AN INTELLIGENT DIFFERENTIAL GPS NAVIGATION SYSTEM

A thesis submitted for the Degree of Doctor of Philosophy
by
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ABSTRACT

This thesis describes an Intelligent Differential GPS Navigation System developed for a PhD research project.

The first part of the work was to apply differential technology to Global Positioning System to locate the current position of the user with an improved positioning accuracy. The essential part of this Differential GPS system is a Differential GPS Reference Station. This DGPS Reference Station includes a DGPS mathematical model and the corresponding algorithms, which calculates the differential correction messages. These messages are then transmitted to a mobile GPS receiver by a radio data link. By using these corrections, the mobile GPS receiver's positioning accuracy can be improved from about 100 m to 4 m.

This DGPS Reference station has been used to implement system software for this research. Differential correction algorithms were modified, characteristics of system components were changed, and different digital filters were also applied at different locations to investigate the impact on system performance. Besides all these capabilities which are needed for the research purpose, this DGPS Reference Station has all the standard functions, and can be used as a standard DGPS Reference Station.

The second part of the work was to combine this Differential GPS system with a suitable digital map to form a navigation system. A suitable digital map database was chosen and modified, and the content of the map was then reproduced on the mobile GPS receiver's host PC screen. This digital map, combined with the current location of the user, provides the basic navigational information for the user to reach a desired destination. To help the user further and demonstrate the potential use of the system, an intelligent route-planing algorithm that can produce the optimum route automatically was also designed.

The system integration was achieved by the design of the mobile navigation unit and the combination of this mobile navigation unit with the constructed DGPS Reference Station. The final system consists of a DGPS Reference Station, a UHF radio data transmitter, a mobile GPS receiver, a digital map system, a route searching and planing algorithm and a UHF radio data receiver. Field trials were carried out to test the system static and dynamic performances. Repeated experiments showed that both the static and dynamic positioning accuracies were within the range of 4 meters.

The constructed system is a prototype navigation system which incorporates the basic navigational functions. It is envisaged that this system can be directly used, or further developed to suit a special need, as required. A typical application of the system would be to guide a user to a desired destination. Other examples include: aircraft auto-landing control system, car self-driving, taxi fleet control, criminal tracing and personal navigation systems.

CONTENTS

CHAPTER ONE: INTRODUCTION

1.1 Project Introduction

Navigation systems have been under development for many years. Their requirement arises from the need of man to be able to travel efficiently in unknown or unfamiliar areas.

A basic navigation system consists of three main parts: the current position of the user, the desired destination and the environment containing navigational information between these two positions. Essentially a navigation system is a positioning system with an information storage and retrieve system, which enables the user to deduce his/her current position and a suitable route to its destination. For an advanced navigation systems, it is also desirable to have route-planing capability so that an optimal route (for example, the shortest or safest route) can be created for the user to follow.

Radio-positioning technology has been developed and used for a few decades [Getting, I. A. 1993]. For example, Loran and Decca systems. Both of these systems suffer from limited coverage. Neither of these systems give a 3-D solution, and also have some other limitations such as they are actually affected by the weather conditions. Only after the Global Positioning System (GPS) was fully functional, did radio-positioning technology become truly global. GPS has also many other advantages over the older systems. It offers continuous coverage, and can even be used to locate other satellites which are in lower orbits than GPS satellites. It is much more accurate, and provides the height information as well as latitude and longitude. It is a all weather system, operating continuously twenty-four hours a day, seven days a week.

The positioning accuracy of the Standard Positioning Service (SPS) of GPS is about 100 m. For an accurate navigation system, this is still not good enough. One effective way to improve the positioning accuracy further is to use real-time differential technology.

From the analysis of man's natural navigation abilities, it can be seen that the basis of navigation is conducted on one's ability to recognise known or familiar reference points. These references include both artificial and intangible ones as well as natural ones such as the sun, stars, fields and the horizon. Artificial references include roads, pavements and pathways. Intangible references include road numbers and names, as well as distance measurements, direction distinguishing, and latitude/longitude readings. If all familiar references between current position and the destination are removed, one becomes totally lost and it is impossible to reach a destination The ultimate intangible reference which combines these elements is the map [Moon, G. 1994].

In this PhD research project, an intelligent satellite navigation system is proposed. The aim of the project is firstly to apply differential technology to GPS, in order to improve the real-time positioning accuracy from 100 m to 2-4 m, so that the user's current position may be accurately located. To achieve this, a DGPS Reference Station has to be built. The task of this DGPS Reference Station is to calculate the differential GPS correction messages and transmit these to a mobile GPS receiver in real-time by a radio data link. Essentially this reference station will provide a necessary differential GPS research platform, and only based on which, system software can be modified, and the characteristics of the system components can be changed to investigate the impact on the system performance.

The second part of the project is to design a proper digital map based on commercially available digital map databases to provide the necessary navigational information surrounding the user's current position and destination. Because the map is digital, it is envisaged that it will be more flexible than ordinary maps. In order to fully utilise the digital map, various different algorithms are required.

For an intelligent system, a route-planing algorithm is also to be incorporated to help the user to find an optimum route between the current position and the destination. It would also be useful to demonstrate the potential applications of the system.

It was envisaged the system integration would be achieved by designing a mobile navigation unit and combining this mobile navigation unit with the constructed DGPS Reference Station. By using this mobile navigation unit, field trials can be carried out to test the system performances. The dynamic performance of the system would be examined by moving the mobile navigation unit along a designed route while the real-time navigation results are shown on the digital map.

It was also envisaged that the proposed system would be a prototype Differential GPS navigation system which would have basic navigational functions to demonstrate the availability of the latest technologies and the principles of satellite navigation systems. Such a system could be easily modified or further developed to suit the needs of a specific application.

1.2 Literature Search and Review

An extensive literature search was carried out. The purpose of the search was to find the relevant information of:

1. The state of the art technology of satellite navigation systems and the availability of relevant services;

2. The current state of GPS and Differential GPS, especially the establishment of the DGPS Reference Station;

3. Digital map databases and digital map systems;

4. Route-planning algorithms for navigation systems.

The main information sources searched included:

1. INSPEC CD-ROM Abstract from 1985 to date;

2. On-line Engineering Index (BIDS Compendex) from 1986 to date;

3. British Library Catalogue for books, periodicals and PhD thesises;

4. ION (Institute of Navigation) proceedings from 1991 to date;

5. Internet web site on-line search, using key word "GPS", "Differential GPS", and "navigation".

6. Related published books and U.S. government documentation.

7. Other sources such as related patent search.

Much information relevant to the above topics has been found, mainly with reference to GPS, Differential GPS and navigation systems. It was found that GPS books usually contain the basic positioning principles and general information of the systems, while the research papers dealt with more specific areas. For this reason, the ION proceedings were found particularly useful for this research. Various internet web sites also contributed useful information of systems and latest developments, especially commercially available services, equipment and facilities [Langley, R. B. 1996]. The bulk of the literature consulted during the research is listed in **REFERENCES**, and the literature review of the background for the relevant specific topics are summarised in relevant sections.

From a general view, it is concluded that it is feasible to establish a satellite navigation system with the desired accuracy by applying differential technology to the GPS. There are two reasons for this conclusion. The first one is that Differential GPS has been available for a few years, and reported positioning accuracy varies according to the literature, and depends on the company offering the service. Generally it is between about 4m to 10 m [Wellenhof, B. H. 1994]. The second one is that with the rapid development of the digital map systems, the navigational information can be effectively extracted and electronically processed, so that the current position of the user located by the positioning system can be effectively combined with the navigational information.

On the system aspect, there are quite a few technical papers and reports about the GPS navigation system, especially for the marine and car navigation applications. Since GPS positioning accuracy is about 100 m, the accuracy of the navigation application is also limited to this level. For the purpose of navigating a ship on the sea, this accuracy is high enough. For the Differential GPS navigation system, literature search revealed relevant information on separate techniques, mainly on the research of applying available differential corrections to the GPS receiver to improve the positioning accuracy. But none of the published paper is directly related to whole DGPS navigation system. The possible reason for this is that differential GPS is relatively a new technology, and the available differential GPS correction signals have been quite limited.

Differential GPS correction message services are generally commercially obtainable in the U.S.A. and Canada. Companies like INMARSAT, Racal in the U.K. transmit correction signals, but to use these is either very expensive, or it is not possible.

Generally speaking, it is still very difficult, if not impossible, to get access to the Differential GPS correction messages in the U.K. and Europe.

The other way of establishing a Differential GPS system is to buy a DGPS Reference Station from a commercial company, such as Trimble, Ashtech etc. and set it up for transmitting purpose. One limitation of this approach is that DGPS Reference Station is expensive. The other main problem is that none of the companies provides the source code of the system software with the DGPS Reference Station, therefore, it is impossible to modify the system components, let alone carrying out research on it.

Digital map databases are currently commercially available. A digital map database is a data file that contains basic geographic information encoded in a certain format. Usually these digital map databases are designed for general purpose, rather than for a specific use. Useful information must primarily be extracted from an original map database, to reproduce a digital map, and then be combined with the proposed positioning technology to build a navigation system. Software and algorithms are then required to convert this geographic data back into its original format, for instance, a route or a car park. To optimise a digital map database, map handling algorithms such as co-ordinates converting, zooming-in and zooming-out are also needed, so that a final map may be effectively reproduced and linked to the positioning system [Harley, J. B. 1975] [Ashkenazi, V. 1986].

For the map handling algorithm, usually it can only be used by a special digital map. As the digital map database varies widely, there are also various map handling packages commercially available. Each of these has its speciality. As the required map handling functions are unique to the project and none of the available packages can be used directly, it is concluded that the map handling algorithms have to be specially designed to suit the need.

Route searching and planning algorithms have also been found during the literature search. The principle of searching and planning varies according to the objectives of the algorithm and the format of the digital map system. Most published algorithms are related to the vehicle navigation systems where the map features are mainly highways [Zhao, Y. 1991]. As the digital map adopted by the system is the Land_Line from the Ordinance Survey, the route searching and planing algorithm therefore must be based on the related map features.

Another interesting finding of the literature search is that though many papers have been published about differential GPS technology, none of them is related directly to the Differential GPS Reference Station's mathematical model and corresponding algorithms [Loomis, P. 1989]. The reason for this is that nearly all available differential GPS correction services are provided by commercial companies, and none are willing to disclose their technical details, should one mathematical model or algorithm be thought of as inferior to that of the rival company [Blanchard, W. F. 1991].

1.3 Objectives and Methodology

As DGPS correction signals are not available in the UK, the first objective of this research is to establish a Differential GPS Reference Station to transmit differential correction messages. There are two ways to do this. One is to set up a commercially available reference station, such as 4000-DS from Trimble and another way is to modify an existing GPS development system into a Differential GPS Reference Station. The problem with the first option is that it is expensive ($16,000 for 4000-DS), another drawback is that access to the system software is impossible, it is therefore not possible to modify the algorithms or change the characteristics of the system components.

The second method was therefore adopted for this research. It was decided to utilise the GPS Builder^{TM} from GEC Plessey Semiconductors as a basic GPS receiver, and then add the necessary DGPS Reference Station mathematical model and corresponding algorithms to fulfil the standard functions of a DGPS reference station. The main advantage of this option is that the control of the whole system is enabled, so different system software may be implemented, and characteristics of the system components can be easily changed. This is particularly important for a DGPS Reference Station which is to be used for research purposes.

The GPS Builder^{TM} is a GPS receiver development system that gives the user flexibility to develop special purpose systems. GPS Builder^{TM} is based on the GEC Plessey GP1010/GP1020 chip set where GP1010 is the RF front end and GP1020 is the six-channel correlator. Two GP1020 chips are used in the Builder to give the designer a 12 channel facility. In the GPS Builder, as the essential system components and raw signals are well under system designer's control, what is needed to turn it into a DGPS Reference Station is to calculate the differential correction messages by employing a proper DGPS mathematical models and corresponding algorithms, in other word, a new system software.

The other advantage of using the GPS Builder^{TM} is that the original software source code in Borland C++ is provided. This is convenient as it is unnecessary to rewrite the very basic GPS signal tracking, correlating and processing algorithms, allowing greater thought to be given to DGPS Reference Station differential correction messages calculations and the corresponding algorithms design.

To transmit DGPS correction messages to a mobile GPS receiver, a real-time radio link is needed. The main consideration for this radio link is that it should cover the experimental field trail area. For this research, the area is the campus of Brunel University. It was decided to use a low power 454 MHz 0.5 watt UHF radio modem, which is licence free at this frequency and power. The coverage distance is about 5 km which is satisfactory at this stage.

The second objective of the research is to design and combine a digital map which contains the necessary navigational information with a mobile GPS receiver that has DGPS facility to produce a mobile unit. This unit, combined with the proposed DGPS Reference Station, would form the proposed navigation system. A route-planing algorithm, which enables effective guidance to a destination, was also considered necessary.

To fulfil this task, suitable digital map database was chosen from which to extract the desired navigational information. The 1:1250 scale Land_Line 93 from the Ordnance Survey was chosen for this purpose, as it includes houses, buildings, routes, pavements, car parks, grass land, short cuts and even fences. It is currently the most detailed digital map database available

To reproduce the contents of the database and redraw the digital map effectively on a PC's screen, map handling algorithm must be designed. To integrate this map with the mobile GPS receiver, co-ordinate conversion is also required, as GPS system and Land-Line digital map database use different geographic reference systems.

The mobile GPS receiver to be used is the SV6 from Trimble Navigation. The SV6 is a six channel receiver with a DGPS facility using Trimble Standard Interface Protocol (TSIP). It is small and compact and suitable for the mobile unit. The other advantage of the SV6 is that its control and interface software is transparent enough, so that freedom is there for the system integrator to modify it for a special need. The system software of the SV6 is written in ANSI C, but Borland C++ can also be used.

The route-planning algorithm was not a major part of the research project, and it was envisaged to be a simple but effective in order to demonstrate the potential use of the system.

A block diagram of the proposed system is shown in **Fig. 1.1.**

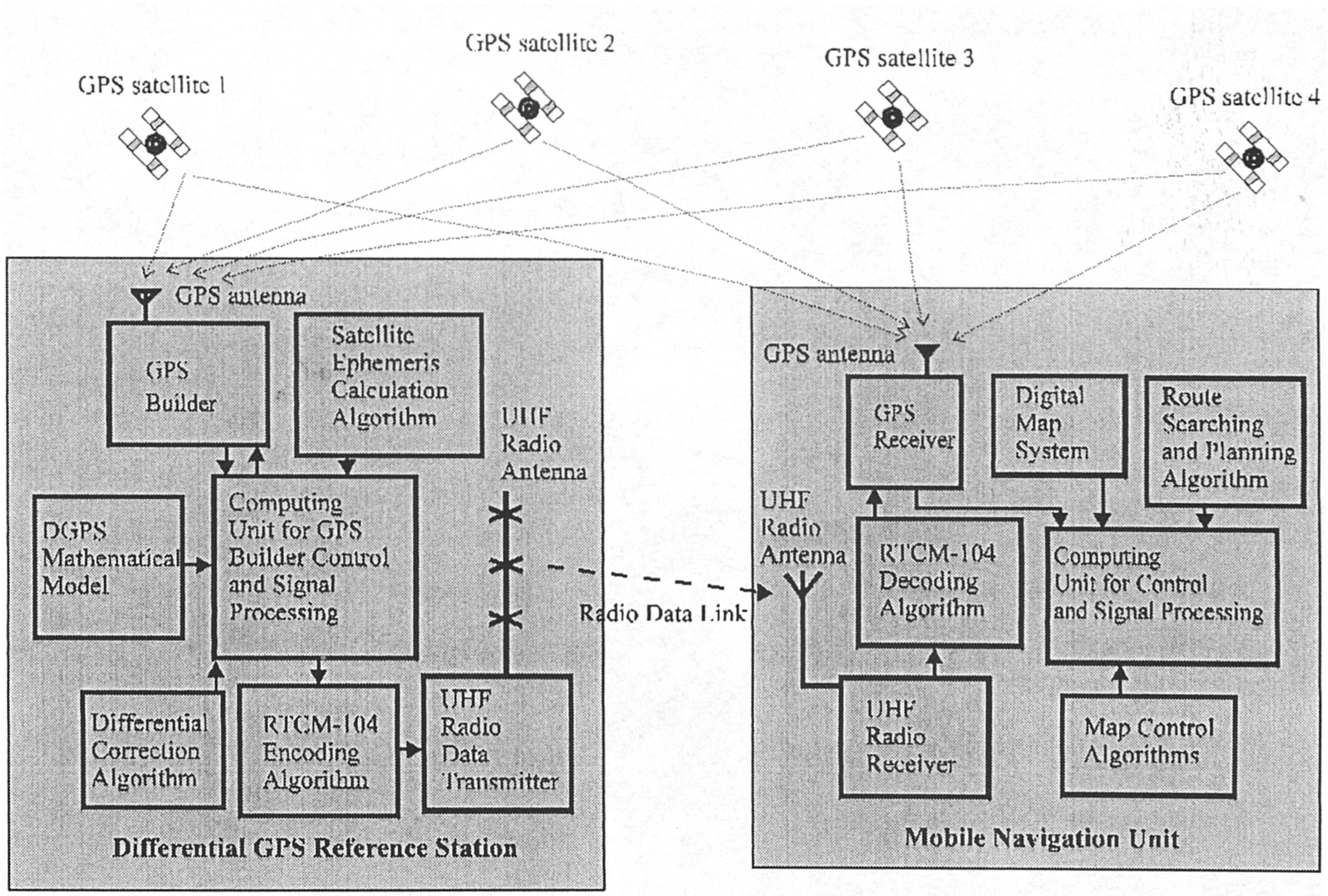


Fig. 1.1 System Block Diagram

1.4 Novelties of the Research Project

As the DGPS is relatively a new technology, and the proposed system is a prototype satellite navigation system which contains various system components, the novelties of the project can be summarised as follows:

- The application of differential technology to the Global Positioning System (GPS) to improve the system positioning accuracy from about 100m to 4m. The reported available DGPS positioning accuracy is from 5m -10m.

- A prototype satellite navigation system was developed which has a real-time system positioning accuracy of 4m. The constructed system has the basic navigational functions and demonstrates the availability of the latest technologies. The system can be either directly used or further developed to suit the needs of a specific application. The fully integrated system contains a DGPS Reference Station, a UHF radio data transmitter, a mobile GPS receiver, a digital map system, a route searching and planing algorithm and a UHF radio data receiver.

- A flexible DGPS Reference Station has been designed and implemented. This station is fully operational at the Brunel University. Within the system software, a DGPS Reference Station mathematical model was developed and relevant differential algorithms were designed. Since none of the literature in the public domain disclosed the details of the model, this model was formulated based on the basic principle of differential technology. The differential corrections are then encoded into the RTCM-104 standard format, and transmitted to the mobile GPS receiver in real time. Besides the above flexibilities which are needed for the research project, the constructed DGPS Reference Station has all the standard functions of a DGPS Reference Station. This means that the differential GPS correction messages transmitted by the Brunel

University DGPS Reference Station can also be used by external GPS receivers to improve their positioning results.

- A digital map covering the campus of Brunel University was constructed by using four tiles of the digital map database 'Land_Line' from the Ordnance Survey. The map features contained in the Land_Line were extracted, and coordinates of the map features were converted from the WGS 84 format to British National Grid. After that, the map was combined with the output of the SV6 GPS receiver, so that the current position of the user can be found in the map surrounded by navigational information.

- Specific map handling algorithms for Land-Line digital map database have been designed to utilized the digital map effectively. As the designed map system is unique to the research project, and the required map handling functions are specific, these map handing algorithms could not be adopted from the commercially available software. The designed map handling functions include: choosing the central place of the map, map zooming in and out control and the output of the numerical real-time positioning results.

- A low-power UHF radio link operating at 456 MHz has been implemented to transmit the differential GPS correction messages. The signal coverage is about 5 km in radius. This coverage is good enough for the research project.

- An effective route searching and planing algorithm has been designed to demonstrate the potential application of the system. Since route searching and planing algorithm depends much on the adopted digital map system, no published algorithms could be directly adopted in this project. The designed route searching and planing algorithm is based on the detection of the boundary of map features. In the system, the algorithm works well.

1.5 The Structure of the Thesis

The work is structured in eight chapters. The first chapter begins with an introducing overview of the project. Then there is an exploration, through the literature search and review, about the current state of the differential GPS navigation system and relevant technologies. It is concluded that it is feasible to establish the proposed system. But the research which had been carried out is mainly on separate technologies, but not on the whole system aspect. After exploring the existing literature, the objectives of the project were clarified. This is followed by a description of the methodology adopted in conducting the research.

Chapter Two provides the technical background of the GPS and Differential GPS systems, based on which further research can be carried out. The third and fourth chapters deal with the theoretical and engineering aspects of the DGPS Reference Station respectively. The DGPS Reference Station mathematical model is designed first, this is an essential part of the research. After this the GPS model and the designed DGPS Reference Station model are compared. The main parts of the DGPS Reference Station can be summarised as three digital loops. These are C/A code tracking loop, carrier tracking loop and navigation loop. The loop structures and characteristics are discussed in Chapter Three by using Phase Locked Loops (PLL) and digital signal processing theories. To implement the various system functions, system software of the DGPS Reference Station is designed. The software structure and the main flowcharts are discussed in Chapter Four.

Chapter Five focus on the design of the digital map system required by the project. As long as the map is concerned, the coordinate system plays an important role. There is a discussion of the existing coordinate systems and the conversion method. The software structure of the finally constructed map system is also included.

In the sixth chapter, the design of the mobile navigation unit is described. The main function of the mobile navigation unit is to combine a GPS receiver, a UHF radio receiver and the digital map together. The characteristics of the GPS receiver, SV6, and the UHF receiver are also studied. Finally the system software of the mobile navigation unit is designed.

Chapter Seven presents the performance of the finally constructed DGPS navigation system. This includes both static and dynamic performances of the system. System optimization is also studied. These include the choice of the different system component parameters, and the study of the impact of Kalman filtering on the performance of the system.

The final chapter, Chapter Eight, draws the conclusions of the research. It also offers the recommendations for the further research.

CHAPTER TWO: TECHNICAL BACKGROUND OF GPS AND DIFFERENTIAL GPS

2.1 Overview of GPS System

Over the last decade, GPS has impinged significantly on the positioning community. Although it was designed as a stand alone positioning system, it has been shown to be suitable for a vast range of applications including navigation, surveying, geodesy and even the positioning of other satellites [Getting, I. A. 1993].

GPS was developed by the Department of Defense (DoD) of the United States to provide continuous positioning ability in real-time to users anywhere in the world, 24 hours a day. At present, GPS consists of a constellation of 24 satellites at a height of about 20,000 km in 6 orbital planes, and each GPS satellite orbits the Earth twice a day. The GPS system is capable of providing horizontal positioning accuracy of about 18 m to selected (military) users. Concerns about a malicious user using GPS to deliver missiles or other weapons against the US have led to a policy of accuracy denial. This is called "Selective Availability" (SA), and essentially it is achieved by inserting man-made timing errors into the GPS satellite signals. As a result of SA, civil users can obtain a Standard Positioning Service (SPS) with an accuracy of about 100 m [Dana, H. P. 1995c].

2.1.1 GPS Signal Structure

All GPS satellites transmit two Right Hand Circular Polarized (RHCP) L-band carriers; L1 at 1575.42 MHz, and L2 at 1227.60 MHz. Both signals contain timing codes, and each satellite has its own timing code, so that a specific satellite can be identified. The reason that two carrier frequencies could be used at the same time is

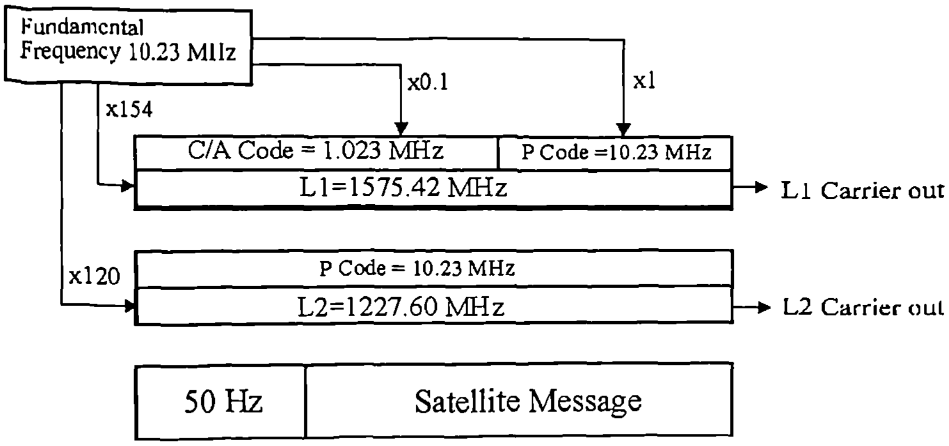


Fig. 2.1 GPS Signal Structure

that it may be useful for a user to correct the Ionospheric delay. **Fig. 2.1** diagramatically shows the GPS signal structure [ICD-GPS-200 1987] [Spiker, J. J. 1978].

It can be seen that there are two different timing codes, the Precise (P) code and Coarse/Acquisition (C/A) code. Both of these are Bipolar-Phase Shift Key (BPSK) modulated on the respective carrier signals. There is also a navigation message which contains navigation data (see **Section 2.1.2**) modulated on these codes.

Both P and C/A codes are pseudo-random binary codes. They appear to be a random sequence, but actually they are generated by precisely known algorithms. The P code has a frequency of 10.23 MHz and a very long period of about 37 weeks. As the P code is made available by the DoD only to authorized users (military users), the discussion followed on will concentrate on the C/A code, and in particular, the C/A code related GPS systems.

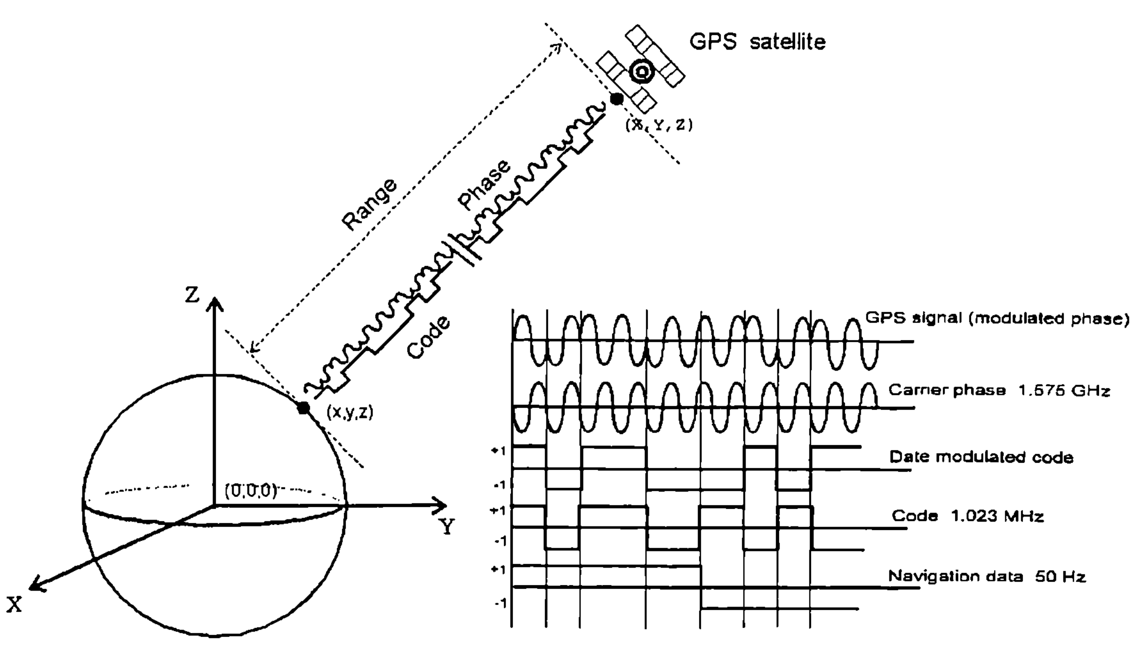


Fig. 2.2 C/A Code

The particular kind of code used in the C/A code is called Gold code and each satellite has a unique Gold code, which identifies that satellite. The Gold code has a chip rate of 1.023 MHz and a period of 1 ms. When modulated on the carrier, it spreads the carrier energy over a 2 MHz bandwidth. Each Gold code unit in GPS technology is referred to as a chip, thus for a period of the C/A code, it contains 1023 chips. The C/A code is used to provide the SPS for civilian users with an accuracy of about 100 m. **Fig. 2.2** shows the C/A code and its application.

2.1.2 GPS Navigation Data (Satellite Message)

The navigation message is broadcast rather slowly, at 50 Hz and is modulated on the C/A code (see **Fig. 2.2**). Each satellite broadcasts details of its own position by using the *Ephemeris* to describe the orbit. The *Ephemeris* is updated every hour, and is effective over four hours. The offset of its own clock from the standard GPS time is

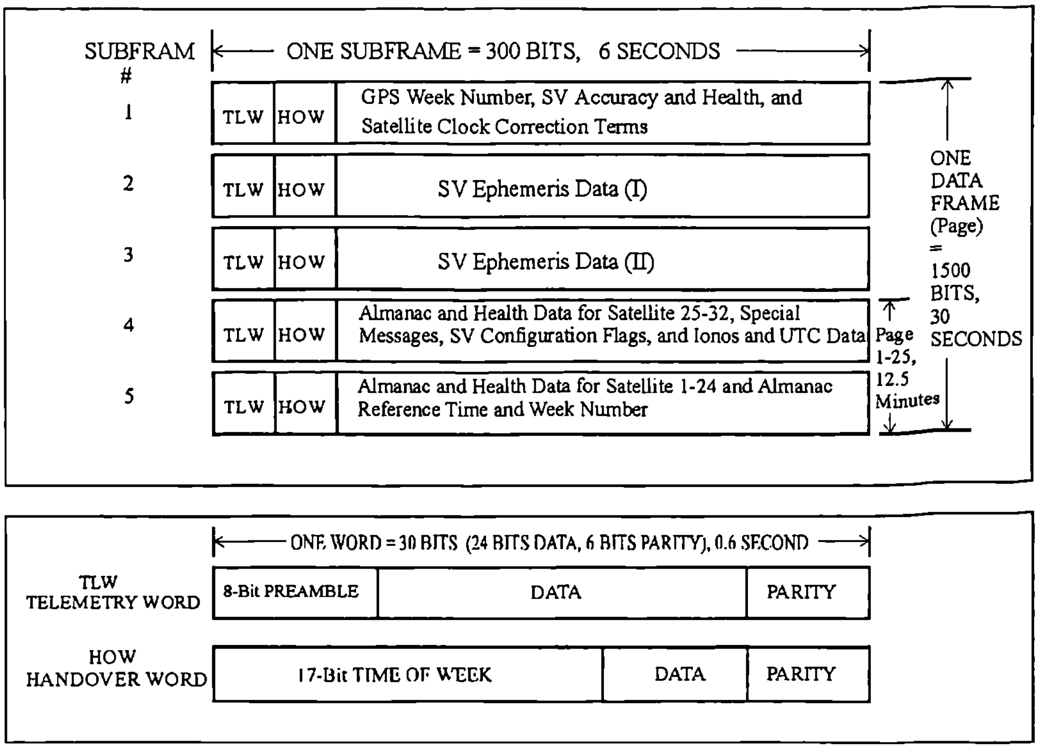


Fig. 2. 3 Navigation Data Format

also included in the message. It also broadcasts approximate positions and health data for its own and other satellites and some other system message by using the *Almanac*. *Almanac* contains satellite orbit data which is less accurate then ephemeris, but which is effective over approximately four months. The almanac is used by GPS receivers to detect the satellites rough positions when the receivers are initially turned on. After that, the receiver can download the more accurate *Ephemeris* [Puterski, R. 1992].

Fig. 2.3 shows the navigation data format. The navigation message frame consists of five subframes. each of 300 bits long. This corresponds to a data rate of 50 Hz for 6 seconds. The first three subframes contain the ephemeris data, satellite clock correction terms and the status of the satellites. These three subframes repeat every frame, i.e. the ephemeris information repeats every 30 seconds. Subframe 4 and 5 contain almanac and other system messages, and it needs 25 frames to complete. Therefore, the total almanac takes 12.5 minutes to transmit.

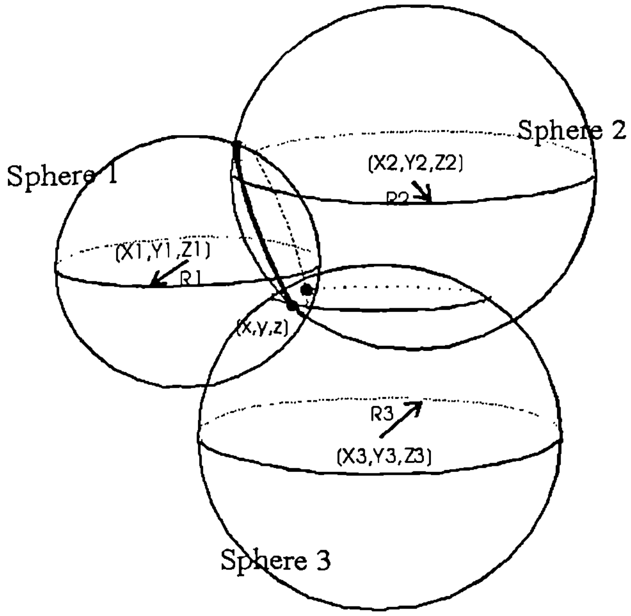


Fig. 2.4 Triangulation From GPS Satellites

Each subframe consists of ten 30-bit GPS words, with a preamble in the front of the first word. At the end of each word, there is a 6-bit parity check, leaving 24 useful bits of data. Some data has to be assembled from different parts of the messages, and all data is fixed point binary, with scale factors given in the specification. All data from the satellite is transmitted in the form of coefficients for the satellite orbit or clock description equations. The user must then input the exact time into these equations to calculate the positions of the satellites.

2.2 Principle of GPS Positioning

GPS positioning principle is based on satellite ranging [Hurn, J. 1989] [Mattos, P. 1992-1993]. The distances from a position to a group of GPS satellites are measured, and this location can then be plotted by triangulation, as shown in **Fig. 2.4**.

In **Fig. 2.4**, R1, R2 and R3 are the ranges from satellites to the GPS receiver, and Xi, Yi and Zi are the co-ordinates of the GPS satellites. From R1, it can be known that the current position lies on the surface of sphere 1. From R2, it can also be known that this current position is also on the surface of sphere 2. By using R1 and R2 together, our current position can be narrowed down to the intersection of these two spheres, in this case, a circle.

To narrow down the possible current positions further, a third satellite is needed. From **Fig. 2.4,** it can be seen that by using three satellites, our current position is limited to only two possible points. Usually, one of the two points can be discarded immediately, as one point may be either far from Earth or 100 km under the Earth surface. It can therefore be concluded that should a 3-d user position x, y and z is needed to be triangulated, three satellites are needed. But in practice, as there is a clock offset in the GPS receiver (see **Section 2.2.1**), four satellites are actually needed to obtain a 3-d user position.

2.2.1 Pseudo-Range Measurement

From the above discussion, it can be seen that the essential point of GPS positioning is accurate satellite ranging. This range calculation process is done by *pseudo-range* measurement by using C/A code matching technique.

When a GPS receiver measures the distance from itself to a GPS satellite, it uses a internally generated C/A Gold code which is exactly the same as the Gold code generated by this GPS satellite. This internally generated code is then shifted to match the received satellite code (see **Fig. 2.5**). As the satellite generated code experiences a time delay for the radio signal to travel from satellite to GPS receiver, it is always a little later than the receiver generated code. The receiver generated code is therefore shifted backwards to reach the match point [Mattos, P. 1989].

After the match point is found, the GPS receiver reads the current time *T1* from the receiver's clock, and satellite time *T2* from the system data. The final satellite signal propagation time delay is $\Delta t = T1 - T2$. This propagation delay multiplied by the speed of light ($\Delta t \times c$) gives the distance between the GPS receiver and the satellite.

When the satellite signal travels through space, it suffers unwanted delays caused by various error sources which are discussed in **Section 2.3.** Therefore the final product of $\Delta t \times c$ is not the true range from the GPS receiver to satellite, but is known as the *pseudo-range*,

Two problems arise with the pseudo-range measurement as discussed above. The first is that it is assumed that both the satellite clock and receiver clock are accurate and are perfectly synchronized. Each of the GPS satellites carries four atomic clocks, and the averaged time of these four atomic clocks is continuously monitored and corrected by GPS ground control segment, and so satellite clock time *T2* can be considered accurate. For the GPS receiver clock, there is always a bias and drift which alters it from the GPS time. To solve this problem, an additional unknown - clock offset T_{off}, is added to the receiver clock time *T1*, and this unknown can be solved in the GPS mathematical model mentioned in **Section 2.2.3.** As this offset T_{off} exists, the satellite generated C/A code is no longer necessarily always later in time than the GPS receiver generated C/A code as mentioned in the second paragraph of **Section 2.2.1.**

The other problem with pseudo-range measurement is the C/A Gold code is used to measure the satellite signal propagation time delay Δt shown in **Fig. 2.5**. As mentioned in **Section 2.1.1**, the period of C/A code is 1 ms, which gives an unambiguous range measuring capability of 300 km ($1\ ms \times c$). After this 1 ms time, the C/A code simply repeats itself. As GPS satellites orbit at a height of about 22,000 km, this raises a question of how to use a 300 km long C/A code ruler to measure the existing 22,000 km long pseudo-range.

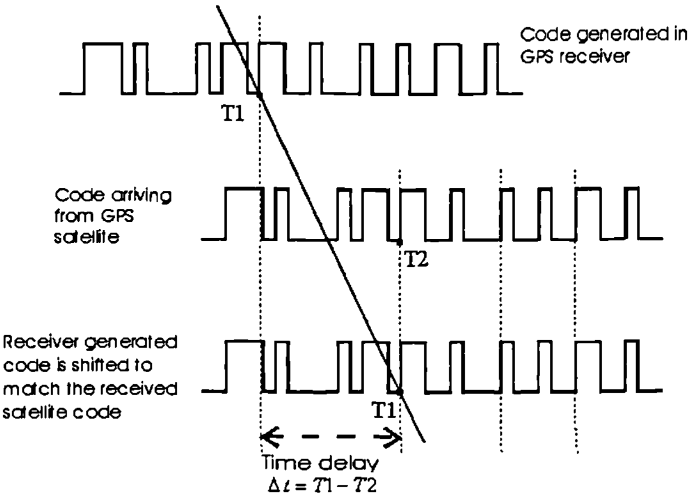


Fig. 2.5 C/A Code Matching

Fig. 2.6 shows the method used in the GPS receiver. When the GPS receiver matches its internally generated C/A Gold with the satellite generated Gold code, it uses a 1ms-epoch counter (counter content 0-19) to count how many satellite code period is shifted and then resets after the content exceeds 19. The carry is then input to a 20ms-epoch counter. As the C/A code is modulated by the navigation data (**Fig. 2.1**), and within the navigation message, there is a Time of Week (TOW) that indicates the exact time of the starting point of each subframe of the navigation data and this starting point is also the starting point of a period of Gold code. During the satellite navigation data decoding process, this starting point is used to reset both the 1ms-epoch and 20ms-epoch counters, so that the starting point of the time of 1ms-epoch and 20ms-epoch counters can be determined. By using this method, the final satellite clock time *T2* can be obtained unambiguously by adding the contents of these two counters i.e. 1ms-epoch and 20ms-epoch to the measured propagation time delay Δt and the TOW.

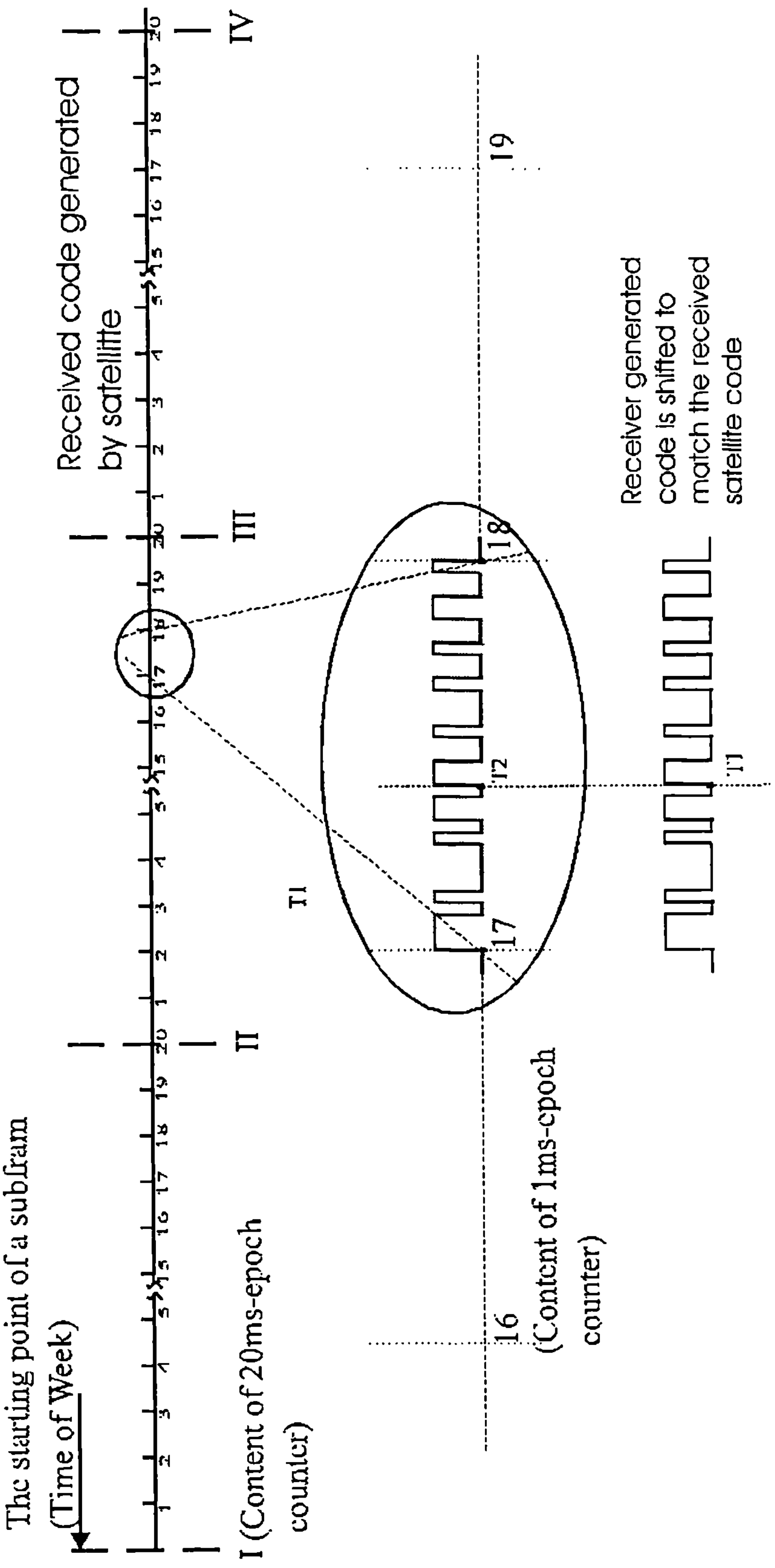


Fig.2.6 1ms-Epoch Counter and 20ms-Epoch Counter of GPS Signal

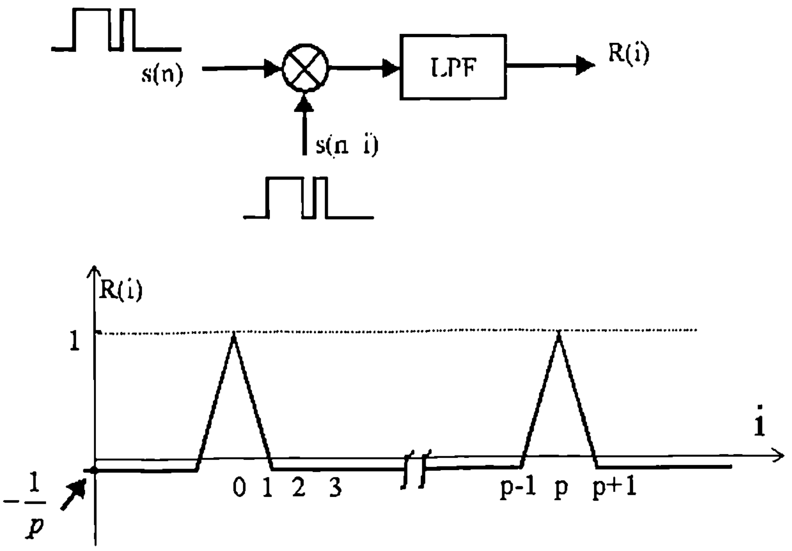


Fig. 2.7 Autocorrelation of C/A Code

2.2.2 Code Correlation and Tracking Loop

To make a pseudo-range measurement, GPS receiver internally generated code must be correlated with the received code from the satellite. If the two states of the binary code are -1 and +1, the multiplication of two identical codes gives an output of unity. If, however, the codes are shifted. the output will be less than unity. To give a true correlation, this product must be taken over the whole of a period of the code and the results integrated. To normalize the correlation, the output is then divided by the period, thus obtaining a correlated output of unity gain.

When two identical codes are correlated, this is known as *auto-correlation*. When a code series $s(n)$ of period p is autocorrelated (with a copy of itself), it can be shown that for a shift of i, the output $R(n) = -1/p$ except when there is no time shift i.e. $t = 0$, then $R(i) = 1$, or when the two codes are within a single chip of each other (see **Fig. 2.7**).

An additional property of the Gold codes is that when two *different* Gold codes (even of the same set) are correlated, the output $R(i)$ is always very low, mostly $= - 1/p$. This

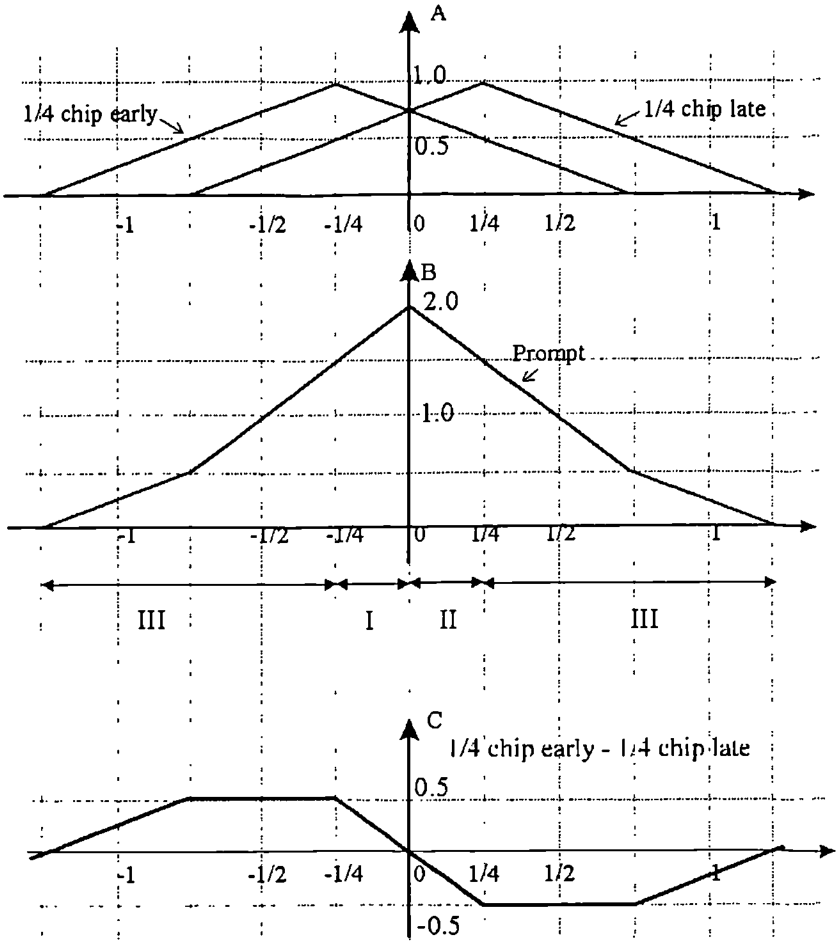


Fig. 2. 8 Early and Late Code Correlators

process of correlating two different codes is referred to as *cross-correlation*. Cross-correlation is the key feature that is used in GPS to distinguish among different GPS satellites. When the GPS receiver searches GPS satellites, it generates all the possible Gold codes and correlates them with the received satellite generated code. A significant correlation output is only obtained (in **Fig.** 2.7 this is 1) when the received satellite Gold code exactly matches that generated internally in the GPS receiver.

The correlating process can be used to detect when the Gold codes are matched, as explained above, however what is needed is a mechanism which allows the GPS receiver generated code to continuously match the received satellite code. This is difficult using only one correlator, because when the codes are not perfectly matched, it is hard to tell whether the internally generated code is shifted too early or too late. This problem can be solved by using two correlators. One correlator produces a peak 1/4 chip early, and the other, 1/4 chip late (**Fig. 2.8**). These two correlation peaks then drive the internal code in the correct shifting direction to match the satellite code. For the prompt correlation result, it can be obtained by properly combining the early and late correlation results.

2.2.3 Mathematical Model of GPS

In order to calculate user current position, the satellite positions X_i, Y_i and Z_i must be determined by solving the satellite orbit Keplerian equations [Kaplan, D. 1996]. Once satellite positions are known, the user position can be calculated by:

$$\begin{cases} \sqrt{(x_j - X_1^j)^2 + (y_j - Y_1^j)^2 + (z_j - Z_1^j)^2} = P_1^j \\ \vdots \\ \vdots \\ \sqrt{(x_j - X_i^j)^2 + (y_j - Y_i^j)^2 + (z_j - Z_i^j)^2} = P_i^j \end{cases} \qquad (2\text{-}1)$$

Where x, y and z are the co-ordinates of the current user position, j is the *jth* step of mathematical iteration, and i is the satellite number (from *1 ~ i*) . The equations in **Eqs. (2-1)** are simple Pythagorean calculations of ranges between the user and the satellites. The P_i^j is the pseudo-range from the user to the i_{th} satellite. As discussed in **Section 2.2.1,** the pseudo-ranges are measured by comparing the GPS receiver clock time $t_{receiver}$ with the GPS satellite clock time $t_{satellite}$. Using T as the time offset between these two clock times, thus:

$$\begin{cases} P_1^j = [(t^j{}_{receivre} + T_j) - t^j{}_{satellite1}] \times c \\ \vdots \\ \vdots \\ P_i^j = [(t^j{}_{receivre} + T_j) - t^j{}_{satellite}\, i] \times c \end{cases} \qquad (2-2)$$

Combining **Eqs. (2-1)** and **Eqs. (2-2)** together produces four unknowns x_j, y_j, z_j and T_j, for which at least four equations are required for calculating their values, i.e. i should be ≥ 4. For where $i > 4$, an over-determined solution will be obtained.

Let user position be:

$$\begin{cases} x_j = x_{j-1} - \Delta x \\ y_j = y_{j-1} - \Delta y \\ z_j = z_{j-1} - \Delta z \end{cases} \qquad (2-3)$$

If multiplying out the combination **Eqs. (2-1)** and **Eqs. (2-2)** by using **Eqs (2-3)** and ignoring second order terms (e.g. $\Delta x \times \Delta y$), the equation is linearized to:

$$\begin{cases} (\sqrt{(x_{j-1} - X_1^j)^2 + (y_{j-1} - Y_1^j)^2 + (z_{j-1} - Z_1^j)^2}\,)^2 - (P_1^j)^2 = 2(x_{j-1} - X_1^j) \\ \times \Delta x + 2(y_{j-1} - Y_1^j) \times \Delta y + 2(z_{j-1} - Z_1^j) \times \Delta z - 2P_1^j \times c \times T_j \\ \vdots \\ \vdots \\ (\sqrt{(x_{j-1} - X_i^j)^2 + (y_{j-1} - Y_i^j)^2 + (z_{j-1} - Z_i^j)^2}\,)^2 - (P_i^j)^2 = 2(x_{j-1} - X_i^j) \\ \times \Delta x + 2(y_{j-1} - Y_i^j) \times \Delta y + 2(z_{j-1} - Z_i^j) \times \Delta z - 2P_i^j \times c \times T_j \end{cases} \qquad (2-4)$$

let:

$$R_i = \sqrt{(x_{j-1} - X_i^j)^2 + (y_{j-1} - Y_i^j)^2 + (z_{j-1} - Z_i^j)^2} \qquad (2\text{-}5)$$

R_i is called *Current Predicted Range* for the *ith* satellite, and compared with this, P_i^j is called *Observed Range.*

Substituting R_i in **Eqs. (2-4)**:

$$\begin{cases} (P_1^{\,j} - R_i)\times(P_1^{\,j} + R_i) = 2(x_{j-1} - X_1^j)\times\Delta x + 2(y_{j-1} - Y_1^j) \\ \times\Delta y + 2(z_{j-1} - Z_1^j)\times\Delta z - 2P_1^j \times c\times T_j \\ \qquad\qquad\vdots \\ \qquad\qquad\vdots \\ (P_i^{\,j} - R_i)\times(P_i^{\,j} + R_i) = 2(x_{j-1} - X_i^j)\times\Delta x + 2(y_{j-1} - Y_i^j) \\ \times\Delta y + 2(z_{j-1} - Z_i^j)\times\Delta z - 2P_i^j \times c\times T_j \end{cases} \qquad (2\text{-}6)$$

Since $R_i \approx P_i^j$, therefore:

$$(P_i^{\,j} - R_i)\times(P_i^{\,j} + R_i) \approx (P_i^{\,j} - R_i)\times 2\times R_i \qquad (2\text{-}7)$$

Replacing the right side of equation of **Eqs. (2-6)** with **Eqs. (2-7)**, the following result is obtained:

$$\begin{bmatrix} P_1^j - R_1 \\ \vdots \\ \vdots \\ \vdots \\ P_i^j - R_i \end{bmatrix} = \begin{bmatrix} \dfrac{X_1^j - x_{j-1}}{R_1} & \dfrac{Y_1^j - y_{j-1}}{R_1} & \dfrac{Z_1^j - z_{j-1}}{R_1} & 1 \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ \dfrac{X_i^j - x_{j-1}}{R_i} & \dfrac{Y_i^j - y_{j-1}}{R_i} & \dfrac{Z_i^j - z_{j-1}}{R_i} & 1 \end{bmatrix} \times \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \\ c \times T_j \end{bmatrix} \qquad (2\text{-}8)$$

If the matrix notation $[\mathrm{Y}] = [\mathrm{X}] \times [\mathrm{A}]$ is used to represent **Eq. (2-8)**, then [Y] is usually called *Pseudo-range Vector,* [X] is the *Directional Derivatives matrix*, and [A] is the *Navigation Update.*

By solving the above matrix equation, the final *Navigation Update* is obtained as:

$$[\mathrm{A}] = \left(\left[[\mathrm{X}]^{\mathrm{T}} \times [\mathrm{X}] \right]^{-1} \times [\mathrm{X}]^{\mathrm{T}} \right) \times [\mathrm{Y}] \qquad (2\text{-}9)$$

2.3 Main Error Sources That Affect GPS Accuracy

The Standard Positioning Service (SPS) accuracy of GPS is about 100 meters. The reason for this is that there are many factors that affect GPS performance. There is even a man-made error deliberately inserted into GPS signal to safeguard against the malicious uses. Mainly, these error factors include the following [Bouhours, G. 1990] [Blanchard, W. F. 1995]:

2.3.1. Ionospheric Propagation Delay

The ionosphere is that area of the atmosphere where free electrons exist and is approximately 50-1000 km above the Earth. When the GPS signal propagates through the ionosphere, it is dispersed to some degree so the delays in signal reception are caused. This delay is variable, depending on the electron density in the ionosphere, and the angle that the GPS signal passed through it. The characteristics of the ionosphere change with the time of the day, due to exposure to the solar wind, and also with season.

When the signal propagation delay is caused by the ionosphere, the delay time is proportional to the square of the frequency, it is possible to eliminate it by making measurements using two different frequencies. For this reason, GPS satellites transmit on both L1 and L2 carrier frequencies (see **Section 2.1.1**). But as the L2 carrier frequency uses P code, and this P code is not available to the public, the commercial user must either use a mathematical model to simulate the Ionospheric propagation delay, or use differential techniques to eliminate it.

Fig. 2.9 shows three mathematical models of the propagation delay caused by ionosphere. It can be seen that it can cause about 60 m of pseudo-range error.

2.3.2 Tropospheric Propagation Delay

The troposphere is closer to the surface of the Earth than the ionosphere and affects the GPS signal in a similar way. The difference is that it varies according to meteorological conditions i.e. temperature, water vapor content, and atmospheric pressure, and is therefore more variable than the ionosphere, and may also fluctuate rapidly. The delay of the signal propagation caused by the troposphere is not dependent on radio frequency, and is roughly the same at all frequencies. It can be quite accurately calculated if local meteorological measurements are available. **Fig. 2.10** shows its effects and it can be seen that the propagation delay is considerably smaller than the Ionospheric effects.

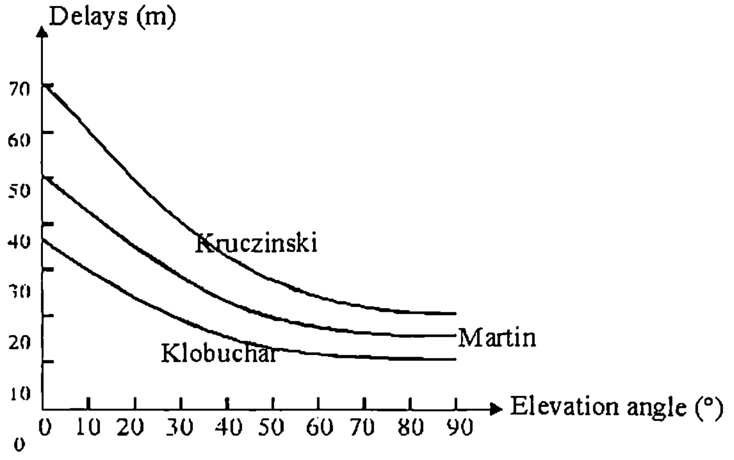


Fig. 2.9 Theoretical Ionospheric Delay

2.3.3 Selective Availability (S/A)

This is a man-made error, deliberately inserted into GPS signals by the DoD, to limit the available accuracy to about 100 m by 95 percent of the time. There are many ways to implement this error. For example, modifying the satellite orbit data (ephemeris) very marginally, or dithering the satellite clock time. A typical pseudo-range error caused by S/A is about 24 m.

The authorized user i.e. military user can remove the distortions caused by S/A by decrypting coded parameters in the navigational message. But for the public, there is no available information on the S/A's characteristics or on how it may be implemented.

2.3.4 Receiver Noise

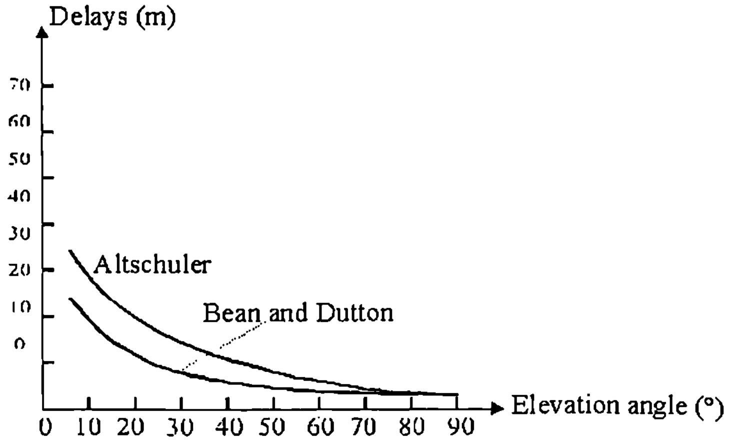


Fig. 2.10 Tropospheric Propagation Delay

This is a random error and its magnitude depends on the design of the receiver. In the past decade, receiver design has improved tremendously through the use of digital technology, so it is no longer a significant problem.

2.3.5 Multipath Effect

This is caused by the GPS signal being reflected from local surfaces i.e. high buildings, trees into the antenna with a time delay caused by the added path length. At GPS frequencies, this can be of considerable amplitude and may be the determining factor in the ultimate accuracy, if GPS antenna is badly situated.

2.4 Differential GPS Concept

2.4.1 Background of Differential GPS

Differential technology is a method of improving the positioning accuracy by establishing a reference station to calculate the pseudo-range corrections. These corrections are then transmitted to a mobile GPS receiver which applies these corrections to its measurements. By applying differential technology, the pseudo-range errors that are caused by sources that are common to both reference station and mobile receiver can be removed. In DGPS, the error sources described in **Sections 2.3.1 - 2.3.3** can be totally eliminated and these three are the major sources that mostly affect the GPS positioning [Blanchard, W. F. 1991] [Morgan-Owen, G.J. 1995].

To implement differential technology, a differential GPS reference station needs to be set up on a fixed known position. **Fig. 2.11** shows the principle of such a system. The DGPS Reference Station, basically, is still a GPS receiver but implanted with a DGPS mathematical model and the corresponding differential correction algorithms to provide the essential differential correction data. As its own position is accurately surveyed, it can then compare the measured pseudo-ranges with the theoretically calculated ones and the corresponding corrections are obtained.. The corrections are encoded into a standard RTCM-104 format, and are then transmitted to a mobile GPS receiver using a real-time radio data link.

Differential techniques are not new, having been used for many years in other radio-positioning systems. However, the latest technology is in the speed of the radio data link that is capable of passing the differential correction messages from the DGPS Reference Station to a mobile user in a fraction of a second. This almost instantaneous transmission makes the system real-time. It has only come about because GPS is the first radio navigation system that has errors correcting over a fairly wide area. It can be used over a distance of 500 km or more from a monitor station, on a 24-hours basis, and is unaffected by weather.

There are two ways to implement differential corrections. One is to calculate the positional corrections on a reference station site, and apply these to the mobile user's measured position expressed in longitude, latitude and height. The other is to calculate

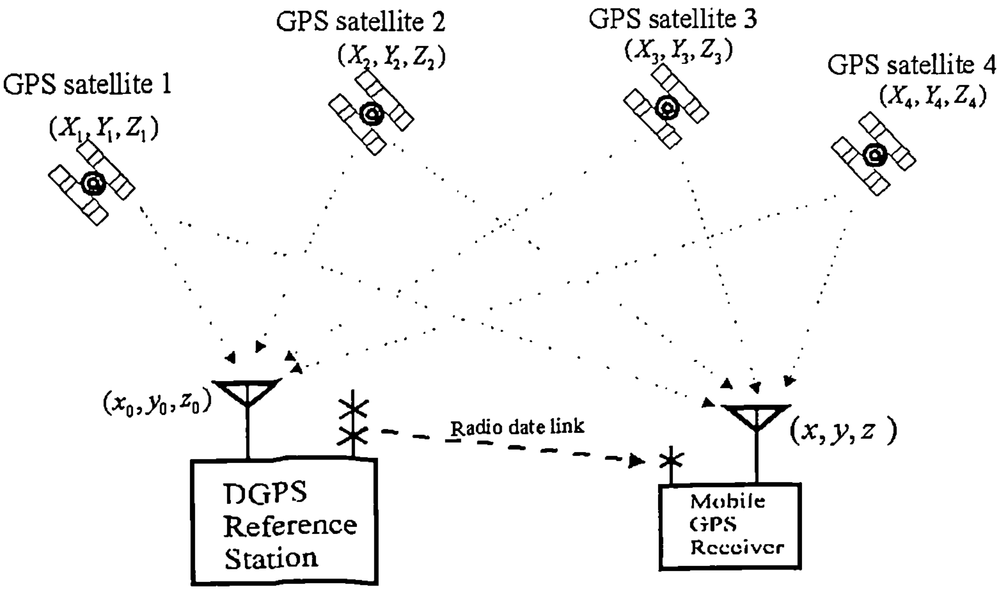


Fig. 2.11 Differential GPS Concept

the pseudo-range corrections for every GPS satellite that is visible to the reference station, and to apply these corrections later to the mobile user's pseudo-range measurements. For the first method, the calculated positional correction message is shorter and therefore easy to transmit, but it has the problem that both user and reference station **MUST** use the same satellites all the time. But this may not happen for the following reasons:

- The receiver criterion for selecting satellites could differ.
- Terrain or earth's curvature might block a low-lying satellite from the user or reference station.
- The user receiver may employ an all-in-view strategy, wherein all visible satellites are used to determine position.
- Satellites available at user location may differ from those available at the reference station.

Should the mobile user and reference station use a different satellite, the positioning errors resulting from this would be far too large.

By transmitting pseudo-range corrections, any satellites that are visible to the reference station can be used by the mobile receiver in the differential mode to determine the position, even though the correction messages are considerably longer than the first method. This also implies that the reference station should be able to reach as many visible satellites in the sky as possible.

2.4.2 DGPS Reference Station Algorithms

As summarized in **Section 1.2,** there are no papers directly describing DGPS Reference Station mathematical model in the public domain. This is also the case of DGPS correction calculating algorithms. Companies which provide DGPS correction data services claim different positioning accuracies, but it is difficult to determine what algorithms are actually being used in their systems. Manufacturers are unwilling to disclose the details, and no manufacturers will admit that their particular method is inferior to that of a rival!

It was therefore decided that a DGPS Reference Station would be built from constructing the appropriate DGPS mathematical model to implement all the related correction message calculating algorithms. Different system software could be therefore implemented and changed, and the impact of the changes of the characteristics of the system components on the system performance could be thus investigated.

CHAPTER THREE: DIFFERENTIAL GPS REFERENCE STATION

3.1 DGPS Reference Station Based on the GPS BuilderTM

As described in **Section 1.3**, it was decided to utilise the GPS Builder^{TM} from GEC Plessey Semiconductors to build the DGPS Reference Station. The GPS Builder is an L1 band C/A code GPS receiver development system with 12 independent tracking channels and gives the user flexibility to design his own special system [GEC Plessey Semiconductors 1994a]. As the essential system components and raw signals are well under user's control, the DGPS Reference Station is implemented by combining the GPS Builder hardware with a new DGPS Reference Station system software which employs a DGPS mathematical model and corresponding algorithms.

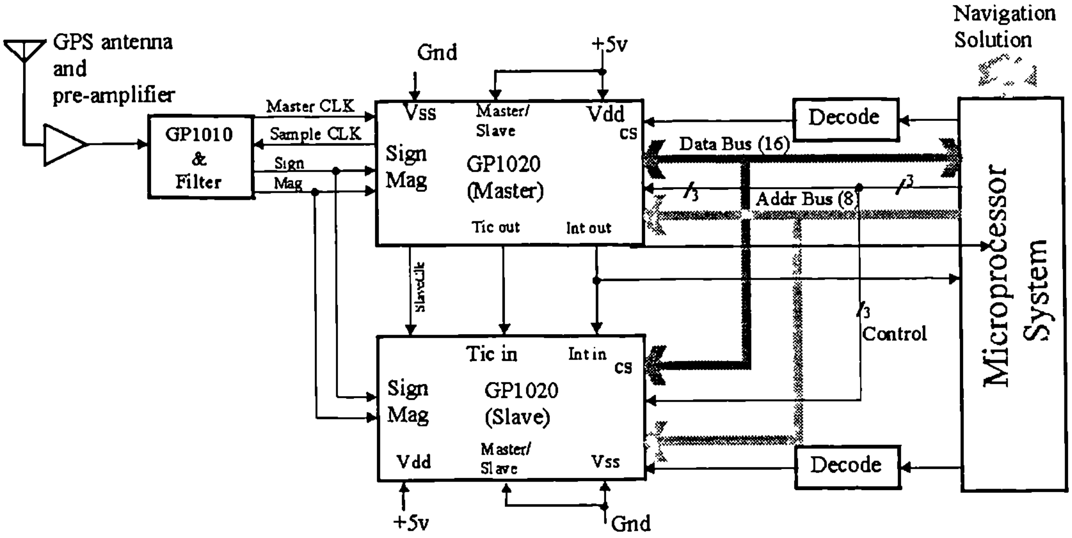


Fig. 3.1 Simplified Block Diagram of GPS Builder (DGPS Reference Station)

Fig. 3.1 shows the simplified block diagram of the GPS Builder. The essential part of the GPS Builder is a GP1010/GP1020 chip set. GP1010 is the RF front end chip that receives the L1 carrier from the GPS antenna with a low noise pre-amplifier [GEC Plessey Semiconductors 1994b]. This L1 signal is firstly triple-down-converted to an intermediate frequency at 4.31 MHz, with a last stage filtering being incorporated on-chip. The final output of GP1010 is 2-bit digital signal, the result of the fourth down-conversion, and this down-conversion is digital (for details, see **Section 3.1.3**). The first bit of this 2-bit signal is the sign of the signal: Sign, the other bit is signal magnitude: Mag. This 2-bit signal is used for the subsequent correlation carried out in GP1020.

GP1020 is a six-channel correlator that was designed to work with GP1010 front end to acquire and track the GPS C/A code. The functions of tracking module of GP1020 is discussed in **Section 3.1.1**. Two 1020 chips are used in the Builder, one as the master chip, the other as slave, to give the system developer 12 channel facility. GPS Builder requires a microprocessor system with a substantial amount of raw computing power (12 satellite tracking channels must be processed every 505 microseconds, with enough time left over to perform a substantial amount of numerical calculation). In this research, a host PC of 486 DX2 66 MHz was used. All the GPS Builder hardware was assembled in a mother-and-daughter ISA card, and this ISA card is hosted by the PC 486.

3.1.1 Tracking Module Simplified Block Diagram of the GP1020

The core of GP1020 correlator is a six-channel tracking module because it contains basic hardware components which are needed to compose the different signal tracking loops [GEC Plessey Semiconductors 1994c]. **Fig. 3.2** shows the block diagram structure of one of these channels. It contains a Carrier DCO, a Code DCO, a Code Generator, two Mixer and four Correlators and Quadruple Integrate and Dumps. All these components are made of the hardware. Each of these components has its own control register, through which, the microprocessor can either control the component, or get access to the output results.

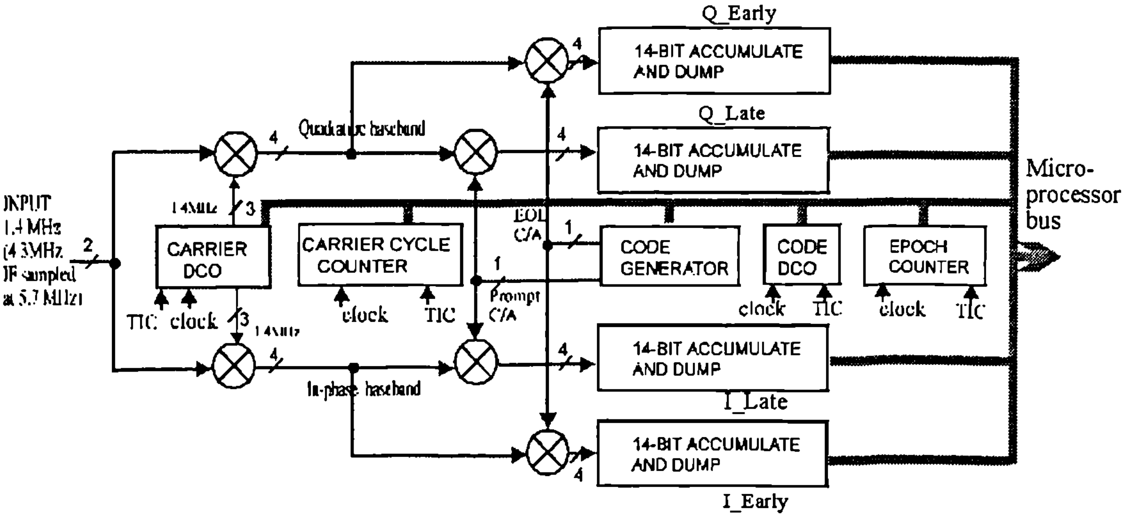


Fig. 3.2 Block Diagram of the Structure of Channel of Tracking Module of GP1020

Each channel of the GP1020 is fed with 2-bit digital signal from the output of GP1010, and this signal is brought down to baseband using an on-chip digital mixer driven by a programmable digital local oscillator. The baseband is then correlated with a C/A code internally generated by a programmable Gold code generator. The correlation result is the sum of the comparisons of individual code chips over a complete code period (code 1ms-epoch). A large positive or a large negative sum indicates good correlation but with opposite modulation, while a small sum indicates poor correlation and the need of adjusting the relevant system loop. The results form the "Accumulated Data" and are fed to the host PC to both control the tracking loops and to give the broadcast satellite navigation data when demodulated. Periodically, the code epoch counter (1ms-epoch counter, as mentioned in **Section 2.2.1**), the code phase, 20ms-epoch counter, and the carrier phase of all channels are sampled at the same instant to produce the "Measurement Data". This measurement data is then used to calculate the pseudo-ranges.

The functions of the sub-block of the tracking module of GP1020 are as follows:

Carrier DCO

The carrier DCO is an accumulator performing addition at a constant rate and with a programmable increment value. It is used to synthesise the digital local oscillator signal required to down-convert the input signal to baseband. It is needed to be adjusted away from nominal frequency to allow for signal Doppler shift caused by the satellite movement and the GPS receiver crystal clock frequency error. The nominal frequency of the output is 1.405396825 MHz, set by loading a 26-bit CHx_CARR_INCR register to 01F7 B1B9 with a resolution of 42.57475 mHz. This very fine resolution is needed to keep the carrier DCO in phase with the satellite L1 carrier signal.

Code DCO

The Code DCO has a similar structure to the Carrier DCO and is used to synthesise the oscillator signal required to drive the C/A code generator at the proper chipping rate and phase. The nominal frequency of the output is 2.046 MHz, to give a chip rate of 1.023 MHz, and is set by loading a 25-bit CHx_CODE_INCR register to 016E A4A8 with a resolution of 85.14949 mHz. Again this very fine resolution is needed to keep the code DCO in phase with received satellite generated C/A code.

Code Generator

This generate a specified Gold code for a specific satellite. Twin generators are used to produce a 1/4 chip early code and a 1/4 chip late C/A code for tracking purpose (details discussed in **Section 2.2.2**). At the end of each code sequence, a signal of DUMP is generated to latch the Accumulated Data, separately for each channel.

Mixer and Correlator

The Mixer and Correlator are all digital multipliers. The Mixer is the multiplier used to mix the digitised 2-bit GP1010 output signal (fourth IF) with the Carrier DCO output to generate baseband signal. This baseband is then correlated in the Correlator with the outputs of Code Generator.

As the carrier DCO actually generates two local signals (in-phase and quadrature), and both of them are mixed with the fourth IF, therefore two Mixers are needed. After mixers, two basebands i.e. in-phase and quadrature are produced (the purpose of this two phase mixing will be discussed later). These two basebands are then correlated with the 1/4 chip early and 1/4 chip late Gold codes respectively in four Correlators. As the result of these four correlators, four signals i.e. Quadrature Early (Q-Early), Quadrature Late (Q-Late), In-phase Early (I-Early) and In-phase Late (I-Late) will be created.

Quadruple Integrate and Dump

The bit-by-bit results of the four correlators are passed to four Quadruple Integrate and Dump units, which integrate the correlation result of individual code chips over a complete code period. According to the theory of digital signal processing, this integrate and dump unit acts as a hardware low-pass digital filter which has the function of picking up the input signal's envelop.

With this integrate and dump unit, there is an Accumulated Data registers, through which the processor can get access to the integration results. These results are then used to either control the relevant system loop or to abstract the useful system navigation information.

3.1.2 System Clock Generation

The system clock generation consists of a MASTER CLK, a SLAVE CLK, a SAMP CLK, a DUMP RATE, an INT OUT and a TIC OUT. The time sequence of the GP1010/GP1020 chip can be summarised as follows:

Master and Slave Clock

The Master Clock has a frequency of 40 MHz and it is used to set the timing of all the functions in GP1020. However, when a multiple GP1020 system is involved, only one chip will serve as the master chip, and this chip is given this Master Clock. The other chips will serve as slave chips and use the clock output of the master chip to synchronise the system. The slave clock frequency is 40 MHz / 2 = 20 MHz.

Sample Clock

The Master Clock is divided by seven to produce a Sampler Clock which has a frequency of 40 MHz / 7 = 5.7142857 MHz. This frequency is used to sample the output of GP1010 to fourthly down-convert the GPS L1 frequency.

DUMP RATE

The Dump Rate period is 1 ms and is used to trigger the output of four Integrate and Dump units. As the C/A code period is also 1 ms, when the Dump Rate occurs, the integrated correlation result of a specified Gold code over a whole period can be obtained.

INT OUT

The INT OUT signal is a free running interrupt timebase which is used to interrupt the microprocessor to initiate the data transfer between the microprocessor and the tracking channel. As the interrupt regularly happens, the microprocessor checks the data at a fixed time intervals. Otherwise a software polling scheme will be necessary, and this will add an extra burden on the microprocessor.

The period of INT OUT is 505.05 μs. As the INT OUT rate is about twice the correlation result rate (Dump Rate) for each channel, so many transfer triggered by the INT OUT will not give new data. **Fig. 3.3** shows the situation. But from **Fig. 3.3,** it can be seen that the correlation result generated by the Dump signal will never be missed.

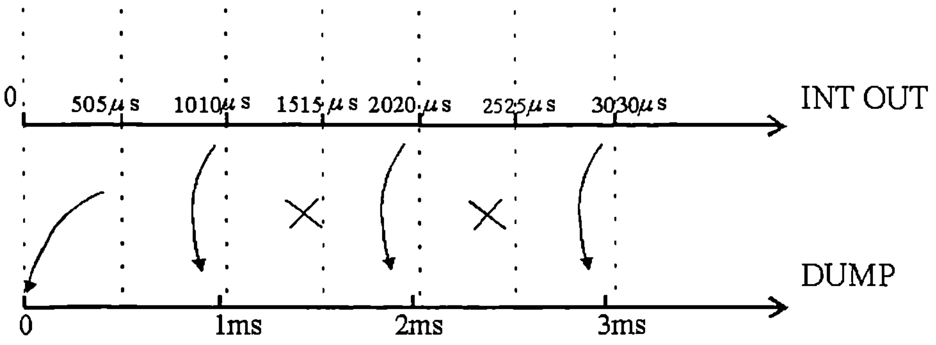


Fig. 3.3 The Relationship between INT OUT and DUMP

To improve the interrupt service efficiency, the required interrupt service can be reduced by examine the relevant registers status to see if the new data is available. Then the interrupt service will only happen when the reading the correlation result is meaningful.

TIC OUT

TIC OUT is a time sequence used to control the cycle of navigation loop (see **Section 3.4**). The period of TIC OUT interval is 571428 Sample CLK cycles, that is:

$$1 \text{ TIC OUT} = 571428 * 7/40000000 = 100 \text{ (ms)}$$

This allows 10 navigation updates per seconds.

3.1.3 Frequency Plan of the GP1010/GP1020 Chip Set

GP1010/GP1020 chip set contains 5 signal down conversion stages to bring the GPS L1 carrier from 1575.42 MHz to baseband. The first three stages are performed by analogue mixers contained in the GP1010. The fourth down conversion is digital, occurring in the sampler which is driven by the 40/7 MHz SAMP CLK output. The final down conversion occurs in the GP1020 correlator, where quadrature outputs of the carrier DCO are mixed with the sampled GPS IF signal to produce the in-phase and quadrature outputs I and Q.

Proper implementation of a DGPS reference station requires a careful study of this frequency plan. The attention is needed to put on the exact intermediate frequencies (IFs) and whether high-side or low-side mixing occurs at each down conversion stage.

In the usual case (low-side mixing), an RF signal is mixed with a local oscillator of lower frequency to produce a down converted IF signal. For low-side mixing, a positive phase movement of the RF results in a positive phase movement of the IF.

In less common cases (high-side mixing), an RF signal is mixed with a higher frequency LO. This often occurs as a result of digitisation of an IF signal at a rate higher than the RF, where the sampling clock serves as an LO to produce a down conversion. The down converted IF is still the frequency difference of the RF and LO, but positive phase movements of the RF result in negative phase movements at the IF (and vice versa). This phase reversal must be accounted for if it occurs. High-side mixing is used at the fourth down conversion stage of the GP1010/GP1020.

The five signal down conversion stages of the GP1010/1020 chip set can be summarised as follows:

First stage: The 1575.42 MHz GPS L1 signal is low-side mixed with a 1400 MHz (40 MHz * 35) LO to produce a 175.42 MHz first IF;

Second stage: The 175.42 MHz first IF is low-side mixed with a 140 MHz (1400 MHz / 10) LO to produce a 35.42 MHz second IF;

Third stage: The 35.42 MHz second IF is low-side mixed with a 31 1/9 MHz (1400 MHz / 45) LO to produce a 4.31 MHz third IF;

Fourth stage: The third IF is sampled by a 5.714 MHz (40 MHz / 7) clock. Over sampling is a high-side mixing process, so a phase reversal occurs in this down conversion stage. The fourth IF is -1.405396852 MHz. The negative frequency indicates the phase reversal which has occurred;

Final stage: The fourth IF is mixed with both the in-phase and quadrature software-controllable carrier DCO generated signals. The outputs of this process are the final basebands with a nominal carrier DCO frequency of 1.4053 MHz. Here the carrier DCO frequency is set by the carrier tracking loop implemented in the system software. An additional phase reversal may or may not occur in the baseband, depending on whether the DCO is set high or low relative to the fourth stage IF.

The resulted in-phase and quadrature basebands will have a residual frequency difference between the original GPS L1 signal and the sum of all the LO frequencies described above. The DGPS system software then adjusts the carrier DCO to first drive this residual frequency difference to zero, and eventually to achieve a near-perfect phase lock to the signal. The nominal carrier DCO frequency setting is 1.405396825 MHz, which would convert a 1575.42 MHz GPS L1 signal to zero frequency.

The following equation can be used to calculate the DCO frequency control word to generate the desired DCO frequency:

$$f_0 = \frac{W \times f_c}{2^N}$$

where f_0 = DCO output frequency

f_c = DCO clock frequency

N = DCO length (bits)

W= DCO input word

So, given carrier DCO clock frequency $f_c = 40/7 = 5.714$ MHz and DCO length $N = 27$, DCO input word W for a given f_0, or, f_0 for a given W can be calculated.

Therefore, the DCO input word W for a nominal DCO frequency of 1.405396825 MHz is:

$$W = \frac{f_0 \times 2^N}{f_c} = \frac{1.405396825 \times 10^6 \times 2^{27}}{5.714 \times 10^6} = 33010104.55$$

The nearest integral value is 01F7 B1B9 (hex), which has an error of about 19 mHz. The resolution of this input word is 42.57475 mHz as mentioned in **Section 3.1.1**.

3.2 C/A Code (correlation) Tracking Loop

The C/A code tracking loop is one of the major system components of the DGPS Reference Station and its main function is to shift C/A code replica, the code generated by the GP1020 Code Generator, to a correct direction to match the C/A code that is modulating a GPS satellite L1 signal. After these two C/A codes match, the shift time Δt can be used to calculate the pseudo-range from the DGPS Reference Station to this satellite (see Section 2.2.1). This matching process also has the function of demodulating the BPSK modulated GPS L1 carrier, so that both the C/A code and Navigation Data can be abstracted [Dixon, R. C. 1984].

Fig. 3.4 shows the structure of C/A code tracking loop. Compared with the channel tracking module shown in **Fig. 3.2**, it can be seen that besides the hardware components contained in the channel tracking module, such as code generator, code DCO, four correlators and four integrate and dump units, it also consists of extra multipliers, adders, subtracters and code loop filters. These extra components are constructed by software algorithms. Therefore, C/A code tracking loop is a mixed hardware and software loop, and the loop is finally closed by host PC regularly updating the content of 25-bit CHx_CODE_INCR register of the Code DCO to adjust generated C/A code rate.

In the design of a GPS receiver, it can be considered adequate to track the C/A code correlation peak to an accuracy of about 1/32 code chip (approximately 9 m). The idea is that code tracking needs not be much better than the Selective Availability error (24m). However, in the design of the DGPS Reference Station, C/A code tracking accuracy becomes a major issue. Differential corrections are applicable only when the reference station's C/A code tracking accuracy is improved to about 1 m.

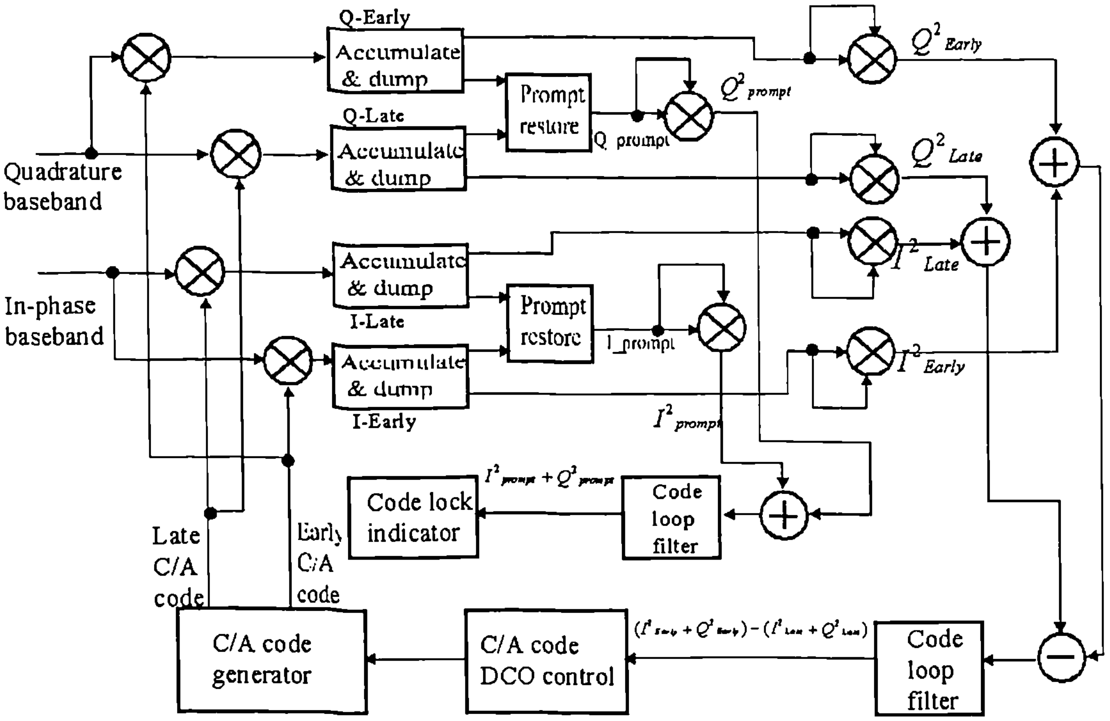


Fig. 3.4 Structure of the C/A Code Tracking Loop

Two methods are used in the design of DGPS Reference Station to increase the accuracy of C/A code tracking. The first method is narrower correlator spacing, the second is carrier aiding, which will be discussed in **Section 3.3.6**.

Correlator spacing is the time difference between the Early and Late samples (see **Section 2.2.2**). The design of the GP1020 correlator enables a wide (1 chip) correlator spacing, with a Prompt channel to sample the signal exactly at its correlation peak and a Dithering channel, which alternates its samples between Early (Prompt - 1/2 chip) and Late (Prompt + 1/2 chip). However, optional setting allows the Dithering channel to be set permanently early and the Prompt channel to be set permanently late. In this case the former Prompt and Dithering channels then have a correlator spacing of 1/2 chip, with the Dithering channel permanently early by 1/4 chip and the Prompt channel permanently late by 1/4 chip. DGPS reference station adopted this method, and this increased the tracking accuracy significantly. One important point to take note is that, in this situation, the correlation result obtained from the prompt channel is not prompt any more. The precise prompt correlation result needs to be calculated by combining the Early and Late correlation results in a proper way.

To see how to construct the precise prompt correlation result, the Early and Late code correlation result shown in **Fig. 2.8** is extended and the result is shown in **Fig. 3.5.**

Fig. 3.5.A shows the 1/4 Early and 1/4 Late correlation results. **Fig. 3.7.C** shows an ideal precise prompt correlation result that shows a clear and distinct peak. However, it is misconception that an addition of 1/4 Early and 1/4 Late correlation results can be used to represent this precise prompt correlation. The reason for this is that the simple addition of 1/4 Early and 1/4 Late correlation will result in **Fig. 3.7.B**. rather then **Fig. 3.7.C**. The problem with is that the correlation losses its peak and has a flat response between the -1/4 chip and +1/4 chip area. If **Fig. 3.7.B** is used in system as a correlation output indicator (see **Section 3.2.1**), it can be seen obviously that it can not indicate an accurate correlation result.

The ideal prompt correlation result descried in the **Fig. 3.7.C** can be constructed as follows:

Area I:	0 < Early - Late < Late,	Prompt= 1/3 Early + 7/3 Late
Area II:	0 < Late - Early < Early,	Prompt= 1/3 Late + 7/3 Early
Area III:	else,	Prompt= Early + Late

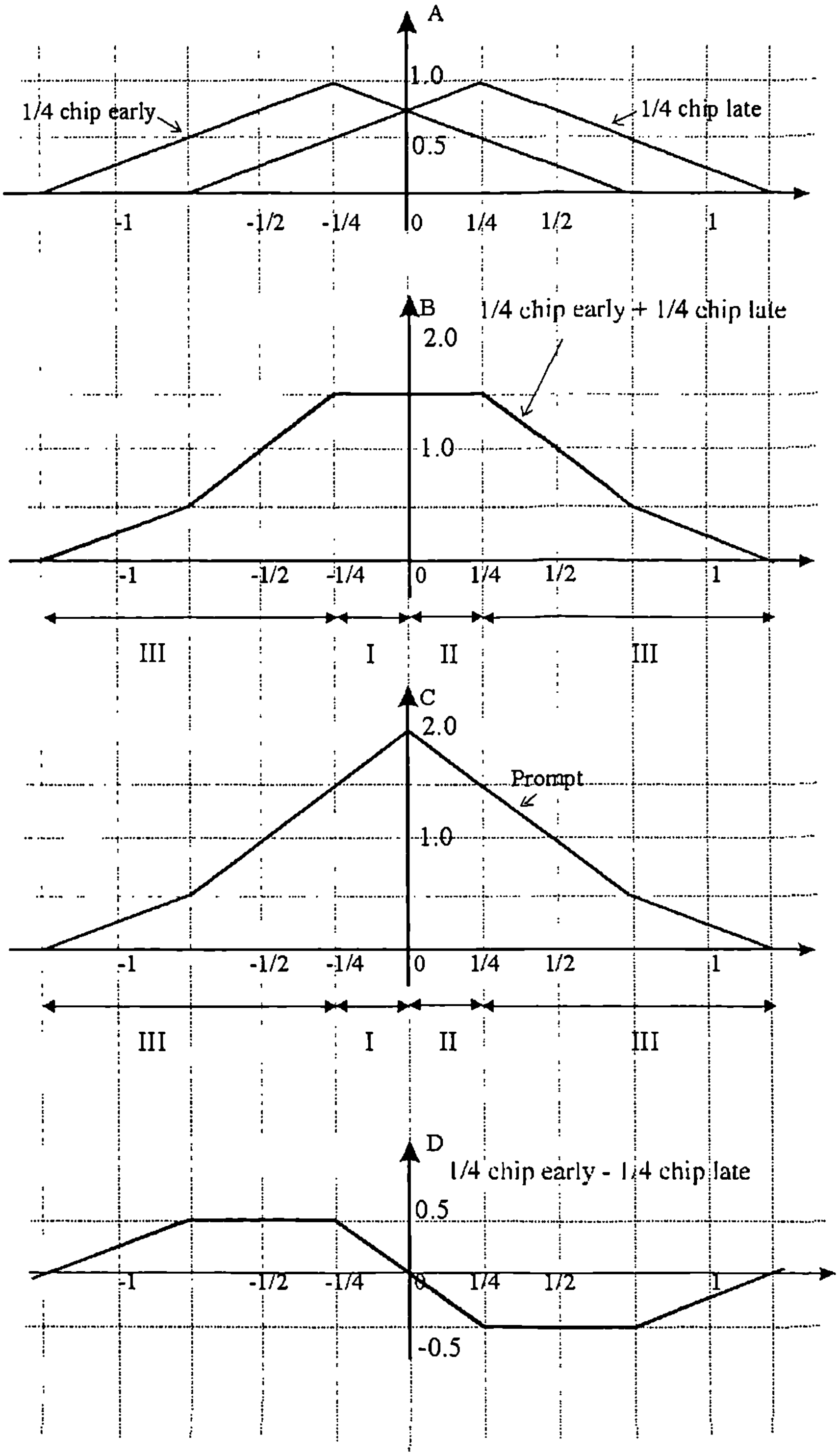


Fig. 3.5 Early and Late Code Correlators

The other point of C/A code tracking loop is that it needs a suitable control signal to drive the Code generator to a correct shifting direction to match the received satellite generated C/A code. The difference of the Early and Late correlation results can be used for this purpose. The actual waveform of Early - Late correlation is shown in **Fig. 3.7.D**. The idea of an Early-Late tracking is to straddle the correlation peak in the middle by comparing the Early and Late correlation results. Any imbalance between the Early and Late correlations indicate the direction to move the local C/A code replica so as to place it more precisely on the signal's correlation peak.

There are two processes involved in the C/A Code tracking loop: search and track. DGPS Reference Station uses a sliding-replica search for the rough C/A code position. This means that the locally generated C/A code is generated at a very slightly higher chip rate than the satellite's C/A code. Since the two codes repeat at intervals of nearly 1 ms, the local C/A code "slides" in time against the satellite's C/A code. When the local C/A code has slid to a point at which it approximately matches the satellite's C/A code, the signal power from the correlator output suddenly increases. When the post-correlation signal power exceeds some detection threshold, the C/A code generator is adjusted so that the local and satellite C/A code stop sliding relative to each other. At this point, the Early - Late tracking loop operates to accurately synchronise the corrector's code replica with the satellite's C/A code.

3.2.1 Correlation Lock Indicator ($I^2_{prompt} + Q^2_{prompt}$)

As discussed above, it is necessary to determine whether the C/A code correlation result has exceeded the pre-set correlation threshold. In other words, a correlation lock indicator is needed to examine the amplitude of the current correlation output result. In the DGPS Reference Station, the signal of $I^2_{prompt} + Q^2_{prompt}$ is used for this purpose. It is important to notice that the I_{prompt} and Q_{prompt} here are the precise prompt correlation results of the In-phase arm and Quadrature arm of the GP1020 correlator shown in Fig. 3.2. They are constructed by the method discussed in the last section, and shown in Fig. 3.7.C.

When the Code tracking loop is locked and the DGPS Reference Station generated C/A code matches the received satellite generated C/A code, the In-phase arm and the Quadrature arm will give the satellite navigation data. This is because the correlation is a demodulation process for the C/A code and this C/A code is modulated by the navigation data (see Fig. 2.2.). Since the internally generated C/A code is not modulated by this navigation data, after the code tracking loop is locked, the satellite L1 carrier phase reversals caused by the C/A code modulation will be (mostly) removed, but the phase reversals caused by navigation data bit modulation will remain as the output of the correlation process.

The value of the correlation output is either +1 or -1, depending on the navigation data value. These values, if accumulated, would have a sum of zero. In order to indicate the correlation result properly, the I^2_{prompt} and Q^2_{prompt} are used to present the correlation output power, rather then I_{prompt} and Q_{prompt}.

The other point needs to be mentioned is that, the satellite L1 carrier tracking loop used in the DGPS Reference Station is a Costas loop, and its characteristics are discussed in details in **Section 3.3.1.** But a brief discussion of some of its properties that affect C/A code tracking loop is followed here.

In the Costas loop that tracks the GPS L1 carrier signal, a quadrature DCO produces two LO signals: In-phase and Quadrature. The phase difference between these two signals is 90°. When the internally generated LO exactly matches the input GPS L1 carrier (zero frequency and phase error), all signal power obtained from the accumulator will appear on In-phase arms and the output of Quadrature arms will be zero. However, this state of "exact match" is quite rare, or when it happens, it can not last long because both the input GPS L1 carrier frequency and the LO frequency change constantly. If the phase difference between the input GPS L1 carrier and the LO reaches 90°, the roles that In-phase and Quadrature arms play will exchange. In this case, all signal power will appear on the Quadrature arms and the output of In-phase arms will be zero. From this it can be seen that the addition of In-phase and Quadrature correlation outputs $I^2_{prompt} + Q^2_{prompt}$ can be used effectively as the correlation lock indicator, and the output signal strength will be doubled so that the system achieves an extra 3 dB gain.

3.2.2 C/A Code Correlation Threshold and Post-detection Signal to Noise Ratio (SNR)

Once the correlation lock indicator is designed, the next question is what is the expected value of $I^2_{prompt} + Q^2_{prompt}$ when no GPS L1 carrier is present (i.e. the noise floor of L1 carrier signal), and what is the expected value of $I^2_{prompt} + Q^2_{prompt}$ when GPS L1 carrier signal is acquired (i.e. the threshold of C/A code correlation)?

In GP1010/GP1020 chip set, the third GPS IF signal output by GP1010 is sampled at a rate of 5.714 MHz at the fourth down-conversion stage. The sine and cosine components are quantitised to a 2-bit signal (with the four levels having values -3, -1 +1, and +3) and integrated over 1 ms periods in 14-bit accumulators.

The GP1010 adjusts its RF gain automatically so that the output of the quantitiser is in the range [-1, +1] 70% of the time. When this condition is achieved, the percentage of samples falling into each quantisation bin is:

-3 15%, -1 35%, +1 35%, +3 15%

a discrete distribution with a numerical variance of $\sigma^2 = 3.4$ and mean of zero.

Within each channel of the tracking module of the GP1020, this 2-bit quantised signal is mixed to baseband using digital representations of in-phase and quadrature LOs. The distribution of the LOs over one cycle is as follows:

In-phase (sin): +2 +2 +1 -1 -2 -2 -1 +1
Quadrature (cos): +1 -1 -2 -2 -1 +1 +2 +2

When the input signal is +3, the product with the in-phase LO over one cycle produces the following distribution:

(+3) * (In-phase) = +6 +6 +3 -3 -6 -6 -3 +3

which has a mean-square value of 22.5.

Likewise, when the input signal is +1, the product with the in-phase LO over one cycle produces the following distribution:

(+1) * (In-phase) = +2 +2 +1 -1 -2 -2 -1 +1

which has a mean-square value of 2.5.

Therefore, over each 1 ms accumulation period, the noise power, I^2_{prompt} in the In-phase accumulator is obtained by combining the mean-square values with their likelihood of occurrence and the sampling rate to give:

$$I^2_{\mathrm{prompt}} = [\ 22.5 * (0.15 + 0.15) + 2.5 * (0.35 + 0.35)\ ] * 5.714 * 1000$$

which gives:

$$I^2_{\mathrm{prompt}} = 48571$$

Therefore,

$$I^2_{\text{prompt}} + Q^2_{\text{prompt}} = 2 * 48571 = 97142$$

i.e., this is the expected noise floor when no L1 carrier is present.

With no signal present, the quantity $I^2_{\text{prompt}} + Q^2_{\text{prompt}}$ is an exponentially distributed random variable [Lindsey, W. C. 1991]. The distribution function is:

$$f(z) = \frac{1}{2\sigma^2}\exp(\frac{-z}{2\sigma^2}) \qquad 0 < z < \infty$$

where the variance of f(z) is $4\sigma^2$ and $\sigma^2 = E[I^2_{prompt}] = E[Q^2_{prompt}] = 48571$ as derived previously. The probability that a signal measured $I^2_{prompt} + Q^2_{prompt}$ value exceeds an acquisition threshold T_A by random chance alone (that is, a false detection event) is:

$$p(z > T_A) = \frac{1}{2\sigma^2}\int_{T_A}^{\infty} \exp(\frac{-z}{2\sigma^2})\, dz = \exp(\frac{-T_A}{2\sigma^2})$$

Signal presence is declared when $I^2_{prompt} + Q^2_{prompt}$ correlator output exceeds the acquisition threshold T_A. The selection of T_A is a matter of engineering judgement. The value of T_A should be set low enough to detect weak signals, but not so low as to waste a lot of time processing false detection.

In the DGPS Reference Station, it is desirable to acquire weak signal which are about 3.5 dB above the noise floor. In this case:

$$T_A = 97142 \times 10^{0.35} = 217473$$

and the false detection rate:

$$p(z > 217473) = \exp(\frac{-217473}{97142}) = 0.107$$

The post-detection signal to noise ratio (SNR) of the input L1 carrier can be estimated as the ratio between the output of $I^2_{prompt} + Q^2_{prompt}$ and the expected noise floor and the typical value of SNR of the DGPS Reference Station is presented in **Chapter Seven.**

3.2.3 The Code DCO Control $(I^2_{Early} + Q^2_{Early})-(I^2_{Late} + Q^2_{Late})$

As mentioned in **Section 3.3.1** and shown in **Fig. 3.7.D**, the difference of Early - Late correlation results can be used to drive the Code DCO to a correct shifting direction to match the received satellite generated C/A code. In the DGPS Reference Station, the signal of $(I^2_{Eerly} + Q^2_{Early})-(I^2_{Late} + Q^2_{Late})$ is used for this purpose. Here I_{Early}, Q_{Early}, I_{Late} and Q_{Late} are the direct outputs of the early and late correlation results of Costas loop's In-phase and Quadrature arms. For the same reason applied to correlation lock indicator, the square signal strength of I^2_{Eerly}, Q^2_{Early}, I^2_{Late} and Q^2_{Late} are used to present the signal power instead of using I_{Early}, Q_{Early}, I_{Late} and Q_{Late}. And again the In-phase and Quadrature outputs are combined together to give the output signal an extra 3 dB gain.

3.3. Carrier Tracking Loop

The carrier tracking loop is another major system components of the DGPS Reference Station and its main function is to track input GPS L1 signal carrier. Only after this carrier is tracked, the C/A code tracking loop can then effectively

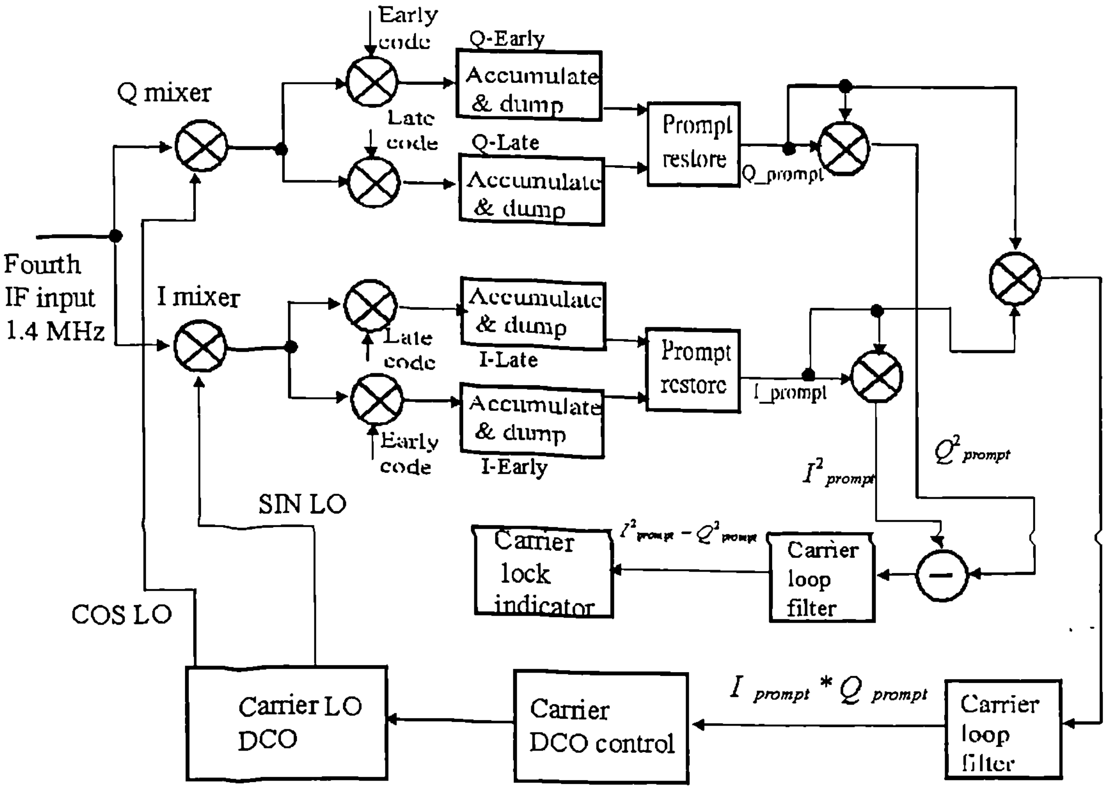


Fig. 3.6 Structure of Carrier Tracking Loop

demodulate the carrier and abstract the C/A code and Navigation Data from it. Besides that, once exact carrier phase tracking is achieved, the integrated carrier phase measurement can be used to improve the pseudo-range measurement.

As GPS satellites move very fast in the sky (orbiting the Earth twice a day), the resulted L1 carrier Doppler shift is quite considerable, sometimes can be as great as 20 kHz. This means that the carrier tracking loop must have the ability to copy with this frequency shifting.

Fig. 3.6 shows the structure of carrier tracking loop. Similar to C/A code tracking loop, it is also a mixed loop and consists of not only hardware components such as carrier DCO, four mixer and four accumulators, but also components constructed by software algorithms such as multiplier, subtracter and carrier loop filter. The loop is finally closed by the host PC regularly updating the content of a 26-bit CHx_CARR_INCR register of carrier DCO to adjust the carrier DCO's output frequency.

3.3.1 Costas Loop Applied to the DGPS Reference Station

The essential part of the carrier tracking loop can be is reduced to a special phase locked loop, Costas loop. The Costas loop (after J. P. Costas) is insensitive to the 180° phase reversals of the input signal [Harolo, B. Killen 1988]. This is particularity important for GPS signal's BPSK modulated data bit which remains on the signal after down conversion.(see **Section 2.1.1**). In order to use phase locked loop theory to analyse the characteristics of carrier tracking loop, **Fig. 3.6** is abstracted and redrawn here as **Fig. 3.7** to show the Costas loop structure. For reference purpose, the related theoretical background of phase locked loops is given in **Appendix I**.

From **Fig. 3.7**, it can be seen that Costas loop contains the same components as an ordinary phase locked loop (see **Fig. A1.1**), but a quadrature DCO is used to replace the single phase VCO. A quadrature DCO is an digital oscillator which produces two phases 90^0 apart, and those are of sine and cosine phases. These two phases are both mixed with the input signal. The outputs of the two mixers are then filtered by a Low-pass filter to form an in-phase baseband output and a quadrature baseband output. The other difference from the standard PLL is that a third multiplier is used to mix the In-phase baseband output and the Quadrature baseband output together, and the output is used to control the VCO [Best, R. E. 1993].

When an input signal is applied to I and Q multipliers, it is multiplied by the in-phase LO signal and the quadrature LO signal respectively. The outputs of the multipliers are then:

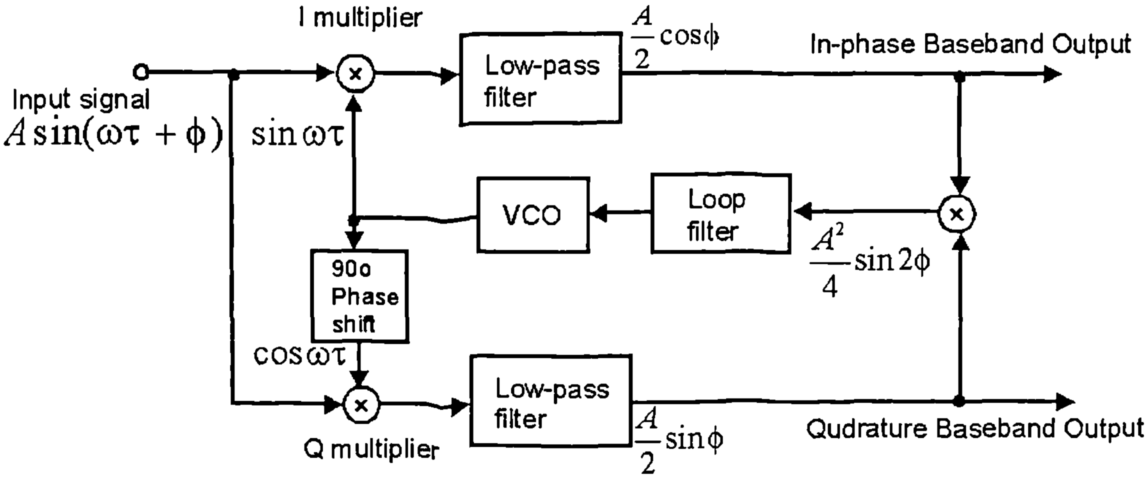


Fig. 3.7 The Costas Loop Applied to the DGPS Reference Station

For I multiplier: $\frac{A}{2}[\cos(2\omega t+\varphi)+\cos\varphi]$

For Q multiplier: $\frac{A}{2}[\sin(2\omega t+\varphi)+\sin\varphi]$

When these two signals pass through the respective low-pass filters, they are converted to $\frac{A}{2}\cos\varphi$ and $\frac{A}{2}\sin\varphi$ respectively. These two signals are then multiplied together by the third mixer to produce a VCO control signal, and that is:

$$\frac{A^2}{2}\sin\varphi\times\cos\varphi=\frac{A^2}{8}\times 2\sin\varphi\times\cos\varphi=\frac{A^2}{8}\sin 2\varphi$$

Again, for small phase error $\sin 2\varphi\approx 2\varphi$, therefore:

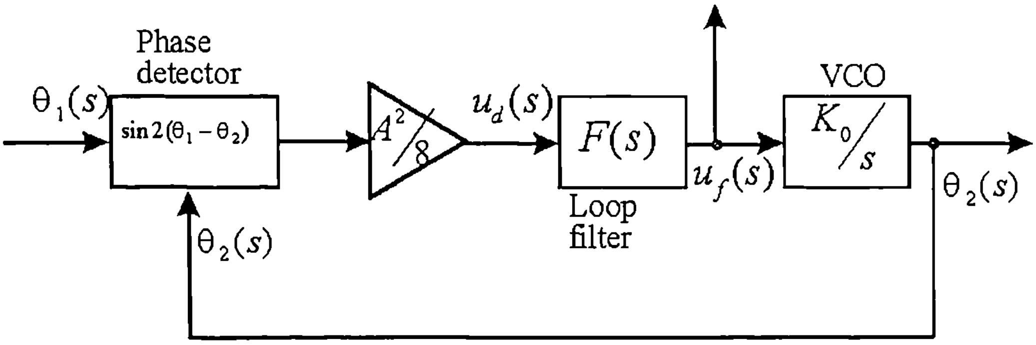


Fig. 3.8 Equivalent PLL Block Diagram for a Costas Loop

$$\frac{A^2}{8}\sin 2\varphi = \frac{A^2}{8}\times 2\varphi = \frac{A^2}{4}\times\varphi$$

Fig. 3.8 shows the block diagram of the substituted equivalent PLL for a Costas loop. Compared with the standard PLL shown in **Fig. A1.1**, it can be seen that the gain of Costas loop is lower. If this gain difference is absorbed in Phase detector, it will lead:

$$\frac{U_{d\,\mathrm{Costas}}}{\theta_{e\,\mathrm{Costas}}} = K_{d\,\mathrm{Costas}} \qquad (3\text{-}1)$$

and comparing **Eq. (3-1)** with **Eq. (A1-4)**, it can be seen:

$$K_{d\,\mathrm{Costas}} = \frac{K_d}{2} \qquad (3\text{-}2)$$

Eq. (3-2) is an important equation that links Costas loop with the standard phase locked loops discussed in **Appendix I**. By replacing K_d with $K_{dCostas}$ in the **Eqs. (A1-17) -(A1-21)**, all the loop phase transfer function and the loop parameters such as: ω_n, ξ, $\Delta\omega_n$, T_p *and* $\Delta\omega_{po}$, that describe the loop characteristics can be obtained.

There two special considerations for implementing Costas loop in the DGPS Reference Station. The first is the method of decreasing the pull-in time. The second is the avoidance of multiplication operations and multiple precision arithmetic, which will be discussed in **Section 3.3.3**.

As discussed earlier, Costas loop attempts to match the frequency and phase of DCO LO to an externally supplied input. In the DGPS Reference Station, this external input is the difference frequency which remains after Doppler-shifted satellite L1 carrier was fourth-down converted. The nominal frequency of this input is 1.404396825 MHz, but actual frequency variation from the nominal frequency can be from zero Hz to 20 kHz. This will lead the output of the Costas loop (baseband) to have a frequency of zero to 20 kHz. The aim of the Costas loop is first to match the frequency of the carrier DCO to this fourth IF to drive the baseband to zero Hz. The second aim is to exactly match the output LO phase to this IF input.

A linear, analogue Costas loop will eventually pull in even from a large initial frequency error (given enough time). However, the digital Costas loop requires a special method for pulling in from a large unavoidable initial frequency error.

In the DGPS Reference Station, the Costas loop operates in two modes. After carrier signal lock has been achieved, it operates as a normal Costas phase-locked loop. But before this locked state is achieved, it operates as a frequency-locked loop (FLL). The FLL error signal is supplied by the four accumulators whose outputs is (on the average) proportional to the frequency difference between the GPS carrier signal and the output of Carrier DCO. The FLL will remove up to several hundred Hz of initial frequency error and bring Costas carrier tracking channel to a near phase-locked condition. The changeover from FLL to Costas tracking occurs at the instant that the carrier lock indicator I^2_{prompt} - Q^2_{prompt} reaches its threshold value for a carrier lock (see **Section 3.3.2**).

The wide frequency range of the input mainly caused by Doppler shift to the Costas loop makes it necessary to use several different acquisition strategies. Briefly:

1. If the difference frequency is too great, the Low-pass filtering (not the Loop filtering, see **Fig. 3.6**) which occurs in the one-millisecond 14-bit accumulate-and-dump will reduce the signal to a point where it can't be detected. This makes it necessary to actually try different widely-spaced carrier DCO settings, looking for signal power. This is called "searching the Doppler bins of input signal";

2. The appearance of signal power while a Doppler bin is being searched means that the current carrier DCO setting is within a few hundred Hz of the correct value. The second acquisition strategy is to adjust the carrier DCO settings to reduce the frequency error. This brings the carrier DCO to within a few Hz of its correct setting;

3. Phase locking is attempted only when the difference frequency is only a few Hz.

3.3.2 Carrier Lock Indicator (I^2_{prompt} - Q^2_{prompt})

In order to judge whether internally generated carrier DCO LO is locked to the input carrier signal, a carrier lock indicator is needed. When the phase of the carrier DCO exactly matches the phase of the GPS L1 carrier signal, virtually all the signal power will appear on the In-phase arms and almost none will appear on the Quadrature arms. This means I^2_{prompt} will reach maxim and Q^2_{prompt} will reduce to zero, thus the signal of $I^2_{prompt} - Q^2_{prompt}$ can be used as carrier lock indicator. Here I^2_{prompt} and Q^2_{prompt} have the same meaning as they have in **Section 3.2.2**.

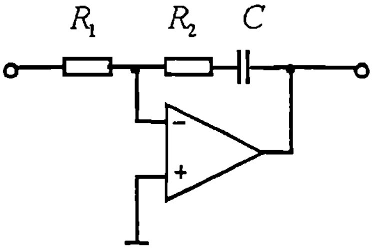
3.3.3 Carrier Tracking Loop Control (sign(I_{prompt})* Q_{prompt})

For a Costas loop, the loop VCO control signal is the multiplication of the outputs of In-phase and Quadrature arms (see **Fig. 3.7**). For the DGPS Reference Station, this control should be of the form of $I_{prompt} * Q_{prompt}$ as discussed in **Section 3.2.2**

When DGPS Reference Station system software is implemented, it is needed to avoid the multiplication operations and multiple precision arithmetic, whenever it is possible, to save the computing time to more important tasks. The multiplication operations of $I_{prompt} * Q_{prompt}$ can be avoided by implementing the Costas loop VCO control as $sign\ (I_{prompt})* Q_{prompt}$. The reason for this is near phase locked condition, the output of In-phase arm is nearly a constant (being proportional to the cosine of the phase error), and is insensitive to the error amplitude.

3.3.4 Digital Loop Filter Design

As discussed in **Appendix I**, for a phase locked loop, once the Phase detector and VCO are chosen, the characteristics of PLL will only depend on the property of the Loop filter. The Loop filter used there is 1st order analogue active-lag filter and its structure is re-drawn here as **Fig. 3.9.**



$T_1 = R_1C$
$T_2 = R_2C$

Fig. 3.9 1st Order Active-lag Loop Filter

In the DGPS Reference Station, this loop filter is a software component and is digital. The design of this digital loop which should have the same characteristics as the 1st order active-lag filter is given below:

The construction starts with the filter's open loop Laplace transfer function *G(s)*. Let *X(s)* and *Y(s)* be the Laplace transforms of the filter input and output functions, then by the definition of transfer functions:

$$G(s) = \frac{Y(s)}{X(s)} = \frac{T_2\, s + 1}{T_1\, s}$$

and

$$T_1 \cdot (Y(s) \cdot s) = T_2 \cdot (X(s) \cdot s) + X(s)$$

According to the definition of Laplace Transfer, it can be expressed in the time domain:

$$T_1 \frac{dy}{dt} = T_2 \frac{dx}{dt} + x$$

since the derivatives can be represented approximately:

$$\frac{dy}{dt} = \frac{y_i - y_{i-1}}{\Delta T}$$

$$\frac{dx}{dt} = \frac{x_i - x_{i-1}}{\Delta T}$$

Where ΔT is the interval between filter inputs. Therefore, the filter outputs can be calculated recursively in software as follows:

$$T_1 \times (y_i - y_{i-1}) = T_2 \times (x_i - x_{i-1}) + x_i \times \Delta T$$

or, in a more convenient form:

$$y_i = y_{i-1} + (T_2 / T_1) \times (x_i - x_{i-1}) + (\Delta T / T_1) \times x_i \qquad (3\text{-}3)$$

From this filter update expression, it can be seen that the characteristic of the software filter depends on two factors, one the type of the filter, the other is the two time constants. In the DGPS reference station, the type of filter is decided first, thus the values of two time constants *T1* and *T2* need to be determined next. In system software, the actual algorithm for the loop filter is:

$$CARRDCO_i = CARRDCO_{i-1} + (I_{prompt\,i} * Q_{prompt\,i} - I_{prompt\,i-1} * Q_{prompt\,i-1})/1024$$
$$+ I_{prompt\,i} * Q_{prompt\,i}/1048576 \qquad (3\text{-}4)$$

Here, the CARRDCO is the content of the 26-bit CHx_CARR_INCR register mentioned in **Section 3.3.** Comparing **Eq. (3-4)** with the theoretical filter update expression **Eq. (3-3),** it can be seen:

$$T_2/T_1 = 1/1024$$

and

$$\Delta T/T_1 = 1/1048576$$

The Carrier tracking loop filter takes its inputs at the DUMP rate, and it has one millisecond intervals, so $\Delta T = 0.001$ second and finally the time constants are solved as follows:

$$T_1 = 0.001 * 2097152 = 1048.576 \text{ second}$$

$$T_2 = T_1 / 1024 = 1.023 \text{ second}$$

3.3.5 Typical Value of the Parameters of Carrier Tracking Loop

According to the phase locked loops theory, the Carrier tracking can be classified as a 2nd order phase locked loop, because the loop filter is of 1st-order type (see **Appendix I**). The parameters of the Costas loop are defined and calculated as follows, where "units" refers to the numerical value which comes out of a detector or controls a DCO:

K_d, phase error detector scaling, units per radian of phase error.

This indicates how to convert the numerical value from the phase error detector into units of radians. For the DGPS Reference Station, this will vary with the post-detection SNR of the satellite, and a typical satellite signal will have a post-detection SNR of 10.0 dB. The power output $I^2_{prompt} + Q^2_{prompt}$ will be 10 times higher than the expected noise power of 97142 (see **Section 3.2.2**), and will be 971420.

When the Costas loop is phase locked (zero phase error), $|Q_{prompt}| = 0$ and $|I_{prompt}| =$ maximum possible value. At this time $I_{prompt} = \sqrt{971240} = 985$. At 90^0 phase error, $|I_{prompt}| = 0$ and $|Q_{prompt}| =$ maximum possible value $= \sqrt{971240} =$

985. Although the Costas loop is slightly non-linear as shown in **Section 3.3.1**, use a linear approximation will result:

K_d = $985\ units/90^o=627.0705$ units per radian of phase error

After this it is needed to find:

K_O , conversion gain of the VCO (in the DGPS Reference Station, this is carrier DCO) , radians per second per unit.

This indicates how much the radian frequency of the DCO is changed per unit of its control number and this quantity can be obtained from GP1020 data sheet, $K_0 = \frac{f_c}{2^N}$, where f_c and N are defined in **Section 3.1.3,** thus:

$$K_0 = \frac{f_c}{2^N} = 42.57475\ milliHz\ /\ unit = 0.2675\ rad\ /\ \sec\ per\ unit$$

When working with K_d and K_O, it is always important to remember and account for any scaling which may occur in digital signal processing. In the Costas loop implemented in the DGPS reference station, the I_{prompt} and Q_{prompt} outputs from the correlators are adjusted (multiplied) by a facter *a1* before going into the Loop filter, and the carrier DCO control value is divided by another factor *a2* before being sent out to 26-bit CHx_CARR_INCR. By adjusting the values of *a1* and *a2*, the values of K_d and K_O can be adjusted. Furthermore, as mentioned in **Section 3.2.1,** In-phase and Quadrature outputs are combined together to obtain an additional 3 dB gain in the carrier tracking loop. Incorporating these scale factors:

$K_d = 627.0705 * 2 * a1$ units per radian of phase error

$K_0 = 0.2675/a2$ rad /sec per unit of DCO control.

In the DGPS Reference Station, $a1 = 8192$ and $a2 = 16$, therefore:

$K_d = 10273924$ units per radian of phase error

$K_0 = 0.01672$ rad /sec per unit of DCO control.

Having identified K_d, K_0, T_1 and T_2, all the properties of the Costas loop implemented in the DGPS Reference Station can be computed as follows (see **Appendix I**):

1). Loop natural frequency

$$\omega_{n\,\mathrm{Costas}} = \sqrt{\frac{K_{d\,\mathrm{Costas}} \times K_0}{T_1 + T_2}} = \sqrt{\frac{K_d \times K_0}{2 \times (T_1 + T_2)}} = 9.05 \text{ rad / sec} = 1.44 \text{ Hz}$$

2). Damping factor

$$\zeta_{Costas} = (T_2 / 2) * \omega_{n\,Costas} = 4.6$$

3). Pull-in range

$$\Delta\omega_{pCostas} = \frac{4}{\pi}\sqrt{2\zeta_{Costas}\omega_{nCostas}K_0 K_{d\,\mathrm{Costas}} - \omega^2_{n\mathrm{Coatas}}} = \frac{4}{\pi}\sqrt{\zeta_{Costas}\omega_{nCostas}K_0 K_d - \omega^2_{n\,\mathrm{Costas}}}$$

$= 3403$ rad/sec $= 541$ Hz

4). Pull-time from an initial frequency error of $\Delta\omega_0$. In the DGPS Reference Station, it is reasonable to consider an initial frequency offset of $\Delta\omega_0 = 5\ Hz = 31.4$ rad / sec;

$$T_{p\,\mathrm{Costas}} = \frac{\pi^2 \Delta\omega_{0\,\mathrm{Costas}}^{\;2}}{16\zeta_{Costas}\,\omega_{n\mathrm{Costas}}^{\;3}} = 0.178 \text{ sec}$$

5). Pull-out range (frequency step which causes the PLL to unlock)

$$\Delta\omega_{p0\ Costas} = 1.8 * \omega_{n\ Costas} * (\zeta_{\ Costas}+1) = 91.2\ rad/sec = 14.5 \text{ Hz}$$

It should be pointed out that these optimum values were obtained by trial and error. During the research, different parameters were used to test the system performance and the corresponding results are discussed and summarised in **Chapter Seven.**

3.3.6 Carrier Phase Aiding

Once carrier lock has been achieved, the carrier phase and phase rate measurement, which is vastly superior to the code rate produced by the Early - Late correlation peak tracker, can be used to improve code tracking and replace the pseudo-range measurements. In the GP1020 tracking module, its hardware allows measurement of integrated carrier phase through its CHx_CARR_CYCLE and CHx_CARR_DCO_PHASE registers. By recording consecutive readings of these registers, a consistent integrated carrier phase can be obtained.

After carrier lock, the Early - Late tracker is used in a bandwidth-narrowed mode to track only the small departures of the correlation peak from the smooth movement

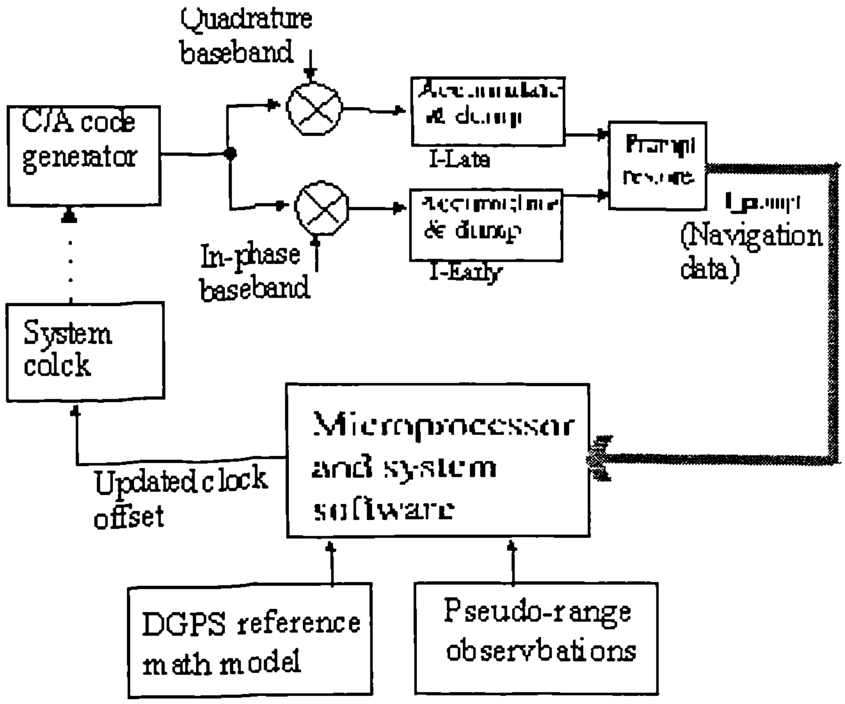


Fig. 3.10 The Structure of Navigation Loop

predicted by the carrier phase rate estimate. This is called carrier aiding, which is mentioned in **Section 3.2**.

3.4 Navigation Loop

The navigation loop is the most important system component of the DGPS Reference Station, and the main function of the loop is to solve the DGPS Reference Station mathematical model to obtain the differential correction messages. The navigation loop is mainly implemented by the components constructed by software algorithms. **Fig. 3.10** shows the structure of the loop, and it includes microprocessor and system software, DGPS Reference Station mathematical model and pseudo-range and navigation data measurements. This loop is finally closed by microprocessor regularly updating the DGPS Reference Station clock offset to correct the system clock.

As discussed in **Section 2.4.1**, to calculate the differential corrections, the exact position of the DGPS Reference Station needs to be provided. After the pseudo-ranges for all the available GPS satellites are obtained and system message found, the DGPS mathematical model is activated to calculate the differential correction message. It is also in the navigation loop that the obtained correction messages are encoded into the standard RTCM-104 format and sent out to the host PC COM port.

When the Costas loop is locked (near zero frequency and phase error), the In-phase arm of the carrier tracking module will produce system navigation data (see **Section 3.2.1**). In the navigation loop, the navigation data is used to calculate the exact positions of the GPS satellites by using Keplerian satellite orbit system, and these satellite positions are used by the DGPS Reference Station mathematical model to calculate differential corrections.

3.4.1 Mathematical Model of DGPS

DGPS Reference Station mathematical model is a vital element of this research project. Since none of the published materials disclosed the details of the model, it had to be formulated based on the basic principle of differential technology, and some assumptions were made to make the equations solvable.

The basic function of the model is to work out the differential pseudo-range corrections (see **Section 2.4.1**). As the station's exact location x_0, y_0 and z_0 is known and the corresponding pseudo-ranges from the station to GPS satellites are obtainable by using C/A code correlation technique, the main unknowns of the model therefore, are the differential corrections for each GPS satellite and the reference station's clock offset T. Accordingly:

$$\begin{cases} \sqrt{(x_0 - X_1^j)^2 + (y_0 - Y_1^j)^2 + (z_0 - Z_1^j)^2} = [(t^j{}_{receiver} + T_j) - t^j{}_{satellite}] \times c - Correc1 \\ \vdots \\ \sqrt{(x_0 - X_i^j)^2 + (y_0 - Y_i^j)^2 + (z_0 - Z_i^j)^2} = [(t^j{}_{receiver} + T_j) - t^j{}_{satellite}] \times c - Correc\ i \end{cases} \qquad (3\text{-}5)$$

where, x_0, y_0 and z_0 are the co-ordinates of the DGPS Reference Station location, and similar to the GPS mathematical model discussed in **Section 2.2.3**, j is the jth step of mathematical iteration, i is the satellite number that is from 1 to i, $t_{receiver}$ is the DGPS Reference Station clock time, $t_{satellite}$ is the satellite clock time.

What is special about the DGPS Reference Station is the differential correction *Correc* for satellite i. And this *Correc i* contains all the errors that affect the pseudo-range measurement. As these errors are common to both DGPS Reference Station and the mobile GPS receiver, therefore, they can be corrected by differential technique. From **Section 2.4.1**, it can be seen *Correc* can be expressed as:

$$\begin{cases} Correc\ 1 = ErrorIonos\ 1 + ErrorTropos\ 1 + \dots\dots\dots ErrorSA\ 1 \\ \vdots \\ Correc\ i = ErrorIonos\ \mathrm{i} + ErrorTropos\ \mathrm{i} + \dots\dots\dots ErrorSA\ \mathrm{i} \end{cases} \qquad (3\text{-}6)$$

Where *ErrorIonos* is the Ionospheric error, *ErrorTropos* is the Tropospheric error and the *ErrorSA* is the error caused by the Selective Availability.

If *TruePR* is used to represent the exact range from DGPS Reference Station to i*th* satellite at *jth* step, and *PR* the pseudo-range, then:

$$\begin{cases} TruePR_1^{\,j} = \sqrt{(x_0 - X_1^{\,j})^2 + (y_0 - Y_1^{\,j})^2 + (z_0 - Z_1^{\,j})^2} \\ \vdots \\ TruePR_i^{\,j} = \sqrt{(x_0 - X_i^{\,j})^2 + (y_0 - Y_i^{\,j})^2 + (z_0 - Z_i^{\,j})^2} \end{cases} \qquad (3\text{-}7)$$

$$\begin{cases} PR_1^{\,j} = (t^j{}_{receiver} - t^j{}_{satellite}) \times c - Correc1 \\ \vdots \\ PR_i^{\,j} = (t^j{}_{receiver} - t^j{}_{satellite}) \times c - Correci \end{cases} \qquad (3\text{-}8)$$

and it will lead:

$$\begin{cases} TruePR_1^{\,j} - PR_1^{\,j} = a_1 = T_j \times c + Correc\,1 \\ \vdots \\ TruePRi^j - PR_i^{\,j} = a_i = T_j \times c + Correc\,\mathrm{i} \end{cases} \qquad (3\text{-}9)$$

Here a is the difference between the true range *TruePR* and the pseudo-range *PR*, an obtainable constant.

The problem with is that T and *Correc* varying from *1* to i altogether result in, but only i equations are available. So the equation has no definite solution. In order to work out these *i+1* unknowns, there are only two possible options: either an additional equation is added into the **Eqs. (3-9)**, or the *(i+1)* unknowns are reduced by one to *i*.

If the later option is chosen, usually the system clock offset *T* is given an arbitrary value. This is because this offset *T* will be finally resolved by the GPS mathematical model after the differential corrections are taken in by the mobile GPS receiver [Parkinson, B. W. 1996]. The main problem for this option is that this arbirary offset *T* in the DGPS Reference Station will leave errors to the calculated corrections.

In this research program, the first option was chosen and an essential assumption was made to produce an additional equation so that it can added to the **Eqs. (3-9)**. This is the sum of the *Correc* is zero. In other words:

$$\sum Correc\ \mathrm{i} = (\mathrm{a}_1 - T_j \times c) + (a_2 - T_j \times c) + \ldots\ldots\ldots + (a_i + T_j \times c) = 0 \qquad (3\text{-}10)$$

Combining this with **Eqs. (3-9)** together will lead:

$$T_j = \frac{a_1 + a_2 + \ldots\ldots + a_i}{i \times c} \qquad (3\text{-}11)$$

After *Tj* is obtained, *Correc i* can be determined by:

$$\begin{cases} Correc\ 1 = a_1 - T_j \times c \\ \vdots \\ \vdots \\ Correc\ \mathrm{i} = a_i - T_j \times c \end{cases} \qquad (3\text{-}12)$$

All the desired *i+1* unknowns are now obtainable.

3.4.2 The Comparison of GPS and DGPS Model

As both GPS mathematical model discussed in **Section 2.2.3** and the DGPS Reference Station model discussed above are available, a comparison of these will show the specialities of DGPS Reference Station model, and clarify some misconceptions.

The first point which can be noticed is that it is a **misconception** that a GPS receiver which can output real-time pseudo-ranges for data log purpose can be used for the purpose of calculating differential corrections. This concept is not correct because of the following reasons:

For a GPS receiver, its main function is to find its current position. However, when a GPS receiver tries to determine this current position from its mathematical model, small steps Δx, Δy and Δz, *(Navigation Update)* are assumed from its original position x_{j-1}, y_{j-1} and z_{j-1} (Section **2.2.3**), and the function of GPS mathematical model is to calculate this navigation update. After this navigation update is found, the current position x_j, y_j and z_j can be obtained by using **Eqs. (2-3).**

From this it can be seen that if a GPS receiver is used for the purpose of calculating differential corrections, and is placed on a fixed position. The true ranges worked out from this receiver to GPS satellites will not be accurate and the errors will be introduced to the calculated correction messages. This is because small steps of Δx, Δy and Δz will affect GPS receiver's current position. In other words, because of Δx, Δy and Δz, the GPS receiver's current position is in fact no longer in a fixed position, but is moving constantly.

The second point which can be concluded is that though an ordinary GPS receiver is not suitable for the purpose of calculating the differential corrections, the GPS

Builder^{TM} is a perfect platform for implementing DGPS Reference Station system software. If a DGPS Reference Station mathematical model and corresponding algorithms are implemented on it.

From the DGPS mathematical models it can be seen that, the essential measurements needed to calculate the differential corrections *Correc i* are: satellite positions X_i, Y_i and Z_i, real-time pseudo-ranges PR_i, receiver clock time $t_{receiver}$ and satellite clock time $t_{satellite}$. All these measurements are available from the GPS Builder^{TM}, and can be effectively utilised by the system. This justifies the methodology related to the implementation of DGPS Reference Station mentioned in **Section 1.3**.

3.4.3 RTCM-104 Differential Correction Format

Once the differential corrections and system navigation data are ready, they are encoded into RTCM-104 Differential Correction Format recommended by the RTCM Special Committee 104, and transmitted to the mobile site. Basically the RTCM-104 includes the message elements that make up the corrections, the status messages, and station parameters [RTCM Special Committee No.104 1990].

The data format of RTCM-104 was similar to the GPS data format, although it diverged from that somewhat as different requirement surfaced. However, the word size, word format, parity algorithm and other features are all the same as GPS data word. The biggest change is a variable length message format, whereas the GPS format has fixed length subframe (300-bit, see **Section 2.1.2**).

The general message format is illustrated in **Fig. 3.11** with details of the first two 30-bit words of each frame or message type. These two words contain data that is pertinent to any type of messages, and those are: Reference Station information, reference time and information required for user's frame synchronisation.

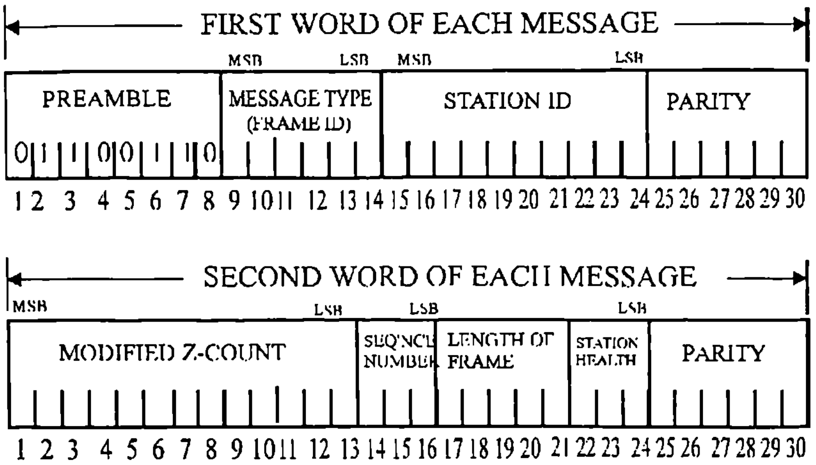


Fig. 3.11 The Header of Message Format of RTCM-104

Each frame (message type) of the RTCM-104 is *N*+2 words long, the first two words are the header, and the rest N words containing the data of the message. This *N* varies with message type as well as within a message type. This means that different message types may have different lengths, and even the length of a message type may vary itself.

Table 3.1 shows the message types of the RTCM-104 format, not all the message types are needed to be transmitted because some of these are tentative. In the DGPS Reference Station message type 1, type 2, type 3 and type 16 were implemented. From **Table 3.1** it can be seen that these four messages are most important ones. But the other messages can be easily added, and this is actually one of the flexibilities of the DGPS Reference Station.

To transmit RTCM-104 messages, a minimum data baud rate of 50-bit per second is required. But with the advancement of the radio data transmitting technology, a much higher rate is easily achievable.

MESSAGE TYPE NO.	CURRENT STATUS	TITLE
1	Fixed	Differential GPS Corrections
2	Fixed	Delta Differential GPS Corrections
3	Fixed	Reference Station Parameters
4	Tentative	Surveying
5	Tentative	Constellation Health
6	Fixed	Null Frame
7	Tentative	Beacon Almanacs
8	Tentative	Pseudolite Almanacs
9	Fixed	High Rate Differential GPS Corrections
10	Reserved	P-code Differential Corrections (all)
11	Reserved	C/A code L1, L2 Delta Corrections
12	Reserved	Pseudolite Station Parameters
13	Tentative	Ground Transmitter Parameters
14	Reserved	Surveying Auxiliary Message
15	Reserved	Ionosphere (Troposphere) Message
16	Fixed	Special Message
17	Tentative	Ephemeris Almanac
18-59	--	Undefined
60-63	Reserved	Differential Loran-c Messages

Table 3-1. RTCM-104 Message Types

3.5 Summary

This chapter discussed the DGPS Reference Station implemented on a GPS Builder^{TM}. The block diagram of the Builder and channel signal tracking module are analysed first, and this is followed by the analysis of the time sequence and frequency plan of GP1010/1020 chip set, which is important for analysing system components (signal tracking loops). Because all the signal tracking loops are implemented and based on the channel tracking module.

The main system components of DGPS Reference Station can be summarised as three digital loops, these are C/A code tracking loop, carrier tracking loop and navigation loop. The main function of the C/A code tracking loop is to track received satellite generated C/A code to calculate the pseudo-ranges. The function of the carrier tracking loop is to track the input GPS L1 carrier, based on which C/A code tracking loop can decode the system navigation data. The core of the carrier tracking loop is a Costas loop, and the characteristics of the Costas loop and the loop parameters are analysed in details. The function of the navigation loop is to solve the DGPS Reference Station mathematical model to obtain the differential correction messages.

After this, mathematical model of the DGPS Reference Station is formulated. Based on this model, relevant algorithms can be written and differential corrections can be worked out. Based on the comparison of GPS and DGPS Reference Station models, a misconception of the use of GPS receiver is clarified.

Finally, the standard RTCM-104 differential correction message format is introduced, and the content of different messages is also discussed.

CHAPTER FOUR: DGPS REFERENCE STATION ENGINEERING AND SYSTEM SOFTWARE IMPLEMENTATION

4.1 DGPS Reference Station Structure

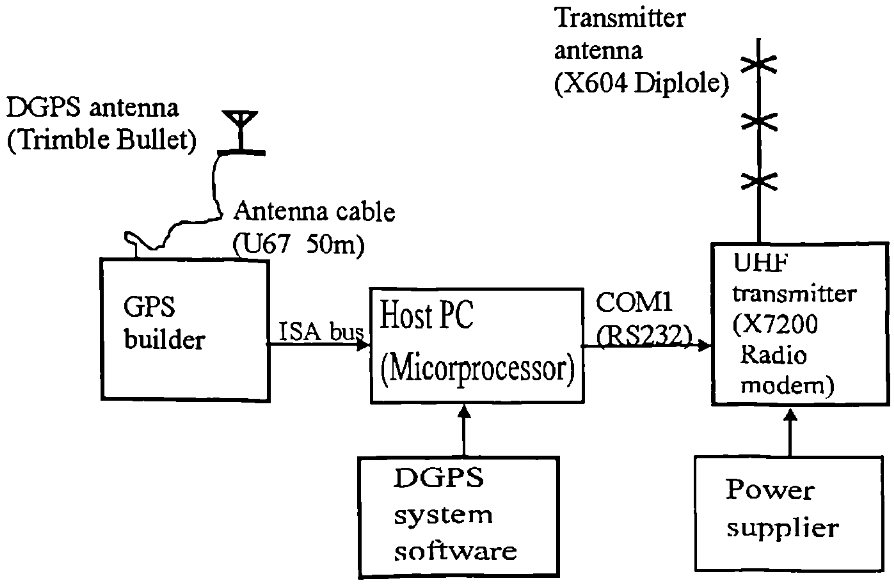


Fig. 4.1 The Structure of the DGPS Reference Station

The main components of the DGPS Reference Station include the GPS Builder^{TM}, system software and host PC. Besides that, a high gain GPS antenna is needed to receiver GPS L1 signal and a UHF radio data link to transmit differential correction messages. **Fig. 4.1** shows the structure of the constructed DGPS Reference Station.

For a DGPS Reference Station, its GPS antenna should be able to reach all the satellite signals available in the sky. In other words, no satellite should be blocked by any obstacles, such as buildings, trees. To achieve this purpose, the GPS antenna was installed at the very top of Tower B on the campus of Brunel University (about 30 m high), but this leads to the problem of a long antenna cable. Consequently, the cable signal attenuation is very high. For the DGPS Reference Station, two methods were used to solve the problem:

1. A Trimble Bullet active GPS antenna is used in the system, instead of using the original ANP-C-114 active GPS antenna distributed with GPS Builder. The gain of Trimble bullet is 35 dB, and the gain of ANP-C-114 is 26 dB, therefore an extra gain of 9 dB is achieved. The other advantage of Trimble bullet antenna is that it is weather proof and watertight, therefore, it is more suitable for outdoor use.

2. An ultra low loss U67 coaxial cable is used to connect the GPS antenna to DGPS Reference Station instead of using original RG58 coaxial cable. The signal attenuation rate of U67 is 2.52 dB @ 1000 MHz per 10 m. Though the GPS L1 carrier frequency is higher than 1000 MHz, it can be estimated that the cable signal loss of U67 for the actual cable length (50 m) is about 15 dB. It can also be estimated that the original RG58 coaxial cable loss (10m long, and attenuation rate of 5.6 dB @ 1000 MHz per 10 m) is about 7 dB.

As the combination of these two measures, it can be seen that for the final GPS signal obtained from the U67 cable, an extra gain of 9 - (15 - 7) = 1 dB is obtained.

The radio data link used here is a X7200 radio modem from Warwick Industrial Electronics, UK. It is a transceiver, therefore, it is the same unit as the UHF radio data receiver used in the navigation mobile unit that is discussed in **Chapter Seven,** where the characteristics of the transceiver are fully discussed.

4.2 System Software Implementation

Once the relevant measurements are ready from the hardware (GPS Builder) and the DGPS Reference Station mathematical model is designed, a system software is needed to implement all the necessary modules and subroutines into operation.

The work involved in software design ranges from real-time system programming to high precision floating point calculation. The size of the system software is very large. Altogether, it includes 14 modules, 74 subroutines and 12,000 lines source code (8,000 lines were adopted from the GPS Builder^{TM}). It is therefore impossible to describe the detailed functions of every module and subroutine. Emphasis are put on the software engineering side to demonstrate the main tasks and the considerations needed to design a DGPS Reference Station. Discussion of the strategy used in concurrent processing and multitasking implementation is reviewed, and the flow chart of the "MAIN" task is drawn to show the program thread. For further reference, descriptions of the functions, and the function prototypes of all the modules and subroutines are listed in **Appendix III**.

4.2.1 Main Tasks of DGPS Reference Station System Software

The main tasks of DGPS Reference Station system software engineering can be summarized as follows:

1. GPS signal processing,
2. Navigational message decoding,
3. Precision floating point navigation calculation,
4. Differential correction calculation,
5. Hardware control,

6. DGPS RTCM -104 message encoding,
7. Differential correction message outputting.

Differential GPS Reference Station is hosted by a PC, this means that only a single microprocessor is used, therefore, all the tasks discussed above must be performed concurrently and the way of how to implement this multitasking is discussed in **Section 4.1.2.** Besides this, to improve the system performance further, a small part of the subroutines where the computing speed is vital, are written in assembly language, and then this assembly block is linked to the system software. As the size of the software is very large, the modular structure has to be used, i.e. the relevant subroutines are grouped into modules, and the modules are combined together to form the final system software, When completed, the final software was found to have the following characteristics:

1. A 1 kHz task which reads and accumulates correlator outputs and controls the corelator hardware,

2. A 50 Hz task to update satellite tracking loops, parse GPS navigation messages, and monitor loop lock conditions,

3. A 10 Hz task to collect satellite measurements, predict pseudo-ranges, update receiver clock offset, calculate the DGPS corrections and encode them in the RTCM 104 format, and finally control the satellite tracking strategy,

4. A 0.01 Hz task to perform satellite ephemeris computations and to calculate satellite position,

5. Interrupt routines to perform communications on serial interface.

4.2.2 Multitasking Implementation in Differential GPS Reference Station

Multitasking is a concept which is frequently used in embedded system design. In the Differential GPS Reference Station, a PC is used as the host, and Borland C/C++ is used to write system software, therefore multitasking needs to be implemented on a high-level language.

The main method used for multitasking in the Differential GPS Reference Station was adopted from GPS Builder^{TM} system software [GEC Plessey Semiconductors 1994a]. There are two reasons for this adoption. One is that in the GPS Builder^{TM} system software, the multitasking implementation proved to be very successful. The other is that, for a DGPS Reference Station, the main signal processing tasks listed in **Section 4.2.1** are similar to the tasks needed by a standard GPS receiver

The basic idea for multitasking is that a regularly occurring software interrupt causes the processor to switch from one task to another, giving a good approximation to the simultaneous execution of each independent tasks. However, in this method, whenever a task switching occurs, the current task's context must be saved somewhere, so that it can be later restored. **Fig. 4.1** shows the multitasking structure of DGPS Reference Station system software.

At the start-up, the DGPS Reference Station system software initialises the runtime environment, allocates a stack for the system, and begins executing at procedure (subroutine) main( ). This execution thread will later become the lowest priority i.e. the least urgent task, which is named MAIN.

In the Differential GPS Reference Station, tasks have separated stack areas and floating point context. Tasks are defined at the beginning of compiling time in a table TCB, which is defined in the module RTEXEC.C. More tasks can be added to the

TCB table during the design. The TCB entry for new tasks must specify the task's starting point (which is a procedure name), and how many bytes of memory should be allocated for the task's stack. The task's priority is implicitly defined by its position in the TCB table, i.e. the most urgent task is at the beginning, and the least urgent task is at the bottom.

During program initialisation, GP1020 correlator interrupts are disabled, and the task switching is inhibited by the initial non-zero value of the control variable PROTECT. PROTECT is a special statement designed to establish regions of code which are protected from task switching. Whenever PROTECT is non zero, task switching is inhibited. Then sentences of PROTECT++ and PROTECT-- are used to control the task switching. Usually, PROTECT++ is used on entry to a protected region, and PROTECT-- on exit.

After this, procedure InitTasks( ) is called to create and initiate the tasks enumerated in TCB. Tasks are always either active (ready to run) or on the suspended list (waiting for a time interval to expire or for explicit activation by another task). InitTasks( ) creates MAIN as the only active task, with all the other tasks initially placed on the suspended list. This means that the program executes in a single thread from the entry point main( ) until it is ready to enter the main program do-forever loop at label MainProgramLoop in procedure DGPSBLDR ( ) in module MAIN.

Task switching begins when GP1020 correlator interrupts are enabled and the control variable PROTECT is set to zero. The GP1020 interrupt service routing (GPISR) is entered every 505 microseconds (INT OUT). After a TIC event which occurs every 1/10 second, GPISR decrements the timer chain of the suspended task list, removing tasks from the suspend list and flagging these active as their suspension intervals expire. GPISR then exits to the highest priority task which is flagged as active list thereby that task's execution is resumed.

Once a task is resumed, it will execute until either:

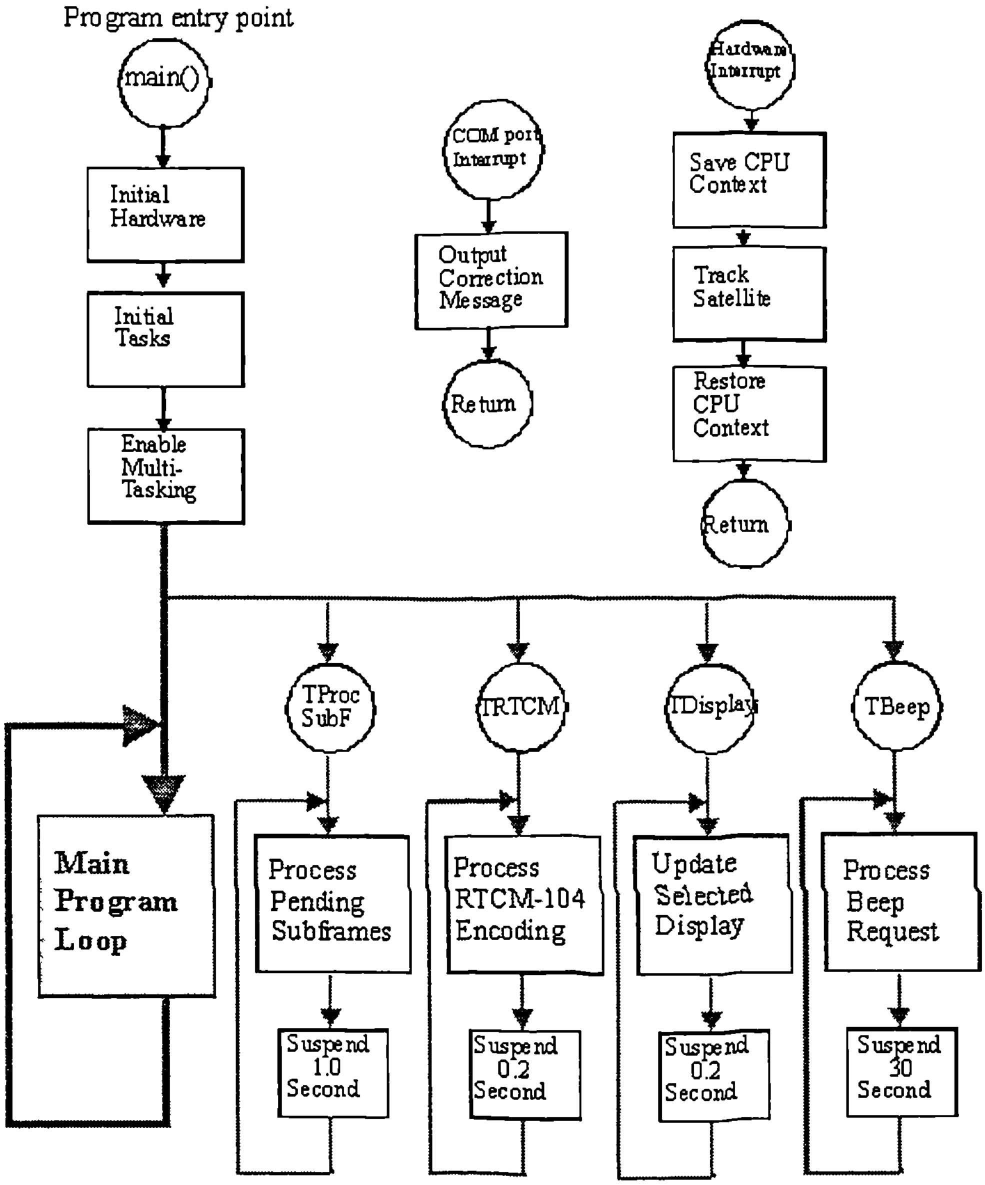


Fig. 4.1 Multitasking Processing Structure of DGPS Reference Station

1. it suspends itself for a specified time, or
2. a higher priority task becomes active.

Tasks may retain the processor by two methods:

1. they may mask interrupts, or
2. they may manipulate the global variable PROTECT.

In the Differential GPS Reference Station, tasks can not terminate. They can only suspend and await reactivation. Each task's separate stack allow the preservation of local variables during the suspension period. It can be understood as all tasks work as queue servers, resuming periodically, processing out any pending requests, and then suspending again.

In **Fig 4.1**, it can be seen that there are four task roots and these are the procedures at which the tasks begin their execution. These are procedure TBeep in module BEEP.C, TDisply in module DISPLAY.C, TRTCM in module RTCM.C, and TProSbf in module PROCSBF.C. Task roots are defined in the data structure TCB which is defined and initialised in module RTEXEC.C. Task MAIN is special case. It is a continuation of the context which begins on entry to the program at procedure main( ).

4.3 Structure of the Source Code of the System Software

4.3.1 The Source Code Structure

To organize the DGPS Reference Station system software efficiently, a modular structure is adopted and a "project" named DGPS is created to compile multiple source files into a single program. All together, there are 14 modules and 74 subroutines, and all the source code lines are contained in the directory C:/DGPS. For further reference, the detailed description of the prototypes and the functions of all subroutines are listed in **Appendix III.**

The source code of sub-routines of the DGPS Reference Station system software is organized according to their name extensions:

1.	.C	C/C++ language source file
2.	.H	Include file
3.	.BAT	Batch command file.

To make the program well-organized and more readable, various include files are used to contain system information, external variables, structures and unions. For example: all the structures and unions used in the software is listed in DGPSSTRUC.H. and all the external declaration for global variations are defined in EXTERNS.H. When compiling the source code, it is therefore, important to specify the proper include file paths in the Borland compiler.

4.3.2 Two Interrupt Service Routines

The first interrupt routing is the procedure newserialint( ) contained in module RTEXEC.C. This procedure is entered when a effective RTCM-104 correction message character is output to the PC's COM port. Its function is to read a character from a circular buffer and put it on the serial output.

In order to control the interrupt, host PC's Programmable Interrupt Controller and the serial port must be programmed properly according to the system requirement. Like other applications of the PC serial port, a circular buffer is necessary to contain differential correction message obtained from the MAIN task before the serial port is regularly available. This regularity is determined by the baud rate which can be chosen by the designer.

The second interrupt routine is the procedure GPINT( ) contained in module RTEXEC.C. It is entered every INT OUT time (505 microsecond), when the master GP1020 correlator requires an interrupt. It saves the current context, calls procedure SVTRACK( ) to perform the essential correlator service (adjusting the system loops by updating the relevant control registers), and some time-critical processing, then either returns to the previous context or perform a task switch.

As long as an interrupt is concerned, there is choice of using C or assembly language to write the interrupt services. In DGPS Reference Station, C is chosen for this purpose. The reason for this is that though interrupt services written in assembly language is faster, the services written in C are more flexible, and therefore more suitable for the research environment.

4.3.3 Flowchart of the DGPS Reference Station

Fig. 4.2 shows the flow chart of the DGPS Reference Station. It also contains the major procedures performed in the Main Program Loop (task MAIN). Once the multitasking starts, a task which has higher priority may interrupt this MAIN task and put it into suspension. However, since the MAIN task is assigned to have the lowest priority in the TCB, it eventually will be activated when all the other tasks are suspended. In this way, the system software main thread is kept going.

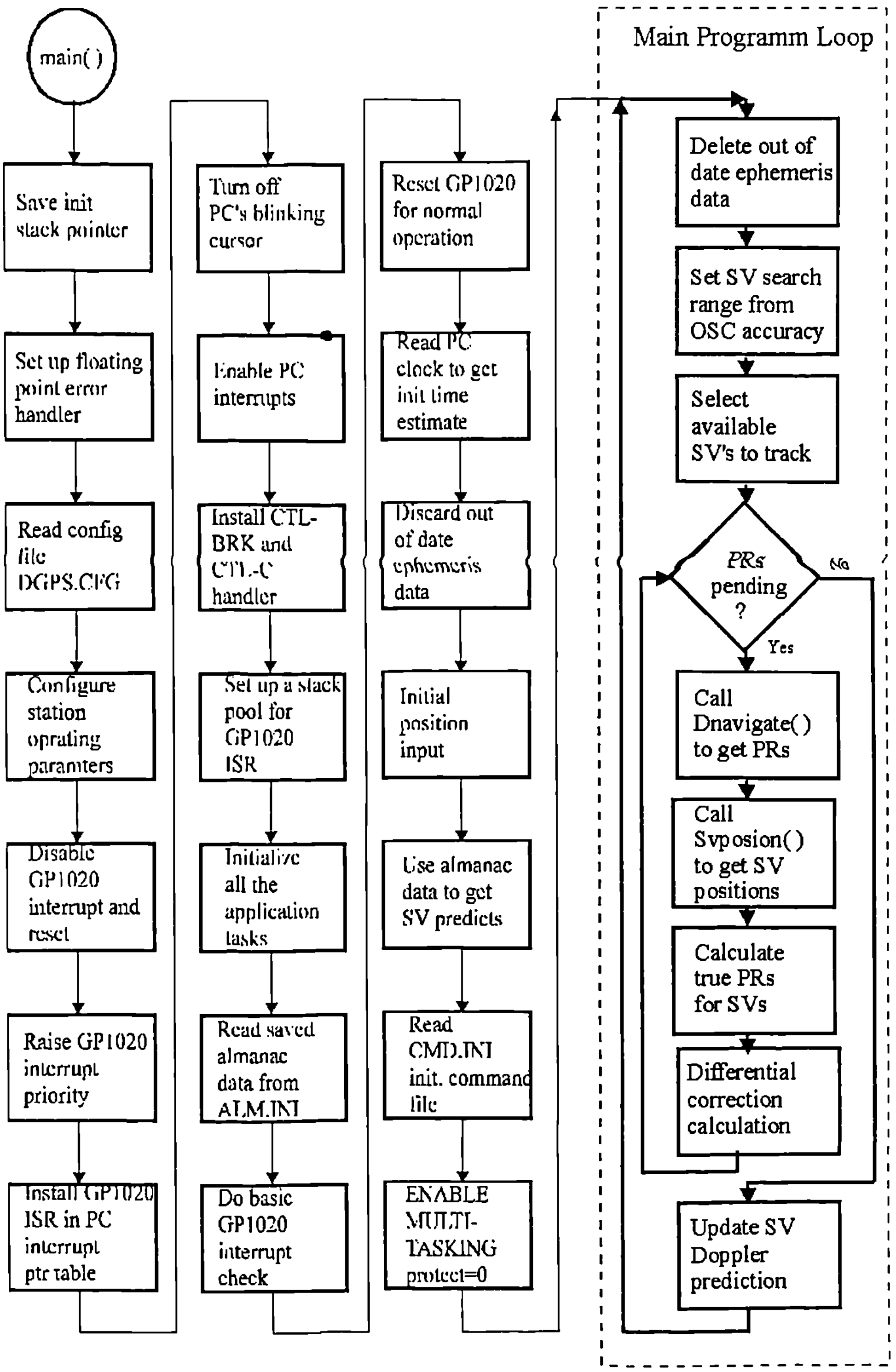


Fig. 4.2 Flow Chart of the Main Procedure

4.3.4 Compiling DGPS Reference Station System Software

DGPS Reference Station system software requires the MS-DOS operating system, version 5.0 or higher. As the processing speed is the main consideration, it is not designed to work under Windows, but DOS instead. The final compiled executive file uses the 80386 instruction set and assumes that it is executing in a 16-bit segment. The DGPS Reference Station system software must be compiled with Borland C/C++ version 3.1 or 4.0. When determined which compiler version is used, the relevant include file needs to be edited to customize it.

CHAPTER FIVE: COORDINATE AND DIGITAL MAP SYSTEMS

5.1 Introduction

Electronic digital map is essentially a digital database. Originally it was used as an abstract of the ordinary map. But with the rapid development of the computer data-processing technology, the digital map database now contains far more information than the ordinary map, and is used more widely.

There are various electronic map database commercially available, such as the Land-Line, Address-Point, and OSCAR from the Ordnance Survey, U.K. [Ordnance Survey, 1994a],. Each of them contains different information, and is suitable for a different purpose. All these databases are written according to certain format, therefore, they can be only read and processed by using the data-processing technology. Usually a software algorithm is needed to abstract desired information and reorganise it to produce a map. This map can then be either shown on a computer screen or printed into a hardcopy.

As the use of the digital map database varies widely, there are also various map database handling software packages commercially available. Each of these has its speciality. For instance, some packages may be used for calculating the area, or the circumference of a map feature (for instance, a pond), and others for presenting the map in a 3-d view. However, the basic map handling functions of all the packages include extracting desired features from the database, reproducing the map in a specific way, and modifying and adding new features into the original database. Besides these, usually some other map handling functions, i.e. map moving, zooming in and out, can also be included to give the user conveniences.

As long as the map is concerned, the coordinate system plays an important role. Different maps may employ different coordinate systems, and these coordinate systems can be either ellipsoidal or rectangular Cartesian. Further to this, ellipsoidal coordinate systems may vary themselves because different reference ellipsoids are employed. In order to integrate a digital map with some other devices which may use different coordinate systems, coordinate system conversion must be carried out [Dana, H. P. 1995b].

For this research project, the main task for map system is firstly to choose a suitable digital map database which will provide the necessary navigational information required by the system. The second task is to reproduce the map and organise the navigational information in an effective way. Finally, the map needs to be linked with the user current position, obtained from a mobile GPS receiver to form the navigation system. Besides these, to reproduce the map effectively, the following map database handling functions are also required:

1. To extract only useful geographic information from the map database to form a compact information pack to reduce the map database computing time;

2. To convert the different coordinate systems employed by the map database and the GPS into British National Grid system;

3. To reproduce the desired map on a PC screen, and be able to move the map in a desired direction effectively and have the zooming control.

From the above specific objectives, it can be seen that the desired map system is unique to the research project, and the required map handling functions are also specific. As none of the commercially available digital map database handling packages can be used directly, the whole map system software has to be designed with all the necessary map handling functions implemented.

5.2. Co-ordinate Systems and Its Conversion

5.2.1. Coordinate Systems

Positions on the Earth are described numerically and unambiguously, making archiving and computation straight forward [Dana, H. P. 1995a]. Any point on the Earth's surface can be either referred to the graticule of latitude and longitude (curvilinear coordinates) on a ellipsoidal computation surface, or a three dimensional Cartesian system with an origin at the Earth's centre of mass. Rectangular Cartesian coordinates are easier to manipulate than curvilinear coordinates but give no concept to height above sea level.

Each system has its uses. GPS system employs a ellipsoidal coordinate system, the reasons for this are:

- It is commonly used and accepted in geometrical geodesy;
- It makes use of closed formulae, meaning that definition is exact;
- The height of the ellipsoidal coordinates is a good approximation to the height above see level.

Ellipsoidal coordinate reference systems define an ellipsoid with an equatorial radius and polar radius. The best of these models can represent the shape of the earth over the smoothed, averaged sea-surface to within about one-hundred meters [Moore, T. 1991].

Fig. 5.1 shows a reference ellipsoid. Reference ellipsoids are defined by a semi-major: a (equatorial radius) and a semi-minor: b (polar radius) axes. Other reference ellipsoid parameters such as flattening: f, and eccentricity: e, are computed from these two terms. By using this reference ellipsoid, a point P's position can then expressed as longitude ϕ , latitude λ and height h distinctively.

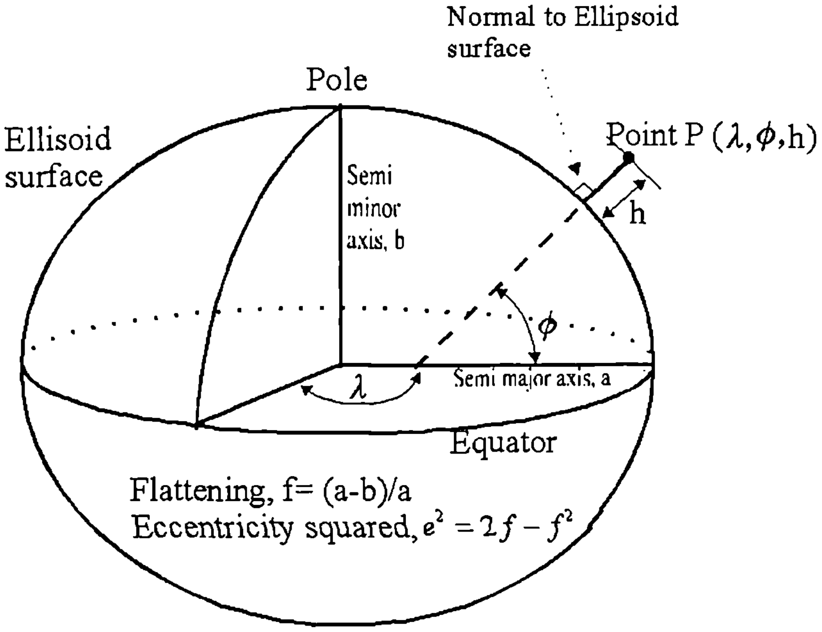


Fig. 5.1 Reference Ellipsoid and Ellipsoidal Coordinate System

Many reference ellipsoids are in use by different nations and agencies, and these lead to the different ellipsoidal coordinate systems. **Table 5.1** shows the useful ellipsoidal constants adopted by three reference systems [Ordnance Survey 1996a]. The symbols and definitions of the symbols are listed in the **Appendix IV** for further reference.

In **Table 5.1,** the Airy ellipsoid is the reference ellipsoid that accompanies British National Grid system which is discussed in **Section 5.2.3**. The Global Reference System (GRS 80) ellipsoid is the reference ellipsoid that accompanies the World Geodetic System (WGS 84) which is the reference system used by GPS.

Ellipsoid	**Airy** (British National Grid)	**International** (1924)	**Global Reference System (GRS 80)** (GRS 80 Grid)
$a \times F_0$	6375020.481	6375836.645	6375593.856
$b \times F_0$	6353722.490	6354369.181	6354217.697
n	0.001673220250	0.001686340651	0.001679220406
e^2	0.006670539762	0.006722670062	0.006694380022
a	6377563.396 m	6378388.000	6378137.000
b	6356256.910 m	6356911.946	6356752.314
True Origin	Lat 49° N Long 2° W	Lat 0° Long 3° W for Zone 30 Lat 0° Long 3° E for Zone 30	Lat 49° N Long 2° W
False Origin	E 400,000 m W of True Origin N 100,000 m N of True Origin	E 500,000 m W of True Origin N 0 m	E 400,000 m W of True Origin N 100,000 m N of True Origin
Grid Coordinates of True Origin (E_0, N_0)	400000 m -100000 m	500000 m 0 m	400000 m -100000 m
Scale on Central Meridian (F_0)	0.9996012717	0.9996	0.9996012717

Table 5.1 Three Ellipsoidal Reference Systems

5.2.2 Map Projection

Map projection is the attempt to portray the surface of the Earth or a portion of the Earth on a flat surface. During the process, some distortions of conformity, distance, direction, scale and area may be resulted. Some projections may minimise distortions in some of these properties at the expense of maximising errors in others. Some projections are attempts to only moderately distort all of these projection [Dana, H. P. 1995d].

The most popular map projection is the Transverse Mercator Projection. It belongs to one of the cylindrical map projections. Cylindrical map projections have straight meridians and the meridians are equally spaced. The surface of the ellipsoid chosen to represent the Earth is represented on a cylinder which touches the ellipsoid along a chosen meridian and which is then unwrapped. The scale is therefore correct along this central meridian and increases on either side of it.

The Transverse Mercator Projection results from projecting the Earth sphere onto a cylinder tangent to a central meridian. Transverse Mercator maps are often used to portray areas with larger north-south than east-west extent (for example, England). Distortions of scale, distance, direction and area therefore, increase away from the central meridian [Dana, H. P. 1995d].

5.2.3 British National Grid System

The British National Grid is a rectangular reference system based on the National Grid System of England and is administered by the British Ordnance Survey. It is obtained by using a modified version of the Transverse Mercator Projection. When applying Mercator Projection, the true origin of the system is at Long. 2° West Lat. 49° North. The problem with this true origin is that if rectangular grid coordinates are calculated from the true origin, the position lying west of the central meridian would be of negative value, and north reading, although all of positive value, would exceed 1000 km in north Scotland.

To avoid inconvenience, a 400 km is added to all easting coordinates and a 100 km subtracted from all northing coordinates. Rectangular grid coordinates are then actually

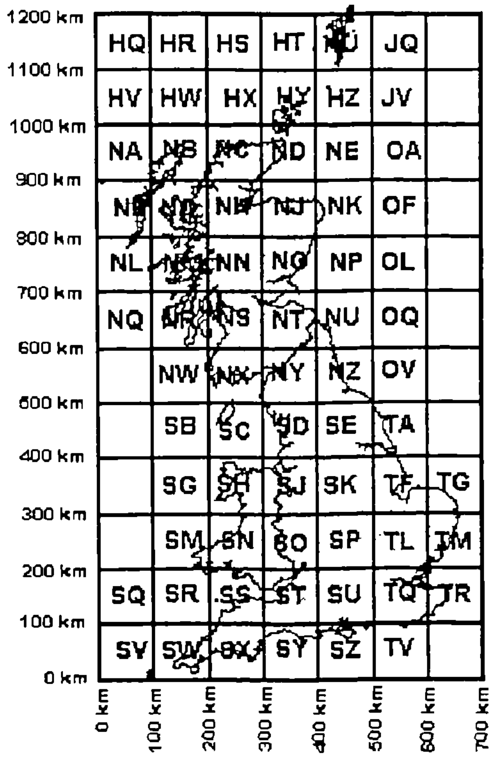


Fig. 5.2 Broth National 100 km Grid

related to a false, or working origin. This false origin lies Long. 7° 33' West Lat. 49° 46', slightly south-west of the Isles of Scilly. As a result, the coordinates of the British National Grid of all places on the mainland of Great Britain are positive and less than 1000 km.

Fig. 5.2 shows the British National 100 km Grids and each grid is referenced by a two-letter identification. For instance, the 100 km square which covers London is TQ.

5.2.4 Coordinate System Conversion

GPS employs a ellipsoidal coordinate system and the coordinates are given in latitude λ, longitude ϕ and height h in WGS 84. In order to combine these coordinates with an Ordnance Survey map which employs British National Grid system, the WGS 84 coordinates have to be converted into a GRS 80 Grid plane coordinates first based on the Transverse Mercator projection. However, it is important to point out that the GRS 80 is the associated ellipsoid accompanying WGS 84, but it is **NOT** the same ellipsoid which accompanies the British National Grid [Ordnance Survey 1996b].

Following formulae are used to convert ϕ and λ into easting reading E and northing reading N (for definitions of the symbols, refer to **Appendix IV**);

1). Get arc of a meridian from ϕ to ϕ_o:

$$M = M_\phi - M_{\phi 0} = b \times \left\{ \begin{array}{c} \{(1+n+\frac{5}{4}n^2+\frac{5}{4}n^3)(\phi-\phi_0)\} \\ -\{(3n+3n^2+\frac{21}{8}n^3)\sin(\phi-\phi_0)\cos(\phi-\phi_0)\} \\ +\{(\frac{15}{8}n^2+\frac{15}{8}n^3)\sin 2(\phi-\phi_0)\cos(\phi-\phi_0\} \\ -\{(\frac{35}{24}n^3\sin 3(\phi-\phi_0)\cos 3(\phi-\phi_0)\} \end{array} \right\}$$

2). Get:

$$I = M + N_o$$

$$II = \frac{v}{2}\sin\phi\cos\phi$$

$$III = \frac{v}{24}\sin\phi\cos^3\phi(5-\tan^2\phi+9\eta^2)$$

$$IIIA = \frac{v}{720}\sin\phi\cos^5\phi(61-58\tan^2\phi+\tan^4\phi)$$

$$IV = v\cos\phi$$

$$V = \frac{\nu}{6}\cos^3\phi\left(\frac{\nu}{\rho} - \tan^2\phi\right)$$

$$VI = \frac{\nu}{120}\cos^5\phi(5 - 18\tan^2\phi + \tan^4\phi + 14\eta^2 - 58\eta^2\tan^{2\phi})$$

3). Finally:

$$N = (I) + P^2(II) + P^4(III) + P^6(IIIA)$$

$$E = E_o + P\ (IV) + P^3(V) + P^5(VI)$$

It should be pointed out that the method of transformation is a two dimensional shift model. This means that 3-d coordinates are now reduced to 2-d. It also means that if WGS 84 coordinates are required from a flat grid coordinates (reverse conversion), the height *h* in WGS 84 will be indeterminate. For the research project, only ellipsoidal to grid system conversion is needed, this does not cause any indetermination.

As a result of the above conversion, the grid coordinates obtained are x (eastings) and y (northings) of the GRS 80 Grid coordinates. To transfer these coordinates into British National Grid, further conversion needs to be carried out. This is because the reference ellipsoid that accompanies British National Grid is Airy, rather than GRS 80 (see **Table 5.1**).

The transformation from GRS 80 Grid coordinates to British National Grid coordinates uses a regular grid of easting-shifts and northing-shifts. The grid covers the whole of Great Britain, each grid square covering an area of 350 km × 350 km. An easting shift and nothing shift is recorded for each corner of each grid square. **Table 5.2** shows the shifts:

		east_shift (m)		
	1400000	99	104	107
	1050000	93	99	106
y (m)	700000	85	97	108
	350000	89	96	105
	0	92	96	102
		0	3500000	700000
			x (m)	

		north_shift (m)		
	1400000	-44	-49	-52
	1050000	-47	-52	-54
y (m)	700000	-58	-62	-62
	350000	-75	-75	-78
	0	-82	-80	-82
		0	3500000	700000
			x (m)	

Table 5.2 Easting and Northing Shifts from GRS 80 Grid to British National Grid

To convert a GRS 80 Grid position (x, y) to a British National Grid position (e, n), the east_shift and north_shift obtained in the tables should be added to the x and y coordinates respectively:

$$e = x + \text{east\_shift}$$

$$n = y + \text{north\_shift}$$

Obviously, in a real case the point to be transferred is unlikely to lie on one of the points in **Table 5.2**. To calculate the shifts at any other points, an interpolation method is required to find the proper shifts.

The accuracy of the above transformation is about 2m, it is good enough for the project, because DGPS positioning accuracy is about 2-5 m. Though some other more accurate conversion methods exist, they are generally more complex to use, and will take more computing time.

5.3 Land_Line 93 Digital Map Database and Map Reproduction

5.3.1 Land_Line 93 Digital Map Database from the Ordnance Survey

The digital map database Land-Line 93 of Ordnance Survey was chosen for the project. The reason for this is that Land-Line contains various detailed features of navigational information which is necessary to the system. The features of Land-Line 93 include [Ordnance Survey 1994c]:

- Buildings (with building names and house numbers)
- Roads (with name and /or Department of Transport (DoT) numbers)
- Fences, walls, hedges and banks (grouped as one feature code)
- Rivers streams, drains, ditches, canals, lakes, reservoirs
- Railways (standard and narrow gauge)
- Tunnel alignments
- Place names and descriptive text
- Administrative and County Boundaries

The other advantage of using a commercially available product is that Ordnance Survey updates the content of the Land_Line regularly, therefore, when the geographic information changes, the change will be reflected into the database in time, and this will minimise maintenance of the database.

Land-Line 93 has been surveyed and supplied at one of the three basic scales: 1:1250, 1:2500 and 1:10000. The most detailed scale is 1:1250 and is utilised for the project. At the time of decision, the coverage of Land_Line for the U.K. is about 70%, and is rapidly expending. But most of the south-east area has been covered.

The digital map database is divided into 500m × 500 m tiles. Each tile has a south-west (SW) corner reference coordinates expressed in British National Grid system. To reduce data volumes, the coordinates of the features contained in Land-Line are given as relative coordinates expressed as distance east and north of the map tile SW corner.

5.3.2 Choice the Tiles from Land_Line Map Database

Since Land_Line 93 is chosen for the system, the next consideration is to select right tiles from Ordnance Survey to cover the campus of Brunel University where the research was carried out. Each tile of the Land_Line is identified firstly by British national 100 km grid two-letter reference (**see Fig. 5.2**). As the Brunel University is in London area, the tiles needed therefore have the name which start with two letter TQ.

Further to this, the 100 km squares is broken down into 1 km squares by adding a four-digit reference to the first two letters. As the size of the tile is 500m × 500 m, each of these 1 km square contains four tiles which have the same four-digit reference. These four tiles can then be distinguished by a further two-letter se, sw, ne and nw extensions.

From the output of a GPS receiver which was placed on the place where most experiment is carried out , it is found that the coordinates of this place are:

W $0^0 28.451'$ N $51^0 31.892'$ (WGS 84)

By using the conversion method discussed in **Section 5.2.4** , the converted coordinates in British National Grid system are:

East 505930 m North 182517 m

After consulting with the Ordnance Survey, the four tiles of the Land_Line 93 digital map database, which cover the whole campus of Brunel University were found to be in **Table 5.3**:

	File name	South west corner coordinates	File size (byte)
Tile A	tq0582ne	505500, 182500	229,040
Tile B	tq0582se	505500, 182000	360,926
Tile C	tq0682nw	506000, 182500	220,059
Tile D	tq0682sw	506000, 182000	97,561

Table 5.3 Four Tiles of Land_Line 93 That Cover Brunel University

Fig. 5.3 shows the combination of the four tiles, and these four tiles covers an area of 1000m × 1000 m. The campus of Brunel University mainly lies in the area covered by the tile A. But it also extends to the areas covered by tiles B, C, and D.

5.3.3 Selection of the Map Display Area and PC Screen Projection

As discussed above, four tiles of selected Land_Line 93 database covers an area of 1000m × 1000m. This is a very large area, and the file size of all the four tiles is about 900 kB. The research is concentrated in a much smaller area, it is therefore needed to choose a suitable display area within this 1000m × 1000m square. After that, only the

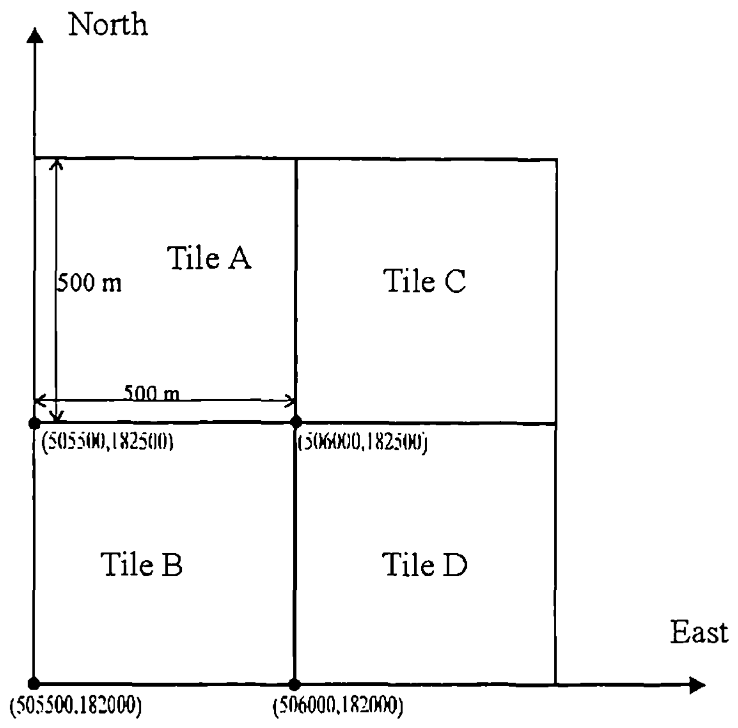


Fig. 5.3 Four Tiles of Land_Line Covering the Campus of Brunel University

map features contained in the relevant tiles will be extracted, and map handling computing time can be reduced significantly.

The selection of the relevant map tiles firstly depends on the position of the desired display area, **Fig. 5.4** shows the four possible situations: a, b, c, and d. As the campus mainly lies within the tile A, therefore tile A is always involved. If the display area extends beyond the area covered by tile A, it may include an area covered by two tiles (Tiles A and B in situation b, Tiles A and C in situation c), or an area covered by all the four tiles (situation d).

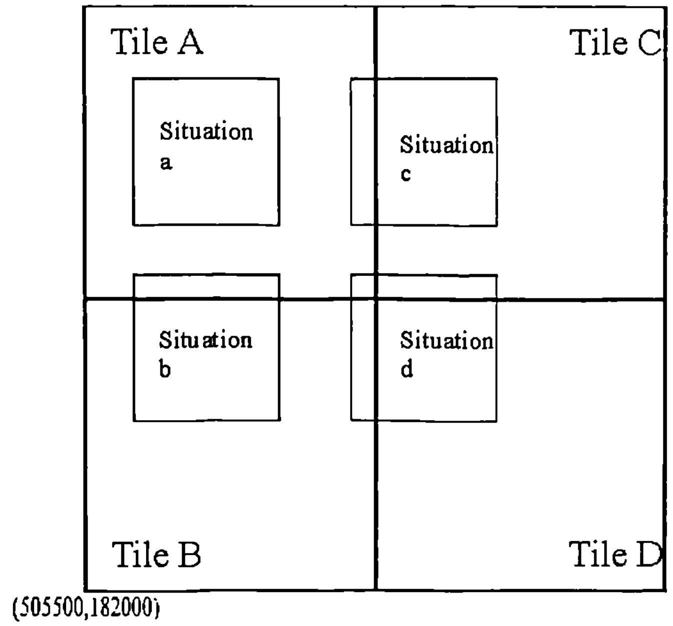


Fig. 5.4 Selection of the Display Area Covered by Map Tiles

The selection of the map tiles secondly depends on the size of this desired display area. If the size of the display area is larger, more tiles are needed, if the size is smaller, only tile A may just cover it.

The size of the map display area is decided by the consideration of utilising the PC screen efficiently to investigate the system performance, because it is this display area that will be finally displayed on the PC screen. In DGPS, the positioning accuracy is within the range of 2-5 m, a display area of 30 m radius should contain all the scatters of the positioning results. In this case, a 60m × 60m display area is designed, and is shown in **Fig. 5.5 B**.

In order to compare the system performance of DGPS with GPS, it is also necessary to investigate the GPS positioning accuracy. As this positioning accuracy is about 100 m, a display area of 150 m radius should be able to contain all the scatters of the

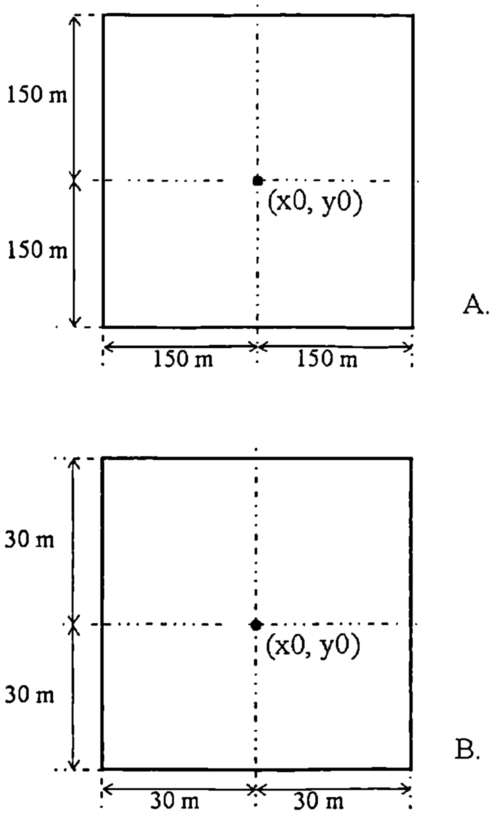


Fig. 5.5 Two Sizes of Display Area

positioning results. In this case, a 300m × 300m display area is designed, and is shown in **Fig. 5.5** A.

The display area shown in **Fig. 5.5 B** is smaller than the display area shown in **Fig. 5.5** A and contains more detailed information, whereas the display area shown in **Fig. 5.5A** contains more extended information. Once these two display areas are linked with positioning results from a GPS receiver, **Fig. 5.5 B** can be considered as the zoomed in display with a zoom factor of 30, and **Fig. 5.5 A** as the zoomed out display with a zoom factor of 150.

After the size of the display area is decided and zoom scale chosen, the exact position of the area relative to the map tiles is decided by the choice of the central point of the

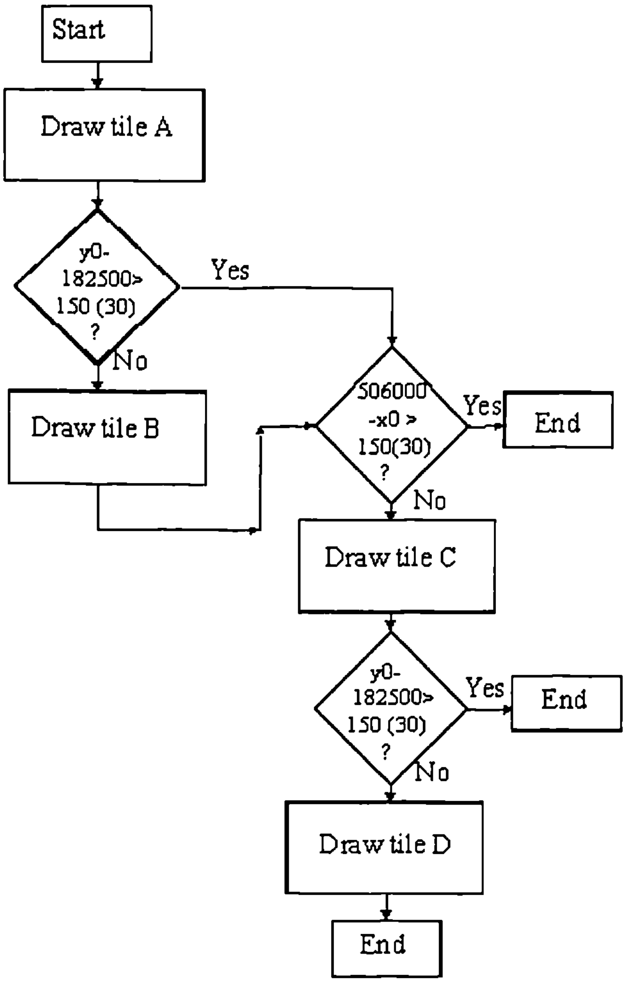


Fig. 5.6 Procedures of Choosing Database Tiles for Map Display Area

display area, and this central point is marked with its two coordinates: *x0, y0*. As the central point of the display area will be always drawn at the centre of PC screen, the map moving function can be effectively achieved by choosing a suitable central position *x0*, *y0*, so that more interested area of the map display area can be moved in. For example, the map can be moved westward by adding a positive Δx to *x0*.

In the map reproducing software, the flowchart shown in **Fig. 5.6** is used to choose the right tiles needed to construct the desired display area with a suitable zoom scale (150 or 30).

The program starts at drawing map features contained in the tile A. It is followed by judging whether the desired display area extends to tile B by comparing the north central point *y0* with the south boundary (182500) of the tile A. If it does, the features contained in the tile B will also be drawn. After that, tile C is judged whether to be involved by comparing the east central point x0 with the west boundary (506000) of the tile C. Finally tile D is judged in a similar way used in deciding tile B.

5.3.4 Land_Line NTF File Format Structure

The Land_Line 93 digital map database is available in two different formats. One is Data Exchange Format (DXF), and the other is National Transfer Format BS 7567 (NTF). DXF complies to the NEDO standard and is usually used for the exchange of two-dimensional CAD drawings. The advantage of DXF is that it can be read directly by AutoCAD, therefore the map reproduction is easier, if no modification is required. In the project, NTF format of Land_Line 93 is chosen to reproduce the map. The reason for this is that NTF format is explained in a much more detailed way than DXF format in the manuals provided by the Ordnance Survey. It is felt that map reproduction base on NTF format is relatively easier.

Land-Line NTF format has a vector "Point and Line" data structure [Ordnance Survey 1994b]. Within this structure a feature of the map may be a point, a line, or a series of lines forming a coherent unit. For example, a house. Each feature is free-standing: that is, it has no topological relationship to any other feature. The most important feature of the Land_Line is, as its name implies, the line. Each linear feature is composed of a string of x, y coordinate pairs implicitly jointed by straight lines. **Fig. 5.7** shows the simplified NTF format.

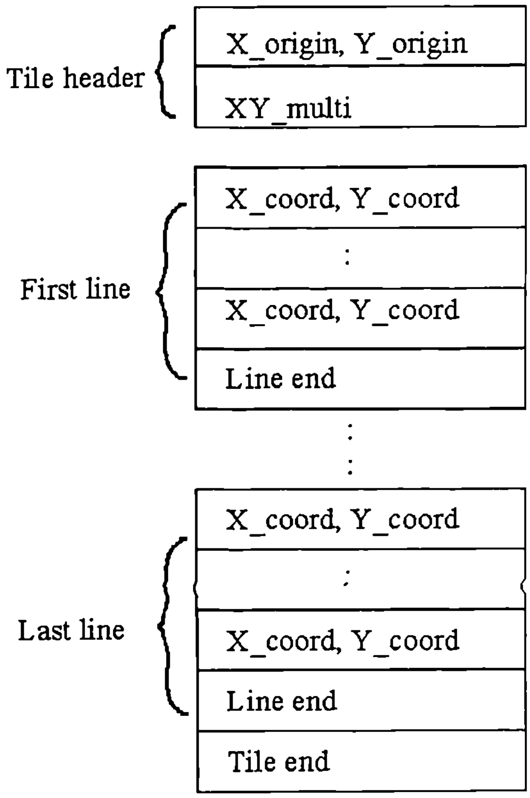


Fig. 5.7 Simplified NTF File Format

All coordinates used in Land-Line NTF are two-dimensional plane coordinates and are based on British National Grid system. To reduce data volumes, feature coordinates are given in easting - northing coordinates pairs in meters relative to the SW corner of the tile. Full British National Grid coordinates can be obtained by using XY_multi, X_origin and Y_origin values contained in the tile head section. The method for calculating is as follows:

$$X = (XY\_multi \times X\_coord) + X\_origin$$
$$Y = (XY\_multi \times Y\_coord) + Y\_origin$$

Where, X_coord and Y_coord are line coordinates read from the line feature.

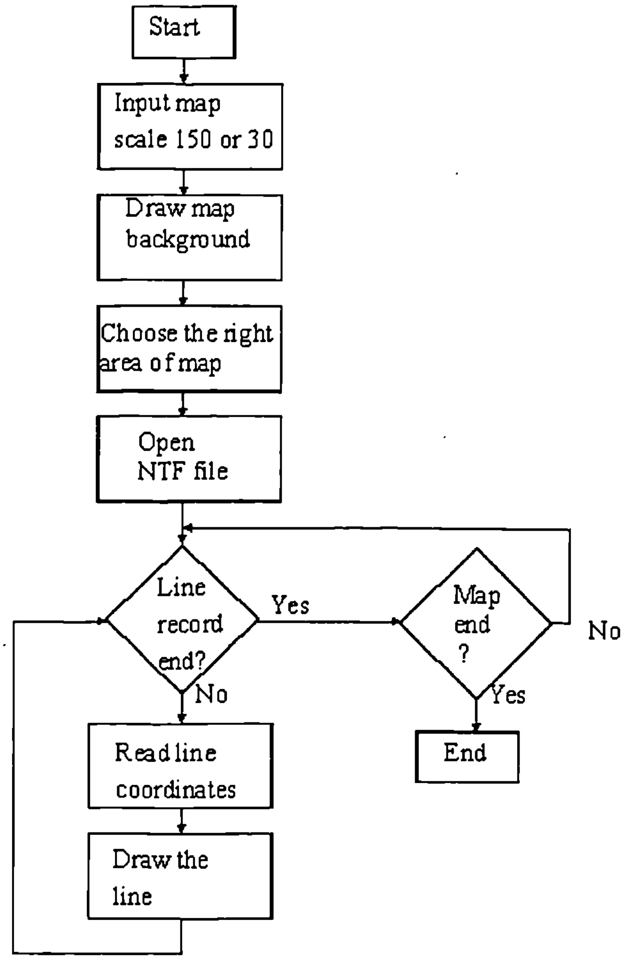


Fig. 5.8 Flowchart of the Map Reproduction Software

5.3.5 Map Reproduction Software and Reproduced Map

The final written map reproduction software is one of the mobile GPS receiver's control software project files (see **Chapter Six**). The description and prototype of the file is also included there. However, the flowchart of the main functions of the map reproduction software is discussed here and shown in **Fig. 5.8**.

The program starts from the choice of map zooming scale, this scale can either be 150 for an unzoomed map or 30 for a zoomed one. The map background information is drawn around the map and on the right part of the PC screen. After these, the right map tiles covering the desired display area need to be decided, and the method is discussed in **Section 5. 3**.3.

The core function of the program is to read the coordinates of related lines that compose a feature. This involves the tile header searching and the search of the beginning of a line feature. Each feature's end also needs to be detected, and this is done by searching a data string of '2' '3' which marks the end of a line feature. Similarly, a data string of '9' '9' marks the end of the tile.

After line's coordinates are obtained, the NTF format coordinate conversion discussed in **Section 5.3.4** needs to be implemented to recover the correct coordinate values, and finally the related lines are linked together to form the feature of the map.

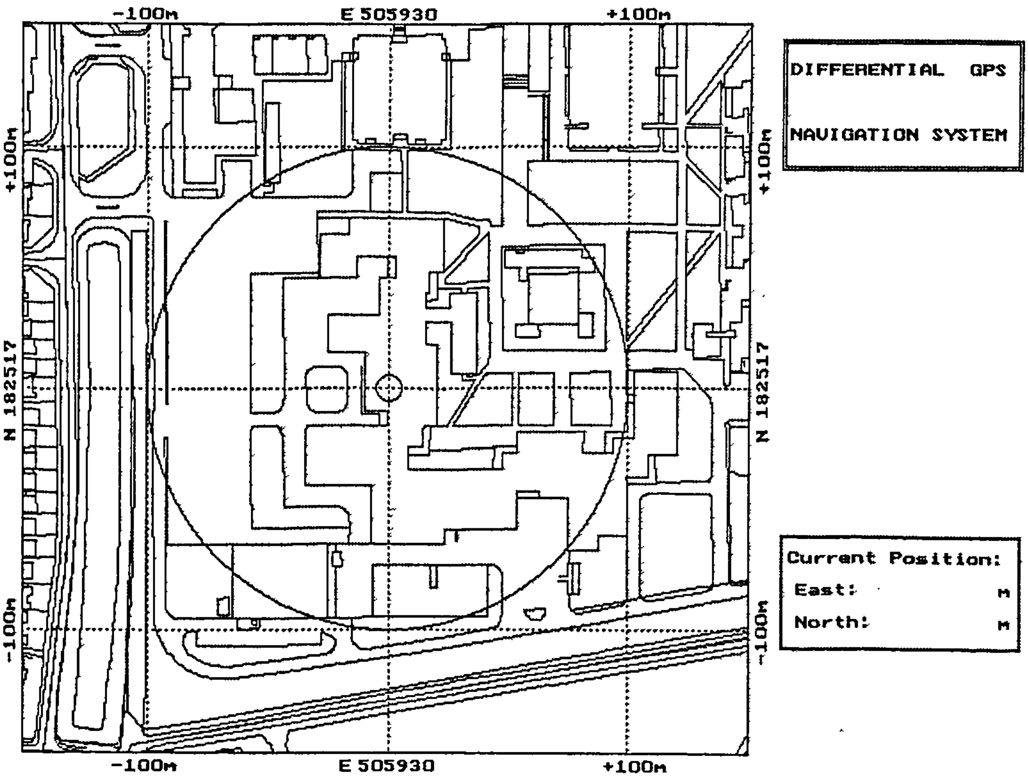
Fig. 5.9 shows a finally constructed digital map and it is a part of the campus of Brunel University with a zoom scale 150. The map has a dimension of 300m × 300m. The origin of the cross dash line is the centre of the display area, and from the map, it can be seen that the coordinates of this origin are:

$$x0=505930 \text{ m}, \quad y0=182517 \text{ m}$$

It can be seen that the map features contained in the Land_Line map database are effectively reproduced around this central point. For the composition of the map, as:

$$y0 - 182500 < 150$$
$$506000 - x0 < 150$$

From the flowchart shown in **Fig.** 5.6, it can be known that the map is composed from all the four tiles A, B, C and D and can be categorised as situation *d*, shown in **Fig. 5.4** .



DIFFERENTIAL GPS
NAVIGATION SYSTEM

Current Position:
East: m
North: m

Fig. 5.9 Reproduced Digital Map of Part of the Brunel University Campus

There is one big circle and one small circle drawn on the map. The radius of the big circle is 100m and the radius of the small circle is 5m. When finally the map is linked with the GPS receiver, these two circles can be effectively used to estimate the positioning accuracy for both GPS and DGPS.

The "Current Position" on the right bottom part of the PC display gives the numerical coordinates of the output of the GPS receiver. In **Fig. 5.9**, this output is invalid, therefore, the display is blank.

Fig. 5. 10 shows another constructed map with the same central point x0, y0 as the above map, but with a zoom scale of 30. The map has a dimension of 60m × 60 m. As the map is effectively zoomed in, it can be seen that it has a much higher resolution than the previous map.

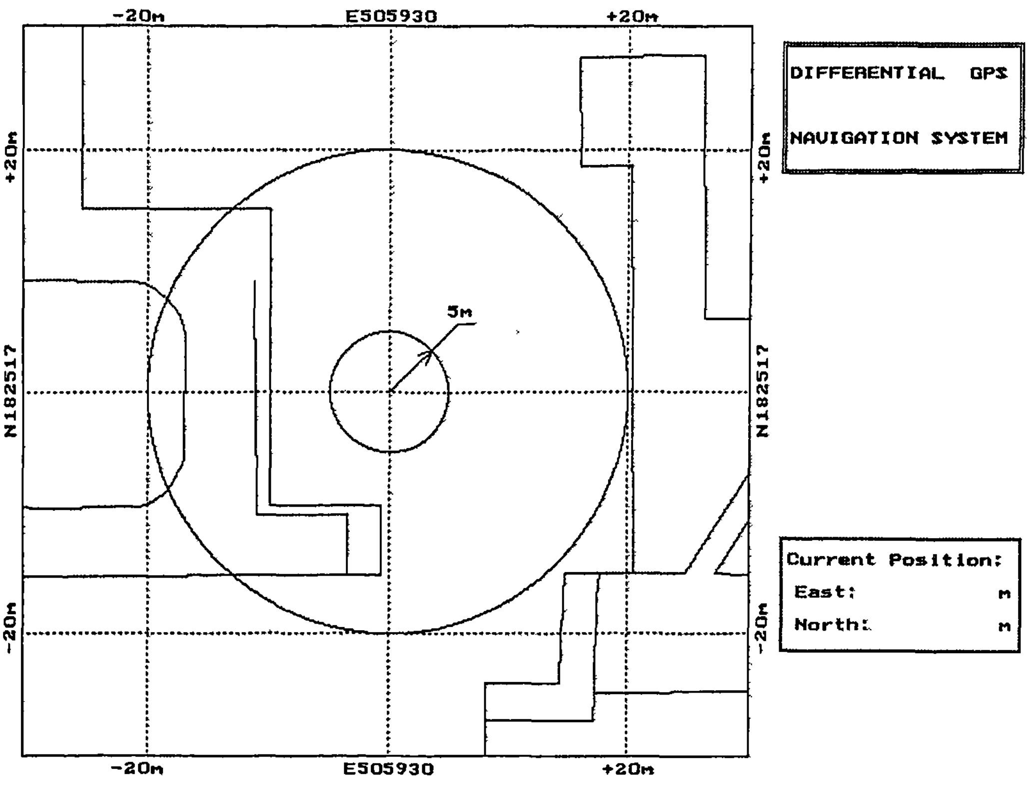


Fig. 5. 10 Zoomed in Digital Map of the Campus of Brunel University

The composition of this map is also different from the previous one. As the zoom scale is now 30, and:

$$y0 - 182500 > 30$$
$$506000 - x0 > 30$$

From the flowchart shown in **Fig. 5**.8, it can be seen this map only contains the area which is covered by tile A and it can be categorised as situation *a*, shown in **Fig. 5.4**. When this map was reproduced, the map computing time is significantly reduced, as only one tile of map database is involved and the file size is reduced (220 kB), Similar to previous map, a small circle of radius of 5m and a big circle of radius of 20 m are drawn on the map for the purpose of estimating the system positioning accuracy when the map is linked with the output of the mobile GPS receiver.

5. 4 Summary

In this chapter, the background of the digital map system is discussed first. This includes the coordinate systems, map projection, and coordinate system conversion. As GPS system uses WGS 84 coordinate system and the digital map system used by the system uses British National Grid coordinate system, the conversion procedures are presented.

The digital map database Land_Line 93 of the Ordnance Survey is adopted by the system to provide the navigational information. After the discussion of the map features of the Land_Line 93, four tiles of the files were chosen to extract the navigation information for the campus of the Brunel University where the experiments and fields are conducted.

The National Transfer Format (NTF) of the Land_Line 93 is discussed. Based on this, map handling functions are designed. These include: choosing the central place of the map, map zooming in and out control and the output of the numerical real-time positioning results. After this, the finally constructed digital map covering Brunel University campus is presented.

CHAPTER SIX: MOBILE NAVIGATION UNIT

Once the DGPS Reference Station and the digital map system are available, the next task of the project is to design a mobile navigation unit to combine a GPS receiver which has DGPS facility with the designed digital map. Essentially the mobile navigation unit has two functions: one is to examine the system performance i.e. the DGPS positioning accuracy, the other is to demonstrate the possible potential applications of the system.

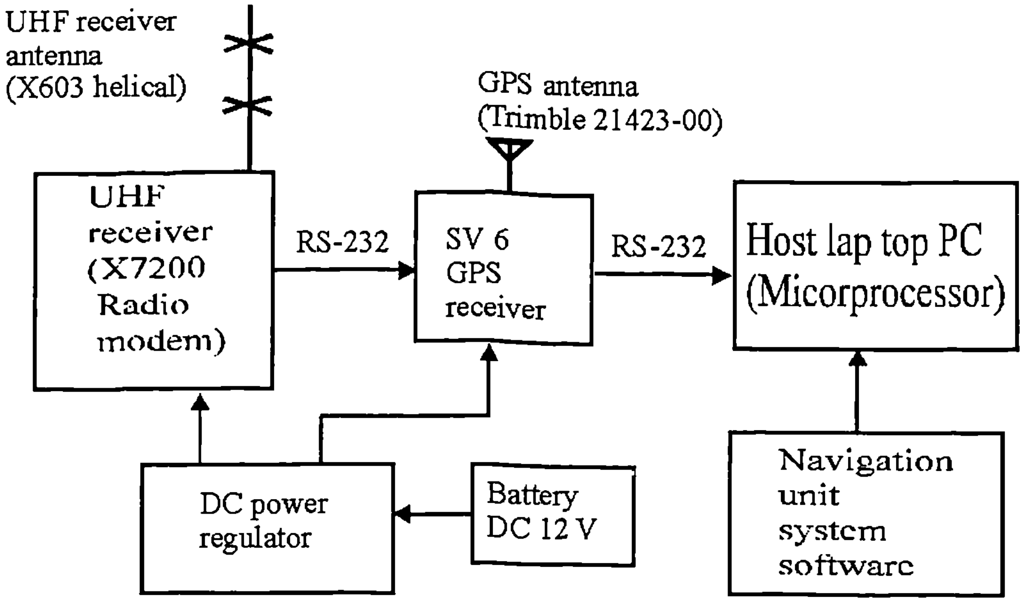


Fig. 6.1 Structure of the Mobile Navigation Unit

Fig. 6.1 shows the structure of the mobile navigation unit. It is mainly composed of a SV6 GPS receiver, a lap top PC, an X7200 UHF radio receiver and the mobile unit system software.

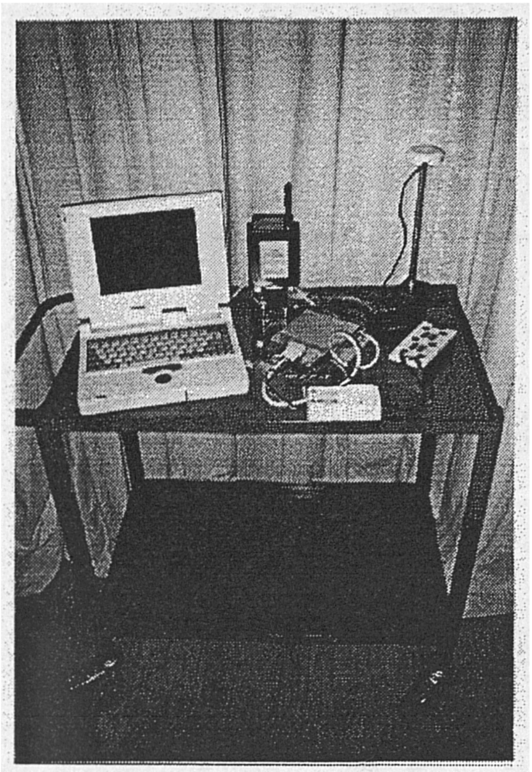


Fig. 6.2 Mobile Navigation Unit

Fig. 6.2 shows the photograph of constructed mobile navigation unit. All the components of the unit are mounted on a trolley, therefore the unit can be easily moved to a desired place to do field trials. The GPS antenna and UHF radio receiver (with antenna) are mounted on magnetic bases, so that they can be moved to suitable places on the trolley to get the best signal reception. When the unit is in operation, the digital map, DGPS positioning results and system information are shown on the PC screen. The system control is achieved by keying the control commands from the PC's keyboard.

6.1 SV-6 Mobile GPS Receiver and Its Control

6.1.1 SV-6 GPS Receiver

The SV-6, from Trimble Navigation Limited, is a low cost, high performance GPS receiver which uses GPS satellite C/A code on L1 frequency [Trimble Navigation 1992]. The reason for choosing SV6 for system integration is that besides the standard functions of a GPS receiver, SV6 provides the flexibility of selecting different hardware configurations and interfacing protocols required by system integration. The other advantage of using SV6 is that a part of the source code of the receiver control software is provided. As this source code is designed in a template style, it is very useful for the system integration. In the process of integrating SV6 with other devices, this template can be effectively re-used in the new system software.

There is a microprocessor inside SV6, and all the basic GPS signal processing is performed by the receiver itself. However, to integrate SV6 with other external device to form a navigation system, interface port of the SV6 needs to be selected so that communications between SV6 and the external device can be established. The SV6's hardware configuration of the interface and the data protocols have the following options:

Electrical:	RS232 (single or dual port) RS422 (single or dual port) TTL
Data Protocols	Trimble Standard Interface Protocol (TSIP) Trimble ASCII Interface Protocol (TAIP) NMEA 0183 (GGA and VTG)

In this work, a lap top PC is used to host the GPS receiver, therefore, a SV6 with dual RS232 data ports was selected. In this case, the host PC can communicate with SV6 directly through its serial communication port COM1 or COM2. The data protocol chosen for the SV6 is TSIP. From the operation manual of the SV6, it can be seen that, the TSIP data protocols give the system integrator more freedom to develop new system software than other protocols, such as TAIP.

SV-6 uses a low profile microstrip patch type antenna, and the gain of the antenna is 35 dB with a cable of length 5m. The pre-amplified signal is fed to the receiver board where six channels are used to track satellite signals. The SV6 is powered by an external DC power source, and the switching power supply module contained in the receiver can tolerate voltage variations between 9 and 32 volts. A 3Ah 12 V dryfit rechargeable lead acid battery is used as the main power supply to power the SV6 and other components of the mobile navigation unit.

The SV-6 can completely self-initialize from cold start. However, when cold started, it takes about 10 minuets to acquire the necessary satellite ephemeris data. To speed the initialization, there is an on board memory that stores the almanac and ephemeris, but this memory needs to be supported by a external backup battery when SV-6 is not operating. For the mobile navigation unit, an additional PP3 9V lithium battery is used to support this memory, and it draws about 100 μA current. As a result, the SV6 can start to track GPS satellites within a few seconds after it is turned on.

When a dual RS232 data port SV6 is used, its data port A can be configured as the input port for differential GPS corrections in RTCM-104 version 2.0 format. In the mobile navigation unit, the data port A is used this way to realize the DGPS function of SV6. The data port A is linked with the UHF radio data receiver to take in the differential correction message generated by the DGPS Reference Station (see **Fig.**

6.1). At this time, the remaining data port B is linked to the host PC's COM1 port and used to communicate with host PC.

As the main GPS signal processing is performed within the SV6, the requirement for the host PC is not high. However, as this PC is also used as the computing unit required by the digital map system, a color 486 DX2-66 lop top PC is used.

The primary output of the SV6 is time-tagged position information i.e. Lat. Long. and height, in WGS 84 format. The output is at intervals of approximately one second, therefore after every one second, the position information is refreshed. Other system information, such as satellite status, signal strength and SV6's operational status, is also obtainable from the host PC's screen, depending on the report packets required and specified by the operator.

6.1.2 TSIP Interface Protocol and Software Structure of SV6

The main software provided with SV6 is TSIPCHAT. It is a program that provides full visibility into the TSIP interface. The essential part of the TSIP interface is a series of command and report packets. By issuing a command packet, the relevant information can be obtained by reading the responding report packet issued by the SV6 [Trimble Navigation 1993].

When TSIPCHAT is in operation, it reports and prints the output of automatically generated report packets to host PC screen. It also allows the user to exercise TSIP commands from keyboard. The other important function of TSIPCHAT is to log TSIP report data into disk files in ASCII formats, so that the positioning results can be used later for analysis.

6.1.2.1 TSIP Command Packets

Packet ID (hex)	TSIPCHAT Keystrokes	Packet Description	Response Report Packet Sent by Receiver
1F	v	Request software version	45
23	i	Input receive initial position	--
27	s	Request GPS signal levels	47
35	O, ^O	Set/request I/O options	55
3D	U, ^U	Configure channel A for RTCM-104 differential GPS	3D

Table 6.1 Examples of the Command Packet of SV6 GPS Receiver

Table 6.1 shows some examples of TSIP command packets. Key storks from the host PC keyboard are interpreted as TSIP commands. For instance, the keystroke 'v' sends the TSIP command packet 0x1F, and this command request a TSIP report packet 0x45 listing the software version. As many TSIP command packets require user-provided data or parameters, for example, a request for configuring data port A as RTCM-104 differential correction messages input port requires the desired baud rate. If parameters for a special command are required, the TSIPCHAT will prompt for it. Then these parameters can be input by the keyboard.

6.1.2.2 TSIP Report Packets

When a TSIP report packet is issued by the SV6, it is received by the TSIPCHAT, translated into a printable form and put on the screen. **Table 6.2** shows some examples of the TSIP report packets. From **Table 6.2**, it can be seen that the packet 0x47 is the report packet responding command packet 0x27 and gives the satellites signal levels.

Packet ID (hex)	Packet Description	Response to Command Pocket Number
42	Single precision position output	25,37
45	Software version information	24
47	Signal level for all satellites	27
5C	Satellite tracking status	3B
83	Double-precision position output in Lat. Lang. and Height.	25, 37

Table 6.2 Examples of the Report Packets of the SV6 GPS Receiver

Besides the report packets specifically requested by a command packet issued by the user, there is a series of automatic report packets. The most common automatic reports are the navigation reports, for example, position, velocity and pseudo-range data. This means that if no command is issued by the user and the receiver is on, the SV6 will regularly report the user position information at the interval of about one second.

6.1.2.3 Software Structure of SV6

The control software of the SV6 is designed in a template style and can be divided into three levels [Trimble Navigation 1993]. The following programs show these three levels in a simplified form as they are used to issue a command package of 0x23 (set initial position of the GPS receiver) and print the output of a report packet 0x42 (position report).

Lever 1 Routines:

```
typedef stuct {
        unsigned char code;
        unsigned char buf[512];
        short int cnt;
             } TSIPKT;


main( )
        {
        unsigned char kbch;
        for (;;) {
          kbch1 = read_rpts_wait_for_kbhit ();
                if (kbch == 0x1B   /* ESCAPE  */) break;
                do_command (kbch);
                }
        }
```

Lever 2 Routines:

```
byte read_rpts_wait_for_kbhit (void)
        {
        static TSIPPKT   rpt;                 /* structure for TSIP report  */
        int         kbch_waiting=FALSE;
        byte        kbch;

        while (!kbch_waiting || rpt.cnt != 0)
                {
                if (kbhit()) {
                        kbch = getch();
                        kbch_waiting = TRUE;
                           }
                accmulate_retbuf (&rpt);
                }
return kbch;
        }

-----------------------------------------------------
```

```
void do_command (byte kbch)
        {
        static TSIPPKT   cmd;                /* structure for TSIP command */

        /* interpret keystoke as a command */
        interpret_keystroke (kch, &cmd.code);

        /* assemble command string */
        proc_kbd (kch, &cmd);

        /* send command string */
        send_com (&cmd);
        }
```

Lever 3 Routines:

```
int interpret_keystroke ( unsigned char kbch, unsigned char *cmdcode)
        {
        ...;
        {"i", 'i', 0x23, "input XYZ pos  "};
        ...;
        }

void proc_kbd (unsigned char kbch, TSIPPKT *cmd)
        {
        switch (cmd.code) {
                        case 0x10D:
                        ...;
                        case 0x23D:
                        set_initial_position (cmd);
                        case 0x24:
                        ...;
                        }
        }
```

```
------------------------------------------------------------------------

void rpt_packet (TSIPPKT *rpt)
        {
        switch (rpt.code)
                {
                case 0x3D:
                ...;
                case 0x42;
                rpt_float_position (rpt);
                case 0x42:
                ...
                }
        }
```

Source code of these general routines (functions) of the three level software and the command and report packets are provided with the SV6 in language Borland C/C++. For the purpose of integrating the receiver with external device into a new system, it is system integrator's task to effectively re-use these templates and design the necessary new command and report packets. The mobile navigation system software that integrates these templates into the system is discussed in **Section 6.3.2**.

6.2 UHF Radio Data Link

The radio data link used in the system is a pair of X7200 FM Radio Modems from Warwick Industrial Electronics Limited, U.K.. X7200 is a transceiver and can be used for both transmitting and receiving UHF signals. In the system, one X7200 is used as the UHF transmitter for DGPS Reference Station and the other is used as UHF receiver for mobile navigation unit. The advantage of using radio modems rather than an ordinary radio data transmitter/receivers for the system is that modem can be interfaced with host PCs' RS-232 serial port directly. Otherwise interfacing electrical level conversion is unavoidable.

The X7200 modem transmits and receives half duplex serial data at either 9600 bits/sec or 4800 bits/sec at a frequency of 458.5 MHz. The RF transmitting power of X7200 is adjustable from 5 mW to 500 mW. It conforms to UK MPT 1329 and the European ETSI- 300-220 standards, and is therefore license free. In this project, only one way communication: from the DGPS Reference Station to the mobile navigation unit, is required, therefore a simplex radio data link would suit the system need. However, the duplex data transmitting ability of XR7200 modem provides the system the potential capability of two way communications, which is a necessary facility for further development of the system (see **Section 8.2.5**).

The serial data transmitted by the X7200 is either 9600 bits/sec or 4800 bits/sec, the Baud rate between the host PC and the modem can range from 150 to 19,200. The odd/even parity or no parity check can also be selected. For both the transmitter used by the DGPS Reference Station and the receiver used by the mobile navigation unit, the RS232 port Baud rates are set at 1,200.

There are three UHF antennas available for X7200. They are helical, end fed dipole and yagi. The helical stub antenna is used by the mobile navigation unit. the reason for this is that helical antenna is robust, low cost and small. The main disadvantage of the helical antenna is that its gain is less than unity. The end fed dipole antenna has a unity gain, and is effective for the omni-direction transmission. In the project, it is used by the DGPS Reference Station. The gain of yagi antenna is higher than the other two antennae, but it is highly directional and is not suitable for the project.

With this antennae arrangement and X7200 transmitter adjusted to the maxim power (500 mW), the achieved radio data coverage is about 5 km in radius, which is large enough for the research project. For the future development, this coverage can be either increased by using a more powerful transmitter, or some other sort of communication data link can be adopted (see **Section 8.2.5**).

The X7200 is needed to be powered from a regulated dc source of between 8.5V to 14V. For the DGPS Reference Station, the X7200 transmitter is powered by a 12V dc power supplier. For the mobile navigation unit, the X7200 receiver is powered by the main 3Ah 12V battery.

6.3 Mobile Navigation Unit System Software

6.3.1 Route Searching and Planning Algorithm

One important component of the mobile unit control software is the route searching and planing algorithm. As discussed in **Section 1.3**, the main purpose of the route-planning algorithm is to demonstrate the potential applications of the system. This is because for a navigation system, it is usually desirable for the system to have some route searching and planning ability to find the optimum route from user's current position to destination. This optimum route can be either the shortest route, or the easiest route, or a route with some special features depending on the specific application.

As discussed in **Section 1.2**, some route searching and planning algorithm have been found during the literature search. But all these algorithms are designed for a special project and usually linked with a special map, therefore, they can not directly adopted by the project. As the Land-Line is used in the system, the route searching and planing algorithm to be designed must be based on this map.

The designed the route-planing algorithm is relatively a simple one. It is based on the digital map drawn on the PC screen. The principle of this route searching and

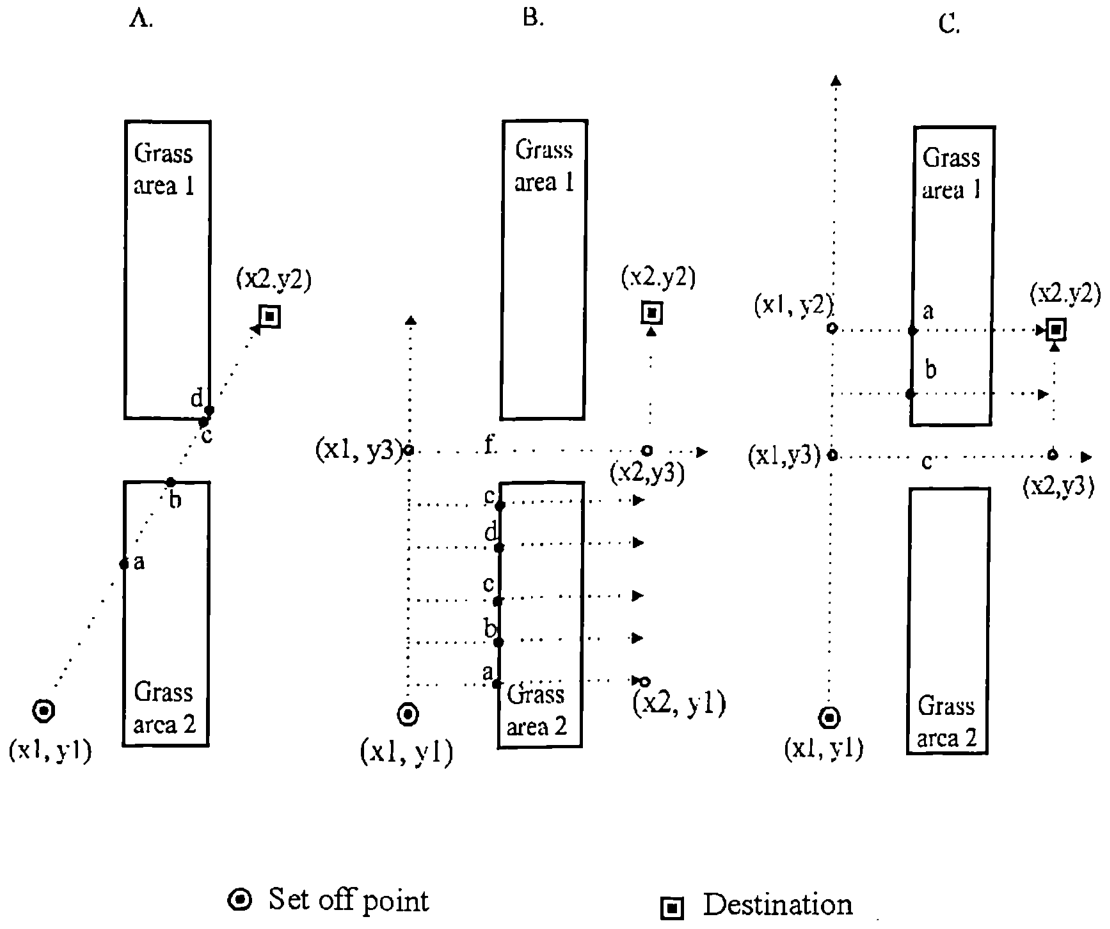


Fig. 6.3 The Principle of Route Searching and Planning

planning is that the program detects the map feature boundaries by checking PC graphic display pixel color change. If a boundary of a map feature is encountered, this means an obstacle lies ahead. In this case, either an adjustment of the direction of current route is required, or an alternate route is needed,.

Fig. 6.3 shows the route searching methods adopted by the system, where ⊙ is the set off point with a pair of PC graphic screen coordinates x1, y1, and ▣ is desired destination with coordinates of x2, y2.

In the situation shown in **Fig. 6.3,** these two places are on the different sides of grass areas one and two. Therefore, the optimum route should be able to link these two places with the shortest length. And at the same time, the trespassing of the grass area should be avoided.

The route searching starts from linking these two places by a straight line (see **Fig. 6.3 A**). To judge whether this straight line can link the places without going through grass areas, an important graphic routine of Borland C/C++ language: getpixel ( ) is utilized. The function of getpixel ( ) is to get the color attribution of the pixel of the PC graphic display located at (x, y). As the background of the digital map is drawn in one color, and the boundary of the map features are drawn in another. By detecting the graphic display's pixel color change, the boundary of a map feature can be found.

In the case shown in **Fig. 6.3 A,** it can be seen that along the straight line from (x1, y1) to (x2, Y2), the output of getpixel ( ) will change at four possible locations: a, b, c and d. *This means the straight line can not link the set off point and the destination* without going through grass areas. To establish a link between these two places, a more complex zigzag route is required.

Fig. 6.3 B shows one method adopted by the program to search the required zigzag route. It starts from searching a horizontal route *a* from (x1, y1) to (x2, y1). Since this route is blocked by grass area one, it then tries another horizontal route *b* which has a northern offset Δy and lies above the route *a*. This searching will continue until the final unblocked horizontal route *f* which is from (x1, y3) to (x2, y3) is obtained. After that, the end point (x2, y3) of the route *f* will be used as the fresh start (set off point) to search the remaining part of the required optimum route. This remaining part is from (x2, y3) to (x2, y2), and in the case of **Fig. 6.3 B**, a vertical straight line will meet the need.

Fig. 6.3 C shows another method used in the system to search the zigzag route. In stead of searching a horizontal route, it starts from searching a vertical route. In this case, a route from (x1, y1) to (x1, y2) can be obtained immediately. After that, the end point (x1, y2) of the vertical route is used as the new set off point to search the remaining horizontal route *a* which links (x1, y2) and the destination. Again, this horizontal route *a* is blocked by the grass area two, a vertical offset of Δy is added to this new set off point (x1, y2) to start a new search. This search is continued until the required unblocked horizontal route *c* which is from (x1, y3) to (x2, y3) is found. The remaining part of the optimum route from (x2, y3) to destination can be found easily, because a straight line will suit the need.

In the program, the route searching and planning algorithm worked well, and the actual optimum route obtained is shown in **Section 7.3.** However, it should be pointed out that the situations shown in **Fig. 6.3** are simple and the required optimum route is short. In some other areas, the layout of map features can be far more complex, and usually, a combination of more than one zigzag routes are needed to link the set off point and destination. In that case, it can not guarantee that the route obtained is optimum, or the required unblocked route can be finally obtained. In this situation, more sophisticated route searching and planning methods are needed to be developed [Zhao, Y. 1991].

6.3.2 Mobile Navigation Unit System Software

Mobile navigation unit system software is based on the SV6 receiver control software's three level software structure. The main requirement of the new system software is to redirect the positioning output of the SV6 to digital map by designing some special command and report packets. At the same time, the original TSIP command packets should be kept, because they are well designed packets and can be used to control and choose the system settings of SV6 effectively.

The main changes of the software happen in the level two and level three structure, especially in the level two's do_command ( ) procedure. The basic idea is that when SV6 detects a key stoke from the PC's keyboard, it tries to judge whether it is a special command for the new system software, or it is the standard TSIP command. If it is a special command required by the mobile navigation unit, then it turns to the direction of map handling. If it is a standard TSIP command, it works like a standard SV6. At this time, the selection of the GPS receiver settings can be performed.

Fig. 6.4 shows the flowchart of the new do_command ( ) procedure. Two new commands represented by the 'F1' and 'F3' are introduced. The function of 'F1' key is to redirect the positioning output of SV6 to an unzoomed map, while 'F3' to a zoomed one. It is at this stage, reproduced digital map systems discussed in **Section 5.3.5** is combined with the mobile navigation unit. By choosing F1 or F3, the positioning results of the mobile navigation unit can be effectively zoomed.

After the map scale is chosen and the map reproduced, the other necessary computations need to be performed. These include: route searching and planning, the coordinate of the SV6 output converting (WGS 84 to National Grid), drawing the positioning results on the map and output the numerical current position to the "Current Position" on the right bottom of the PC screen.

As the actual command processing happens at the level three structure, corresponding changes are needed to accommodate the new command and report packets. Besides that, some of the original TSIP packets are also needed to be modified to suit the mobile navigation unit requirements. For example, the data log procedure should be changed from logging positioning results in Lat. Lang. and Height format to British National Grid's east, north format.

6.3.3 Source Code Structure of Mobile Navigation Unit System Software

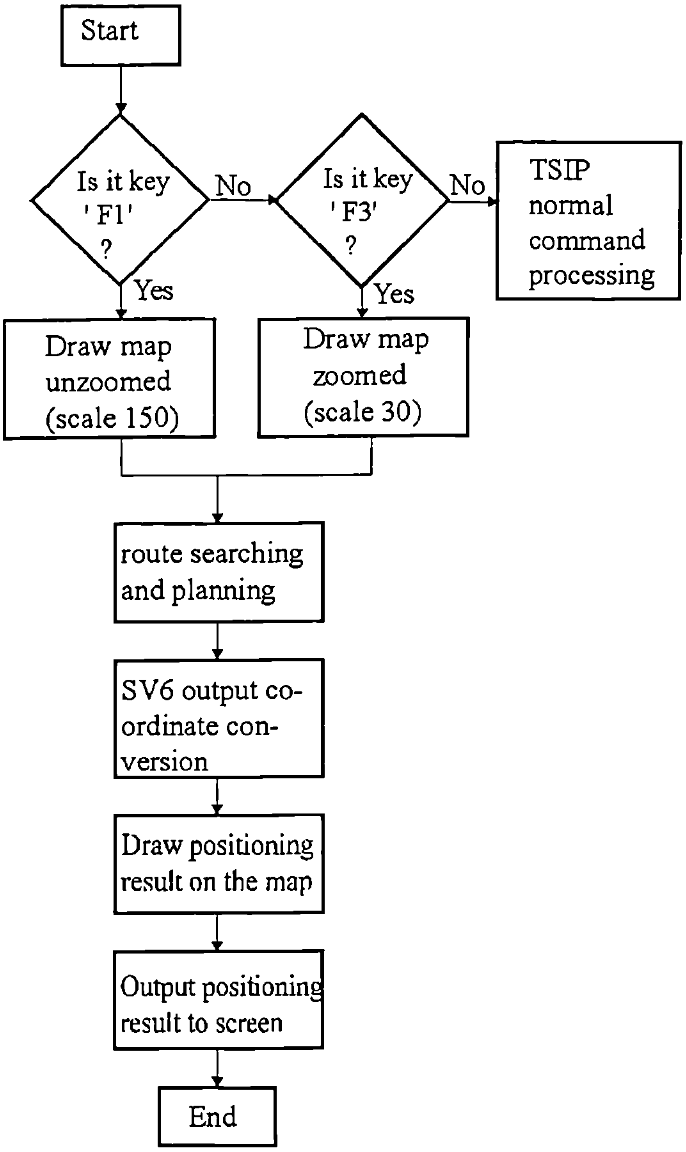


Fig. 6.4 Flowchart of the Do_command ( ) Procedure

The finally designed mobile navigation unit system software worked well. The output of the SV6 GPS receiver was successfully combined with the reproduced digital map, and the real-time positioning results are linked with the navigational information. These positioning results can also be stored in the log file for later analyses. Meanwhile, the basic system control functions of the original TSIP commands are well reserved, therefore the system control can be achieved by keying in the relevant commands. The graphical output of the mobile navigation unit is shown in **Section 7.1.2.**

A Borland C project named "SV6_CON" is produced to compile multiple source files together into a single program. All together, there are 10 file modules as follows and the source code lines are contained in the directory C:/SV6_CON.

Sv6.c (main)
Tsip_utl.c
Tsip_cmd.c
Tsip_rpt.c
Tsip_alm.c
Tsip_ifc.c
Map.c
Wgs_grid.c
Routeplan.c
Filelog.c

The detailed description of the functions of the modules are listed in **Appendix III** for reference.

6.4 Summary

A mobile navigation unit is constructed to examine the navigation system performance and to demonstrate the possible application of the system. The mobile unit consists of a SV6 GPS receiver, a lap top host PC, an X7200 UHF radio receiver, DC power supply and unit system software.

From the UHF radio receiver, the differential correction messages transmitted by the DGPS Reference Station are received. They are then fed into the SV6 GPS receiver. By using these differential corrections, the SV6's positioning accuracy is substantially increased, this means that the function of differential GPS is successfully realized.

The structure of SV6 GPS receiver's control software is discussed. The source code templates of the SV6 are re-used in the design of the mobile unit system software. The final designed mobile navigation unit system software can effectively combine the SV6 GPS receiver with the digital map, and positioning data log function is also realized.

The route searching and planing algorithm is another component of the mobile navigation unit. The implemented algorithm is relatively a simple one, but can effectively find the optimum route from the set off point to the desired destination.

The experiment results obtained from the mobile navigation unit are presented in **Chapter Seven**.

CHAPTER SEVEN: SYSTEM PERFORMANCE AND OPTIMIZATION

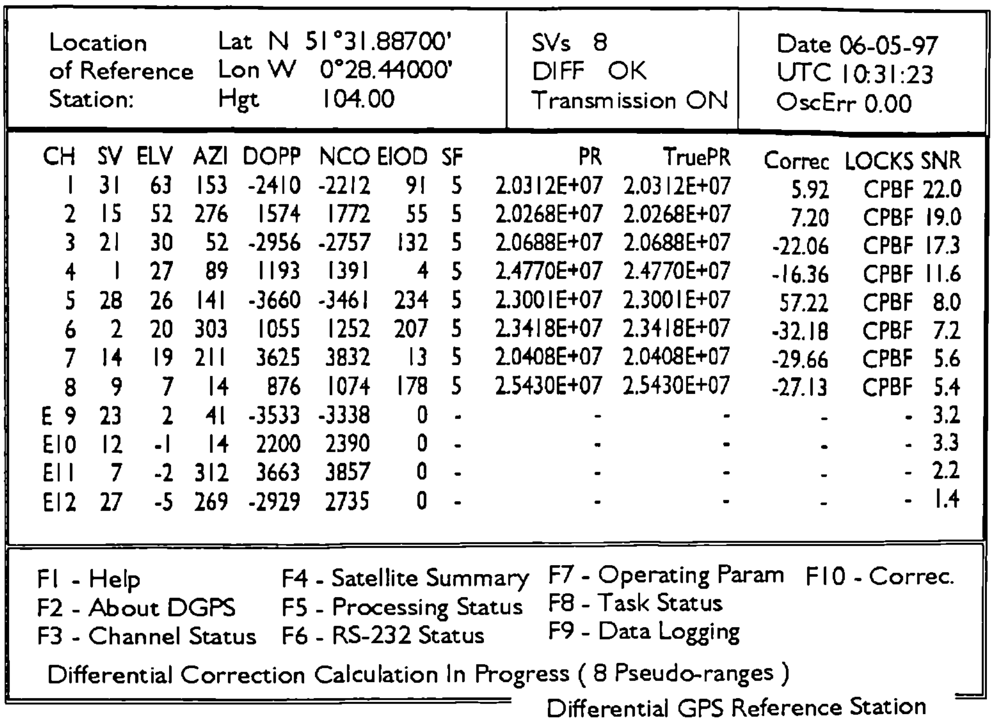
7.1 System Performance

The finally constructed system is a complete navigation system consisting of a DGPS Reference Station and a mobile navigation unit. As the DGPS Reference Station is a very important part of the research project, its performance is discussed separately from the whole navigation system.

7.1.1 Performance of DGPS Reference Station

Fig. 7.1 shows one of the console screens of the operating DGPS Reference Station. This console display consists of three blocks. The top block gives the current navigation status information. Below this is a selectable display (selected by function keys F1-F10), which provides channel and signal processing information. What is shown in **Fig 7.1** is a channel status display, which is automatically selected when the DGPS Reference Station is turned on. It also can be activated by the function key F10. The lower block of the console screen is the description of function keys, and the current processing status. The error messages which may result from the system performance is also displayed here.

The *Location of Reference Station* on the right part of the top block shows station coordinates in WGS-84 format. This position can be keyed in at the beginning of the execution of the system software. Usually this position should be surveyed to provide the accurate position information. For the constructed DGPS Reference Station, due to the limitation of the budget, an average of two days accumulation of a GPS receiver's positioning result is used instead.



```
Location        Lat N  51°31.88700'     SVs  8               Date 06-05-97
of Reference    Lon W   0°28.44000'     DIFF   OK            UTC 10:31:23
Station:        Hgt      104.00         Transmission ON      OscErr 0.00

 CH  SV ELV  AZI  DOPP   NCO EIOD SF        PR       TruePR   Correc LOCKS SNR
  1  31  63  153 -2410 -2212   91  5  2.0312E+07  2.0312E+07    5.92  CPBF 22.0
  2  15  52  276  1574  1772   55  5  2.0268E+07  2.0268E+07    7.20  CPBF 19.0
  3  21  30   52 -2956 -2757  132  5  2.0688E+07  2.0688E+07  -22.06  CPBF 17.3
  4   1  27   89  1193  1391    4  5  2.4770E+07  2.4770E+07  -16.36  CPBF 11.6
  5  28  26  141 -3660 -3461  234  5  2.3001E+07  2.3001E+07   57.22  CPBF  8.0
  6   2  20  303  1055  1252  207  5  2.3418E+07  2.3418E+07  -32.18  CPBF  7.2
  7  14  19  211  3625  3832   13  5  2.0408E+07  2.0408E+07  -29.66  CPBF  5.6
  8   9   7   14   876  1074  178  5  2.5430E+07  2.5430E+07  -27.13  CPBF  5.4
 E 9 23   2   41 -3533 -3338    0  -           -           -       -     -  3.2
 E10 12  -1   14  2200  2390    0  -           -           -       -     -  3.3
 E11  7  -2  312  3663  3857    0  -           -           -       -     -  2.2
 E12 27  -5  269 -2929  2735    0  -           -           -       -     -  1.4

F1 - Help          F4 - Satellite Summary  F7 - Operating Param  F10 - Correc.
F2 - About DGPS    F5 - Processing Status  F8 - Task Status
F3 - Channel Status F6 - RS-232 Status     F9 - Data Logging
Differential Correction Calculation In Progress ( 8 Pseudo-ranges )
                                          Differential GPS Reference Station
```

Fig. 7.1 The Channel Status of the Operating DGPS Reference Station

The rest part of the top block provides following information:

SVs	Number of satellites used for differential correction calculation
DIFF	Whether differential processing is in progress, OK or NO
Trans-mission	The differential correction message transmitting status. ON or OFF
UTC	Universe Coordinate Time
OscErr	DGPS Reference Station oscillator error, ppm (+ means frequency is high, - means frequency is low)

The channel status display is organized in one line for each of the 12 channels. Each line contains the following information:

Satellite status:

E = below elevation mask
D = deselected by user
U = unhealthy

CH	Channel numbers (1-12)
SV	Space vehicle (satellite) number (1-32)
ELV	Predicted SV elevation, degrees
AZI	Predicted SV azimuth, degrees east of north
DOPP	Predicted SV Doppler shift at L1 frequency, Hz (+ means SV approaching, - means SV receding)
NCO	Measured SV Doppler shift (if tracking), or Doppler bin of the current search (if not tracking)
EIOD	Ephemeris issue of data
SF	Last subframe received from this SV (1-5)
PR	Measured pseudo-range from this SV
TruePR	Actual pseudo-range calculated for this SV
Correc	Differential correction, meters
LOCKS	C = Correlation lock (Early-Late tracker) P = Phase lock (Costas loop) B = Bit synchronized (bit edge detector) F = Frame synchronized (subframe parser)
SNR	Post-detection Signal to Noise Ratio, dB

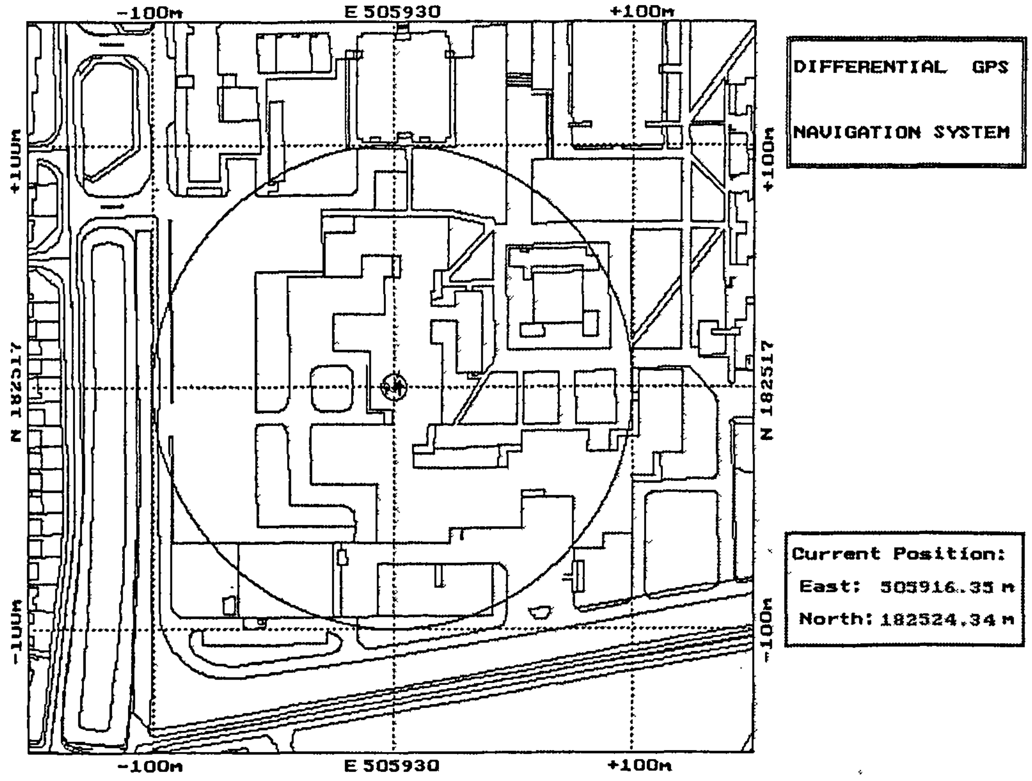
From **Fig. 7.1**, it can be seen that there are eight satellites available at the time of reception. The differential corrections for these satellites range from -32 to 57 m. These differential corrections are the most important messages and are encoded into RTCM 104 format and transmitted to the mobile navigation unit. It can also be seen the Post-detection Signal to Noise Ratio (SNR) for eight satellites are from 5.4 to 22 dB. It is well within the range of the estimated value made in the **Section 3.3.5**.

Besides this Channel Status display, the middle block of the console screen can also be used to show other system and signal processing information. This can be activated by the relevant function keys from F1 to F10.

7.1.2 Performance of the Mobile Navigation Unit

Fig. 7.2 shows a hardcopy of the host PC screen of the mobile navigation unit when it is in operation. Basically it is the digital map described in **Section 5.3.5** combined with the positioning output of the SV6 receiver. From the hardcopy, it can be seen that the positioning result of the SV6 is combined with navigational information contained in the Land_Line digital map. The map's zoom scale here is 150 and provides a dimension of 300m × 300m. A zoomed in map that shows the detailed navigational information in a dimension of 60m × 60m is shown in **Section 7.3.3**. This zoom control and the TSIP commands of the SV6 can be effectively obtained by keying the relevant command in the lap top PC's keyboard, as expected in **Section 6.3.2**.

In this experiment, the mobile unit was placed statically on the location of interest, therefore, this is a static performance of the system. The dynamic positioning results were also obtained when the mobile unit was pushed along to do field trials. The experiment results are discussed in **Section 7.1.3**.



Current Position:
East: 505916.35 m
North: 182524.34 m

Fig. 7.2 A Typical Static Positioning Result of the Navigation System

The "Current Position" on the right bottom part of the PC gives the real-time numerical positioning result in British National Grid. This result updates every second. From **Fig. 7.2**, it can be seen the current position of the mobile navigation unit is:

x (east) = 505916.4 m;
y (north) = 182524.3 m

7.1.3 Static Performance of the Navigation System

What shown in **Fig. 7.2** is also a typical static performance of the complete navigation system. From the digital map, it can be immediately seen that the scatters of the position result are well within the small circle of radius 5m. More detailed numerical result is obtained from the analysis of the data log files and it was found:

x (mean) = 505931.2 m; σ_x (Standard deviation) =1.7 m

y (mean) = 182516.0 m σ_y (Standard deviation) =1.2 m

What is of interest is system positioning accuracy δs, and δs can be expressed as:

$$\delta s = \sqrt{(\delta x)^2 + (\delta y)^2}$$

According to the theory of statistics, if the obtained positioning result complies to Normal distribution, and if $\delta x = 2\sigma_x$, $\delta y = 2\sigma_y$, the probability of the system positioning accuracy is within the range of δs is *95.44 %*. [Topping, J. 1972]. In this case:

$$\delta s = \sqrt{(2\sigma_x)^2 + (2\sigma_y)^2} = \sqrt{(2 \times 1.7)^2 + (2 \times 1.2)^2} = 4.1 \text{ (m)}$$

As a comparison, **Fig. 7.3** shows the positioning result of GPS, where the mobile navigation unit was placed on the same location, but the DGPS Reference Station is turned off. The final results are:

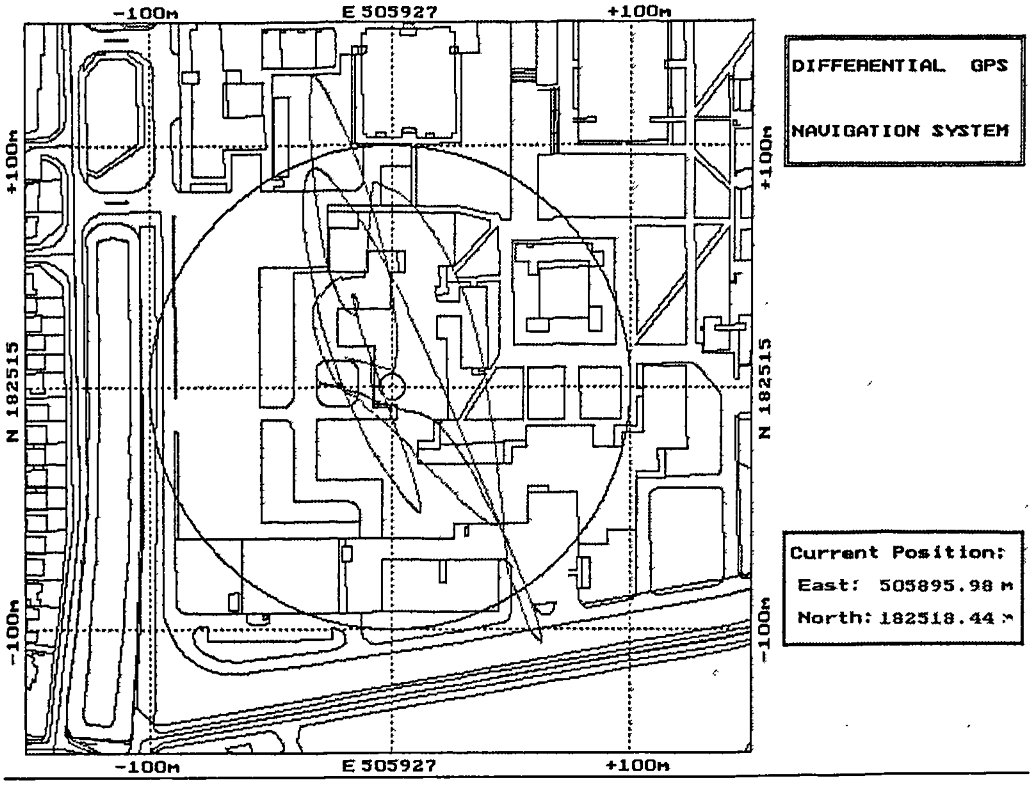


Fig. 7.3 A Typical Performance of the GPS System

x (mean) = 505924.3 m; σ_x (Standard deviation) =31.4 m

y (mean) = 182520.0 m σ_y (Standard deviation) =51.3 m

and $$\delta s = \sqrt{(2\sigma_x)^2+(2\sigma_y)^2} = \sqrt{(2\times 26.4)^2+(2\times 41.3)^2} = 98.0 \text{ (m)}$$

From this comparison, it can be seen that the differential technology is successfully applied to the GPS, and the system positioning accuracy is improved from about 98.0 m to 4.1 m.

Repeated experiments of the static positioning results were also carried out where the mobile navigation unit were placed at the different places within the campus of Brunel University covered by the available four Land_Line tiles. **Table 7. 1** shows

Places			Positioning Results		
	x(mean), m	y(mean), m	σ_x, m	σ_y, m	$\delta s = \sqrt{(2\sigma_x)^2 + (2\sigma_y)^2}$, m
A	505920.2	182531.8	1.8	1.2	4.3
B	505847.5	182590.5	2.1	1.3	4.9
C	505830.4	182432.8	2.2	1.5	5.3
D	505951.5	182515.3	1.4	1.5	4.1
E	505957.6	182520.4	1.5	1.3	4.0

Table 7.1 Static Positioning Results of the Navigation System

the experiment results. From **Table 7. 1**, it can be seen that the calculated system position accuracy is within the range of 4-5m.

7.1.4 Route Searching and Planning Algorithm and System Dynamic Performance

Fig. 7.4 shows the dynamic system performance. The optimum route (thick dash line) created by the route searching and planning algorithm is also shown on the map. It can be seen that it links the set off point ⊙ and the desired destination ▣ successfully, and two adjacent grass areas are avoided.

The thin red line is the real-time dynamic positioning result when the mobile navigation unit is pushed along the optimum route. It can be seen that it follows the optimum route closely. At some point, there are some jitters, but generally speaking, the deviation from the red line to dash line is within 5 m.

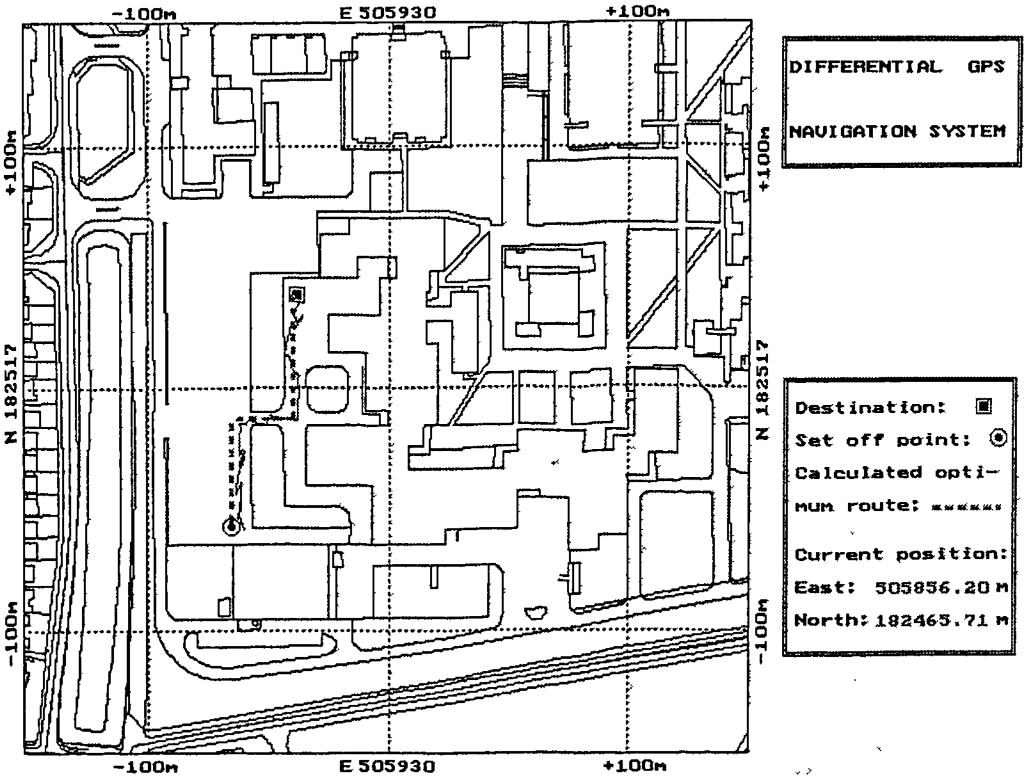


Fig. 7.4 Dynamic Performance of the Navigation System

During the experiment, it was found the jitters of the positioning results were caused by the block of the satellite signals from the adjacent trees in the grass area. Once the signals were re-gained, the positioning results came back to normal.

It should be pointed out that the experimental result obtained in **Fig. 7.4** was in a low dynamic situation and is a demonstration of the system dynamic performance. It is expected that the system should work well in most low to medium dynamic situations. Because the differential correction messages are reliable for a quite large area (see **Section 2.4.1**). However, if the system is to be used in a much higher dynamic situation, for example, the aircraft auto-landing system, the system dynamic characteristics must be fully investigated. It may be also required that some system characteristics are modified to suit the specific application.

7.2 Optimisation of the Carrier Tracking Loop of the DGPS Reference Station

As mentioned in **Section 3.3.5**, different parameters were used in the carrier tracking loop (Costas loop) to test the system performance. **Table 7.1** shows four groups of these parameters. **Table 7.2** shows the system performance corresponding to these four group parameters.

Group	A	B	C	D
$T1$ second	2097	1048	2097	1048
$T2$ second	0.256	1.023	0.256	4.09
Kd units per radian of phase error	5136962	10273924	321024	10273924
K_0 radian / (second per unit)	0.01672	0.01672	0.01672	0.01672
ω_n radian/second	4.52	9.05	1.13	9.05
ω_n Hz	0.72	1.44	0.18	1.44
ζ	0.58	4.6	0.145	18.4
$\Delta\omega_p$ radian/second	604	3403	37	6806
$\Delta\omega_p$ Hz	96	541	6.0	1028
T_p second	11.4	0.178	421.5	0.178
$\Delta\omega_{po}$ radian/second	12.8	91.2	2.32	316.0
$\Delta\omega_{po}$ Hz	2.0	14.5	0.37	50.3

Table 7.1 Four Groups of Parameters Tested in the Costas Loop

Group	L1 carrier signal pull-in time (the first satellite that reaches 'CPBF' lock status), second	System signal tracking performance
A	21	Signal pull-in is quick. It took a little time to track the rest available satellites in the sky.
B	16	Signal pull-in is quick and system is steady. After the first satellite was tracked, the rest available satellites were tracked in seconds.
C	55	Signal pull-in is slow and it was difficult to reach 'CPBF' lock status for all satellites (took about 150 seconds).
D	--	Occasionally a satellite was tracked, but the tracking is lost easily. It was impossible to track all the satellites.

Table 7.2 Performance of the Carrier Signal Tracking Loop

From **Table 7.2**, it can be seen that different parameters of the carrier tracking loop have significant impacts on the system signal tracking performance. With the loop parameters changing, the system could possibly lose its signal tracking ability, or the system becomes unsteady.

The carrier signal tracking loop using group B parameters has been found to have the best performance. Under these parameters, the signal pull-in time is short and the system is steady. After the first GPS satellite was tracked, the rest satellites available in the sky were tracked within seconds. This group of parameters is adopted by the final system.

To the contrary of parameters of group B, the carrier tracking loop using the group D parameters has the worst performance. In this circumstance, only occasionally a satellite signal is tracked, and this tracking status is lost easily. It is impossible for the system to track all the GPS satellites available in the sky, therefore, the DGPS Reference Station virtually dose not work.

7.3 The Impact of Digital Filtering on the DGPS Reference Station

7.3.1 Recursive First-Order Digital Filter

Digital filters used in the DGPS Reference Station are recursive digital filters as they are implemented by recursive software,. These filters are used in the system because the system software program can do the recursive calculation effectively, and the characteristics of constructed filter can be easily adjusted. The most effective way to investigate the characteristic of the digital filter is the z transform and its z-plane's zero and pole analysis. In the DGPS Reference Station, due to the limitation of the computing power, only the first-order low-pass filter is used, the discussion below concentrates on this type of filter. However, the higher order, high-pass and band-pass filters can also be analyzed exactly the some way.

For a first-order digital filter's z transfer function $H(z)$, there are three factors involved. These are filter gain factor A, zero B and pole C. All these factors are real numbers, in other words, they are on the real axis of the z-plane [Otnes, R., 1972] [Hutchings, H. 1991].

According to the definition of zero, pole, and gain, $H(z)$ can be expressed:

$$H(z) = A\frac{(z-B)}{(z-C)} \qquad (7\text{-}1)$$

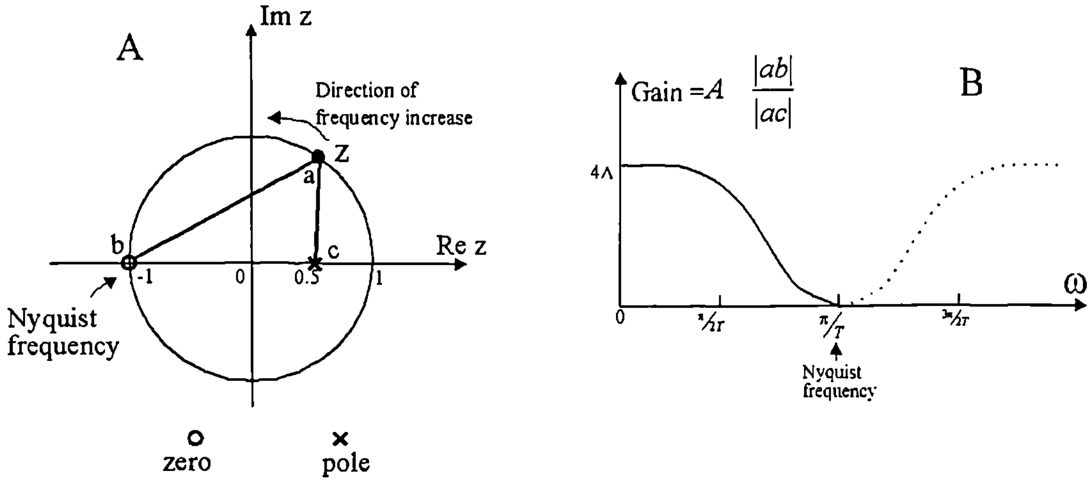


Fig. 7.5 Z-plane and the Magnitude of Frequency Response of Low-pass Filter.

Fig 7.5 A shows the z-plane of a low-pass filter with the following factors:

Pole	$C = 0.5$
Zero	$B = -1$
Gain	$A = 1$

The magnitude of filter's frequency response is shown in **Fig. 7.5. B**, where the filter gain is proportional to the ratio of the length of zero vector 'ab' to the length of pole vector 'ac'. From **Fig. 7.5**, it can be seen that once these factors are determined, the characteristics of the filter are fixed. For instance, for the first-order filter, if the zero B is on the right side of the pole C, the filter will have high-pass characteristic; if the pole C is on the right side of the zero B, the filter will have low-pass characteristic. According to this, the filter's characteristic is usually adjusted by changing the locations of its zero and pole on z-plane, so that a filter with desired characteristic can be designed.

Once the zero *B*, pole *C* and gain *A* of the filter are decided, the exact expression of the z transfer function *H(Z)* is determined by **Eq. (7-1).** After that, what is needed is to implement this filter in software program by recursive expressions.

If *Y(z)* is used to represent the z transform of the filter output, and *X(z)* the z transform of the filter input, re-arranging **Eq. (7-1)**:

$$Y(z)\cdot(z-C)=X(z)\cdot A\cdot(z-B) \qquad (7\text{-}2)$$

and this is:

$$Y(z)=A\cdot x(z)-A\cdot B\cdot\frac{x(z)}{z}+C\cdot\frac{y(z)}{z} \qquad (7\text{-}3)$$

In the digital system, the signal of current output of the filter is represented by *y(n)* in time domain, and the previous output is represented by *y(n-1).* From the property of the z transform, it can be seen that:

$$Y(z)\rightarrow y(n)$$

$$\frac{y(z)}{z}\rightarrow y(n-1)$$

These two properties are important. By applying these to **Eq. (7-3),** the recursive expression of the desired digital filter can be obtained in the time domain:

$$y(n) = A \cdot x(n) - A \cdot B \cdot x(n-1) + C \cdot y(n-1) \qquad (7\text{-}4)$$

By using **Eq. (7-4)**, either a recursive digital filter can be implemented immediately by inserting the filter factors zero *B*, pole *C* and gain *A* into the expression; or the values of the zero *B*, pole *C* and gain *A* of a filter can be obtained from its recursive expression.

7.3.2 Three Places to Implement Digital Filter in the DGPS Reference Station

Digital filters were inserted in three different places in the DGPS Reference Station to filter different measurements to investigate the impact of digital filtering. These measurements include pseudo-range PR_i, differential correction $Correc_i$ and system clock offset T.

It has been found that the filter applied to the pseudo-range PR_i appears to play a more important role than others. The system performance benefits significantly as the filter smoothes the output of differential corrections effectively. The system improvement gained by using this filter is discussed in **Section 7.3.3**.

For the filter applied to differential correction $Correc_i$, it appears to be less effective. More than this, the filter applied here affects convergence of the system software significantly. In the final optimized system, this filter was removed.

The impact of the digital filter on the reference station clock offset T is that it can reduce the amplitude of the offset greatly while it smoothes it. As discussed in **Section 3.4.1**. this uncompensated offset T in the DGPS mathematical model is contained in the calculated differential correction as a bias. After correction messages are finally received by the mobile GPS receiver, this offset T can be resolved by the GPS mathematical model (see **Eq. (2-8)**). On the DGPS Reference Station side, this clock offset should be as small as possible. This is because the true range *TruePR* from the user to GPS satellite is decided by the accurate satellite position in the sky (see **Section 3.4.1**), and this position is calculated by inserting the accurate time into Keplerian equations that describe the satellite orbit (see **Section 2.1.1**).

7.3.3 The Impact of the Digital Filter on Measured Pseudo-Ranges

The actual filter applied to the measured pseudo-range in the DGPS Reference Station is of the form:

$$PR_i[nsv] = 0.25 * PR_{i-1}[nsv] + 0.75 * pseudo\text{-}range[nsv]$$

Comparing this with **Eq. (7-4)**, it can be seen that the filter has a zero $B = 0$, a pole $C = 0.25$ and a gain factor $A = 0.75$. It should be pointed out that filter's gain factor $A = 0.75$ should not be confused with the filter gain. The above filter's low frequency gain is unity. This can be seen clearly if the magnitude of the frequency response like **Fig. 7.5 B** is drawn. This unity gain is important, because when a filter is inserted in the system, it should not bring any additional gain to the signal that is being filtered.

Fig. 7.6 shows positioning result of the system with this filter implemented. The map here is zoomed in with a zoom scale 30, to give detailed positioning scatters. The numerical positioning results are:

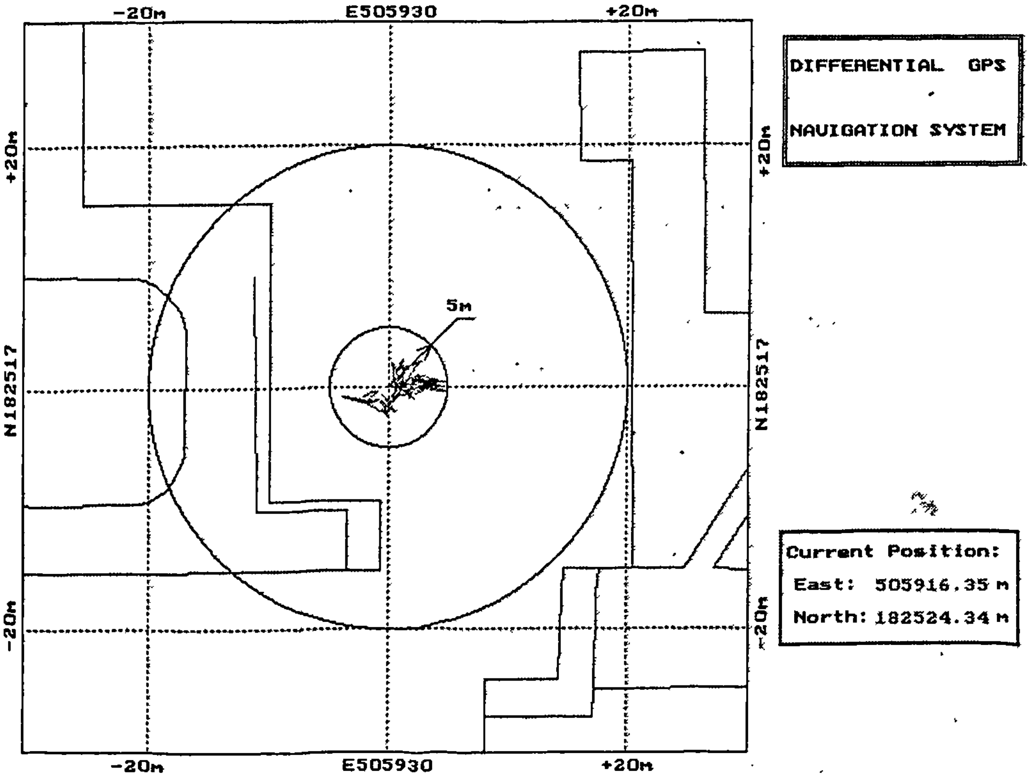


Fig. 7.6 System Positioning Results with Low-pass Filter Applied to Pseudo-Ranges in the DGPS Reference Station

x (mean) = 505931.8 m; σ_x (Standard deviation) =1.6 m

y (mean) = 182517.0 m σ_y (Standard deviation) =1.0 m

and

$$\delta s = \sqrt{(2\sigma_x)^2 + (2\sigma_y)^2} = \sqrt{(2\times 1.6)^2 + (2\times 1.0)^2} = 3.4 \text{ (m)}$$

Clearly, the system positioning accuracy is increased by about 1m, compared with the result obtained in **Section 7.1.2**.

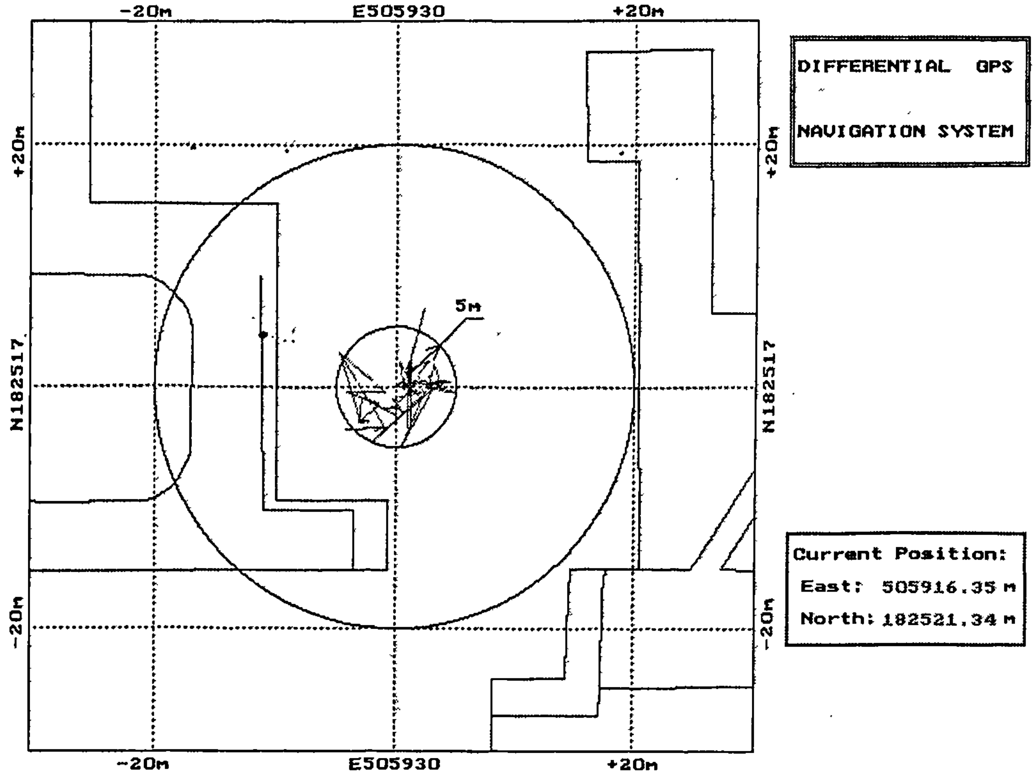


Fig. 7.7 Zoomed in Positioning Results of Fig. 7.2

As a graphical comparison, **Fig 7.7** shows the zoomed positioning results originally shown in **Fig 7.2**, where no filter is used in the DGPS Reference Station. From these two figures, it can be clearly seen that, with the proper filter implementation, the scatter of the positioning results becomes more convergent, and the jitters become smaller.

Repeated experiments showed the same positive effect of the filter. **Table 7.3** shows the static positioning results of the system when the mobile navigation unit were placed exactly at the same places as A, B, C, D and E as shown in **Table** 7.1. By the comparison of two tables, it can be seen that the system positioning accuracy are generally increased by about 1m.

From **Table 7.3**, it can also be seen that the system positioning accuracy is within the range of 3.3m to 4.7m with a statistical probability of 95.44 %. According to

Places			Positioning Results		
	x(mean), m	y(mean), m	σ_x, m	σ_y, m	$\delta s = \sqrt{(2\sigma_x)^2 + (2\sigma_y)^2}$, m
A	505921.3	182532.1	1.6	1.1	3.9
B	505844.4	182587.1	1.8	1.3	4.4
C	505831.4	182430.8	1.7	1.6	4.7
D	505948.5	182511.1	1.7	1.3	4.3
E	505952.6	182522.4	1.2	1.1	3.3

Table 7.3 Static Positioning Results of the System with Digital Filter Applied to the Pseudo-Ranges

this, a figure of 4m is used to describe the finally achieved system positioning accuracy.

During the research, it is also noticed that how this filter is implemented needs careful consideration. If the measured pseudo-ranges are too heavily smoothed, the system dynamic performance will suffer. This means the system may not track satellites properly. This is especially crucial when the available GPS satellites in the sky change, so that DGPS Reference Station needs to track newly arisen satellites [Liu, L. 1997].

7. 4 Summary

In this chapter, the performance of the constructed DGPS Reference Station is discussed firstly. It is a twelve-channel reference station and can track all the GPS satellites available in the sky. The differential correction messages are successfully calculated and encoded into RTCM-104 format, these messages are then transmitted to the mobile GPS receiver in real time.

After that, the performance of the whole navigation system is discussed. This includes the route searching and planing algorithm and both static and dynamic system performances. In the experiment, the optimum route created by the route searching and planing algorithm successfully links the set off point and the desired destination. Repeated experiments showed the system has a static positioning accuracy of about 4m with a probability of 95.44 %. The system dynamic performance is also tested, and it worked well in the experiment which was done in a low dynamic situation.

Finally, the impact of the digital filtering on the system performance is discussed. It is found that the digital filter applied to the measured pseudo-ranges plays a more important role than the others and can increase the system positioning result by about 1m.

CHAPTER EIGHT: CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

8.1 Conclusions

After four years research and countless effort, the proposed Intelligent DGPS Navigation System is finally completed and fully operational. All the objectives envisaged in **Section 1.3** have been fulfilled and the final achievements of the project can be summarized as follows:

- A prototype satellite navigation system with a real-time system positioning accuracy of 2-4 m has been designed and built by applying differential technology to the Global Positioning System (GPS). The constructed system has the basic navigational functions and demonstrates the availability of the latest technologies. The system can be either directly used or further developed to suit the needs of a specific application.

- A DGPS Reference Station has been designed and constructed and the station is fully operational on the campus of Brunel University. Within the system software, a DGPS Reference Station mathematical model was developed and relevant differential algorithms were designed. Since none of the literature in the public domain disclosed the details of the model, this model was formulated based on the basic principle of differential technology. An important assumption "the sum of the differential corrections is zero" was made to make the equations solvable. In the constructed DGPS Reference Station, this mathematical model calculates the differential corrections successfully, and these differential corrections are then encoded into the RTCM-104 standard format, and transmitted to the mobile GPS receiver in real time.

- Characteristics of the system components of the DGPS Reference Station were analyzed by using phase locked loop (PLL) and digital signal processing theories. Different parameters of the GPS L1 carrier signal tracking loop were tested to improve reference station's signal tracking ability. A group of the parameters under which the L1 carrier signal pull-in is quick and the system is steady has been obtained.

- Digital filters were applied to different measurements of the DGPS Reference Station to examine the impact of digital filtering on the system performance. These measurements included measured pseudo-ranges, differential corrections and the system clock offset. It was found that the digital filter applied to the measured pseudo-ranges plays a more important role than the others. The applied filter effectively smoothes the differential corrections. As a result, the scatter of the positioning results became more convergent, the jitters became smaller and the system positioning accuracy was increased by about 1m.

- Besides the above flexibilities which are needed for the research project, the constructed DGPS Reference Station has all the standard functions of a DGPS Reference Station. This means that the differential GPS correction messages transmitted by the Brunel University DGPS Reference Station can also be used by external GPS receivers to improve their positioning results.

- A digital map covering the campus of Brunel University was constructed by using four tiles of the digital map database 'Land_Line' from the Ordnance Survey. The map features contained in the Land_Line were extracted, and coordinates of the map features were converted from the WGS 84 format to British National Grid. After that, the map was combined with the output of the SV6 GPS receiver, so that the current position of the user can be found in the map surrounded by navigational information.

- Map handling algorithms have been designed to utilize the digital map effectively. As the designed map system is unique to the research project, and the required map handling functions are specific, these map handing algorithms could not be adopted from the commercially available software. The designed map handling functions include: choosing the central place of the map, map zooming in and out control and the output of the numerical real-time positioning results.

- A low-power UHF radio link of frequency 456 MHz has been established to transmit RTCM-104 differential correction messages, and the signal coverage is found to be about 5 km in radius. This coverage is good enough for the research project. If a large coverage is needed, this can be achieved either by using a high-power radio transmitter, or by utilizing other radio data links such as mobile cellular network (see **Section 8.2.5.)**.

- A simple route searching and planing algorithm has been designed to demonstrate the potential application of the system. Since route searching and planing algorithm depends much on the adopted digital map system, no published algorithms could be directly adopted in this project. The designed route searching and planing algorithm is based on the detection of the boundary of map features. In the system, the algorithm worked well, though more experiments are needed to find out the limitations when the algorithm is used in more complex environment.

- The system integration was achieved by the design of the mobile navigation unit and the combination of this mobile navigation unit with the constructed DGPS Reference Station. The final system consists of a DGPS Reference Station, a UHF radio data transmitter, a mobile GPS receiver, a digital map system, a route searching and planing algorithm and a UHF radio data receiver. Field trials have been carried out to test the system static and dynamic performances. Repeated experiments showed that the positioning accuracy for the whole navigation system has been about 4 m. The dynamic performance was also tested when the mobile navigation unit was moved along a designed route while the real-time navigation results were shown on the digital map. Although this experiment was carried out in a low dynamic situation, it is expected the system would work well in most low to medium dynamic situations.

8.2 Suggestions for Further Research

By the completion of this research project, a versatile DGPS Reference Station and Navigation System research platform is available. It is felt that, based on this platform, further research can be effectively carried out and possible applications exploited. It is also felt that the system positioning accuracy could be increased further, if some system components are improved and further optimized.

8.2.1 Further Improvements of the System

Further improvements of the system implementation may include:

1. Have the DGPS Reference Station GPS antenna location exactly surveyed rather than using the average of two days accumulation of a GPS receiver output (see **Section 7.1.1.**), so that reference position can be more accurate.

2. Use a faster PC, for example, Pentium 200 to host the DGPS Reference Station to provide more computing power. During the research, it was found that as a real-time system, the computing unit has been stretched to the limit and some tasks had to be given low priorities to save the computing power to more urgent tasks. If a faster PC is used, these tasks will get more computing power. By using a faster host PC, it will also reduce the cycle periods of various digital loops. According to the digital signal processing theory, this reduced cycle periods will increase the Nyquist frequency. As a result, the digital filter function can be effectively increased.

3. Using higher order digital filters in the DGPS Reference Station. Due to the limitation of the computing power, only first-order filter was applied to the measured pseudo-ranges. Furthermore, digital filters need to be applied to both DGPS Reference Station and the mobile GPS receiver, so that the GPS receiver's performance can match the performance of the DGPS Reference Station.

8.2.2 To Compare the DGPS Reference Station Mathematical Model with Others

Compare the developed DGPS Reference Station mathematical model with the others contained in the commercially available DGPS Reference Station if possible. Based on this, the corresponding differential correction calculation algorithms may be improved. Extensive literature search had been carried out to locate any such information in the public domain and none has been found. This comparison may only be achieved by collaborating with the relevant commercial companies, such as Trimble, Ashtech etc. that are current marketing DGPS Reference Station.

8.2.3 To Adopt an Atomic Clock to DGPS Reference Station

From **Eq. (3-32),** it can be seen that the reference station's clock offset is one of the major unknowns of the DGPS Reference Station mathematical model. From **Section 3.3.3,** it can also be seen that the main function of the navigation loop is to update this offset. The amplitude of the offset itself is not important, because it will be finally composted by the navigation loop. The important point is the drifting rate of the clock. As long as this drifting exists, the offset will be always there, and the existence of this offset will affect the amplitude of the corrections (**Eq. (3-32)**).

In the DGPS Reference Station, the system clock is an ordinary quarts oscillator adopted by the GPS Builder$^{\text{TM}}$, and it is found that its drifting rate changes with different quart crystals. It is envisaged that if an accurate atomic clock is used in the DGPS Reference Station, the system performance can be improved significantly.

8.2.4 To Improve the Route Searching and Planing Algorithm

The designed route searching and planing algorithm in the system is a simple one to demonstrate the potential application of the system. This algorithm needs to be improved further, so that it can work out the desired optimum route in a more complex environment. This algorithm is important, if the system is used in an application that guides the user to the destination automatically.

8.2.5 Using Cellular Mobile Telephone Date Link to Replace UHF Transceivers

During the research, it is felt that with the rapid increase of the coverage of the cellular mobile telephone, the cellular phone technology could be a perfect replacement of the UHF transceivers adopted by the system.

Basically, the cellular telephone can be used as a bi-directional data link to transfer the digital data as well as an audio link to provide voice communication. If the DGPS is combined with the cellular network, firstly, the DGPS differential correction messages can be sent to the user by the mobile phone. After the current position of the user is obtained by the mobile GPS receiver, this position can be possibly sent back to a specially established navigation service center to process, rather than being processed on the mobile user side. In this circumstance, at the navigation center, the current position of the mobile will be combined with the digital map, so that the necessary navigational information around this current position can be obtained and shown on a computer screen. The cellular telephone can be finally used as an audio link through which the trained navigation staff in the service center can guide the user to their desired destinations by the voice conversation.

Based on this idea, a British patent application (Application No: 96-15771.4) has been filed.

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APPENDIX I: PHASE LOCKED LOOPS THEORY APPLIED TO THE DGPS REFERENCE STATION

Phase locked loops (PLLs) are of particular importance in the design of GPS receiver and DGPS Reference Station. The core of the carrier tracking loop in the DGPS Reference Station is a Costas loop, a special PLL. In order to have a thorough understanding of the device, hence the principle of DGPS reference station, the basic theory and characteristics of the phase locked loops are reviewed below.

An elementary phase locked loop consisting of a phase detector, a low-pass loop filter, and a voltage controlled oscillator VCO is illustrated in **Fig. A1.1**.

The majority of conventional PLLs perform one of the three functions:

$N = 1$, the PLL is a tracking filter,
$N > 1$, the PLL is a frequency multiplier,
$N < 1$, the PLL is a frequency synthesiser

In DGPS Reference Station, PLL is used to track the GPS signal, therefore from now on, we assume $N = 1$, and in this case: $u_2(t) = u_3(t)$.

A PLL is basically a servo system controlling the phase θ_2 of its output signal $u_2(t)$ in such a way that the phase error between output phase θ_2 and reference phase θ_1 of the input signal $u_1(t)$ reduces to a minimum. The exciting function applied to the reference input will have to be expressed as a variation of the reference phase θ_1 and not as a variation of the input voltage and current. The transient response of the PLL will then be obtained as variation of output phase θ_2.

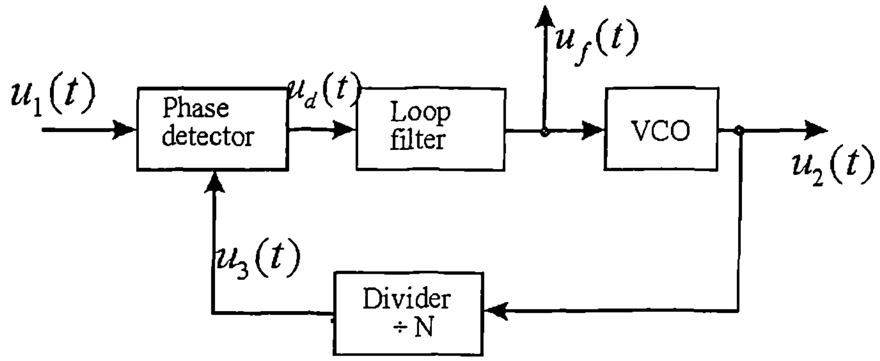


Fig. A1.1 An Elementary Phase Locked Loop

Assume that the input signal of a PLL is a sine-wave signal of the form:

$$u_1(t) = U_1 \sin[\omega_0 t + \theta_1(t)] \qquad \text{(A1-1)}$$

and the output of the VCO is:

$$u_2(t) = U_2 \cos[\omega_0 t + \theta_2(t)] \qquad \text{(A1-2)}$$

The choice of a cosine instead of a sine function is arbitrary. If a linear PLL is operating at its centre frequency, there is a phase shift of $\pi/2$ between the input and output signals. If these two signals are defined as a sine and cosine function respectively, the phase error $\theta_e = \theta_I - \theta_2$ then becomes exactly zero.

The phase detector used in PLLs can be of various forms. The property of a specific phase detector will affect the performance of PLL greatly. As we only discuss the property of PLL used in the DGPS Reference Station, therefore, the discussion is focused to the specific phase detector used there. In this case the phase detector is a digital mixer (multiplier) with a gain of k. Its output $u_d(t)$ is of the type:

$$u_d(t) = k \times u_1(t) \times u_2(t) = \frac{kU_1U_2}{2}[\sin(\theta_1 - \theta_2) + \sin(2\omega_0 t + \theta_1 + \theta_2)] \qquad \text{(A1-3)}$$

Eq. (A1-3) reveals that phase detector's output $u_d(t)$ is a superposition of a dc and an ac component. The ac component will be almost completely filtered out by the loop filter applied, thus only the dc or the average component of $u_d(t)$ needs to be considered, which is given by:

$$u_d(t) = K_d \sin\theta_e \qquad \text{(A1-4)}$$

Where $\theta_e = \theta_1 - \theta_2$ is the phase error and $K_d = \frac{kU_1U_2}{2}$ is the phase detector gain.

In classical control theory, the dynamic performance of a system is generally discussed in the complex frequency domain by applying the Laplace transform. The Laplace transform can be only used for linear system. However, as shown in **Eq. (A1-4),** the phase detector used in the system is a sine function and that exhibits nonlinearity. This problem can be solved by assuming that the PLL system stays locked at all times and that the phase error θ_e remains relatively small. This in practice is indeed the case of DGPS Reference Station, and as the result, $\sin\theta_e \approx \theta_e$, therefore:

$$u_d(t) = K_d \times \theta_e \qquad \text{(A1-5)}$$

Fig. A1.2 shows a linearized block diagram of the PLL in complex frequency domain.

The three functional blocks of the PLL have the following transfer functions:

Phase detector: $$\frac{U_d(s)}{\theta_e(s)} = K_d \qquad \text{(A1-6.a)}$$

Loop filter: $$\frac{U_f(s)}{\theta_d(s)} = F(s) \qquad \text{(A1-6.b)}$$

VCO: $$\frac{\theta_2(s)}{U_f(s)} = \frac{K_0}{s} \qquad \text{(A1-6.c)}$$

The transfer function of Phase Detector follows directly from **Eq. (A1-5).** The transfer function of Loop Filter depends on what sort of filter is used in the PLL, and at present it remains undetermined. The transfer function of VCO also depends on the property of the VCO employed. In most cases, and it is also the case in DGPS reference station, a linear VCO is used, and the output ω_2(t) of the VCO is given by:

$$\omega_2(t) = \omega_0 + K_0 u_f(t) \qquad \text{(A1-7)}$$

Where ω_0 is the centre angular frequency of the VCO and K_0 is the VCO gain.

As the phase of a signal is equal to the time integral of angular frequency

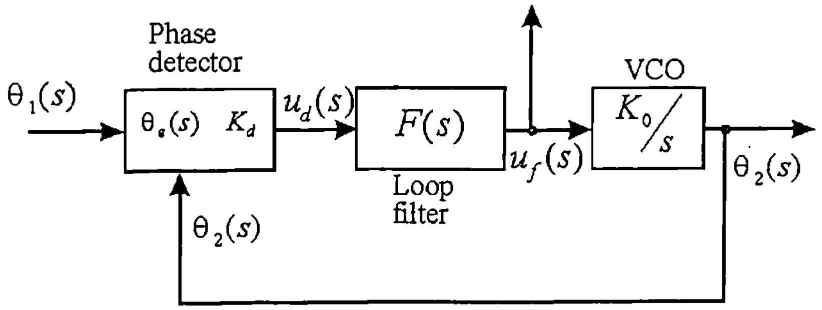


Fig. A1.2 The Block Diagram of the PLL in Complex Frequency Domain

$$\int_0^t \omega_2(t)dt = \int_0^t (\omega_0 + K_0 u_f(t))dt = \omega_0 t + K_0 \int_0^t u_f(t)dt \tag{A1-8}$$

Comparing **Eq. (A1-2)** with **Eq. (A1-8)**, and applying the Laplace transform,

$$\theta_2(s) = \frac{K_0 \times U_f(s)}{s} \tag{A1-9}$$

which immediately leads to the transfer function of VCO given in **Eq. (A1-6 .c)**.

From **Eqs. (A1-6)**, both $\theta_e(s)$ and $\theta_2(s)$ can be expressed as the function of $\theta_1(s)$,

$$\theta_2(s) = \theta_1(s)\frac{K_0 K_d F(s)}{s + K_0 K_d F(s)} \tag{A1-10}$$

$$\theta_e(s) = \theta_1(s)\frac{s}{s + K_0 K_d F(s)} \qquad \text{(A1-11)}$$

From the above, both phase and error transfer functions can be derived.

Phase transfer function:

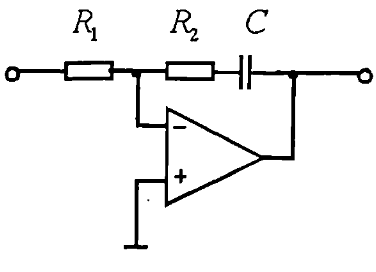
$$H(s) = \frac{\theta_2(s)}{\theta_1(s)} = \frac{K_0 K_d F(s)}{s + K_0 K_d F(s)} \qquad \text{(A1-12)}$$

and error transfer function:

$$H_e(s) = \frac{\theta_e(s)}{\theta_1(s)} = \frac{s}{s + K_0 K_d F(s)} \qquad \text{(A1-13)}$$

From these two transfer functions it can be seen that for a given Phase detector and the VCO of the PLL, the characteristics of the PLL only depends on the property of loop filter. The order of the loop filter is used to calculate the order of the PLL. If the dynamic response of a system is described by an *n*th-order differential equation, the order of the system is said to be *n*. The denominator of the corresponding transfer function is then an *n*th-order polynomial in *s*. From **Eq. (A1-12)** and **Eq. (A1-13)** it can be seen that ***the order of the PLL system is equal to the order of the loop filter plus 1***.

In the DGPS Reference Station, the actual loop filter used is a digital recursive filter and is of the first-order active-lag type, the one that is commonly used in phase locked loops. The phase locked loop used in this application is a second order system. The details of the construction of this digital filter which has the first-order active-lag type property is discussed in Section **3.3.3.** Analogue filter of this type is usually constructed with an operational amplifier, two resistors and a capacitor connected in a specific way shown in **Fig. A1.3.**



$T_1 = R_1C$
$T_2 = R_2C$

Fig. A1.3 First-order Analog Active-lag Filter

For the analogue active-lag filter, it may have an unavoidable hardware gain factor which is often denoted as K_A. In the digital world we can always conveniently set $K_A=1$ simply by not scaling the calculations, so from now on we assume the active filter gain is always equal to one. For a first-order active-lag type filter, the filter's open-loop transfer function is:

$$F(s) = \frac{T_2 s + 1}{T_1 s} \qquad \text{(A1-14)}$$

where T_1 and T_2 are two time constants that completely characterise active-lag loop filters. Stable filters of this type must obey the rule $T_1 > T_2 > 0$. (say why)

Now we can combine **Eqs. (A1-14)** and **(A1-12)** together to find the clear expression of the transfer function of the second-order PLL, and we have:

$$H(s)=\frac{K_0K_d(sT_2+1)(T_1+T_2)}{s^2+s(\frac{1+K_0K_dT_2}{T_1+T_2})+\frac{K_0K_d}{T_1+T_2}} \qquad \text{(A1-15)}$$

We can also write Eq. (A1-15) in a normalised form:

$$H(s)=\frac{s\omega_n(2\zeta-\frac{\omega_n}{K_0K_d})+\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2} \qquad \text{(A1-16)}$$

Where $\omega_n=(\frac{K_0K_d}{T_1+T_2})^{1/2}$ is the natural frequency of the PLL. However, the natural frequency ω_n must never be confused with the centre frequency ω_0 of the PLL. And $\zeta=\frac{1}{2}(\frac{K_0K_d}{T_1+T_2})^{1/2}(T_2+\frac{1}{K_0K_d})$ is the damping factor.

From **Eq. (3-16),** we can see that besides ω_n and, only one further parameter K_0K_d is left. The term K_0K_d is called the loop gain. Usually the loop gain $K_0K_d \gg \omega_n$,then the phase transfer function can be approximated as:

$$H(s)=\frac{2s\xi\omega_n+\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2} \qquad \text{(A1-17)}$$

Similarly, from the **Eq. (A1-13)** we can finally get the error-transfer function:

$$H_e(s) = \frac{s^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \qquad \text{(A1-18)}$$

If we discuss the properties of these two transfer functions further, we will find some other parameters of the PLL such as:

Pull-in range $\Delta\omega_p$;

$$\Delta\omega_p = \frac{4}{\pi}\sqrt{2\zeta\omega_n K_0 K_d - \omega_n^2} \qquad \text{(A1-19)}$$

Pull-in time T_p from initial frequency error of $\Delta\,\omega_0$ (rad/sec);

$$T_p = \frac{\pi^2 \Delta\omega_0^2}{16\zeta\omega_n^3} \qquad \text{(A1-20)}$$

Pull-out range $\Delta\omega_{po}$ (frequency step which causes the PLL unlock);

$$\Delta\omega_{p0} = 1.8\omega_n(\zeta + 1) \qquad \text{(A1-21)}$$

These parameters are important and useful for the design of the PLL, because each of them describes one of the different characteristics.

APPENDIX II: DGPS REFERENCE STATION SOFTWARE MODULE AND SUBROUTINE CONTENTS

Module:	**Procedure:**	**Procedure Function and the Prototype:**
BEEP.C	TBeep	Take beep requests out of the beep request queue, initiate beeps by communicating with the correlator ISR, then suspend awaiting more beep requests. void TBeep(void)
BEEP.C	Beep	This is TBeep's request-generating routine. void Beep(unsigned FreqHzunsigned)
BORLAND.C	cbrk_handle	Receives control when the user presses CTL-BREAK. int cbrk_handler(void)
BORLAND.C	Suppress Cursor	Saves the PC's current cursor type setting, then turns it off. A blinking cursor is inappropriate for displays which are updated in a random access fashion. void SuppressCursor(void)
BORLAND.C	Restore Cursor	Restores the previously saved PC cursor type setting. Call this routine at termination to restore the previously active cursor on the CRT display. void RestoreCursor(void)
BORLAND.C	Check point	Record a checkpoint to indicate that a task did something for debugging purpose. Void Checkpoint(char *ProcName, unsigned UserCheckpoint)
BORLAND.C	Comment	Record a comment regarding something that a task did. void Comment(char * CommentString)
BORLAND.C	Dump Check points	Dump a log of saved checkpoints and terminate execution. void DumpCheckpoints(void)
BORLAND.C	FPERROR	Coprocessor exception handler. void FPERROR(int code, int subcode)
BORLAND.C	SetFPErr Handler	This sets the Borland floating point exception handler to call FPERROR, void SetFGErrHandler(void)
DISPLAY.C	TDisplay	Task root for TDisplay, Update the station console display. void TDisplay (void)
GPSRAM.C		This module contains all the global variables and data structures used by the system software.
MAIN.C	main	Root of task MAIN, program entry point.

		void main (void)
MAIN.C	configDGPS	Set the operating parameters of the reference station. void configDGPS(void)
MAIN.C	SaveAlm	Save almanacs, ionospheric/UTC models, and current ephemerides to a disk file. void SaveAlm(char *fname)
MAIN.C	iniGP1020	Initialize data structures used by the GP1020 correlator interrupt, then perform correlator reset and initialization. void iniGP1020(void)
MAIN.C	CompareInt	Auxiliary function to compare two integers. The comparison is reverse because it is used to sort a table of satellites into descending order according to their elevation angles. void CompareInt(const void *a, const void *b)
MAIN.C	NextSV2Srch	NextSV2SRCH returns the PRN number of the next satellite to be searched for in the Cold Start mode. int NextSV2Srch(void)
MAIN.C	DGPSBLDR	Initialize the DGPS Reference Station hardware and software, then initiate multitasking and run the program until it is terminated. void DGPSBLDR(void)
MAIN.C	predall	Predict Doppler, elevation, azimuth, and deterministic corrections for all satellites having ephemeris or almanac data. void predall(void)
MAIN.C	cmdget	Get and process the next character of a command line void cmdget(void)
MAIN.C	cmdproc	Recognize and process command void cmdproc(void)
MAIN.C	keyboard	Call cmdget to get and process command characters from the keyboard or a disk file. void keyboard(void)
MAIN.C	track	The caller periodically performs a satellite selection process which decides which satellites should be tracked and which channels they should be assigned to. This procedure updates the SV's Doppler prediction in the channel control block, then if necessary switches the channel to a new satellite. void track(int chan, int newsv, double dopp)
MATHSUBS.C	square	Return the square of the argument. double square(double x)
MATHSUBS.C	invP	Compute the deviation such that the area under a standard Gaussian probability density function between -infinity and that deviation is the given probability p.

		double InvP(double p)
MATHSUBS.C	gjinv	Invert an n x n matrix using Gauss-Jordan elimination with column shifting to maximize pivot elements. int gjinv(int n, double cmat[ ])
NAV.C	mzdiff	Return the difference, in seconds, between an RTCM-104 modified Z count and a specified GPS time. double mzdiff(double gsec, int mzcount)
NAV.C	omtrue	Compute correction for a SV int omtrue(int sv, double obssec, double PR, double TruePR,double Correc)
NAV.C	Dnavigate	Perform one navigation cycle. Use measured observation to update system clock model and navigation states. int Dnavigate (obsstruc *obs)
POSTIM.C	curTIC	Get the current TIC counter value. void curTIC (unsigned long *ctic)
POSTIM.C	Rcvrtm	Return the station time to a TIC void Rcvrtm(unsigned long curTIC, int *gwk, double *gsec)
POSTIM.C	GpsTime	Return GPS to a TIC void GpsTime(unsigned long curTIC, int *gwk, double *gsec)
POSTIM.C	llhxyz	Convert WGS 84 to ECEF. void llhxyz(double lat, double lon, double hgt, double *x, double *y, double *z);
POSTIM.C	xyzllh	Convert ECEF to WGS 84. void xyzllh(double x, double y, double z, double *lat, double *lon, double *hgt);
POSTIM.C	lldegmin	Convert radian to degrees. void lldegmin(double lat, double lon, char latdegmin[], char londegmin[])
POSTIM.C	CvtPosStr	Convert degrees to radian. int CvtPosStr(char *s, double *lat, double *lon, double *hgt)
PROCSBF.C	TProSbf	Root of task TProSbf. void TProcSbf(void);
PROCSBF.C	procsbf	Process GPS navigation message subframe & update database. void procsbf(int sv, unsigned long *g, unsigned long dataTIC)
RTCM.C	TRTCM	Root of task of TRTCM void TRTCM(void)
RTCM.C	message1	Encode RTCM-104 message type 1. void message1 (void)
RTCM.C	message2	Encode RTCM-104 message type 2. void message2 (void)

RTCM.C	message3	Encode RTCM-104 message type 3. void message3 (void)
RTCM.C	message 16	Encode RTCM-104 message type 16. void message16 (void)
RTCM.C	emit	Emit RTCM-104 messages void emit (void)
RTCM.C	RTCM	Process the next byte of RTCM data in 6-0f-8 format. void RTCM (int newbyte)
RTCM.C	rtcmproc	Process the next bit of an RTCM-104 message void rtcmproc (void)
RTCM.C	hdradder	Add two 30-bit words to messages. int hdradder (unsigned long w1, unsigned long w2)
RTCM.C	cmaybe	Complement message bits of RTCM format. unsigned long cmaybe (unsigned long w)
RTEXEC.C	InitTasks	Allocate stacks for each task from the far heap. Initialize all the tasks preassigned in the data structure TCB. void InitTasks(void);
RTEXEC.C	Exec_ Suspend Function	Suspend the calling task. void interrupt far Exec_Suspend_Function(void);
RTEXEC.C	Suspend	This is an interface between Exec_Suspend_Function and calling tasks. void Suspend(unsigned SuspTics);
RTEXEC.C	Exec_ Activate_ Function	Activate a specified task. void interrupt far Exec_Activate_Function(void);
RTEXEC.C	Activate	This is an interface between Exec_Activate_Function and calling tasks. void Activate(char *TaskName);
RTEXEC.C	quit_ dgps	This routine quits the application in a graceful way. It closes files, restores the preexisting interrupt environment, restores the previous cursor mode, and returns all memory blocks that may have been allocated. void quit_dgps(void);
RTEXEC.C	get_key	This procedure returns a key code from the keyboard. int get_key(void);
RTEXEC.C	output	Writes a character string to the CRT display at a specified row/column position void output(int col, int row, char *str);
RTEXEC.C	outputch	Writes a single character to the CRT display at a specified row/column position. void outputch(int col, int row, char ch);
RTEXEC.C	clr2eol	Clears the CRT from a specified position to the end of line. void clr2eol(int col, int row)

RTEXEC.C	GPISR	GP1020 correlator interrupt service routine (505 us). void far interrupt GPISR( );
SERIAL.C	initserial_port	Initialize serial port (COM1 or COM2) void initserial_port (int portnum)
SERIAL.C	restore_serialint	Restore serial port (COM1 or COM2) void restore_port (int portnum)
SERIAL.C	new serial_int	Send a character to serial port from the circular buffer. void far interrupt newserial_int (void)
SERIAL.C	write_serial	Write a character to serial output port (unbuff). int write_serial (int c)
SERIAL.C	read_buffer	Read a character from the buffer. int read_buffer (int c)
SVCALC.C	svelv	Compute a satellite's elevation, azimuth, Doppler, and deterministic pseudorange corrections. This calculation will be based on ephemeris data if it is available, otherwise on almanac data if it is available. void svelv (int sv, int wk, double sec, double t[3][3], double x, double y, double z, double obslat, double obslon, double obshgt)
SVCALC.C	svalm	Compute SV position from time and almanac data. void svalm(int sv, int wk, double sec, double *x, double *y, double *z)
SVCALC.C	sveph	Compute SV position from time and ephemeris data. void sveph(ephstruc *es, double sec, double *svirel, double *X, double *Y, double *Z, double *Xdot, double *Ydot, double *Zdot, double *Xddot, double *Yddot, double *Zddot)
SVTRACK.C	pargen	Check the parity bits in a 30-bit GPS word. int pargen(unsigned long gpsword)
SVTRACK.C	form10	Convert the 364-bit buffer to 12 30-bit GPS words. int form10(unsigned *b, unsigned long *g)
SVTRACK.C	procdbit	The 50 Hz navigation message bit stream is demodulated by the operation of the Costas loop. Data bits are shifted into a 364-bit data buffer. This buffer will accommodate the 300 bits of a subframe, plus the 60 bits which constitute the header of the next subframe. In order to make consistency checks, a subframe is not emitted to the parsing task until the header of the next subframe has been decoded and found to be consistent. void procdbit(chanstruc _ds *CHPTR, unsigned dbit, unsigned _20ms_epoch)
SVTRACK.C	Proc Accum	ProcAccum operates on accumulated data stored in buffers (in each channel's control block) by the

	·	BufferAccum process void ProcAccum(register chanstruc _ds *CHPTR)
SVTRACK.C	Take Meas	Read the correlator to obtain measurements that became ready at the instant of the last TIC. void TakeMeas(register chanstruc _ds *CHPTR)
SVTRACK.C	Buffer Accum	This routine is called for each SV for which accumulated data has become available. Read early and late I, Q accumulations. The combined I, Q samples are inputs to a Costas loop which is updated to acquire or maintain carrier phase lock. void BufferAccum(register chanstruc _ds *CHPTR)
SVTRACK.C	SVTRACK	Routine to process correlator interrupt. void SVTRACK(void)

APPENDIX III: MOBILE NAVIGATION UNIT CONTROL SOFTWARE CONTENTS

Module:	**Module Functions:**
Sv6.c	Program entry point. It contains the main routine for SV6, and the first level routines.
Tsip_utl.c	User interface routines.
Tsip_cmd.c	Command generator. The TSIP command is generated here, and the keystroke from the keyboard of the host PC is explained into relevant commands.
Tsip_rpt.c	Report interpreter. Reports required either by the relevant commands or the auto-generated by the receiver are generated here, and shown on the screen.
Tsip_alm.c	Take almanacs from the file and put them into receiver to find available SVs in the sky.
Tsip_ifc.c	Standard command/report interface for TSIP.
Map.c	Digital map reproducing and map handling routines.
Wgs_grid.c	Routines used to convert the output of the SV6 in WGS 84 coordinate into British National Grid. The output of the SV6 is then re-directed in the digital map rather than the text screen. In this way, the GPS receiver is combined with the digital map to form the navigation system.
Routeplan.c	Routines for route searching and planning algorithms.
Filelog.c	Log system positioning results into a file in British National Grid format for later analysis.

APPENDIX IV: SYMBOLS AND DEFINITIONS USED IN MAP COORDINATE CONVERSION

a	major semi-axis of ellipsoid	m
b	minor semi-axis of ellipsoid	m
e	eccentricity	-
e^2	$=\frac{a^2-b^2}{a^2}$	-
n	$=\frac{a-b}{a+b}$	-
v	$=\frac{a}{(1-e^2\sin^2\phi)^{1/2}}$	m
ρ	$=\frac{a(1-e^2)}{(1-e^2\sin^2\phi)^{3/2}}=\frac{v(1-e^2)}{(1-e^2\sin^2\phi)}$	m
η^2	$=\frac{v}{\rho}-1$	-
ϕ	latitude of a point	rad
λ	longitude of a point	rad
H	height of a point above ellipsoid	m
ϕ_0	latitude of true origin	rad
λ_0	longitude of true origin	rad
E_0	grid eastings of true origin	m
N_0	grid northings of true origin	m
E	grid eastings	m
N	grid northings	m
y	$E-E_0$	-
x	$N-N_0$	-
F_0	scale factor on the central meridian	-
F	scale factor at a point	-
P	$\lambda-\lambda_0$	-

APPENDIX V: GPS GLOSSARY USED IN THE THESIS

2-D, 3-D: Refers to two-dimensional and three-dimensional positions. A 2-D position fix provides latitude and longitude. Altitude is assumed to be fixed. Only three satellites are required to provide a 2-D position with a user-supplied altitude. A 3-d position provides the altitude in addition to LAT/LOG and requires four satellites.

Almanac: Data transmitted by a GPS satellite which includes orbit information on all the satellites, clock correction, and atmospheric delay parameters. These data are used to facilitate rapid SV acquisition. The orbit information is subset of the ephemeris data with reduced accuracy.

C/A code: The Coarse/Acquisition code modulated onto the GPS L1 signal. This code is a sequence of 1023 pseudo-random binary biphase modulations on the GPS carrier at a chipping rate of 1.023 MHz, thus having a code repetition period of one millisecond. This code was selected to provide good acquisition properties.

Carrier: A radio wave having at least one characteristic (such as frequency, amplitude, phase) which may be varied from a known reference value by modulation.

Carrier frequency:

The frequency of the unmodulated fundamental output of a radio transmitter. The GPS L1 carrier frequency is 1575.42 MHz.

Channel: The receiver hardware that is required to lock to a satellite's signal, make the range measurements and collect data from the satellite.

Chip: The length of time transmit either a zero or a one in a binary pulse code.

Chip rate: Number of chips per second (e.g. C/A code's chip rate is 1.023 MHz).

Clock offset: Constant difference in the time reading between two clocks.

DGPS: Differential GPS

Doppler shift: The apparent change in frequency of a received signal due to the rate of change of the range between the transmitter and receiver.

Earth-centred earth-fixed (ECEF):

Cartesian coordinate system where the X direction is the intersection of the prime meridian (Greenwich) with the equator. The vectors rotate with the earth. Z is the direction of the spin axis.

Eccentricity: The ratio of the distance from the centre of an ellipse to its focus to the semi major axis.

Elevation: Height above mean sea level. Vertical distance above the geoid.

Elevation Mask Angle:

That angle below which satellites should not be used. This varies according to the task and location, e.g. for land surveying it is normally set to 15 degrees to avoid interference problems caused by buildings, trees and multipath effects. For marine navigation on the other hand, the angle can be lowered to 5 degrees. Please note that, because of the greater thickness of the ionosphere and troposphere travelled by the signal at low angles together with the increased distance of the satellite, the signal is weaker.

Ellipsoid: In geodesy, unless otherwise specified, a mathematical figure formed by revolving an ellipse about its minor axis. It is often used interchangeably with spheroid. Two quantities define an ellipsoid; these are usually given as the length of the semimajor axis, a, and the flattening, f=(a-b)/a, where b is the length of the semiminor axis.

Ellipsoid height:

The measure of vertical distance above the ellipsoid. Not the same as elevation above sea level. GPS receivers output position-fix height in the WGS-84 datum.

Ephemeris: A list of accurate positions or locations of a celestial object as a function of time. For GPS navigation purposes the broadcast ephemeris is always used and updated every hour. It is sent as a set of 8 elements of the Keplerian orbit equation and used by the receiver to compute the instantaneous position of that satellite.

Geodetic datum:

A mathematical model designed to best fit part or all of the geoid. It is defined by an ellipsoid and the relationship between the ellipsoid and a point on the topographic surface established as the origin datum. This relationship can be defined by six quantities, generally (but not necessarily) the geodetic latitude, longitude, and the height of the origin, the two components of the deflection of the vertical at the origin, and the geodetic azimuth of a line from the origin to some other point. The GPS uses WGS-84 datum.

Geoid: The actual physical shape of the Earth which is hard to describe mathematically because of the local surface irregularities and sea-land variations. In geodetic terms it is the particular equipotential surface which coincides with mean sea level, and which may be imagined to extend through the continents. This surface is everywhere perpendicular to the force of gravity.

GPS: Global Positioning System

GPS time: The length of the second is fixed and is determined by primary atomic frequency standards. Leap-seconds are not used, as they are in UTC. Therefore, GPS time and UTC differ by a variable whole number of seconds.

Greenwich mean time (GMT):

See Universal Time. They are often used interchangeably, although Universal Time is now defined as the accepted standard.

HOW: Handover word. The word in the GPS message that contains time synchronisation information for the transfer from the C/A code to the P-code.

IODE: Issue of Data, Ephemeris. Part of the navigation data. It is the issue number of the ephemeris information. A new ephemeris is usually available on the hour. Especially important for Differential GPS operation that the IODE change is tracked at both the reference station and mobile receivers.

Ionospheric delay:

A wave propagating through the ionosphere experience delay. Phase delay depends on electron content and affects carrier signals. Group delay depends on dispersion and affects signal modulation.

L1: The primary L-band signal radiated by each GPS satellite at 1575.42 MHz. The L1 carrier is modulated with the C/A code and P-code.

L band: The radio-frequency band extending from 390 MHz to 1550 MHz.

Multipath effect:

A positioning error resulting from the interference between radio waves which have travelled between the transmitter and the receiver by two paths of different electrical lengths.

P-code: The protected or precise code used on both L1 and L2 GPS carriers. This code will be made available by the DoD only to authorised users. The P-code is a vary long sequence of pseudo-random binary biphase signal with a chip rate of 10.32 MHz, which repeats about every 267 days.

PRN: Pseudo-random noise, a sequence of digital 1s and 0s which appears to be randomly distributed like noise, but which can be exactly reproduced. The important property of PRN codes is that they have a low auto-correlation value for all delays or lags except when they are exactly coincident. Each GPS satellite has its own unique C/A and P pseudo-random noise codes.

Pseudo-range: A measurement of the apparent propagation time from the satellite to the receiver antenna, expressed as a distance. Pseudo-range is obtained by multiplying the apparent signal propagation time by the speed of light. Pseudo-range differs from the actual range by the amount that the satellite and user clocks are offset, by propagation delays, and other errors.

The apparent propagation time is determined from the time shift required to align (correlate) a replica of the GPS code generated in the receiver with the received GPS code. The time shift is the difference between the time of signal reception (measured in the receiver time frame) and the time of emission (measured in the satellite time frame).

RTCM: Radio Technical Commission for Maritime Service. Commission set up to define a differential data link to relay GPS correction messages from a monitor station to a field user. RTCM-SC 104 recommendations defines the correction message format and 16 different correction message types.

SA: See Selective Availability

Selective Availability (SA):

A DoD program to control the accuracy of pseudo-range measurements, whereby the user receives a false pseudo-range which is in error by a controlled amount. Differential GPS techniques can eliminate or reduce these effects.

Spread spectrum:

The received GPS signal is a wide bandwidth, low-power signal (-160 dBW). This property results from modulating the L-band signal with a PRN code in order to spread the signal energy over a bandwidth which is much greater than the signal information bandwidth. This is done to provide the ability to receive all satellites unambiguously and to provide some resistance to noise and multipath.

Standard Positioning Service (SPS):

The level of dynamic- or static- positioning capacity that is provided by GPS, based on the single-frequency C/A code. The accuracy of this service is about 100 meters.

Static positioning:

Positioning applications in which the positions of static or near static points are determined.

SV: Space Vehicle.

TOW: Time of week, in seconds, from midnight Sunday UTC.

Universal time:

Local solar mean time at Greenwich Meridian.

WGS 84: World Geodetic System (1972): the mathematical ellipsoid used by GPS since January 1987.