

UNIVERSITY COLLEGE LONDON
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AND SURVEYING

AN INVESTIGATION OF GPS
DATA PROCESSING

BY

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CONTENTS

1	INTRODUCTION	
1.1	What is the project about	1
1.2	Introduction to Least Squares	2
2	NAVSTAR GLOBAL POSITIONING SYSTEM (GPS)	
2.1	Introduction	7
2.2	Space segment	7
2.2.1	GPS signals	8
2.3	Ground segment	10
2.4	User segment	11
2.4.1	Geodetic receivers	11
2.5	GPS observables	12
2.5.1	Pseudo-ranging	12
2.5.2	Carrier phase	16
2.6	GPS observables and data processing	16
2.6.1	Single differences	18
2.6.2	Double differences	19
2.6.3	Triple differences	20
2.7	Linear combinations of carrier phases	21
2.8	Cycle slip	22
2.9	Error sources	24
2.10	GLONASS is like GPS	27
3	PROGRAMS AND DATA PROCESSING	
3.1	Introduction	29
3.2	The GPPS program	29
3.3	Control of static processing	33
3.4	The GPS_baseline simulation program	38
3.4.1	Program structure and user's guide	38
3.4.2	Input and output file structure	40
3.4.3	Computing satellite coordinates	42
3.5	Analysis of GPS_baseline	46
3.5.1	Least squares estimation and ambiguity resolution	46
3.5.2	Matrix preparation within the procedures	51

4	RESULTS AND ANALYSIS	
4.1	Introduction	54
4.2	The GPPS results	56
4.3	The GPS_baseline simulation program results	67
5	CONCLUSIONS AND FUTURE WORK	73
	REFERENCES	75

Appendix One	Examples of files from the GPPS package
Appendix Two	List of the GPS_baseline simulation program
Appendix Three	Example of input and output files from the simulation program
Appendix Four	Graphs of the root mean squares and the coordinate differences vs epoch time
Appendix Five	Tables of line quality for all vectors processed

CHAPTER ONE

INTRODUCTION

1.1 What is the project about

As part of the University College London, Department of Photogrammetry and Surveying field trip to the Isle of Wight in March 1992 a two days Global Positioning System campaign was carried out. Three baselines were observed with two dual frequency GPS Ashtech LM-XII receivers. The baseline lengths were 2 km (Batt-Yave), 6.2 km (Tenn-Quar) and 8.1 km (Gele-Quar). The receivers were operated in conjunction with Ashtech's Geodetic Post Processing Software (GPPS) with a 20 second measurement interval.

The Isle of Wight baseline data was processed using the facilities provided by the GPPS software. Different strategies and techniques were used in processing the baselines, these are discussed in chapter three.

During the field course itself only the L1 data was processed by GPPS and because of the time taken to do this, it was not possible to process all the linear combinations for all lines at that time.

So what is the purpose of the project ? The first of two aims for carrying out this project was to process the Isle of Wight data using different strategies as mentioned above. The second and more general aim was to find ways of overcoming certain limitations of the GPPS software. GPPS is a closed program; the user entry is restricted and only selected parts can be changed at certain times; such as the run times parameters. If it were necessary for example: to introduce some sort of uncertainty to the quality of start coordinates, or change the quality of the ephemeris, or add different noise levels to the observation etc to see how these had

an effect on the precision of the line one would be prohibited by the software restrictions. To the end of overcoming these limitations a simulation program was written.

The work carried out on this project can be considered in three parts. The first part, which started in June was spent using the GPPS software. Lines were processed several times and various approaches were made when processing the data set to obtain a more general information about the performance of the program. During the middle section the GPS_baseline simulation program was written. Another reason for doing this was to compare the results obtained with those of the GPPS software. The last part of the summer was spent carrying out analysis of the results obtained and report writing.

The report is divided into five chapters. An introduction to least squares is discussed in this chapter. Chapter two provides an introduction to GPS. It deals with various components of the system, reviews the pseudo and the carrier phase observables, the processing of the observations and main sources of errors in GPS signals. The latter part of this chapter gives a comparison between GLONASS and GPS. Chapter three goes into more detail about the GPPS package used in this project and discusses the general procedure for processing different methods of a baseline. It also includes a full discussion of the GPS_baseline simulation program that was written. Chapter four shows graphical and numerical results for different linear combinations computed from Ashtech's instrument and the results achieved from the simulation program.

1.2 Introduction to Least Squares

Least squares theory requires that; 'the sum of the squares of the residuals be a minimum'. This section introduces and relates the separate steps of the least squares estimation process. The mathematical functional models are used in estimation of

least squares problems which relate measurements, or observed parameters to the required quantities, or unobserved parameters.

The first step in least squares analysis is the formation of the model. To be consistent, the best estimates and the provisional values must satisfy the mathematical models exactly, thus

$$\mathbf{F}(\hat{\mathbf{x}}; \hat{\mathbf{l}}) = \mathbf{0} \quad \text{and} \quad \mathbf{F}(\dot{\mathbf{x}}; \dot{\mathbf{l}}) = \mathbf{0} \quad 1.1$$

where $\hat{\mathbf{x}}$ and $\hat{\mathbf{l}}$ are the best estimates of the parameters and the observations of the unobserved parameters, $\dot{\mathbf{x}}$ and $\dot{\mathbf{l}}$ are the selected provisional values of these parameters and observations.

This general function describes a series of functions each associated with a different set of observations; for example, these might relate to observations at different epochs for a GPS receiver or to different coordinates differences in the network.

If we now introduced the corrections $d\mathbf{x}$ and $d\mathbf{l}$ in order to be applied to these estimates to obtain the best estimates of the parameters

$$\mathbf{F}(\hat{\mathbf{x}}, \hat{\mathbf{l}}) = \mathbf{F}(\dot{\mathbf{x}} + d\mathbf{x}, \dot{\mathbf{l}} + d\mathbf{l}) = \mathbf{0} \quad 1.2$$

Applying Taylors expansion to 1.2

$$\mathbf{F}(\hat{\mathbf{x}}, \hat{\mathbf{l}}) = \mathbf{F}(\dot{\mathbf{x}}, \dot{\mathbf{l}}) + \left[\frac{\partial \mathbf{F}}{\partial \dot{\mathbf{x}}} \right] d\mathbf{x} + \left[\frac{\partial \mathbf{F}}{\partial \dot{\mathbf{l}}} \right] d\mathbf{l} = \mathbf{0} \quad 1.3$$

therefore

$$\left[\frac{\partial \mathbf{F}}{\partial \dot{\mathbf{x}}} \right] d\mathbf{x} + \left[\frac{\partial \mathbf{F}}{\partial \dot{\mathbf{l}}} \right] d\mathbf{l} = \mathbf{0} \quad 1.4$$

Looking at the relationships for the observations and parameters which are summarised as follows

$$\text{Observations} \quad \hat{\mathbf{l}} = \dot{\mathbf{l}} + d\mathbf{l} \quad 1.5$$

$$\text{Parameters} \quad \hat{\mathbf{x}} = \mathbf{x} + d\mathbf{x} \quad 1.6$$

however if $\hat{\mathbf{l}}^0$ is the observed value and $\mathbf{v}$ is the residual then the best estimate is given as

$$\hat{\mathbf{l}} = \hat{\mathbf{l}}^0 + \mathbf{v} = \mathbf{l} + d\mathbf{l} \quad 1.7$$

thus from 1.5

$$d\mathbf{l} = \hat{\mathbf{l}} - \mathbf{l} = \hat{\mathbf{l}}^0 - \mathbf{l} + \mathbf{v} = \mathbf{L} + \mathbf{v} \quad 1.8$$

substituting 1.8 into 1.4

$$\left[\frac{\partial \mathbf{F}}{\partial \mathbf{x}} \right] d\mathbf{x} + \left[\frac{\partial \mathbf{F}}{\partial \mathbf{l}} \right] (\mathbf{L} + \mathbf{v}) = \mathbf{0} \quad 1.9$$

and

$$\left[\frac{\partial \mathbf{F}}{\partial \mathbf{x}} \right] d\mathbf{x} + \left[\frac{\partial \mathbf{F}}{\partial \mathbf{l}} \right] \mathbf{v} + \left[\frac{\partial \mathbf{F}}{\partial \mathbf{l}} \right] \mathbf{L} = \mathbf{0} \quad 1.10$$

Considering that there are m observations in n parameters linked together by r equations similar to equation 1.10, in matrix form this set of equations may be written as

$$\begin{array}{ccccccc} \mathbf{A} & \mathbf{x} & + & \mathbf{C} & \mathbf{v} & + & \mathbf{C} \quad \mathbf{L} = \mathbf{0} & 1.11 \\ (r \times n)(n \times 1) & & & (r \times m)(m \times 1) & & & (r \times m)(m \times 1) & (r \times 1) \\ & (r \times 1) & & (r \times 1) & & & (r \times 1) & (r \times 1) \end{array}$$

Because $\mathbf{L} = \hat{\mathbf{l}}^0 - \mathbf{l}$, are both known, and the design matrices $\mathbf{A}$ and $\mathbf{C}$ are also known from the form of the mathematical model, the product $\mathbf{CL}$ is also known, thus let

$$\mathbf{CL} = -\mathbf{b} \quad 1.12$$

and 1.11 becomes

$$\mathbf{Ax} + \mathbf{Cv} = \mathbf{b} \quad 1.13$$

It is at this stage that we must apply the least squares criteria to provide a unique solution for $\mathbf{x}$, the criteria requires that the sum of squares of the residuals ($\mathbf{v}^T \mathbf{v}$) is minimum.

Introducing a vector of Lagrangian multipliers $\boldsymbol{\lambda}$, of dimension ($r \times 1$) we can say

$$\Omega = \mathbf{v}^T \mathbf{v} + 2\boldsymbol{\lambda}^T (\mathbf{Ax} + \mathbf{Cv} - \mathbf{b}) \quad 1.14$$

It should be noted that the function Ω is a single number (1×1). If we now partially differentiate this function with respect to the variables $\mathbf{x}$ and $\mathbf{l}$, and equate them to zero. Prior to this let us first establish that differentiation with respect to the observed parameter $\mathbf{l}$; and it is the same as differentiation with respect to $\mathbf{v}$.

$$\left[\frac{\partial \Omega}{\partial \mathbf{l}} \right] = \left[\frac{\partial \Omega}{\partial \mathbf{v}} \right] \left[\frac{\partial \mathbf{v}}{\partial \mathbf{l}} \right] \quad 1.15$$

and because $\mathbf{l} = \mathbf{L} + \mathbf{v}$, and $\mathbf{L}$ is a constant, $\left[\frac{\partial \mathbf{v}}{\partial \mathbf{l}} \right] = \mathbf{I}$

$$\left[\frac{\partial \Omega}{\partial \mathbf{l}} \right] = \left[\frac{\partial \Omega}{\partial \mathbf{v}} \right] \quad 1.16$$

For a minimum value of Ω , $\left[\frac{\partial \Omega}{\partial \mathbf{v}} \right] = \mathbf{0}$ and $\left[\frac{\partial \Omega}{\partial \mathbf{x}} \right] = \mathbf{0}$

therefore

$$\frac{\partial \Omega}{\partial \mathbf{x}} = -2 \boldsymbol{\lambda}^T \mathbf{A} = \mathbf{0} = \mathbf{A}^T \boldsymbol{\lambda} \quad 1.17$$

and

$$\frac{\partial \Omega}{\partial \mathbf{v}} = \mathbf{v}^T - 2 \boldsymbol{\lambda}^T \mathbf{C} = \mathbf{0}$$

thus

$$\mathbf{v} = \mathbf{C}^T \boldsymbol{\lambda} \quad 1.18$$

substituting for $\mathbf{v}$ from 1.18 in 1.13 gives

$$\mathbf{Ax} + \mathbf{CC}^T \boldsymbol{\lambda} = \mathbf{b}$$

putting

$$\boldsymbol{\lambda} = (\mathbf{CC}^T)^{-1} (\mathbf{b} - \mathbf{Ax}) \quad 1.19$$

substituting 1.19 into 1.17 gives

$$\mathbf{A}^T (\mathbf{CC}^T)^{-1} \mathbf{Ax} = \mathbf{A}^T (\mathbf{CC}^T)^{-1} \mathbf{b} \quad 1.20$$

therefore, we have

$$\mathbf{N} \mathbf{x} = \mathbf{b}_1 \quad 1.21$$

Equation 1.21 is called normal equation and $\mathbf{N}$ is symmetrical and square; and it is very important in network design, and from 1.13 and 1.20 we obtain another important result which is

$$\mathbf{A}^T (\mathbf{CC}^T)^{-1} \mathbf{C} \mathbf{v} = \mathbf{0} \quad 1.22$$

and the residuals can be found by substituting 1.19 into 1.18

$$\mathbf{v} = \mathbf{C}^T (\mathbf{CC}^T)^{-1} (\mathbf{b} - \mathbf{Ax}) \quad 1.23$$

The individual applications of least squares within the GPS_baseline simulation program will be discussed latter, in chapter three.

CHAPTER TWO

NAVSTAR GLOBAL POSITIONING SYSTEM (GPS)

2.1 Introduction

In 1974 the global positioning system (GPS) was born. In mid-1980's the NAVSTAR (Navigation Satellite Timing and Ranging) superseded the TRANSIT Doppler system which had been operational since the mid-1960's. GPS shifts the sense of surveying operations from *ground to ground* measurements to *ground to sky*, with obvious implications: operations are possible in nearly all kinds of weather and can be performed during day or night; other features are high positional accuracy and velocity determination in three dimensions, global coverage and continuous availability.

The major components of the global positioning system are given in Figure.2.1.

2.2 Space Segment

The initial specification for orbital constellation was for 24 satellites, but the 1989 system completion date was delayed because of the Challenger disaster and the final constellation for the GPS satellites is yet to be decided. There are currently 18 to 19 usable satellites in the orbit, which are in six orbital planes at about 20200 km altitude, each having an inclination of 55°, allowing for simultaneous visibility of at least four (and sometimes up to nine) satellites at any time of day almost anywhere in the world. The orbital path will be close to circular with a semimajor axis of about 26,000 km and the orbital period is slightly less than 12 hours. Whatever the final constellation looks like, the satellite coverage will be evenly distributed over the globe.

2.2.1 GPS signals

As far as the user is concerned each GPS satellite broadcasts on two L Band carrier frequencies $L1 = 1575.42$ MHz (equivalent to a wave length of approximately 19 cm) and $L2 = 1227.60$ MHz (equivalent to a wave length of approximately 24 cm).

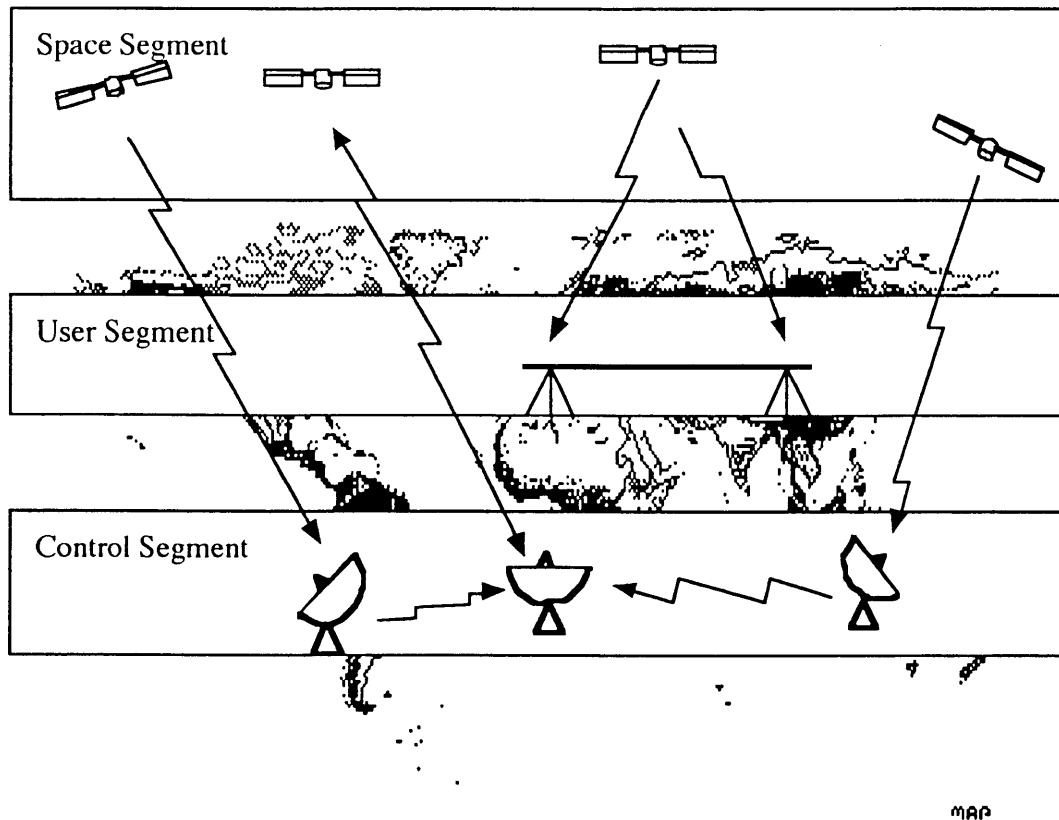


Fig.2.1 The three main components GPS segment (after *Leick*)

The carriers are phase modulated to carry 2 codes, known as the P-code or Precise Code or PPS (Precise Positioning Service) and the C/A-code or Course/Acquisition code or SPS (Standard Positioning Service). The C/A-code has a chipping rate of 1.023×10^6 bits/sec (1.023 MHz) and code repeats every millisecond. This means that the sequence that makes up the C/A-code is only 1023 bits long. Multiplied by the speed of light each bit is then 293 m long and the whole code about 300 kms. The P-code chips at 10.23×10^6 bit/sec and repeats itself for 267 days. This 267

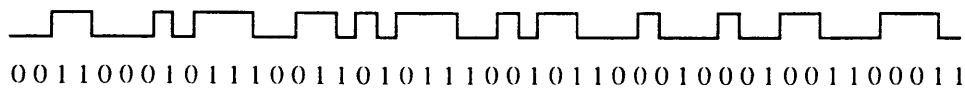
day sequence is subdivided in such a manner that each satellite is assigned a unique 1 week portion of the code that does not overlap with that assigned to any other satellite.

P code

10.23 Mbps

bit length = 29.3 m

repetition 1 week

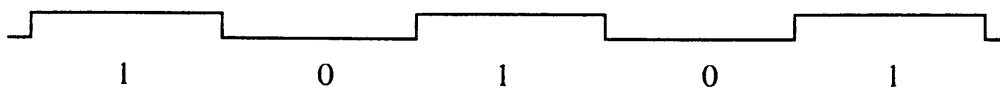


C/A code

1.023 Mbps

bit length = 293 m

repetition 1 ms



L1 carrier

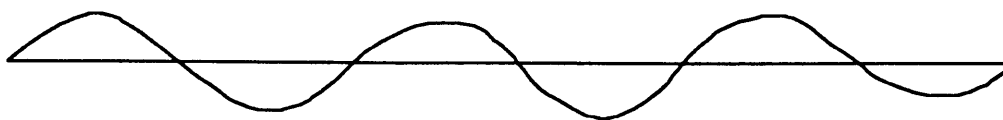


Fig.2.2 Signal Modulations

The precision P-code is the principal code used for navigation. It is a Pseudo Random Noise (PRN) code generated mathematically by mixing two other codes. The C/A-code can be used for the rapid acquisition of the P-code or as a medium-accuracy navigation signal. The C/A-code is very helpful because it allows accurate time synchronization and the reading of the navigation message. The C/A-code is available on the L1 carrier, and it can also be put on the L2 carrier. The navigation message is modulated on both the L1 and the L2 carriers at a chipping rate of 50

Hz. It contains the following information: the satellite ephemeris, i.e its position in space with respect to time; GPS time; clock behaviour; and system status messages. Figure 2.2 summarizes the GPS signals.

2.3 Ground Segment

The information contained in satellite navigation messages is provided by the ground or control segment of the system, the primary function of which is to provide each user, via the baseline constellation, with sufficient data for computing a position fix. This segment of GPS is a complex communication network linking tracking stations and data handling centres and consists of :

Monitor Stations, at widely spaced locations at Hawaii, Guam, Alaska and Vandenburg Air Force Base California.

Master Control Station at Colorado Springs, USA.

An Up-load Station at Vandenburg Air Force Base, USA.

The Monitor Stations are remote unmanned stations with a GPS receiver, caesium clock, meteorological sensors, data processor and teleprinter with a modem. Their functions are to observe the broadcasted satellite navigation message and the satellite clock errors and drifts. The data is automatically gathered and processed by each Monitor Station and is transmitted to the Monitor Control Station. By comparing the data from the various Monitor Stations the Master Control Station can compute the errors in the current navigation messages and satellite clocks, and so can compute updated navigation messages for future satellite transmissions. These up-load navigation messages are passed to the up-load Station by modem and are in turn processed for transmission to the satellites by the ground antenna. The Monitor Station then receives the updated navigation messages and so the data transmission and processing circle is complete. In practice the satellite navigation messages are updated about once every 24 hours or every second orbit.

2.4 User Segment

The particular user's own equipment represents the User Segment. Each GPS navigation receiver will have the following main components (Figure.2.3)

- an antenna with pre-amplifier
- section with signal identification and signal processing (channel)
- microprocessor for receiver control, data sampling, and data processing (navigation solution)
- precision oscillator
- power supply
- user interface, command and display unit
- memory, data storage

The user segment consists of a wide spectrum of users; it ranges from static surveying to high speed moving platform navigation. The US Government will permit general, or commercial use of the Standard Positioning Service (SPS), but for Precise Positioning Service (PPS) it is another matter. Basically the PPS is only available to US and allied military users because of high national security interest.

2.4.1 Geodetic receivers

The currently available GPS receivers that are used in geodesy, surveying, and precise navigation, started as single frequency C/A-code receivers with the ability to track more than four satellites. In a second step, the access to L2 was added, based on a squaring technique, and the number of tractable satellites was increased. In the third step, all leading manufactures included the P-code ability on L2, and partly on L1, mainly with the objective of increasing the L2 data quality and providing the full cycle length on L2.

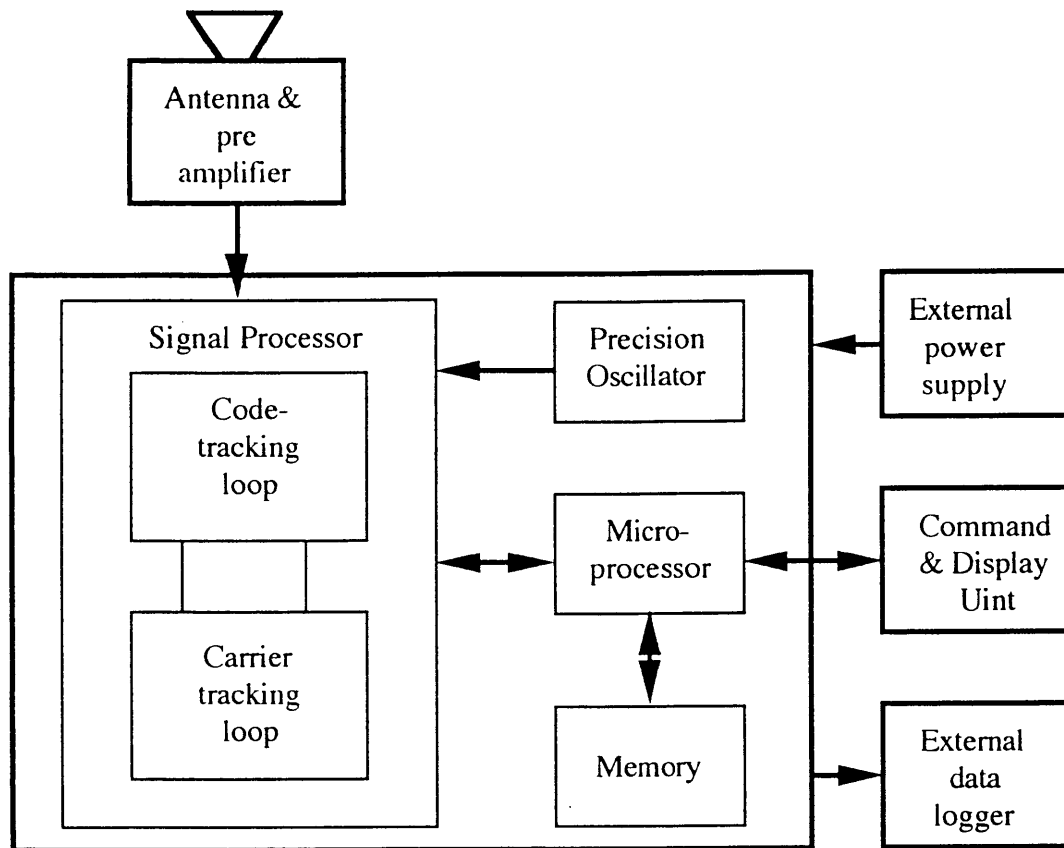


Fig.2.3 Major components of a GPS receiver.

2.5 GPS observables

The GPS signals can be used, by geodetic receivers such as those in Figure 2.4, (these geodetic receivers were used at the Isle of Wight in March 1992 as part of the UCL field trip) for positioning in a number of ways, two of which will be considered here: *pseudo-ranging* and *carrier phase measurement*.

2.5.1 Pseudo-ranging

Pseudo-ranging is the time shift required to correlate a replica of the GPS code generated in the receiver with the incoming GPS code. Multiplication by velocity of light then yields the distance. Pseudo-ranging can be obtained either from P-code or C/A-codes. GPS satellites carry extremely accurate Caesium clocks, which are



Fig 2.4 (a) Ashtech Instrument LM-XII dual-frequency 12 channel GPS geodetic receiver with antenna, used for collecting data at the Isle of Wight in March 1992 as part of the University College field trip.



Fig.2.4 (b) Wild - System 200.GPS geodetic receiver.

The hardware comprises of 9 channels dual-frequency handheld CR233 GPS controller with SR299 Microstrip antenna type and internal memory card recording system.

updated every time a new message is uploaded. Receiver clocks are usually of a much lower quality, and the time of generation of the receiver random sequences is liable to contain a significant clock error. For this reason the functional models used to solve the pseudo-ranging positioning problem always contain this error.

The pseudo-ranging is defined as:

$$P_A^i = |X_i - X_A| + cdt = c\tau_i \quad 2.1$$

$$= \sqrt{(X_i - X_A)^2 + (Y_i - Y_A)^2 + (Z_i - Z_A)^2} + cdt \quad 2.2$$

The symbols have the following meaning: P_A^i is the geometrical distance between satellite antenna i and receiver antenna A ; the (X_A, Y_A, Z_A) and (X_i, Y_i, Z_i) denote the Cartesian coordinates of receiver A and the satellite i in the conventional terrestrial reference system; c is the velocity of light; dt clock error between GPS system time and receiver clock; τ_i observed signal travel time between satellite i and observer antenna A .

The coordinates of the observer station X_A can be derived from simultaneous range measurements to four satellites, (Figure 2.5).

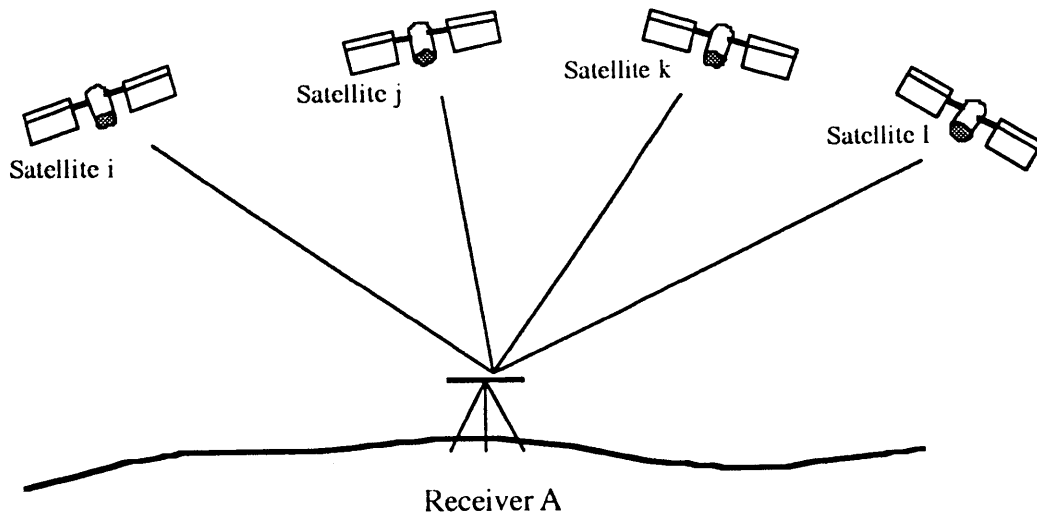


Fig.2.5 Pseudo ranging to four satellites.

The application of pseudo-ranging measurement are where low accuracy and instantaneous positions are required.

2.5.2 Carrier phase

Carrier phase is the difference between the transmitted carrier phase $\phi^i(t)$, defined in the satellite time frame, and the phase of the reference signal $\phi_A(\tau)$, defined in the receiver time frame. The carrier phase measurement is like a very precise pseudo-range but with an integer number of carrier cycles (wavelength) missing, the so-called integer-cycle ambiguity. The integer-cycle ambiguity can be thought of as the (unknown) number of whole carrier wavelengths between receiver and satellite, while the phase measurement is the fraction of a cycle remaining in the receiver satellite range. The main difficulty, related to this method, is the determination of cycle ambiguity N_A^i (given in equation 2.3), because the observable only determines the phase within one wavelength. The ambiguity term N_A^i has to be determined with appropriate methods, for example, rapid static methods, semi kinematic methods and pure kinematic method, for more detail on these methods refer to *Seeber* (1992).

2.6 GPS observables and data processing

The carrier phase leaves the satellite antenna at the epoch (τ), measured in the satellite time frame. The signal state propagates with approximately the velocity of light (1500×10^6 / second), and reaches the receiver antenna at the epoch (t), measured in the receiver time frame. Note that the phase states of the received signals are identical to the phase states of the transmitted signals. In other words, the phase state at the receiver means measuring the time of signals transmission at the satellite.

The basic carrier phase observables equation is given as:

$$\phi_A^i(t) = \phi^i(t) - \phi_A(t) + N_A^i + \text{noise} \quad 2.3$$

where $\phi_A^i(t)$ is the carrier phase observable reading at satellite i to the receiver A at a time t , $\phi^i(t)$ is the received phase of satellite i as measured at the receiver A , and $\phi_A(t)$ denotes the receiver oscillator. All terms refer to same epoch t . The N_A^i is an integer ambiguity in the observed phase (a number of a whole wavelengths of the carrier between the receiver and the satellite).

The received satellite phase can be related to the transmitted phase by:

$$\phi^i(t) = \phi_T^i(t - \tau) \quad 2.4$$

Where τ is the travel time of the signal.

Expression (2.4) can be expand by Taylor series:

$$\phi^i(t) = \phi_T^i(t) - \frac{d\phi}{dT}(t) \tau + \frac{1}{2} \frac{d^2\phi}{dT^2}(t) \tau^2 + \text{high order terms} \quad 2.5$$

Where $\frac{d\phi}{dT}(t)$ and $\frac{d^2\phi}{dT^2}(t)$ are respectively the time rates of change and acceleration of the phase, that is, the frequency and frequency drift. The last term of equation (2.5) is small and can be neglected for GPS observations. The time derivative of the phase $\frac{d\phi}{dT}(t)$ is equal to the frequency:

$$\frac{d\phi}{dT}(t) = f \quad 2.6$$

Therefore from (2.6), substituting into (2.5) gives:

$$\phi^i(t) = \phi_T^i(t) - f\tau \quad 2.7$$

Substituting (2.7) into (2.3) gives:

$$\phi_A^i(t) = \phi^i(t) - f\tau - \phi_A(t) + N_A^i + \text{noise} \quad 2.8$$

But the travel time τ is related to the geometrical distance $\rho_A^i(t)$ which will be:

$$\tau = \rho_A^i(t) / c \quad 2.9$$

Finally, substituting (2.9) into (2.8) gives the basic expression for the carrier phase observables:

$$\phi_A^i(t) = \phi^i(t) - \frac{f}{c} \rho_A^i(t) - \phi_A(t) + N_A^i \quad 2.10$$

Equation (2.10) is the equation for the undifferenced carrier phase observables. Note that symbol $\rho_A^i(t)$ represents the geometrical distance that the carrier phase travels from satellite to the receiver. Given satellite ephemeris and approximate position of the receiver, this distance can be computed iteratively.

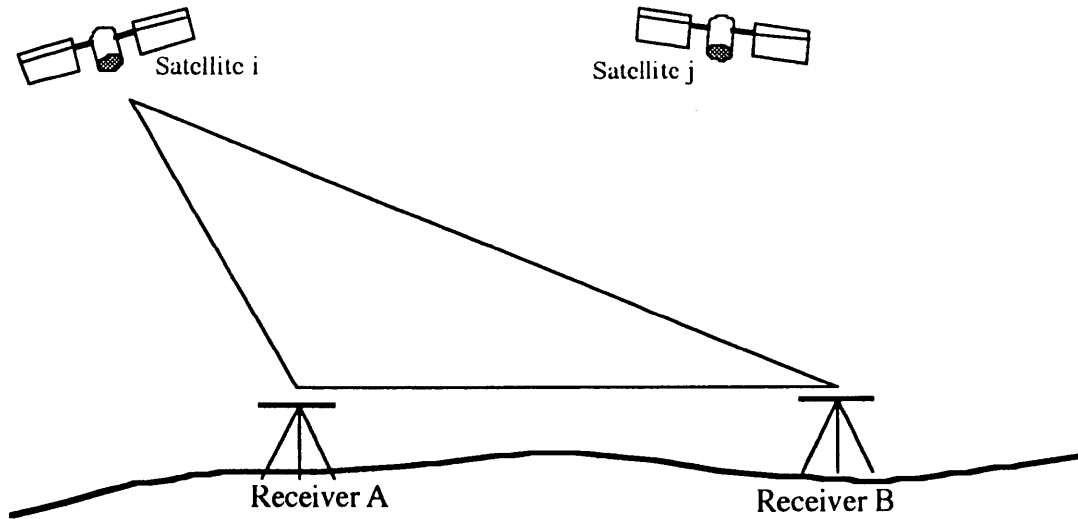


Fig.2.6 Single difference observable.

2.6.1 Single differences

If two receivers A and B observe the same satellite i at the same epoch, the equation of single difference phase observation is then obtained. Figure 2.6 shows a view of the single difference observables. The model equation for single difference phase

observation is obtained by subtracting the carrier phase observable (equation 2.10) of receiver A from the carrier phase observable of receiver B.

$$\phi_{AB}^i = \phi_B^i - \phi_A^i \quad 2.11$$

$$= \frac{f}{c} \left[-\rho_B^i(t) + \rho_A^i(t) \right] - \left[\phi_B^i(t) - \phi_A^i(t) \right] + N_{AB}^i \quad 2.12$$

Note that the phase $\phi^i(t)$ (satellite clock error) has cancelled, because it is common to both phase expressions. Where new initial integer ambiguity is

$$N_{AB}^i = N_B^i - N_A^i \quad 2.13$$

The primary application of single differenced observable is for orbit determination.

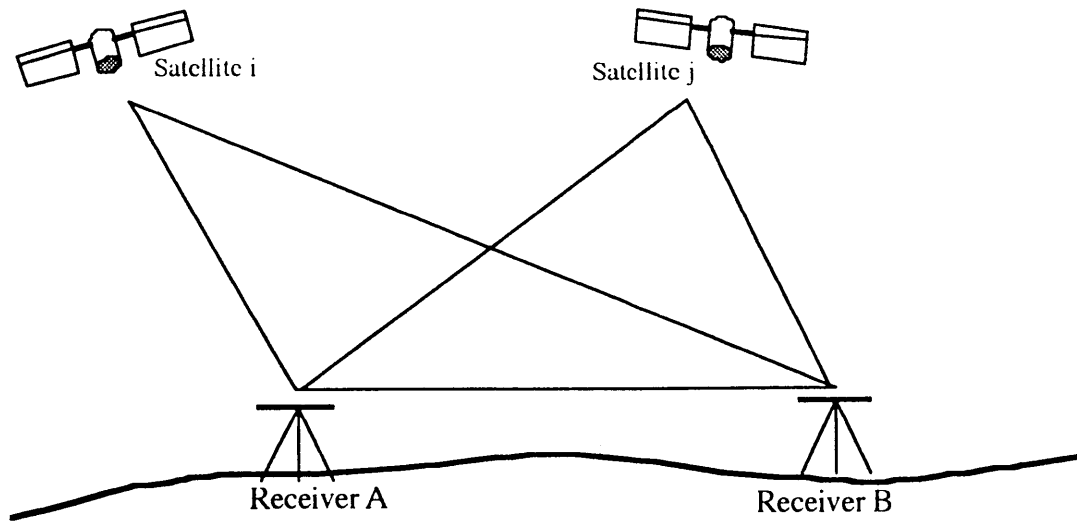


Fig.2.7 The double difference observable.

2.6.2 Double differences

If two receivers A and B observe two satellites i and j at the same time, the double difference phase observable is:

$$\phi_{AB}^{ij} = \phi_{AB}^j - \phi_{AB}^i \quad 2.14$$

The initial integer ambiguity N_{AB}^{ij} has cancelled from the observation equation (2.17). What remains is a linear combination of all pseudoranges and the biases which are not included in the equation (the residual propagation and the orbital biases), figure 2.8 illustrates the triple difference observables.

Triple differences are often used to provide approximate (Doppler) solutions. They are also very useful for the remove of cycle slips (discussed latter) in an automatic editing process. For a more complete presentation and for complete expressions see *Leick* (1990).

2.7 Linear combinations of carrier phases:

In principle there are an unlimited number of possibilities exists in combining different observables, and forming derived observables, but the most commonly used are the following (*Wells et al.*, 1986)

- observation between receivers
- observation between satellites
- observation between epochs
- between observations of the same type
- between observations of different type

The most frequently used linear combinations are between receivers and satellites, (*single, double and triple* differences of the carrier phase measurements).

Linear combinations between observations of the same type can be formed between carrier and code phases. The main advantage of such linear combinations is the elimination of the ionospheric delay. In recent years, the linear combinations of carrier phases supported the determination of ambiguities, *Seeber* (1992).

Moreover it is possible to form many different linear combinations of L1 and L2, and each of these linear combinations may in principle be used for processing.

The linear combinations of carrier phases actually used in GPPS software and GPS_baseline simulation program are summarized in table 1.

Phase	Name	λ
ϕ_1	L1 carrier	19cm
ϕ_2	L2 carrier	24cm
ϕ_3	L1c ionosphere free combinations	-
ϕ_4	L1+L2 narrow lane	10.7cm
ϕ_5	L1-L2 wide lane	86cm

Table 2.1 Carriers and their linear combinations

Different linear combinations have different advantages:

Well known linear combinations are the wide lane. The advantages of the wide lane observation, compared with the original observation, is that the ambiguity has to solved for a signal with a four times larger wavelength. This means that ambiguity resolution in this linear combination is much less affected by systematic errors.

The narrow lane has the lowest noise level of all linear combinations and hence yields the best results. Its ambiguity is, however, difficult to resolve. The narrow lane is mainly used over short lines, *Seeber*.

2.8 Cycle Slip

The phase observable is a measurement of the beat frequency phase, i.e the difference between the satellite oscillator phase and the receiver oscillator phase. This can be considered as two portions; first the fractional portion of the phase observable (which remains unchanged), and second: the integer component, which is the number of complete beat frequency cycles that have been observed since the first measurement. Cycle slips occur when the receiver loses phase lock of the satellite signal. The causes of cycle slips are the following:

- obstruction of satellite signal.
- low signal strength because of low satellite elevation.
- irregular receiver and satellite oscillator output.

Carrier Phases				Single Difference	
$\phi_A^i(t-2)$	$\phi_B^i(t-2)$	$\phi_A^j(t-2)$	$\phi_B^j(t-2)$	$\phi_{AB}^i(t-2)$	$\phi_{AB}^j(t-2)$
$\phi_A^i(t-1)$	$\phi_B^i(t-1)$	$\phi_A^j(t-1)$	$\phi_B^j(t-1)$	$\phi_{AB}^i(t-1)$	$\phi_{AB}^j(t-1)$
$\phi_A^i(t)$	$\phi_B^i(t)$	$\phi_A^j(t)+CS$	$\phi_B^j(t)$	$\phi_{AB}^i(t)+CS$	$\phi_{AB}^j(t)$
$\phi_A^i(t+1)$	$\phi_B^i(t+1)$	$\phi_A^j(t+1)+CS$	$\phi_B^j(t+1)$	$\phi_{AB}^i(t+1)+CS$	$\phi_{AB}^j(t+1)$
$\phi_A^i(t+2)$	$\phi_B^i(t+2)$	$\phi_A^j(t+2)+CS$	$\phi_B^j(t+2)$	$\phi_{AB}^i(t+2)+CS$	$\phi_{AB}^j(t+2)$

Double Difference	Triple Difference
$\phi_{AB}^{ij}(t-2)$	
$\phi_{AB}^{ij}(t-1)$	$\phi_{AB}^{ij}(t-1, t-2)$
$\phi_{AB}^{ij}(t)-CS$	$\phi_{AB}^{ij}(t, t-2)-CS$
$\phi_{AB}^{ij}(t+1)-CS$	$\phi_{AB}^{ij}(t+1, t)$
$\phi_{AB}^{ij}(t+2)-CS$	$\phi_{AB}^{ij}(t+2, t+1)$

Table 2.2 Effect of Cycle Slip on Single, Double, and Triple Differences

Cycle slips usually occur for the first reason. The nature of the obstruction may be physical (for example, buildings, trees), or atmospheric (for example, severe signal refraction caused by high ionospheric activity).

Cycle slips have either to be removed from the data at the preprocessing level, or a new ambiguity has to be determined for the particular pseudorange. One of the various methods for cycle slip fixing is to carry out a triple difference solution. This

is because only individual triple difference observations are affected. This is shown in table 2.2.

The notation corresponds to Figure 2.8 and to expression 2.17. A cycle slip (CS) has occurred in the phase observation between station B and satellite i at epoch t . All single and double differences, starting with epoch t , are corrupted by the cycle slip where as only one of the triple differences is affected. For a more detailed explanation refer to *Seeber* (1992) and *Leick* (1990).

2.9 Error Sources

In this section there follows an explanation of the main sources of error in the GPS signal. The propagation delay in the **ionosphere** (ranges approximately from 50 km to 1000 km above the earth's surface) depends on the total electron content (TEC) along the signal path from satellite to the receiver expressed in electron/m² (el/m²) and the frequency used. The total electron content is a function of many variables; among them are local time, season, geographic (geomagnetic) location, and state of solar and the earth's magnetic activity.

It is possible to eliminate the ionospheric effect with dual-frequency receivers because of time delay on the frequency. (i.e, by combining the observations from the L1 and L2 solutions the effect can be cancelled).

Leick (1990) demonstrates the formation in the following way:

The basic phase equation (2.10) can be written as

$$\lambda_{L1} \phi_{A,L1}^i = \lambda_{L1} (\phi_{L1}^i - \phi_{A,L1} - \frac{f_{L1}}{c} \rho_A^i + N_{A,L1}^i) \quad 2.18$$

where λ is the wavelength of the carrier frequency, changes the phase equation to a distance equation. The expression for the measured pseudo ranges, the geometrical distance, and the ionosphere time delays are related by

$$\rho_{A,L1}^i = \rho_A^i + c \frac{a}{f_{L1}^2} \quad 2.19$$

where a is the residual errors in the ionospheric modelling, this equation can conceptually be compared with (2.18). Because $\lambda=c/f$, the ionospheric advance of the received phase is incorporated as follows

$$\lambda_{L1} \phi_{A,L1}^i + \lambda_{L1} \frac{a}{f_{L1}} = \lambda_{L1} (\phi_{L1}^i - \phi_{A,L1} - \frac{f_{L1}}{c} \rho_A^i + N_{A,L1}^i) \quad 2.20$$

Dividing by λ gives

$$\phi_{A,L1}^i = \phi_{L1}^i - \phi_{A,L1} - \frac{f_{L1}}{c} \rho_A^i + N_{A,L1}^i - \frac{a}{f_{L1}} \quad 2.21$$

and similarly for L2

$$\phi_{A,L2}^i = \phi_{L2}^i - \phi_{A,L2} - \frac{f_{L2}}{c} \rho_A^i + N_{A,L2}^i - \frac{a}{f_{L2}} \quad 2.22$$

The phases are related by the formula

$$\phi_{L2} = \frac{f_{L2}}{f_{L1}} \phi_{L1} \quad 2.23$$

Substituting 2.23 into 2.22 gives

$$\phi_{A,L2}^i = \phi_{L1}^i \frac{f_{L2}}{f_{L1}} - \phi_{A,L1} \frac{f_{L2}}{f_{L1}} - \frac{f_{L2}}{c} \rho_A^i + N_{A,L2}^i - \frac{a}{f_{L2}} \quad 2.24$$

Multiplying 2.21 by

$$\alpha = \frac{f_{L1}^2}{f_{L1}^2 - f_{L2}^2} \quad 2.25$$

and 2.24 by

$$\beta = \frac{f_{L1} f_{L2}}{f_{L1}^2 - f_{L2}^2} \quad 2.26$$

Finally, adding the equations gives

$$\alpha \phi_{A,L1}^i + \beta \phi_{A,L1}^i = \phi_{L1}^i - \phi_{A,L1}^i - \frac{f_{L1}}{c} \rho_A^i + \alpha N_{A,L1}^i + \beta N_{A,L2}^i \quad 2.27$$

This linear function of combination observations on L1 and L2 yields the ionospheric free linear combination. The errors in the ionospheric modelling (a) have disappeared from the equation, but unfortunately the integer ambiguities NL1 and NL2 can no longer be identified, because of the multipliers α and β .

Residual errors in the ionospheric modelling are cancelled out, for the most part, through relative observations at two stations over short distances, since the satellites are observed through nearly the same condition. The remaining error for single frequency equipment is estimated to less than 2 cm over 10 km and it is valid for a quiet ionosphere *Seeber* (1992), and for observations in mid-latitudes only.

The lower **tropospheric** propagation delay (from earth's surface to about 50 km) is critical for precise position and baseline determination, tropospheric delay is independent of the frequency; hence it is not possible for it to be determined from dual-band measurements. Atmospheric measured data such as temperature, pressure, and water vapour content should be included in the model used. The dry part can be accurately modeled to about 2 - 5 %. The problem is with the wet portion which cannot be accurately predicted. The total delay ranges from 1.9 - 2.3 m in zenith direction, and increases to 20 - 28 m near the horizon at 5° - 10° elevation.

In a small network or if the stations are close together, less than 50 km (as in the case of Isle of Wight control marks) the tropospheric residual error almost completely disappears by differencing in the relative observation mode. While computing a baseline, mean meteorological data is to be introduced for both ends of the line, because the local measurements usually do not represent the regional atmospheric situation, and hence introduce biases into the solution.

Multipath is the largest instrumental error remaining in doubly-differenced phase observations after the receiver clocks are properly synchronized *King et al* (1985), it means that one or more reflected signals reach the antenna in addition to the direct signal. The causes of reflection is due to, for example, buildings, streets, vehicles, and water ways.

Seeber (1992) gives the following values for multipath effect, which varies between 1.3 m in a benign environment to 5 m in a highly reflective environment. Multipath propagation affects both code and carrier measurements. Under the worst conditions the code signal multipath may cause the receiver to lose phase lock, which leads to cycle slips (2.7).

2.10 GLONASS is like GPS

Since the 1970s the former Soviet Union has been developing a navigation (military) system similar in design to GPS system under the name, GLONASS (GLObal NAVigation Satellite System). In 1988 the official Soviet sources started to release information and data, and offered the system for international use.

An agreement covering the possible common use of GPS and GLONASS for civil aircraft navigation has been signed between the United States and the Soviet Union, and manufacturers have been encouraged to develop integrated receivers for the combined use of both systems.

The future of GLONASS is in doubt because of the situation in the former socialist countries. There are also technical doubts because only about one fifth of the more than 50 GLONASS satellites launched so far remain operational in early 1992. It should also be kept in mind that GLONASS is not operational, and is still in the experimental phase. Table 2.3 compares GPS with GLONASS as given by *Seeber* (1992).

Table 2.3 Comparison of GPS and GLONASS

Parameter	GPS	GLONASS
Number of Satellites (full operational system)	21 + 3 spares	21 + 3 spares
Number of orbital planes	6	3
Inclination	55 ⁰	64.8 ⁰
Orbital altitude	20,180 km	19,100 km
Orbital period	12 hours less 4 min	11 hours 15 min.
Repeat ground tracks	every 8 days	every day
Ephemeris representation	Keplerian elements and interpolation coefficients	9 parameters (position, velocity, acceleration) in the ECEF Cartesian system
Geodetic datum	WGS 84	SGS 85
Satellite signal division	Code division	Frequency division
Frequency band L1	1,575 MHz	1,602 - 1,615 MHz
Frequency band L2	1,228 MHz	1,246 - 1,256 MHz
Codes	different for all satellite C/A-code on L1 P-code on L1, L2	same for all satellite C/A-code on L1 P-code on L1, L2
Code type	Gold code	PRN sequence
Code frequency	C/A-code 1.023 MHz P-code 10.23 MHz	C/A-code 0.511 MHz P-code 5.11 MHz

CHAPTER THREE

PROGRAMS AND DATA PROCESSING

3.1 Introduction

The data collected during the field course on the Isle of Wight by the two Ashtech LM-XII receivers was processed using the Geodetic Post Processing Software (GPPS) program module. The software written by Ashtech Inc in California provides the following data processing methods; *Static*, *Pseudo kinematic*, and *Kinematic*. The version (4.2.02), released on the 23rd December 1991 was used. The GPPS software deals with all sorts of data processing, starting from downloading the field measurements data from the receivers to the processing of a series of GPS baselines and finally, performing a network adjustment.

The GPPS program was installed into a Dell computer System 200, and it had a dot matrix printer attached to it. This computer was operating with a standard DOS operating system.

In this chapter a discussion on the general procedure for processing different methods of a baseline will be given in order to give the reader who is inexperienced in the practical handling of GPS measurements data a feel for what goes on this important stage of GPS surveying.

A full discussion on the GPS_baseline simulation program, the least squares estimation, the ambiguity resolution and partial derivatives of the phase observable will be demonstrated and viewed in this part of the project.

3.2 The GPPS program

The field observations GPS data which had been downloaded from the receivers to the computer was stored on 5.25" floppy discs. The data collected comprises of

three sessions. Session A, data was collected between stations Battary and Yave, session B, between stations Tenn and Quarrey and session C, between Gele and Quarrey. Only sessions A and C were processed, unfortunately session B was not processed because one of the B-files was lost.

The first step of processing is to reload all the data files from the floppy disc drive A to the IOW92 subdirectory of the directory GPPS on the hard disc C.

All the data files and the GPPS programs have been stored in the same directory, in order to recopy the files within the hard disc if necessary.

All the operations were done using the DOS command facilities, for example to move a data file, or to copy a file, etc.

Most of the files generated by GPPS refer to their contents; the remainder of the name refers to the station concerned, the session day and the Julian day on which the observations were made. The field observation data is stored on three different types of files; the ephemeris data file, the bendata file which contains the observations of the carrier phase and the site data file of local information (E, B, and S-files respectively).

```
*****
View: C:\...ow92\iow92a\s batta92.087   Col 0           485 Bytes   100%
===== SITE INFORMATION =====
NAME  WORDS  WEEK  TIME  SES  RCR  ANT  MMDD  OPR  CODE          TYPE
BATT  220536  637   494489  A   870  824  0327  DRM  P_KINE_12FEB_ GEO

      HI      T-DRY      T-WET      HUMIDITY      PRESSURE
BEFORE  1.5000      4          2          0          1013.0
AFTER   1.5000      4          2          0          1013.0

RECEIVER Type:   LM-XII2 Nav: 6F   Channel: P3   Options: C21
*****
```

Fig.3.1 A site data file.

The E-file contains the ephemeris information transmitted in thirty second orbit messages from each satellite written in binary code. The data is recorded at hourly interval and may consist of several records for a single satellite. If a satellite was not tracked during a given hour, there will be no entry for that satellite for that hour. The E-file cannot be opened directly.

The B-file contains the raw measurement file information downloaded from the GPS receiver. Each record corresponds to one epoch, and the B-file will be discussed later.

The S-file (site file) is an ASCII text file containing the information entered by the field survey operator using the GPS receiver. It can be viewed by using the DOS command TYPE. An example of the data site file is given in figure 3.1.

As with all files in GPS, user entry is restricted and only selected parts can be altered at certain times.

It should be noted that no meteorological data was measured during the Isle of Wight field course for the baselines observation, only approximate data values were tapped in by the receiver user (operator) in the field.

GPPS is the all-in-one executive program which allows the user to step through all of the processing steps with easy to understand menus. Once the program has begun execution, the Ashtech standard version screen will then be displayed. Then the GPPS main menu will be displayed as in figure 3.2. As it is shown the processing can be done either automatically or manually. The auto processing approach was used throughout this project,

Processing of the observations involves the execution of the following individual program modules:

COMNAV is the GPPS program module which consolidates all the satellite ephemeris files (E-files) from one day observations for different

receivers and different sessions; and produces one common navigation file COMMON.NAV.

MAKEUFIL organizes the data for the processing programs (LINECOMP, etc) which evaluates the measurement data and produces the results. MAKEUFIL reads the common navigation file and a receiver measurements file (B-file); and produces an undifferenced data file called U-file.

MAKEINP creates and edits the BASELINE.INP file used by the post processing program LINECOMP. It contains information about the known station parameters, unknown station parameters and run-time processing parameters.

Geodetic Post Processing Software

A) Auto Processing

B) Download Receiver

C) Editing / Planning

D) Manual Processing

E) Post Processing

<F1> - DOS SHELL

<F5> - SEL DIR

<ESC> - QUIT

Fig.3.2 GPPS main menu

LINECOMP processes static data collected by two receivers and computes the baseline vector between these two stations. Intermediate results for the triple difference solution, float double difference solution, and fixed

double difference solution will be displayed during processing. This program module takes the longest time to run compared to the previous ones. For the Isle of Wight data it took an average of 20 minutes per line to process.

During the baseline processing, three files are created which have a slightly different naming convention because they involve two stations. The files are the input files for LINECOMP which start with an I, the baseline solution output files which start with an O and the plotfiles which start with a P. These files contain data from which the program PLOT can generate a graph which shows the measurement residuals for the double difference vector solution from each pair of satellites against time. A reference satellite is automatically selected by the software against which each of the others are differenced, and it is possible to view all the graphs for each solution simultaneously. Unfortunately it was not possible to obtain printouts of the graphs to be included in this report. It seems that when the choice of space reference vehicle is left to GPPS the program selects the satellite with the lowest number which was visible for the whole of the observation session. SV 20 was picked as a reference satellite for the lines computed for the Isle of Wight data. An O or a BASELINE.OUT file is shown in appendix one for static Isle of Wight 1992 stations of Batt and Yave. This file is a summary of the processing results, for a discussion on the meaning and the value of the parameters refer to the Ashtech GPPS user manual (MAKEINP reference section).

The program forms one further file, which contains a summary of the baseline. An example of a summary file vector list can be found in appendix one.

3.3 Control of static processing

Some measure of control over the data to be processed can be done by two editing possibilities; one is *edit project file* and the other is *edit run-time parameters*, figure 3.3.

Menu 2.0

Editing Options:

A) Edit Project File

B) Edit Run - Time Parameters

C) Process Project

<F1> - DOS SHELL

(F5) - RETURN TO MAIN

<ESC> - DONE

Fig.3.3 Control options

Menu 1.1 - Project Station Information

	SITE	SESSION	KNOWN	SLANT	LATITUDE	LONGITUDE	ELIP_HT
Y	BATT	A	8	0.000	N 50 39 8.45374	W 1 9 30.36235	257.5465
Y	YAVE	A	8	0.000	N 50 39 44.72017	W 1 8 14.94604	70.2941

TEMP-DRY (C) 20.00 (F) 68.00

TEMP-WET (C) 13.80 (F) 56.84

PRESSURE (Mb) 1010 (in) 29.88

HUMIDITY (H) 50.00

<ESC> - ABORT

F10 - ACCEPT

ESC QUIT F1 SITE F3 ANT F5 POS F7 METS F9 ADD F10 SAVE

Fig.3.4 Project station information

By selecting the edit project file option, it is possible to examine and modify the project station information. In the first column the site station can be either included or omitted in the processing. The known column indicates whether the station is known or unknown. For example, a 9 is used to indicate that the station is unknown and an O means that it is a fixed control station; and its coordinates must be entered in the last three columns. The slant column is used to correct the difference between the antenna and the station. With the Isle of Wight data nothing was entered here and the provisional coordinates were taken automatically from the pseudo-ranging navigation fix contained in the Bendata file.

The run-time parameters control the operation of the post-processing analysis program LINECOMP. Each parameter will have an affect on the baseline solution. Selecting this option will result in the following display:

First-and last epoch to process allow one to specify the beginning and ending epochs to use in the processing. The defaults are (1) for begin at the first epoch, and (-1) for end at the last available epoch. These options are used to delete epochs from the beginning or the end of a session, or to select a portion of data from the middle of a session.

```
*****
Menu 1.1.4 - Run-Time Parameters

1 (epoch)           First epoch to process.
-1 (epoch)          Last epoch to process.
15.0 (degrees)      Elevation cutoff angle.
1                   process data (1 = L1, 2 = L2, 3 = L1c).
0.010000            Convergence criterion (meters).
00 00 00 00 00 00 00 Satellites to omit during processing (up to 7).
10 (iterations)     Maximum number of dlsq and tlsq iterations.
00 00 00 00 00 00 00 Forbidden reference SV's (up to 7).
Y (Y/N)             Apply tropospheric delay correction.
L                   Output Format (Short, Long).

(F1)-DOS Shell      <F3>-MORE <F10>-Done/Accept <Esc>
*****
```

Fig.3.5 Run-time parameters

This option offers the possibility of deleting noisy data from the raw data. More analysis will be given in chapter 4.

Approximate seconds for tlsq processing affects only the triple least squares processing. The default is (100.0) which tells tlsq processing to use every epoch for its processing. The epoch spacing is computed by dividing this number by epoch interval. The default value was maintained throughout the project.

Elevation cutoff angle specifies the satellite mask angle below which data will be ignored. In this project the cutoff angle is set to 15° . Generally, this value should not be decreased, as data at elevation below 15° are subject to large amounts of tropospheric delay.

Process data parameters allows different linear combinations of carrier phases on L1 and L2 to be formed. Different linear combinations have different advantages. The Isle of Wight data was processed with the following linear combinations:

- 1 processing only on L1 carrier, 19cm wavelength.
- 2 processing only on L2 carrier, 24cm wavelength.
- 3 processing on L1c, ionosphere free linear combination.
- 4 processing on L1+ L2 narrow lane, 10cm wavelength.
- 5 processing on L1- L2 wide lane, 86cm wavelength.

The analysis of these linear combinations is given in chapter four.

Edit data with residuals greater than this * rms_cutoff: any data that lies outside this number times the computed RMS of fit will be discarded for the current iteration only. This factor applies to all iterations of tlsq except the first, and all iterations of the double least squares

algorithms. This number was not changed whilst processing the Isle of Wight data.

Tlsq convergence criterion specifies the amount of change (in meters) allowed between the position computed in the previous iteration and the position computed in the current iteration. If this criterion is met before the maximum number of iterations occur, the tlsq routine will have converged and will end.

Any reference space vehicle can be chosen to be a base reference satellite by forbidding all others. Though no satellites were omitted from the Isle of Wight data, some experiments were done on the effect of using different satellites as a reference space vehicle.

```
*****
                                FILE UTILITIES
BENDATA FILES:
    A) Look at a bendata file
    B) Full precision look at the bendata
    C) Join two or more bendata files
    D) Thin a bendata file to selected epoch interval
    E) Pick selected epochs from a bendata file
    F) Print the Bendata structure format (withheader)

U-FILES:
    G) Display the U-file header

NAV/EPHM FILES:
    H) Read a navdata file
    I) Remove a satellite from a navdata file

GENERAL FILES
    J) Split any file, or join previously split files

<F1> - DOS Shell      <ESC> - Quit    <CR> or <F10> - Accept Selection
*****
```

Fig.3.6 Filetool main menu.

Additional run-time parameters were available on a pop up menu, these were left without any changes to their default values.

FILETOOL is another important program module available. It allows the raw measurement data files to be viewed and edited. FILETOOL also provides the capability both to correct for field errors due to incorrect settings, and to eliminate malfunctioning satellites. In addition to that, it provides the capability to split or join any large data file for transferring to or from floppy diskettes. The main menu of the FILETOOL is shown in figure 3.6.

Because of incorrect data collecting settings for one of the GPS receivers, option D was used to thin the data from 5 seconds epoch interval to 20 second epoch interval.

3.4 The GPS_baseline simulation program

This section discusses the structure, method and use of the GPS_baseline simulation program and supplements the documents included within the program.

GPS_baseline simulation program was developed on the Apple Macintosh computer using the Turbo Pascal version 1.1 programming environment. The program can be defined as;

- baseline oriented, the program accepts only the computations of two stations at same time, from an input data file.
- the observable used is the phase double difference observable.
- the program is capable of resolving the phase ambiguities for baselines, (tested only for short baselines, 2 and 8 kms).

3.4.1 Program structure and user's guide

The GPS_baseline program can be divided into three major parts. These parts can be defined as:

- The input and the output file data part.
- The orbit part, (generates circular orbit).
- The processing part, (double phase processing, parameter estimation technique, and the matrix manipulation).

Prior to the start of the program it is necessary for the user to decide on two things, the wavelength (10cm, 24cm, etc) to be used and the level of random noise (1mm, 0.1mm, etc) to be introduced in the system. These need to be changed manually by the user as shown in bolds in appendix two.

Once the program is started it asks for the names of the input and the output data files. The input data file should be prepared in advance, an example is given in appendix three. Let us take an example. A typical conversation with this program will look as follows, where the material in italics is typed by the program and the rest by the user:

```

Name of input file? batt_yave
Name of results file? results
iteration at epoch: 0
iteration at epoch: 20
.....
iteration at epoch: 1000

```

{At the end of the iteration the solution vector for the free point and the ambiguity terms will be displayed and at the same time this information is stored into the output file}

```

    ### {dx}
    ### {dy}
    ### {dz}
    ### {4 ambiguity terms for 5 satellites}
    ###
    ###
    ###

```

```

Another iteration(y/n) n
Do you wish to fix the ambiguities? 1
Fix and change the ambiguities? 2
End the program 3
Response 1,2,3 ..... 2
Which number ambiguity should be changed 3

```

{The number of the ambiguity terms depend on the number of satellites initially specified in the input file, for example if there are 4 satellites there will be 3 ambiguity terms, 5 satellites 4 ambiguity terms and so on. It should be noted that the first ambiguity term starts with number 2, the second ambiguity term with 3 and so on}.

By how much should this be changed? +1

{At this stage statistical tests are then applied to decide whether the best integer biases are selected for each ambiguity term in the following way: by adding +1 or -1 to the first ambiguity term and leaving others with the same values and repeating this process for all the ambiguity terms in the same manner}

```
iteration at epoch: 0
iteration at epoch: 20
.....
iteration at epoch: 1000
```

```
### {dx}
### {dy}
### {dz}
```

sum of squares of residuals = ###

{after several tests the sum of squares of the residuals of the second best solution is divided by the best solution to find ratio as per expression 3.23 in chapter three}

Another iteration(y/n) n

To end the conversation, the user types (n).

In figure 3.7 the main components of the GPS_baseline simulation program are laid out.

3.4.2 Input and output file structure

The input data file (an example is given in appendix 3) used by the GPS_baseline program contains the following information:

- the first row consists of: start-time, end-time and epoch-interval (all in seconds).

Obviously these can be altered to the required time.

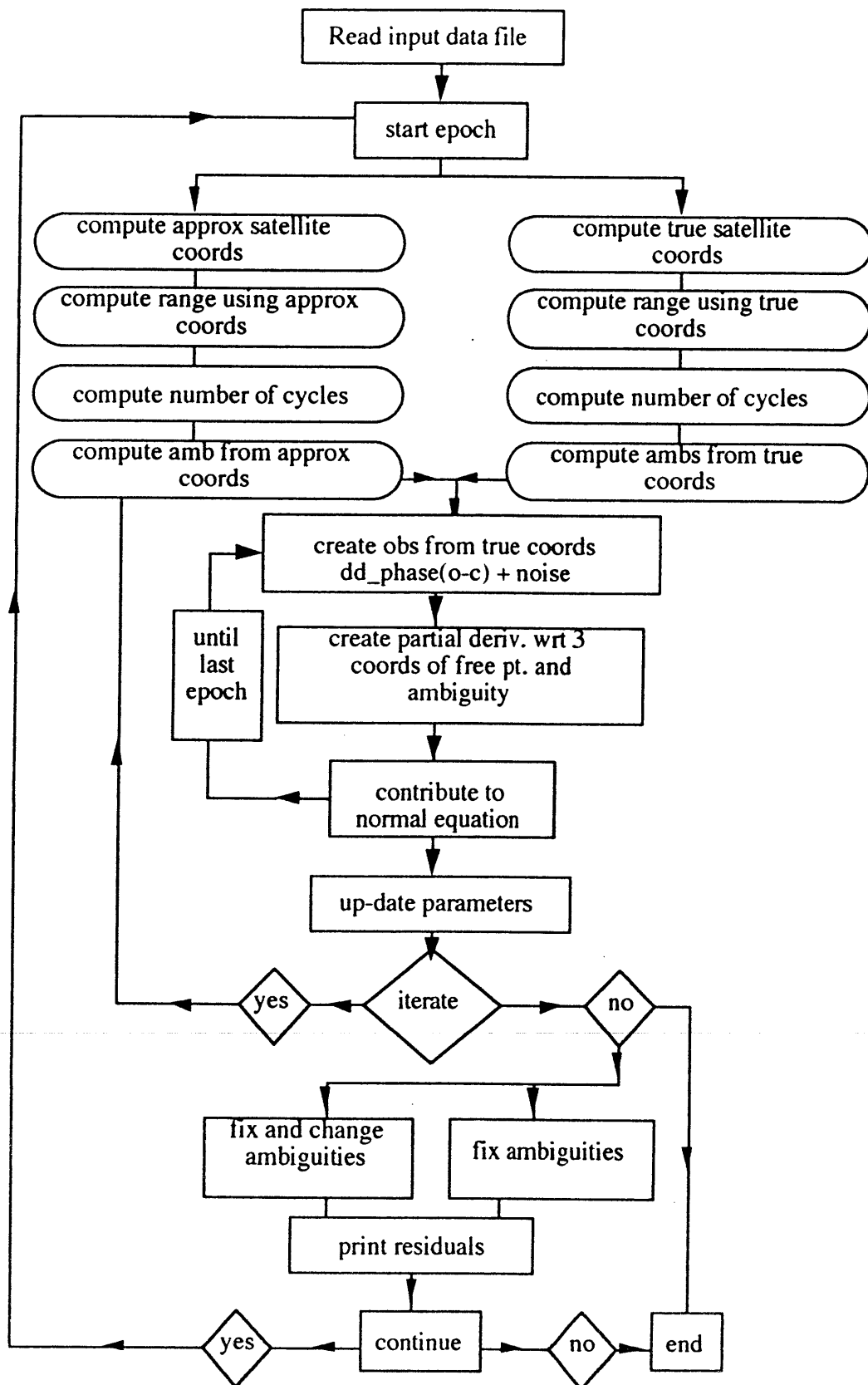


Fig.3.7 Functional flow diagram of static GPS_baseline simulation program.

- the approximate and true Cartesian coordinates of the baseline are given in the second and third row respectively.
- the number of the satellites in the orbit, the orbital radius, the GM of earth (where G and M are the Newtonian gravitational constant and the mass of the attracting body), and the inclination of the satellite orbits are given in 4th row. Note that, the last three terms are constant.
- and finally, we have the azimuth and the elevation of each satellite.

The data on any one line does not need to correspond to any particular format. The important thing is the order of the data and hence the lines.

The output file consist of three parts; the unknown parameters of the free point, the ambiguity parameters and finally the sum of the squares of the residuals.

3.4.3 Computing satellite coordinates

Computations in three dimensions are the natural method where satellites are involved. This section discusses and derives formulae which are used by the simulation program for computations in rectangular coordinates in three dimensions.

A satellite orbiting in a perfectly spherical gravity field, and sensing forces due only to that field, follows what is known as a normal orbit. Real earth satellites follow perturbed orbits due to the attraction of the non-sphericity of the earth's gravitational field and other forces (for example, the gravitational attractions of the sun, moon and planets, atmospheric drag, solar radiation pressure and tidal effects).

In this project we consider a simple orbit with the following assumptions:

- The orbit is a circle, its centre coincides with the centre of the earth.
- The orbital period T squared is proportional to the semi-major axis A cubed.
- The earth is stationary.

Figure 3.8 shows a simple orbit, and the following notations refer to it.

The ascending node AN is the point on the orbit where the satellite crosses the equator when passing from the south to the north. P is the perigee (in this case, the distance from the centre of the earth to the perigee and the apogee is equal).

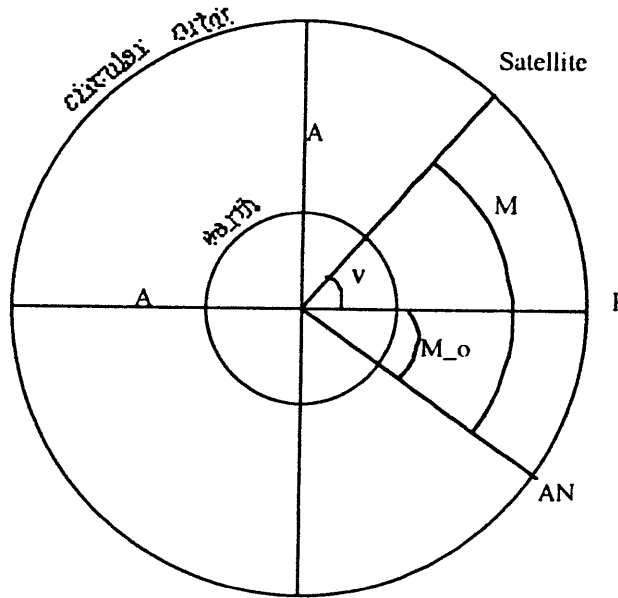


Fig.3.8 Simple circular orbit

The perigee argument M_o is the angle between the ascending node and the perigee. The position of the satellite in the orbit is given by the angle M , and v is the angle between the ascending node and the satellite, it is given by

$$v = \sqrt{\frac{GM}{A^3}} \quad 3.1$$

where G and M are the Newtonian gravitational constant and the mass of the attracting body respectively. The value of GM is approximately $398600 \text{ km}^3 \text{ s}^{-2}$, as given by *Bomford* (1980).

Satellite orbits are normally described and computed in inertial space. The definition of an inertial coordinate system is given in Figure 3.9, with its X_i , Y_i plane in the equator and X_i direction towards the vertical equinox (the first point of Aries), γ .

The orbit and the position of the satellite at any instant can be described by six orbital quantities, known as Keplerian elements, i , Ω , v , A , e , and t_p .

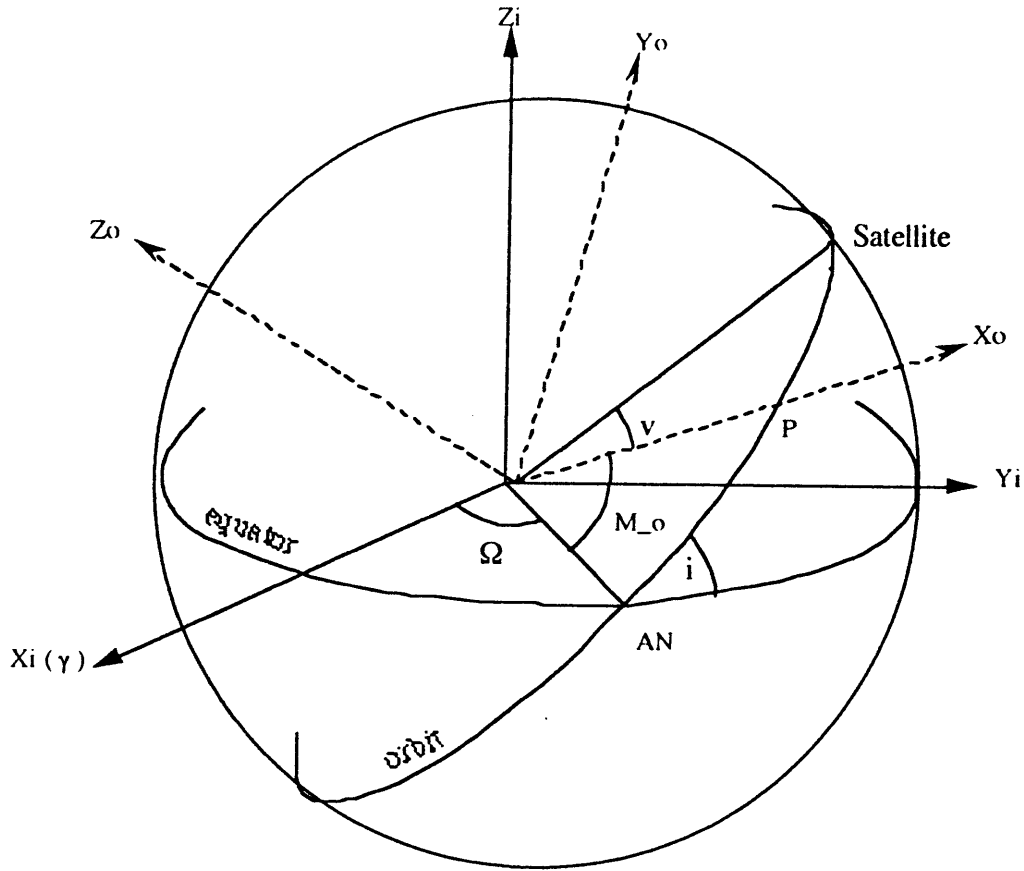


Fig.3.9 Satellite orbital and inertial coordinate system

They defined as follows:

i , is the inclination of the plane of the satellite orbit to that of the equator.

Ω , is the right Ascension of the ascending node (the angle between AN and γ).

A and e , the semi-major axis and the eccentricity of the orbital ellipse, but since we are considering a circular orbit e is neglected, i.e eccentricity is equal to zero.

v , is the true anomaly, i.e the orientation of the orbit within its plane.

t_p , is the time when v is zero and the satellite is at the perigee.

A knowledge of the Keplerian elements, enables the computation of the satellite's position in the inertial coordinate system at any time t . The computational procedure is as follows:

- compute the mean anomaly M from

$$M = M_o + v (t - t_p) \quad 3.2$$

where v is computed from 3.1.

- compute the orbital coordinates of the satellite, X_o , Y_o and Z_o , where orbital coordinates are defined as having their X axis towards the perigee, as in Figure 3.9.

$$X_o = A \cos M \quad 3.3$$

$$Y_o = A \sin M \quad 3.4$$

$$Z_o = 0 \quad 3.5$$

- rotate the orbital coordinate to equatorial coordinates using

$$\begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix} = \begin{bmatrix} \cos \Omega & -\sin \Omega & 0 \\ \sin \Omega & \cos \Omega & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos i & -\sin i \\ 0 & \sin i & \cos i \end{bmatrix} \begin{bmatrix} X_o \\ Y_o \\ Z_o \end{bmatrix} \quad 3.6$$

substitute 3, 4 and 5 into 6, gives:

$$X_i = A [\cos \Omega \cos M - \sin \Omega \cos i \sin M] \quad 3.7$$

$$Y_i = A [\sin \Omega \cos M + \cos \Omega \cos i \sin M] \quad 3.8$$

$$Z_i = A \sin i \sin M \quad 3.9$$

Equations 7, 8 and 9 are included in the GPS_baseline program for computing the coordinates of the satellites in a circular orbit. These are included in a function (subprogram) called sat_pos.

In case of perturbed orbits, the process of computing coordinates of a satellite is rather more complex and beyond the scope of this project.

3.5 Analysis of GPS_baseline

Given a model for the observable and the partial derivatives of the observable with respect to station coordinates and other parameters, (for example, ambiguity terms, satellite orbit, etc), one can use least squares estimation technique to determine improved values of these coordinates and parameters. In the following section we view the least squares estimation used in the GPS_baseline simulation program, the derivation of the partial derivatives of the phase observable with respect to the parameters of interest; and finally we discuss computational procedures, ambiguity resolution and the matrix manipulation used within the program.

3.5.1 Least squares estimation and ambiguity resolution

The mathematical model used in the least squares adjustment for the results established in this project is of the double difference phase observable, (recall equation 2.15).

Different biases can be estimated with the station parameters. Bias parameters may be, for instance corrections to the satellite orbit, clock parameters, and ambiguity terms. The biases which were included in the adjustment model for this project are the station parameters and the ambiguity terms.

The GPS_baseline program forms a maximum set of linearly independent double differences for each epoch.

For example, if n satellites ($i, j, k, \dots, n$) are observed from a two stations baseline A and B at epoch t , a maximum of $2 * (n-1)$ linearly independent double differences may be formed at time t .

The observation equation corresponding to the double difference observable will be:

$$(\phi^O - \phi^C) + v = \frac{\partial \phi}{\partial x_A} dx_A + \frac{\partial \phi}{\partial y_A} dy_A + \dots + \frac{\partial \phi}{\partial z_B} dz_B$$

$$+ \frac{\partial \phi_{AB}^{ij}}{\partial N_{AB}^{ij}} dN_{AB}^{ij} + \dots + \frac{\partial \phi_{AB}^{jn}}{\partial N_{AB}^{jn}} dN_{AB}^{jn} \quad 3.10$$

In this project we assumed that, point A is fixed and point B is free, then the unknown parameters are:

$$dx_B, dy_B, dz_B, \quad dN_{AB}^{ij}, dN_{AB}^{jk}, \dots, dN_{AB}^{in} \quad 3.11$$

We require the **partial derivatives** of the phase observables with respect to the site coordinates, and the ambiguity terms. These represent the amount by which the observed differenced phase would change in the parameters, taken one at a time.

The expressions for the partial derivatives, for the situation in which the satellite ephemerides are treated as known quantities are as follows:

The terms for the receiver coordinates are introduced using the expression:

$$\rho_B^i = \sqrt{(x_B - x^i)^2 + (y_B - y^i)^2 + (z_B - z^i)^2} \quad 3.12$$

with appropriate subscripts and superscripts for each value of ρ . Values of x^i , y^i and z^i are obtained from the broadcast ephemeris. The expression (2.10) must be partially differentiated with respect to unknown parameters (equation 3.11) to find the coefficients of A matrix, $\frac{\partial \phi}{\partial x}$ and $\frac{\partial \phi}{\partial N_{AB}^{in}}$.

All partial derivatives for the stations coordinate parameters will be similar, as an example:

$$\begin{aligned} \frac{\partial \phi_{AB}^{ij}}{\partial x_B} &= \frac{f}{c} \frac{1}{2} ((x_B - x^j)^2 + (y_B - y^j)^2 + (z_B - z^j)^2)^{-\frac{1}{2}} * 2(x_B - x^j) - \\ &\quad \frac{f}{c} \frac{1}{2} ((x_B - x^i)^2 + (y_B - y^i)^2 + (z_B - z^i)^2)^{-\frac{1}{2}} * 2(x_B - x^i) \\ &= \frac{f}{c} \left[\frac{(x_B - x^j)}{\rho_A^j} - \frac{(x_B - x^i)}{\rho_A^i} \right] \end{aligned} \quad 3.13$$

The partial derivatives of the phase observables with respect to a bias parameter is unity, and it is given as:

$$\frac{\partial \phi_{AB}^{ij}}{\partial N_{AB}^{ij}} = 1 \quad 3.14$$

and, similarly for

$$\frac{\partial \phi_{AB}^{ik}}{\partial N_{AB}^{ik}}, \dots, \frac{\partial \phi_{AB}^{in}}{\partial N_{AB}^{in}} = 1 \quad 3.15$$

The mathematical model (recall equation 3.10) used for the double difference phase data reduction in its matrix form (similar to equation 1.11, putting $C = I$) is given by:

$$L_t + v_t = A_t x_t \quad 3.16$$

where:

L_t represents the observed minus computed double difference phase observation vector at epoch t (with dimension $n \times 1$),

v_t is the vector contains the measurements residuals at epoch t ,

A_t is the least squares design matrix for epoch t , contains the partial derivatives of the observations with respect to the unknowns,

x_t is the state vector containing the unknown parameters, is given by:

$$x_t = [dx_B, dy_B, dz_B, dN_{AB}^{ij}, dN_{AB}^{ik}, \dots, dN_{AB}^{in}] \quad 3.17$$

which can be partitioned as follows:

$$x_t = \begin{bmatrix} c x_t & a x_t \end{bmatrix} \quad 3.18$$

The least squares best estimates of the parameters, denoted $\hat{\mathbf{x}}_t$ are obtained by minimising the sum of the squared residuals $\mathbf{v}^T \mathbf{v}$. The solution to the least squares problem is given by:

$$\hat{\mathbf{x}}_t = \hat{\mathbf{x}}_{t-1} + (\mathbf{A}_t^T \mathbf{A}_t)^{-1} \mathbf{A}_t^T \mathbf{L}_t \quad 3.19$$

and the normal equation matrix is

$$\mathbf{N} = \mathbf{A}_t^T \mathbf{A}_t \quad 3.20$$

The normal matrix used in the simulation program is inverted using the Cholesky decomposition method given in (3.5.2).

The initial phase ambiguities represent the integer number of wavelengths between the receiver and the satellite at the start of carrier phase tracking.

The double difference observable has the effect of reducing many errors associated with raw phase measurements. The only terms which are left are the station coordinate parameters and phase ambiguities (expression 3.17). So once we formed the observation equation, the situation can be solved according to usual principles, as stated earlier, minimising the sum of the squared of residuals. Although we know that these ambiguity terms $\hat{\mathbf{a}}_t$ should be integers, but unfortunately there is no simple method for forcing them to be integers. Ideally, values for unknown parameters obtained from a preliminary solution will be close to integers. These estimates are rounded to the nearest integer and the least squares solution is repeated with the biases terms held fixed at these values.

Before constraining the ambiguity values, the coordinate parameter vector must converge to zero (i.e, $\mathbf{x}_t = 0$), this means that the ambiguity values are sufficiently close to an integer and can be rounded. Constraint of a bias value to its correct integer improves the estimation of the other biases. This is due to mathematical correlation that exists between double difference that share a reference satellite.

So if the final solution vector $\mathbf{x}_t$ approaches to zero. Then the residuals can be found from expression 3.16, which will be:

$$\mathbf{v}_t = -\mathbf{L}_t \quad 3.21$$

hence, the sum of squared residuals are given as

$$\mathbf{v}_t^T \mathbf{v}_t = \mathbf{L}_t^T \mathbf{L}_t \quad 3.22$$

Suppose we have a case that these ambiguities are not close to an integer number; and by having any kind of noise in the system it is seriously effect the confident to resolve these ambiguities. If this is the situation then the first thing to do is to fix these to nearest integer and repeat the least squares solution. Then we do the whole process again and statistical tests are then applied to decide whether the best integer biases are selected. For example by adding +1 or -1 to the first integer and leaving others the same, and this procedure is repeated for all the ambiguities. So there are many combinations in which we have some high, some low and some negatives values.

The whole point of this process (the least squares process) is to minimize the sum of squares of residuals. If the integer ambiguities are fixed to wrong integers then the solution is even worse than the floating solution, and if it is fixed to the wright integer then the solution is much better than the float solution.

Then the question arises, how to be sure that we got the right one ? Suppose we got the best one, but suppose the best one is marginally better than the second best, what we are looking for is the one which absolutely stands out as being much better than the others. The key indicator of the results obtained, based on the ratio of the sum of squares of the residuals of the second fixed solution divided by the sum of squares residuals of the best fixed solution

$$\text{Ratio} = \frac{(\sum v^2)_2}{(\sum v^2)_1} \geq 3 \quad 3.23$$

If ratio = 3, it means that the best solution is three times better than the second best, then it can be said that the integers have been fixed to the right values.

3.5.2 Matrix preparation within the procedures

Least squares is a technique whose application is greatly simplified by the use of matrices which are also a useful device in the programming of computers.

The Pascal procedures which are being used in the GPS_baseline program for least squares process are: *mtranspose*, *minverse* and *contribute*. The first two procedures was written by *King* (1991). The *mtranspose* simply computes the transpose matrix. The *minverse*, uses Choleski's method; in which the matrix is divided into a lower and upper triangular matrix L and L^T such that, $\text{matrix} = L \times L^T$. From this it follows that,

$$L^{-1} \times L = (L^T)^{-1} \quad 3.24$$

The elements can be computed by a process of elimination. As it is not necessary to know the off diagonal elements of $(L^T)^{-1}$ which are not equal to zero, $(L^T)^{-1}$ is calculated by inverting the diagonal elements only. A full description of Choleski's method is given later.

The procedure *contribute* is used to form the normal matrix by the method of contribution. The observation equation in this program is in the form of a one dimensional array (*obs_vec*). The elements at the zero position are the "observed minus computed" values. Each time when an observation equation (*obs_vec*) is formed, *contribute* will test each element inside (*obs_vec*) to see whether it is zero or not. If it is zero, *contribute* will skip that element and continue testing until a non-zero element is found, then it will calculate the cross product of that element with all the other coefficients as well as itself. After doing that, it will add them to the corresponding elements inside the normal matrix N . At the same time *contribute*

will calculate the products of the "observed minus computed" values with all the other coefficients in (obs_vec), then it will add these values to the array (d_vec), which represents the matrix $\hat{A}^T L_t$ in the standard least squares equation 3.19.

Formation of the normal matrix with the method of contribution has the advantages of not having to store the entire coefficients of matrix A_t and the vector L_t .

Using an algorithm based on the **Cholesky decomposition** method the vector matrix of the best estimates of the parameters $\hat{x}_t$ was found. The technique can be demonstrated as:

Step 1

Decompose N into LL^T as follows:

$$\begin{pmatrix} L_{11} & 0 & 0 & 0 \\ L_{21} & L_{22} & 0 & 0 \\ L_{31} & L_{32} & L_{33} & 0 \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ L_{n1} & L_{n2} & L_{n3} & L_{nn} \end{pmatrix} \begin{pmatrix} L_{11} & L_{21} & L_{31} & L_{n1} \\ 0 & L_{22} & L_{32} & \cdot \\ 0 & 0 & L_{33} & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & 0 & L_{nn} \end{pmatrix} = \begin{pmatrix} N_{11} & N_{12} & N_{13} & N_{nn} \\ N_{21} & N_{22} & N_{23} & \cdot \\ N_{31} & N_{32} & N_{33} & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ N_{n1} & N_{n2} & N_{n3} & N_{nn} \end{pmatrix} \quad 3.25$$

from ordinary rules of matrix multiplication

$$L_{11}^2 = N_{11} \quad 3.26$$

$$L_{11}L_{21} = N_{12} \text{ etc} \quad 3.27$$

Step 2

Forward substitution:

Once L is found then, $Nx = b$ becomes

$$LL^T x = b \quad 3.28$$

let

$$L^T x = f \quad 3.29$$

therefore

$$\mathbf{L} \mathbf{f} = \mathbf{b} \quad 3.30$$

$$\begin{pmatrix} L_{11} & 0 & 0 & 0 \\ L_{21} & L_{22} & 0 & 0 \\ L_{31} & L_{32} & L_{33} & 0 \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ L_{n1} & L_{n2} & L_{n3} & L_{nn} \end{pmatrix} \begin{pmatrix} f_1 \\ f_2 \\ f_3 \\ \cdot \\ \cdot \\ f_n \end{pmatrix} = \begin{pmatrix} b_1 \\ b_2 \\ b_3 \\ \cdot \\ \cdot \\ b_n \end{pmatrix} \quad 3.31$$

again using basic rules of matrix algebra we obtain the column vector $\mathbf{f}$.

Step 3

Backwards substitution

$$\begin{pmatrix} L_{11} & L_{21} & L_{31} & L_{n1} \\ 0 & L_{22} & L_{32} & \cdot \\ 0 & 0 & L_{33} & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & 0 & L_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ \cdot \\ \cdot \\ x_n \end{pmatrix} = \begin{pmatrix} f_1 \\ f_2 \\ f_3 \\ \cdot \\ \cdot \\ f_n \end{pmatrix} \quad 3.32$$

hence the solution for the unknowns.

What is particularly interesting here is that as $\mathbf{N}$ is symmetrical only just over half of this matrix needs to be kept in storage. Also once each item within the $\mathbf{N}$ matrix has been used to obtain the values within $\mathbf{L}$ then the L_{ij} term can replace the N_{ij} term in store.

CHAPTER FOUR

RESULTS AND ANALYSIS

4.1 Introduction

The first six to seven weeks of this work were spent on familiarisation with GPPS package and in obtaining results for different approaches to processing the Isle of Wight data which was taken from a two-day GPS campaign (27-28th March, 1992). In the middle section of the summer a Pascal simulation program was written in order to compare and assess the GPPS results obtained, based on the ratio between the squared residuals of the best and the second best fixed solution (which will be described from here on as the ratio). This chapter will describe the results achieved with the GPPS during this initial period and, also shows the results obtained from the GPS_baseline simulation program, in the middle of the summer and finally, some general conclusion will be drawn about the effects of different approaches for both programs.

Prior to these it is necessary to describe the situation that existed during the campaign in terms of data that had been collected. The two-day Isle of Wight observation campaign incorporated five stations. The three lines are sketched in figure 4.1. These lines had been computed using different linear combinations carrier phases, the default values supplied by GPPS (20°C, 50% humidity and 1010mbars pressure for each station). This campaign was carried out during a field course for the Geodesy students from the University College London. In order to give all students hands on experience with the receiver, each person was involved in the planning and collection of GPS observations. The initials of the operator for each station were written onto the site file via the receiver, so any problems could

be referred back to them but site information form was not collected which meant for example that the antenna heights tagged in the receiver could not be confirmed. Data was collected using two Ashtech Instrument LM-XII dual frequency GPS receivers. The observation rate was 20 seconds for all tracked satellites. Figure 4.2 shows the positions of the observed GPS satellites in terms of azimuth and elevation as seen from the Isle of Wight. The satellites are identified by their PRN numbers. All satellites are observed above an elevation of 15 degrees; satellites 03 and 20 are rising, satellites 12 and 13 are setting.

An approximately one hour period observation records of these two days was found to be free of any cycle slips and gross errors.

Prior to the start of the project a fair amount of work had already been done on the data. The main aim born in mind whilst further processing was carried out was to try and improve the quality of lines using different processing approaches by the facilities provided by GPPS software.

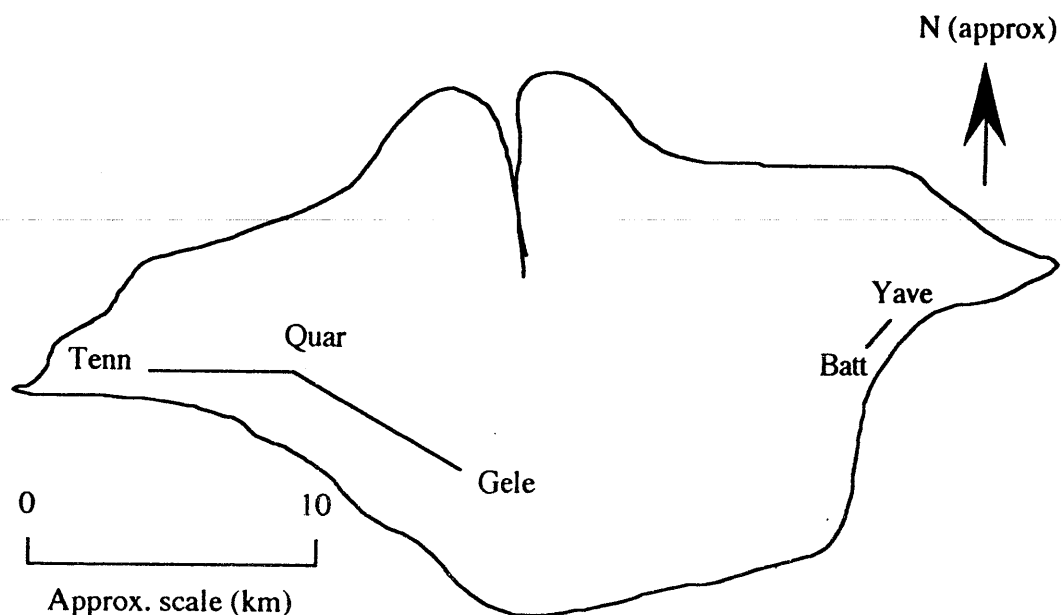


Fig.4.1 Isle of Wight Test Baselines (not to scale).

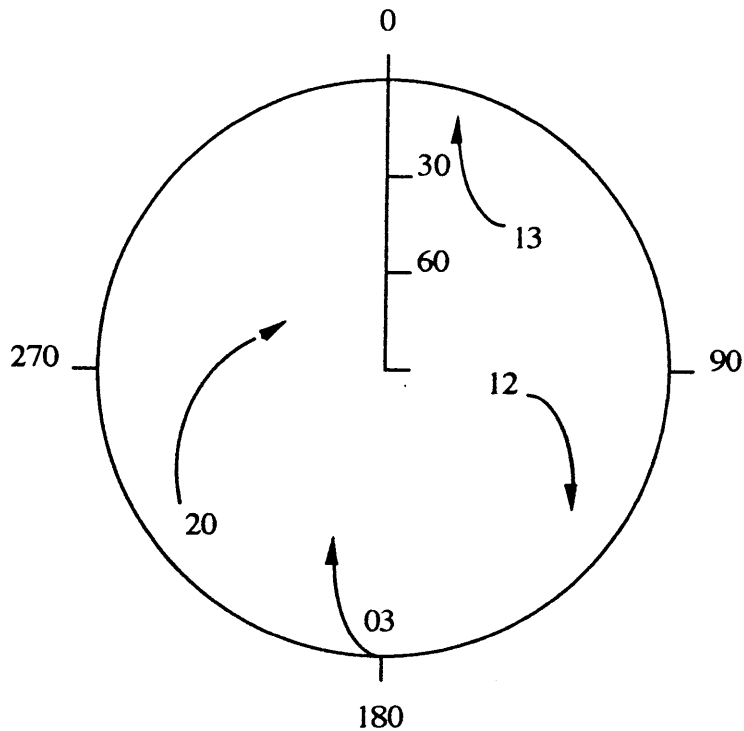


Fig.4.2 Polar plot of GPS satellites, Isle of Wight, 27th Mar.1992, day 087.

4.2 GPPS results

Having established the technique for looking at the bendata files via the Filetool program module it was therefore possible to look at the effect of using different carrier frequencies and to consider the quality of the linear combinations. Different line computations had been carried out, all of these have triple difference and float double difference solutions, all with the exception of the ionospheric combination lines have a fixed double difference solution of varying quality. Different approaches were tried on all the lines which demonstrated the varying qualities that had been achieved. The results obtained were summarised by each day including line lengths, observation time and actual vectors values recorded. For each line there are three possible measures of quality that were also noted; the root mean square of each solution (though this statistic seemed to be rather insensitive), the sum of standard errors of the coordinates differences and the ratio concerning best

to second best fixed difference solutions. This ratio was to be taken as the generally used indicator of the quality of the solution. Once the data had been collected from all the different summary files it was a simple matter to transfer it to the Microsoft Excel software package from which all of the following graphs and tables are generated.

Table 4.1 2 kilometer baseline processing output.

SESSION A , 2 km line								
1	2	3	4	5	6	7	8	9
Epoch#,(min)	dx (m)	dy (m)	dz (m)	dx1-2,...	dy1-2,...	dz1-2,...	Ratio, Sol	rms (m)
Processing only L1 data								
200 (66)	-998.882	1588.8796	801.0992				123.7 FXD	0.007053
180 (60)	-998.8821	1588.8797	801.099	0.0001	-1E-04	0.0002	82.72 FXD	0.007202
160 (53)	-998.8825	1588.8797	801.0977	0.0005	-1E-04	0.0015	68.95 FXD	0.007095
140 (46)	-998.8819	1588.8797	801.0978	-1E-04	-1E-04	0.0014	38.94 FXD	0.007354
120 (40)	-998.8819	1588.8798	801.0974	-1E-04	-2E-04	0.0018	25.31 FXD	0.00757
100 (33)	-998.8814	1588.8796	801.0974	-6E-04	0	0.0018	11.02 FXD	0.007955
80 (26)	-998.8807	1588.8797	801.0977	-0.001	-1E-04	0.0015	3.64 FXD	0.008339
70 (23)	-998.9445	1588.8436	801.0744	0.0625	0.036	0.0248	6.6 FXD	0.005985
60 (20)	-998.9398	1588.8255	801.0741	0.0578	0.0541	0.0251	3.66 FXD	0.006134
Processing L2 data								
200	-998.8624	1588.8763	801.0901				172.4 FXD	0.007153
180	-998.8614	1588.876	801.0903	-1E-03	0.0003	-2E-04	100.31 FXD	0.007263
160	-998.8613	1588.8757	801.0888	-0.001	0.0006	0.0013	70.78 FXD	0.007063
140	-998.8609	1588.8754	801.0894	-0.001	0.0009	0.0007	51.43 FXD	0.006927
120	-998.8609	1588.8751	801.089	-0.001	0.0012	0.0011	23.81 FXD	0.006985
100	-998.8605	1588.8748	801.0878	-0.002	0.0015	0.0023	13.55 FXD	0.006836
80	-998.8618	1588.8742	801.0859	-6E-04	0.0021	0.0042	5.3 FXD	0.006941
70	-998.8617	1588.8738	801.0853	-7E-04	0.0025	0.0048	3.11 FXD	0.00662
60	-998.956	1588.9269	801.0582	0.0936	-0.051	0.0319	7.28 FXD	0.005567
Processing only L1 corrected data (L1/L2 ionosphere free combination)								
200	-998.9015	1588.8963	801.1535				N/A - FLT	0.012796
180	-998.905	1588.8839	801.1515	0.0035	0.0124	0.002	N/A - FLT	0.013052
160	-998.8985	1588.8746	801.1443	-0.003	0.0217	0.0092	N/A - FLT	0.013334
140	-998.8881	1588.862	801.1385	-0.013	0.0343	0.015	N/A - FLT	0.01352
120	-998.8916	1588.8292	801.1307	-0.01	0.0671	0.0228	N/A - FLT	0.01365
100	-998.8663	1588.7987	801.1334	-0.035	0.0976	0.0201	N/A - FLT	0.013808
80	-998.9545	1588.7474	801.1157	0.053	0.1489	0.0378	N/A - FLT	0.013451
70	-998.9648	1588.7036	801.1258	0.0633	0.1927	0.0277	N/A - FLT	0.013576
60	-998.9866	1588.6445	801.1364	0.0851	0.2518	0.0171	N/A - FLT	0.013099

Processing L1-L2 data, wide lane (86.2 cm)								
200	-998.9599	1588.8929	801.1286				118.2 FXD	0.027826
180	-998.9641	1588.8948	801.127	0.0042	-0.002	0.0016	72.87 FXD	0.02769
160	-998.9673	1588.8964	801.1266	0.0074	-0.004	0.002	41.39 FXD	0.02786
140	-998.9691	1588.8973	801.125	0.0092	-0.004	0.0036	30.47 FXD	0.02809
120	-998.9702	1588.9	801.1245	0.0103	-0.007	0.0041	15.37 FXD	0.02803
100	-998.9627	1588.8988	801.1306	0.0028	-0.006	-0.002	7.4 FXD	0.026243
80	-998.8132	1588.6958	801.1784	-0.147	0.1971	-0.05	4.95 FXD	0.026575
70	-998.7598	1588.6189	801.1896	-0.2	0.274	-0.061	3.22 FXD	0.024797
60	-998.9406	1588.4322	801.1125	-0.019	0.4607	0.0161	3.47 FXD	0.031685
processing L1 + L2 data, narrow lane (10.7 cm)								
200	-998.8744	1588.8785	801.0948				54 - FXD	0.005777
180	-998.8742	1588.8784	801.0948	-2E-04	1E-04	0	30.0 - FXD	0.005933
160	-998.8744	1588.8783	801.0936	0	0.0002	0.0012	21.4 - FXD	0.005756
140	-998.8743	1588.8782	801.0939	-1E-04	0.0003	0.0009	14.6 - FXD	0.005815
120	-998.8735	1588.8781	801.0938	-9E-04	0.0004	0.001	7.19 - FXD	0.006109
100	-998.8732	1588.8779	801.0932	-0.001	0.0006	0.0016	3.92 - FXD	0.006189
80	-998.9201	1588.8702	801.0581	0.0457	0.0083	0.0367	0 - FRD	0.004899
70	-998.9506	1588.8747	801.0671	0.0762	0.0038	0.0277	3.36 - FXD	0.004814
60	-998.9593	1588.8633	801.0754	0.0849	0.0152	0.0194	0 - FRD	0.004874

The tedious collection of data was well rewarded by the Excel package which enabled the nature of any possible relationships within the data to be quickly and efficiently investigated.

Tables 4.1 and 4.2 summarises the results obtained for the carrier linear combinations. Several informations are given in both tables, column 1 the different time epochs starts with the entire data set 4000 seconds (around 66 minutes) and ends up to 1200 seconds (20 minutes). In column 8 the ratio is given for each wavelength at a number of different epochs, this ratio is used as a key indicator in any manufacturers software, almost all the analysis and the results obtained from both programs in this project are based on this indicator; columns 5, 6 and 7 are generated from the line vectors of columns 2, 3 and 4; by taking the line vectors processed at 200 epochs as a reference and subtracting all the remaining vectors processed at different epochs. In my view these do not tell us much but since some work was carried out at the early stages of the project I am showing them as a matter of interest. Graphs in appendix four compare 2km with 8km baselines results for the narrow and the wide lane wavelengths.

Table 4.2 8 kilometer baseline processing output.

SESSION C , 8 km line								
1	2	3	4	5	6	7	8	9
Epoch#,(min)	dx (m)	dy (m)	dz (m)	dx1-2...	dy1-2...	dz1-2...	Ratio, Sol	rms (m)
Processing only L1 data								
200,66min	-3455.012	-6864.307	2690.092				10.1 FXD	0.017592
180 (60)	-3455.011	-6864.333	2690.119	-0.001	0.0261	-0.027	10.26 FXD	0.017614
160 (53)	-3455.012	-6864.342	2690.126	-2E-04	0.0349	-0.034	10.99 FXD	0.018045
140 (46)	-3455.01	-6864.337	2690.134	-0.002	0.0305	-0.043	8.01 FXD	0.019121
120 (40)	-3455.013	-6864.307	2690.107	0.0008	0.0007	-0.015	8.57 FXD	0.017814
100 (33)	-3455.02	-6864.278	2690.049	0.0077	-0.028	0.0426	6.49 FXD	0.014906
80 (26)	-3455.17	-6864.632	2690.045	0.1578	0.3256	0.0468	0 - FRD	0.009799
60 (20)	-3455.178	-6864.592	2689.985	0.1659	0.2858	0.1068	0 - FRD	0.009751
Processing L2 data								
200	-3454.99	-6864.316	2690.114				10.32 FXD	0.021415
180	-3454.988	-6864.347	2690.144	-0.002	0.0307	-0.03	9.98 FXD	0.021353
160	-3454.99	-6864.351	2690.145	-2E-04	0.0346	-0.031	8.95 FXD	0.022156
140	-3454.989	-6864.35	2690.149	-5E-04	0.0339	-0.035	6.99 FXD	0.023271
120	-3454.992	-6864.318	2690.115	0.0022	0.0021	-0.001	5.67 FXD	0.022151
100	-3455.004	-6864.277	2690.019	0.0145	-0.039	0.0946	12.15 FXD	0.013881
80	-3455.011	-6864.276	2689.977	0.0207	-0.04	0.1375	5.25 FXD	0.013
60	-3455.154	-6864.563	2689.975	0.1655	0.2163	0.1693	0 - FRD	0.012414
Processing only L1 corrected data (L1/L2 ionosphere free combination)								
200	-3454.956	-6864.234	2690.046				N/A - FLT	0.029348
180	-3454.971	-6864.299	2690.073	0.0143	0.0649	-0.028	N/A - FLT	0.021347
160	-3454.994	-6864.383	2690.099	0.0377	0.149	-0.053	N/A - FLT	0.020739
140	-3455.018	-6864.452	2690.132	0.0614	0.2181	-0.086	N/A - FLT	0.020165
120	-3455.101	-6864.578	2690.14	0.1443	0.3437	-0.094	N/A - FLT	0.018173
100	-3455.171	-6864.723	2690.142	0.2147	0.4894	-0.097	N/A - FLT	0.016999
80	-3455.269	-6864.833	2690.103	0.3131	0.5991	-0.057	N/A - FLT	0.016245
60	-3455.216	-6864.622	2689.996	0.2602	0.3876	0.0495	N/A - FLT	0.014635
Processing L1-L2 data, wide lane (86.2 cm)								
200	-3455.087	-6864.278	2690.014				70.84 FXD	0.037036
180	-3455.087	-6864.293	2690.034	0.0003	0.0147	-0.02	52.93 FXD	0.03756
160	-3455.089	-6864.31	2690.055	0.0018	0.0324	-0.041	44.52 FXD	0.038512
140	-3455.085	-6864.294	2690.087	-0.002	0.0164	-0.073	32.48 FXD	0.038837
120	-3455.088	-6864.267	2690.076	0.0009	-0.011	-0.061	21.56 FXD	0.03914
100	-3455.081	-6864.271	2690.118	-0.006	-0.007	-0.104	18.49 FXD	0.039721
80	-3455.078	-6864.208	2690.06	-0.009	-0.07	-0.046	9.22 FXD	0.038057
60	-3455.079	-6864.17	2689.938	-0.008	-0.108	0.0763	9.96 FXD	0.02867
50	-3455.076	-6864.171	2689.961	-0.012	-0.107	0.0532	3.95 FXD	0.030445
processing L1 + L2 data, narrow lane (10.7 cm)								
200	-3454.811	-6864.146	2690.08				0 - FRD	0.015567
180	-3454.831	-6864.201	2690.1	0.02	0.0554	-0.02	0 - FRD	0.015447
160	-3454.831	-6864.225	2690.099	0.0196	0.0793	-0.019	0 - FRD	0.015073
140	-3454.836	-6864.253	2690.102	0.0247	0.1076	-0.023	0 - FRD	0.015311
120	-3454.882	-6864.307	2690.094	0.0706	0.1608	-0.014	0 - FRD	0.015312
100	-3455.02	-6864.426	2690.049	0.2093	0.2805	0.0302	0 - FRD	0.011134
80	-3455.02	-6864.278	2690.049	0.2086	0.1325	0.0304	0 - FRD	0.010003
60	-3455.167	-6864.58	2689.981	0.3562	0.4339	0.099	0 - FRD	0.010332

The root mean square of each solution is given in the last column, though this statistic seemed to be rather insensitive. However, these are plotted against the epoch time and the graphs are given in appendix four.

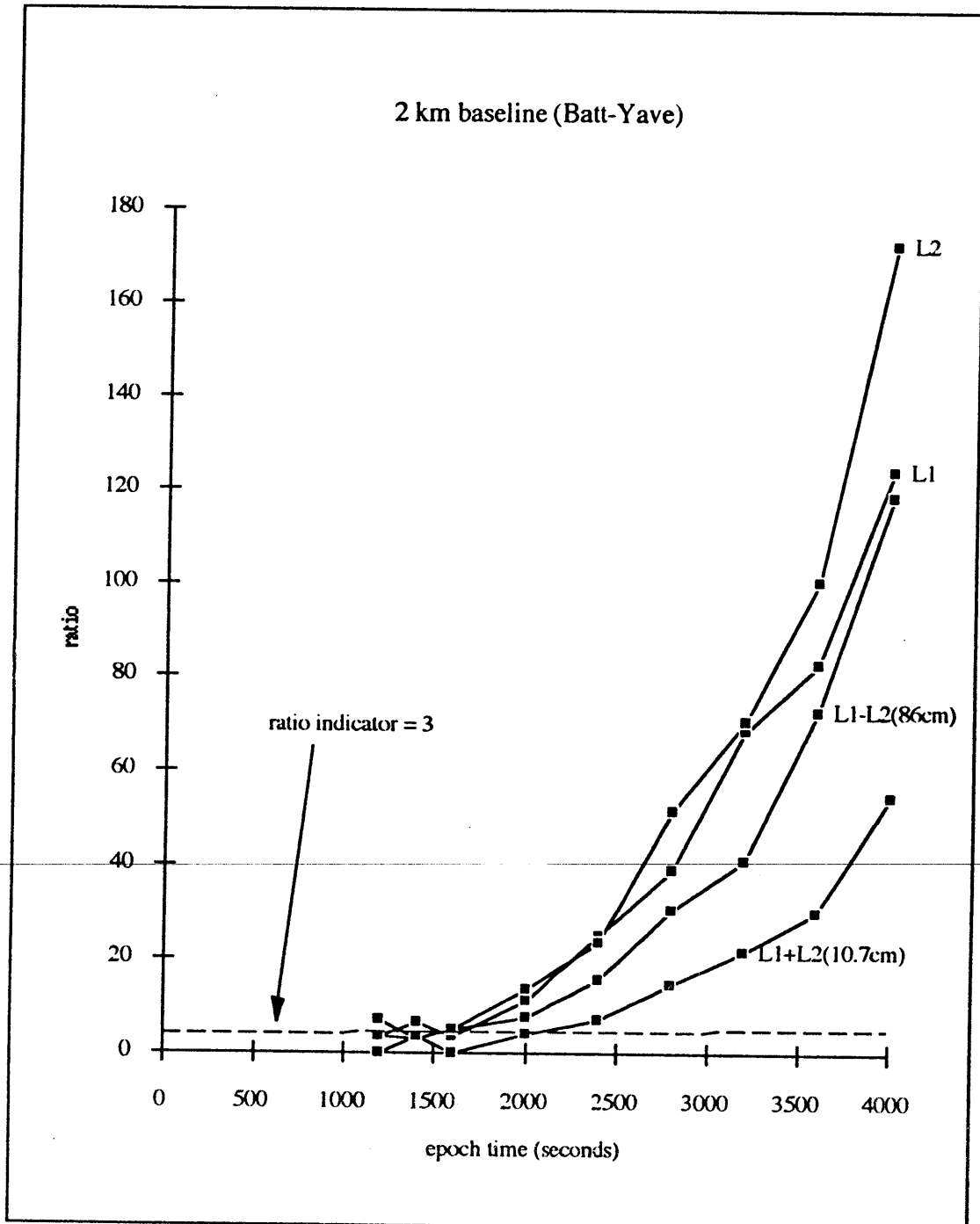


Fig.4.3 Fixed double difference ratio vs number of epochs using different linear combinations on the 2 km baseline.

Comparisons of data processing using different linear combinations for 2km (Batt-Yave) and 8km (Gele-Quar) are shown in figures 4.3 and 4.4 respectively. As it is clearly shown the data was processed by cutting down the number of epochs in order to see its effects on the ratio (i.e, resolving phase ambiguities).

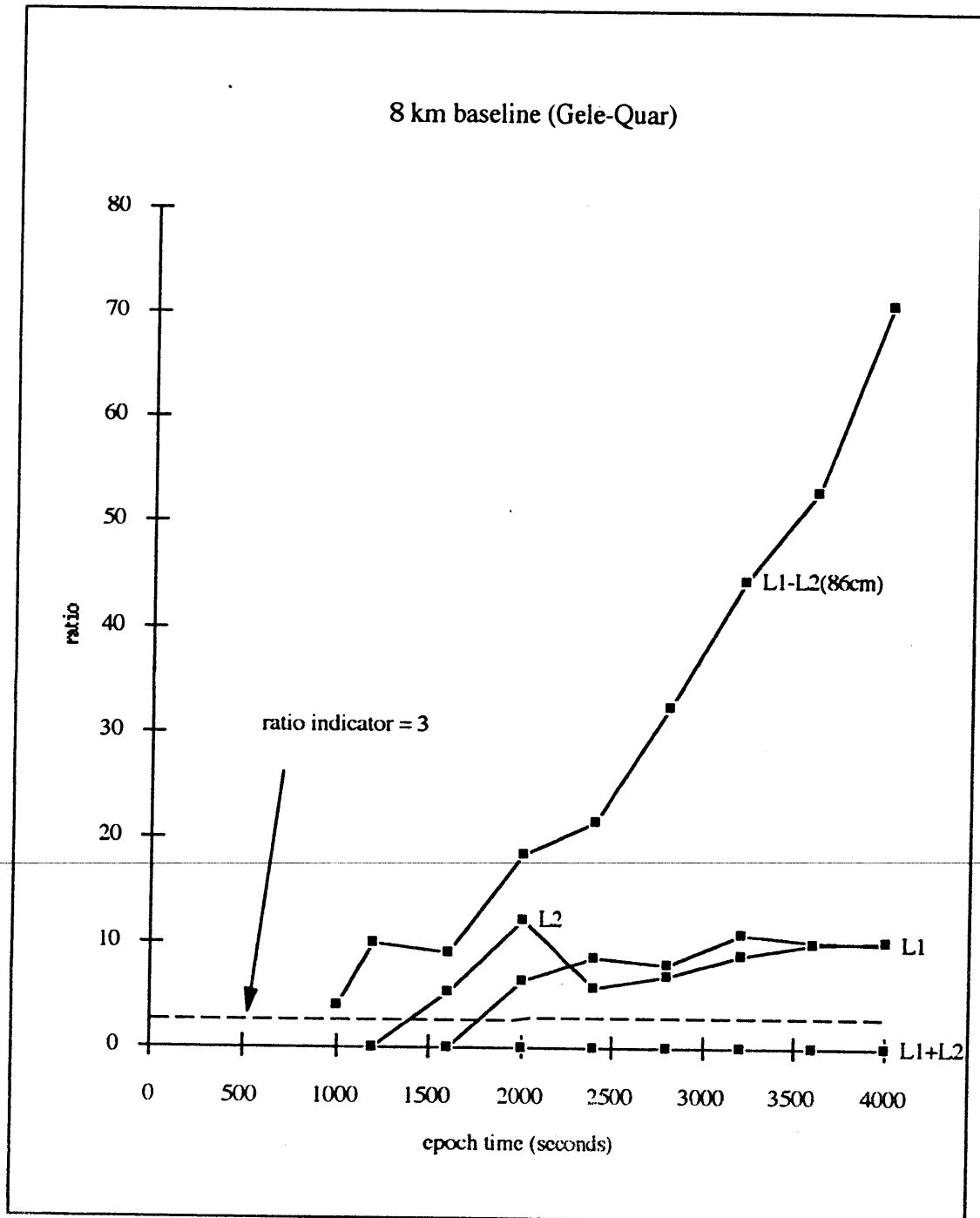


Fig.4.4 Fixed double difference ratio vs number of epochs using different linear combinations on the 8 km baseline.

The combination of dual frequency GPS data into so-called wide lane combinations for 8km compared with 2km baseline has proven very effective for resolving phase ambiguities, particularly over the 8km baseline as shown clearly in the figures 4.3 and 4.4. For 2km baseline (the short line), separated double difference L1 and L2 solutions as it seems may be preferable as in figure 4.3.

For 2km baseline static operation, data collection could have been stopped after 1200 seconds (20 minutes), since the ratio had reached a value of more than 3. Time would have been better spent occupying another point in the survey.

For 8km baseline the situation is different again; data collection could have stopped after 20 minutes for the long wavelength combination of L1 and L2 phase ($\approx 86\text{cm}$) only, but for the separated double difference L1 and L2 solutions, the point needed to be occupied for at least 25 minutes to reach the safe allowable solution.

As has been discussed in chapter two, the narrow lane is mainly used over short lines and has the lowest noise level of all linear combinations and hence yields the best results. Its ambiguity is, however, difficult to resolve as can be indicated from its ratio, figure 4.4. Another possible measure of quality that has been looked at is the sum of the standard errors of the coordinate differences (σ_x , σ_y and σ_z) for each line; these values are given in meters. Each of these sigmas were squared to get the coordinate variances (m^2). In the following discussion we are interested in factors like epoch and coordinate variance of the fixed double difference solutions.

Different processing techniques can be compared in terms of their absolute accuracy on the three axis x, y and z. A small value of the coordinate variance represents a high quality solution. Figures 4.5, 4.6, 4.7 and 4.8 gives a general feeling for the data with which we are dealing and the effect of considering different epochs. The standard errors of the ionosphere free L1c and the wide-lane L1-L2 combinations coordinate differences were up to three times larger than those obtained when the L1 carrier and the narrow-lane L1+L2 were being used.

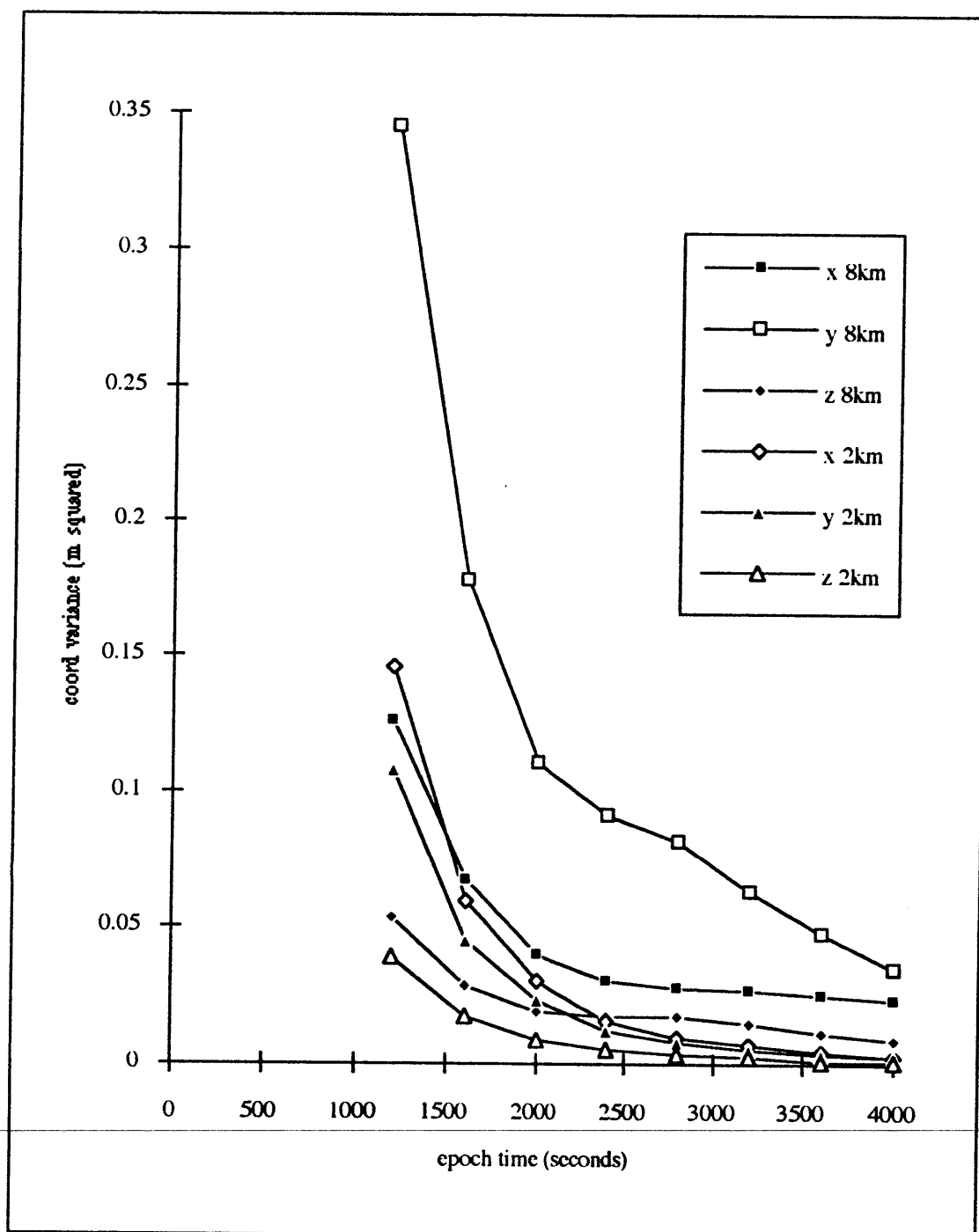


Fig.4.5 Coordinate precision convergence for free ionosphere combinations L1c (2km and 8km baselines)

Note that value coordinate variance for the ionosphere free combinations of L1 and L2 are given in squared meter and all the others are in squared cm. As it can be seen from the above graph that the 8km coordinate convergence time is almost twice as the 2km one.

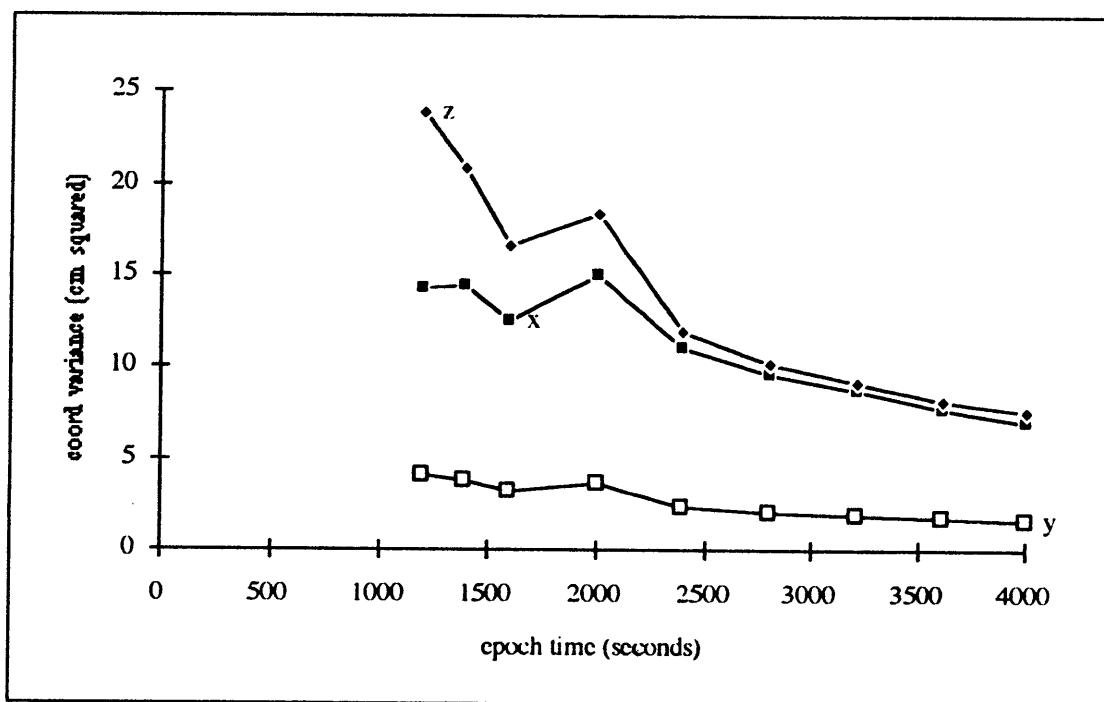


Fig.4.6 (a) Coordinate precision convergence for wide lane L1-L2 (2km baseline)

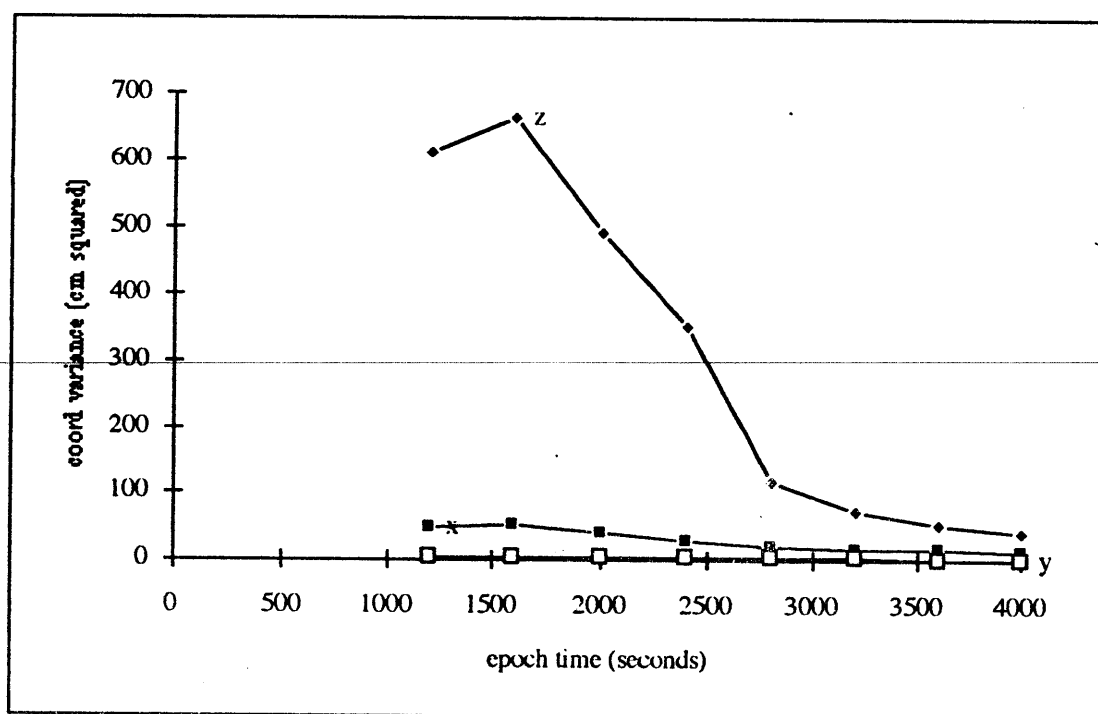


Fig.4.6 (b) Coordinate precision convergence for wide lane L1-L2 (8km baseline)

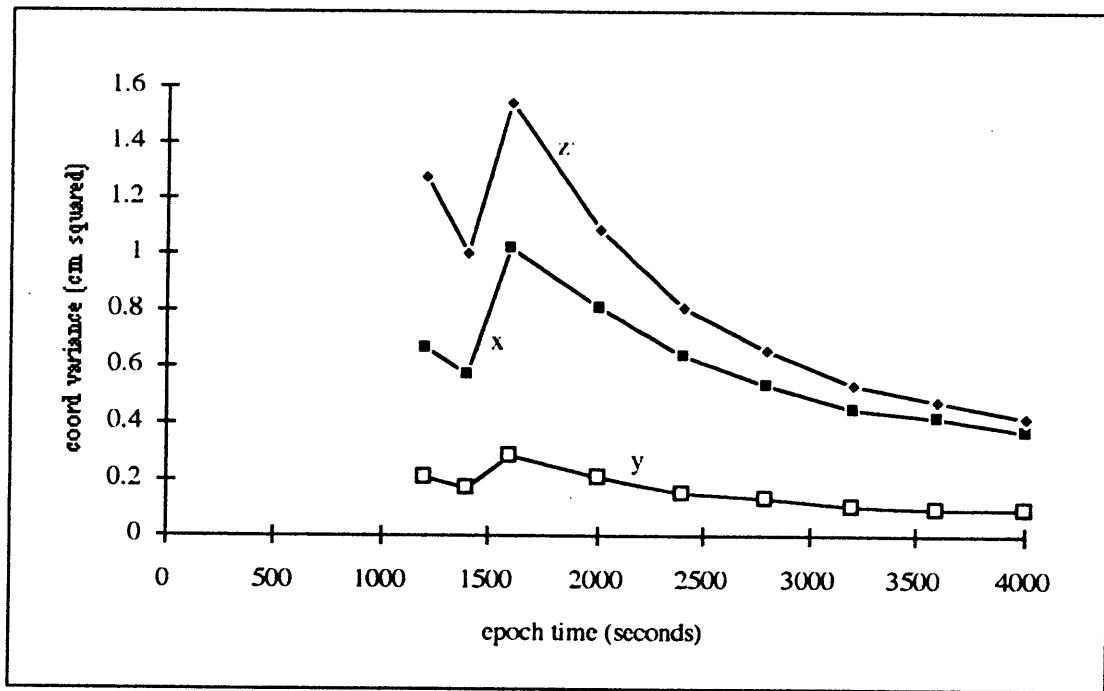


Fig.4.7 (a) Coordinate precision convergence for L1 (2km baseline)

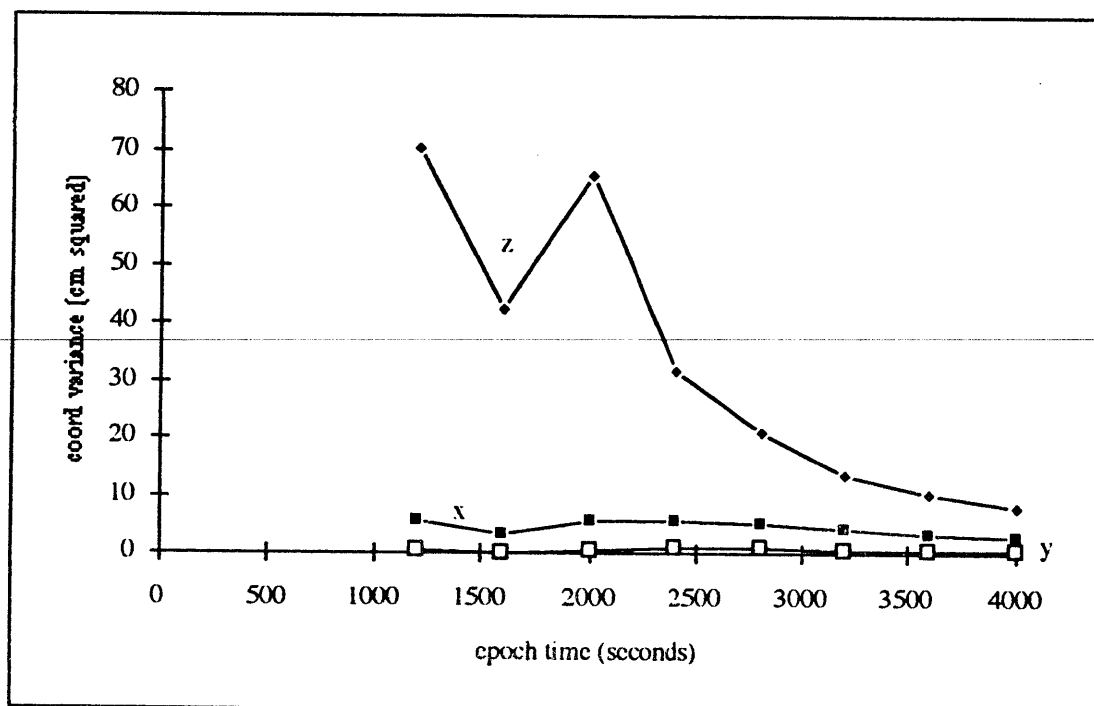


Fig.4.7 (b) Coordinate precision convergence for L1 (8km baseline)

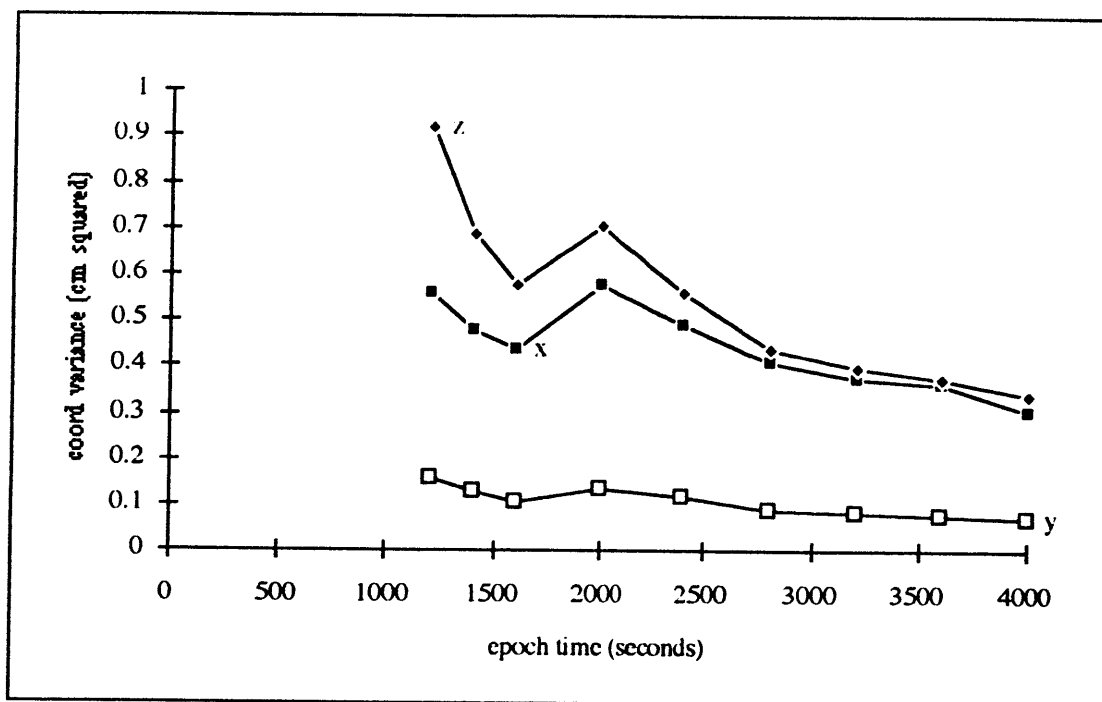


Fig.4.8 (a) Coordinate precision convergence for narrow lane L1+L2 (2km baseline)

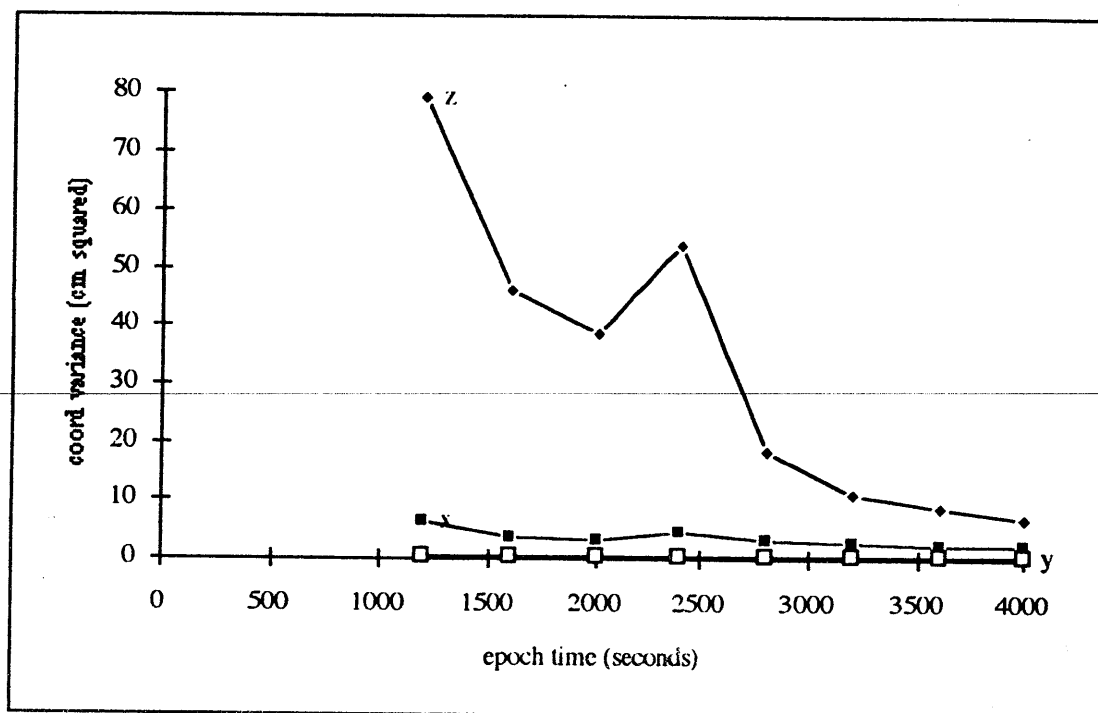


Fig.4.8 (b) Coordinate precision convergence for narrow lane L1+L2 (8km baseline).

Perhaps the main conclusion to be drawn from these graphs is that combinations of L1 and L2 carrier phase into wide-lane and ionosphere-free combinations magnify the measurement noise of the separated observables. For short lines, separated observables double difference L1 and L2 solutions may be preferable *Talbot* (1991). The L1c and the wide-lane can be grouped together in terms of coordinate convergence time and they are almost identical. Similarly this is true for the L1 carrier and the narrow-lane L1+L2.

4.3 The GPS_baseline simulation program results

Most of the middle summer weeks of the project were spent developing the GPS_baseline simulation program and in obtaining results for different approaches. This section will describe the results achieved during this period, as well as comparing these results with those obtained from GPPS.

It should be noted that the assessment of the most probable linear combinations and the reliability of the results obtained were based on the sum of the squares of the measurement residuals, hence the ratio.

Three aims were born in mind while processing was carried out. The first was to examine the quality of start coordinates by introducing approximately a 100m vector of uncertainty into the baseline as shown in figure 4.9 and seeing how it effected the baseline solution vector dx , etc. An example of an input file which contains these coordinate values is given in appendix three. The second aim was to carry out several tests for different noise levels; for example $\pm 1\text{mm}$, $\pm 0.1\text{mm}$, etc. These generated random noises were added each time to the double difference observable equation used in the program and the effects on the results while using different linear combination approaches were noted. Figure 4.10 shows a histogram of $\pm 1\text{mm}$ level of random noise, this is generated in the simulation program by a function (subprogram) noise. The number of times that a random noise (error)

lands in each class was plotted against its class interval on a block diagram, called a histogram. The sources of these errors are discussed in chapter two (2.9).

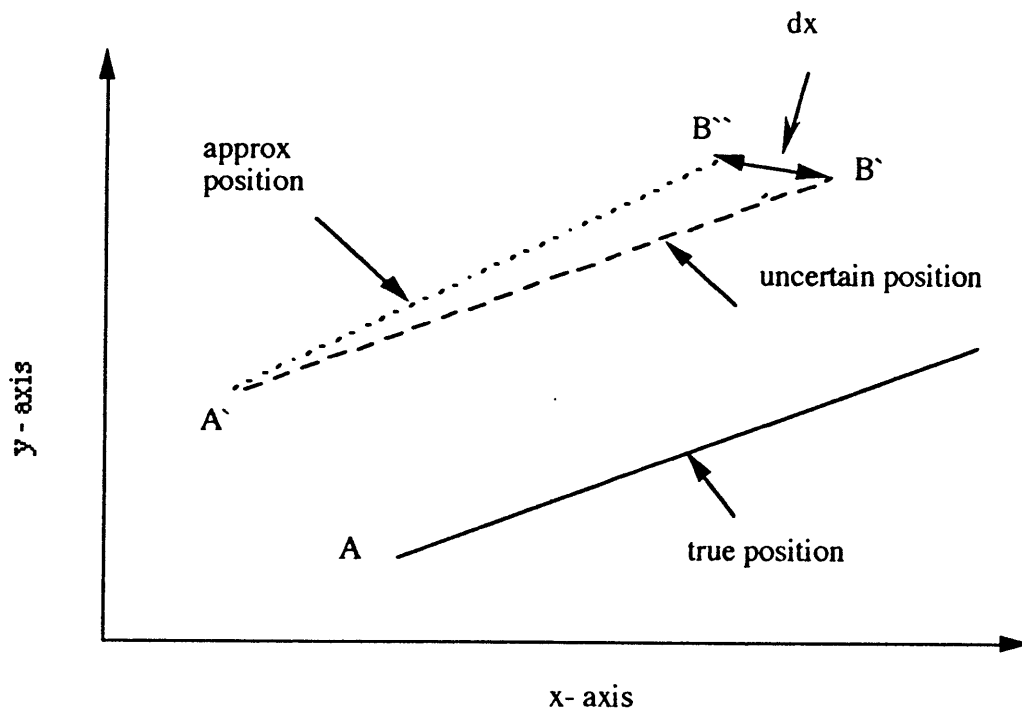


Fig.4.9 A baseline diagram

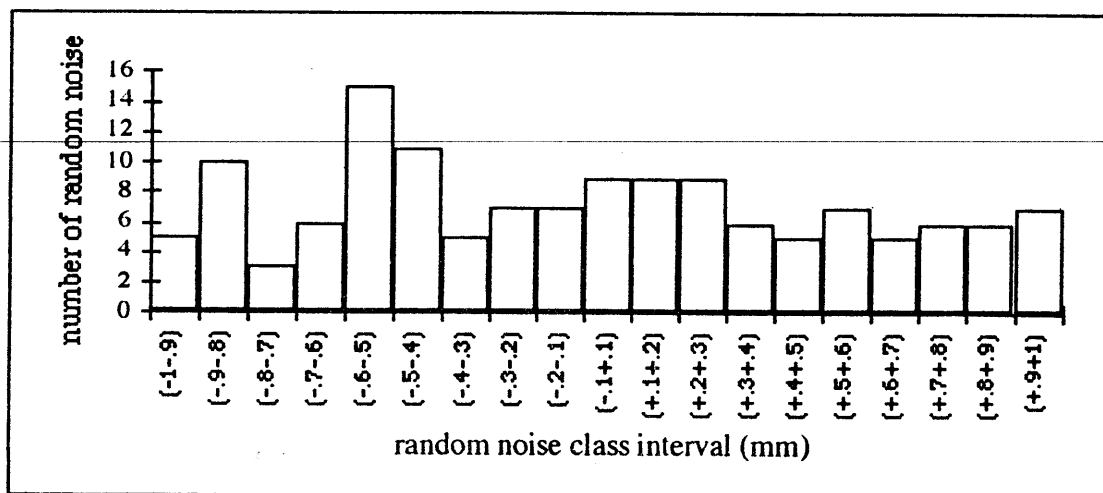


Fig.4.10 A histogram of ± 1 mm level of random noise.

Whilst working towards these first two aims a third general motive was to see how the quality of the ephemeris had an effect on the lines, unfortunately it was realised that there was not enough time to process and consider this third aim.

As a result of using the techniques mentioned above the 2km baseline was the only one which was tested, again because of time pressures non of these tests were carried out on the 8km baseline which was frustrating. Different approaches were tried on the 2km line which showed the varying qualities that had been achieved. For the purpose of the analysis the actual vector values were not of interest. For a line to process there are two measures of quality that were noted from the output file (an example is shown in appendix three). The solution vector dx shown in figure 4.9 and the sum of squares of the residuals of the best and the second best double difference solution, yields to the ratio which is used as an indicator of quality of the solution. Once these values had been collected from different approaches the following graphs are drawn.

It should be noted that several individual tests were carried out on the first and the second aims mentioned above but unfortunately non of these tests were giving the expected results so as to be compared to those results obtained from GPPS. For this reason it was decided to combine the two aims and see their effects on the baseline. Also some trials were carried out on the satellites geometry in the orbit, for example by grouping them all in one quadrant, or by using a different number of satellites, etc. Number of satellites, satellite positions (azimuth and elevation) and the coordinates of the 2km baseline were taken from the GPPS output file for the line (Batt-Yave). All these values are given in appendix three.

Figures 4.11, 4.12 and 4.13 demonstrate the result of trying to combine the effect of quality of start coordinates and different random noise levels separately. These figures compare different linear combinations solutions L1, L2 single frequency solutions, L1-L2 wide-lane, and L1+L2 narrow-lane fixed double difference

solutions. Different amounts of random noise level (± 0.1 , ± 0.5 and ± 1 mm) were incorporated into the double difference observable result. In the following discussion we try to examine and compare individual results obtained for each linear combination solution for the three different approaches. The separated double difference L1 and L2 solutions were generally of a higher quality but the differences were often only marginal. The data collection could have been stopped after 20, 27

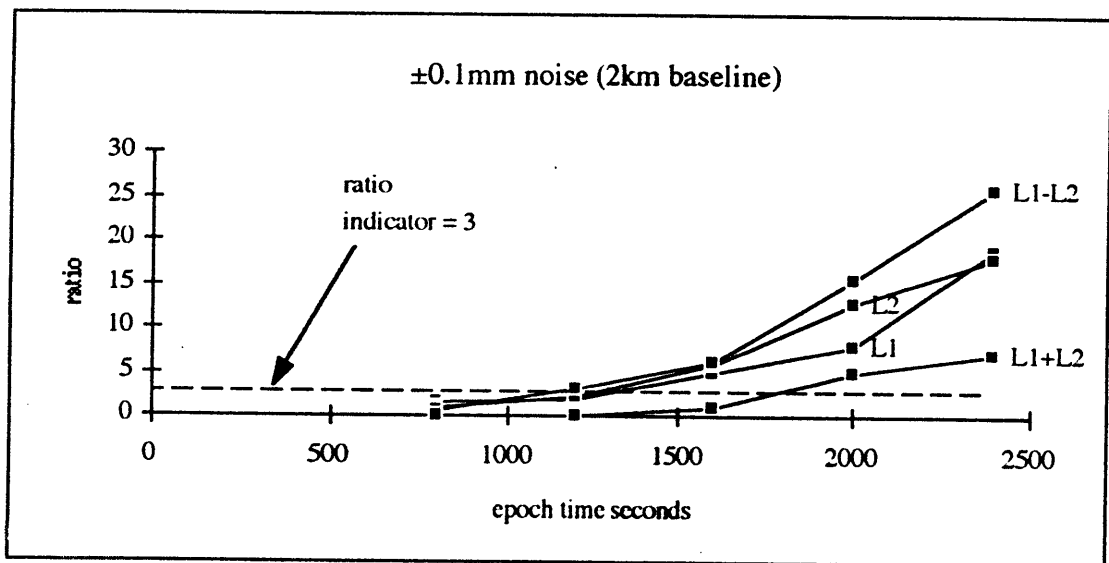


Fig.4.11 ratio vs number of epochs for ± 0.1 mm random noise level.

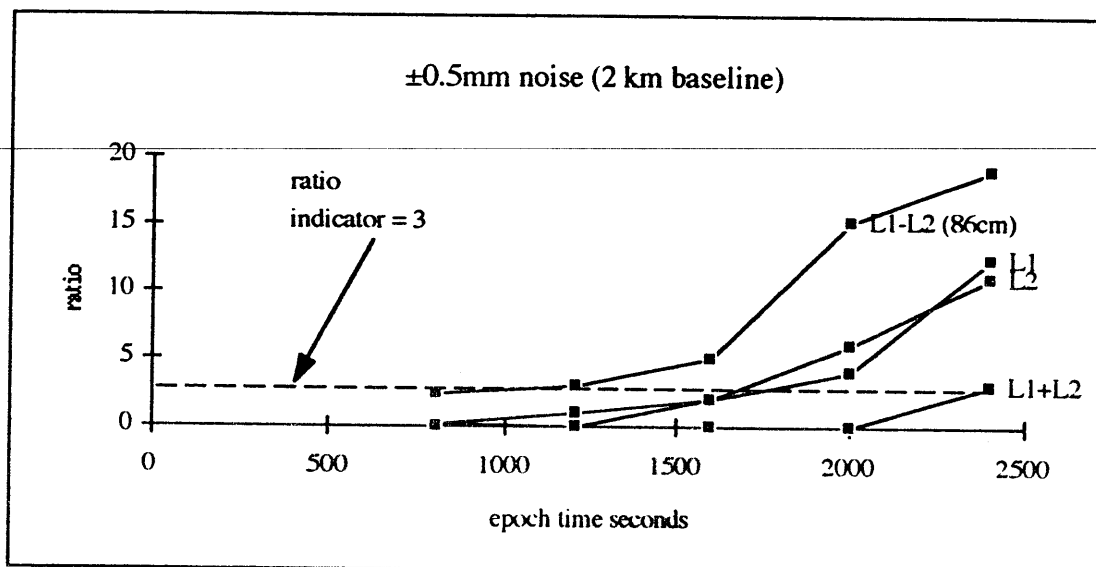


Fig.4.12 ratio vs number of epochs for ± 0.5 mm random noise level.

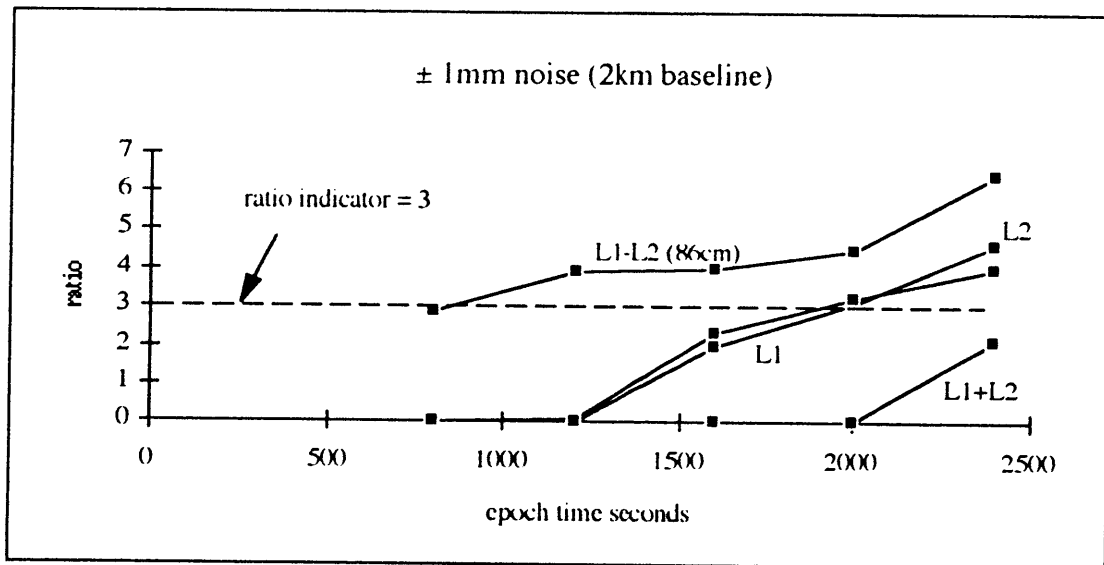


Fig.4.13 ratio vs number of epochs for ± 1 mm random noise level.

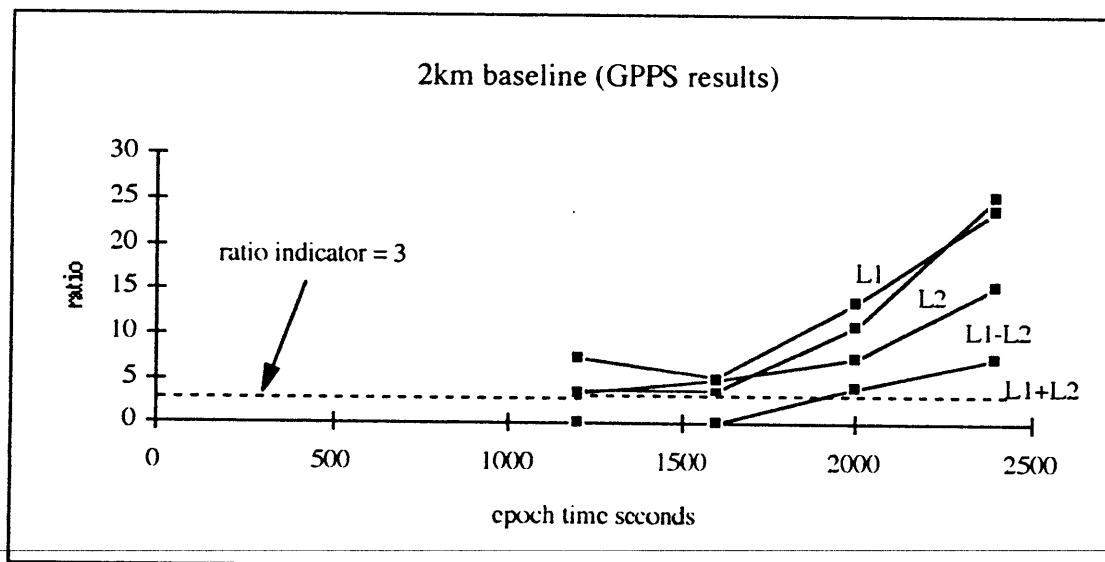


Fig.4.14 ratio vs number epochs 2km baseline (original figure 4.3).

and 34 minutes for 0.1, 0.5 and 1mm noise respectively, as it is shown by the key indicator (ratio = 3). As has already been discussed narrow lane is used for short lines, but due to an increase in the amount of noise level figure 4.13, its ambiguity was found difficult and needed more time to be resolved. These figures shows the correlation between epoch and the ratio for double difference solution. Confidence

in the successful processing of a line is always at a maximum when a high ratio value has been achieved.

Table 4.3 Comparison between GPPS and simulation results

epoch seconds	GPPS results	0.1mm	0.5mm	1mm
processing only L1 (19cm)				
2400	25.3	18.9	12.3	4.6
2000	11	8.1	4	3.1
1600	3.6	5.1	2.1	2
1200	3.7	2.1	1.1	0
800		1.6	0.2	0
processing only L2 (24cm)				
2400	23.8	18	11	4
2000	13.6	12.7	6	3.2
1600	5.3	6	2	2.3
1200	7.3	2.2	0	0.1
800		1.1	0.2	0
processing only L1-L2 (86cm)				
2400	15.4	25.8	19	6.4
2000	7.4	15.7	15.1	4.5
1600	5	6.3	5	4
1200	3.5	3.3	3	3.9
800		0.9	2.5	2.9
processing only L1+L2 (10cm)				
2400	7.2	7	3	2.1
2000	3.9	5.1	0.1	0
1600	0	1.1	0	0
1200	0	0	0	0
800		0	0	0

The underlying trend is clearly of an improvement in quality for all three types of solution with increase in observation length as it is can be seen from the above table.

CHAPTER FIVE

CONCLUSION AND FUTURE WORK

First, the GPPS results showed that the combination of dual-frequency data into the so-called wide-lane combinations has proven very effective for resolving phase ambiguities as it can be seen from the key indicator (ratio), particularly over the 8km baseline (figure 4.4), but on other hand it magnified the measurement noise as indicated by the values of the standard error of the coordinate σ_x , σ_y and σ_z shown in figure 4.6. This is also true for the ionospheric-free combinations L1c (figure 4.5). For the 2km baseline, the narrow-lane and the separated double difference L1 and L2 solutions are preferable since their measurement noise was three times lower (figures 4.7 and 4.8) compared to the wide-lane. Tests conducted on a 2 and 8km baseline revealed that all ambiguities (i.e ratio = 3) could be successfully isolated in less than 20 minutes with the long wavelength combinations.

Second, the GPS_baseline simulation program is still in the development stage. At the moment, the software is not perfect, failing to converge the solution vector dx to the submillimeter level when adding a 1mm or more noise to the observation equation. With the current version of the program the computing step which includes reading the data sets, processing the fixed double difference observable and computing the inverse and the sum of the squares of the residuals takes in the order of 45 to 60 minutes on an Apple Macintosh computer. Another drawback is that the user interaction is required during the estimation process once the input data file is specified. One advantage of the style in which the program was written lies in the fact that changes can be made relatively easily. If time had permitted one of the first avenues of investigation would have been to look more closely at the problems mentioned above, especially where the statistical tests are applied and the user

interaction is needed to decide whether the best integer biases are selected for each ambiguity term (discussed in chapter four), this would have been far too time consuming and tedious. In the event of any user wanting to modify the program GPS_baseline this should be found to be relatively straight forward as the procedures and functions for all necessary operations already exist within it.

Third, the results shown in figures 4.11, 4.12, 4.14 and 4.15 and table 4.3 are self-explanatory; these show the different amount of random noise contaminating the observations for different approaches. This brings us to the last and most interesting part of the analysis, the comparison between the GPPS and the simulation technique. In order to make a meaningful comparison it is necessary to take the following into account : the data that was used is not a real GPS data, although the same baseline coordinate was used and the satellite positions were almost (elevation and azimuth) similar to that of the Isle of Wight data, given in appendix three; the coordinate uncertainties for both stations were 100m vector in horizontal and vertical.

Certainly, the analysis of only three tests for 2km baseline can not be used to derive generally valid conclusions regarding these errors, but it is clear that the greater the amount of noise the greater the effects on the accuracy of a line which yields to an increase in the observation time.

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Appendix One

Examples of files from the GPPS package

Mon Oct 5 13:29:53 1992

1

Ashtech, Inc. GPPS-L

Program: LINECOMP
Fri Jul 24 11:10:01 1992

Version: 4.2.01

Project information

GPS Survey |25-character project name [The | is in column 26.]
0872A |5-character session name

Project information

Known-station parameters

00 |Receiver identifier used in "LOGTIMES" file
000000 |Project station number
BATT |4-character short name
FIXED STATION |25-character long name
870 824 DRM P_KINE_12FEB_ |25-character comment field
0 |Position extraction (0=below,1=U-file,2=proj. file)
N 50 39 2.64790 |Latitude deg-min-sec (g=good;b=bad)
E 358 50 24.89118 |E-Longitude deg-min-sec (g=good;b=bad)
W 1 9 35.10882 |W-Longitude deg-min-sec (g=good;b=bad)
91.4999 |Ellipsoidal height (m) (g=good;b=bad)
0.0000 |North antenna offset (m)
0.0000 |East antenna offset (m)
1.5000 0.0000 0.0000 |Vert antenna offset (m): slant/radius/added_offset
4.0 |Temperature (degrees C)
0.0 |Humidity (percent)
1013.0 |Pressure (millibars)
UBATTA92.087 |Measurement filename (restricted to 24 characters)

Known-station parameters

Unknown-station parameters

00 |Receiver identifier used in "LOGTIMES" file
000000 |Project station number
YAVE |4-character short name
UNKNOWN STATION |25-character long name
965 001 FOS ADDAAAAA |25-character comment field
0 |Position extraction (0=below,1=U-file,2=proj. file)
N 50 39 44.72017 |Latitude deg-min-sec (g=good;b=bad)
E 358 51 45.05396 |E-Longitude deg-min-sec (g=good;b=bad)
W 1 8 14.94604 |W-Longitude deg-min-sec (g=good;b=bad)
70.2941 |Ellipsoidal height (m) (g=good;b=bad)
0.0000 |North antenna offset (m)
0.0000 |East antenna offset (m)
1.6200 0.0000 0.0000 |Vert antenna offset (m): slant/radius/added_offset
4.0 |Temperature (degrees C)
0.0 |Humidity (percent)
1013.0 |Pressure (millibars)
UYAVEA92.087 |Measurement filename (restricted to 24 characters)

Unknown-station parameters

Run-time parameters

1 |First epoch to process
100 |Final epoch to process (-1 = last available)
15.0 |Elevation cutoff angle (degrees)
1 |Data to process (1=L1;2=L2;3=L1c;4=L1-L2;5=L1+L2)
0.010000 |Convergence criterion (meters)
00 00 00 00 00 00 00 |Omit these satellites (up to 7)
10 |Maximum iterations for tlsq and dlsq
slow |Speed: fast/slow
00 00 00 00 00 00 00 |Forbidden reference SVs (up to 7)
yes |Apply tropo delay correction
Long |Output Format (Short, Long)

Run-time parameters

LINECOMP 4.2.01 10/24/91

Mon Oct 5 13:29:53 1992

2

FIXED U-File from P-Code receiver.
UNKWN U-File from P-Code receiver.

FIXED U-File used BROADCAST orbits.
UNKWN U-File used BROADCAST orbits.

Common start of two UFILES: 1992/03/27 16:01:40.00
Common end of two UFILES: 1992/03/27 17:21:20.00

Selected first epoch: 1

Selected last epoch: 100

For SV 3 there are 63 triple-difference measurements.
For SV 12 there are 97 triple-difference measurements.
For SV 13 there are 25 triple-difference measurements.
For SV 20 there are 97 triple-difference measurements.
For SV 24 there are 97 triple-difference measurements.
For SV 25 there are 97 triple-difference measurements.
Epoch interval (seconds): 20.000000

THE TRIPLE DIFFERENCE SOLUTION (L1)

Measure of geometry: 0.000502

num_meas = 379 num_used = 379 rms_resid = 0.003769 (m)
Post-Fit Chisq = 21726.811 NDF = 3.509

Sigmax (m): 1.505259
Sigmay (m): 0.782742
Sigmaz (m): 0.903232

x y z
x 1.00
y 0.19y 1.00
z 0.04z 0.01z 1.00

del_station: -0.000094 0.000006 -0.000000

Station1: FIXED STATION

(00000) (BATT)

Latitude: 50.65073553 50 39 2.64790
E-Long : 358.84024755 358 50 24.89118
W-Long : 1.15975245 1 9 35.10882
E-Height: 91.4999

Station2: UNKNOWN STATION

(00000) (YAVE)

50.66246481 50 39 44.87331
358.86242895 358 51 44.74421
1.13757105 1 8 15.25579
57.7467

Baseline vector: -998.8276 1588.9088 801.0968

Mark1_xyz : 4051379.0143 -82017.1849 4909071.9446
Az1 El1 D1 : 50.23630 -0.9569 2040.5989
El N1 U1 : 1568.7659 1304.8025 -33.7532
Mark2_xyz : 4050380.1868 -80428.2761 4909873.0414
Az2 El2 D2 : 230.25345 0.9386 2040.5989
E2 N2 U2 : -1568.3669 -1304.7982 33.7532

Double-Difference Epochs:

Prn: 3 Start epoch: 38 End epoch: 100
Prn: 12 Start epoch: 2 End epoch: 100
Prn: 13 Start epoch: 9 End epoch: 35
Prn: 20 Start epoch: 2 End epoch: 100
Prn: 24 Start epoch: 2 End epoch: 100
Prn: 25 Start epoch: 2 End epoch: 100

THE FLOAT DOUBLE DIFFERENCE SOLUTION (L1)

Measure of geometry: 0.000109 Wavelength = 0.190294 (m/cycle)

num_meas = 385 num_used = 384 rms_resid = 0.006061 (m)
Post-Fit Chisq = 284.363 NDF = 3.556

Mon Oct 5 13:29:53 1992

3

Reference SV: 20

SV	Ambiguity	FIT	Meas	SV	Ambiguity	FIT	Meas
3	-3810221.939f	0.024	64	12	-335216.040f	0.029	98
13	1202116.061f	0.020	27	24	112673.982f	0.037	98
25	246501.063f	0.036	97				

Sigmax (m): 0.074020
Sigmay (m): 0.065385
Sigmaz (m): 0.040538
SigmaN (cy): 0.248965
SigmaN (cy): 0.333709
SigmaN (cy): 0.503076
SigmaN (cy): 0.428754
SigmaN (cy): 0.298160

x y z N N N N N
x 1.00
y -0.22y 1.00
z 0.18z 0.05z 1.00
N 0.43N -0.09N -0.79N 1.00
N -0.23N 0.92N -0.32N 0.25N 1.00
N -0.89N 0.64N -0.13N -0.36N 0.61N 1.00
N -0.56N 0.91N -0.21N -0.06N 0.92N 0.86N 1.00
N -0.74N -0.48N -0.29N -0.23N -0.38N 0.37N -0.09N 1.00

del_station: -0.002509 0.000258 -0.000694

Station1: FIXED STATION

Station2: UNKNOWN STATION

	(00000)	(BATT)		(00000)	(YAVE)
Latitude:	50.65073553	50 39 2.64790		50.66246518	50 39 44.87464
E-Long :	358.84024755	358 50 24.89118		358.86242836	358 51 44.74209
W-Long :	1.15975245	1 9 35.10882		1.13757164	1 8 15.25791
E-Height:	91.4999			57.6964	

Baseline vector: -998.8921 1588.8684 801.0839

Mark1_xyz :	4051379.0143	-82017.1849	4909071.9446
Az1 El1 D1 :	50.23466	-0.9583	2040.5939
El1 N1 U1 :	1568.7242	1304.8435	-33.8035
Mark2_xyz :	4050380.1223	-80428.3165	4909873.0284
Az2 El2 D2 :	230.25182	0.9400	2040.5939
E2 N2 U2 :	-1568.3253	-1304.8392	33.8035

INTEGER FIXED DOUBLE DIFFERENCE (L1) SOLUTION

CONTRAST	15.943712	0	
CHISQ	289.129306	Change	4.766277
CONTRAST	11.047823	4	
CHISQ	295.079978	Change	5.950673
CONTRAST	11.016926	1	
CHISQ	295.879530	Change	0.799551
CONTRAST	496.822142	3	
CHISQ	373.051982	Change	77.172452
CONTRAST	221.780159	2	
CHISQ	490.200337	Change	117.148355

rms_resid = 0.007955(m)

Sigmax (m): 0.008964
Sigmay (m): 0.004616
Sigmaz (m): 0.010396

x y z
x 1.00
y 0.01y 1.00
z 0.58z 0.29z 1.00

Mon Oct 5 13:29:53 1992

4

del_station: 0.010701 0.011187 0.013511

Station1: FIXED STATION

(00000) (BATT)

Latitude: 50.65073553 50 39 2.64790
E-Long : 358.84024755 358 50 24.89118
W-Long : 1.15975245 1 9 35.10882
E-Height: 91.4999

Station2: UNKNOWN STATION

(00000) (YAVE)

50.66246518 50 39 44.87465
358.86242852 358 51 44.74267
1.13757148 1 8 15.25733
57.7134

Baseline vector: -998.8814 1588.8796 801.0974

Mark1_xyz : 4051379.0143 -82017.1849 4909071.9446
Az1 El1 D1 : 50.23486 -0.9579 2040.6027
El N1 U1 : 1568.7356 1304.8440 -33.7865
Mark2_xyz : 4050380.1330 -80428.3053 4909873.0419
Az2 El2 D2 : 230.25201 0.9395 2040.6027
E2 N2 U2 : -1568.3367 -1304.8397 33.7865

THE FIXED DOUBLE DIFFERENCE SOLUTION (L1)

Measure of geometry: 0.000001 Wavelength = 0.190294 (m/cycle)
num_meas = 385 num_used = 384 rms_resid = 0.007955(m)
Post-Fit Chisq = 490.200 NDF = 3.556

Reference SV: 20

Integer Search Ratio = 11.017

SV	Ambiguity	FIT	Meas	SV	Ambiguity	FIT	Meas
3	-3810222.000X	0.026	64	12	-335216.000X	0.046	98
13	1202116.000X	0.061	27	24	112674.000X	0.037	98
25	246501.000X	0.044	97				

Sigmax (m): 0.008964
Sigmay (m): 0.004616
Sigmaz (m): 0.010396

x y z

x 1.00
y 0.01y 1.00
z 0.58z 0.29z 1.00

del_station: 0.000000 0.000000 0.000000

Station1: FIXED STATION

(00000) (BATT)

Latitude: 50.65073553 50 39 2.64790
E-Long : 358.84024755 358 50 24.89118
W-Long : 1.15975245 1 9 35.10882
E-Height: 91.4999

Station2: UNKNOWN STATION

(00000) (YAVE)

50.66246518 50 39 44.87465
358.86242852 358 51 44.74267
1.13757148 1 8 15.25733
57.7134

Baseline vector: -998.8814 1588.8796 801.0974

Mark1_xyz : 4051379.0143 -82017.1849 4909071.9446
Az1 El1 D1 : 50.23486 -0.9579 2040.6027
El N1 U1 : 1568.7356 1304.8440 -33.7865
Mark2_xyz : 4050380.1330 -80428.3053 4909873.0419
Az2 El2 D2 : 230.25201 0.9395 2040.6027
E2 N2 U2 : -1568.3367 -1304.8397 33.7865

Fri Jul 24 11:12:53 1992

Project information

GPS Survey |25-character project name [The | is in column 26.]
 0872A |5-character session name

Project information

Known-station parameters

00 |Receiver identifier used in "LOGTIMES" file
 000000 |Project station number
 BATT |4-character short name
 FIXED STATION |25-character long name
 870 824 DRM P_KINE_12FEB_ |25-character comment field
 0 |Position extraction (0=below,1=U-file,2=proj. file)
 N 50 39 2.64790 |Latitude deg-min-sec (g=good;b=bad)
 E 358 50 24.89118 |E-Longitude deg-min-sec (g=good;b=bad)
 W 1 9 35.10882 |W-Longitude deg-min-sec (g=good;b=bad)
 91.4999 |Ellipsoidal height (m) (g=good;b=bad)
 0.0000 |North antenna offset (m)
 0.0000 |East antenna offset (m)
 1.5000 0.0000 0.0000 |Vert antenna offset (m): slant/radius/added_offset
 4.0 |Temperature (degrees C)
 0.0 |Humidity (percent)
 1013.0 |Pressure (millibars)
 UBATTA92.087 |Measurement filename (restricted to 24 characters)

Known-station parameters

Unknown-station parameters

00 |Receiver identifier used in "LOGTIMES" file
 000000 |Project station number
 YAVE |4-character short name
 UNKNOWN STATION |25-character long name
 965 001 FOS ADDAAAAA |25-character comment field
 0 |Position extraction (0=below,1=U-file,2=proj. file)
 N 50 39 44.72017 |Latitude deg-min-sec (g=good;b=bad)
 E 358 51 45.05396 |E-Longitude deg-min-sec (g=good;b=bad)
 W 1 8 14.94604 |W-Longitude deg-min-sec (g=good;b=bad)
 70.2941 |Ellipsoidal height (m) (g=good;b=bad)
 0.0000 |North antenna offset (m)
 0.0000 |East antenna offset (m)
 1.6200 0.0000 0.0000 |Vert antenna offset (m): slant/radius/added_offset
 4.0 |Temperature (degrees C)
 0.0 |Humidity (percent)
 1013.0 |Pressure (millibars)
 UYAVEA92.087 |Measurement filename (restricted to 24 characters)

Unknown-station parameters

Run-time parameters

1 |First epoch to process
 100 |Final epoch to process (-1 = last available)
 15.0 |Elevation cutoff angle (degrees)
 1 |Data to process (1=L1;2=L2;3=L1c;4=L1-L2;5=L1+L2)
 0.010000 |Convergence criterion (meters)
 00 00 00 00 00 00 00 |Omit these satellites (up to 7)
 10 |Maximum iterations for tlsq and dlsq
 slow |Speed: fast/slow
 00 00 00 00 00 00 00 |Forbidden reference SVs (up to 7)
 yes |Apply tropo delay correction
 Long |Output Format (Short, Long)

Run-time parameters

Appendix Two

The GPS_baseline simulation program

Program baseline(input,output,infile,outfile);

```
const
    maxsize=15;
type
    twodarray=array[1..maxsize,1..maxsize] of double;
    onedarray=array[1..maxsize] of double;
    twinvec=array[1..2,1..maxsize] of longint;
var
    infile,outfile                :text;
    indata,result                 :string;
    epoch,epoch_interval,start_time,end_time :double;
    xa,xt                         :array[1..2,1..3] of double;
    start_amb                     :twinvec;
    amb_app                       :array[2..6] of longint;
    obs_vec,null_vec,M_o,omeg     :onedarray;
    no_sats,no_unknowns,i,j       :integer;
    wavelength,x,level            :double;
    dd_phase_o,dd_phase_c         :double;
    rad_orbit,inclin,rot_rate,GM_earth :double;
    norm_mat,inv_norm_mat,null_mat :twodarray;
    d_vec,sol_vec                 :onedarray;
    iterate,fix,continue,found    :boolean;
    rep                           :char;
    rep_no                        :integer;
    amb_no,change_amb             :integer;
    sum_sq                        :double;
```

function noise(level:double):double;
{Computes the random noise at specified level, (e.g, $\pm 0.1\text{mm}$, $\pm 2\text{mm}$, etc.)}

```
var
    rand_no :double;
begin
    rand_no:= abs(ln(sqr(sin(x*pi/180))));
    rand_no:= rand_no*1000*1000*100;
    rand_no:= rand_no - trunc(rand_no);
    noise:= rand_no*level/0.5 - level;
    x:= x + rand_no;
end;
```

function sat_pos(sat_no,coord :integer):double;
{Computes a coordinate of the position of a particular satellite, in an circular simplified orbit, coord can equal 1,2, or 3 (x,y,z).}

```
var
    M :double;
begin
    M:=M_o[sat_no]+rot_rate*(epoch-start_time);
    if coord=1 then
        sat_pos:=rad_orbit*(cos(M)*cos(omeg[i])-sin(M)*cos(inclin)*sin(omeg[i]))
```

```

        else if coord=2 then
            sat_pos:=rad_orbit*(cos(M)*sin(omeg[i])+sin(M)*cos(inclin)*cos(omeg[i]))
        else if coord=3 then
            sat_pos:=rad_orbit*sin(M)*sin(inclin)
    end;

function range_a(stat_no,sat_no :integer):double;
{Computes range from specified station to specified satellite. Uses approximate
coordinates of the station}

var
    h :double;
begin
    range_a:= abs((sat_pos(sat_no,1) - xa[stat_no,1])*sqrt(1 +
    sqr((sat_pos(sat_no,2) - xa[stat_no,2])/ (sat_pos(sat_no,1) - xa[stat_no,1]))+
    sqr((sat_pos(sat_no,3) - xa[stat_no,3])/ (sat_pos(sat_no,1) - xa[stat_no,1]))));
end;

function range_t(stat_no,sat_no :integer):double;
{Computes range from specified station to specified satellite. Uses true coordinates of
the station}

var
    h :double;
begin
    range_t:= abs((sat_pos(sat_no,1) - xt[stat_no,1])*sqrt(1 +
    sqr((sat_pos(sat_no,2) - xt[stat_no,2])/ (sat_pos(sat_no,1) - xt[stat_no,1]))+
    sqr((sat_pos(sat_no,3) - xt[stat_no,3])/ (sat_pos(sat_no,1) - xt[stat_no,1]))));
end;

function cycles(stat_no,sat_no :integer; sort :char):double;
{Computes number of cycles from specified station to specified satellite, using either
approximate or true position of the station.}

begin
    if sort='a' then cycles:= range_a(stat_no,sat_no)/wavelength;
    if sort='t' then cycles:= range_t(stat_no,sat_no)/wavelength;
end;

```

```

procedure contribute;
{Forms normal equations by contribution from each observation equation}

var
    i,j :integer;
begin
    for i:= 1 to no_unknowns do
        begin
            for j:= 1 to no_unknowns do
                begin
                    norm_mat[i,j]:= norm_mat[i,j]+obs_vec[i]*obs_vec[j];
                end;
                d_vec[i]:= d_vec[i]+obs_vec[i]*(dd_phase_o - dd_phase_c)
            end;
        end;
    end;
end;

```

```

procedure mtranspose (matrix:twodarray;rows,columns:integer;var transpose
                    :twodarray);

```

{This procedure was written by Andy King for his MSc project, 1991, computes the transpose of matrix}

```

var
    i,j    :integer;
begin
    for i:=1 to rows do
        for j:=1 to columns do
            begin
                transpose[j,i]:=matrix[i,j];
            end;
        end;
    end;

```

```

procedure minverse (matrix:twodarray;n:integer; var inverse:twodarray);

```

{This procedure was written by Andy King for his MSc project, 1991}

{ uses Choleski's method; the matrix is divided into a lower and upper triangular matrix L and Lt such that matrix=L*Lt. From this it follows that inverse*L=Lt(inv). The elements can be computed by a process of elimination. As it is not necessary to know the off diagonal elements of Lt(inv) which are not equal to zero Lt(inv) is calculated by inverting the diagonal elements only. A full description of Choleski's method is given in chapter three}

```

var
    p,k,i,j    :integer;
    L,LT,LTinv :twodarray;

```

{This loop calculates the L matrix, the nested loop describes a lower triangular matrix starting at the top left corner. Values are found passing down each column. From the second column onwards values found in the previous columns are used to calculate more elements of the matrix}

```

begin
    for j:=1 to n do
        for i:=j to n do
            begin
                L[i,j]:=0; LT[i,j]:=0; LTinv[i,j]:=0;
            end;
        end;
    end;

```

```

    for j:=1 to n do
        for i:=j to n do
            begin
                p:=j-1;
                l[i,j]:=matrix[i,j];
                for k:=p downto 1 do

```

{ This loop incorporates values which have been found already so the elements of L can be found right through the matrix }

```

            begin
                l[i,j]:=l[i,j]-l[i,k]*l[j,k];
            end;
            if i=j then
                begin
                    l[i,j]:=sqrt(l[i,j]);

```

```

        end
      else
        l[i,j]:=l[i,j]/l[j,j];
      end;
    end;

```

{The L matrix has now been completely found }

```

mtranspose (L,n,n,LT);

```

```

for i:=1 to n do

```

{This loop finds the required elements of the LT(inv) matrix }

```

  begin
    LTinv[i,i]:=1/LT[i,i];
  end;

```

{matrix(inv) will be symmetric so it is necessary only to work through one diagonal half of it. Knowing that L is lower triangular this nested loop works through the matrix from the bottom right using the zeros in L to immediately establish the first element of N(inv) then using this to find more elements and these in turn to find more}

```

    for i:=n downto 1 do
      for j:=i downto 1 do
        begin
          inverse[i,j]:=LTinv[i,j];

          if i and j <> n then
            begin
              k:=j+1;
              for p:=k to n do
                begin
                  inverse[i,j]:=inverse[i,j]-inverse[i,p]*L[p,j];
                end;
              end;

              inverse[i,j]:=inverse[i,j]/L[j,j];
              inverse[j,i]:=inverse[i,j];
            end;
          end;
        end;
      end;
    end;

```

{opposite elements of the matrix must be found as the loop progresses as these are used within the incremental loop which is based on rows}

```

      end;
    end;

```

procedure update_params;

{Up-dates the approximate coordinates of the unknown station. Ambiguity parameters are not updated, but are re-computed from the new coordinates}

```

var
  i :integer;
begin
  for i:= 1 to 3 do
    begin
      xa[2,i]:= xa[2,i] + sol_vec[i];
    end;
  end;

```

end;

Begin

{Define null arrays}

for i:= 1 to maxsize do

begin

 null_vec[i]:= 0;

 for j:= 1 to maxsize do

 begin

 null_mat[i,j]:= 0;

 end;

end;

write('Name of input file? '); readln(indata); reset(infile,indata);

write('Name of results file? '); readln(result); rewrite(outfile,result);

 readln(infile,start_time,end_time,epoch_interval);

 {Read approximate coordinates and true coordinates}

 readln(infile,xa[1,1],xa[1,2],xa[1,3],xa[2,1],xa[2,2],xa[2,3]);

 readln(infile,xt[1,1],xt[1,2],xt[1,3],xt[2,1],xt[2,2],xt[2,3]);

 {Simplified satellite orbits: assume circular progress from one point to another point.}

 readln(infile,no_sats,rad_orbit,GM_earth,inclin);

 inclin:= inclin*pi/180;

 for i:= 1 to no_sats do

 begin

 readln(infile,omeg[i],M_o[i]);

 omeg[i]:=omeg[i]*pi/180;

 M_o[i]:=M_o[i]*pi/180;

 end;

wavelength:= 0.10; {It's up to user to specify the required
 wavelength .e.g. L1=19cm, L2=24, L1-L2=86cm, L1+L2=10cm}

 rot_rate:=sqrt(GM_earth/rad_orbit)*(1/rad_orbit);

 rad_orbit:=rad_orbit*1000;

epoch:= start_time;

{Compute TRUE ambiguity at the start, from true coordinates. This is in order to be able to create supposed observations}

{for i:=1 to 2 do

begin

 for j:=1 to no_sats do

 begin

 start_amb[i,j]:= trunc(cycles(i,j,'t'));

 writeln(start_amb[i,j]:5,trunc(cycles(i,j,'t')):12,cycles(i,j,'t'):15:3);

 end;}

 start_amb[1,1]:= trunc(cycles(1,1,'t'));

 start_amb[1,2]:= trunc(cycles(1,2,'t'));

 start_amb[1,3]:= trunc(cycles(1,3,'t'));

 start_amb[1,4]:= trunc(cycles(1,4,'t'));

```

start_amb[1,5]:= trunc(cycles(1,5,'t'));
start_amb[2,1]:= trunc(cycles(2,1,'t'));
start_amb[2,2]:= trunc(cycles(2,2,'t'));
start_amb[2,3]:= trunc(cycles(2,3,'t'));
start_amb[2,4]:= trunc(cycles(2,4,'t'));
start_amb[2,5]:= trunc(cycles(2,5,'t'));

end;

fix:= false;
continue:= true;

repeat
iterate:= true;

repeat
x:= 10;

if fix=false then no_unknowns:= 2 + no_sats
else
no_unknowns:= 3;

norm_mat:= null_mat; inv_norm_mat:= null_mat; d_vec:= null_vec; sol_vec:=
null_vec;
if fix=false then
begin
{Compute ambiguities at start from approximate coordinates, from each
combination of pairs of satellites}
for j:= 2 to no_sats do
begin

amb_app[j]:= trunc(cycles(2,j,'a')) - trunc(cycles(1,j,'a')) -
trunc(cycles(2,1,'a')) + trunc(cycles(1,1,'a'));

end;
end;

while (epoch<end_time) do
begin
sum_sq:= 0.0;
for j:= 2 to no_sats do
begin
obs_vec:= null_vec;

{create observation from true coordinates and adds noise to obs}
{the value of noise level to be specified by the user, e.g, 1mm,
0.1mm, 0.5mm, etc.}
dd_phase_o:= (cycles(2,j,'t') - start_amb[2,j])
-(cycles(1,j,'t') - start_amb[1,j])
-(cycles(2,1,'t') - start_amb[2,1])
+(cycles(1,1,'t') - start_amb[1,1])
+noise(0.0001);

dd_phase_c:= cycles(2,j,'a') - cycles(1,j,'a') - cycles(2,1,'a')
+cycles(1,1,'a') - amb_app[j];
{writeln('dd(o-c)= ',dd_phase_o:10:3,dd_phase_c:10:3)};

```

```

sum_sq:= sum_sq + (dd_phase_o - dd_phase_c)*(dd_phase_o -
dd_phase_c);
{partial derivatives wrt the 3 coordinates of free point}
obs_vec[1]:= ((xa[2,1] - sat_pos(j,1))/range_a(2,j)
-(xa[2,1] - sat_pos(1,1))/range_a(2,1))/wavelength;

obs_vec[2]:= ((xa[2,2] - sat_pos(j,2))/range_a(2,j)
-(xa[2,2] - sat_pos(1,2))/range_a(2,1))/wavelength;

obs_vec[3]:= ((xa[2,3] - sat_pos(j,3))/range_a(2,j)
-(xa[2,3] - sat_pos(1,3))/range_a(2,1))/wavelength;

if fix=false then
{partial derivative wrt the relevant ambiguity}
obs_vec[j+2]:= -1;

contribute; {to the normal equations}

end;
writeln('iteration at epoch: ',epoch:4:0);
epoch:= epoch + epoch_interval;

end;

minverse(norm_mat,no_unknowns,inv_norm_mat);

for i:= 1 to no_unknowns do
begin
for j:= 1 to no_unknowns do
begin
sol_vec[i]:= sol_vec[i] + inv_norm_mat[i,j]*d_vec[j];
end;
if i<=3 then
writeln(sol_vec[i]:8:3);
if i<=3 then
writeln(outfile,sol_vec[i]:8:3)
else
writeln(sol_vec[i]:7:3);
writeln(outfile,sol_vec[i]:7:3);

end;

if fix = true then
writeln('Sum of squares of residuals = ',sum_sq:4:10);
writeln(outfile,'Sum of squares of residuals = ',sum_sq:4:10);

update_params;
writeln(outfile,' x',' y',' z');writeln(outfile);
writeln(outfile,xa[2,1]:10:3,xa[2,2]:15:3,xa[2,3]:15:3);
writeln;
write ('Another iteration? (y/n) '); readln(rep);
if rep='y' then
begin
epoch:= start_time;
iterate:= true;

```

```

        end
        else iterate:= false;

until iterate=false;

writeln;
writeln('Do you wish to fix the ambiguities? 1 ');
writeln('Fix and change the ambiguities?    2 ');
writeln('End the program                    3 ');
writeln;
write  ('Response 1,2,3 .....'); readln(rep_no);
case rep_no of
1:      begin
            fix:= true; continue:= true; epoch:= start_time;
            for i:= 2 to no_sats do
                amb_app[i]:= amb_app[i] + round(sol_vec[i+2]);

            end;

2:      begin
            write ('Which number ambiguity should be changed? ');
            readln(amb_no);
            write ('By how much should this be changed? '); readln(change_amb);
            fix:= true; continue:= true; epoch:= start_time;
            for i:= 2 to no_sats do
                amb_app[i]:= amb_app[i] + round(sol_vec[i+2]);
                amb_app[amb_no]:= amb_app[amb_no] + change_amb;

            end;

3:      continue:= false;
end;

until continue=false;

close(infile); close(outfile);

end.

```

Appendix Three

Example of input and output files from the simulation program

1. An example of an input data file for 8km baseline (Gele-Quar)

0 2000 10

4052164.941 96088.128 4908184.781 4048699.628 102962.078 4910884.376
4052234.941 96018.128 4908174.781 4048779.628 102882.078 4910864.376

5 26559.012 398600.5 55

272 72
088 22
106 39
302 19
182 15

2. An example of an input data file for 2km baseline (Batt-Yave)

0 1200 20

4051277.456 81993.280 4909322.749 4050288.522 80414.461 4910134.009
4051347.456 81923.280 4909312.749 4050348.522 80334.461 4910114.009

5 26559.012 398600.5 55

272 72
88 22
106 39
302 19
182 15

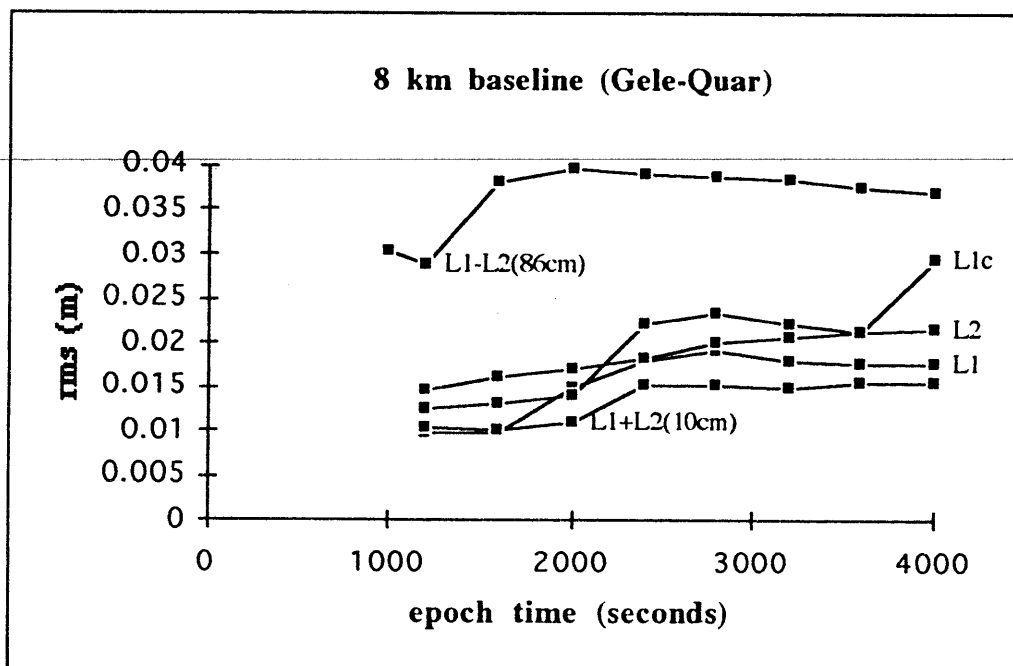
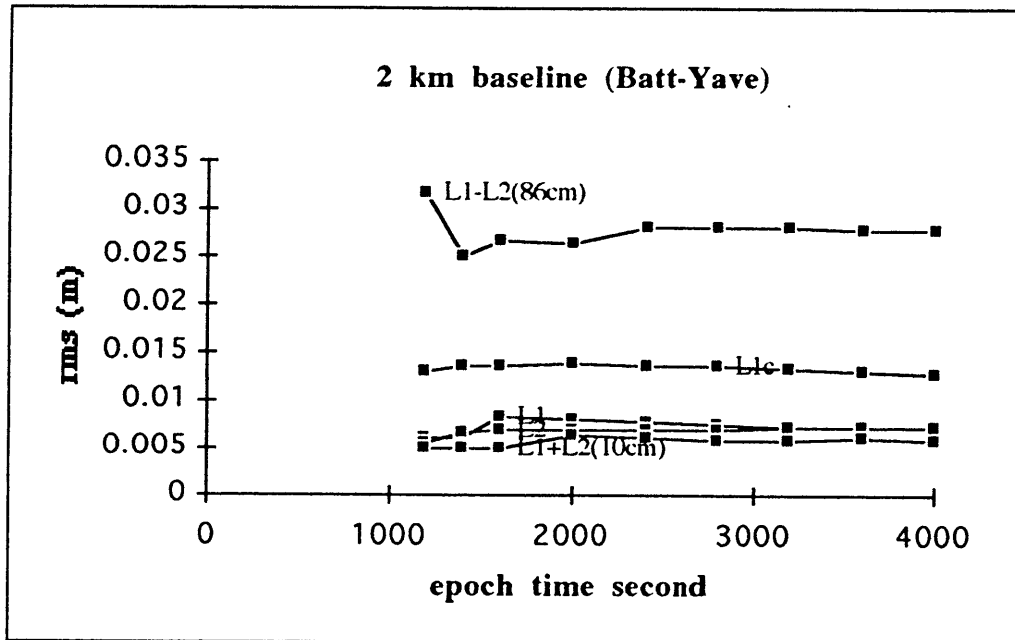
3. An example of an output data file

```
9.979
-8.120
-11.259
-14.937
+15.938
-15.939
-14.941
x      y      z
4048709.607 102953.958 4910873.117
0.001
-0.011
0.010
0.063
-0.938
-0.939
0.059
x      y      z
4048709.608 102953.947 4910873.127
0.000
0.000
-0.001
0.063
-0.938
-0.939
0.059
x      y      z
4048709.608 102953.947 4910873.126
-0.208
9.627
-7.093
Sum of squares of residuals = 0.0147881722
x      y      z
4048709.400 102963.574 4910866.033
```

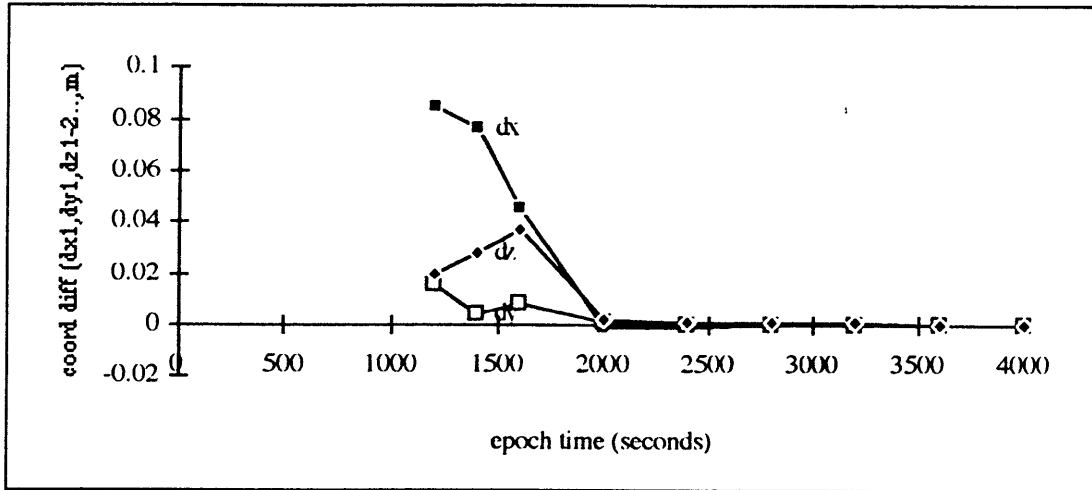
Appendix Four

Graphs of the root mean squares and the coordinate differences vs epoch time

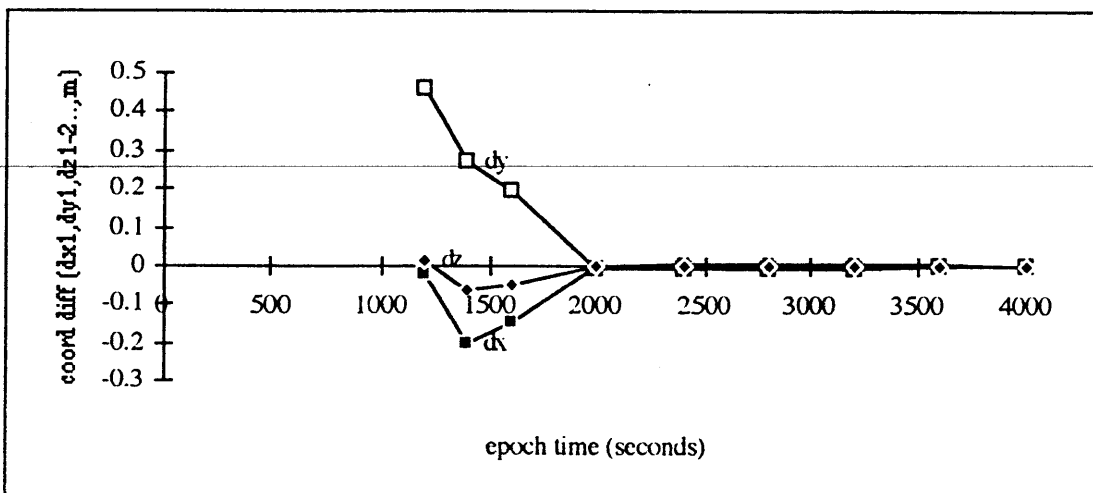
1. Graphs of the root mean squares vs epoch time



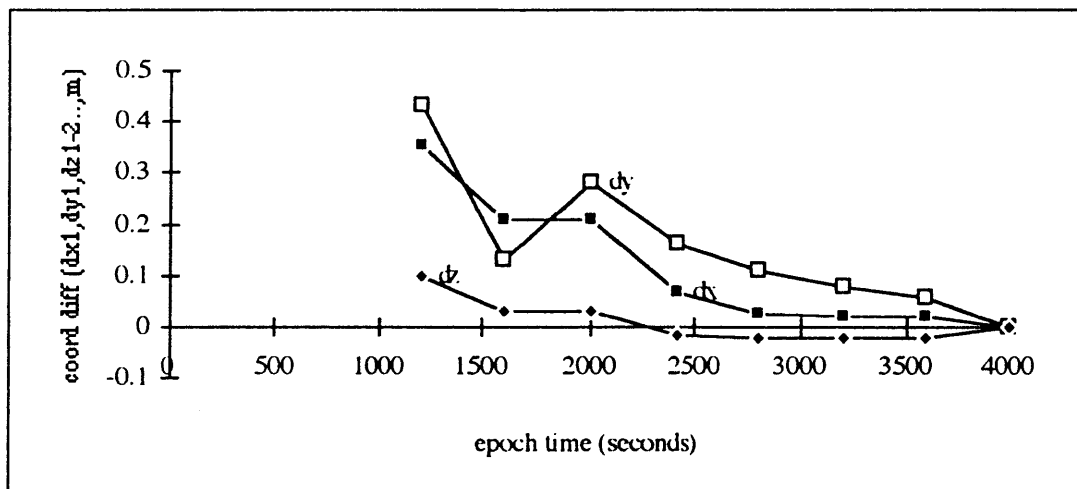
2. Graphs of the coordinate differences vs epoch time



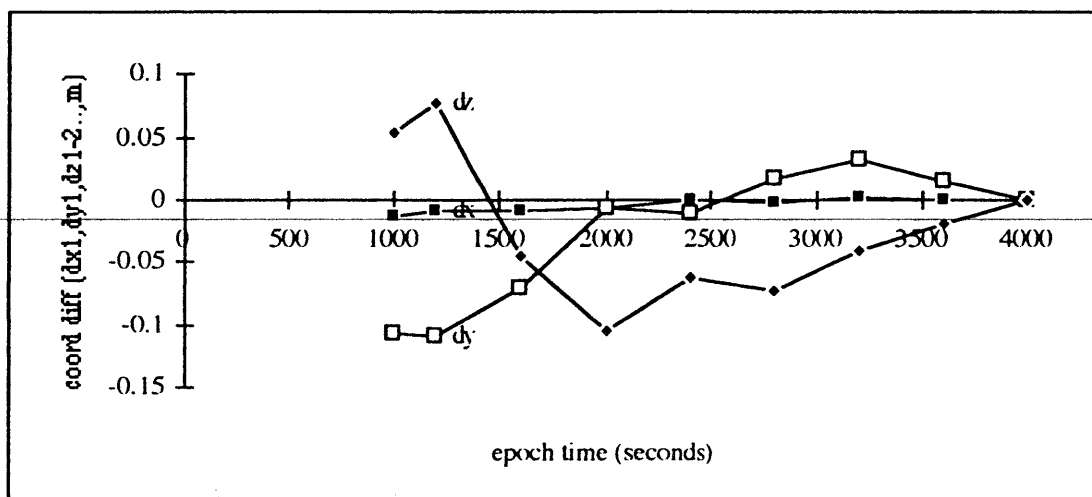
Coord diff. vs Epoch time for L1+L2 narrow lane 10cm wavelength (2km baseline).



Coord diff. vs Epoch time for L1-L2 wide lane 86cm wavelength (2km baseline).



Coord diff. vs Epoch time for L1+L2 narrow lane 10cm wavelength (8km baseline)



Coord diff. vs Epoch time for L1-L2 wide lane 86cm wavelength (8km baseline).

Appendix Five

Tables of line quality for all vectors processed (GPPS)

2km baseline (Batt-Yave)				8km baseline (Gele-Quar)			
<i>processing only L1 (19cm) data</i>				<i>processing only L1 (19cm) data</i>			
time	sigma x	sigma y	sigma z	time	sigma x	sigma y	sigma z
(seconds)	(m)	(m)	(m)	(seconds)	(m)	(m)	(m)
4000	0.0061	0.0031	0.0065	4000	0.0173	0.0071	0.0286
3600	0.0065	0.0032	0.0069	3600	0.0184	0.0076	0.032
3200	0.0067	0.0033	0.0073	3200	0.0203	0.0083	0.0371
2800	0.0073	0.0037	0.0081	2800	0.0233	0.0093	0.046
2400	0.008	0.004	0.009	2400	0.0241	0.0092	0.0563
2000	0.009	0.0046	0.0104	2000	0.024	0.0082	0.0812
1600	0.0101	0.0054	0.0124	1600	0.0188	0.0059	0.0652
1400	0.0076	0.0042	0.01	1200	0.0239	0.0067	0.084
1200	0.0082	0.0046	0.0113				
<i>processing only L2 (24cm) data</i>				<i>processing only L2 (24cm) data</i>			
time	sigma x	sigma y	sigma z	time	sigma x	sigma y	sigma z
(seconds)	(m)	(m)	(m)	(seconds)	(m)	(m)	(m)
4000	0.0069	0.0033	0.0071	4000	0.0211	0.0087	0.0365
3600	0.0073	0.0035	0.0075	3600	0.0223	0.0093	0.0412
3200	0.0076	0.0036	0.0077	3200	0.0249	0.0102	0.0496
2800	0.0077	0.0036	0.0079	2800	0.0285	0.0114	0.066
2400	0.008	0.0039	0.0086	2400	0.031	0.0115	0.1062
2000	0.0084	0.0041	0.0093	2000	0.0225	0.0077	0.0776
1600	0.0094	0.0048	0.0187	1600	0.0252	0.0078	0.0882
1400	0.0095	0.0049	0.0114	1200	0.0304	0.0085	0.107
1200	0.0086	0.0046	0.0111				
<i>processing L1-L2 (86cm) data</i>				<i>processing L1-L2 (86cm) data</i>			
time	sigma x	sigma y	sigma z	time	sigma x	sigma y	sigma z
(seconds)	(m)	(m)	(m)	(seconds)	(m)	(m)	(m)
4000	0.0266	0.0128	0.0277	4000	0.0365	0.0151	0.0629
3600	0.0279	0.0133	0.0285	3600	0.0394	0.0163	0.0722
3200	0.0296	0.0139	0.0304	3200	0.0434	0.0178	0.0857
2800	0.0311	0.0146	0.032	2800	0.0477	0.019	0.1086
2400	0.0333	0.0156	0.0345	2400	0.055	0.0204	0.1877
2000	0.0388	0.0191	0.0428	2000	0.0645	0.022	0.2221
1600	0.0354	0.0179	0.0408	1600	0.0741	0.023	0.2582
1400	0.0379	0.0197	0.0456	1200	0.0714	0.0199	0.2473
1200	0.03789	0.0203	0.0489				
<i>processing L1+L2 (10cm) data</i>				<i>processing L1+L2 (10cm) data</i>			
time	sigma x	sigma y	sigma z	time	sigma x	sigma y	sigma z
(seconds)	(m)	(m)	(m)	(seconds)	(m)	(m)	(m)
4000	0.0055	0.0027	0.0058	4000	0.0153	0.0063	0.0264
3600	0.006	0.0028	0.0061	3600	0.0162	0.0067	0.03
3200	0.0061	0.0029	0.0063	3200	0.0169	0.007	0.0335
2800	0.0064	0.003	0.0066	2800	0.0187	0.0075	0.0429
2400	0.007	0.0034	0.0075	2400	0.0214	0.008	0.0734
2000	0.0076	0.0037	0.0084	2000	0.018	0.0062	0.0623
1600	0.0066	0.0033	0.0076	1600	0.0194	0.006	0.0678
1400	0.0069	0.0036	0.0083	1200	0.0253	0.0071	0.089
1200	0.0075	0.004	0.0096				

<i>processing Llc ionospheric-free data</i>				<i>processing Llc ionospheric-free data</i>			
time	sigma x	sigma y	sigma z	time	sigma x	sigma y	sigma z
4000	0.052	0.049	0.0355	4000	0.1521	0.1854	0.0933
3600	0.0642	0.0587	0.0351	3600	0.1585	0.2187	0.1069
3200	0.0821	0.0735	0.04773	3200	0.1628	0.2521	0.1198
2800	0.0987	0.0876	0.0564	2800	0.1671	0.2862	0.1318
2400	0.1246	0.1095	0.0692	2400	0.1735	0.3019	0.133
2000	0.1739	0.1518	0.0947	2000	0.2008	0.3322	0.139
1600	0.2446	0.2123	0.1303	1600	0.2598	0.4213	0.17
1400	0.3071	0.2657	0.1616	1200	0.3548	0.5875	0.2317
1200	0.3816	0.3285	0.1978				