. Report No. 76, Univ. of New Brunswick, Canada, 1981.

[19] R.A. Snay, "Network Design Strategies Applicable to GPS Surveys Using Three or Four Receivers", *Bull. Géodesique*, Vol. 60, No. 1, 1986.

[20] R. Duval and N. Beck, "Guidelines and Specifications for GPS Surveys", Geodetic Survey Division, Ottawa, Canada Centre for Surveying, 1990.

[21] M.R. Cramer, D.E. Wells, P. Vanicek and R.L. Devlin, "Specifications for Urban GPS Surveys", *Surveying and Land Information Systems*, Vol. 50, No. 4, Dec. 1990.

[22] DORIS Newsletter, No.1, CLS, Toulouse, France, 1990.