GPS in Navigational Applications

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Abstract
The Global Positioning System (GPS) is a very accurate positioning tool and has been successfully applied to surveying, geodesy, navigation and many other fields. The paper provides an overview of GPS in navigation. It first briefly describes the development and principles of GPS; then discusses the different GPS based positioning methods in navigation; and finally, reviews the various systems for air, land and marine navigation.

I. INTRODUCTION

Global Positioning System (GPS) has for several years been a buzzword for professionals in many fields including surveying, geodesy, GIS, meteorology, and geodynamics. The reason for this GPS wonder perhaps lies in the superior capability of GPS: it offers solutions to many problems that we could not or felt difficult to solve, and also enables us to do many things better than before. Navigation is one of these things, which has been greatly changed from the development of GPS.

This paper will provide an overview of GPS as applied to navigation. It will first describe briefly the principles of GPS. The different GPS based positioning methods in navigation will then be discussed, followed by an review of GPS based systems for air, land and marine navigation.

II. PRINCIPLES OF GPS POSITIONING

GPS is a satellite based passive positioning system that was initially designed primarily for military use. It was developed and has been maintained by the United States Department of Defense (US DoD). The system is now used by both the military and civilian users to obtain high accuracy position, velocity and time information, 24 hours a day, under all weather conditions, and anywhere in the world. The system was declared to reach the requirement of an initial operational capability (IOC) in December 1993 and full operational capability (FOC) in April 1995 [12].

The Components of GPS

One common way to look at GPS is to resolve it into three *segments*:

The space segment refers to GPS satellites that are orbiting at an altitude of about 20,200 km above the earth surface. The full operational capacity of GPS is achieved with 24 active satellites. There are currently 27 operational satellites, three of that are the *active spares* that can be used as replacements when the active satellites are out of services. The key components in a GPS satellite are the antennas sending and receiving signals, two large wings covered with solar cells to generate power for the satellite to consume, and atomic clocks that are accurate to about 1 second in 3,000,000 years.

The control segment consists of 5 monitor stations, 3 ground antennas, and 1 master control station. The monitor stations passively track all satellites in view, accumulating ranging data. The tracked data are processed at the master control station to determine satellite orbits and to update each satellite's Navigation Message. The updated information is transmitted to each satellite via the ground antennas.

The user segment is anybody who has a GPS receiver. The surveyors, the navigators and the GIS data collectors are examples of the users.

The signals that GPS satellites send out consist of two codes, the coarse acquisition (C/A) code and the precise (P) code, and a Navigation Message. The GPS codes are just like a series of 1's and 0's that are arranged into certain sequences, Figure 1. The C/A code is used for the Standard Positioning Service (SPS) available to all users. The service offers a positional accuracy of about 100 m horizontally and 156 m vertically at the 95% probability level.

The P code is used for the Precise Positioning Service (PPS) and can be accessed only by authorised users

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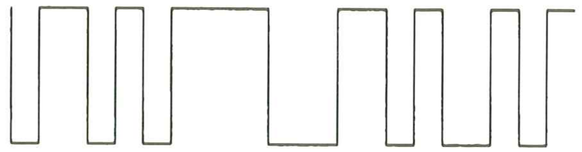

Figure 1. Illustration of GPS code signals

such as the US military and its allies. The service provides a positional accuracy of about 15 m horizontally and 25 m vertically at the 95% probability level.

The GPS Navigation Message contains such information as the orbital elements of the satellites, clock behavior, and an almanac that gives the approximate data for each active satellite.

Two carrier frequencies on L-band, L1 and L2 are used to carry the signals described above. L1 has a wavelength of about 19 cm (1575.42 MHz) and L2 a wavelength of about 24 cm (1227.60 MHz). Both L1 and L2 are microwave frequencies and can penetrate the atmosphere. L1 carries both the C/A and the P codes and L2 the P code only. The Navigation Message is carried on both of the two frequencies.

To the more sophisticated users such as the surveyors, positioning using the code information cannot fulfil their accuracy requirements, say at the centimeter or millimeter level. In this case, the L1 or L2, or both L1 and L2 carrier phases are also observed and used for positioning (e.g., [12]).

The Working Principles of GPS

GPS measures positions by measuring distances. GPS satellites have known orbits and therefore known positions at any instant time. Therefore, if the distances to three or more GPS satellites can be measured from a point anywhere on or near the earth surface, the three-dimensional position of the point can be calculated, Figure 2.

The distances between the point and the satellites are determined either using the code or the carrier phase observations. The same GPS codes are generated at the same time by both the satellites and the GPS receiver. When the receiver receives the code information from the satellites, it correlates the signals it generates and those received from the satellites, Figure 3, which can determine the time that takes for the GPS signal to travel from a satellite to the receiver. The time can then be used to calculate the distance.

As the clock of the receiver has usually a much lower accuracy than those on a GPS satellite, the clock time

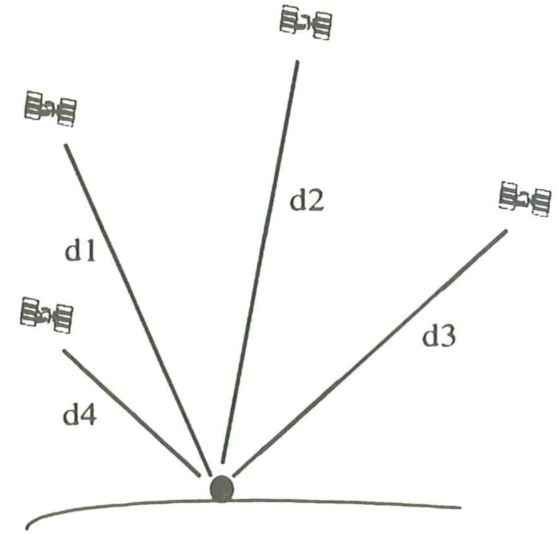

Figure 2. Measuring distances to GPS satellites

is in practice commonly considered as an unknown parameter which is solved together with the position of the receiver point. In this case, signals from at least four GPS satellites are required, as there are four unknown values to be solves for.

When carrier phase observations are used in GPS positioning, the distance between a receiver point and a satellite is determined using,

$$\text{Distance} = N\lambda + \Delta\lambda \quad (1)$$

where λ is the wavelength of the carrier wave; N is the whole wave numbers counted from a satellite to the receiver and $\Delta\lambda$ is the length that is shorter than one wavelength, Figure 4. $\Delta\lambda$ is determined directly from the phase measurements. N is the integer ambiguity and is usually solved for based on continuous phase observations over some extended time.

Pros and Cons of GPS

Some general points on the advantages of GPS are given here only. First, it covers the whole globe spatially, hence the word 'Global' in its name, and continuously in time for 24 hour a day. Second, the system offers high positioning accuracy at an affordable price to the user. Besides, GPS is convenient to use in many applications.

GPS also has its disadvantages. Perhaps the biggest problem that it has is the requirement of line of sight to GPS satellites. GPS signals can penetrate the atmosphere but not any solid objects such as buildings, trees, and mountains. This requirement seriously limits the use of GPS in environments such as dense urban areas and underground. Another problem with GPS is the multipath effects that contribute to sig-

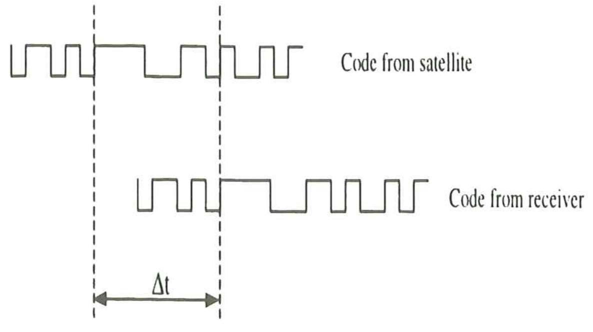

Figure 3. Time measurement by code correlation

nificant errors when a receiver is surrounded by smooth reflective surfaces.

III. GPS BASED POSITIONING METHODS IN NAVIGATION

GPS was designed primarily as a tool for navigation. It has been successfully applied for the navigation of vehicles such as cars, ships and airplanes, as well as for the guidance of weaponry objects such as missiles. This section will look at the different positioning methods of using GPS in navigation.

Single Receiver Positioning

The simplest way to use GPS for navigation is to carry a GPS receiver whenever you go. The receiver can offer in real-time the SPS positioning accuracy that was discussed earlier, as long as signals from four or more GPS satellites can be received. Since such an application is very basic, almost any commercial GPS receivers on the market can be used for this purpose. Many of the receiver units cost less than US$100. This simple GPS positioning method is used very commonly for recreational activities such as hiking and fishing, fieldwork in remote areas such as in the desert or forest, and travel on the sea.

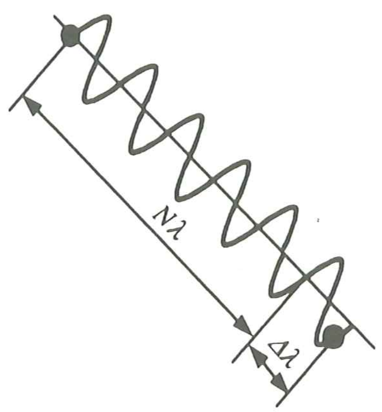

Figure 4. Carrier waves and phase measurement

Differential GPS (DGPS) Positioning

If the positioning accuracy described above is insufficient, an easy and affective way to increase the accuracy is to use differential GPS. In this operation mode, two GPS receivers are required, one set on a station whose position has been accurately determined, and the other carried around to where the position needs to be determined. In this case, the first receiver is called the reference station and the second the roving station.

If the user is close enough to the reference station, various GPS errors, such as the effect of the atmosphere, are very similar for both of the two stations. The reference station can be used to determine the errors in the three coordinate components. Corrections can be worked out for the position of the roving station based on the errors determined at the reference station. The positioning accuracy can be greatly improved by doing this 'differential' operation. DGPS technique has been repeatedly demonstrated to achieve a positioning accuracy of 2 to 5m (1σ) over baselines up to 1,000 km [3.14].

If real-time positioning is required, a data communication link between the two stations is required. A common approach is to use a pair of radios if the distance between the two stations is short, say within a few kilometres. For distances up to a few hundred kilometres, a broadcasting station can also be used to send the correction messages to the entire designated area. For example, Hong Kong has established a permanent GPS reference station on its Kau Yi Chau island. A transmitter is used to broadcast correction messages to an area of 500 km in diameter which covers the entire Hong Kong region. The claimed accuracy of the system is within 1 m [6].

The simple differential operation described above has relatively limited coverage, and is restricted by the coverage of the terrestrial communication system. Besides, the positioning accuracy decreases as the separation between the user and the reference station increases [1].

A technique called Wide Area Differential GPS (WADGPS) can be used to overcome the problems of the simple differential method. WADGPS uses a number of GPS reference stations to cover a wide area such as a whole country or continent. The GPS positioning errors are separately modelled and applied to the roving user station in a way that breaks the position dependence. Therefore the limitation in the navigation accuracy due to the user-reference station separation can be largely eliminated. Positioning accuracy of about 2 m and 3 m for the horizontal and the

height components respectively is achieved over baselines ranging from 2,000 km to 3,500 km [1,5]. The limitation in the coverage of the data links is also overcome by using geostationary communication satellites.

GPS Aided with Additional Sensors and Information

As said above, the requirement of direct line of sigh to GPS satellites makes it very difficult to use GPS in restricted areas such as high rise cities. For example, recent tests have shown that only about 30 percent of Hong Kong can receive signals from four or more GPS satellites [4]. One way to solve the problem is to aid GPS with sensors such as compasses, odometers, inertial navigation systems (INS), which basically use gyros and accelerometers for the determination of positions, or additional information such as existing maps and databases.

Pseudolite, a pseudo-satellite as its name implies, is a device that can transmit GPS-like signals. A pseudolite can be placed at strategic locations such as on a tall building at a road intersection to transmit signals to nearby areas. The signals from a pseudolite can be treated in the same way as those from a real satellite.

GPS can also be used in combination with GLONASS (GLObal NAvigation Satellite System), a system developed and maintained by Russia. The design and working principles of GLONASS are to certain extent similar to GPS. Efforts have been made by both researchers and instrument manufacturers to integrate the two systems to achiever better positioning accuracy and especially better satellite coverage in difficult environments. Receivers capable of receiving signals from both GPS and GLONASS satellites have been developed. A currently undergoing International GLONASS EXperiment (IGEX-98) campaign organised by IAG, IERS, IGS, and ION is expected to establish a global network and bring research and international collaboration together [15].

The system integrity and future continuity of GLONASS has always been a concern, especially when the number of GLONASS satellites in space has dropped dramatically in 1997-1998 [7,2].

The accuracy of differential GPS+GLONASS has been reported to be better than 0.5m (1σ) [2].

IV. GPS BASED NAVIGATION SYSTEMS

Various GPS based navigation systems have been developed. This section will take a brief look at these and also the basic requirements for land, air and marine navigation.

Airplane Navigation

It is understandable that navigation has different requirements under different circumstances. There are however some general considerations when designing different navigation systems, which are the accuracy, availability, continuity and integrity of the systems. Table 1 below lists the current requirements specified by the US Federal Aviation Administration (FAA) for a primary means or sole means system for aircraft navigation and landing guidance [8].

Although GPS and GLONASS combined provide very good positioning capability, they still however, when used alone, cannot meet the criteria as a sole means for navigation in aircraft navigation and landing guidance, or for safety-critical use in the marine and land environment. To meet these requirements, the GNSS-

Table 1. Navigation and Category I Landing Guidance Performance Requirements [8]

	En Route Through Non-Precision Approach	Precision Approach CAT I[1]
Availability	0.99999	0.999
Accuracy (95%)		
Horizontal	100m	7.6m
Vertical	not specified	7.6m
Integrity		
Probability of HMI*	10^{-7}/hour	$4x10^{-8}$/approach
Continuity	$1\text{-}10^{-8}$/hour	0.99995/approach

* Hazardously Misleading Information

[1] CAT-I: A Precision approach procedure which provides for approach to a height above touchdown of not less than 200 feet and with runway visual range of not less than 2,400 feet [8].

1 and GNSS-2 (GNSS also comes from Global Navigation Satellite System) have been proposed. GNSS-1 is a satellite navigation system having GPS and/or GLONASS as backbone, augmented by other techniques. GNSS-1 is expected to meet the requirement for sole means of navigation up to non-precision approach and Cat I precision approach [17]. GNSS-2 is the second-generation satellite navigation system, which can meet all users' requirements, independent of any other means of radionavigation. Though the system architecture of GNSS-2 has not been defined yet, its design goal is to provide sole means use for Category IIIb[2] precision approach for landing [18].

The following are some of the developments in the scope of GNSS-1:

European Geostationary Navigation Overlay Service (EGNOS)
In Europe, a Tri-Partite Group made up of the European Organisation for the Safety of Air Navigation (EUROCONTROL), the European Space Agency (ESA) and the European Commission (EC) jointly manages the EGNOS. The EC is responsible for institutional and policy issues and funding. EUROCONTROL defines the user requirements and is also involved in the test and validation phase of the system development. ESA manages the development of EGNOS within GNSS-1 [18]

The coverage of EGNOS will be the footprint of Inmarsat Atlantic Ocean Regions East (AORE) and Indian Ocean Regions (IOR) as EGNOS uses these satellites as core transponder of the system. EGNOS is planned to reach its Initial Operational Capability (IOC) in 1999 and Final Operational Capability (FOC) in 2002 [18]. FOC is intended to meet sole-means requirements for en-route to Cat-I.

EGNOS will include GPS/GLONASS, GPS-like ranging system, wide area differential systems, ranging and integrity monitoring stations (RIMS), and geostationary integrity channel. When the Final Operational Capability (FOC) is declared the use of GPS/(GLONASS)/EGNOS/RAIM (Receiver Autonomous Integrity Monitoring) as sole means of navigation for up to Cat-I service shall be reached [17].

Wide Area Augmentation System (WAAS)
WAAS has been developed by the US Federal Aviation Administration (FAA). The ground network of the system includes 25 reference stations and 2 master stations providing differential and ionospheric corrections for improved accuracy. To achieve the various requirements of all phases of flight up to Cat-I, WAAS will also broadcast integrity messages and additional GPS-like signal, beside the GPS differential corrections [9]. The initial supplemental service, phase I of the system, has been scheduled for September 2000 [11].

The WAAS aims at providing service for precise approach up to Cat-I. Local Area Augmentation System (LAAS), which is similar in principle to WAAS but with a smaller area of coverage and higher positioning accuracy, will be employed for more stringent requirements of Cat-II/III precise approaches [9,13].

MTSAT Satellite Based Augmentation System (MSAS)
The Japanese Multi-functional Transport Satellite (MTSAT) Satellite Based Augmentation System (MSAS) is developed by the Japan Civil Aviation Bureau (JCAB) to support sole means navigation services for en-route to precision approach phases of flight. The first MTSAT is scheduled to be launched in 1999. Initial phase I (Cat-I) of the system is to be completed by 2001 and the final MSAS capability (CAT-II/III) is scheduled at 2005 [16].

MSAS in designed to provide Air Traffic Support (ATS) and meteorological mission. The system configuration is similar to the US WAAS, consisting of ground network for broadcasting integrity and correction data and to provide additional GPS-like ranging system from geostationary satellite for improving availability and continuity.

The development of GNSS-2 has to consider institutional issues regarding the ownership, control and interoperability of the systems. With the consent of the ICAO (International Civil Aviation Organization) members, an interoperability working group has been set up and held its first meeting on July 1998 to discuss these issues. The interoperability demonstration for WAAS/EGNOA and WAAS/MSAS has been scheduled [10].

Land Vehicle Navigation

Land vehicle navigation systems need basically to provide information on, for example, the real-time position of the vehicle, and the shortest route to travel from one place to another or the route that takes the shortest time to travel. A complete navigation system is also supplemented by real-time display of the position of the vehicle on a map. Besides, when it is necessary to track the positions of vehicles, such as a fleet of taxis or buses, at a central control station, a wireless data communication link is also required between each vehicle and the control station.

[2] Last stage of landing with runway visual range of not less than 150 feet.

Intelligent Transport System (ITS) is an area of interests to many researchers as well as government transport departments. Beside the functionality of a basic land vehicle navigation system discussed above, an ITS may also include features such as automatic toll paying, intelligent control of traffic signals, etc.

The block of satellite signals by objects such as tall buildings, bridges, pedestrians, and surrounding vehicles is a major problem for satellite based land vehicle navigation, especially in dense and high rise cities like Hong Kong. Therefore, it is often necessary to supplement a satellite based positioning system with additional sensors such as compasses, odometers and INS. To achieve the required positioning accuracy in difficult areas while keeping the cost of the navigation system low is still an area of research.

Marine Navigation

The foremost requirement of a marine navigation system is to provide information on the position and direction of a ship when travelling on an open sea. It is also necessary to provide information for precision approaches and en-route collision avoidance. Marine navigation can use a single GPS receiver, DGPS or the more sophisticated systems such as a GNSS depending on the navigational requirements.

V. CONCLUSIONS

In this paper, an introduction to GPS has been given; various GPS-based positioning methods, including using a single GPS receiver, differential GPS, GPS aided with additional sensors and information, were discussed; an overview of the development of GPS based navigation technology has been given; and some existing systems for air, land and marine navigation have also been briefly reviewed.

GPS is a new and powerful tool for many positioning applications such as surveying and navigation. It offers an unprecedented coverage both spatially and in time. The system is easy to apply and provides a high positioning accuracy at a relatively low cost to the end user. The major disadvantages of GPS include the requirement of line of sight to GPS satellites and multipath errors.

It seems clear that, to provide safer, more efficient and less costly means of navigation services, satellite-based navigation system will be an integrated system consisting of different sensors and technologies and it will provide global coverage and interoperability with integrity.

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Predicting Land-Cover Changes with Gray Systems Theory and Multitemporal Aerial Photographs

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Abstract
In this study, we report a new technique based on gray systems theory for land-cover change prediction. Historical land-cover data were obtained from aerial photo interpretation. Change prediction was carried out for seven land-cover types in Claremont Canyon, Alameda County, California. The prediction results demonstrated that the prediction technique was effective.

I. INTRODUCTION

Monitoring and prediction of land-cover/use are critical to the modeling of global change and management of ecosystems. A large number of methods for detecting changes in land surface conditions has been proposed. With remote sensing, a simple but effective method for change detection is taking the difference of the spectral responses at the same spatial location among a set of two or more images acquired at different times (e.g., Kushwaha, 1990; and Franklin and Wilson, 1991). The spectral difference between different times may be extended to differences of multitemporal vegetation indices derived from remotely sensed data (e.g., Hashem et al., 1996). Other techniques include multidate principal component analysis (PCA), Kauth-Thomas transformation of multispectral data (Kauth and Thomas, 1976) and Gramm-Schmidt (GS) orthogonalization (Collins and Woodcock, 1994). Most change detection methods with PCA perform PCA transformation directly to the original multispectral bands acquired at different times, then analyzing several minor principal components to determine change information (location, patterns, and amplitude) (e.g., Collins and Woodcock, 1996, Muchoney and Haack, 1994, and Miller et al., 1998). However, Gong (1993) followed by Parra et al. (1996), employed PCA to difference images which led to better change detection results. Recently, some researchers using artificial neural network (ANN) to predict or detect changes in grass or forest lands (e.g., Tan and Smeins, 1996; Gopal and Woodcock, 1996) thought that a nonlinear technique such as the ANN might be more applicable to describe the change behavior of land use/cover.

In this study, we proposed a new technique to predict changes of land-cover types based on the gray systems theory (GST) (Yuan, 1991) and multitemporal aerial photographs in a relative short time series. A prediction model based on GST is to infer a system condition from the past to the future based on known or indeterminate information of both past and present then to determine the system's tendency of development and change in the future and to provide the basis for planning and decision-making (Yuan, 1991). The GST prediction model may use limited data with a very short time sequence to predict changes of some condition while other techniques such as linear regression and nonlinear neural network algorithms perform improperly or simply do not work under this condition. Therefore, the objective of this study is to demonstrate the effectiveness of the GST model in predicting land-cover changes.

II. STUDY AREA AND AERIAL PHOTOGRAPHS

Study Area

The study area is located at the Claremont Canyon, Alameda County, California. It is a portion of the East Bay Hills of the San Francisco Bay Area, with an area of approximately 250 hectares. The elevation in Claremont Canyon varies from 120 m to 520 m above sea level. The mild climate and relatively large elevation and slope range enable many vegetation types to grow in this area. Primary vegetation types consist of Monterey pine, coastal redwood, and Eucalyptus, cypress, bay/oak woodland, *Baccharis pilularis*, and coyote brush. In addition, the land-cover types have been changing over time due to changes of climate variables and human activities, especially the latter (Sanders and Dow, 1993). Based on the relative stability of existing land-cover types (primary vegetation types) in the Claremont Canyon

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