DETERMINATION OF EARTH ROTATION PARAMETERS AND ADJUSTMENT OF A GLOBAL GEODETIC NETWORK USING THE GLOBAL POSITIONING SYSTEM

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PREFACE

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May 1994

PREFACE

This technical report is a reproduction of a thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering in the Department of Geodesy and Geomatics Engineering, April 1994. The research was supervised by Dr. Richard B. Langley, and funding was provided partially by the Natural Sciences and Engineering Research Council of Canada.

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ABSTRACT

This thesis focuses on the determination of the Earth rotation parameters (ERP) and the adjustment of a global geodetic network using the Global Positioning System (GPS) technique. Based on the GPS DIfferential POsitioning Program (DIPOP) software package of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, the advanced software named as DIPOP.ERP has been implemented. DIPOP.ERP accompanied by preprocessors PREDD.ERP and PREGE.ERP has been extensively used to process data collected during the GPS'92 campaign organized by the International GPS Geodynamics Service (IGS). Data from a seven-day period (from 25 to 31 July, 1992) collected from this campaign have been processed.

Four strategies were designed for the software testing and parametric estimation on daily and seven-day bases. In the first three of them, the number of the different fixed stations was chosen. In the last strategy, the precise orbits were used. In addition to the coordinates of the 28 IGS core stations equipped with dual frequency Rogue receivers, the initial orbital parameters of 18 GPS satellites, the tropospheric scale factor for each station and ambiguities, daily Earth rotation parameters were estimated, based on the double difference algorithm for the carrier beat phase measurement. The results of this experiment demonstrate that the Earth rotation parameters can be recovered with an accuracy of about a few tenths of a milli-arcsecond. A comparison of the estimated polar motion values with those provided by the International Earth Rotation Service (IERS) shows agreement with the IERS values at the few milli-arcsecond level. The daily repeatabilities from a few parts to ten parts in 10^9 for most of the continental baselines over eight thousand kilometres in length was achieved. The daily repeatabilities for the coordinates of most stations ranged from a few centimetres to about ten centimetres.

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First of all, I would like to express my special thanks to my supervisor Dr. Richard B. Langley for accepting me as his student so that I had an opportunity to study in the Department of Surveying Engineering at the University of New Brunswick (UNB), and to know many open-eyed frontier areas in this Department. Without his guidance and support, and free choice of research topics, I would never have touched on the mysterious quasars and appreciated the enchantment of theory and practice of the GPS technique. His comments and suggestions on my thesis and seminar papers were valuable. I can't thank him enough for his spending much time on my thesis. His rigorous scientific attitude, to recite the words "Scientists never guess", profound knowledge and patience with the students impressed me. Funding for this research was provided by the Natural Sciences and Engineering Research Council of Canada, held by Dr. Richard B. Langley.

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CHAPTER 1
INTRODUCTION

1.1 Historical Background

The theory of the Earth's rotation stems from Newton’s mechanics in the seventeenth century. After Newton's theory, Euler presented the so-called Euler’s dynamical and kinematical equations in the middle of the eighteenth century. Since that time, the above fundamentals and many discoveries have been essential in developing the theory and promoting the corresponding observation techniques in the study of the Earth's rotation. The studies can vary from considering the rotating elliptical rigid Earth in a simple way up to the rotating elliptical, deformable, simplified anelastic Earth with atmosphere, oceans, and core in a quite complicated way, based on Newton’s mechanics and Euler’s theory with consideration of some boundary conditions and application of the mathematical tools. In addition to the development of theory, the technique of measuring the Earth's rotation is equally important. The history of regular observation of the Earth's rotation can be traced back to the end of the nineteenth century. The International Association of Geodesy (IAG) organized the International Latitude Service (ILS) in 1899, after F. Küstner found the opposite variations in latitude at stations Berlin and Honolulu in 1884, where the difference between their longitudes is 180 degrees. Since then, variations of the Earth's rotation have been continuously and closely observed by using a variety of classical and modern techniques.

The classical instrumentation had been invented and updated from time to time. It includes transit instruments, the meridian circle, the visual zenith telescope, the impersonal astrolabe, and the photographic zenith tube. All of these are optical instruments, whose construction is based on the astrometric principles of measuring directions to stars. For almost a century they were used extensively by regular services for monitoring the Earth's rotation by organizations such as the Bureau International de l'Heure (BIH) in 1912 and the International Polar Motion Service (IPMS) in 1962. After the international project MERIT - Monitoring of the Earth's Rotation and Intercomparison of the Techniques of observations and analyses during the period 1983-1984, the classical technique had been gradually replaced by modern techniques. The new organization of service of the Earth's rotation, i.e. the International Earth Rotation Service (IERS), was established in 1987 replacing the BIH and IPMS. The classical technique had played a great role in the determination of the Earth's rotation. The accumulated Earth rotation parameters over 80 years, with a resolution of at least 5 days and an accuracy of better than tens of milli-arcseconds, are valuable for the scientific studies in long term geodynamics.

Since the late 1960s, the techniques used for detecting variations of the Earth's rotation have changed dramatically. These modern techniques are: satellite Doppler, Satellite Laser Ranging (SLR), Lunar Laser Ranging (LLR), Very Long Baseline Interferometry (VLBI), and the Navstar Global Positioning System (GPS). In the following paragraphs, the modern techniques applied to monitoring variations of the Earth's rotation are briefly introduced, with particular emphasis on the GPS technique.

Doppler technique: The Doppler technique of tracking satellites is based on the principle of the Doppler effect, which is the difference between the transmitted and received frequencies, i.e., Doppler shift of the radio signals emitted by the transmitters of the orbiting satellites can be continuously measured. The operation of this technique is supported by the satellite system and the ground stations equipped with portable Doppler receivers. The U.S. Navy Navigation Satellite System (NNSS), for instance, is the most important one which includes six active satellites in near polar, circular orbits, and at a height of about 1100 km. The details on NNSS may be found in various papers (e.g., Kouba, [1983]). Since 1967, the components of polar motion were successfully determined by the Doppler technique [Anderle and Beuglass, 1970], and later on UT1–UTC and length of day [Anderle and Malyevac, 1982]. The routine determination of the Earth rotation parameters (ERP) was previously performed by the Dahlgren Polar Monitoring Service, later by the Defense Mapping Agency Polar Monitoring Service (DPMS), and the results were published regularly by the BIH (1972-1983).

SLR technique: The fundamental measured quantity in the SLR technique is the recorded roundtrip travel time of the photons from a laser-equipped telescope to the satellites (Starlette, Lageos, Ajisai, Etalon, etc.) equipped with the laser corner cube reflectors. The corresponding range accuracy of the current third generation SLR systems is a few centimetres. Since the 1970s, this technique has been applied to the determination of variations in the Earth's rotation, precise satellite orbit determination, to improve the model of the Earth's gravity potential as well as studies in geodynamics [Smith et al., 1972, 1979, 1989; Tapley, 1982; Reigber et al., 1989; Degnan, 1993]. The SLR technique is also the most precise one for current rapid routine monitoring of variations of the Earth's rotation at the few centimetre level as seen from the recent IERS reports. At the present time, there are more than 150 SLR sites including those visited by mobile SLR instruments. The SLR equipment is relatively heavy and expensive in its construction, maintenance and transportation. Its applications are constrained by high technical demands and are weather dependent.

LLR technique: The LLR technique involves measuring the roundtrip travel time of photons from a receiving telescope to the corner retroreflectors positioned on the surface of the Moon. It is one of the most sophisticated and demanding techniques, because there must be sufficient laser energy in order to receive the very weak signals returning from the distant retroreflectors. During the early LLR experiments, the components of the Earth's rotation were derived and presented by some research groups through analysis of the observation data sets [Stolz et al., 1976; King et al., 1978; Langley et al., 1981a; Shelus et al., 1993]. Their results were introduced into the BIH. Due to the difficulties of the LLR technique, i.e., heavy, expensive instrumentations, only about ten LLR systems in observatories around the world were developed and only two or three of them now range to the moon on a regular basis.

VLBI technique: The VLBI technique was introduced to geodesy in the late 1960s. This technique involves the measurement of the relative time delay and the rate of the relative time delay of radio signals emitted by extragalactic sources, as received by radio telescopes at two or more stations separated by thousands of kilometres. At least two baselines formed by three stations are necessary for determination of the ERP. The early experiments for the determination of ERP were performed at the end of the 1970s [Robertson et al., 1979, 1983]. Since 1980 these results have been introduced into the BIH. The VLBI technique is most successfully used to determine the extragalactic radio source positions and the Earth's orientation parameters including the ERP and variations in nutation with an accuracy better than 0.1 milli-arcseconds (mas) by using the Mark III system. The applications of this technique are very wide in the areas of astrophysics, astrometry, geodesy and geophysics. The number of VLBI stations is limited due to their high cost and technical sophistication.

GPS technique: The GPS technique is one of the marvels of modern technology. This most promising technique is having a great impact on geodesy and geophysics [Beutler, 1992; Blewitt, 1993]. GPS consists of three segments: space, control and user systems. The space and control systems are operated by the U.S. Air Force for the U.S. Department of Defense. The fundamental observables are: pseudoranges with the C/A-code and/or the P-code, carrier beat phase, and the rate of the carrier phase, i.e., Doppler observable. When fully completed, the GPS satellite constellation will contain 21 Block II satellites plus 3 active spares. The satellites are arranged in 6 orbital planes inclined at 55 degrees to the equator. Each orbit is near circular with a nominal altitude of 20183 km. The corresponding orbital period is 12 sidereal hours. This technique can provide a variety of military and civilian users with continuous all-weather precise navigation with at least four satellites simultaneously visible in good geometry for any point on the Earth. With the revolution of the GPS technique, widespread and diverse applications have been found. For example, GPS has contributed to monitoring crustal deformation, plate motions, ionospheric and tropospheric activities, and variations of the Earth's rotation. With precise orbits of GPS satellites determined by processing global GPS data sets, superior global and regional geodetic networks can be established, and precise real-time kinematic positioning of mobile platforms can be implemented. From the first GPS experiment for the IERS and Geodynamics (GIG'91) from January to February 1991, it has been demonstrated that the ERP can be obtained with a high temporal resolution from days to hours and with an accuracy at the centimetre level.

1.2 Importance of the ERPs in Geodynamics

The Earth rotation parameters have important applications in astronomy, geodesy, geodynamics and space navigation. In the geodynamical realm, the variations of the Earth's rotation are tightly linked with the various perturbing sources coming from external celestial bodies (the Moon and Sun), movement of the atmosphere and ocean on the Earth and the coupling mechanisms of the Earth's interior. How complicated in structure and active in motion does the Earth look? In general, the structures and properties of the Earth can be described by a simplified rotating deformable ellipsoidal anelastic body with the fluid layers of the atmosphere and oceans, the solid crust and mantle, the solid ellipsoidal inner and viscous outer cores. This planet is not static, but very vigorous as seen from the following examples: solid, ocean and atmosphere tides; wind; ocean currents; atmospheric movement; polar ice melting; earthquakes; plate motions and mantle convection; core-mantle interaction; groundwater activity. Based on the conservation of angular momentum, the derivative of the angular momentum is equal to the torque of the external volume force, which is expressed by Euler's dynamical equations and can be applied to the solid Earth. The Earth's rotation has the corresponding changes to some extent, just as these phenomena cause the redistribution of the mass of the Earth, relative motions of the parts of the Earth, and exert torques on the Earth. From the viewpoint of the transfer relation, the perturbing sources can be considered as the input, and the ERP as output having passed through the Earth "filter". Since the Earth has complicated structures and diverse properties, the responses of the Earth, considered as a system, to the external and internal excitation sources are different. The routine calculations and analysis of atmospheric angular momentum are a striking example for demonstration of the angular momentum conservation of the Earth's system with respect to polar motion [Wilson and Haubrich, 1976a, 1976b; Jochmann, 1981] and for the Length of Day (L.O.D.) [Barnes et al., 1983; Rosen et al., 1990] in the annual and semi-annual periods, as well as 40-60 day high frequency variation in the L.O.D. [Langley et al., 1981b, 1982; Dickey et al., 1990]. However, there are still some inextricable problems remaining in the study of the ERP and geodynamics, such as Chandler wobble, polar drift, mechanism of variations of the ERP of high frequency from a few days to hours, and core-mantle coupling. Therefore, monitoring of the Earth's rotation and increasing the precision and resolution of the ERP will contribute to revealing and solving these problems, and will also allow researchers to gain deep insight into the whole dynamical process of the Earth.

Tables 1.1 and 1.2 depict the major components in the variations of the Earth rotation [Langley, 1992]:

Table 1.1 Variations in length of day

Variation	ΔL.O.D.	Causes
secular	$2 \cdot 10^{-3}$ sec/century	tidal friction
decade	0.0007 sec/year	core-mantle interaction
annual semi-annual	0.5 msec 0.3 msec	atmospheric movement; tides
50-day monthly fortnightly day to hours	0.2 msec 0.5 msec 0.5 msec 0.1 msec	atmospheric movement; tides

Table 1.2 Variations in polar motion

Variation	x_p , y_p	Causes
secular	0.003"/year	core-mantle interaction
Chandler wobble	0.15"	eigenvalue
annual semi-annual	0.1" 0.05"	atmospheric movement; tides
monthly fortnightly day to hours	a few milli-arcseconds	atmospheric movement; tides

1.3 Thesis Contributions

DIPOP software has been modified by considering the following aspects: (1) to determine the daily Earth rotation parameters; (2) to improve and precisely predict the daily GPS satellite orbits; (3) to adjust the global geodetic network; and (4) to check and guarantee the quality of GPS data sets collected from the global stations. The corresponding observation equations, parameter partial derivatives with respect to the geodetic and geodynamical parameters are further developed for completeness of the models. The rigorous noise and cycle slip criteria have been imposed.

The new version software DIPOP.ERP has been carried out in Time Sharing Operation (TSO) environment for daily estimation of the Earth rotation parameters by processing seven-day global GPS observation data sets provided by 29 stations equipped with Rogue receivers from the IGS'92 campaign. The main processing software DIPOP.ERP, preprocessing softwares PREDD.ERP and PREGE.ERP implemented in the mainframe IBM 9121, model 320 are more efficient, flexible and versatile in many respects. They can be used to process daily (24 hours) GPS data sets with more than 30 stations and all usable satellites based on the double difference algorithm. The software PREDD.ERP is efficient in detecting and fixing the cycle slips in an automated way at better than a 90% success level or in a manual way, depending on the data quality and gaps. By using the auxiliary software connected with the Statistic Analysis Software (SAS) graphics package available on the mainframe, the cycle slips and outliers remaining in the data sets can be easily found and removed before or after main processing, based on the criteria proposed.

The daily solutions using three strategies, a seven-day solution for determination of the Earth rotation parameters, adjustment of a global GPS geodetic network and improvement of the GPS satellite orbits have been obtained and compared.

1.4 Thesis Outline

Chapter 1 briefly introduces the historical background and importance of this research in geodesy and geodynamics as well as the thesis contributions.

Chapter 2 highlights two kinds of essential reference systems and time systems, based on which the theory and practice can be described.

Chapter 3 explicitly presents how the Earth rotation disturbs the satellite orbits in the kinematic and dynamical viewpoints. It will be helpful to understand why the Earth rotation parameters and satellite orbital parameters have to be solved for simultaneously.

Chapter 4 describes the objectives of the GPS'92 campaign and the major processing centres, and gives some details in our data preparation collected from the IGS core stations. The history of DIPOP software development is shortly introduced. The new version of this software modified in this research and its structure is outlined.

Chapter 5 sheds light on the GPS principles and fundamental observation equation models, which are used in Chapters 6 and 7.

Chapter 6 further linearizes the observation equations and develops the partial derivatives with respect to the geodetic and geodynamical parameters.

Chapter 7 deals with the algorithms in the differential positioning technique, which are invoked in this research. The application of these algorithms used in the preprocessing and some sample results are presented.

Chapter 8 describes the scheme of implementation of postprocessing GPS'92 data sets collected from the global permanent stations, by using the modified DIPOP software. The results from the geodetic network adjustment are presented, discussed, and compared.

Chapter 9 summarizes the accomplishment in this experiment and gives some concluding remarks. Recommendations for further improvements are provided.

CHAPTER 2
REFERENCE SYSTEMS AND TIME SYSTEMS

2.1 Reference Coordinate Systems

There are two fundamental reference systems which are often of concern in applications of astronomy and geodesy. They are the Conventional celestial Inertial reference coordinate System (CIS) and the Conventional Terrestrial reference coordinate System (CTS), to which all relevant observations can be referred and in which theories or models for the motions of objects can be described. In order to meet the requirements of monitoring variations of the Earth's rotation, it is necessary to understand the CIS and CTS based on definitions, standards, analysis and transformations for the new techniques.

2.1.1 Conventional Celestial Inertial Reference Coordinate System

In classical mechanics, any reference frame meeting the requirement of Newton's first law of motion can be called an inertial frame. It is either at rest or in a state of uniform and rectilinear motion without acceleration of its origin. In the frame of Newton's theory, any obvious and observable departures from Newton's mechanics can be taken into account and corrected in the general relativistic theory. In general, any one CIS should be as inertial, easily accessible and accurate through applications of various and satisfactory physical models, as possible.

In practice, the celestial reference frame chosen depends on how easily it can be approached and used. It can be described by a basic equatorial plane, origin and orientation, which are defined by objects in inertial space by using right ascension and declination, which refer to a fixed point (usually the vernal equinox is chosen) and a celestial equator respectively. From this the positions of the stars and the extragalactic objects for the optical and radio interferometry techniques can be described. Owing to the differences in techniques, constants adopted, physical and mathematical models chosen, kinematics of the observed objects, etc., there are many different and comparable systems, not only for the same technique, but also for different techniques. This situation is suited to the terrestrial system as well. So a CIS reference frame depends on the motion of the observed object and on the method used to determine it.

There are several celestial inertial reference coordinate systems that have been established for use by different techniques, such as Stellar-CIS, VLBI-CIS and Satellite-CIS. They can be either kinematical or dynamical according to the form of motion of the observed objects. For instance, the description of proper motions of some celestial bodies belongs to kinematics, while the description of the motion of a satellite or planet around the Earth or Sun belongs to the dynamical one. Currently, the VLBI-CIS is the best. It is defined by a set of designated extragalactic radio sources, with theories and constants chosen so that there is no net rotation between the reference frame and the set of radio sources. The VLBI celestial inertial reference frame is defined by the positions and motions of the designated radio sources. The origin of the frame is the barycentre of the solar system. Its equator and reference origin of the right ascensions are defined by the coordinates of radio sources in the VLBI-catalogue referred to a certain epoch, usually to J2000.0. One of the essential differences between extragalactic radio sources and the stars is that there exists no observable proper motion in the radio sources, because they are so remote (further than 1000 Mpc if their red shifts are cosmological) and compact (the size of their pointlike cores is less than 1 mas) [Ma, 1989], so any apparent change in the positions of the extragalactic radio sources can be mainly attributed to the changes of the intermediate reference systems, e.g. changes in precession or nutation. Hence, we can use suitable long spans of VLBI observation data to investigate variations of precession and nutation, and the equinox correction. The VLBI-CIS is a kinematic one. Its reference origin of right ascensions remains arbitrary due to the relative positioning characteristic of the VLBI technique. Therefore, this reference origin needs to be tied to the equinox for several reasons, one of which, for example, is to distinguish between the corrections of precession and the position of the vernal equinox. There are two ways to connect them. One is to use timings of pulsars, another is to use interferometric measurements of the artificial radio sources that are provided by transmitters placed either on the surface of celestial bodies or in well-established heliocentric orbits [Green, 1985]. Currently, this reference origin can be chosen so as to be close to the FK5 equinox by choosing one or more stable and compact radio sources as the fiducial point. It has turned out from the analysis of the source structures from the VLBI observations [Tang, 1988; Charlot et al., 1988] that a number of quasars, including 3C273B, which can be observed by both optical and VLBI techniques, are not structurally stable. They have relatively changeable structures with time which results in the displacement of the centroids of radiation. Also, even stable quasars could have extended structures which would have different apparent centroids depending on the VLBI baseline and its orientation [Langley, 1989]. The criteria of how to select adequate reference radio sources for establishing a good catalogue and for defining the origin of right ascension of the VLBI-CIS have been discussed by, e.g., Carter et al. [1987] and Tang [1988] and catalogues and compact radio sources used for definition of the origin of right ascension have been given. In general, the positions of the radio sources can be determined with a precision of better than 0.1 mas, so the VLBI-CIS is superior to any other and can be considered as a long-term conventional inertial system with high stability, with which any other CIS could be compared.

IERS has implemented one unified VLBI-CIS, called RSC(IERS) (Radio Source Coordinates), by combining various radio source catalogues from different organizations. For instance, RSC(IERS) 92 C 01 referred to epoch J2000.0 is released currently by combining two individual radio source catalogues: RSC(GSFC) and RCS(JPL). As seen from the IERS Annual Report for 1991 [IERS, 1992], RSC(IERS) 92 C 01 was materialized from the coordinates of 422 extragalactic compact radio sources (including 65 primary, 152 secondary and 205 complementary sources) uniformly distributed on the sky (declinations from –82 to +85 degrees). The coordinates for a set of 65 primary sources with formal uncertainties in the range 0.2 to 0.4 mas have been adopted to define the orientation of the axes of RSC(IERS) 92 C 01.

2.1.2 Conventional Terrestrial Reference Coordinate System

The CTS is defined by a set of designated reference stations, theories and constants chosen so that there is no net rotation and translation between the reference frame and the surface of the Earth. The terrestrial reference frame is to be realized by a set of positions (usually Cartesian or geodetic coordinates) and motions (their velocities) referred to some epoch for the designated reference stations so that the mean equator and orientation of the CTS can be determined. The CTS can also be divided into kinematical and dynamical forms. The reasons are the same as those for the CIS. The accuracy of the CTS depends on the globally distributed, qualified observation sites, techniques and theoretical models adopted. There are conceptually considerable differences in these respects so that the CTS frames established by the new techniques (VLBI, LLR, SLR and GPS) are more stable than those established by the classical techniques due to i) considering for example, the relative motions of the sites due to the global plate movement, ii) because their observations are no longer referenced to the local plumblines, and iii) SI (International System) scale implemented in the sense of the relativistic theory.

There are several terrestrial reference coordinate systems that have been established through the use of various new techniques, such as VLBI-CTS and Satellite-CTS. The best CTS chosen may be one globally combined CTS realized through the collocation of the sites of different observation techniques and the consideration of their various features. For instance, unlike the satellite-CTS, the VLBI-CTS is not sensitive to the mass centre of the Earth because it is kinematical. The relative coordinates of the sites occupied by the stations with the new techniques can be determined with an accuracy of better than a few centimetres by fixing the coordinates of one or more sites.

IERS provides a kind of unified CTS, called the IERS Terrestrial Reference Frame (ITRF), such as the ITRF91 and the current ITRF92, which is based on the IERS standards (1989) [McCarthy, 1989] and a set of collocated sites with accuracies of better than tens of centimetres which have been occupied by VLBI, SLR and GPS techniques. The main characteristics of the ITRF91 are: (1) its origin is located at the Earth's centre of mass; (2) SI scale in a local frame comoving with the Earth; (3) its orientation is given by the orientation of the BIH CTS at 1984.0; and (4) its time evolution following a no global net rotation and translation with respect to the crust (Tisserand condition). More details about ITRF91 can be found in the IERS Technical Note No. 12 [Boucher et al., 1992] and the IERS Annual Report for 1991 [IERS, 1992].

2.1.3 Relation between the CIS and CTS

The motion of the CTS referenced to the CIS can be described by precession, nutation and the Earth's rotation, so that the orientation of the Earth in space can be determined. The transformation from the CTS to the CIS may be written as

$$[CIS] = PNS\ [CTS] \tag{2-1-3-1}$$

where P, N and S are the precession, nutation and Earth rotation matrices respectively and are expressed by the following:

$$P = R_z(\zeta_0)\, R_y(-\theta)\, R_z(z) \tag{2-1-3-2}$$

$$N = R_x(-\varepsilon)\, R_z(\Delta\psi)\, R_x(\varepsilon + \Delta\varepsilon) \tag{2-1-3-3}$$

$$S = U\ Y\ X$$

$$= R_z(\theta_G)\, R_x(y_p)\, R_y(x_p) \tag{2-1-3-4}$$

where the rotation matrix $U = R_z(\theta_G)$; matrices of polar motion $Y = R_x(y_p)$, $X = R_y(x_p)$; and the rotation angles of matrices P and N, defined by Lieske [1979] and Lieske et al. [1977] and referenced to epoch J2000.0, describe the motions of the Conventional Celestial Ephemeris Pole (CEP) with respect to a space-fixed coordinate system; the Earth rotation parameters include three components, i.e. the polar motion (x_p , y_p) and the L.O.D. or equivalently any one of the following: UT1, spin velocity ω_3, or θ_G which is Greenwich Apparent Sidereal Time (GAST). GAST may be determined from

$$\theta_G = GMST_0 + (1 + k)\ UT1 + \Delta\varepsilon \cos\psi \tag{2-1-3-5}$$

where $GMST_0$ is the Greenwich Mean Sidereal Time at 0^hUT1, $\Delta\varepsilon \cos\psi$ is a correction to the equinox due to the nutation in obliquity $\Delta\varepsilon$, and $(1 + k)$ is a factor for transforming universal time to sidereal time:

$$(1 + k) = 1 + 0.002737909350795 + 5.9006 \times 10^{-11}\ T_u - 5.9 \times 10^{-15}\ T_u^2 \tag{2-1-3-6}$$

T_u is the number of centuries of 36525 days of universal time elapsed since 12^hUT1, January 1, 2000, (JD 2451545.0^hUT1, i.e. J2000.0).

Polar motion describes the motion of the CEP with respect to a body-fixed coordinate system, i.e. the angular separation of the average figure axis of the CTP (Conventional Terrestrial Pole) and the axis of the CEP of the Earth; and L.O.D. describes the length of day in terms of SI seconds. Figure 2.1 depicts the relationship between the CIS and the CTS, where γ is the true vernal equinox and G indicates the Greenwich observatory, so the ERP make a tie between the CIS defined by the true celestial equator and equinox at epoch T and the CTS defined by the conventional (or mean) terrestrial equator.

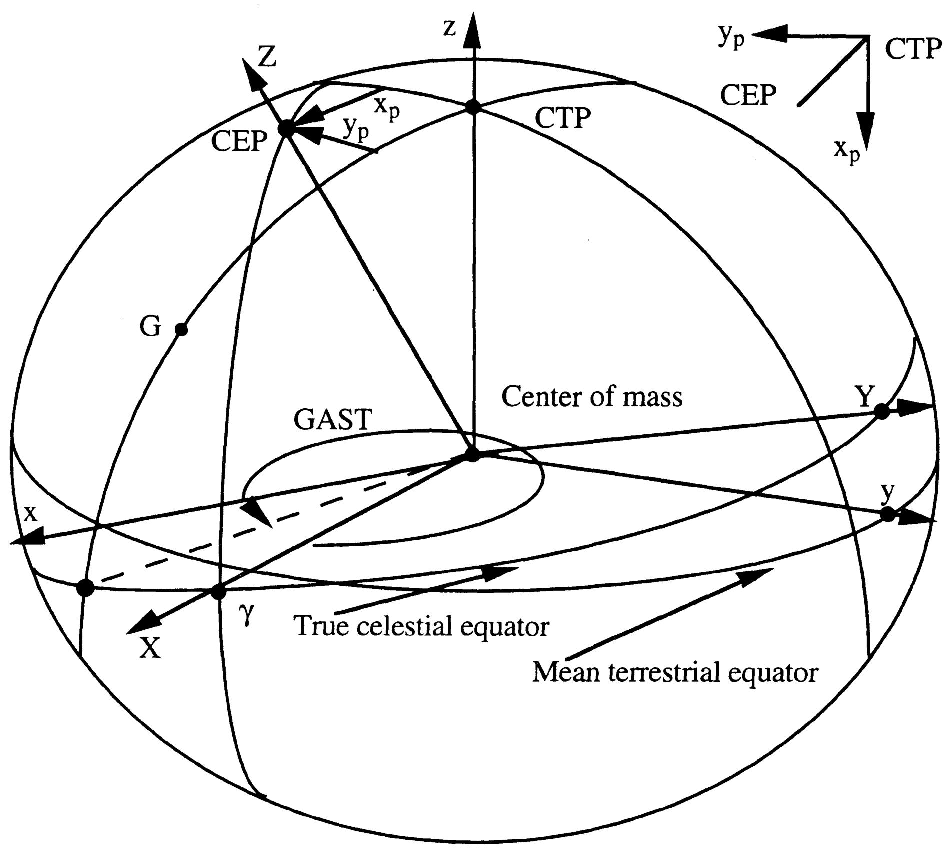

Figure 2.1 Definition of the Earth rotation parameters

The nutation series of the CEP is based on the 1980 IAU theory of nutation with accuracies approaching the truncation error of 0.1 mas is given in Wahr [1981], and on geophysical model 1066A of Gilbert and Dziewonski [1975], and therefore includes the effects of a solid inner core and a liquid core outer core, and a distribution of elastic parameters inferred from a large set of seismological data. Recently, the coefficients of the nutation terms computed from VLBI data, and those based on the 1980 IAU theory of nutation have been found to be generally in agreement to several milli-arcseconds. Nevertheless, corrections of several main nutation terms have been estimated with uncertainties of ±0.1 mas [Herring et al., 1988], but for the long period nutation term (6798.4 days) with those of ±3.0 mas [Himwich and Harder, 1988]. The physical reasons for the corrections of the nutation series are under active investigation mainly related to the interaction between the core and the mantle.

The series offsets ($\delta\Delta\varepsilon$, $\delta\Delta\psi$) from the IAU values can be obtained from the regular services of the IERS and the International Radio Interferometric Surveying (IRIS) service. It is known that if the intermediate reference frame defined by the nutation and precession transformation matrices is changed, either the S matrix must be changed by adding the respective corrections to polar motion (x_p , y_p) and GAST or the orientation of the CTS is changed. There are seven options for maintenance of the CTS corresponding to the change of the CIS to be chosen according to preference of the user [Zhu and Mueller, 1983]. If the CTS is to be kept unchanged, the corrections of the polar motion and UT1 caused by the offsets ($\delta\Delta\varepsilon$, $\delta\Delta\psi$) of the nutation series can be represented in the following equations

$$\Delta x_p = \delta\Delta\varepsilon \ \sin(\theta_G) + \delta\Delta\psi \sin\varepsilon \ \cos(\theta_G) \quad (2\text{-}1\text{-}3\text{-}7)$$

$$\Delta y_p = -\ \delta\Delta\varepsilon \ \cos(\theta_G) + \delta\Delta\psi \sin\varepsilon \ \sin(\theta_G) \quad (2\text{-}1\text{-}3\text{-}8)$$

$$\Delta(\mathrm{UT1}) = \delta\Delta\psi \cos\varepsilon \quad (2\text{-}1\text{-}3\text{-}9)$$

where $\Delta\psi$ is the nutation in longitude.

Based on recent results from two decades of LLR data and one decade of VLBI data analysed by Charlot et al. [1990], it was found that corrections of about a few milli-arcseconds are required for six major terms: those with a period of 18.6 years in precession, and 1 year, 0.5 year, 14 days and 433.2 days in nutation. It can be estimated that the maximum direct effect on GPS satellite orbits from these corrections comes from the correction term of 0.5 year in nutation and has a level of about 10^{-8} radian in the satellite motion with a period of about 1622 days. The effect of the nutation corrections on the GPS satellite orbits was discussed and presented by Zhu and Groten [1990].

2.2 Time Systems

The time systems are essential to geodetic positioning and for monitoring the variations of the Earth's rotation. Several different time systems are used in theory and practice, for instance, proper time, atomic time, coordinate time and coordinated universal time. In the GPS technology, the highly precise atomic clocks onboard GPS satellites are employed to control the generation of the carrier frequencies and codes. Each Block II GPS satellite contains four atomic frequency standards: two rubidiums and two cesiums, one of which can be commanded by the GPS control system to be the controlling clock. Also a high precision clock may be required by a GPS receiver for purposes of timing, time transfer, and time synchronization. The frequency standard of the GPS receiver can come from either the internal clock within the receiver or an external clock (cesium or hydrogen maser with stability of better than 10^{-13} over a one-day period for precise positioning and long term monitoring of variations of the Earth's rotation). Most GPS receivers are equipped with a quartz crystal oscillator with stability of 10^{-10} over a one-day period, which are small, light, power-saving and inexpensive. The biases of the GPS satellite clocks from

GPS time can be solved for by using the pseudorange and carrier beat phase measurements so that the time synchronization between two remote clocks can be reached at 0.1 microseconds (μs) accuracy or better. In the following the different time systems being used are briefly introduced.

2.2.1 Proper Time and Atomic Time

Proper time is an essential time argument or observable in theory of relativity. It is physically and mathematically thought to be uniform time provided by a standard clock (i.e. an ideal atomic clock without the environment influence, such as temperature, atmospheric pressure, etc.) resting at one point in space-time. The distance between two points with occurrence of one event measured by the standard clock at each point is known as a geodesics or worldline. If there exists no common area with the same time-space properties, for instance, a spatially-varying same gravitational potential for this area, then the proper times provided by these two standard clocks can not be compared, because proper time is a function of the worldline depending on the space-time metric. Even though proper time is formally used for mathematical and physical descriptions in the general relativistic theory, in practice proper time can be realized by atomic time, which is provided by an atomic clock with a stability of better than 10^{-13} over a one-day period. In 1967, the atomic second was defined as follows [Guinot, 1989]: "The second is the duration of 9 162 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium-133 atom". Based on the definition of the second, the metre has the definition [Guinot, 1989]: "The metre is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second." Then the speed of light c is 299 792 458 metre/second as a derived value. Therefore, the atomic time scale is established based on the use of a number of laboratory-grade atomic clocks and some standards, such as the SI scale mentioned above. In practice, the drift and some corrections associated with temperature, pressure, etc., for the atomic clocks have to be taken into account in order to serve atomic time as proper time.

2.2.2 Coordinate Time

Coordinate time is one of the independent variables in the description of dynamical phenomena in general relativistic space-time. Coordinate time can not be directly measured, but served or realized by a dynamical time scale in an ephemeris calculation. There are different coordinate times depending on the adopted coordinate systems associated with different gravitational potentials. For instance, the origin of the coordinate system for Terrestrial Dynamical Time (TDT) is at the mass centre of the Earth; for Barycentric Dynamical Time (TDB) at the barycentre of the solar system. The expressions and differences between TDB and TDT have been fully explained by a number of authors (e.g., Moyer [1981a, 1981b]; Fairhead et al. [1987]; Fukushima [1989]). The major terms describing the differences between the two time scales are listed in the following:

$$\begin{aligned} TDB - TDT = {} & 1656.675 \sin(E - 102.9377^\circ) + 22.418 \sin(E - J - 179.916^\circ) \\ & + 13.840 \sin(2E + 154.124^\circ) + 4.770 \sin(J - 8.888^\circ) \\ & + 4.677 \sin(E - S - 179.995^\circ) + 2.257 \sin(S - 92.481^\circ) \\ & + 1.686 \sin(4E - 8M_m + 3J + 106.882^\circ) + 1.555 \sin D \\ & + 1.277 \sin(2V - 2E - 179.893^\circ) + 1.193 \sin(E - 2J + 177.357^\circ) \\ & + 1.115 \sin(V - E + 0.009^\circ) + 10.216\, T_u \sin(E + 142.985^\circ) \quad (\mu s) \end{aligned} \qquad (2\text{-}2\text{-}2\text{-}1)$$

where the symbols V, E, M_m, J and S are the mean longitudes of Venus, the Earth-Moon barycentre, Mars, Jupiter and Saturn, respectively; D is the mean elongation in longitude of the Moon from the Sun; and T_u is the TDB in Julian centuries from J2000.0.

Since the relationship between proper time and coordinate time is expressed by the general relativistic theory, coordinate time can be used to compare the different proper times provided by atomic clocks located at the different sites. For instance, the proper times provided by the standard clocks can be reduced from the surface of the Earth to the geoid so that they are comparable, since the standard clocks beat at same rate on the geoid by approximation of the general relativistic theory. In order to implement comparisons of atomic time from different atomic clocks, the International Atomic Time abbreviated as TAI has been adopted. TAI is a coordinate time scale defined in a geocentric reference frame with the SI second and realized on the rotating geoid. The relationship between TAI and TDT is defined by

$$TDT = TAI + 32.184 \quad \text{seconds} \qquad (2\text{-}2\text{-}2\text{-}2)$$

The accuracy for a reading of TAI can approach the 10-50 nanonseconds (ns) level in laboratories with an increase of accuracy of time comparison achieved by using GPS receivers [Guinot, 1989].

2.2.3 Coordinated Universal Time

The coordinated universal times, such as UTC, UT1, UT2, etc., are often used. Some users need them in real time by approximation, others with some delay by using accurate published values. For the purpose of transformation between the celestial coordinate and terrestrial systems from eq.(2-1-3-5) for calculation of GAST, it is obvious that UT1 needs to be known. UT1 can be written in terms of TDB as

$$\begin{aligned} UT1 = TDB - (TDB - TDT) - (TDT - TAI) - (TAI - GPS) \\ - (GPS - UTC) + (UT1R - UTC) + (UT1 - UT1R) \end{aligned} \qquad (2\text{-}2\text{-}3\text{-}1)$$

where TDB–TDT is expressed in eq.(2-2-2-1); UT1R represents the corrected values of UT1 by removing the effects of the zonal tides. The corrections UT1–UT1R can be found in Tables I-5a and I-5b of the IERS Annual Report for 1989 [IERS, 1990], based on the development by Yoder et al. [1981]. The values of UT1R–UTC can be found in IERS Bulletin B.

Normally, the quantities observed by GPS receivers, i.e., pseudorange and carrier beat phase, are referenced to GPS time. GPS time used by the control segment is derived from UTC as maintained by a sets of atomic clocks of the U.S. Naval Observatory (USNO). GPS time was set equal to UTC on Sunday 6, January, 1980 at 0^hUTC without the leap second since then. UTC has the leap second and has been adjusted about once a year, usually at July 1, 0^hUTC or January 1, 0^hUTC, by accumulatively inserting positive leap seconds into TAI, that is

$$TAI - UTC = K \quad \text{(K is an integer number of seconds)} \qquad (2\text{-}2\text{-}3\text{-}2)$$

so that UTC has being kept sufficiently close to UT1, i.e. $|UT1 - UTC|<0.9$ seconds. During the time interval from 0^hUTC of July 1, 1980 to 0^hUTC of January 1, 1981, we have K=19 seconds. Of course, GPS – UTC=0 second. Figure 2.2 depicts the integer difference between GPS time and UTC with one negative leap second at each epoch 0^hUTC introduced into UTC.

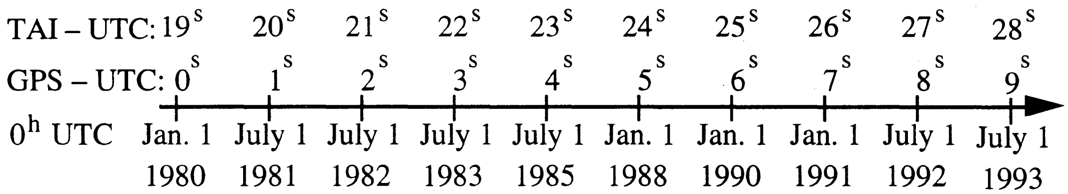

Figure 2.2 Differences for GPS – UTC and TAI – UTC from 1980 to 1993

Because GPS time is maintained to about 1μs from UTC(USNO) and UTC – UTC(USNO) is normally smaller than 5μs [Guinot, 1989] then GPS time can provide UTC and TAI in real time about 5μs everywhere.

CHAPTER 3
PERTURBATIONS OF THE EARTH'S ROTATION

3.1 Principles

The Earth rotation parameters are small quantities. The major components of variations in polar motion are Chandler wobble with amplitude of about 0.15" and period of about 1.2 years, and annual motion with an amplitude of about 0.1". So the maximum radius of the path of polar motion is about 7 metres. Comparing with UTC time, the excess length of day (that is defined as D' used in the IERS annual report), which has the same value with an opposite sign for the time varying rate of UT1–UTC (that is defined as D used in the thesis), is about 2 ms which corresponds to a displacement at the Earth's equator of about 1 metre. The major variation in L.O.D. is the annual motion with amplitude of about 0.4 ms (0.2 metre) , which corresponds an amplitude of about 23 ms in UT1–UTC. It is obvious that if the Earth rotation parameters are neglected or only roughly approximated in any transformation of the coordinates of satellites or stations, in computing the forces from the gravitational potential of the Earth acting on the satellites, as well as in the partial derivatives with respect to the orbital and dynamical parameters of the satellites between the CIS and the CTS, errors will be introduced into the observation equations. Therefore, the Earth rotation parameters can be determined under conditions of determination of precise satellite orbit and precise ranging from globally distributed stations.

The Earth rotation parameters can be determined from two viewpoints, depending on whether the coordinates of the satellites and stations are expressed in the CTS or the CIS. From the first viewpoint, if the reference orbit of the satellite to be integrated is fixed in the CIS, the station coordinates to be expressed in the CIS will be disturbed by the Earth's rotation. From the second viewpoint, if the station coordinates are considered as fixed in the CTS, the satellite coordinates have to be transformed from the CIS to the CTS. In this way, the satellite coordinates will be disturbed by the Earth's rotation. For both cases, the errors coming from coordinate transformation of the satellites or stations will be introduced into the observation equations. This major effect is kinematic due to the direct coordinate transformation. In addition, there is a dynamical effect on the observation equations, because the geopotential coefficients of the Earth expressed in the CTS are considered as constant. Based on the theory of the gravitational potential of the Earth [Vaníček, 1973], the time varying disturbing potential R used to calculate the major forces acting on the satellites can be written in the general form:

$$R = R_G + R_D + R_P + R_T + R_R + R_M + R_{KC} + R_{DC} \tag{3-1-1}$$

where the disturbing gravitational potential of the Earth $R_G = R_E + R_{IS} + R_{IN}$, R_E is called an ellipticity term, i.e. J_2 term; irregular terms R_{IS} and R_{IN} are called the zonal harmonic terms, tesseral and sectorial terms respectively. R_D is the air drag term; R_P is the solar radiation pressure term; R_T is the tidal term including solid, ocean and atmospheric tides and the tide caused by polar motion; R_R is the relativistic term; R_M is an electromagnetic perturbation term; the last two terms R_{KC} , R_{DC} are the kinematic and dynamical effects of the coordinate perturbations to be introduced in the following sections. They can be neglected if accurate Earth rotation parameters are adopted in the coordinate transformation. If the satellite orbit is integrated in the CIS, these forces must be transformed to the CIS, or the geopotential coefficients of the Earth have to be expressed by considering the effect of the Earth's rotation. Therefore, if the Earth's rotation is not properly considered, errors will be introduced into the satellite orbit, and further into the observation equations. So this effect is dynamical due to the time variation of the geopotential of the Earth with the Earth's rotation. In the following, the kinematic and dynamical effects coming from the Earth's rotation are discussed.

3.2 Kinematic Effect

As presented by Reigber [1981,1989], if the satellite orbit is integrated in the moving frame with a rotation vector , the additional coordinate perturbation will be introduced into the right sides of differential equations of the Lagrange planetary equations for $\frac{di}{dt}$, $\frac{d\omega}{dt}$, $\frac{d\Omega}{dt}$ [Liu and Zhao, 1979], where i is the inclination, ω is the argument of perigee and Ω is the right ascension of the ascending node. But there is no effect on $\frac{da}{dt}$, $\frac{de}{dt}$, $\frac{dM}{dt}$ because of the invariance of a (major axis), e (eccentricity) and M (mean anomaly). If the rotation vector $\vec{\omega}_m$ is considered as the Earth's rotation, i.e. $\vec{\omega}_m = [\omega_x \quad \omega_y \quad \omega_z]^T$, where $\omega_x = -\dot{y}_p$, $\omega_y = -\dot{x}_p$ ($\dot{x}_p$ and $\dot{y}_p$ are the time varying rates of polar motion) and $\omega_z = 15\,(1 + k)\,\frac{d}{dt}(UT1 - UTC)$, or $\omega_z = 15\,(1 + k)\,D$, where D is equal to time varying rate of (UT1 − UTC), the additional coordinate perturbations for i, Ω and ω can be expressed by

$$\left(\frac{\partial i}{\partial t}\right)_p = \dot{y}_p \cos(\Omega - \theta_G) + \dot{x}_p \sin(\Omega - \theta_G) \tag{3-2-1}$$

$$\left(\frac{\partial \Omega}{\partial t}\right)_p = -\,15\,(1 + k)\,D + \cot i\,[\,-\,\dot{y}_p \sin(\Omega - \theta_G) + \dot{x}_p \cos(\Omega - \theta_G)] \tag{3-2-2}$$

$$\left(\frac{\partial \omega}{\partial t}\right)_p = \csc i\,[\,-\,\dot{x}_p \cos(\Omega - \theta_G) + \dot{y}_p \sin(\Omega - \theta_G)] \tag{3-2-3}$$

By directly integrating eqs. (3-2-1) to (3-2-3), their approximate solutions can be written as follows

$$\Delta i = y_p \cos(\Omega - \theta_G) + x_p \sin(\Omega - \theta_G) \tag{3-2-4}$$

$$\Delta\Omega = -15\,(1 + k)\,(UT1 - UTC) + \cot i\,[-y_p \sin(\Omega - \theta_G) + x_p \cos(\Omega - \theta_G)] \tag{3-2-5}$$

$$\Delta\omega = \csc i\,[-x_p \cos(\Omega - \theta_G) + y_p \sin(\Omega - \theta_G)] \tag{3-2-6}$$

From eqs. (3-2-4) to (3-2-6) it is demonstrated that the satellite orbits are disturbed by the Earth's rotation in a kinematic way, and that UT1 – UTC cannot be separated from the longitude of the ascending node Ω of the satellite, i.e., they can not be determined simultaneously so that one of them has to be fixed or highly constrained. Usually UT1 – UTC is constrained and the bias of UT1 – UTC will be absorbed to $\Delta\Omega$ in the orbital improvement. It is also obvious that the orbit errors will be on the tens of metres level for GPS satellites if the Earth's rotation is omitted in the coordinate transformation. In addition, if the approximate values of polar motion have errors of 0.002", which is about the maximum daily change of the polar motion, then an error of about 0.3 metre will be introduced into satellite orbit and observation equations. Therefore, the daily estimation of the Earth's rotation needs a precise determination of the satellite orbits and precise ranging to the GPS satellites.

3.3 Dynamical Effect

If polar motion is neglected or approximated in the orbital integration, errors also will be introduced into the expression of the gravitational potential of the Earth in the moving frame, and further into the satellite orbit. The first-order approximation of the disturbing function caused by polar motion can be written as follows

$$R_{DC} = -\frac{3}{4} J_2\, a_E^2\, n^2\, (1 - e^2)^{-\frac{3}{2}} \sin 2i\, [x_p \sin(\Omega - \theta_G) + y_p \cos(\Omega - \theta_G)] \tag{3-3-1}$$

where a_E is the radius of the Earth. By substituting eq. (3-3-1) into the Lagrange planetary equations, the approximate disturbing equations due to polar motion can be obtained as follows:

$$(\frac{da}{dt})_p = 0 \quad , \quad (\frac{de}{dt})_p = 0 \tag{3-3-2}$$

$$(\frac{di}{dt})_p = \Omega_1[\, -x_p \cos(\Omega - \theta_G) + y_p \sin(\Omega - \theta_G)] \tag{3-3-3}$$

$$(\frac{d\Omega}{dt})_p = 2\,\Omega_1 \cot 2i\ [x_p \sin(\Omega - \theta_G) + y_p \cos(\Omega - \theta_G)] \tag{3-3-4}$$

$$(\frac{d\omega}{dt})_p = \Omega_1 \frac{4 - 5\cos^2 i}{\sin i}\ [x_p \sin(\Omega - \theta_G) + y_p \cos(\Omega - \theta_G)] \tag{3-3-5}$$

$$(\frac{dM}{dt})_p = 3\,\Omega_1 \sqrt{1 - e^2} \sin i\ [x_p \sin(\Omega - \theta_G) + y_p \cos(\Omega - \theta_G)] \quad . \tag{3-3-6}$$

where $\Omega_1 = -\frac{3}{4} J_2\, n\, (\frac{a_E}{a})^2 (1 - e^2)^{-2} \cos i$ is a coefficient of the secular term in the longitude variation of the ascending node Ω of the satellite. For GPS satellites, Ω_1 is about 2.2 degrees/day, i.e., the period of Ω is about 163.6 days. The approximated solutions of eqs. (3-3-3) to (3-3-6) are expressed by

$$(\Delta i)_p = \frac{\Omega_1}{\dot{\theta}_A} [x_p \sin(\Omega - \theta_G) + y_p \cos(\Omega - \theta_G)] \tag{3-2-7}$$

$$(\Delta\Omega)_p = \frac{2\,\Omega_1}{\dot{\theta}_A} \cot 2i\ [x_p \cos(\Omega - \theta_G) - y_p \sin(\Omega - \theta_G)] \tag{3-2-8}$$

$$(\Delta\omega)_p = \frac{\Omega_1}{\dot{\theta}_A} \frac{4 - 5\cos^2 i}{\sin i} \left[x_p \cos(\Omega - \theta_G) - y_p \sin(\Omega - \theta_G)\right] \tag{3-2-9}$$

$$(\Delta M)_p = \frac{3\Omega_1}{\dot{\theta}_A} \sqrt{1 - e^2} \sin i \left[x_p \cos(\Omega - \theta_G) - y_p \sin(\Omega - \theta_G)\right] \quad . \tag{3-2-10}$$

From the above approximate solutions, the disturbing amplitudes of the Keplerian elements due to polar motion are about 10^{-8} radians. The effects on the orbit of GPS satellites are tens of centimetres (typically 0.5 metre). Therefore, the dynamical effect on the satellite orbits due to the Earth rotation has to be taken into account. In addition, the biases or errors remaining in the coefficients of the geopotential of the Earth will also contribute to satellite orbital errors. For instance, considering $\Delta C_{21} = -0.17 \times 10^{-9}$ and $\Delta S_{21} = +1.19 \times 10^{-9}$ [McCarthy, 1989; Feltens, 1992] and using $\Delta C_{21} = \Delta x_p C_{2C}$ and $\Delta S_{21} = -\Delta y_p C_{20}$ [Lambeck, 1971], they are equal to biases in polar motion of approximately Δx_p = +0.0724" and Δy_p = –0.5070". Therefore these biases also significantly contribute to the satellite orbit.

CHAPTER 4
GPS'92 CAMPAIGN AND DATA PREPARATION

4.1 Objectives

Following initial discussions at the 1989 IAG General Meeting in Edinburgh, the International GPS Geodynamics Service (IGS) under IAG auspices was subsequently developed [Beutler, 1992]. During the XX General Assembly of the IUGG in Vienna in August 1991, Resolution 5 was approved, which recognizes the rapid and increasing use of the GPS for geodesy and geophysics with a major role for it over the next decades in global and regional studies of the Earth and its evolution, and notes that the full scientific potential of GPS applications can only happen through international cooperation. After several meetings of the IGS planning committee, the IGS was established to organize the campaign for planning observation stations and calling for the establishment of data analysis centres as its first activity. From June 21, 1992 the GPS'92 campaign took place. More than 40 globally distributed GPS core stations participated in this campaign. Most of the stations were equipped with Rogue high accuracy receivers and located near VLBI or SLR stations. The data sets collected by those stations have been daily downloaded and transmitted to the processing centres.

In order to fully implement a regular service of providing GPS orbits and the ERP, the IGS processing centres have, in a timely fashion, provided precise orbits of the GPS satellites to meet the demands of regional and local GPS analysis centres obviating the need for further orbital improvement, and accurately estimated the ERP with daily resolution for further studies in geodynamics. During this campaign, a lot of local or regional campaigns have taken place in a number of countries to establish their precise national geodetic networks by using the GPS technique. The processing centres selected for the GPS'92 campaign were Centre for Orbit Determination in Europe (CODE), Centre for Space Research at the University of Texas (CSR/UTX), Energy Mines and Resources Canada (EMR), European Space Operations Centre (ESOC), GeoForschungsZentrum (GFZ), the Jet Propulsion Laboratory (JPL), and Scripps Institute of Oceanography (SIO). The products, i.e., precise orbits and the ERP, were generated and stored in the NASA Crustal Dynamics Data Information System (CDDIS). The ERPs obtained by the GPS technique also have been submitted to the IERS for comparison with those estimated by VLBI, SLR, and LLR techniques.

4.2 Data Collection

Table 4.1 shows the names of the stations and locations from which the GPS data was collected. Code1 and Code2 in Table 4.1 are their abbreviated names used for the file management in processing.

Table 4.1 Station name catalogue

No.	Station name	Location	Code1	Code2
1	Albert Head	Canada	ALBH	AB
2	Algonquin	Canada	ALGO	AL
3	Penticton	Canada	DRAO	PE
4	Fairbanks	U.S.A.	FAIR	FA
5	Goldstone (DSN)	U.S.A.	GOLD	GO
6	Graz	Austria	GRAZ	GR
7	Hartebeesthoek	South Africa	HART	HA
8	Herstmonceux	U.K.	HERS	HE
9	Pasadena	U.S.A.	JPLM	JP

10	Kokee Park	U.S.A	KOKB	KK
11	Kootwijk	Netherlands	KOSG	KO
12	Madrid (DSN)	Spain	MADR	MD
13	Maspalomas (ESA)	Spain	MASP	MP
14	Matera	Italy	MATE	MA
15	McMurdo	Antarctica	MCMU	MC
16	Metsahovi	Finland	METS	ME
17	Ny Alesund	Norway	NYAL	NY
18	Onsala	Sweden	ONSA	ON
19	Pamate/Tahiti	French Polynesia	PAMA	PA
20	Pinyon Flat	U.S.A	PIN1	PI
21	Santiago	Chile	SANT	SA
22	St. John's	Canada	STJO	ST
23	Tai-Shi	China	TAIW	TW
24	Tidbinbilla (DSN)	Australia	TIDB	TI
25	Tromso	Norway	TROM	TR
26	Usuda	Japan	USUD	US
27	Wettzell	Germany	WETT	WT
28	Yaragadee	Australia	YAR1	YA
29	Yellowknife	Canada	YELL	YE

In Table 4.1, there are five GPS stations belonging to Active Control Points (ACP), which are permanent tracking stations for geodetic and geodynamical applications under the operation of the Geodetic Survey of Canada, and have been continuously analysed since 1989 [Kouba and Chen, 1992; Tétreault et al., 1992]. From their presented results, a repeatability at a few parts in 10^8 or well below the 0.1 p.p.m. level was obtained for a baseline of about 2000 km.

Table 4.2 shows the details about the seven day data sets collected from July 25 to 31, 1992 during the GPS'92 campaign.

Table 4.2 GPS data holdings from July 25 to August 1, 1992 for the campaign GPS'92

(Receiver type: ROGUE)

day of	month	25	26	27	28	29	30	31	01
day of	week	Sat.	Sun.	Mon.	Tue.	Wed.	Thr.	Fri.	Sat.
GPS	week	654	655	655	655	655	655	655	655
day of	year	207	208	209	210	211	212	213	214
GPS	second	5.184d5	6.048d5	8.64d4	1.728d5	2.592d5	3.456d5	4.32d5	5.184d5
No.	Code1								
1	ALBH	y	y	y	y	y	y	y	y
2	ALGO	y	y	y	y	y	y	y	y
3	DRAO	y	y	y	y	y	y	y	y
4	FAIR	y	y	y	y	y	y	y	y
5	GOLD	no	y	y	y	y	y	y	y
6	GRAZ	y	y	y	y	y	no	y	y
7	HART	y	y	y	y	y	y	y	y
8	HERS	y	y	y	y	y	y	y	y
9	JPLM	no	y	y	y	y	y	y	y
10	KOKB	y	y	y	y	y	y	y	y
11	KOSG	y	y	y	y	y	y	y	y
12	MADR	no	y	y	y	y	y	y	y
13	MASP	y	y	y	y	y	y	y	y
14	MATE	y	y	y	y	y	y	y	y
15	MCMU	no	y	y	y	y	y	y	y
16	METS	y	y	y	y	y	y	y	y
17	NYAL	no	y	y	y	y	y	y	y
18	ONSA	y	y	y	y	y	y	y	y
19	PAMA	y	y	y	y	y	y	y	y
20	PIN1	y	y	y	y	y	y	y	y
21	SANT	y	y	y	y	y	y	y	y
22	STJO	y	y	y	y	y	y	y	y
23	TAIW	y	y	y	y	y	y	y	y
24	TIDB	no	y	y	y	y	y	y	y
25	TROM	y	y	y	y	y	y	y	y
26	USUD	no	no	y	y	y	y	y	y
27	WETT	y	y	y	y	no	y	y	y
28	YAR1	y	y	y	y	y	y	y	y
29	YELL	y	y	y	y	y	y	y	y

(Note: y means that the data set is available for that day; no means unavailable)

The data sets were provided by 29 IGS core stations equipped with dual frequency Rogue receivers. The observed quantities are the dual frequency carrier beat phase with a noise level of a few millimetres and the dual frequency pseudorange with a noise level of about a few tens of centimetres (f_{L1} = 1575.42 MHz, f_{L2} = 1227.60 MHz, or λ_{L1} = 19.029 cm, λ_{L2} = 24.421 cm) over 24 hours. There is an updated version for the data sets based on the RINEX format. There are 18 satellites available in the data set: Block I satellites PRN 3, 11, 12 and 13 with an average inclination of 64 degrees and Block II satellites PRN 2, 14, 15, 16, 17, 18, 19, 20, 21, 23, 24, 25, 26 and 28 with nominal inclination of 55 degrees. The adopted CTS is nominally ITRF'91. The fiducial station coordinates used are referenced to epoch 1992.5.

Figure 4.1 shows the geographical distribution of the IGS core stations and the general arrangement of the baselines used in this work for the single differences.

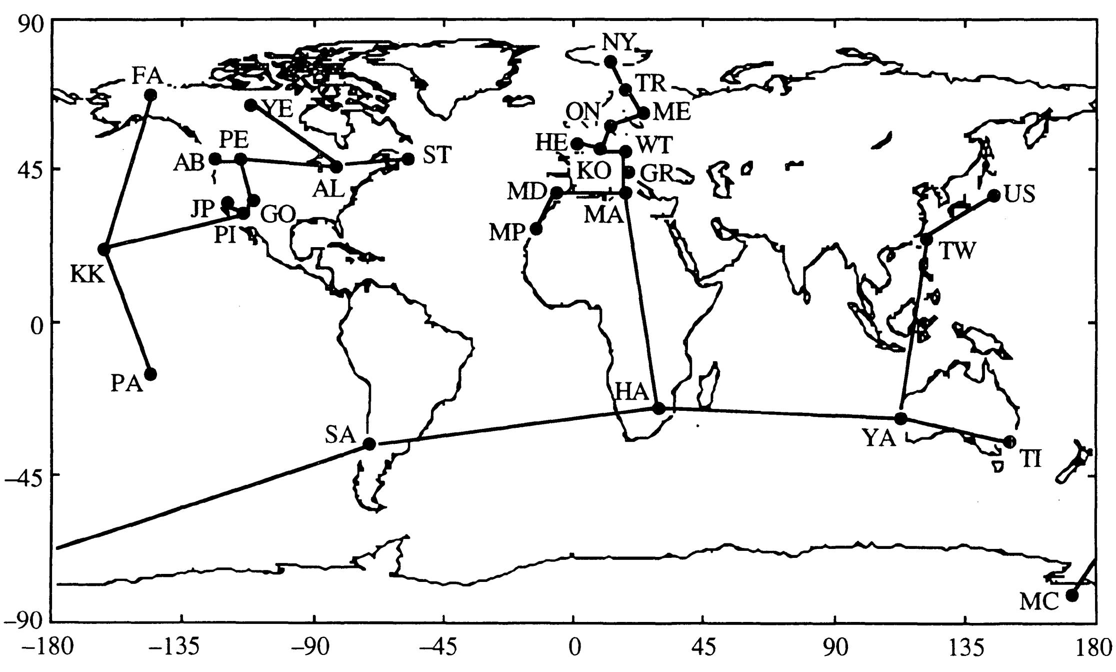

Figure 4.1 Distribution of the IGS core stations and arrangement of the baselines during 25-31 July for the GPS'92 campaign

4.3 Advantages

The potential for monitoring the variations of the Earth's rotation by means of the GPS technique has been proposed and investigated through the early simulations [Zelensky et al., 1990; Pâquet and Louis, 1990; Freedman, 1991] and the first short GPS experiment GIG'91 [Lichten et al., 1992; Lindqwister et al., 1992; Ferland, 1992]. The advantages of determining the Earth rotation parameters by GPS techniques can be summarized as follows:

(1) More economical than VLBI, SLR and LLR techniques due to its use of relatively low cost instruments, requiring less manpower, and ease of transport (more portable);

(2) Full GPS constellation of 21 or more satellites available, many globally-distributed GPS tracking stations in a consistent ground network, and high speed data communication.

(3) More redundant observation equations for the robust solution of the ERP by using efficient GPS software, an essentially real-time service of the ERP with a high temporal resolution (hours to day) and an accuracy at the few centimetre level, avoidance of the major errors in the ERP prediction by extrapolation.

4.4 DIPOP Software Development

DIPOP is the GPS DIfferential POsitioning Program package developed by the Department of Surveying Engineering of the University of New Brunswick. The first version, DIPOP 1.0, was developed on the Department of Surveying Engineering's HP-1000 minicomputer during 1984 and 1985 and described by Vaníček et al. [1985], Santerre et al. [1985], and Langley [1986]. Afterwards, the modified version DIPOP 2.0 with an efficient procedure for the sequential least-squares parameteric adjustment of GPS geodetic networks was released in 1987 [Santerre, et al., 1987]. Since 1987, use of the DIPOP software has boomed. It has been used by many companies and universities around world, and has been further advanced in step with the development of GPS technology. After about two years, there are a variety of advanced DIPOP versions with different functions floating around the Department of Surveying Engineering. These versions work on microcomputers, such as Macintosh computer family and UNIX-based workstations. The advanced documented versions are DIPOP 2.1 described by Kleusberg et al. [1989], and DIPOP-E described by Chen [1991].

The function of orbital improvement has been added to several versions of the DIPOP software. The first improvement for short arc orbits of the GPS satellites was completed and implemented in 1988. The model was tested with data from the Spring 1985 High Precision Baseline Test [Parrot, 1989]. The resulting baselines had an accuracy at about the 0.1 ppm level. Subsequently, a more extensive model with which the orbits of GPS satellites over arcs as long as five days can be improved was developed. This model was incorporated into the version known as DIPOP-E. The numerical integration procedure in this version uses a multi-step predictor-corrector method with arbitrary order. The equations of motion of the satellite are integrated in a space-fixed system to permit the use of longer orbital arcs. The orbital force model includes the model GEM-L2 of the Earth's gravity field up to degree 8 and order 8, the gravity fields of the Sun and Moon, solar radiation pressure, and solid Earth tides. The solar radiation pressure is parameterized and the parameters estimated in the reduction of the GPS observations. This version of the software was tested with the Standard GPS Data Set of the IAG Special Study Group 1.104 (SSG data sets). The solution for the baselines, which spanned lengths of tens of kilometres to over 2200 kilometres, gave an RMS of only 8.5 mm and a daily repeatability of about 0.05 ppm.

In the middle of May 1991, DIPOP-E was selected as the platform to further develop algorithms and software for the estimation of the ERP. Due to some limitations of this software: working on a microcomputer, i.e. Macintosh family with limited memory (about 4 Mbytes on machines readily available in the department), processing 6-7 hour GPS data sets with 6 satellites, it was deemed advantageous to transfer it to the main frame IBM 3090 (now an IBM 9121, model 320, with 256 Mbytes memory), in order to make it competent to process the global GPS data sets with a high sampling rate of 30 seconds over 24 hour observing periods. Figure 4.2 shows the general work flow chart and features of DIPOP.ERP software.

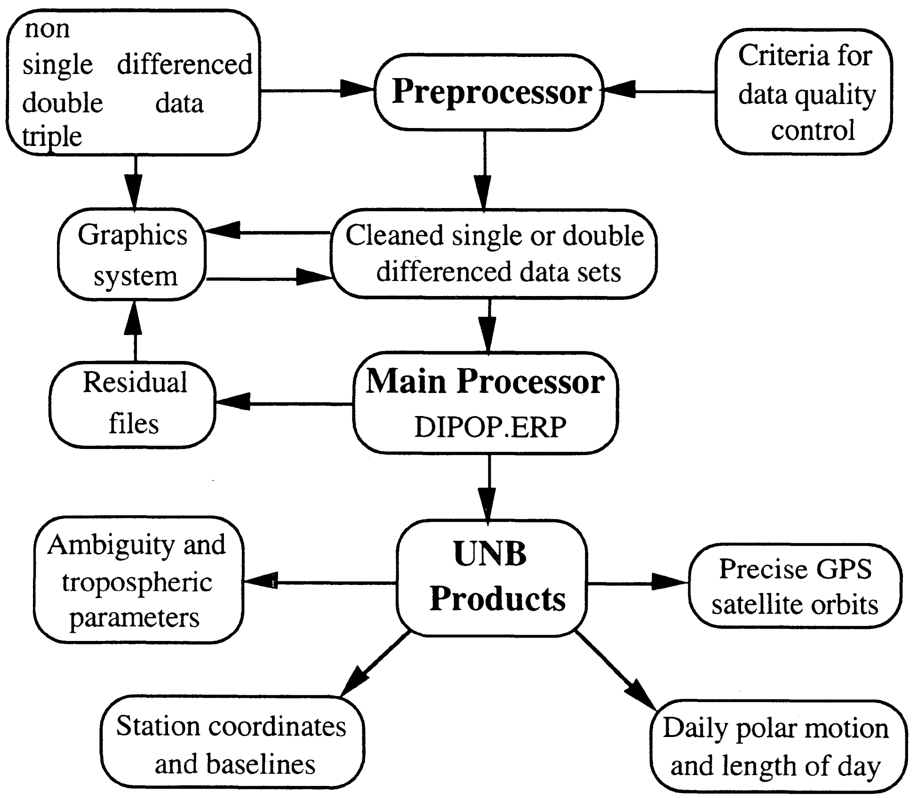

Figure 4.2 Flow chart of DIPOP.ERP software

In order to modify this software, much work has been done to meticulously test the software in Macintosh computer and on the IBM mainframe by compiling all of the subroutines and adjusting them in the correct form under considerations of efficiency, flexibility and versatility, by processing part of the SSG data sets and data sets from CIGNET (Cooperative International GPS NETwork) and the IGS'92 campaign [Li and Langley, 1993]. The most important changes to the software are those in the preprocessing and mainprocessing stages for daily estimation of the ERP in the main frame environment and prediction of the precise GPS satellite orbits by using the global GPS data sets. In Figure 4.2, there are three main parts in the new version of software: preprocessor, main processor and products. The contributions to the software development will be further described in the following chapters.

CHAPTER 5
PRINCIPAL OBSERVATION EQUATIONS

The principle of operation and observation procedures by means of the GPS technique were described in detail by Wells et al. [1986], Sovers and Border [1990], and Leick [1990]. In this chapter, the fundamental observation equations are formulated. They can be used for the double differenced algorithm and further developed as functions of the geodetic and geodynamical parameters, especially the functions of the Earth rotation parameters.

5.1 Single Frequency Pseudorange Measurement

The pseudorange P_0 from the receiver to the satellite can be obtained by measuring the clock time shift at the receiver clock time (GPS time) τ_r between two identical pseudorange noise (PRN) codes, which are generated by the satellite and receiver, through the correlation process. The observable P_0 can be written as

$$P_0 = c\,(\,\tau_r - \tau^s\,) \qquad (5\text{-}1\text{-}1)$$

where c is the speed of light in vacuum; τ^s and τ_r are the clock times of the satellite and the receiver, at which the signal has been emitted by the satellite and picked up by the receiver respectively (see Figure 5.1).

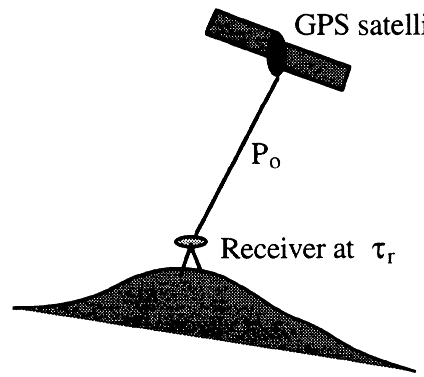

Figure 5.1 GPS observation

On the other hand, the calculated pseudorange P_c can be obtained by

$$P_c = c\,[(\tau_r - \bar{\tau}_r) + (\bar{\tau}_r - t_r) + (t_r - t^s) - (\bar{\tau}^s - t^s) - (\tau^s - \bar{\tau}^s)] + B + b + d_{ion} + d_{trop} \qquad (5\text{-}1\text{-}2)$$

where

$\bar{\tau}_r$ and $\bar{\tau}^s$ ---- the proper time of the receiver and the satellite after corrections of their clock biases at time of signal reception and transmission, respectively;

t_r and t^s ---- the coordinate time of the receiver and the satellite at time of signal reception and transmission, respectively;

B ---- the pseudorange bias depending only on the receiver;

b ---- the pseudorange bias depending only on the satellite;

d_{ion} ---- the ionospheric delay correction;

d_{trop} ---- the tropospheric delay correction.

In terms of general relativity, the relationships between coordinate time and proper time for the satellite and receiver can be separately expressed by the following forms. For the satellite it is

$$t^s = (1 + \frac{3}{2}\frac{GM_E}{c^2 a})\tau' + \frac{2(\vec{r}^s \cdot \dot{\vec{r}}^s)}{c^2} + \text{constant} \qquad (5\text{-}1\text{-}3)$$

where constant means a constant coming from integration of the equation for $d\tau$ and dt. For the receiver it is

$$t_r = (1 + \frac{U_{geoid}}{c^2} - \frac{g(\phi)\,h}{c^2})\,\bar{\tau}_r + \text{constant} \qquad (5\text{-}1\text{-}4)$$

where

τ' ---- the non-adjusted proper time of the satellite clock;

GM_E ---- the geocentric constant of gravitation;

a ---- the semi-major axis of the satellite orbit;

U_{geoid} ---- the geopotential on the geoid;

h ---- the height of the receiver above the geoid;

ϕ ---- the latitude of the receiver;

$g(\phi)$ ---- the latitude dependent gravity acceleration on the geoid;

$\vec{r}^s$ ---- vector from the Earth's centre to the satellite;

$\dot{\vec{r}}^s$ ---- velocity vector of the satellite.

In the above, $g(\phi)$ can be approximately expressed by [Soffel, 1989]

$$g(\phi) \approx (9.78027 + 0.05192\,\sin^2\phi) \times 10^2 \ \text{cm/second}^2 \qquad (5\text{-}1\text{-}5)$$

Equation (5-1-3) can be reorganized as

$$t^s = (1 + \frac{3}{2}\frac{GM_E}{c^2 a} - \frac{U_{geoid}}{c^2})\tau' + \frac{U_{geoid}}{c^2}\tau' + \frac{2(\vec{r}^s \cdot \dot{\vec{r}}^s)}{c^2} + \text{constant}$$

By adjusting the proper time τ' to $\bar{\tau}^s$, i.e. letting $\bar{\tau}^s = (1 + \frac{3}{2}\frac{GM_E}{c^2 a} - \frac{U_{geoid}}{c^2})\tau'$ and by considering $\tau' \approx \bar{\tau}^s$, then eq.(5-1-3) can be further rearranged to the following form

$$t^s = \bar{\tau}^s + \frac{U_{geoid}}{c^2}\bar{\tau}^s + \frac{2(\vec{r}^s \cdot \dot{\vec{r}}^s)}{c^2} + \text{constant} \quad (5\text{-}1\text{-}6)$$

In fact, the clock time or frequencies of the GPS satellites have been adjusted before their launch. In practice, the coordinate time absorbs the term $-\frac{U_{geoid}}{c^2}\bar{\tau}$. Therefore, by letting t replace the term $t - \frac{U_{geoid}}{c^2}\bar{\tau}$ in eqs.(5-1-4) and (5-1-6), the coordinate times for the receiver and satellite can be expressed by

$$t_r = \bar{\tau}_r - \frac{g(\phi)\, h}{c^2}\bar{\tau}_r + \text{constant} \quad (5\text{-}1\text{-}7)$$

and

$$t^s = \bar{\tau}^s + \frac{2(\vec{r}^s \cdot \dot{\vec{r}}^s)}{c^2} + \text{constant} \quad (5\text{-}1\text{-}8)$$

Furthermore, the following expression is obtained by using eqs.(5-1-7) and (5-1-8)

$$(\bar{\tau}_r - t_r) - (\bar{\tau}^s - t^s) = \frac{g(\phi)\, h}{c^2}\bar{\tau}_r + \frac{2(\vec{r}^s \cdot \dot{\vec{r}}^s)}{c^2} + \text{constant} \quad (5\text{-}1\text{-}9)$$

Considering that

$$\bar{\tau}_r - \frac{g(\phi)\, h}{c^2}\bar{\tau}_r = (UTC)_r \quad (5\text{-}1\text{-}10)$$

and

$$t_r = (TDT)_r \quad (5\text{-}1\text{-}11)$$

then the difference between eqs.(5-1-10) and (5-1-11) is

$$(\bar{\tau}_r - t_r) = (UTC - TDT)_r + \frac{g(\phi)\, h}{c^2}\, \bar{\tau}_r \quad (5\text{-}1\text{-}12)$$

Similarly, by considering that

$$\bar{\tau}^s + \frac{2(\vec{r}^{\,s} \cdot \dot{\vec{r}}^{\,s})}{c^2} = (UTC)^s \quad (5\text{-}1\text{-}13)$$

and

$$t^s = (TDT)^s \quad (5\text{-}1\text{-}14)$$

then subtracting eq.(5-1-14) from eq.(5-1-13) gives

$$-(\bar{\tau}^s - t^s) = -(UTC - TDT)^s + \frac{2(\vec{r}^{\,s} \cdot \dot{\vec{r}}^{\,s})}{c^2} \quad (5\text{-}1\text{-}15)$$

In the above, $(UTC - TDT)_r = (UTC - TDT)^s$ can be considered for the GPS measurement because of

$$\begin{aligned} UTC - TDT &= -(TAI - UTC) - (TDT - TAI) \\ &= -(K + 32.184) \quad \text{(seconds)} \quad (5\text{-}1\text{-}16) \end{aligned}$$

where K is positive leap seconds expressed in eq.(2-2-3-2). In addition, according to the theory of general relativity the radio wave in the direction from the GPS satellite to the receiver in the gravitational field will be curved, and its coordinate speed will be slowed down, so that the coordinate time delay dt_r^s occurs. By considering the effects of the potentials of the Earth and the Sun, then the difference between the coordinate times for the receiver and satellite can be written as

$$(t_r - t^s) = \frac{\rho}{c} + dt_r^s \tag{5-1-17}$$

where $\rho = \rho(t_r, t^s) = \left|\vec{\rho}(t_r, t^s)\right|$ and

$$\vec{\rho}(t_r, t^s) = \vec{r}^s - \vec{r}_r \tag{5-1-18}$$

by denoting $\vec{r}_r = \vec{r}_r(t_r)$, where $\vec{r}_r$ is a vector from the Earth's centre to the receiver at t_r, and $\vec{r}^s = \vec{r}^s(t^s)$. The gravitational coordinate time delay dt_r^s can be expressed by

$$\begin{aligned} dt_r^s &= (1 + \gamma_{PPN}) \frac{GM_E}{c^3} \ln \frac{r^s + r_r + \rho}{r^s + r_r - \rho} \\ &= g\, \gamma_g \end{aligned} \tag{5-1-19}$$

where denoting that $\gamma_g = 1 + \gamma_{PPN}$, g is its coefficient, and

γ_{PPN} ---- the space curvature parameter in the PPN (Parameterized Post-Newtonian) coordinate system ($\gamma_{PPN} \approx 1$).

For a GPS measurement, the maximum coordinate time delay dt_r^s will be about 62.2 ps corresponding to a distance delay 18.7 mm.

In eq.(5-1-2) the receiver clock bias dT and satellite clock bias dt can be modelled by the following quadratic functions:

$$\begin{aligned} (\tau_r - \bar{\tau}_r) &= dT \\ &= a_r + b_r(\tau_r - \tau_{r0}) + c_r(\tau_r - \tau_{r0})^2 \end{aligned} \tag{5-1-20}$$

and

$$(\tau^s - \bar{\tau}^s) = dt$$
$$= a^s + b^s (\tau^s - \tau^{s0}) + c^s (\tau^s - \tau^{s0})^2 \qquad (5\text{-}1\text{-}21)$$

where

a_r , b_r, c_r , and a^s , b^s , c^s ---- the unknown parameters of the clock bias models of the receiver and satellite;

τ_{r0} and τ^{s0} ---- their reference time epoches.

In practice, the term $\frac{g(\phi)\, h}{c^2} \bar{\tau}_r$ in eq.(5-1-9) can be absorbed into the receiver clock bias model. Then the constant part will vanish for the GPS measurement. Therefore, by substituting eqs.(5-1-9), (5-1-17), (5-1-20) and (5-1-21) into eq.(5-1-2), the calculated pseudorange P_c can be finally written as

$$P_c = \rho + c\,[\, a_r + b_r (\tau_r - \tau_{r0}) + c_r (\tau_r - \tau_{r0})^2 - a^s - b^s(\tau^s - \tau^{s0}) - c^s(\tau^s - \tau^{s0})^2 + \frac{2\,(\vec{r}^s \cdot \dot{\vec{r}}^s)}{c^2} + dt_r^s \,] + B + b + d_{ion} + d_{trop}$$

or

$$P_c = \rho + c\,[\, dT - dt + \frac{2(\vec{r}^s \cdot \dot{\vec{r}}^s)}{c^2} + g\,\gamma_g \,] + B + b + d_{ion} + d_{trop} \qquad (5\text{-}1\text{-}22)$$

Since τ_r is known, once the receiver clock bias is obtained, then t_r and t^s can be calculated by using the following iterative equation

$$t^{s\,(i+1)} = t^{s\,(i)} + \frac{t_r - t^{s\,(i)} - \rho^{(i)}/c - dt_r^{s\,(i)}}{1 + (\hat{\rho}^{(i)} \cdot \dot{\vec{r}}^{s\,(i)})/c} \qquad (5\text{-}1\text{-}23)$$

where denoting $\hat{\rho} = \vec{\rho}/\rho$. Then the approximate and final values of t^s can be calculated by adopting those of t_r . Since

$$t_r = \tau_r - (\tau_r - \bar{\tau}_r) - (\bar{\tau}_r - t_r) \qquad (5\text{-}1\text{-}24)$$

and the parameters of the bias model of the receiver clock are unknown, the approximate value of t_r can be assumed to be

$$t_r \approx \tau_r - (\bar{\tau}_r - t_r)$$
$$= \tau_r - (K + 32.184) \quad \text{(seconds)}$$

by neglecting the clock bias term. After estimating the parameters of the receiver clock bias, the final value of t^s can be accurately calculated based on eq.(5-1-24).

Figure 5.2 describes the steps of the time calculation:

$\tau_r \longrightarrow \bar{\tau}_r$	$\bar{\tau}_r = \tau_r - (\tau_r - \bar{\tau}_r);$
$\bar{\tau}_r \longrightarrow t_r$	$t_r = \bar{\tau}_r + (K + 32.184)$ (seconds);
$t_r \longrightarrow t^s$	Eq.(5-1-23);
$t^s \longrightarrow \bar{\tau}^s$	$\bar{\tau}^s = t^s - (K + 32.184) - \frac{2(\vec{r}^s \cdot \dot{\vec{r}}^s)}{c^2}$ (seconds);
$\bar{\tau}^s \longrightarrow \tau^s$	$\tau^s = \bar{\tau}^s + (\tau^s - \bar{\tau}^s)$

Figure 5.2 The steps in the time calculations for satellite and receiver clocks

If assuming that the pseudorange measurement noise is v_{po} and the remaining unmodeled error is v_c, then the pseudorange measurement equation can be expressed by

$$v_p = P_o - P_c \tag{5-1-25}$$

where $v_p = v_c - v_{po}$ denotes the residual.

5.2 Single Frequency Carrier Beat Phase Measurement

The observed carrier phase range $P_{\Phi o}$ will be

$$P_{\Phi o} = \lambda\,(\Phi_r - \phi^s) = \lambda\,\Phi_o \qquad (5\text{-}2\text{-}1)$$

where $\lambda = c/f$, is the carrier wavelength, f is the carrier frequency; $\Phi_o = \Phi_r - \phi^s$, is the accumulated phase difference in units of cycles.

In addition, the calculated carrier phase range $P_{\Phi c}$ can be expressed by

$$P_{\Phi c} = \rho + c\,[\,a_r + b_r(\tau_r - \tau_{r0}) + c_r(\tau_r - \tau_{r0})^2 - a^s - b^s(\tau^s - \tau^{s0}) - c^s(\tau^s - \tau^{s0})^2 + \frac{2\,(\vec{r}^s \cdot \dot{\vec{r}}^s)}{c^2} + dt_r^s\,] - \lambda N + \lambda\,(\Phi - \phi) - d_{ion} + d_{trop}$$

or

$$P_{\Phi c} = \rho + c\,[\,dT - dt + \frac{2(\vec{r}^s \cdot \dot{\vec{r}}^s)}{c^2} + g\,\gamma_g\,] - \lambda N + \lambda\,(\Phi - \phi) - d_{ion} + d_{trop} \qquad (5\text{-}2\text{-}2)$$

where

Φ , ϕ ---- the initial phases of the oscillators of the receiver and the satellite;

N ---- the ambiguity.

Therefore, the carrier phase measurement residual v_Φ is

$$v_\Phi = P_{\Phi c} - P_{\Phi o} \qquad (5\text{-}2\text{-}3)$$

where $v_\Phi = v_c - \lambda v_{\Phi o}$, where $v_{\Phi o}$ denotes the noise of the carrier phase measurement Φ_o in units of cycles.

5.3 Dual Frequency Pseudorange Measurement

From eq.(5-1-22) the equation for the pseudorange L1 measurement can be written as

$$P_{c,L1} = \rho + c\,[\,dT - dt + \frac{2(\vec{r}^{s}\cdot\dot{\vec{r}}^{s})}{c^2} + g\,\gamma_g\,] + B_{L1} + b_{L1} + d_{ion,L1} + d_{trop} \qquad (5\text{-}3\text{-}1)$$

and for L2 it is

$$P_{c,L2} = \rho + c\,[\,dT - dt + \frac{2(\vec{r}^{s}\cdot\dot{\vec{r}}^{s})}{c^2} + g\,\gamma_g\,] + B_{L2} + b_{L2} + d_{ion,L2} + d_{trop} \qquad (5\text{-}3\text{-}2)$$

Assuming that the ionospheric correction is made to the first-order term, i.e.

$$d_{ion} = \frac{I_0}{f^2} \qquad (5\text{-}3\text{-}3)$$

where I_0 is constant (a function of the electron content along the path travelled by the signals), f is the L1 or L2 frequency, then the difference between the ionospheric delays for L1 and L2 observations can be expressed by

$$d_{ion,L1} - d_{ion,L2} = (P_{c,L1} - P_{c,L2}) - (B_{L1} - B_{L2}) - (b_{L1} - b_{L2}) \qquad (5\text{-}3\text{-}4)$$

From eq.(5-3-3) the constant I_0 can be expressed by

$$I_0 = \frac{f_{L2}^2\, f_{L1}^2}{f_{L2}^2 - f_{L1}^2}\,(\,d_{ion,L1} - d_{ion,L2}\,) \qquad (5\text{-}3\text{-}5)$$

According to eqs.(5-3-3) to (5-3-5), the first-order ionospheric correction can be determined by using simultaneous dual frequency pseudorange observations. From eqs.(5-3-1) and (5-3-2), the following equation can be formed:

$$f_{L1}^2 P_{c,L1} - f_{L2}^2 P_{c,L2} = (f_{L1}^2 - f_{L2}^2) [\rho + c\, dT - c\, dt + \frac{2 (\vec{r}^s \cdot \dot{\vec{r}}^s)}{c} + c\, g\, \gamma_g] + f_{L1}^2 (B_{L1} + b_{L1}) - f_{L2}^2 (B_{L2} + b_{L2}) + (f_{L1}^2 - f_{L2}^2)\, d_{trop} \quad (5\text{-}3\text{-}6)$$

Assuming that

$$\alpha' = \frac{f_{L1}^2}{f_{L1}^2 - f_{L2}^2} \qquad \beta' = \frac{f_{L2}^2}{f_{L1}^2 - f_{L2}^2}$$

and considering $P_c = P_o + v_{po} - v_c$, then the ionosphere-free dual frequency pseudorange observation equation is obtained as

$$\alpha' P_{o,L1} - \beta' P_{o,L2} + v_r^s = \rho + c\, [dT - dt + \frac{2(\vec{r}^s \cdot \dot{\vec{r}}^s)}{c^2} + g\, \gamma_g] + \alpha' (B_{L1} + b_{L1}) - \beta' (B_{L2} + b_{L2}) + d_{trop} \quad (5\text{-}3\text{-}7)$$

where

$$v_r^s = \alpha' v_{po,L1} - \beta' v_{po,L2} - v_c \quad (5\text{-}3\text{-}8)$$

5.4 Dual Frequency Carrier Beat Phase Measurement

From eq.(5-2-2) the equation for the carrier phase L1 measurement can be written as

$$P_{\Phi c,L1} = \rho + c\, [dT - dt + \frac{2 (\vec{r}^s \cdot \dot{\vec{r}}^s)}{c^2} + g\, \gamma_g] - \lambda_{L1} N_{L1} + \lambda_{L1} (\Phi_{L1} - \phi_{L1}) - d_{ion,L1} + d_{trop} \quad (5\text{-}4\text{-}1)$$

and for L2 it is

$$P_{\Phi c,L2} = \rho + c\,[\,dT - dt + \frac{2\,(\vec{r}^{s}\cdot\dot{\vec{r}}^{s})}{c^{2}} + g\,\gamma_g\,]\; - \lambda_{L2}\,N_{L2} + \lambda_{L2}\,(\Phi_{L2} - \phi_{L2}) - d_{ion,L2} + d_{trop} \qquad (5\text{-}4\text{-}2)$$

Therefore, the difference between the ionospheric delays for L1 and L2 observations can be expressed by

$$d_{ion,L2} - d_{ion,L1} = (P_{\Phi c,L1} - P_{\Phi c,L2}) + (\lambda_{L1}\,N_{L1} - \lambda_{L2}\,N_{L2}) - (\lambda_{L1}\,\Phi_{L1} - \lambda_{L2}\,\Phi_{L2}) + (\lambda_{L1}\,\phi_{L1} - \lambda_{L2}\,\phi_{L2}) \qquad (5\text{-}4\text{-}3)$$

According to eqs.(5-3-3), (5-3-5) and (5-4-3), therefore, the first-order ionospheric correction can be computed, in principle, by using the dual frequency carrier phase observation. It is clear that eqs.(5-3-4) and (5-4-3) provide a way, which removes the ionospheric and tropospheric effects, to solve the ambiguities and the initial biases by using the observations of the dual frequency pseudorange and the dual frequency carrier phase if pseudorange observations can be made with sufficient precision.

From eqs.(5-4-1) and (5-4-2), the following equation can be formed

$$f_{L1}^{2}\,P_{\Phi c,L1} - f_{L2}^{2}\,P_{\Phi c,L2} = (f_{L1}^{2} - f_{L2}^{2})\,[\rho + c\,dT - c\,dt + \frac{2\,(\vec{r}^{s}\cdot\dot{\vec{r}}^{s})}{c} + c\,g\,\gamma_g\,] - c\,(f_{L1}\,N_{L1} - f_{L2}\,N_{L2}) + c\,f_{L1}\,(\Phi_{L1} - \phi_{L1}) - c\,f_{L2}\,(\Phi_{L2} - \phi_{L2}) + (f_{L1}^{2} - f_{L2}^{2})\,d_{trop} \qquad (5\text{-}4\text{-}4)$$

By considering eqs.(5-2-1) and (5-2-3), then eq.(5-4-4) can be written in the following form, which is the ionosphere-free dual frequency carrier phase observation equation:

$$\alpha\,\Phi_{o,L1} - \beta\,\Phi_{o,L2} + v_{\Phi,f} = \rho + c\,[\,dT - dt + \frac{2(\vec{r}^{s}\cdot\dot{\vec{r}}^{s})}{c^{2}} + g\,\gamma_g\,] - \alpha\,N_{L1} + \beta\,N_{L2} + \alpha\,(\Phi_{L1} - \phi_{L1}) - \beta\,(\Phi_{L2} - \phi_{L2}) + d_{trop} \qquad (5\text{-}4\text{-}5)$$

where

$$\alpha = \frac{c\ f_{L1}}{f_{L1}^2 - f_{L2}^2} \qquad \beta = \frac{c\ f_{L2}}{f_{L1}^2 - f_{L2}^2}$$

and

$$v_{\Phi,f} = \alpha\ v_{\Phi o,L1} - \beta\ v_{\Phi o,L2} - v_c \tag{5-4-6}$$

In eq.(5-4-6) $v_{\Phi,f}$ is the combined residual.

CHAPTER 6
PARTIAL DERIVATIVES WITH RESPECT TO THE PARAMETERS

In order to estimate the geodetic and geodynamic parameters, particularly the Earth rotation parameters, as well as other "nuisance" parameters, the calculated ranges P_c and $P_{\Phi c}$ appearing in eqs.(5-1-22) and (5-2-2) as functions of those parameters have to be linearized. Also, it is necessary to take the partial derivatives of the ranges with respect to the parameters. The procedure used is based on the theoretical work by Sovers and Border [1990].

6.1 Clock Parameters, Biases and Ambiguities

By neglecting term d_r^s, from eq.(5-1-17) the theoretical range ρ can be approximately written as

$$\rho \approx c\,(t_r - t^s) \qquad (6\text{-}1\text{-}1)$$

Since the geometric range is accurately expressed by

$$\rho = |\vec{r}^s(t^s) - \vec{r}_r(t_r)| \qquad (6\text{-}1\text{-}2)$$

it is clear that t^s is a function of t_r , and t_r is a function of the receiver clock parameters due to the calculation of t_r by eq.(5-1-24) including the parameters of the receiver clock bias model. Therefore, from eq.(5-1-22) the partial with respect to the receiver clock parameters can be given by

$$\frac{\partial P_c}{\partial a_r} = c + \frac{\partial \rho}{\partial a_r} \tag{6-1-3}$$

By squaring eq.(6-1-2), the derivative on the right hand side of eq.(6-1-3) can be expressed by

$$\frac{\partial \rho}{\partial a_r} = \hat{\rho} \cdot (\dot{\vec{r}}^s \frac{\partial t^s}{\partial t_r} - \dot{\vec{r}}_r) \frac{\partial t_r}{\partial a_r} \tag{6-1-4}$$

In addition, by squaring eqs.(6-1-1) and (6-1-2) it is easy to obtain the following derivative

$$\frac{\partial t^s}{\partial t_r} = \frac{\rho\ c + \vec{\rho}\dot{\vec{r}}_r}{\rho\ c + \vec{\rho}\dot{\vec{r}}^s} \tag{6-1-5}$$

Since from eq.(5-1-24) the derivative

$$\frac{\partial t_r}{\partial a_r} = -1 \tag{6-1-6}$$

so by substituting eqs.(6-1-5) and (6-1-6) into eq.(6-1-4), the derivative can be found as follows

$$\frac{\partial \rho}{\partial a_r} = -\frac{\hat{\rho} \cdot (\dot{\vec{r}}^s - \dot{\vec{r}}_r)}{1 + \hat{\rho} \cdot \dot{\vec{r}}^s / c} \tag{6-1-7}$$

In addition, from eq.(6-1-1) the derivative can be written by

$$\dot{\rho} = \frac{\partial \rho}{\partial t_r}$$
$$= c\ (1 - \frac{\partial t^s}{\partial t_r})$$

Substituting eq.(6-1-5) into the above, then the variation of the distance $\dot{\rho}$ can be expressed by the variations of the position of the satellite and the receiver:

$$\dot{\rho} = \frac{\hat{\rho}\cdot(\dot{\vec{r}}^s - \dot{\vec{r}}_r)}{1 + \hat{\rho}\cdot\dot{\vec{r}}^s/c} \tag{6-1-8}$$

So eqs.(6-1-7) and (6-1-3) can be written as follows

$$\frac{\partial \rho}{\partial a_r} = -\dot{\rho} \tag{6-1-9}$$

$$\frac{\partial P_c}{\partial a_r} = c - \dot{\rho} \tag{6-1-10}$$

Similarly, the partial derivatives with respect to the other two clock parameters can be obtained as follows

$$\frac{\partial P_c}{\partial b_r} = (c - \dot{\rho})\ (\tau_r - \tau_{r0}) \tag{6-1-11}$$

and

$$\frac{\partial P_c}{\partial c_r} = (c - \dot{\rho})\ (\tau_r - \tau_{r0})^2 \tag{6-1-12}$$

The partials with respect to the satellite clock parameters also can be expressed by

$$\frac{\partial P_c}{\partial a^s} = -c \qquad (6\text{-}1\text{-}13)$$

$$\frac{\partial P_c}{\partial b^s} = -c\,(\tau^s - \tau^{s0}) \qquad (6\text{-}1\text{-}14)$$

$$\frac{\partial P_c}{\partial c^s} = -c\,(\tau^s - \tau^{s0})^2 \qquad (6\text{-}1\text{-}15)$$

From eq.(5-2-2), it is obvious that the partials with respect to the receiver and satellite clock parameters for the carrier phase measurement are the same as the above.

The partials with respect to the pseudorange bias (B + b) and the carrier phase bias $(\Phi - \phi)$ and ambiguity N are

$$\frac{\partial P_c}{\partial (B + b)} = 1 \qquad (6\text{-}1\text{-}16)$$

$$\frac{\partial P_{\Phi c}}{\partial (\Phi - \phi)} = 1 \qquad (6\text{-}1\text{-}17)$$

$$\frac{\partial P_{\Phi c}}{\partial N} = -\lambda \qquad (6\text{-}1\text{-}18)$$

6.2 Geodetic and Geodynamical Parameters

Assuming that $\vec{r}_r$ includes a class of the parameters η (for instance, the station coordinates, Love numbers and the seven transformation parameters), and that $\vec{r}^s$ includes a class of the parameters ξ (for instance, the satellite initial orbital elements, the parameters of the solar radiation pressure, Earth rotation parameters, the geocentric constant of gravitation and the coefficients of the gravitation of the Earth), from eqs.(6-1-1) and (6-1-2), it is obvious that t^s is a function of t_r , η and ξ , i.e. $t^s = t^s(t_r , \xi , \eta)$. Therefore, from eq.(6-1-2), the following derivative can be given

$$\frac{\partial \rho}{\partial \eta} = \hat{\rho} \cdot (\dot{\vec{r}}^s \frac{\partial t^s}{\partial \eta} - \frac{\partial \vec{r}_r}{\partial \eta}) \qquad (6\text{-}2\text{-}1)$$

In addition, from eq.(6-1-1) the above derivative also can be written as follows

$$\frac{\partial \rho}{\partial \eta} = -c \frac{\partial t^s}{\partial \eta}$$

which is compared with eq.(6-2-1), therefore, the following derivative can be found

$$\frac{\partial t^s}{\partial \eta} = \frac{\hat{\rho} \cdot \frac{\partial \vec{r}_r}{\partial \eta}}{c + \hat{\rho} \cdot \dot{\vec{r}}^s} \qquad (6\text{-}2\text{-}2)$$

Substituting eq.(6-2-2) into the right hand side of eq.(6-2-1) gives the following result

$$\frac{\partial \rho}{\partial \eta} = -\frac{\hat{\rho} \cdot \frac{\partial \vec{r}_r}{\partial \eta}}{1 + \hat{\rho} \cdot \dot{\vec{r}}^s / c} \qquad (6\text{-}2\text{-}3)$$

From eqs.(6-1-2) and (6-1-1), the partial derivatives can be written as follows

$$\frac{\partial \rho}{\partial \xi} = \hat{\rho} \cdot \left(\frac{\partial \vec{r}^s}{\partial \xi} + \dot{\vec{r}}^s \frac{\partial t^s}{\partial \xi}\right) \tag{6-2-4}$$

and

$$\frac{\partial \rho}{\partial \xi} = -c \frac{\partial t^s}{\partial \xi} \tag{6-2-5}$$

Therefore, comparing eq.(6-2-4) with eq.(6-2-5) the following derivative can be found

$$\frac{\partial t^s}{\partial \xi} = \frac{\hat{\rho} \cdot \frac{\partial \vec{r}^s}{\partial \xi}}{c + \hat{\rho} \cdot \dot{\vec{r}}^s} \tag{6-2-6}$$

Substituting eq.(6-2-6) into eq.(6-2-4) gives

$$\frac{\partial \rho}{\partial \xi} = \frac{\hat{\rho} \cdot \frac{\partial \vec{r}^s}{\partial \xi}}{1 + \hat{\rho} \cdot \dot{\vec{r}}^s / c} \tag{6-2-7}$$

If we denote

$$\hat{\hat{\rho}} = \frac{\hat{\rho}}{1 + \hat{\rho} \cdot \dot{\vec{r}}^s / c}$$

then eqs.(6-2-3) and (6-2-7) can be reorganized as

$$\frac{\partial \rho}{\partial \eta} = -\hat{\hat{\rho}} \cdot \frac{\partial \vec{r}_r}{\partial \eta} \tag{6-2-8}$$

and

$$\frac{\partial \rho}{\partial \xi} = \hat{\hat{\rho}} \cdot \frac{\partial \vec{r}^s}{\partial \xi} \tag{6-2-9}$$

If we assume $\vec{r}_r$ and $\vec{r}^s$ to include a class of the common parameters ζ , then the following derivative can be given

$$\frac{\partial \rho}{\partial \zeta} = \hat{\rho} \cdot \left(\frac{\partial \vec{r}^s}{\partial \zeta} - \frac{\partial \vec{r}_r}{\partial \zeta}\right) \qquad (6\text{-}2\text{-}10)$$

Therefore, the theoretical range ρ can be linearized in the following form

$$\rho = \rho_0 - \hat{\rho} \cdot \frac{\partial \vec{r}_r}{\partial \eta_j} d\eta_j + \hat{\rho} \cdot \frac{\partial \vec{r}^s}{\partial \xi_j} d\xi_j + \hat{\rho} \cdot \left(\frac{\partial \vec{r}^s}{\partial \zeta_j} - \frac{\partial \vec{r}_r}{\partial \zeta_j}\right) d\zeta_j \qquad (6\text{-}2\text{-}11)$$

where ρ_0 is the approximate value of ρ, i.e. $\rho_0 = \left| \vec{r}_{r0}(t_r) - \vec{r}^{s0}(t^s) \right|$; $d\xi_j$, $d\zeta_j$ and $d\eta_j$ are the corrections to the parameters.

Since $\vec{r}_r$ is expressed in the inertial frame, i.e. $\vec{r}_r = M \vec{r}_e$, where M is the product of the matrices for precession P, nutation N, rotation rate U, and polar motion X and Y, and

$$\vec{r}_e = (1 + m) R(\vec{\theta}) [\vec{r}_G + \dot{\vec{r}}_G (t - t_0)] + \vec{r}_0 \qquad (6\text{-}2\text{-}12)$$

where

$\vec{r}_G$ ----the vector from the Earth's centre of mass to the receiver expressed in the GPS Earth-fixed reference frame;

$\dot{\vec{r}}_G$ ----the time rate of vector $\vec{r}_G$ due to plate motion;

$\vec{r}_e$ ----the vector from the Earth's centre of mass to the receiver expressed in any other Earth-fixed reference frame of high accuracy (such as the reference frames obtained by VLBI, LLR, SLR and GPS techniques);

m, $\vec{\theta}$ and $\vec{r}_0$ ----the seven transformation parameters between $\vec{r}_e$ and $\vec{r}_G$: the scale factor, the transformation angle vector, and the origin offset vector of the reference frame.

Taking the total differential of $\vec{r}_r$ gives

$$d\vec{r}_r = M\, d\vec{r}_e + dM\, \vec{r}_{G0} \tag{6-2-13}$$

$$= \frac{\partial \vec{r}_r}{\partial \eta_j}\, d\eta_j$$

where $\vec{r}_{G0}$ is the approximate value of $\vec{r}_G$, and

$$d\vec{r}_e = (1 + m_0)\, R(\vec{\theta}_0)\, [d\vec{r}_G + d\dot{\vec{r}}_G\, (t - t_0)] + dm\, \vec{r}_{G0} + d\vec{r}_0 + R_0(d\vec{\theta})\, \vec{r}_{G0} + d\vec{r}_{tide} + d\vec{r}_{ltide} + d\vec{r}_{ptide} + d\vec{r}_{pc} \tag{6-2-14}$$

$$= \frac{\partial \vec{r}_e}{\partial \eta_j}\, d\eta_j$$

where m_0 and $\vec{\theta}_0$ are approximate values of m and $\vec{\theta}$, $R_0\,(d\vec{\theta}) = R(d\vec{\theta}) - I$, I is the unit matrix, and

$d\vec{r}_{tide}$ ----the deformation correction due to the solid tide;

$d\vec{r}_{ltide}$ ----the deformation correction due to the oceanic load tide;

$d\vec{r}_{ptide}$ ----the deformation correction due to polar motion;

$d\vec{r}_{pc}$ ----the correction of the phase centre of the receiver (it may be different for L1 and L2);

and

$$dM = \frac{\partial M}{\partial \eta_j} d\eta_j \qquad (6\text{-}2\text{-}15)$$

In addition

$$\vec{r}^s = \vec{r}^{s0} + d\vec{r}^s + d\vec{r}^s_{pc} \qquad (6\text{-}2\text{-}16)$$

where $\vec{r}^{s0}$ is the approximate value of $\vec{r}^s$, $d\vec{r}^s_{pc}$ is the correction to the phase centre of the satellite, and

$$d\vec{r}^s = \frac{\partial \vec{r}^s}{\partial \xi_j} d\xi_j \qquad (6\text{-}2\text{-}17)$$

6.2.1 Station Coordinates, Satellite Orbital Parameters, Tropospheric Model

From eqs.(6-2-13) and (6-2-14), it is easy to obtain the partial derivatives with respect to the station coordinate and the seven transformation parameters. For station coordinates

$$\frac{\partial \vec{r}_r}{\partial \vec{r}_G} = -\hat{\rho}^T M (1 + m_0) \vec{R}(\theta_0) \qquad (6\text{-}2\text{-}1\text{-}1)$$

Partial derivatives with respect to the satellite orbital and dynamical parameters can be written in the following general forms:

$$\frac{\partial \vec{r}^s}{\partial \vec{\sigma}_0} = \frac{\partial \vec{r}^s}{\partial \vec{\sigma}} \frac{\partial \vec{\sigma}}{\partial \vec{\sigma}_0} \qquad (6\text{-}2\text{-}1\text{-}2)$$

where $\vec{\sigma}$ is the satellite state vector and $\vec{\sigma}_0$ is the satellite initial state vector. The detailed descriptions of the partial derivatives can be found in the technical reports by Langley et al. [1984] and Wu et al. [1986].

The tropospheric model adopted is Hopfield's model [Hopfield, 1969] which was implemented in the original DIPOP software [Vaníček et al., 1985]. Alternative models and associated partial derivatives may be found in the JPL publication by Sovers and Border [1990]

6.2.2 Earth Rotation Parameters

The partials with respect to the Earth rotation parameters can be developed in the following manner.

(1) If the satellite and station vector is expressed in the space-fixed frame, then the partial derivatives of the station vector with respect to the time varying rate of (UT1–UTC) D (ms/day) and its derivative $\dot{D}$ (ms/day^2) can be expressed by

$$\frac{\partial \vec{r}_r}{\partial D} = 2\pi\,(1 + k)\frac{10^{-3}}{86400^2}(t - t_0)\ P\ N\frac{\partial U}{\partial \theta_G}\ Y\ X\ \vec{r}_e \qquad (6\text{-}2\text{-}2\text{-}1)$$

and

$$\frac{\partial \vec{r}_r}{\partial \dot{D}} = \frac{(t - t_0)}{86400}\frac{\partial \vec{r}_r}{\partial D} \qquad (6\text{-}2\text{-}2\text{-}2)$$

where (1 + k) is expressed by eq.(2-1-3-6), and

$$\frac{\partial U}{\partial \theta_G} = \begin{bmatrix} -\sin\theta_G & -\cos\theta_G & 0 \\ \cos\theta_G & -\sin\theta_G & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (6\text{-}2\text{-}2\text{-}3)$$

Partial derivatives with respect to the coordinates x_p , y_p of polar motion are obtained in the following forms

$$\frac{\partial \vec{r}_r}{\partial y_p} = P\,N\,U \frac{\partial Y}{\partial y_p}\, X\,\vec{r}_e \quad (6\text{-}2\text{-}2\text{-}4)$$

and

$$\frac{\partial \vec{r}_r}{\partial x_p} = P\,N\,U\,Y \frac{\partial X}{\partial x_p}\,\vec{r}_e \quad (6\text{-}2\text{-}2\text{-}5)$$

where

$$\frac{\partial Y}{\partial y_p} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & -y_p & 1 \\ 0 & -1 & -y_p \end{bmatrix} \qquad \frac{\partial X}{\partial x_p} = \begin{bmatrix} -x_p & 0 & -1 \\ 0 & 0 & 0 \\ 1 & 0 & -x_p \end{bmatrix} \quad (6\text{-}2\text{-}2\text{-}6)$$

(2) If the satellite vector $\vec{R}^s$ and station vector $\vec{R}_r$ are expressed in the Earth-fixed frame, then the partial derivatives of the satellite vector with respect to D (ms/day) and its derivative $\dot{D}$ (ms/day^2) can be obtained in the following forms

$$\frac{\partial \vec{R}^s}{\partial D} = 2\,\pi\,(1+k)\,\frac{10^{-3}}{86400^2}\,(t-t_0)\,X^T\,Y^T\,\frac{\partial U^T}{\partial \theta_G}\,U\,Y\,X\,\vec{R}^s \quad (6\text{-}2\text{-}2\text{-}7)$$

and

$$\frac{\partial \vec{R}^s}{\partial \dot{D}} = \frac{(t - t_0)}{86400} \frac{\partial \vec{R}^s}{\partial D} \tag{6-2-2-8}$$

Partial derivatives with respect to the coordinates x_p , y_p of polar motion are expressed by

$$\frac{\partial \vec{R}^s}{\partial x_p} = \frac{\partial}{\partial x_p} (X^T)\, X\, \vec{R}^s \tag{6-2-2-9}$$

and

$$\frac{\partial \vec{R}^s}{\partial y_p} = X^T \frac{\partial}{\partial y_p} (Y^T)\, Y\, X\, \vec{R}^s \tag{6-2-2-10}$$

CHAPTER 7

DIFFERENTIAL POSITIONING TECHNIQUES

7.1 Undifferenced Observation Equations and Combinations

The linearized form of eq.(6-2-11) for ρ can be written in the following form:

$$\begin{aligned} \rho &= \rho_0 + \frac{\partial \rho}{\partial \nu_j} \nu_j \\ &= \rho_0 + d_j \, \nu_j \end{aligned} \tag{7-1-1}$$

where d_j denotes the partial derivatives $d_j = \frac{\partial \rho}{\partial \nu_j}$, and ν_j may be ξ_j , ζ_j and η_j (or their corrections $d\xi_j$, $d\zeta_j$ and $d\eta_j$) . By considering eqs.(6-1-10) to (6-1-12), from eqs.(5-1-22) and (5-1-25) the undifferenced single frequency pseudorange observation equation can be expressed by

$$v_P = (c - \dot{\rho})\, dT + c\, [\, - dt + \frac{2\, (\vec{r}^{s} \cdot \dot{\vec{r}}^{s})}{c^2} + g\, \gamma_g\,] + B + b + d_{ion} + d_{trop} + d_j \nu_j + L_P \tag{7-1-2}$$

where $L_p = \rho_0 - P_o$, $v_P = v_{Po} - v_c$.

Similarly, from eqs.(5-2-2) and (5-2-3) the undifferenced single frequency carrier phase observation equation can be expressed by

$$\begin{aligned} v_\Phi = (c - \dot{\rho}\,)\, dT + c\, [\, - dt + \frac{2\, (\vec{r}^{s} \cdot \dot{\vec{r}}^{s})}{c^2} + g\, \gamma_g\,] - \lambda\, N + \lambda\, (\Phi - \phi) \\ - d_{ion} + d_{trop} + d_j \nu_j + L_\Phi \end{aligned} \tag{7-1-3}$$

where $v_\Phi = \lambda\, v_{\Phi o} - v_c$, and $L_\Phi = \rho_0 - P_{\Phi o}$

From eqs.(5-3-7) and (5-3-8), the ionospheric-free undifferenced dual frequency pseudorange observation equation is obtained as

$$\begin{aligned} v_{P,f} = &(c - \dot{\rho})\, dT + c\, [\, - dt + \frac{2(\vec{r}^s \cdot \dot{\vec{r}}^s)}{c^2} + g\, \gamma_g\,] \\ &+ \alpha' (B_{L1} + b_{L1}) - \beta' (B_{L2} + b_{L2}) + d_{trop} + d_j\, v_j + L_{P,f} \end{aligned} \qquad (7\text{-}1\text{-}4)$$

where $L_{P,f} = \rho_0 - \alpha' P_{o,L1} + \beta' P_{o,L2}$. From eq.(5-4-5), the ionospheric-free undifferenced dual frequency carrier beat phase observation equation is obtained as

$$\begin{aligned} v_{\Phi,f} = &(c - \dot{\rho})\, dT + c\, [\, - dt + \frac{2\,(\vec{r}^s \cdot \dot{\vec{r}}^s)}{c^2} + g\, \gamma_g\,] - \alpha\, N_{L1} + \beta\, N_{L2} \\ &+ \alpha\, (\Phi_{L1} - \phi_{L1}) - \beta\, (\Phi_{L2} - \phi_{L2}) + d_{trop} + d_j\, v_j + L_{\Phi,f} \end{aligned} \qquad (7\text{-}1\text{-}5)$$

where $L_{\Phi,f} = \rho_0 - \alpha\, \Phi_{o,L1} + \beta\, \Phi_{o,L2}$.

Letting

$$F = (c - \dot{\rho})\, dT + c\, [\, - dt + \frac{2\,(\vec{r}^s \cdot \dot{\vec{r}}^s)}{c^2} + g\, \gamma_g] + B + b + d_{trop} + d_j v_j + \rho_0$$

and applying eqs.(7-1-2) and (7-1-3) to the dual frequency (L1 and L2) observations, the different linear combinations of the pseudorange and carrier phase observations can be organized in the following forms:

(a) RID (Range Ionospheric-Delay) combination:

$$P_{o,L2} - P_{o,L1} = (d_{ion,L2} - d_{ion,L1}) + (B_{L2} - B_{L1}) + (b_{L2} - b_{L1}) + v_{P,d} \qquad (7\text{-}1\text{-}6)$$

(b) RIF (Range Ionospheric-Free) combination:

$$\beta' P_{o,L2} - \alpha' P_{o,L1} = - F + \beta' (B_{L2} + b_{L2}) - \alpha' (B_{L1} + b_{L1}) + v_{P,f} \qquad (7\text{-}1\text{-}7)$$

(c) PID (Phase Ionospheric-Delay) combination:

$$\begin{aligned} \lambda_{L2}\Phi_{o,L2} - \lambda_{L1}\Phi_{o,L1} = {} & (d_{ion,L1} - d_{ion,L2}) + \lambda_{L1}N_{L1} - \lambda_{L2}N_{L2} \\ & - \lambda_{L1} (\Phi_{L1} - \phi_{L1}) + \lambda_{L2} (\Phi_{L2} - \phi_{L2}) + v_{\Phi,d} \end{aligned} \qquad (7\text{-}1\text{-}8)$$

(d) PIF (Phase Ionospheric-Free) combination:

$$\begin{aligned} \beta\, \Phi_{o,L2} - \alpha\, \Phi_{o,L1} = {} & - F + \alpha\, N_{L1} - \beta\, N_{L2} \\ & - \alpha (\Phi_{L1} - \phi_{L1}) + \beta (\Phi_{L2} - \phi_{L2}) + v_{\Phi,f} \end{aligned} \qquad (7\text{-}1\text{-}9)$$

(e) PWL (Phase Wide Lane) combination:

$$\begin{aligned} \lambda_{L4} (\Phi_{o,L2} - \Phi_{o,L1}) = {} & - F + \lambda_{L4} \left(\frac{d_{ion,L1}}{\lambda_{L2}} - \frac{d_{ion,L2}}{\lambda_{L1}}\right) + \lambda_{L4} (N_{L1} - N_{L2}) \\ & - \lambda_{L4} (\Phi_{L1} - \phi_{L1}) + \lambda_{L4} (\Phi_{L2} - \phi_{L2}) + v_{\Phi,w} \end{aligned} \qquad (7\text{-}1\text{-}10)$$

In eqs.(7-1-6), (7-1-7), (7-1-8), (7-1-9) and (7-1-10), $v_{P,d}$, $v_{P,f}$, $v_{\Phi,d}$, $v_{\Phi,f}$ and $v_{\Phi,w}$ denote the residuals of the different combinations, and the coefficients are $\lambda_{L4} = \lambda_{L1}\, \lambda_{L2}/(\lambda_{L2} - \lambda_{L1})$, $\alpha = \lambda_{L1}\, \lambda_{L2}^2/(\lambda_{L2}^2 - \lambda_{L1}^2)$, $\beta = \lambda_{L2}\, \lambda_{L1}^2/(\lambda_{L2}^2 - \lambda_{L1}^2)$, $\alpha' = \alpha/\lambda_{L1}$ and $\beta' = \beta/\lambda_{L2}$.

7.2 Differenced Algorithms

Compared with the undifferenced eqs.(7-1-2) to (7-1-10), the differenced observation equations have certain advantages for GPS positioning and parameter estimation. Their algorithms and applications have been elaborated on in a number of papers (e.g. Langley et al., [1984]; Vaníček et al., [1985]; Wells et al., [1987]). Denoting

Δ----between-receiver single difference;

∇----between-satellite single difference;

δ ----between-epoch single difference,

then any combination of the above three kinds of the single difference can be formed to give various double differences or triple differences for different uses. For example, the double differenced observables $\nabla\Delta$(RIF) and $\nabla\Delta$(PIF) remove the satellite clock bias and most parts of the receiver clock bias; the epoch differenced observables $\delta(\cdot)$ make cycle slips obvious and easily detected, where $(\cdot)$ represents any kind of combination data sets, such as (PIF), (PWL), (PID) and their single or double differences. However, for differenced data sets, a shortcoming will occur if there is no common observation period or no simultaneous observation for a pair of stations. From eqs.(7-1-2) to (7-1-10), the independent observation equations can be chosen to provide redundant conditions for estimation of unknown parameters. Based on them, the differenced observation equations can be formed.

7.3 Automated Algorithm for Cycle Slip Detection and Fixing

Cycle slips and gaps in the phase data collected by the global GPS observation network can be quite troublesome. The causes of cycle slips can be arranged in the following order of importance: ionospheric activity, low satellite elevation, obstructions. Preprocessing double differenced GPS data sets dealing with cycle slips and gaps was described by Kleusberg et al. [1989]. In the following, cycle slip detection for different data types and technical criteria for assessing data quality have been proposed in order to implement automatic preprocessing. To detect cycle slips, the epoch differenced data sets $\delta(\cdot)$ can be used. In the preprocessing stage, cycle slips can be detected in the following cases:

(1) one station and one satellite by using data types δ(PIF), δ(PWL) and δ(PID);

(2) two stations and one satellite by using data types $\delta\Delta$(PIF), $\delta\Delta$(PWL) and $\delta\Delta$(PID);

(3) two stations and two satellites by using data types $\delta\nabla\Delta$(PIF), $\delta\nabla\Delta$(PWL) and $\delta\nabla\Delta$(PID).

The epoch differenced data sets of (PIF) are much better than the others for cycle slip detection because they are free from ionospheric influence.

If there are some cycle slips dN_{L1} and dN_{L2} in the carrier phase observations $\Phi_{o,L1}$ and $\Phi_{o,L2}$, the discontinuities in eqs.(7-1-8), (7-1-9) and (7-1-10) for the phase combination data sets can be expressed by d(PID), d(PIF) and d(PWL), where deviation $d(\cdot)$ is defined by $d(\cdot) = (\cdot) - (\cdot)^*$, and $(\cdot)^*$ is the contiguous predicted observable of $(\cdot)$. Therefore, cycle slips dN_{L1} and dN_{L2} can be resolved into their integer numbers by using the following combinations:

(1) d(PIF) and d(PWL):

$$dN_{L1} = \frac{\lambda_{L4}\, d(PIF) - \beta\, d(PWL)}{\lambda_{L4}\, (\alpha - \beta)} \tag{7-3-1}$$

and

$$dN_{L2} = \frac{\lambda_{L4}\, d(PIF) - \alpha\, d(PWL)}{\lambda_{L4}\, (\alpha - \beta)} \tag{7-3-2}$$

(2) d(PIF) and d(PID):

$$dN_{L1} = \frac{\lambda_{L2}\, d(PIF) - \beta\, d(PID)}{\alpha\lambda_{L2} - \beta\lambda_{L1}} \tag{7-3-3}$$

and

$$dN_{L2} = \frac{\lambda_{L1}\, d(PIF) - \alpha\, d(PID)}{\alpha\lambda_{L2} - \beta\lambda_{L1}} \tag{7-3-4}$$

(3) d(PWL) and d(PID):

$$dN_{L1} = \frac{\lambda_{L2}\, d(PWL) - \lambda_{L4}\, d(PID)}{\lambda_{L4}(\lambda_{L2} - \lambda_{L1})} \tag{7-3-5}$$

and

$$dN_{L2} = \frac{\lambda_{L1}\, d(PWL) - \lambda_{L4}\, d(PID)}{\lambda_{L4}(\lambda_{L2} - \lambda_{L1})} \tag{7-3-6}$$

The above combination equations can also be applied in the determination of single and double difference cycle slips ΔdN_{L1} and ΔdN_{L2} , and $\nabla\Delta dN_{L1}$ and $\nabla\Delta dN_{L2}$ by using single and double differenced data sets $\Delta(\cdot)$ and $\nabla\Delta(\cdot)$. From eqs.(7-3-1) to (7-3-6) it is obvious that the determination of a cycle slip is affected by deviation $d(\cdot)$ and its noise due to the data quality. If the epoch differenced data sets $\delta(\cdot)$ are used, the relation between dN and $d\delta(\cdot)$ can be generally described as

$$dN = \frac{GAP}{A}\, d\delta(\cdot) \tag{7-3-7}$$

where GAP (GAP ≥ observation sampling rate) is the time difference between the two sequential observation epochs, and A is the particular coefficient listed in Table 7.1, which shows how much of a deviation $d\delta(\cdot)$ will be caused by a cycle slip of one cycle in the phase data sets.

Table 7.1. Theoretical deviations $d\delta(\cdot)$ for detection of a cycle slip of one cycle (GAP = 30 seconds)

No.	data type	A	cycle slip (1 cycle)	deviation $d\delta(\cdot)$ (metre/second)
(1)	δ(PIF)	λ_{L1}	dN_{L1}	0.0063
		λ_{L2}	dN_{L2}	0.0081
	δ(PID)	$\lambda_{L1}\,\lambda_{L2}/\alpha$	dN_{L1}	0.0041
		$\lambda_{L1}\,\lambda_{L2}/\alpha$	dN_{L2}	0.0032
(2)	δ(PIF)	$\alpha - \beta$	dN_{L1}	0.0036
		$\alpha - \beta$	dN_{L2}	0.0036
	δ(PWL)	λ_{L2}	dN_{L1}	0.0081
		λ_{L1}	dN_{L2}	0.0063
(3)	δ(PWL)	λ_{L1}	dN_{L1}	0.0063
		λ_{L2}	dN_{L2}	0.0081
	δ(PID)	$\lambda_2 - \lambda_1$	dN_{L1}	0.0018
		$\lambda_2 - \lambda_1$	dN_{L2}	0.0018

In Table 7.1, the algorithms in terms of the three groups for the solution of the cycle slip should yield same results. The values $d\delta(\cdot)$ can be used as criteria for detecting cycle slips and assessing data quality. Once the deviation (p – o), which is the difference between the predicted and observed values, is bigger than the theoretical value $d\delta(\cdot)$, a cycle slip or bad data point will be apparent.

In the preprocessing of the global GPS data sets provided by Rogue receivers from the GPS'92 campaign for the period of 25 to 31, July 1992 and from CIGNET for the period of March 29 to 3 April, 1992, the deviations for most of the data sets meet the above criteria, except for data sets provided by stations Graz (GR) with a Rogue receiver from 25 to 31 July, 1992, and Herstmonceux (HE) with a Rogue receiver from March 29 to April 3, 1992. Figures 7.1 to 7.6 present some samples from the results of preprocessing the single differenced data sets $\delta\Delta$(PIF), $\delta\Delta$(PWL) and $\delta\Delta$(PID) observed. Figure 7.1 shows that the deviations (p – o) from processing the single differenced data sets $\Delta(\cdot)$ provided by stations Goldstone(GO) and Madrid (MD) belonging to the Deep Space Network (DSN) for satellite PRN21 on 29 March 1992 (file GO-MD.March29.PRN21) meet the criteria.

However, the single difference deviations (p – o) for all satellites for the baselines formed by stations Wettzell and Herstmonceux from March 29 to April 3, 1992 and stations Wettzell (WT) and Graz from July 25 to 31, 1992 exceed the criteria. Figures 7.2 and 7.5 are two samples from files WT-HE.March29.PRN6 and WT-GR.July25.PRN16. This situation also occurs when combining data sets provided by stations station or Graz with the other stations. The reason could be the relatively large noise in the Rogue receivers at stations Herstmonceux and Graz during the observation periods mentioned above. The single difference deviations (p – o) for all satellites meet the criteria when combining data sets provided by the Wettzell station with other stations, such as Madrid or Kootwijk (KO) for all days processed. Figures 7.3 and 7.6 are two examples from files WT-MD.March29.PRN21 and WT-KO.July25.PRN16.

The standard deviations of the cycle slips for stations Herstmonceux and Graz are worse due to the bad data quality. However, by randomly sampling and checking the data sets provided by stations Herstmonceux and Wettzel from CIGNET for June 23, 1992 and during the GPS'92 campaign from 25 to 31 July, the quality of the data sets for station Herstmonceux was back to normal. In the following, Figure 7.4 just is one sample from file WT-HE.June23.PRN2.

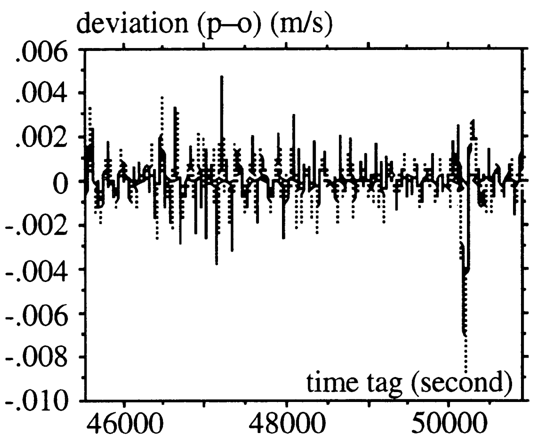

Figure 7.1 Deviations for GO-MD. March29.PRN21

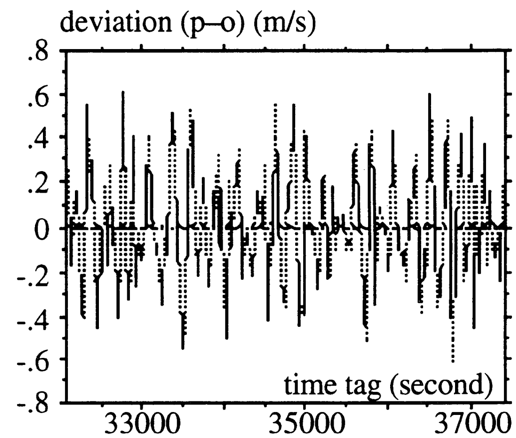

Figure 7.2 Deviations for WT-HE. March29.PRN6

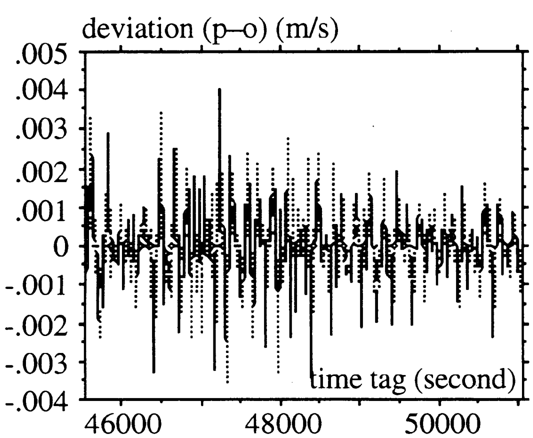

Figure 7.3 Deviations for WT-MD. March29.PRN21

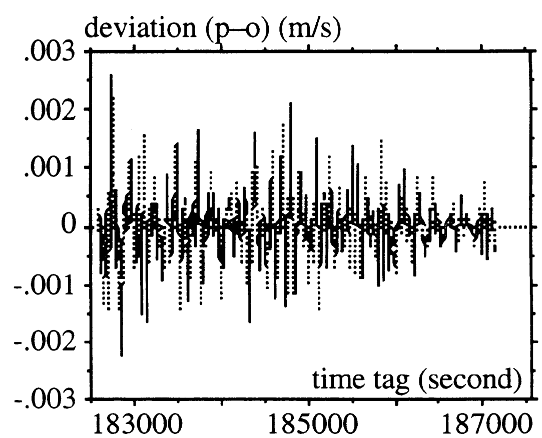

Figure 7.4 Deviations for WT-HE. June23.PRN2

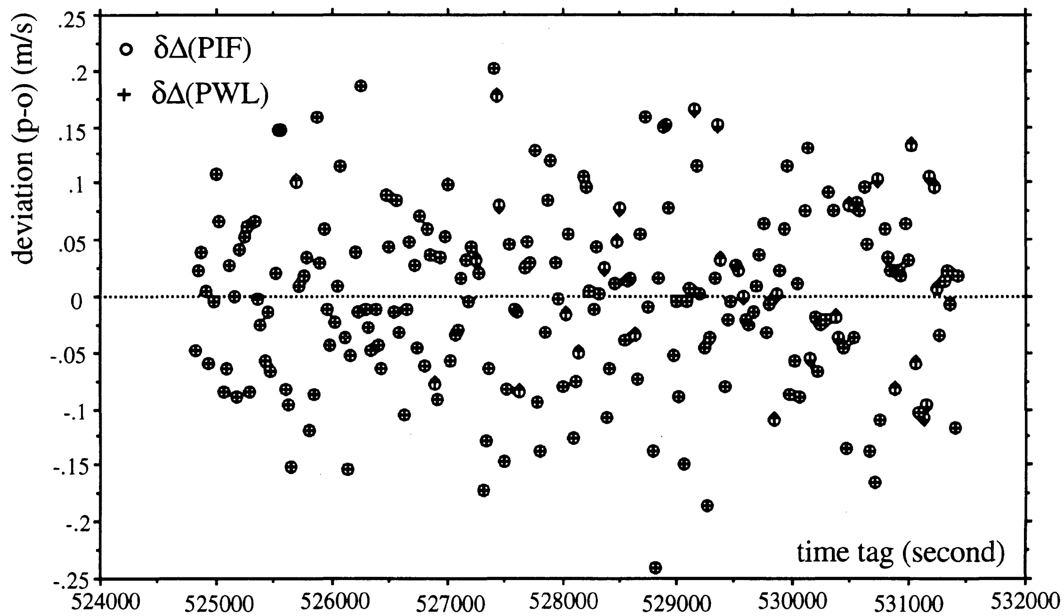

Figure 7.5 Deviations for WT-GR.July25.PRN16

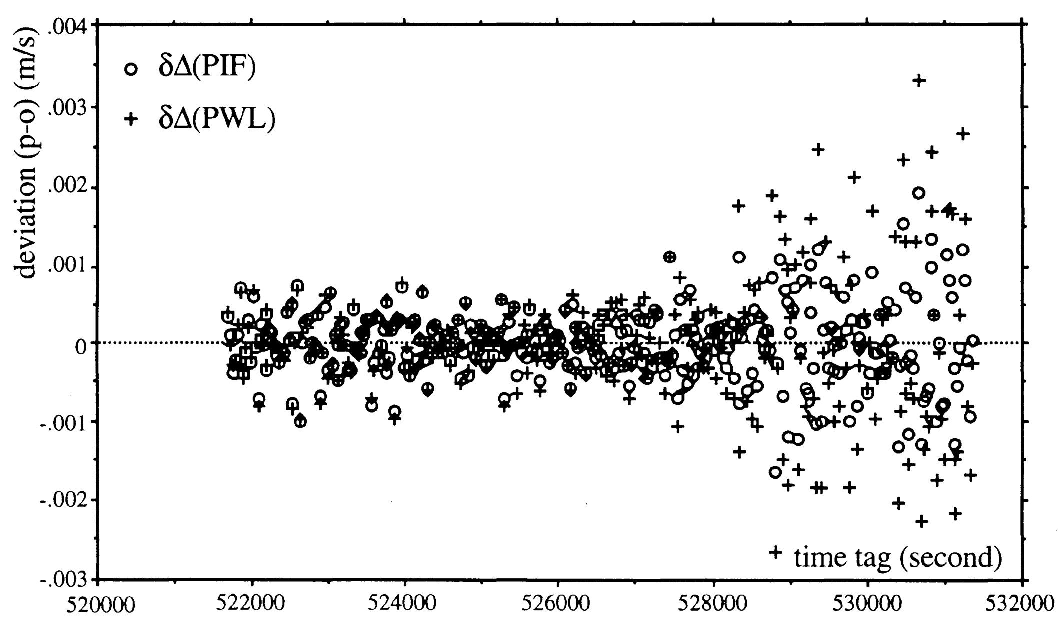

Figure 7.6 Deviations for WT-KO.July25.PRN16

Tables 7.2 and 7.3, below, show samples from the results of cycle slip determination. The cycle slip values determined by two different data combinations are the same. Their standard deviations depend on the noise of the data types and the size of any gaps.

Table 7.2 Cycle slip determination for file GO-MD.March29 (solved by ΔPIF and ΔPID)

time tag (s)	sv	gap (s)	c. slip(L1) cycle	std.1 cycle	c. slip (L2) cycle	std.2 cycle
26700	24	240	21225037	1.39	16538987	1.43
48330	12	90	−2005379	0.18	−1562634	0.18
48780	12	120	1068128	0.67	832306	0.69
49170	12	90	1016013	0.81	791697	0.81
50220	23	120	9047955	1.10	7050334	1.10
81870	15	30	−10398460	0.42	−8102633	0.39
82050	15	120	10894727	1.14	8489333	1.06
82080	15	30	−11337668	0.23	−8834480	0.22
83100	15	30	15951993	0.08	12430045	0.08
83190	15	90	311718	0.25	242897	0.25
83220	15	30	−16263713	0.08	−12672943	0.08
84000	11	90	−219968	0.46	−171351	0.46

Table 7.3 Cycle slip determination for file GO-MD.March29
(solved by ΔPIF and ΔPWL)

time tag (s)	sv	gap (s)	c. slip(L1) cycle	std.1 cycle	c. slip (L2) cycle	std.2 cycle
26700	24	240	21225037	2.54	16538987	2.89
48330	12	90	−2005379	0.33	−1562634	0.38
48780	12	120	1068128	1.21	832306	1.38
49170	12	90	1016013	1.49	791697	1.69
50220	23	120	9047955	2.06	7050334	2.33
81870	15	30	−10398460	0.81	−8102633	0.89
82050	15	120	10894727	2.19	8489333	2.42
82080	15	30	−11337668	0.45	-8834480	0.49
83100	15	30	15951993	0.15	12430045	0.17
83190	15	90	311718	0.46	242897	0.52
83220	15	30	−16263713	0.15	−12672943	0.17
84000	11	90	−219968	0.84	−171351	0.95

In addition, it should be mentioned that the data sets provided by station Ny Alesund for the GPS'92 campaign from 25 to 31 July also were used, even though they had an excessive number of cycle slips (about 200 cycle slips per day).

7.4 Summary

The fully developed GPS observation equations for carrier phase and pseudorange measurements have been presented in various combination forms that can be chosen independently to improve GPS static positioning. The independent combinations of the differenced observation equations have their own advantages to eliminate the nuisance parameters or biases, which are not perfectly modeled. In order to reliably process GPS observations from the global network, procedures for automatic preprocessing with criteria for cycle slip fixing at the one cycle level have been proposed and tested using data sets provided by stations equipped with Rogue receivers and Ashtech receivers from the GPS'92 campaign and from selected observations of the CIGNET network. For most of the stations, the data sets meet the criteria for efficient preprocessing. A few stations with bad data could be identified. The standard deviations for the cycle slip determination generally meet the proposed requirement; they are dependent on the qualities of the data types and the size of data gaps. Generally, the ability of the automated preprocessing of GPS data sets from globally distributed stations can be achieved at the 90% level or better. Appendix I lists a sample of command files for PREDD.ERP (for stations Algonquin and St. John's). For more details, the advanced preprocessors PREDD.ERP and PREGE.ERP can be referenced.

CHAPTER 8
IMPLEMENTATION AND RESULTS

8.1 Strategies

Based on the seven-day data sets collected during the GPS'92 campaign, the geodetic and geodynamic parameters as well as nuisance parameters have been estimated by using the software DIPOP.ERP developed on the UNB mainframe. The adjusted parameters are: station coordinates, 6 a priori initial orbital elements plus two parameters for solar radiation for each satellite, daily zenith troposphere scale for each station, daily Earth rotation parameters, and carrier beat phase ambiguities as real values. The formed design matrix is based on the ionosphere-free, double differenced, dual frequency carrier beat phase observation equations.

During the period of testing the DIPOP.ERP software using the global GPS data sets, four strategies were followed for the global geodetic network adjustment and parameter estimation. These strategies tested how sensitive to the fixed stations the estimated parameters and the r.m.s. are, and gave an indication of how to get the best results.

(1) Strategy-1: fixing a number of stations (8 stations or less on some day described in Table 8.1 were not available: ALGO, FAIR, HART, KOKB, MADR, TROM, YAR1, YELL) with a constraint of 10^{-5} metre (see Appendix II); the estimated stations with a constraint of 100 metres (see Appendix II); 6 a priori initial orbital elements plus two parameters for solar radiation with loose constraints (their a priori standard deviations can be found in Appendix III) for the first and second iterations in the orbital improvement; daily tropospheric scale parameters for each station; daily Earth rotation parameters with loose constraints of 0.1" (about 3 metres) for polar motion and 0.5 ms/day for the rate of

UT1–UTC (see Appendix II); and carrier beat phase ambiguities as real values. The fixed and estimated coordinates are three-dimensional Cartesian coordinates referenced to epoch 1992.5 in the reference frame ITRF91. No special care for different constraints on the vertical and horizontal directions, i.e. the geodetic coordinates, was taken. A seven-day sequential adjustment solution for this strategy was considered.

Figure 8.1 shows the general view of the baseline formation for the double differences from the global stations.

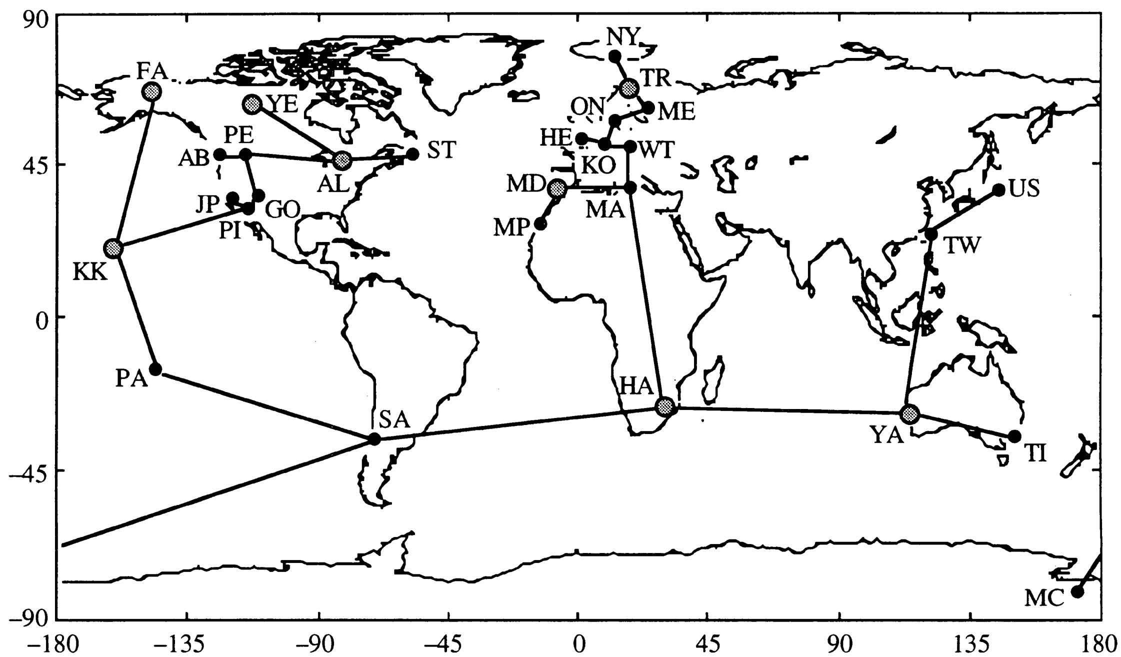

Figure 8.1 Distribution of the IGS core stations and arrangement of the baselines during 25-31 July for the GPS'92 campaign

(strategy-1)

(◎ represents a fixed station ; • represents an adjusted station)

The details about the constrained and estimated stations and data sets available for daily processing are given in Table 8.1. A few stations occasionally have no observation during that time. Station Graz (GR) was removed due to its poor data quality.

Table 8.1 The estimated and fixed stations from July 25 to August 1, 1992

(strategy-1)

("f" ---- coordinates of ground station kept fixed)

("e" ---- coordinates of ground station estimated)

("-" ---- ground station not included on that day)

no.	code	code	25	26	27	28	29	30	31
1	ALBH	AB	e	-	e	e	e	e	e
2	ALGO	AL	f	f	f	f	f	f	f
3	DRAO	PE	e	e	e	e	e	e	e
4	FAIR	FA	f	f	f	f	f	f	f
5	GOLD	GO	-	e	e	e	e	e	e
6	GRAZ	GR	-	-	-	-	-	-	-
7	HART	HA	f	f	f	f	f	f	f
8	HERS	HE	e	e	e	e	e	e	e
9	JPLM	JP	-	e	e	e	e	e	e
10	KOKB	KK	f	f	f	f	f	f	f
11	KOSG	KO	e	e	e	e	e	e	e
12	MADR	MD	-	f	f	f	f	f	f
13	MASP	MP	e	e	e	e	e	e	e
14	MATE	MA	e	e	e	e	e	e	e
15	MCMU	MC	-	e	e	e	e	e	e
16	METS	ME	e	e	e	e	e	e	e
17	NYAL	NY	-	e	e	e	e	e	e
18	ONSA	ON	e	e	e	e	e	e	e
19	PAMA	PA	e	e	e	e	e	e	e
20	PIN1	PI	e	e	e	e	e	e	e
21	SANT	SA	e	e	e	e	e	e	e
22	STJO	ST	e	e	e	e	e	e	e
23	TAIW	TW	e	e	e	e	e	e	e
24	TIDB	TI	-	e	e	e	e	e	e
25	TROM	TR	f	f	f	f	f	f	f
26	USUD	US	-	-	e	e	e	e	e
27	WETT	WT	e	e	e	e	-	e	e
28	YAR1	YA	f	f	f	f	f	f	f
29	YELL	YE	f	f	-	f	f	f	f

(2) Strategy-2: the estimated parameters for strategy-2 are the same as strategy-1. The only difference is the fixing of many stations (17 stations or less on some day seen in Table

8.2: ALGO, DRAO, FAIR, GOLD, HART, JPLM, KOKB, KOSG, MADR, MATE, ONSA, PIN1, TIDB, TROM, USUD, YAR1, YELL) with the same constraint of 10^{-5} metre.

Figure 8.2 shows the general view of the fixed and estimated stations, and the baseline formation for double differences from the global stations. Details concerning the constrained and estimated stations and data sets available for daily processing are given in Table 8.2.

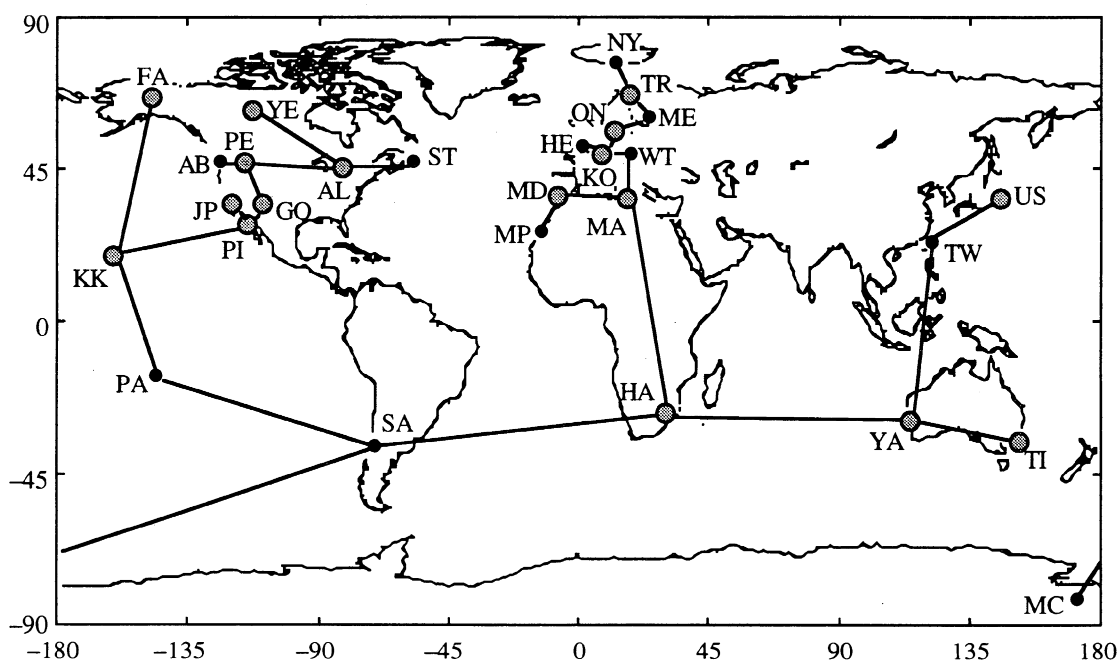

Figure 8.2 Distribution of the IGS core stations and arrangement of the baselines during 25-31 July for the GPS'92 campaign (strategy-2)

(◍ represents a fixed station ; • represents an adjusted station)

Table 8.2 The estimated and fixed stations from July 25 to August 1, 1992
(strategy-2)
("f" ---- coordinates of ground station kept fixed)
("e" ---- coordinates of ground station estimated)
("-" ---- ground station not included on that day)

no.	code	code	25	26	27	28	29	30	31
1	ALBH	AB	e	-	e	e	e	e	e
2	ALGO	AL	f	f	f	f	f	f	f
3	DRAO	PE	f	f	f	f	f	f	f
4	FAIR	FA	f	f	f	f	f	f	f
5	GOLD	GO	-	f	f	f	f	f	f
6	GRAZ	GR	-	-	-	-	-	-	-
7	HART	HA	f	f	f	f	f	f	f
8	HERS	HE	e	e	e	e	e	e	e
9	JPLM	JP	-	f	f	f	f	f	f
10	KOKB	KK	f	f	f	f	f	f	f
11	KOSG	KO	f	f	f	f	f	f	f
12	MADR	MD	-	f	f	f	f	f	f
13	MASP	MP	e	e	e	e	e	e	e
14	MATE	MA	f	f	f	f	f	f	f
15	MCMU	MC	-	e	e	e	e	e	e
16	METS	ME	e	e	e	e	e	e	e
17	NYAL	NY	-	e	e	e	e	e	e
18	ONSA	ON	f	f	f	f	f	f	f
19	PAMA	PA	e	e	e	e	e	e	e
20	PIN1	PI	f	f	f	f	f	f	f
21	SANT	SA	e	e	e	e	e	e	e
22	STJO	ST	e	e	e	e	e	e	e
23	TAIW	TW	e	e	e	e	e	e	e
24	TIDB	TI	-	f	f	f	f	f	f
25	TROM	TR	f	f	f	f	f	f	f
26	USUD	US	-	-	f	f	f	f	f
27	WETT	WT	e	e	e	e	-	e	e
28	YAR1	YA	f	f	f	f	f	f	f
29	YELL	YE	f	f	-	f	f	f	f

(3) Strategy-3: the estimated parameters are the same as strategy-1. The only differences are to increase moderately the number of fixed stations based on the strategy-1

(11 stations or less on some day described in Table 8.3: ALGO, FAIR, HART, KOKB, KOSG, MADR, MATE, ONSA, TROM, YAR1, YELL) with a constraint of 10^{-5} metre, and to remove three stations ALBH, GOLD and JPLM, used to form short baselines; the estimated stations had a constraint of 100 metres. A seven-day sequential adjustment solution for this strategy was considered.

Figure 8.3 shows the general view of the fixed and estimated stations, and the baseline formation for the double differences from the global stations. Details concerning the constrained and estimated stations and data sets available for daily processing are given in Table 8.3.

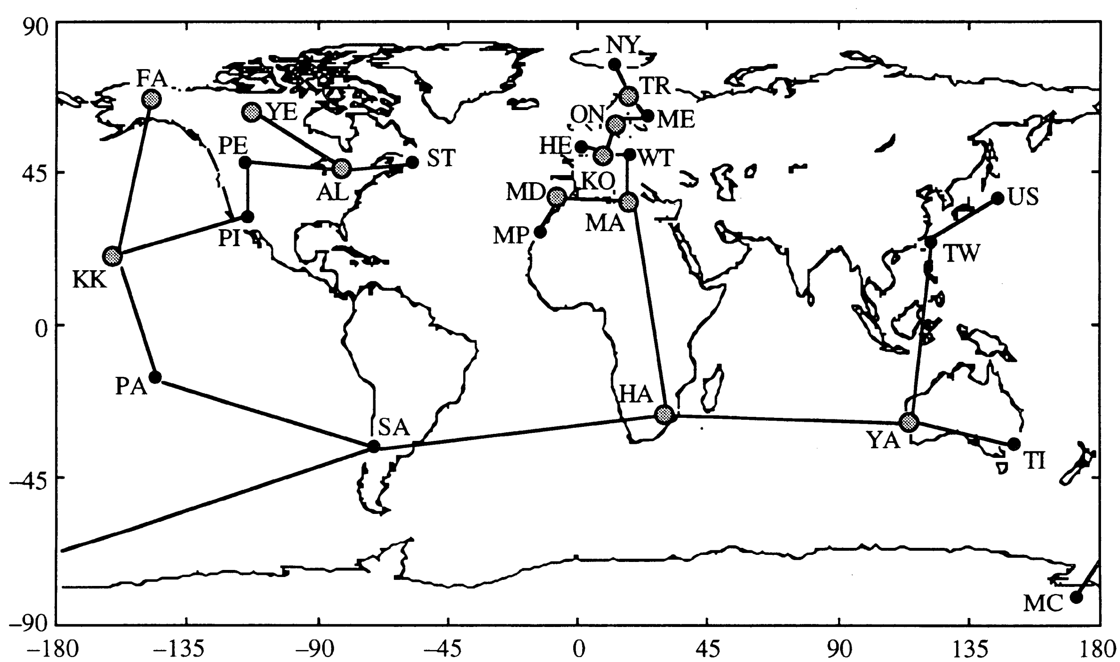

Figure 8.3 Distribution of the IGS core stations and arrangement of the baselines during 25-31 July for the GPS'92 campaign (strategy-3)

(◍ represents a fixed station; • represents an adjusted station)

Table 8.3 The estimated and fixed stations from July 25 to August 1, 1992
(strategy-3)
("f" ---- coordinates of ground station kept fixed)
("e" ---- coordinates of ground station estimated)
("-" ---- ground station not included on that day)

no.	code	code	25	26	27	28	29	30	31
1	ALBH	AB	-	-	-	-	-	-	-
2	ALGO	AL	f	f	f	f	f	f	f
3	DRAO	PE	e	e	e	e	e	e	e
4	FAIR	FA	f	f	f	f	f	f	f
5	GOLD	GO	-	-	-	-	-	-	-
6	GRAZ	GR	-	-	-	-	-	-	-
7	HART	HA	f	f	f	f	f	f	f
8	HERS	HE	e	e	e	e	e	e	e
9	JPLM	JP	-	-	-	-	-	-	-
10	KOKB	KK	f	f	f	f	f	f	f
11	KOSG	KO	f	f	f	f	f	f	f
12	MADR	MD	-	f	f	f	f	f	f
13	MASP	MP	e	e	e	e	e	e	e
14	MATE	MA	f	f	f	f	f	f	f
15	MCMU	MC	-	e	e	e	e	e	e
16	METS	ME	e	e	e	e	e	e	e
17	NYAL	NY	-	e	e	e	e	e	e
18	ONSA	ON	f	f	f	f	f	f	f
19	PAMA	PA	e	e	e	e	e	e	e
20	PIN1	PI	e	e	e	e	e	e	e
21	SANT	SA	e	e	e	e	e	e	e
22	STJO	ST	e	e	e	e	e	e	e
23	TAIW	TW	e	e	e	e	e	e	e
24	TIDB	TI	-	e	e	e	e	e	e
25	TROM	TR	f	f	f	f	f	f	f
26	USUD	US	-	-	e	e	e	e	e
27	WETT	WT	e	e	e	e	-	e	e
28	YAR1	YA	f	f	f	f	f	f	f
29	YELL	YE	f	f	-	f	f	f	f

(4) Strategy-4: by using the SIO precise orbits, the stations remaining fixed are the same as those in strategy-1, i.e. a number of stations (8 stations or less on some day:

ALGO, FAIR, HART, KOKB, MADR, TROM, YAR1, YELL) with a constraint of 10^{-5} metre are fixed; the estimated stations with a constraint of 100 metres; using SIO precise orbits with a tabulated time interval of 22 minutes and 30 seconds and NGS format; daily tropospheric scale parameters for each station; carrier beat phase ambiguities estimated as real values; the orbits and the Earth rotation parameters are not estimated. A seven-day sequential adjustment solution for this strategy was also considered.

8.2 Analysis Results: the Cartesian Coordinates and Baselines

The mean values of the station coordinates from the daily solutions using strategy-1 and strategy-3 are presented in Tables IV.1 and IV.2 of Appendix IV. Table IV.3 in Appendix IV lists a seven-day solution of the station coordinates for strategy-4. It is obvious that the daily repeatabilities for most stations are only a few centimetres and the standard deviations are about a few millimetre s for strategy-1 and strategy-3. However, the repeatability and standard deviation exceed ten centimetres and ten millimetres respectively for stations McMurdo, Santiago, Tidbinbilla, and especially for the two stations Tai-Shi and Usuda. That could be attributed to some cycle slips and outliers still remaining in the data sets. The unfavourable geometrical condition and little intervisibility also could be the causes, since the number of double differenced observations for some long baselines are seriously decreased. Table 8.4 lists the daily repeatabilities of the geodetic coordinates for strategy-1 and strategy-3.

Table 8.4 Daily repeatability of the geodetic coordinates for strategy-1 and strategy-3

CODE	Strategy-1			Strategy-3		
	Latitude (mm)	Longitude (mm)	Height (mm)	Latitude (mm)	Longitude (mm)	Height (mm)
AB	13	21	30			
GO	21	16	35			
HE	56	49	37	7	15	14
JP	17	45	50			
KO	59	50	41			
MA	61	52	40			
MC	145	115	62	163	127	96
ME	15	19	44	9	12	27
MP	55	75	43	13	21	21
NY	12	17	48	10	16	43
ON	17	29	60			
PA	50	60	77	53	53	87
PE	9	19	41	8	18	41
PI	12	46	60	8	44	50
SA	35	133	155	29	139	150
ST	10	24	38	11	21	26
TI	40	83	119	29	82	113
TW	125	372	246	114	337	226
US	155	323	147	138	288	141
WT	64	49	40	4	10	11

The results from daily or seven-day baseline solutions for strategy-1, strategy-3 and strategy-4 are listed from Appendix V to Appendix VII. Figures 8.4, 8.5, 8.6 and 8.7 show the daily repeatabilities of the baselines for these four strategies. The average daily repeatabilities for these four strategies are 21 p.p.b., 16 p.p.b., 14 p.p.b., and 19 p.p.b. respectively. It is obvious that the precision of the baselines is increased a little bit for strategy-3. The daily repeatability of the short baseline PI-JP (about 172 km) is poor at about 17.6 mm (0.1 p.p.m.) for strategy-1 and strategy-4. This could be attributed to the cycle slips and bad data points still remaining in the data sets. From Table V.1 in Appendix V and Table VI.1 in Appendix VI, it is obvious that the daily repeatabilities are between 15 p.p.b. and 6 p.p.b. for most baselines.

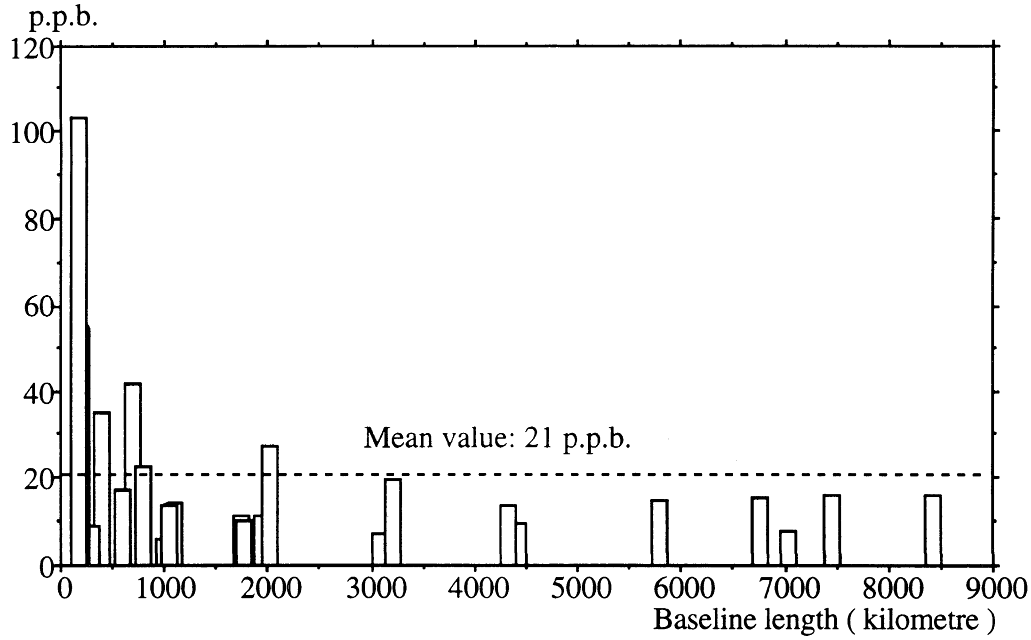

Figure 8.4 Baseline daily repeatabilities for strategy-1

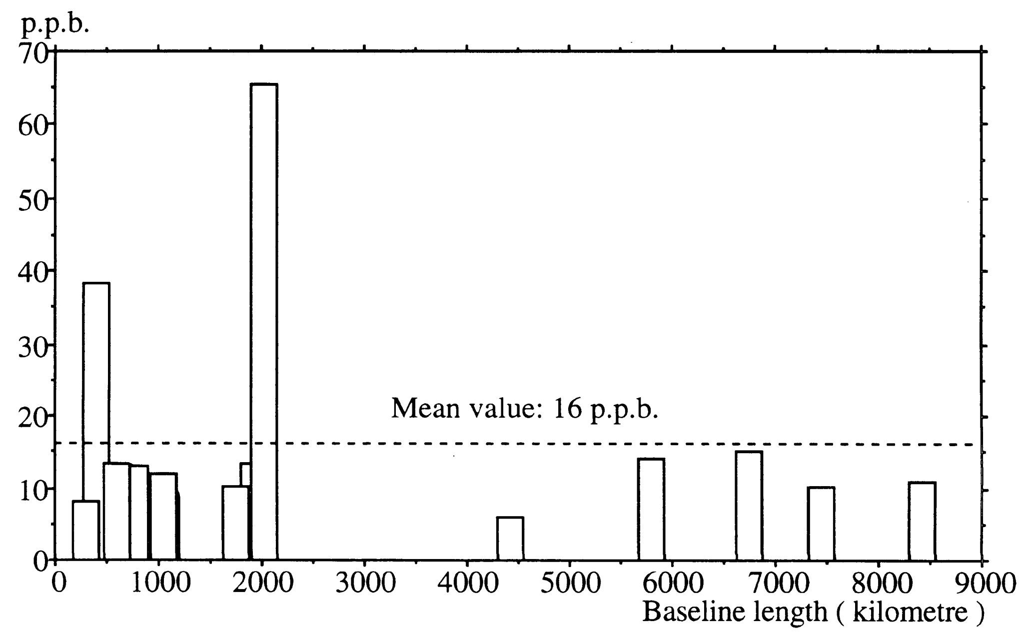

Figure 8.5 Baseline daily repeatabilities for strategy-2

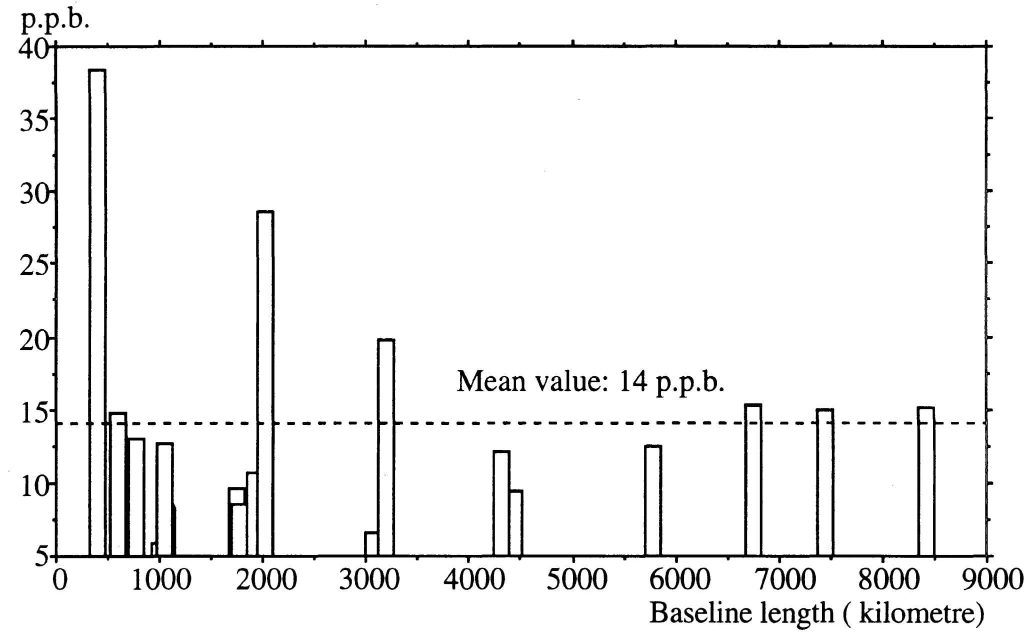

Figure 8.6 Baseline daily repeatabilities for strategy-3

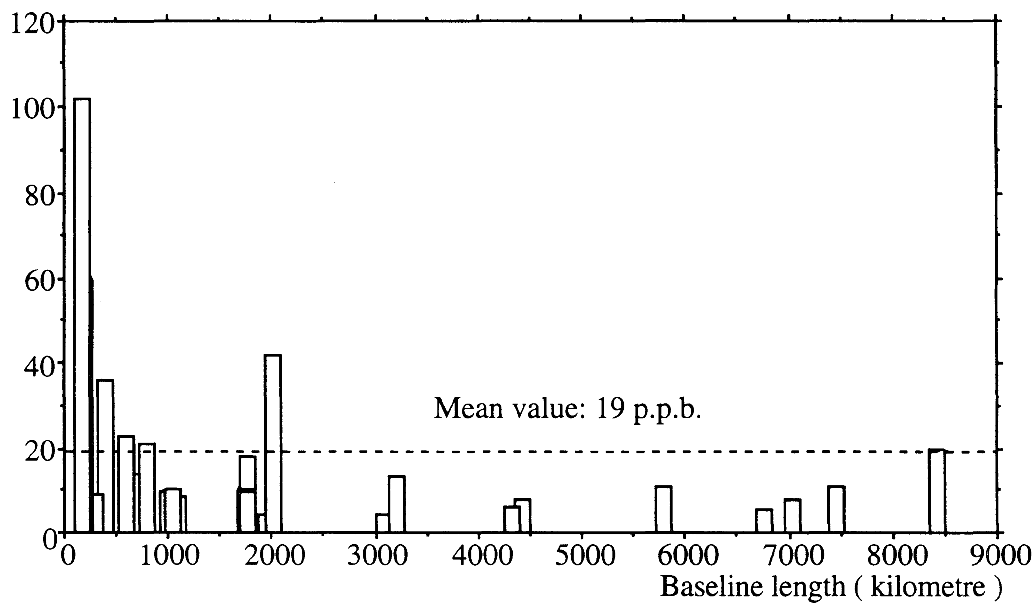

Figure 8.7 Baseline daily repeatabilities by using the SIO precise orbits

It is worth mentioning that some long baselines over a thousand kilometres, which are formed by two stations from the double difference observation, have high accuracies (with uncertainties from a few millimetres to centimetres). Their daily repeatabilities are better than 16 parts in 10^9. They are: Penticton - Algonquin (3075 km), Pinyon Flat - Kokee Park (4320 km), Kokee Park - Pamate (4431 km), Santiago - McMurdo (6760 km), Matera - Hartebeesthoek (7033 km), Santiago - Pamate (7449 km), and Hartebeesthoek - Santiago (8426 km).

In all processing, a priori r.m.s. for the carrier beat phase measurement has been set to 15 mm as a default value for all files. The a posteriori variance factors obtained from daily solutions for the four strategies are listed in Table 8.5. The a posteriori variance factors obtained from daily solutions for strategy-3 are between 1.72 and 2.43, which means that the r.m.s. obtained from main processing are between 1.97 cm and 2.34 cm. Compared with strategy-1 and strategy-2, strategy-3 presents a small r.m.s. for the daily solution due to the different station constraints and removal of some short baselines. From Table 8.5, the a posteriori variance factor obtained from a seven-day solution for strategy-4 is 5.81, so its r.m.s. is 3.62 cm, while the r.m.s. for strategy-1 and strategy-3 from the seven-day solutions are 5.96 cm and 6.40 cm. It is obvious that strategy-4 presents a small r.m.s. for a seven-day solution due to the fact that the orbits are calculated by using the daily orbital solution, while the orbits used in strategy-1 and strategy-3 are calculated from the seven-day orbital arcs solutions. Therefore, a solution for the multi-day orbit arcs is not recommended for parametric estimation by using GPS observation if some force model components are not adequate. It is necessary to estimate the daily GPS satellite orbits for the multi-day orbit arcs and improve the orbital models, in order to accurately determine the other parameters.

Table 8.5 The a posteriori variance factors for four strategies
(f represents a posteriori variance factor)

day	25	26	27	28	29	30	31	7-day solution
strategy-1 (f)	1.694	2.282	2.352	2.108	2.469	2.783	2.998	15.782
r.m.s. (cm)	1.95	2.27	2.30	2.18	2.36	2.50	2.60	5.96
strategy-2 (f)	1.910	4.445	4.458	4.946	4.896	5.332	6.152	
r.m.s. (cm)	2.07	3.16	3.17	3.34	3.32	3.46	3.72	
strategy-3 (f)	1.815	2.078	2.060	1.720	2.071	2.208	2.430	18.178
r.m.s. (cm)	2.02	2.16	2.15	1.97	2.16	2.23	2.34	6.40
strategy-4 (f)	5.996	5.530	5.367	4.666	5.942	6.028	5.843	5.809
r.m.s. (cm)	3.67	3.53	3.48	3.24	3.66	3.68	3.63	3.62

It is necessary to mention that the number of daily double differenced observation is more than 170,000 for strategy-1, strategy-2 and strategy-4, and 150,000 for strategy-3. The CPU time for the main processing of the daily solutions is about 55 minutes, while it is about 4.3 hours for the seven-day solution on the mainframe IBM 9121, model 320. Even though the r.m.s. obtained from the main processing is about a few centimetres, the cycle slips and poor data points (outliers) could still have a contribution and they would influence the parametric estimation to some extent. In addition, the errors from the satellite orbits and the tropospheric corrections also contribute to the r.m.s. significantly. Therefore, it is essential to establish procedures for the quality control of the data sets to yield high accuracy estimates of the parameters. The part of this work in preprocessing was described in chapter 7. After postprocessing, the data quality also can be further checked through the residual files.

8.3 Analysis Results: the Earth Rotation Parameters

The a priori Earth rotation parameters adopted during period of data processing are listed in Table 8.6 and Appendix III. They were provided by IERS (IGS Mail No. 80, EOP(IERS) 90 C 04). The values D (excess length of day) were obtained by differentiating UT1–UTC.

Table 8.6 IERS values of the ERP

Day	MJD	x_p	y_p	D
		0.1 mas	0.1 mas	ms
25.5	48828.5	–1030.6	4324.3	–1.236
26.5	48829.5	–1011.1	4342.5	–1.196
27.5	48830.5	–0991.6	4360.7	–1.260
28.5	48831.5	–0972.2	4379.4	–1.405
29.5	48832.5	–0952.7	4398.9	–1.651
30.5	48833.5	–0933.0	4419.5	–1.885
31.5	48834.5	–0913.1	4441.3	–2.069

8.3.1 Earth Rotation Parameter Values from Strategy-1

From Table 8.7, the corrections (Δx_p , Δy_p and ΔD) to the polar motion and rate of change of UT1–UTC were daily estimated using strategy-1. m_x , m_y , and m_D are their standard deviations. x_p , y_p , and D are obtained by adding these corrections to the adopted values in Table 8.6. Their daily standard deviations are less than 0.2 mas. If the mean biases with respect to the IERS values of the ERP are simply defined by $\Delta\bar{x}_p = \Sigma\left|\Delta x_p\right| / 7$, $\Delta\bar{y}_p = \Sigma\left|\Delta y_p\right| / 7$ and $\Delta\bar{D} = \Sigma\left|\Delta D\right| / 7$, then $\Delta\bar{x}_p$ = 2.52 mas, $\Delta\bar{y}_p$ = 1.96 mas and $\Delta\bar{D}$ = 0.147 ms are obtained from Table 8.7 for the daily solutions of the ERP.

It is obvious from Table 8.7 that there exists a maximum bias of 5.65 mas with respect to the IERS value for x_p component for day 25.

Table 8.7 Daily solutions of the ERP for strategy-1

MJD	x_p	Δx_p	m_x	y_p	Δy_p	m_y	D	ΔD	m_D
	0.1 mas	0.1 mas	0.1 mas	0.1 mas	0.1 mas	0.1 mas	ms	ms	ms
48828.5	–974.1	56.5	0.8	4311.6	–12.7	1.9	–1.438	–0.202	0.012
48829.5	–994.6	16.5	0.9	4359.0	16.5	1.8	–1.597	–0.401	0.013
48830.5	–972.9	18.7	0.9	4380.4	19.7	1.7	–1.464	–0.203	0.011
48831.5	–949.5	22.7	0.9	4411.0	31.6	2.0	–1.417	–0.012	0.013
48832.5	–922.6	30.1	1.0	4368.2	–30.6	1.9	–1.543	0.108	0.014
48833.5	–911.2	21.8	1.0	4423.4	3.9	2.0	–1.810	0.074	0.014
48834.5	–903.1	10.0	1.0	4463.8	22.5	1.8	–2.043	–0.026	0.013

In the following, Figures 8.8, 8.9, and 8.10 are plotted based on Table 8.7. It is obvious that there exists a significant systematic bias between the values reported here and the IERS values for component x_p, while one is not obvious for y_p and D.

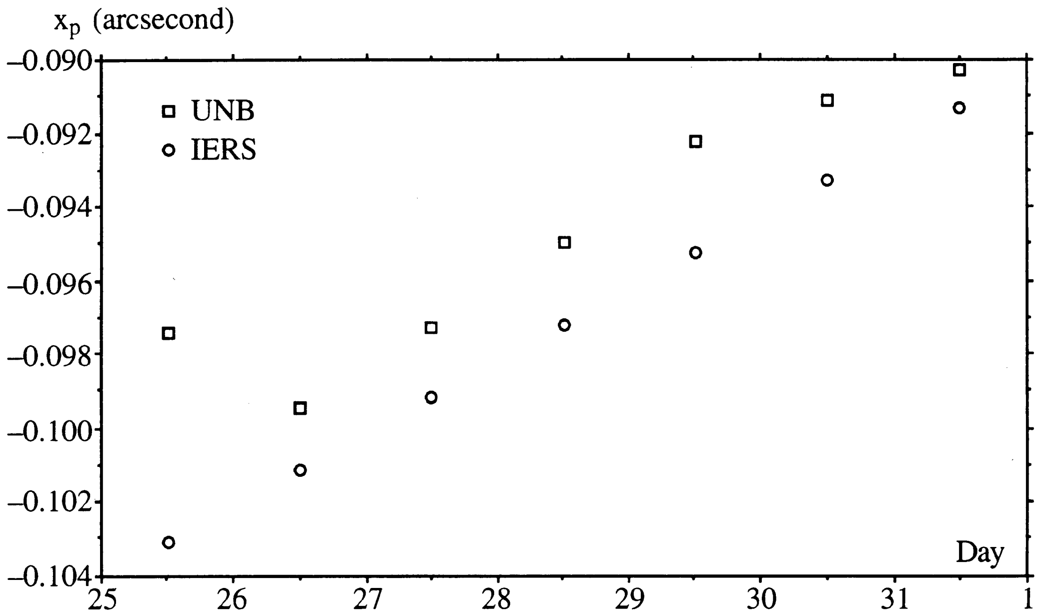

Figure 8.8 Daily solutions of x_p from July 25 to 31 for strategy-1

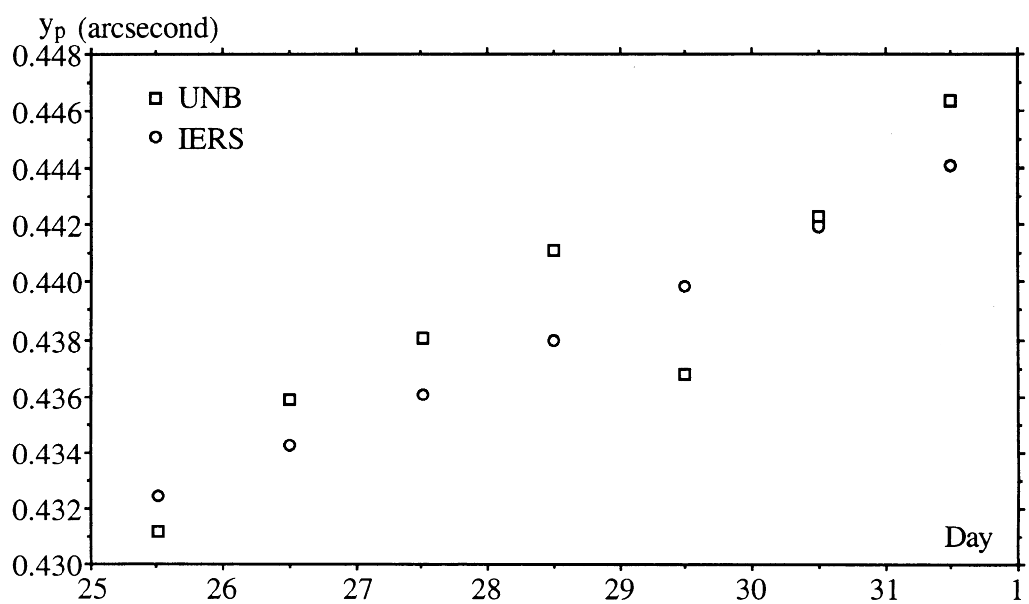

Figure 8.9 Daily solutions of y_p from July 25 to 31 for strategy-1

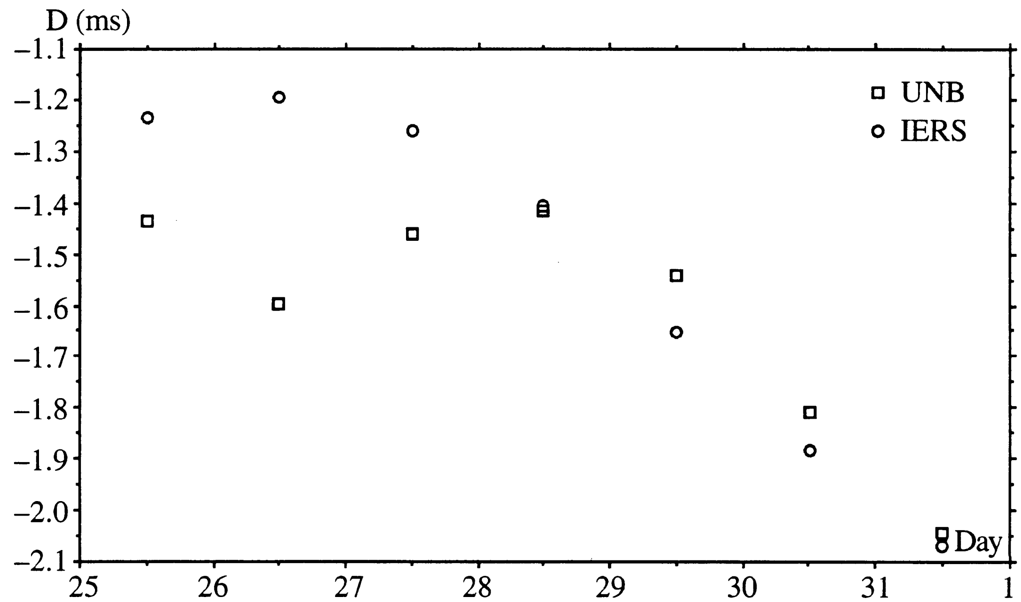

Figure 8.10 Daily solutions of D from July 25 to 31 for strategy-1

8.3.2 Earth Rotation Parameter Values from Strategy-2

Table 8.8 lists the daily solution for strategy-2. The standard deviations of the parameters are less than 0.15 mas, and their mean biases with respect to the IERS values are $\Delta\overline{x}_p$ = 1.63 mas, $\Delta\overline{y}_p$ = 4.16 mas and $\Delta\overline{D}$ = 0.167 ms. Figures 8.11, 8.12, and 8.13 are plotted based on Table 8.8.

Table 8.8 Daily solutions of the ERP for strategy-2

MJD	x_p	Δx_p	m_x	y_p	Δy_p	m_y	D	ΔD	m_D
	0.1 mas	0.1 mas	0.1 mas	0.1 mas	0.1 mas	0.1 mas	ms	ms	ms
48828.5	−990.8	39.8	0.8	4345.5	21.2	1.2	−1.548	−0.312	0.013
48829.5	−998.2	12.9	1.1	4392.7	50.2	1.4	−1.663	−0.467	0.017
48830.5	−985.2	6.4	1.0	4408.4	47.7	1.2	−1.332	−0.072	0.015
48831.5	−938.4	33.8	1.2	4411.3	31.9	1.5	−1.514	−0.109	0.019
48832.5	−941.7	11.0	1.1	4430.6	31.7	1.4	−1.511	0.140	0.018
48833.5	−923.4	9.6	1.2	4475.5	56.0	1.5	−1.840	0.045	0.019
48834.5	−912.7	0.4	1.1	4494.1	52.8	1.4	−2.093	−0.024	0.018

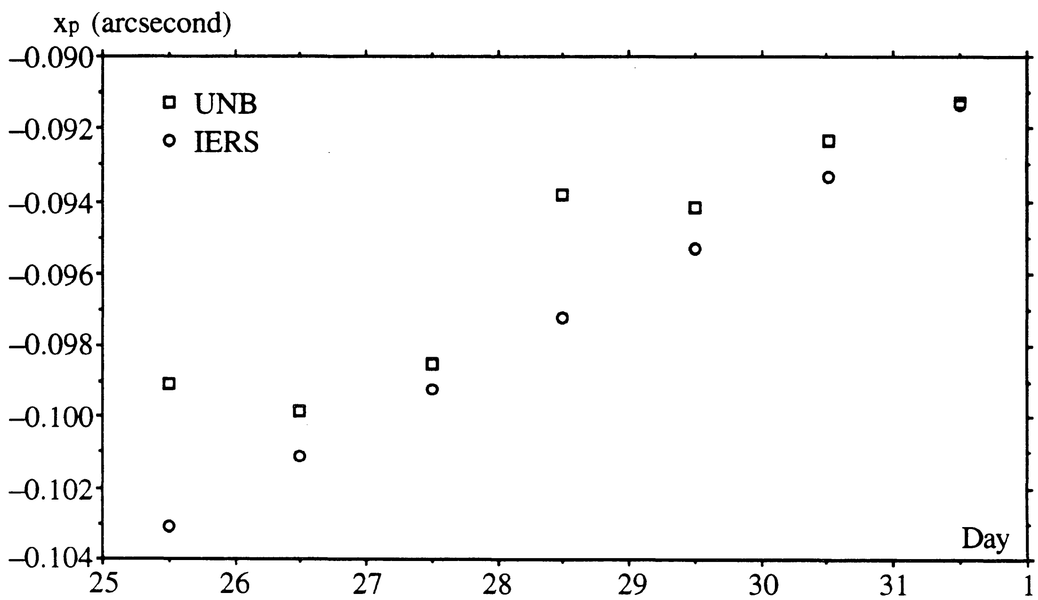

Figure 8.11 Daily solutions of x_p from July 25 to 31 for strategy-2

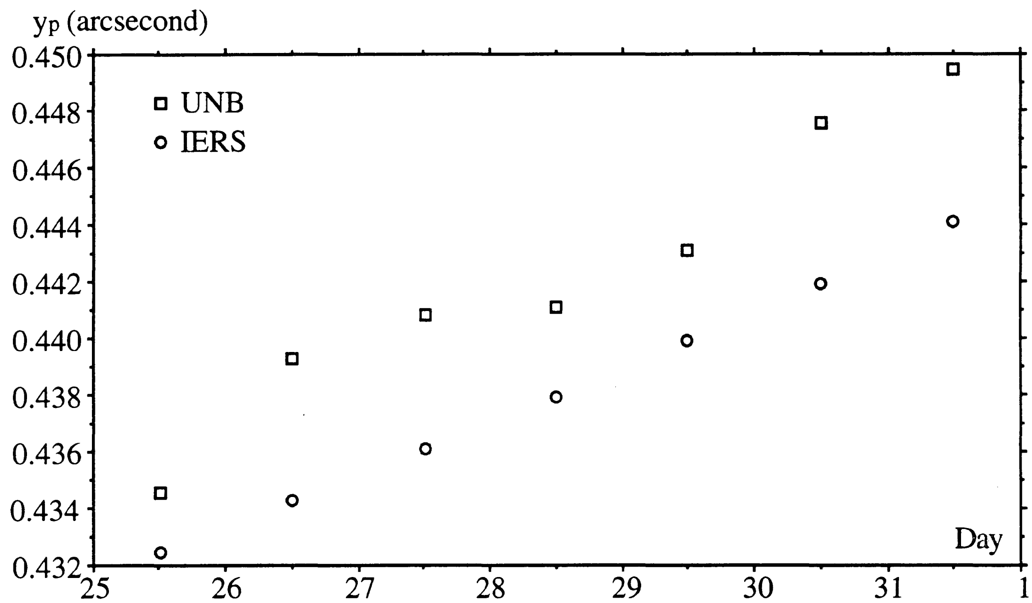

Figure 8.12 Daily solutions of y_p from July 25 to 31 for strategy-2

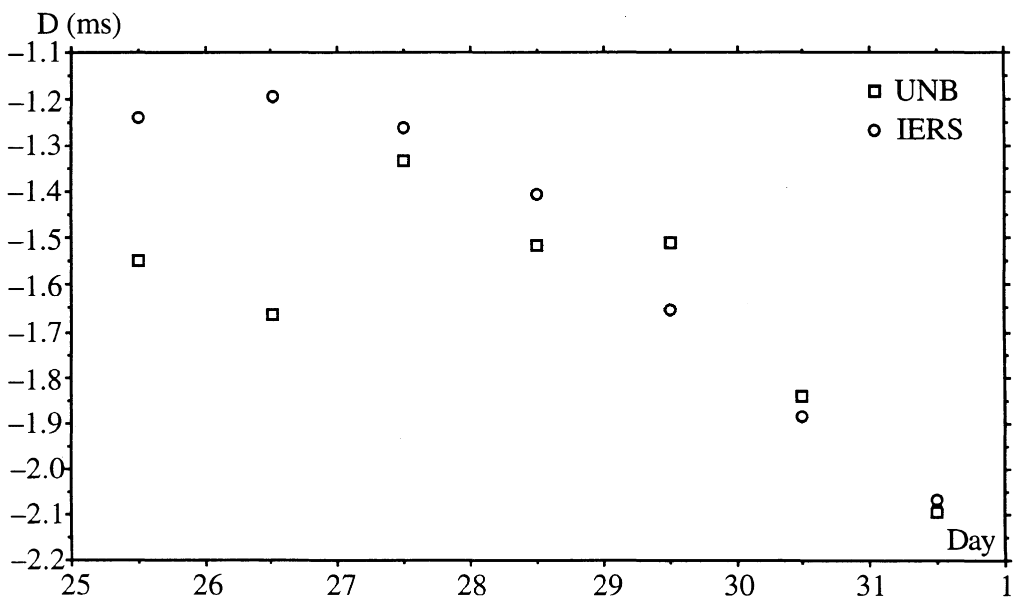

Figure 8.13 Daily solutions of D from July 25 to 31 for strategy-2

8.3.3 Earth Rotation Parameter Values from for Strategy-3

Tables 8.9 and 8.10 list the solutions for strategy-3. The standard deviations are less than 0.17 mas, and their mean biases with respect to the IERS values are $\Delta\bar{x}_p$ = 1.87 mas, $\Delta\bar{y}_p$ = 2.98 mas and $\Delta\bar{D}$ = 0.168 ms as obtained from the daily solutions of the ERPs; and $\Delta\bar{x}_p$ = 2.83 mas, $\Delta\bar{y}_p$ = 5.33 mas and $\Delta\bar{D}$ = 0.087 ms from a seven-day solution of the ERPs.

From Table 8.9 for the daily solutions, there appear to be present some systematic biases with respect to the IERS values for the polar motion components. From Table 8.10 for the seven-day solution, the maximum bias with respect to the IERS value for the polar motion is about 11 mas for component y_p of day 26, and the biases of the polar motion components with respect to the IERS values are irregular. It is obvious that the ERP are recovered with a better accuracy than those in the seven-day solution. Figures 8.14, 8.15, 8.16, 8.17, 8.18, and 8.19 are plotted on Tables 8.9 and 8.10.

Table 8.9 Daily solutions of the ERP for strategy-3

MJD	x_p	Δx_p	m_x	y_p	Δy_p	m_y	D	ΔD	m_D
	0.1 mas	0.1 mas	0.1 mas	0.1 mas	0.1 mas	0.1 mas	ms	ms	ms
48828.5	–0991.3	39.3	0.8	4326.0	1.7	1.7	–1.530	–0.294	0.013
48829.5	–0996.2	14.9	0.8	4379.0	36.5	1.4	–1.621	–0.425	0.012
48830.5	–0977.1	14.5	0.8	4401.5	40.8	1.2	–1.497	–0.237	0.010
48831.5	–0949.5	22.8	0.8	4422.1	42.7	1.4	–1.488	–0.083	0.011
48832.5	–0935.9	16.8	0.8	4407.6	8.7	1.3	–1.587	0.064	0.012
48833.5	–0920.4	12.6	0.8	4456.8	37.3	1.5	–1.839	0.046	0.012
48834.5	–0903.0	10.1	0.8	4482.2	40.9	1.3	–2.092	–0.024	0.011

Table 8.10 A seven-day solution of the ERP for strategy-3

MJD	x_p	Δx_p	m_x	y_p	Δy_p	m_y	D	ΔD	m_D
	0.1 mas	0.1 mas	0.1 mas	0.1 mas	0.1 mas	0.1 mas	ms	ms	ms
48828.5	–1001.4	29.2	1.1	4348.7	24.4	1.3	–1.323	–0.087	0.018
48829.5	–1021.1	–10.0	1.0	4449.3	106.8	1.3	–1.206	–0.010	0.008
48830.5	–0998.3	–6.7	1.0	4392.8	32.1	1.3	–1.339	–0.079	0.005
48831.5	–0947.2	25.0	1.0	4357.3	–22.1	1.5	–1.551	–0.146	0.004
48832.5	–0899.7	53.0	1.0	4329.0	–69.9	1.4	–1.783	–0.132	0.003
48833.5	–0897.9	35.1	1.0	4362.3	–57.2	1.4	–1.990	–0.105	0.002
48834.5	–0952.0	–38.9	1.0	4502.2	60.9	1.4	–2.119	–0.050	0.002

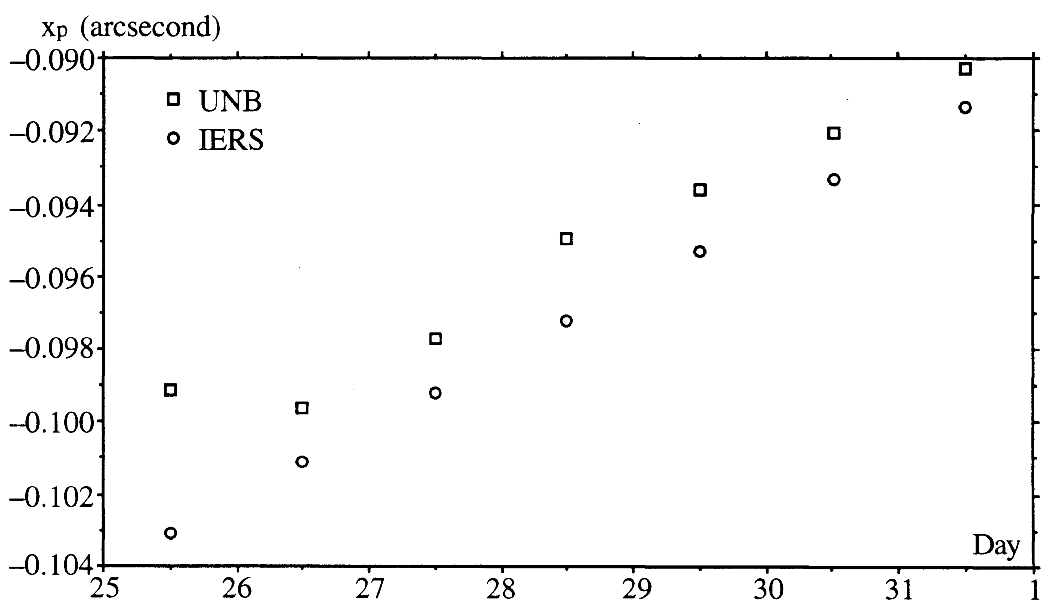

Figure 8.14 Daily solutions of x_p from July 25 to 31 for strategy-3

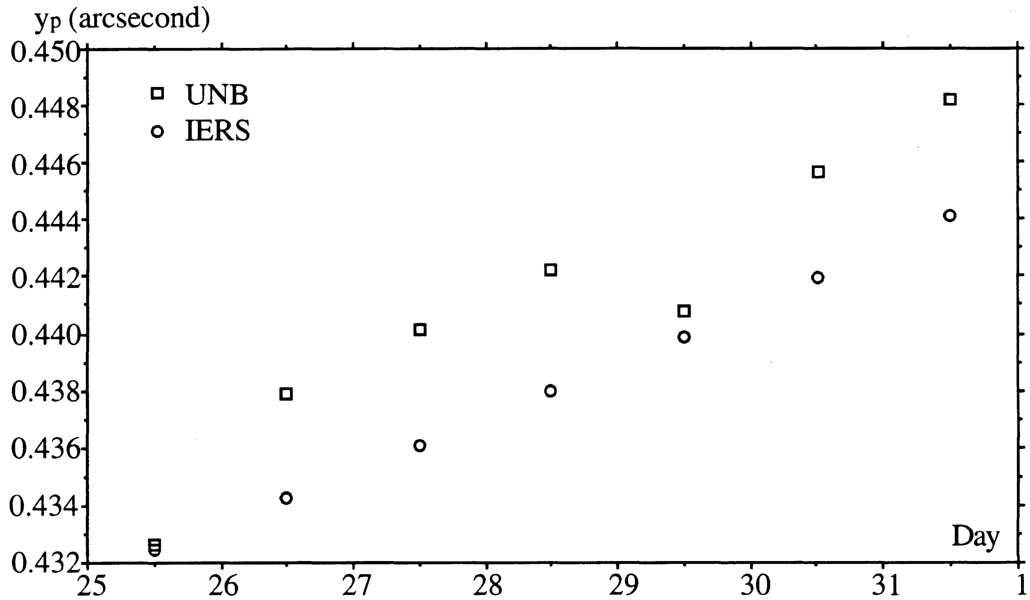

Figure 8.15 Daily solutions of y_p from July 25 to 31 for strategy-3

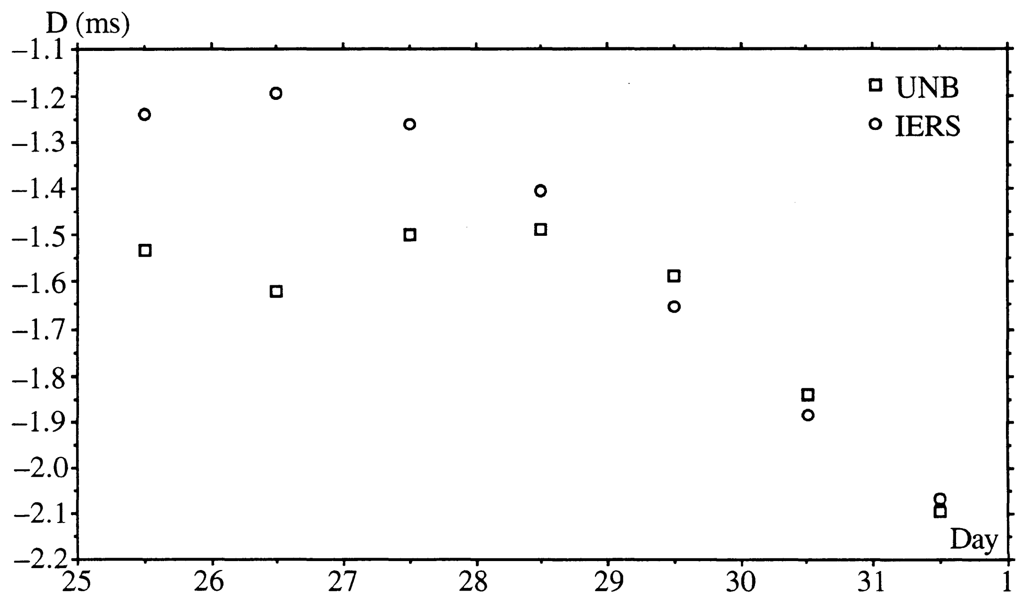

Figure 8.16 Daily solutions of D from July 25 to 31 for strategy-3

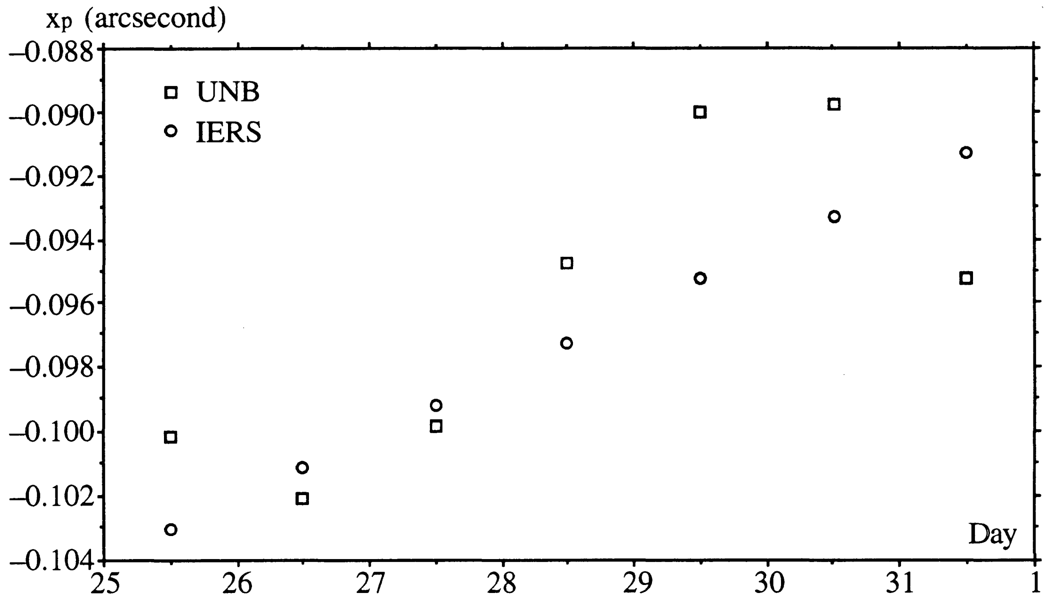

Figure 8.17 Seven-day solution of x_p from July 25 to 31 for strategy-3

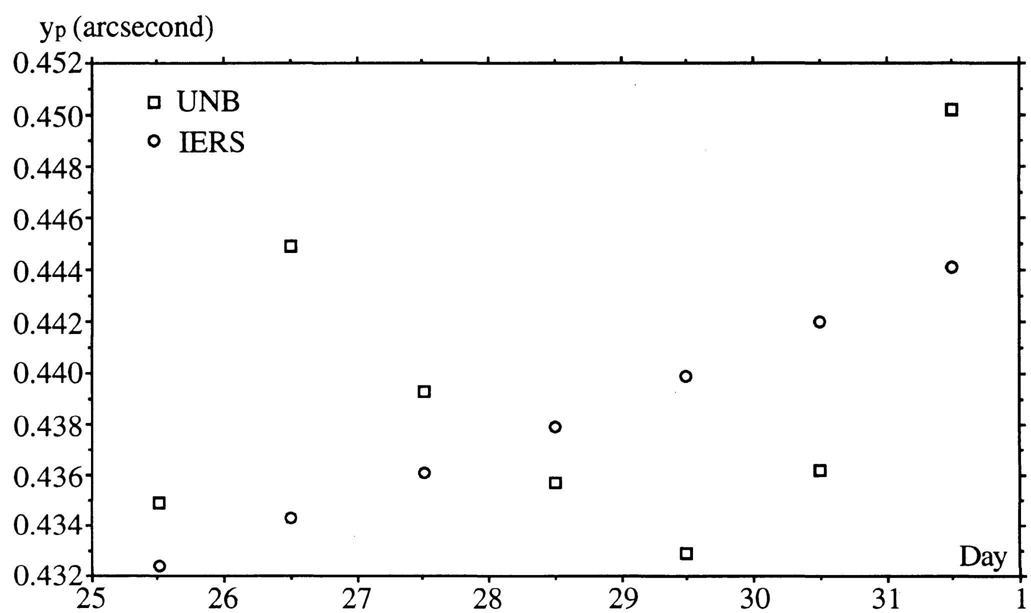

Figure 8.18 Seven-day solution of y_p from July 25 to 31 for strategy-3

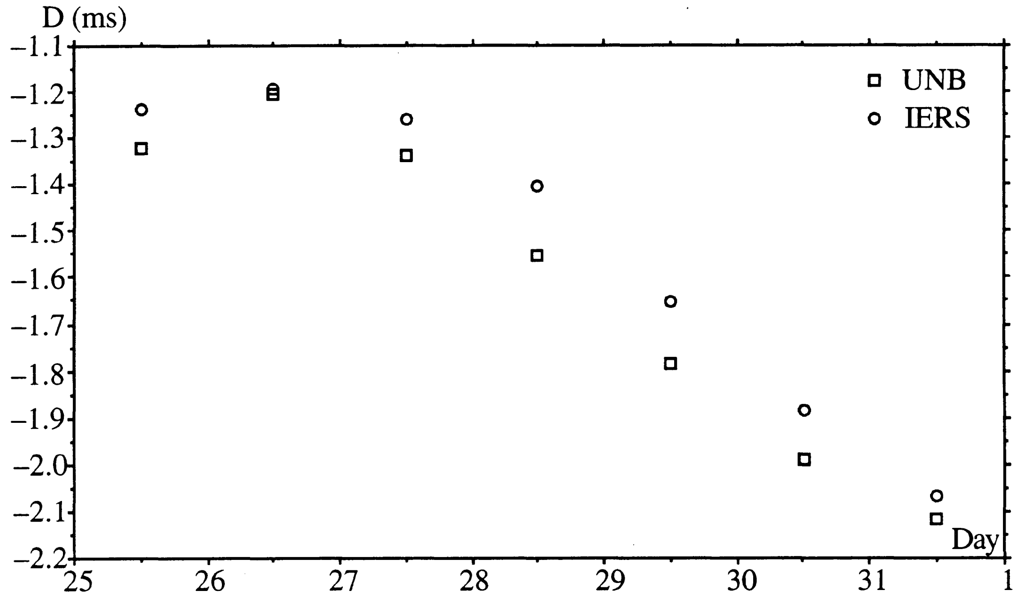

Figure 8.19 Seven-day solution of D from July 25 to 31 for strategy-3

8.4 Analysis Results: GPS Satellite Orbits

Two samples of the satellite orbit results, i.e. a seven-day solution and a daily solution (July 25) for strategy-3 have been selected and are presented in Appendix VIII and Appendix IX respectively. The GPS satellite orbital parameters include six a posteriori initial Keplerian elements, i.e. semi-major axis a, inclination i, eccentricity e, argument of perigee ω, right ascension of the ascending node Ω, reference epoch T_0 for the satellite initial orbital elements, and two solar radiation parameters: i.e. the direct radiation pressure parameter p_D and the Y-direction radiation pressure parameter p_Y. All of them are referenced to GPS time: GPS week 654 and 518400.0 GPS seconds, i.e the beginning of the first day of data set. The standard deviations of the satellite orbits are at about the decimetre level. Compared our precise orbit results at a rate of 30 seconds with those from other groups and broadcast orbits [Li and Langley, 1993], it demonstrated that the precise

GPS satellite orbits with a mean precision of less than one metre were provided by our software, and that the mean differences between the precise and broadcast orbits appeared to be less than five metres.

8.5 Analysis Results: Tropospheric Parameters and Ambiguities

The tropospheric parameters were estimated for each station for each day. The meteorological data sets observed at the GPS stations were not used in the processing. Two samples of tropospheric parameter solutions are listed in Table 8.11 and in Appendix IX; one sample of the ambiguity solution is also listed in Appendix IX. The a priori zenith delay was computed from default meteorological data using the Hopfield model: pressure =1000 (millibars), temperature =0 (centigrade degree), relative humidity =50 (%).

Table 8.11 One sample of a seven-day solution of the tropospheric scale corrections & zenith delay corrections for 25 July from strategy-3
(Hopfield default data : pressure = 1000 mb, temp. = 0° C, relative humidity = 50 %)

Code	Scale	r.m.s.	Zenith delay correction	r.m.s.
			mm	mm
AL	0.0547	0.000	126	1
FA	0.0734	0.001	169	1
HA	0.0642	0.001	148	2
HE	0.0554	0.001	128	2
KK	0.0916	0.001	211	1
KO	0.0748	0.001	173	1
MA	0.0770	0.001	178	1
ME	0.0541	0.001	125	1
MP	0.0433	0.001	100	2

ON	0.0596	0.001	137	2
PA	0.1476	0.001	341	2
PE	0.0899	0.001	208	1
PI	0.0590	0.001	136	1
SA	0.0109	0.002	25	3
ST	0.0666	0.001	154	1
TR	0.0805	0.001	186	1
TW	0.1001	0.002	231	4
WT	0.0980	0.001	226	1
YA	0.0629	0.001	145	2
YE	0.0396	0.001	91	1

CHAPTER 9
CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

It has been theoretically and practically demonstrated that the Earth rotation parameters can be recovered via the GPS technique, based on the double difference algorithm. The software DIPOP.ERP which was developed was useful for processing daily global GPS data sets and estimating daily-values of the Earth rotation parameters. From the results of experimentation with the software and the GPS data sets provided by IGS'92 campaign from July 25 to 31, it is indicated that the recovered Earth rotation parameters have an uncertainty of about a few tenths of a milli-arcsecond and a bias of a few milli-arcseconds with respect to the IERS values.

After the global network adjustment, the daily repeatabilities from a few centimetres to ten centimetres for most global station coordinates were reached. Most baselines ranging from a few hundred kilometres to 8426 km (average baseline length is about 2800 km) have their standard deviations within about ten millimetres. The average daily repeatabilities obtained were 21 p.p.b. , 16 p.p.b. , 14 p.p.b. , and 19 p.p.b. from solutions for strategy-1, strategy-2, strategy-3, and strategy-4 respectively.

From results presented in Chapter 8, it is obvious that a daily solution for stategy-3 is better than the others in the estimation of the Earth rotation parameters and the adjustment of the geodetic network, because its r.m.s. is smaller than the others, and it provides relatively stable Earth rotation parameters. From the results for strategy-2, it is clear that the r.m.s. is increased if many stations are considered fixed, because the coordinates of some fixed stations still are not good enough. If a few stations were considered fixed, the global

9.2 Recommendations

Global geodynamical studies need elaborates and painstaking work in planning, design, construction and implementation in both theory and practice. Software development is one such important activity linked with theory and practice. Even though the present software DIPOP.ERP has the functions for adjusting the global geodetic network, improving satellite orbits, and estimating the Earth rotation parameters, there is still a lot of theoretical and practical work to be undertaken in order to come up with developments at the frontier of research involving novel applications of the GPS technique, especially for studies of the long-term geodynamical phenomena. In the following paragraphs some constructive suggestions are made:

(1) Firstly, it is essential to implement precise orbit determination. This is critical for stably estimating the Earth rotation parameters with high resolution and precision, for geodetic network adjustment, and estimation of other parameters. Without the precise orbits associated with complete force models with sufficient accuracies, geodynamical phenomena cannot be explained precisely nor related-parameters recovered properly. Some parts of the force models adopted from DIPOP-E need to be carefully and thoroughly tested for accuracy and completeness. From the results of externally examining the force modelling by using SIO precise orbits, there appears to be some unknown problem with the orbital improvement in DIPOP-ERP. Concerning the models related to the satellite orbit, a comparison needs to be made with the standard models described in the IERS standards (1992) [McCarthy, 1992]. Presently missing from DIPOP-ERP, for instance, are perturbations coming from ocean and atmospheric tides, polar motion deformation, and various relativistic effects. Also, different models are recommended, such as the GEM-T1 gravitational potential model; the planetary and lunar ephemerides, i.e. the JPL Development Ephemeris DE200 and the Lunar Ephemeris LE200.

(2) The choice of "observable" is also important for the software. Although the double difference algorithm currently implemented in the software has its advantages for removing some unknown and known biases, such as clock biases of the satellites and stations, and part of the orbital errors, some disadvantages are still introduced. For instance, some information such as details of clock biases is lost. Also data sets are not fully used unless there are simultaneous observations for two stations and two satellites. It is recommended that an undifferenced algorithm be implemented for comparison.

(3) With sufficiently precise orbits, the geodetic and geodynamical parameters may be recovered at intervals of less than one day. It should be possible, for instance, to estimate hourly Earth rotation parameters, tropospheric scale or vertical delay corrections for each station, and solar radiation pressure parameters. In this way, the biases and errors can be properly treated and removed from observations, and the resolution of the Earth rotation parameters and the precision of the global geodetic network can be increased.

(4) The models related to the troposphere and ionosphere, as well as orbital force models, e.g. solar radiation model still have to be further developed, and the parameter estimation process should be implemented by using various independent combinations of GPS observations. The pseudorange observables have to be optionally added into the observation equations and software.

(5) Even though the preprocessor PREDD.ERP has a function to detect and fix cycle slips in an automated way at a 90% reliability level or better by using various combinations, there is still a lot of work left to perfect it further.

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APPENDIX I

A SAMPLE OF COMMAND FILES FOR PREDD.ERP

(FOR STATIONS ALGONQUIN AND ST. JOHN'S)

```
****************** COMMAND FILE FOR PREDD.ERP ********************
*          a file name should be less than 45 in length              *
*              INFORMATION COMMON FOR ALL THE SESSION                *
*----+----1----+----2----+----3----+----4----+----5----+----6----+----7-
/T1212X.PREDD.DBG.IGS.JULY25(ALST2071)
N                              !USE INITIAL CONDITION AS ORBIT? Y/N
/T1212X.DIPOP.ERP.CMD.ORBIT.CIGNET.JULY25
1                                                  !NGSYN(0 OR 1)?
1992    7   25
/T1212X.GPS654.SIO.ORBIT.JULY25
300.0D0                                            ! GAP(SECOND)
600.0D0                                            ! CON(SECOND)
30.0D0                         !(DELOBS)SAMPLING INTERVAL(SECOND)
4                              !(IDEGC) CHEBY. POLYNOMIAL DEGREE FOR CYCLE SLIP DETERM.
10                             !(NDND)NUMBER POINTS FOR FITTING FOR DETECTING CYCLE SLIP.
11          !(NBOBS=NDND+1 FITTING POINT NO. FOR BEGINNING CS. DETECTING(SEE SUB WRTOBS)
4.0D0       !(CVC2=4 FOR USUAL CASE SEE SUB.DTBCSP) FOR DETECTING BEGINNING CYCLE SLIP.
Y                              !(FCSLIP)WETHER OR NOT FIXING CYCLE SLIP.
10.0D0                         !(FOR CUT OFF H IN SUB. CUTOFH)
1                              !(ICSLP0)TIMES OF CRITERION.
   CCSPS(I,1)   CCSPS(I,2)   CCSPS(I,3)   CCSPS(I,4)   CCSPS(I,5)   (I=1 FOR OBS;I=2 FOR DOBS)
      0            0           2.6           0            0
      0            0           0             2.6          0.9
65                                                 ! DEBUG LEVEL (7)
```

```
........................................................................
(-           ! Line for separation
C Orbital session 1: The beginning and the ending time of the window
654   518400.00   654   604800.00
/T1212X.GLOBL207.ORB
1       ! CONVERT OBSERVATIONS FROM RECEIVER TO GPS TIME TAG ?
0      ! USE INTEGRATED ORBIT FOR DAT PROCESSING   ?
CC     ! BROADCAST EPHEMERIS FORMAT     ?
0      ! OUTPUT THE IMPROVED EPHEMERIS TO OBSERVATION FILES ?
25     ! DAY NUMBER
********  STATION COORDINATE & PREGE OUTPUT FILE   ***********
01 AL  C        918129.6280   -4346071.2180    4561977.7810
/T1212X.PREGE.CIGNET.OUT.JULY25(ALGO2071)
02 ST  C       2612665.7011   -3426797.2816    4686763.7265
/T1212X.PREGE.CIGNET.OUT.JULY25(STJO2071)
-1
********  INFORMATION RELATED TO A PARTICULAR BASELINE   ***********

AL   ST   1
/T1212X.PREDD.CIGNET.OUT(ALST2071)
20000        ! MAXIMUM NUMBER OF SINGLE DIFFERENCES (100 - 5000)
50           ! DEBUGGING LEVEL  (0 - 100)
N            ! RELATIVE COORDINATE IMPROVEMENT (Y/N)
2            ! NUMBER OF FREQUENCIES ( 1 OR 2 )
2            ! RECEIVER MODEL (1 = WM101 OR TRIMBLE,2 = TI4100)
10           ! CYCLE SLIP DETECTION THRESHOLD (CM.)
```

APPENDIX II

A SAMPLE OF COMMAND FILES FOR DIPOP.ERP

(FOR JULY 25)

```
*
*   |||||||||  CONTROL FILE FOR MAIN-PROCESSOR OF DIPOP.ERP  ||||||||
*
* Syntax for inputs:
* 1. all the lines beginning with the character '*' or "#" are the
*    comment lines and they are skipped in processing the file.
* Don't start a line beginning with '*' or '#', if it isn't a comment.
* 2. a comment line (as described above) can be added anywhere in
*    the control file except in the input area for the
*    observation files
* 3.a input line will begin with:'==>',or'n ==>',or without any special
*    sign, where n means that this line corresponds
*    to the preceding comment with the same number 'n'.
* 4. the characters following '!' (including '!') in a input line
*    function as comments and are ignored.
* 5. lines beginning with '=======',  '-------', '++++++++', are
*    title lines or separation lines for different input areas (or
*    blocks) and can not be changed arbitrarily
* 6. the maximum number of characters in an input line is 200.
* 7. DIPOP.ERP command file cannot be used for DIPOP's command file,
*    (of any version) and vice versa.
*------------------------------------------------------------------
*
VERSION                               : 3.00
DEBUG LEVEL                           : 60
*
* ========= PART 1. FILE NAMES CREATED IN THE PROCEDURE (A64) =========
#1. MAIN-PROCESSOR ERROR, DEBUG, AND SUM               FILE NAME ?
#2. FINAL OUTPUT                                       FILE NAME ?
#3. RESIDUAL                                           FILE NAME ?
#4. DISCREPANCY                                        FILE NAME ?
#5. FINAL SOLUTION & COV. FOR NEXT RUNNING,            FILE NAME ?
*   NOT IMPLEMENTED
#6. FIRST  TEMPORARY                                   FILE NAME ?
#7. SECOND TEMPORARY                                   FILE NAME ?
#8. THIRD  TEMPORARY                                   FILE NAME ?
#9. FORTH  TEMPORARY                                   FILE NAME ?
#10 FIFTH  TEMPORARY                                   FILE NAME ?
*
* Caution: you should give different names for these
* intermediate files
*---------------------------------------------------------------------
1 ==> /T1212X.DIPOP.ERP.OUT.DEBUG
2 ==> /T1212X.DIPOP.ERP.OUT.JULY25(stra3)
3 ==> /T1212X.DIPOP.ERP.OUT.TEST
4 ==> /T1212X.DIPOP.ERP.OUT.DIS
5 ==> /T1212X.DIPOP.ERP.OUT.FIN
6 ==> /T1212X.DIPOP.ERP.OUT.TRO
```

```
7 ==> /T1212X.DIPOP.ERP.OUT.NUI
8 ==> /T1212X.DIPOP.ERP.OUT.TEMP3
9 ==> /T1212X.DIPOP.ERP.OUT.TEMP4
10==> /T1212X.DIPOP.ERP.OUT.TEMP5
*
* ========= PART 2.  CONTROL FOR THE ADJUSTMENT ===========
#1. NUMBER OF THE ITERATION IN THE FINAL ADJUSTMENTS                 ?
*   THE ABOVE HAVEN'T BEEN FULLY TESTED YET, SPECIFY      1
#2. ITERATION CONTROL: USE VALUE '-1' AT THE MOMENT
#3. ORBITAL IMPROVEMENT(Y/N)                                           ?
#4. COMMAND FILE FOR ORBITAL INFORMATION                               ?
#5. CONSIDER DOUBLE DIFF. CORRELATION Y(1) (0 AT THE MOMENT)           ?
#6. COMPUTE RESIDUALS: 1 (YES) ? 2 (DEFAULT RESIDUAL FILE NAME)        ?
#7. STATION COORDINATES SEQ. SOLUTION at EACH m EPOCH                  ?
#8. CROSS-CORRELATION VALUE OF COMPARISON                              ?
#9. CUT OFF ELEVATION ANGLE (IN DEGREES)                               ?
#10 DEFAULT MSL METEOROLOGICAL VALUES P(MB), T(C), RH(%)               ?
#11 ESTIMATE THE TROPOSPHERE SCALE AND ITS A PRIORI STD DEVIATION      ?
#12 ESTIMATE EARTH ROTATION PARAMETERS (1: XP; 2: YP; 3: D; 4: DT) ?
#12 ( 3  STD(XP)=0.1";  STD(YP)=0.1";  STD(D)=0.5MS/DAY)
#13.VERTICAL TIDAL CORRECTION Y/N(1/0) AND THE FIRST LOVE'S NUMBER     ?
#14.RESTORE PERMANENT TIDE Y/N(1/0)                                    ?
*---------------------------------------------------------------------
1 ==> 1
2 ==> -1
3 ==> Y
4 ==> /T1212X.DIPOP.ERP.CMD.ORBIT.IGS.JULY25
5 ==> 0
6 ==> 2
7 ==> 999
8 ==> .999
9 ==> 10.0D0
10==> 1000.00  00.00  50.00
11==> 1    0.80
12==> 3    0.1    0.1     0.5
13==> 1    0.62
14==> 1
*====== PART 3. A-PRIORI STATION COORDINATES AND STD. DEVIATION (M) ====
#1. COORDINATES ?
* FROM THIS FILE(1 OR 2). 1: FOR CART COOR.  2: FOR GEOD. COOR.
* FROM PREVIOUS SOLUTION(3) (NOT IMPLEMENTED YET)
==> 1
#2. IF 3 IS SPECIFIED IN THE ABOVE LINE: PLEASE INSERT FILE NAME AFTER
*THIS COMMENT (NOT BEGINNING WITH ==>DELETE ALL INPUTS CORRESPONDING TO
*   COMMENT #3 AND COMMENT #4
#3. REFERENCE ELLIPSOID IN ORDER OF: SEMI-MAJOR, INVERSE OF FLAT,
*   X Y Z -SHIFT (FREE FORMAT)
* ELLIPSOID IS ONE USED IN CONVERSION FROM (OR TO) CARTESIAN COORDINATE
*   X Y Z ARE SHIFT BETWEEN STATION COORDINATE SYSTEM AND EPHEMERIS
*   COORDINATE SYSTEM
    6378137.0   298.257223563    0.000      0.000      0.000
*
#4. IF 1 OR 2 IN #1, INPUT THE COORDINATES EXACTLY AS FORMAT
*   DESCRIBED AND THE LINE FOLLOWING EACH STATION COORDINATES ARE
*   CORRESPONDING STD DEVIATION
*   SYMBOL "##": SEQUENCE OF THE STATION; "NN": STATION NAME
*   CORRESPONDING TO THOSE IN THE OBSERVATION FILE
```

```
*
## C. FORMAT:XXXXXXX.XXXX    YYYYYYY.YYYY     ZZZZZZZ.ZZZZ
01 AB        -2341332.9510   -3539049.6700     4745791.5790
                1.0D+02         1.0D+02          1.0D+02
02 AL          918129.6160   -4346071.2240     4561977.8000
                1.0d-05         1.0d-05          1.0d-05
03 FA        -2281621.3270   -1453595.7750     5756961.9760
                1.0d-05         1.0d-05          1.0d-05
04 GO        -2353614.0640   -4641385.3830     3676976.4950
                1.0D+02         1.0D+02          1.0D+02
05 GR         4194424.0960    1162702.4560     4647245.2890
                1.0D+02         1.0D+02          1.0D+02
06 HA         5084625.4040    2670366.4990    -2768494.0390
                1.0d-05         1.0d-05          1.0d-05
07 HE         4033470.603       23672.6920    4924301.3600
                1.0D+02         1.0D+02          1.0D+02
08 JP        -2493304.0480     -4655215.6140     3565497.3590
                1.0D+02         1.0D+02          1.0D+02
09 KK        -5543838.0800   -2054587.5220     2387809.5700
                1.0d-05         1.0d-05          1.0d-05
10 KO         3899225.3470     396731.7590     5015078.2960
                1.0d-05         1.0d-05          1.0d-05
11 MA         4641949.814     1393045.203      4133287.266
                1.0d-05         1.0d-05          1.0d-05
12 MC        -1310696.5250     310468.8620    -6213368.4750
                1.0D+02         1.0D+02          1.0D+02
13 MD         4849202.5020    -360329.1790     4114913.0030
                1.0d-05         1.0d-05          1.0d-05
14 ME         2892561.7890    1311839.2840     5512616.2880
                1.0D+02         1.0D+02          1.0D+02
15 MP         5439189.1160   -1522054.9210     2953464.0530
                1.0D+02         1.0D+02          1.0D+02
16 NY         1202430.7490     252626.6550     6237767.5900
                1.0D+02         1.0D+02          1.0D+02
17 ON         3370658.7570     711876.9890     5349786.8120
                1.0d-05         1.0d-05          1.0d-05
18 PA        -5245194.6200   -3080472.2270    -1912825.4890
                1.0D+02         1.0D+02          1.0D+02
19 PE        -2059164.6070   -3621108.4200     4814432.4630
                1.0D+02         1.0D+02          1.0D+02
20 PI        -2369510.3700   -4761207.2370     3511396.0790
                1.0D+02         1.0D+02          1.0D+02
21 SA         1769693.0870   -5044574.2870    -3468321.0350
                1.0D+02         1.0D+02          1.0D+02
22 ST         2612631.4110   -3426806.9970     4686757.7810
                1.0D+02         1.0D+02          1.0D+02
23 TI        -4460996.1530    2682557.2810    -3674444.1340
                1.0D+02         1.0D+02          1.0D+02
24 TR         2102940.4510     721569.3790     5958192.0720
                1.0d-05         1.0d-05          1.0d-05
25 TW        -3024781.7620     4928936.9570    2681234.4530
                1.0D+02         1.0D+02          1.0D+02
26 US        -3855262.5810    3427432.4160     3741020.8230
                1.0D+02         1.0D+02          1.0D+02
27 WT         4075578.6830     931852.6340     4801569.9800
                1.0D+02         1.0D+02          1.0D+02
28 YA        -2389025.3310    5043316.8300    -3078530.9260
```

```
               1.0d-05            1.0d-05            1.0d-05
29 YE       -1224452.3690   -2689216.0480    5633638.2860
               1.0d-05            1.0d-05            1.0d-05
-1
## G. FORMAT:DD MM SS.SSSSSS DDD MM SS.SSSSSS HHH.HHHHH
*01 HE          50 52  2.230       0 20 11.84       99.3302
*                 1.0D-08           1.0D-08           1.0D-08
*02 AL          45 57 21.930     281 55 41.61      158.6565
*                 1.0D+02           1.0D+02           1.0D+02
*03 D1          35 25 33.23      243 06 37.68     1003.2287
*                 1.0D+02           1.0D+02           1.0D+02
*04 D4         -35 24  8.05      148 58 48.13      699.6805
*                 1.0D+02           1.0D+02           1.0D+02
*05 D6          40 25 52.34      355 45  7.15      866.4561
*                 1.0D+02           1.0D+02           1.0D+02
*06 FA          64 58 41.060     212 30  2.94      353.7733
*                 1.0D+02           1.0D+02           1.0D+02
*07 HA         -25 53 13.560      27 42 29.01     1582.1404
*                 1.0D+02           1.0D+02           1.0D+02
*08 KK          22 07 34.700     200 20  7.47     1318.2113
*                 1.0D+02           1.0D+02           1.0D+02
*09 KO          52 10 42.35000     5 48 35.65000  120.5918
*                 1.0D+02           1.0D+02           1.0D+02
*10 MA          40 38 56.820      16 42 17.07      554.1366
*                 1.0D+02           1.0D+02           1.0D+02
*11 ON          57 23 43.090      11 55 33.00       68.5542
*                 1.0D+02           1.0D+02           1.0D+02
*12 PE          49 19 21.480     240 22 30.70      540.9577
*                 1.0D+02           1.0D+02           1.0D+02
*13 PI          33 36 43.430     243 32 30.70     1234.6282
*                 1.0D+02           1.0D+02           1.0D+02
*14 TH         -17 34  0.620     210 25 33.10      374.2129
*                 1.0D+02           1.0D+02           1.0D+02
*15 TR          69 39 45.930      18 56 18.90      158.9137
*                 1.0D+02           1.0D+02           1.0D+02
*16 US          36 07 55.440     138 21 51.30     1553.1783
*                 1.0D+02           1.0D+02           1.0D+02
*17 WT          49 08 39.15000 -167 07 14.90000  665.1487
*                 1.0D+02           1.0D+02           1.0D+02
*18 YA         -29 02 47.690     115 20 52.20      321.9808
*                 1.0D+02           1.0D+02           1.0D+02
*19 YE          62 28 51.180     245 31 11.00      203.9825
*                 1.0D+02           1.0D+02           1.0D+02
*20 ME          60 13  4.12       24 23 42.18      159.1214
*                 1.0D+02           1.0D+02           1.0D+02
#############  LATITUDE  ####  LONGITUDE  ###  HEIGHT  #####
*
*==========     PART 4. OBSERVATION FILE INFORMATION    ===============
#0.  OBS. FILES, BINARY(0) OR ASCII(1)  ?
*    ONLY 1 CAN BE SPECIFIED AT THE MOMENT.
==> 1
*    ENTER (ANSWER) THE FOLLOWING LINES FOR THE OBSERVATION DATA
*
*    AT THE BEGINNING OF A NEW WINDOW, ENTER FOLLOWING TWO LINES
#1.  A BLANK LINE FOR DELIMITER
#2.  COMMENT LINE BEGINNING WITH '*'
#3.  THE TIME INTERVAL OF THE OBSERVATION WINDOW:
```

```
*    GPS WEEK AND THE TIME AT THE BEGINNING OF THE WINDOW,
*    GPS WEEK AND THE TIME AT THE ENDING OF THE WINDOW.
*    Free FORMAT is used.
*
#4.  Station name & its corresponding meteorological and antenna height
*    file name for the observation window (A64). Station name & its
*    corresponding meteorological and antenna height file name are
*    separated by one space.  Input for other stations are made
* similarly; one line for each station.All the stations which appear in
*    the observation files of the window should be input.  A station
*    name should be consistent with the station name in its met. and
*    observation files.
*
#5.  A blank line for separation.
#6.  Obs. & sat. position file name (A64)
#7.  A-priori std. deviation of double difference obs. (mm) (*)
#8.  Clock parameters.(st.2 wrt st.1) and respective std. dev. (sec) (*)
*    This option has not been implemented yet.
#9.  L1:1, L2:2, L1 & L2:3; estimate amb.? Y(1); residual computation
*    for this observation file Y(1).
*
#10. Repeat steps 4 through 9 for observation files in the same block.
*
*    The following two lines (#11 and #12) mark the beginning of a
*    new block.
#11. Following the last input of the observation file in the previous
*    block, enter a blank line.
#12. Enter a line beginning with "(-".
#13. Similar to the inputs of steps 4 through 12, inputs for a new block
#14. Repeat step 1 to 13 for new windows
*
*Notice:  don't input "(-" and the end of the last block.
*
*--------------------------------------------------------

* window for day 25: start and the stop time
654   5.184D5  654   6.048D5
AB /T1212X.CIGNET.MET.JULY(AB25)
AL /T1212X.CIGNET.MET.JULY(AL25)
FA /T1212X.CIGNET.MET.JULY(FA25)
GO /T1212X.CIGNET.MET.JULY(GO25)
GR /T1212X.CIGNET.MET.JULY(GR25)
HA /T1212X.CIGNET.MET.JULY(HA25)
HE /T1212X.CIGNET.MET.JULY(HE25)
JP /T1212X.CIGNET.MET.JULY(JP25)
KK /T1212X.CIGNET.MET.JULY(KK25)
KO /T1212X.CIGNET.MET.JULY(KO25)
MA /T1212X.CIGNET.MET.JULY(MA25)
MC /T1212X.CIGNET.MET.JULY(MC25)
MD /T1212X.CIGNET.MET.JULY(MD25)
ME /T1212X.CIGNET.MET.JULY(ME25)
MP /T1212X.CIGNET.MET.JULY(MP25)
NY /T1212X.CIGNET.MET.JULY(NY25)
ON /T1212X.CIGNET.MET.JULY(ON25)
PA /T1212X.CIGNET.MET.JULY(PA25)
PE /T1212X.CIGNET.MET.JULY(PE25)
PI /T1212X.CIGNET.MET.JULY(PI25)
```

```
SA /T1212X.CIGNET.MET.JULY(SA25)
ST /T1212X.CIGNET.MET.JULY(ST25)
TI /T1212X.CIGNET.MET.JULY(TI25)
TR /T1212X.CIGNET.MET.JULY(TR25)
TW /T1212X.CIGNET.MET.JULY(TW25)
US /T1212X.CIGNET.MET.JULY(US25)
WT /T1212X.CIGNET.MET.JULY(WT25)
YA /T1212X.CIGNET.MET.JULY(YA25)
YE /T1212X.CIGNET.MET.JULY(YE25)

/T1212X.PREDD.CIGNET.OUT.JULY25(ALST2071)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(FAKK2071)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(HASA2071)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(HASAGP2)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(HASAGP4)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(HEKO2071)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(HEKOGP2)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(HEKOGP3)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(HEKOGP4)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(HEKOGP5)
 15
```

```
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(HEKOGP6)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(HEKOGP7)
 15
0   1.0D-06   1.0D-06
3  1  0

(-

/T1212X.PREDD.CIGNET.OUT.JULY25(HEKOGP8)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(HEKOGP9)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(HEKOGP10)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(HEKOGP11)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(HEKOGP12)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(KKPA2071)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(KKPAGP2)
 15
0   1.0D-06   1.0D-06
3  1  0

(-

/T1212X.PREDD.CIGNET.OUT.JULY25(KKPAGP3)
 15
0   1.0D-06   1.0D-06
3  1  0
```

```
/T1212X.PREDD.CIGNET.OUT.JULY25(KOON2071)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(KOONGP2)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(MAHA2071)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(MAHAGP4)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(MAHAGP7)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(MAHAGP9)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(MAHAGP10)
 15
0   1.0D-06   1.0D-06
3  1  0

(-

/T1212X.PREDD.CIGNET.OUT.JULY25(MAMP2071)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(MAWT2071)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(MAWTGP2)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(MAWTGP3)
 15
0   1.0D-06   1.0D-06
3  1  0
```

```
/T1212X.PREDD.CIGNET.OUT.JULY25(MAWTGP4)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(ONME2071)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(ONMEGP3)
 15
0   1.0D-06   1.0D-06
3  1  0

(-

/T1212X.PREDD.CIGNET.OUT.JULY25(PEAL2071)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(PEPI2071)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(ALYE2071)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(PIKK2071)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(SAPAGP2)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(SAPAGP3)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(SAPAGP4)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(SAPAGP6)
 15
0   1.0D-06   1.0D-06
3  1  0
```

```
/T1212X.PREDD.CIGNET.OUT.JULY25(SAPAGP7)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(SAPAGP8)
 15
0   1.0D-06   1.0D-06
3  1  0

(-

/T1212X.PREDD.CIGNET.OUT.JULY25(SAPAGP9)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(SAPAGP10)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(SAPAGP11)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(TRME2071)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(TWYA2071)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(TWYAGP4)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(TWYAGP5)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(TWYAGP8)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(TWYAGP9)
 15
0   1.0D-06   1.0D-06
3  1  0
```

```
/T1212X.PREDD.CIGNET.OUT.JULY25(WTKO2071)
 15
0   1.0D-06   1.0D-06
3  1  0

(-

/T1212X.PREDD.CIGNET.OUT.JULY25(WTKOGP2)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(WTKOGP3)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(WTKOGP4)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(YAHAGP3)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(YAHAGP4)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(YAHAGP6)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(YAHAGP7)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(YAHAGP10)
 15
0   1.0D-06   1.0D-06
3  1  0

/T1212X.PREDD.CIGNET.OUT.JULY25(YAHAGP11)
 15
0   1.0D-06   1.0D-06
3  1  0
```

APPENDIX III

A SAMPLE OF ORBITAL COMMAND FILE FOR DIPOP.ERP

(FOR GPS WEEK 654 AND GPS SECOND 518400)

```
**                                                                  **
**   ******* ORBIT INTEGRATION AND IMPROVEMENT INFORMATION ******   **
**                                                                  **
* Notice: the rules of inputs are similar to the
*         command file for the adjustment
*    for the test just input as shown in the sample
*     command file.
* Orbit improvement with the ephemeris (1: yes; 0: no)     ?       *
==> 1
*
* ========= PART 1. FORCE MODELLING INFORMATION ===========
*
#1. File name for the gravity coef.(free format)                          ?
==> /T1212X.GEML2.GRAV.NOTIDE
#2. degree and order of the gravity field                                 ?
==> 8
#3. Gravity potential coefficients:  normalized yes(1)                    ?
==> 1
#4. Effect of the moon yes(1)                                             ?
==> 1
#5. Effect of the sun yes(1)                                              ?
==> 1
#6  Interval (in hours) to approximate the positions of the moon and the
*   sun for an observation window (SEE SUB. PMNSN)                        ?
==> 0.1D0
```

```
#7. Use TDT time for UT1 to call SR.s of moon and sun (in second)       ?
==> 1
#8. 0.0D0 for this input
*   (for test only) Off-set between time for SRs of the Moon and the Sun
*   and the time of TDT time (in seconds)                               ?
==> 0.0D0
#9. In the orbit improvement with observations, how many radiation parameters
*   are estimated -- 1:direct radiation. only; 2: both direct and y-bias;
*   0:none                                                              ?
==> 2
#10 In the orbit improvement with ephemeris, how many radiation parameters
*   are estimated -- 1:direct radiation. only; 2: both direct and y-bias;
*   0:none                                                              ?
==> 2
#11 1 for this input.
*   (for test only) include the Y-bias radiation in the force model     ?
==> 1
#12 The solid Earth tidal gravity ? Yes (1)                             ?
==> 1
#13 The second Love's number for the second and the third order tidal harmonics ?
*   the third order effect has not been implemented.
==> 0.29D0  0.14D0
#14 0 for this input.  (other value is only for test of program)
*   Include the secular variation for the partial (1 or 2, if 1 then
*   include the Earth's oblatness for the partials for the radiation
*   not fully implemented and tested yet.
==> 0
*
* ============== PART 2. SATELLITE INFORMATION  ================
*
#1. Initial epoch for integration: GPS week and time (IN SECONDS)      ?
*
*  Notice: at the moment, the time must be the same as the start time
*  of the first observation window as it is specified in the adjustment
*  control file
==> 654   5.184D5
```

```
#2  Initial conditions at the initial epoch                                   ?
*   the satellites can be in any order
*   Don't beginning with '==>' for this input
*PRN           a                      e                      i                  ascending node
*              w                      T0              direct radiation            y-bias
  2     0.265613693836D+08    0.108332498372D-01    0.958152542017D+00    0.830997372239D+00
       -0.290973217371D+01    0.501875507362D+06    0.957563244167D-07    0.863720048656D-09
  3     0.265579632700D+08    0.128454385833D-01    0.112236399159D+01    0.222383015048D+01
        0.249371167261D+01    0.522461186749D+06    0.814495487737D-07    0.276291795264D-09
 11     0.265620655852D+08    0.134281166285D-01    0.111343008883D+01    0.221274978754D+01
       -0.225303811949D+01    0.503795468008D+06    0.825590253810D-07   -0.941472379897D-09
 12     0.265581862887D+08    0.122737348473D-01    0.109600325048D+01    0.686150191336D-01
       -0.334985806727D+00    0.526992871545D+06    0.807781011734D-07   -0.364154436012D-08
 13     0.265595874145D+08    0.384984160289D-02    0.110908206283D+01    0.219546767120D+01
       -0.251595427412D+01    0.517188027412D+06    0.857312192330D-07   -0.999465266444D-10
 14     0.265612414469D+08    0.419352296154D-02    0.960520866410D+00   -0.226728979270D+01
       -0.332698524487D+01    0.512978043948D+06    0.960022604382D-07    0.633179405532D-09
 15     0.265589229075D+08    0.722739428735D-02    0.961959528737D+00    0.298395609247D+01
       -0.437923383365D+01    0.497345023113D+06    0.915950781370D-07    0.538156388218D-08
 16     0.265591729740D+08    0.118189864630D-02    0.957675288384D+00   -0.225448636511D+01
        0.332292765671D+01    0.530549474498D+06    0.944491453404D-07    0.545686750238D-09
 17     0.265597328220D+08    0.682663408782D-02    0.963412425004D+00    0.301677999968D+01
        0.144392441818D+01    0.521687179344D+06    0.900862323023D-07    0.376144006641D-08
 18     0.265598138755D+08    0.474245481754D-02    0.945627434566D+00   -0.126184619183D+01
        0.109843713898D+01    0.511234650993D+06    0.934520532881D-07    0.197415408084D-08
 19     0.265589909957D+08    0.147602669952D-02    0.943693773191D+00   -0.200553422412D+00
       -0.462077758910D+00    0.507610790481D+06    0.964533438639D-07    0.480045406099D-09
 20     0.265618080599D+08    0.416017506212D-02    0.963908321895D+00    0.836447780779D+00
       -0.467061546278D+01    0.506630775470D+06    0.972652461259D-07    0.482575579455D-09
 21     0.265607001406D+08    0.100921585792D-01    0.954318187675D+00   -0.229293398700D+01
        0.244498862582D+01    0.539648127572D+06    0.961667529836D-07    0.566269772142D-09
 23     0.265617842017D+08    0.604785373039D-02    0.958123554396D+00   -0.226261988153D+01
       -0.248899751022D+01    0.501997200625D+06    0.754845166408D-07    0.112259752617D-08
 24     0.265607174453D+08    0.410246169755D-02    0.967240552359D+00    0.293784212088D+01
        0.386735145324D+01    0.525896197314D+06    0.839177134780D-07    0.134557354049D-08
 25     0.265618269939D+08    0.625710601271D-02    0.953438183314D+00   -0.206441256293D+00
```

```
     -0.379159072502D+01    0.512863353750D+06    0.884272381243D-07   -0.227070522065D-10
 26   0.265613914481D+08    0.813337136567D-02    0.960425541062D+00   -0.125062299378D+01
     -0.148553446244D+01    0.507112507557D+06    0.967377370369D-07    0.268740414551D-09
 28   0.265607012072D+08    0.764268303533D-02    0.963194594297D+00    0.189602902374D+01
      0.271909721001D+01    0.532739870060D+06    0.923249092771D-07    0.337045671087D-08
#3. Antenna phase center offset in the i direction                                  ?
==> 0.211
#4. Antenna phase center offset in the k direction (to the center of the Earth)
==> 0.886
#5. Variances of orbit elements (in the orbit improvement using ephemeris)?
==> 100.0D0  2.0D-6  2.0D-6  2.0D-6  2.0D-6   1.0D0  4.0D-7  4.0D-7
#6. 0.00 for this input
*   Correlation between T0 and w (for test only)
==> -0.00
#7. Variances of orbit elements (in the final orbit improvement using phase
*   observations)?
=>  100.0D0  2.0D-6  2.0D-6  2.0D-6  5.0D-6   1.0D0  2.0D-7  2.0D-7
*   The above three inputs should be moved to the line after #2  in a
*   later version.
*
* ============== PART 3. TIME & THE EARTH ORIENTATION INFORMATION =============
*
#1. POLAR MOTION  AND TIME CORRECTIONS (FREE FORMAT) ?
*    DON'T BEGIN INPUT LINES WITH '==>' FOR THIS INPUT
*    THE VALUES CAN BE AT ANY TIME INTERVAL
*   YEAR, MONTH,  DAY, HOUR;    XP,    YP,    UT1-UTC,   GPS-UTC    ?
*                          (in arc-seconds)  (in seconds)
    1992  07     22.0  0.0  -0.1103  0.4250   0.415173     8
    1992  07     23.0  0.0  -0.1081  0.4273   0.413688     8
    1992  07     24.0  0.0  -0.1061  0.4294   0.412293     8
    1992  07     25.0  0.0  -0.1041  0.4314   0.410979     8
    1992  07     26.0  0.0  -0.1021  0.4334   0.409741     8
    1992  07     27.0  0.0  -0.1001  0.4353   0.408541     8
    1992  07     28.0  0.0  -0.0981  0.4372   0.407278     8
    1992  07     29.0  0.0  -0.0962  0.4390   0.405869     8
    1992  07     30.0  0.0  -0.0943  0.4408   0.404218     8
```

```
    1992  07     31.0  0.0  -0.0924  0.4427   0.402335    8
    1992  08     01.0  0.0  -0.0904  0.4451   0.400270    8
    1992  08     02.0  0.0  -0.0883  0.4477   0.398111    8
    1992  08     03.0  0.0  -0.0862  0.4501   0.396002    8
    1992  08     04.0  0.0  -0.0843  0.4525   0.394043    8
    1992  08     05.0  0.0  -0.0824  0.4545   0.392294    8
#2. SEPARATE TIDAL VARIATIONS IN UT1 for interpolation               ?
==> 1
#3. specify "0" for this purpose
*   (for test only) INTEGRATE IN BARYCENTRIC TIME SCALE ? YES(1), NO (0)
==> 0
#4. (FOR TEST ONLY) OFFSET FOR THE GPS TIME (IN DAYS)
*   for test only; specify "0.0" for general purpose
==> 0.0D0
*
* ================ PART 4. INTEGRATION INFORMATION ====================
*
#1. Number of iterations in the orbital improvement process using
*   ephemeris files                                                    ?
==> 0
#2. input 1.0D-4
*   (for test only) Convergence control in the starter
*   The maximum allowed sum of the differences between the previous
*   loop and the current one
==> 1.0D-6
#3. Step size of the integration (in seconds)                          ?
==> 30
#4. The lengths of segmentations for orbital representation (in hours) ?
==> 2.0D0
#5. Order of the integrator                                            ?
==> 12
#6. input 1.0D-9
*   (for test only) Convergence control in the starter for partial
*   derivatives
==> 1.0D-10
#7. Step size of the integration for partial derivatives (in seconds)  ?
```

```
==> 30
#8. The order of the integrator for partial derivatives               ?
==> 12
#9. Order of the representing polynomials for satellite positions      ?
==> 50
*
* =========== part 5. Orbit improvement with the ephemeris data (not used) =========
* Warning: input from #0 through #6 are for test only, the users should
*    leave it as it is in this sample file.
#0   specify 0 for this input
*   (This option is only for test purpose)
#0.1 Test the consistency of partial derivatives and with initial
*    integration
*
==> 0
#0.2 no input if previous input is '0'.
* (test only)  initial condition to generate simulated orbits.
*
#1. specify "F"
*  (for test only) Computation of clock offset coefficients
==> F
#2. (for test only) OUTPUT CLOCK FILE NAME                                          ?
==> /T1212X.DIPOP.ERP.OUT.SVCLK
#3. (for test only) GM correction Y(1), priori accuracy, and its value ?
==> 0  5.0D7  0.398600440D+15
#4. (for test only) Scale factor Y(1), translation estimation Y(1)                 ?
==> 0 0
#5. (for test only) Prior values and accuracy, (scale, X,Y,Z)                      ?
==> 0.0  0.0  0.0   0.0  1.0D-6 100.0  100.0   100.0
#6. (for test only) Scale factor in the force model? Y(1)                          ?
==> 0
#7. Maximum time interval of the positions of a satellite from
*   the ephemeris file or simulated orbit                             ?
==> 120.0D0
*8. Enter the following lines
#a. Delimiter (blank)
```

```
#b. a comment line
#c. GPS time interval during which positions of satellites are computed
*   GPS week and time at the beginning of the interval; GPS week and time
*   at the end of the interval, and length of sub-intervals
#d. ephemeris filename.
#e. ephemeris type.
*   specify 1 for the broadcast ephemeris.
#f. the format of the ephemeris.
#g. comment line.
#h. (for test only leave as it was in this sample command file)
*   interval for SV clock approximation, its length of segmentation, and
*   the order of the approximating polynomial.
#i. Repeat steps #a through #i for other ephemeris files.  They can be
*   the same ephemeris file, but for different time period.
*
* Caution: you can not enter comment lines arbitrarily after
*   the following line
* Not has been used in the following:
----------------------------------------------------------

* orbital session 1: start and the stop time
 654   518400.00   654   604800.00  86400.0D0
/T1212X.GLOBL207.ORB
1
CC
* Clock coefficient approximation interval (developed for debug only)
0        0          0
```

APPENDIX IV
THE SOLUTIONS OF THE STATION COORDINATES

Table IV.1 The mean values of the station coordinates from strategy-1 daily solutions (July 25 to 31, 1992)
(rep is the daily repeatability; std is the mean value of the standard deviations)

st	x meter	rep mm	std mm	y meter	rep mm	std mm	z meter	rep mm	std mm
AB	-2341332.884	21	2	-3539049.509	26	3	4745791.420	19	3
AL	918129.616			-4346071.224			4561977.800		
FA	-2281621.327			-1453595.775			5756961.976		
GO	-2353614.138	31	4	-4641385.386	25	4	3676976.434	19	4
HA	5084625.404			2670366.499			-2768494.039		
HE	4033470.500	55	5	23672.709	49	4	4924301.342	38	5
JP	-2493304.466	56	3	-4655215.354	30	5	3565497.293	30	3
KK	-5543838.080			-2054587.522			2387809.570		
KO	3899225.396	58	3	396731.791	54	3	5015078.308	37	3
MA	4641949.867	44	4	1393045.267	64	3	4133287.244	43	3
MC	-1310696.493	158	23	310468.877	97	17	-6213368.389	112	19
MD	4849202.502			-360329.179			4114913.003		
ME	2892561.698	21	2	1311839.083	14	1	5512616.063	43	3
MP	5439189.174	69	6	-1522054.856	61	4	2953464.147	44	4
NY	1202430.744	13	3	252626.678	19	3	6237767.550	47	9
ON	3370658.748	34	3	711877.002	25	2	5349786.769	55	3
PA	-5245195.196	76	12	-3080472.583	64	10	-1912825.508	48	3
PE	-2059164.638	24	2	-3621108.389	28	2	4814432.428	28	2
PI	-2369510.515	31	3	-4761207.125	62	3	3511396.092	32	3
SA	1769692.942	134	16	-5044574.508	132	16	-3468321.326	87	11
ST	2612631.436	20	3	-3426806.976	32	3	4686757.748	27	3
TI	-4460996.142	56	6	2682557.106	105	7	-3674443.984	93	6

TR	2102940.451			721569.379			5958192.072		
TW	-3024781.944	361	34	4928936.579	272	31	2681234.605	101	8
US	-3855262.844	319	38	3427432.003	179	37	3741021.076	127	13
WT	4075578.728	55	3	931852.670	57	4	4801569.988	43	3
YA	-2389025.331			5043316.830			-3078530.926		
YE	-1224452.369			-2689216.048			5633638.286		

Table IV.2 The mean values of the station coordinates from strategy-3 daily solutions (July 25 to 31, 1992)

(rep is the daily repeatability; std is the mean value of the standard deviations)

st	x meter	rep mm	std mm	y meter	rep mm	std mm	z meter	rep mm	std mm
AL	918129.616			-4346071.224			4561977.800		
FA	-2281621.327			-1453595.775			5756961.976		
HA	5084625.404			2670366.499			-2768494.039		
HE	4033470.453	12	3	23672.682	15	2	4924301.330	10	3
KK	-5543838.080			-2054587.522			2387809.570		
KO	3899225.347			396731.759			5015078.296		
MA	4641949.814			1393045.203			4133287.266		
MC	-1310696.474	181	21	310468.935	105	14	-6213368.330	92	17
MD	4849202.502			-360329.179			4114913.003		
ME	2892561.695	12	1	1311839.077	12	1	5512616.091	26	2
MP	5439189.152	32	5	-1522054.864	23	3	2953464.152	24	3
NY	1202430.752	9	3	252626.680	18	2	6237767.536	42	8
ON	3370658.757			711876.989			5349786.812		
PA	-5245195.169	87	11	-3080472.550	58	9	-1912825.519	46	3
PE	-2059164.641	22	2	-3621108.384	27	2	4814432.425	28	2
PI	-2369510.531	35	2	-4761207.147	51	3	3511396.108	26	2
SA	1769692.969	140	14	-5044574.462	117	14	-3468321.338	97	10
ST	2612631.433	19	2	-3426806.984	23	3	4686757.759	19	3

TI	-4460996.133	53	6	2682557.115	106	6	-3674444.014	79	5
TR	2102940.451			721569.379			5958192.072		
TW	-3024782.002	328	31	4928936.485	251	29	2681234.586	84	8
US	-3855262.863	294	39	3427431.930	161	28	3741021.041	100	11
WT	4075578.676	9	2	931852.618	9	1	4801569.997	8	2
YA	-2389025.331			5043316.830			-3078530.926		
YE	-1224452.369			-2689216.048			5633638.286		

Table IV.3 A seven-day solution of the station coordinates from strategy-4 (using the SIO precise orbits)

st	x meter	std mm	y meter	std mm	z meter	std mm
AB	-2341332.931	1	-3539049.424	1	4745791.439	2
AL	918129.616		-4346071.224		4561977.800	
FA	-2281621.327		-1453595.775		5756961.976	
GO	-2353614.227	2	-4641385.369	2	3676976.474	2
HA	5084625.404		2670366.499		-2768494.039	
HE	4033470.499	2	23672.653	1	4924301.391	2
JP	-2493304.565	1	-4655215.332	2	3565497.335	1
KK	-5543838.080		-2054587.522		2387809.570	
KO	3899225.414	1	396731.725	1	5015078.369	2
MA	4641949.951	2	1393045.201	1	4133287.324	1
MC	-1310696.166	8	310469.171	6	-6213368.538	8
MD	4849202.502		-360329.179		4114913.003	
ME	2892561.736	1	1311839.049	1	5512616.105	1
MP	5439189.104	3	-1522054.886	1	2953464.151	2
NY	1202430.730	1	252626.736	1	6237767.544	5
ON	3370658.784	1	711876.952	1	5349786.825	2
PA	-5245195.066	5	-3080472.131	4	-1912825.585	1
PE	-2059164.690	1	-3621108.332	1	4814432.461	1

PI	-2369510.622	1	-4761207.082	1	3511396.123	1
SA	1769693.006	5	-5044574.434	5	-3468321.392	4
ST	2612631.470	1	-3426807.185	1	4686757.821	1
TI	-4460996.255	3	2682557.353	3	-3674444.081	2
TR	2102940.451		721569.379		5958192.072	
TW	-3024781.770	12	4928937.073	11	2681234.544	3
US	-3855262.621	14	3427432.350	12	3741020.930	5
WT	4075578.779	2	931852.611	1	4801570.070	2
YA	-2389025.331		5043316.830		-3078530.926	
YE	-1224452.369		-2689216.048		5633638.286	

APPENDIX V

DAILY AND SEVEN-DAY BASELINE SOLUTIONS FROM STRATEGY-1

Table V.1 Baselines from strategy-1 network solution
(Average repeatability is 21.14 p.p.b.; All means a seven-day solution)

Day	St. 1	St. 2	Baseline length	r.m.s.	Repeatability
			meter	mm	p.p.b.
25	AL	ST	1931826.4147	2	11.32
26			1931826.4034	2	
27			1931826.3721	2	
28			1931826.4309	3	
29			1931826.3717	2	
30			1931826.3835	3	
31			1931826.3742	2	
All			1931826.3596	2	
	AL	YE	2912779.2285		
	FA	KK	4728047.9226		
25	HA	SA	8426081.4967	16	16.18
26			8426081.3363	18	
27			8426081.3970	15	
28			8426081.6926	15	
29			8426081.6231	18	
30			8426081.7303	17	
31			8426081.5338	15	
All			8426081.4301	12	
25	HE	KO	406737.3760	2	35.12
26			406737.3452	2	
27			406737.3918	2	
28			406737.3567	2	

29			406737.3598	2	
30			406737.3712	2	
31			406737.3570	2	
All			406737.3646	2	
25	KK	PA	4431375.6028	3	9.59
26			4431375.6545	4	
27			4431375.5942	4	
28			4431375.5999	4	
29			4431375.5376	4	
30			4431375.6806	4	
31			4431375.6047	4	
All			4431375.5466	3	
25	KO	ON	700520.5565	5	41.86
26			700520.4789	1	
27			700520.4669	1	
28			700520.5015	1	
29			700520.4812	1	
30			700520.4628	1	
31			700520.4913	1	
All			700520.4778	1	
25	MA	HA	7032929.2917	4	7.51
26			7032929.4275	2	
27			7032929.4277	2	
28			7032929.4545	3	
29			7032929.4019	3	
30			7032929.3875	3	
31			7032929.4592	3	
All			7032929.4507	2	
29	MA	KO	1523757.0885	1	
All			1523757.1042	1	
26	MA	MD	1765676.3806	2	9.21
27			1765676.3880	2	
28			1765676.4231	2	

29			1765676.3957	3	
30			1765676.4075	3	
31			1765676.3754	3	
All			1765676.4275	2	
25	MA	MP	3244284.5064	3	
All			3244284.5026	3	
25	MA	WT	989988.2496	1	6.25
26			989988.2327	1	
27			989988.2392	1	
28			989988.2451	1	
30			989988.2330	1	
31			989988.2367	1	
All			989988.2515	1	
26	MD	MP	1745466.7703	2	11.16
27			1745466.7510	2	
28			1745466.8136	2	
29			1745466.7623	2	
30			1745466.7686	3	
31			1745466.7756	2	
All			1745466.7797	2	
25	ON	ME	784247.8030	3	22.49
26			784247.8245	1	
27			784247.8228	1	
28			784247.8520	1	
29			784247.8446	1	
30			784247.8491	1	
31			784247.8528	1	
All			784247.8389	1	
25	PE	AB	301768.3969	1	8.93
27			301768.3994	1	
28			301768.4012	1	
29			301768.3985	1	
30			301768.3926	1	

31			301768.3989	1	
All			301768.3985	1	
25	PE	AL	3074668.3424	2	7.16
26			3074668.3372	2	
27			3074668.3814	2	
28			3074668.3747	2	
29			3074668.3345	2	
30			3074668.3578	2	
31			3074668.3951	2	
All			3074668.3649	2	
25	PE	PI	1758989.3413	1	10.14
26			1758989.2922	1	
27			1758989.3069	1	
28			1758989.3162	1	
29			1758989.2799	1	
30			1758989.3076	1	
31			1758989.3035	1	
All			1758989.2952	1	
26	PI	GO	205004.3743	1	55.21
27			205004.3785	1	
28			205004.3572	1	
29			205004.3800	1	
30			205004.3789	1	
31			205004.3517	1	
All			205004.3694	1	
26	PI	JP	171715.2445	1	103.02
27			171715.2417	1	
28			171715.2739	1	
29			171715.2876	1	
30			171715.2667	1	
31			171715.2832	1	
All			171715.2669	1	
25	PI	KK	4320253.8079	3	13.52

26			4320253.6922	3	
27			4320253.6793	3	
28			4320253.6377	3	
29			4320253.6657	3	
30			4320253.6406	3	
31			4320253.6178	3	
All			4320253.7042	2	
26	SA	MC	6760219.6905	11	15.64
27			6760219.7120	11	
28			6760219.8639	10	
29			6760219.8950	10	
30			6760219.9712	10	
31			6760219.9273	10	
All			6760219.8803	8	
25	SA	PA	7448887.0264	14	15.96
26			7448887.1602	15	
27			7448887.2255	13	
28			7448887.9488	15	
29			7448887.3063	14	
30			7448887.1129	17	
31			7448887.0026	14	
All			7448887.1457	11	
25	TR	ME	1081877.1024	1	14.15
26			1081877.0526	1	
27			1081877.0791	1	
28			1081877.0927	1	
29			1081877.0733	1	
30			1081877.0900	1	
31			1081877.0710	1	
All			1081877.0653	1	
26	TR	NY	1053084.7089	5	13.85
27			1053084.7012	2	
28			1053084.7292	5	

29			1053084.7280	2	
30			1053084.7421	2	
31			1053084.7366	3	
All			1053084.7058	2	
25	TW	YA	5795875.0565	8	14.74
26			5795875.1602	8	
27			5795875.1048	7	
28			5795874.9939	6	
29			5795875.1824	8	
30			5795875.2472	12	
31			5795875.0197	9	
All			5795875.1034	6	
27	US	TW	2016770.1949	36	27.29
28			2016770.2003	13	
29			2016770.2295	13	
30			2016770.3375	22	
31			2016770.1915	10	
All			2016770.3090	9	
25	WT	KO	602528.5476	1	17.41
26			602528.5396	1	
27			602528.5282	1	
28			602528.5546	3	
30			602528.5598	1	
31			602528.5525	1	
All			602528.5480	1	
	YA	HA	7847449.9969		
26	YA	TI	3197086.4128	8	19.66
27			3197086.4284	5	
28			3197086.4924	5	
29			3197086.4636	7	
30			3197086.5957	6	
31			3197086.4213	6	
All			3197086.4860	4	

APPENDIX VI

DAILY AND SEVEN-DAY BASELINE SOLUTIONS FROM STRATEGY-3

Table VI.1 Baselines from strategy-3 network solution
(Average repeatability is 14.24 p.p.b.; All means a seven-day solution)

Day	St. 1	St. 2	Baseline length	r.m.s.	Repeatability
			meter	mm	p.p.b.
25	AL	ST	1931826.4044	2	10.65
26			1931826.4043	2	
27			1931826.3696	2	
28			1931826.4209	2	
29			1931826.3627	2	
30			1931826.3779	2	
31			1931826.3716	2	
All			1931826.3548	2	
	AL	YE	2912779.2285		
	FA	KK	4728047.9226		
25	HA	SA	8426081.4151	17	15.18
26			8426081.3064	17	
27			8426081.3810	14	
28			8426081.6657	14	
29			8426081.5308	16	
30			8426081.6656	15	
31			8426081.4908	14	
All			8426081.3851	13	
25	HE	KO	406737.3713	2	38.43
26			406737.3422	2	
27			406737.3911	2	

28			406737.3497	2	
29			406737.3539	2	
30			406737.3681	2	
31			406737.3502	2	
All			406737.3598	2	
25	KK	PA	4431375.5968	4	9.48
26			4431375.6594	4	
27			4431375.6086	4	
28			4431375.5947	4	
29			4431375.5532	4	
30			4431375.6909	4	
31			4431375.6089	4	
All			4431375.5504	3	
	KO	ON	700520.4827		
	MA	HA	7032929.4432		
	MA	KO	1523757.0453		
	MA	MD	1765676.3615		
25	MA	MP	3244284.4847	3	
All			3244284.4308	2	
25	MA	WT	989988.2218	0	5.95
26			989988.2184	0	
27			989988.2244	0	
28			989988.2278	1	
30			989988.2104	1	
31			989988.2144	0	
All			989988.2234	1	
26	MD	MP	1745466.7680	2	9.57
27			1745466.7419	2	
28			1745466.7960	2	
29			1745466.7544	2	
30			1745466.7631	3	
31			1745466.7728	2	
All			1745466.7705	2	

25	ON	ME	784247.8455	1	13.05
26			784247.8367	1	
27			784247.8351	1	
28			784247.8427	1	
29			784247.8544	1	
30			784247.8636	1	
31			784247.8337	1	
All			784247.8397	1	
25	PE	AL	3074668.3475	2	6.52
26			3074668.3426	2	
27			3074668.3861	2	
28			3074668.3714	2	
29			3074668.3408	2	
30			3074668.3652	2	
31			3074668.3956	2	
All			3074668.3611	2	
25	PE	PI	1758989.3388	1	8.59
26			1758989.3020	1	
27			1758989.3166	1	
28			1758989.3119	1	
29			1758989.2862	1	
30			1758989.3217	1	
31			1758989.3112	1	
All			1758989.2968	1	
25	PI	KK	4320253.7964	3	12.17
26			4320253.7058	3	
27			4320253.6954	2	
28			4320253.6404	3	
29			4320253.6603	3	
30			4320253.6588	3	
31			4320253.6290	2	
All			4320253.7190	2	
26	SA	MC	6760219.6582	12	15.24

27			6760219.7113	11	
28			6760219.8817	11	
29			6760219.8522	9	
30			6760219.9348	9	
31			6760219.9081	9	
All			6760219.8764	9	
25	SA	PA	7448886.9944	14	14.94
26			7448887.1630	15	
27			7448887.2457	13	
28			7448886.9770	13	
29			7448887.2698	13	
30			7448887.0845	15	
31			7448887.0189	13	
All			7448887.1528	11	
25	TR	ME	1081877.0715	2	8.40
26			1081877.0475	1	
27			1081877.0651	1	
28			1081877.0739	1	
29			1081877.0581	1	
30			1081877.0719	1	
31			1081877.0566	1	
All			1081877.0571	1	
26	TR	NY	1053084.7029	5	12.62
27			1053084.6893	2	
28			1053084.7148	4	
29			1053084.7171	2	
30			1053084.7262	1	
31			1053084.7272	2	
All			1053084.6973	2	
25	TW	YA	5795875.0463	9	12.43
26			5795875.1610	8	
27			5795875.0917	6	
28			5795874.9925	6	

29			5795875.1535	7	
30			5795875.2061	11	
31			5795875.0366	8	
All			5795875.1048	6	
27	US	TW	2016770.1064	33	28.64
28			2016770.1803	12	
29			2016770.1981	12	
30			2016770.2869	20	
31			2016770.1782	9	
All			2016770.2994	9	
25	WT	KO	602528.5192	1	14.78
26			602528.5282	1	
27			602528.5210	1	
28			602528.5137	2	
30			602528.5410	2	
31			602528.5309	1	
All			602528.5166	1	
	YA	HA	7847449.9969		
26	YA	TI	3197086.3954	7	19.66
27			3197086.4221	5	
28			3197086.4931	5	
29			3197086.4567	7	
30			3197086.5839	5	
31			3197086.4192	6	
All			3197086.4845	5	

APPENDIX VII

DAILY AND SEVEN-DAY BASELINE SOLUTIONS FROM STRATEGY-4

Table VII.1 Baselines from strategy-4 network solution (using SIO precise orbits)
(Average repeatability is 19.27 p.p.b.; All means a seven-day solution)

Day	St. 1	St. 2	Baseline length	r.m.s.	Repeatability
			meter	mm	p.p.b.
25	AL	ST	1931826.3358	3	4.28
26			1931826.3316	2	
27			1931826.3196	3	
28			1931826.3362	3	
29			1931826.3391	3	
30			1931826.3364	3	
31			1931826.3167	2	
All			1931826.3283	1	
	AL	YE	2912779.2285		
	FA	KK	4728047.9226		
25	HA	SA	8426081.3358	19	19.92
26			8426081.3581	15	
27			8426081.2338	14	
28			8426081.5853	15	
29			8426081.7638	15	
30			8426081.5562	15	
31			8426081.5398	13	
All			8426081.4573	6	
25	HE	KO	406737.3774	3	36.22
26			406737.3517	3	
27			406737.3990	3	
28			406737.3560	3	

29			406737.3649	3	
30			406737.3692	3	
31			406737.3609	3	
All			406737.3686	1	
25	KK	PA	4431375.5591	4	8.06
26			4431375.5838	4	
27			4431375.5987	4	
28			4431375.6244	4	
29			4431375.5335	4	
30			4431375.6465	4	
31			4431375.6099	4	
All			4431375.5903	1	
25	KO	ON	700520.5041	8	13.63
26			700520.4877	1	
27			700520.4709	1	
28			700520.4936	1	
29			700520.4909	1	
30			700520.4813	2	
31			700520.4895	1	
All			700520.4837	1	
25	MA	HA	7032929.6246	5	7.51
26			7032929.4762	3	
27			7032929.4609	2	
28			7032929.4917	3	
29			7032929.5125	3	
30			7032929.4633	4	
31			7032929.5283	3	
All			7032929.4916	1	
29	MA	KO	1523757.1195	1	
All			1523757.1094	1	
26	MA	MD	1765676.3394	2	17.92
27			1765676.3498	2	
28			1765676.3730	3	

29			1765676.3535	3	
30			1765676.2852	4	
31			1765676.2959	2	
All			1765676.3442	1	
25	MA	MP	3244284.4781	3	
All			3244284.4363	1	
25	MA	WT	989988.2471	1	9.69
26			989988.2536	1	
27			989988.2501	1	
28			989988.2650	2	
30			989988.2349	1	
31			989988.2405	1	
All			989988.2517	0	
26	MD	MP	1745466.7585	2	10.05
27			1745466.7568	2	
28			1745466.7681	2	
29			1745466.7312	3	
30			1745466.7904	4	
31			1745466.7562	3	
All			1745466.7697	1	
25	ON	ME	784247.8092	5	20.74
26			784247.8334	2	
27			784247.8317	2	
28			784247.8441	2	
29			784247.8567	2	
30			784247.8602	2	
31			784247.8495	2	
All			784247.8426	1	
25	PE	AB	301768.4055	2	8.92
27			301768.4048	1	
28			301768.4095	1	
29			301768.4060	1	
30			301768.4003	1	

31			301768.4056	1	
All			301768.4051	1	
25	PE	AL	3074668.4311	2	3.97
26			3074668.4277	2	
27			3074668.4377	2	
28			3074668.4105	2	
29			3074668.4070	2	
30			3074668.4426	2	
31			3074668.4260	2	
All			3074668.4267	1	
25	PE	PI	1758989.3606	1	9.64
26			1758989.3146	1	
27			1758989.3426	1	
28			1758989.3185	1	
29			1758989.3280	1	
30			1758989.3064	1	
31			1758989.3288	1	
All			1758989.3279	0	
26	PI	GO	205004.3712	2	60.20
27			205004.3798	2	
28			205004.3549	2	
29			205004.3791	2	
30			205004.3773	1	
31			205004.3484	1	
All			205004.3685	1	
26	PI	JP	171715.2443	2	102.27
27			171715.2421	2	
28			171715.2732	2	
29			171715.2885	2	
30			171715.2667	2	
31			171715.2818	2	
All			171715.2662	1	
25	PI	KK	4320253.6405	2	5.93

26			4320253.5901	2	
27			4320253.5816	2	
28			4320253.5631	2	
29			4320253.5694	2	
30			4320253.5622	2	
31			4320253.5681	2	
All			4320253.5799	1	
26	SA	MC	6760219.9124	12	5.33
27			6760219.8575	11	
28			6760219.9764	9	
29			6760219.9100	10	
30			6760219.8870	10	
31			6760219.9195	9	
All			6760219.9152	4	
25	SA	PA	7448887.0661	16	10.73
26			7448887.1848	17	
27			7448887.2986	13	
28			7448887.2184	13	
29			7448887.2404	14	
30			7448887.1455	16	
31			7448887.0729	14	
All			7448887.1465	5	
25	TR	ME	1081877.0747	2	8.62
26			1081877.0581	1	
27			1081877.0788	1	
28			1081877.0795	1	
29			1081877.0843	1	
30			1081877.0697	1	
31			1081877.0598	1	
All			1081877.0723	0	
26	TR	NY	1053084.7079	7	10.06
27			1053084.6902	3	
28			1053084.7048	7	

29			1053084.7217	3	
30			1053084.7206	2	
31			1053084.7114	3	
All			1053084.7093	1	
25	TW	YA	5795874.9638	8	10.79
26			5795875.0468	9	
27			5795875.0091	6	
28			5795874.9692	6	
29			5795875.1578	8	
30			5795874.9856	15	
31			5795874.9946	10	
All			5795875.0200	3	
27	US	TW	2016770.0688	44	42.07
28			2016770.1881	18	
29			2016770.2558	17	
30			2016770.3257	31	
31			2016770.2205	12	
All			2016770.2045	5	
25	WT	KO	602528.5402	2	22.76
26			602528.5604	1	
27			602528.5477	1	
28			602528.5843	4	
30			602528.5614	2	
31			602528.5585	1	
All			602528.5602	1	
	YA	HA	7847449.9969		
26	YA	TI	3197086.3412	8	13.11
27			3197086.3557	4	
28			3197086.3707	5	
29			3197086.3071	7	
30			3197086.4089	4	
31			3197086.4335	4	
All			3197086.3780	2	

APPENDIX VIII

A SEVEN-DAY ORBITAL ARC SOLUTION FROM STRATEGY-3

Table VIII.1 A sample seven-day solution of GPS satellite orbits from strategy-3 (All orbital elements are referenced to GPS time: GPS week 654 and 518400.0 seconds. Units: meter for a, radian for i, Ω and ω; second for T_0, and meter/(sec)^2 for p_D and p_Y)

PRN	Orbit elements	Final orbital results	Standard deviations
2	a	0.265613696977D+08	0.236601010216D-02
	e	0.108332134370D-01	0.501608883317D-09
	i	0.958152527100D+00	0.866327616653D-09
	Ω	0.830997366265D+00	0.157215037726D-08
	ω	-0.290972781124D+01	0.409670562298D-07
	T_0	0.501875536852D+06	0.284422244583D-03
	p_D	0.965063182351D-07	0.402607594473D-11
	p_Y	0.583667400666D-09	0.107390201810D-11
3	a	0.265579631649D+08	0.162085977912D-02
	e	0.128453692046D-01	0.628042301322D-09
	i	0.112236399659D+01	0.734947872483D-09
	Ω	0.222383010575D+01	0.131808719273D-08
	ω	0.249371184318D+01	0.244470978656D-07
	T_0	0.522461188552D+06	0.166384142940D-03
	p_D	0.823144282608D-07	0.524801591167D-11
	p_Y	0.266574166896D-09	0.424028245360D-12
11	a	0.265620654066D+08	0.189205418314D-02
	e	0.134281219470D-01	0.356768193821D-09
	i	0.111343007373D+01	0.721535715264D-09
	Ω	0.221274980694D+01	0.110276974841D-08
	ω	-0.225303731841D+01	0.421901876708D-07
	T_0	0.503795473828D+06	0.292878837021D-03

	p_D	0.833216860115D-07	0.514619361452D-11
	p_Y	-0.518154189183D-09	0.564054181893D-12
12	a	0.265581881477D+08	0.154432525897D-02
	e	0.122738053855D-01	0.315885186264D-09
	i	0.109600324016D+01	0.668713821492D-09
	Ω	0.686149341057D-01	0.115859169428D-08
	ω	-0.334979950909D+00	0.470893577136D-07
	T_0	0.526992908129D+06	0.324992819675D-03
	p_D	0.824457614656D-07	0.413372260335D-11
	p_Y	0.491375127623D-09	0.786994704764D-12
13	a	0.265595870435D+08	0.200674344263D-02
	e	0.384984318425D-02	0.352759796126D-09
	i	0.110908209073D+01	0.717603989892D-09
	Ω	0.219546770345D+01	0.120072249381D-08
	ω	-0.251594892934D+01	0.145038573868D-06
	T_0	0.517188065877D+06	0.100023556903D-02
	p_D	0.860931176883D-07	0.500429406632D-11
	p_Y	0.120094501273D-09	0.547992157244D-12
14	a	0.265612416189D+08	0.191209629645D-02
	e	0.419356377991D-02	0.300943941302D-09
	i	0.960520859962D+00	0.602739044851D-09
	Ω	-0.226728983731D+01	0.123424679489D-08
	ω	-0.332697942793D+01	0.130385494870D-06
	T_0	0.512978083000D+06	0.893257976320D-03
	p_D	0.968661650241D-07	0.484313155564D-11
	p_Y	0.712987247102D-09	0.548163263994D-12
15	a	0.265589230898D+08	0.143084024856D-02
	e	0.722737026471D-02	0.457142120010D-09
	i	0.961959597058D+00	0.698220073238D-09
	Ω	0.298395611067D+01	0.121032723212D-08
	ω	-0.437922648289D+01	0.518284955175D-07
	T_0	0.497345072133D+06	0.350866799043D-03
	p_D	0.915159793327D-07	0.324966739135D-11

	p_Y	0.593469727786D-09	0.209330326801D-11
16	a	0.265591728183D+08	0.295508011500D-02
	e	0.118194291320D-02	0.455481455316D-09
	i	0.957675287393D+00	0.809470149615D-09
	Ω	-0.225448639108D+01	0.158307548737D-08
	ω	0.332293833013D+01	0.506128759626D-06
	T_0	0.530549547401D+06	0.346565408680D-02
	p_D	0.963375737285D-07	0.569038999787D-11
	p_Y	0.459482723802D-09	0.805785028442D-12
17	a	0.265597325872D+08	0.116997590045D-02
	e	0.682656827376D-02	0.387577603926D-09
	i	0.963412399576D+00	0.783168887833D-09
	Ω	0.301678001855D+01	0.133696821584D-08
	ω	0.144393241081D+01	0.489099724044D-07
	T_0	0.521687233982D+06	0.331333512340D-03
	p_D	0.912235349790D-07	0.292481330858D-11
	p_Y	0.105901801911D-08	0.228286774953D-11
18	a	0.265598129837D+08	0.167863401014D-02
	e	0.474248961546D-02	0.287020935813D-09
	i	0.945627416338D+00	0.575361633537D-09
	Ω	-0.126184621126D+01	0.125684728691D-08
	ω	0.109844205700D+01	0.104385267088D-06
	T_0	0.511234687406D+06	0.710296802315D-03
	p_D	0.954327985328D-07	0.104835157168D-10
	p_Y	0.904336073642D-09	0.387184063676D-12
19	a	0.265589910970D+08	0.160368115507D-02
	e	0.147605912077D-02	0.311605540758D-09
	i	0.943693794631D+00	0.681415684929D-09
	Ω	-0.200553412797D+00	0.132346255754D-08
	ω	-0.462049678097D+00	0.265980136368D-06
	T_0	0.507610982967D+06	0.182201131311D-02
	p_D	0.973826980401D-07	0.299833377264D-11
	p_Y	0.385732587716D-09	0.548741822400D-12

20	a	0.265618079734D+08	0.175179074002D-02
	e	0.416014139840D-02	0.483686271553D-09
	i	0.963908321677D+00	0.599745617516D-09
	Ω	0.836447778407D+00	0.120430640921D-08
	ω	-0.467062064932D+01	0.113648670690D-06
	T_0	0.506630741101D+06	0.775003524237D-03
	p_D	0.974086749031D-07	0.489722185547D-11
	p_Y	0.259545036379D-09	0.794603031021D-12
21	a	0.265606999217D+08	0.201425089795D-02
	e	0.100922053482D-01	0.346067789802D-09
	i	0.954318203891D+00	0.806307924276D-09
	Ω	-0.229293401039D+01	0.124207336888D-08
	ω	0.244499209102D+01	0.420229227488D-07
	T_0	0.539648150564D+06	0.289187236248D-03
	p_D	0.969626921144D-07	0.387133919593D-11
	p_Y	0.153828018933D-09	0.570480224520D-12
23	a	0.265617839030D+08	0.167319901894D-02
	e	0.604788304408D-02	0.351641619517D-09
	i	0.958123561979D+00	0.730288885502D-09
	Ω	-0.226261986272D+01	0.119033424096D-08
	ω	-0.248899469415D+01	0.646912015742D-07
	T_0	0.501997220106D+06	0.448121663101D-03
	p_D	0.771185103767D-07	0.388297662472D-11
	p_Y	0.217036833440D-09	0.481440559887D-12
24	a	0.265607176390D+08	0.228539064587D-02
	e	0.410253171636D-02	0.334476628320D-09
	i	0.967240592110D+00	0.766151959257D-09
	Ω	0.293784215676D+01	0.139192478469D-08
	ω	0.386736104671D+01	0.136544995047D-06
	T_0	0.525896262564D+06	0.942087289515D-03
	p_D	0.851729462853D-07	0.371961762667D-11
	p_Y	0.121286212489D-08	0.209831714920D-11
25	a	0.265618271125D+08	0.239961361287D-02

	e	0.625706849103D-02	0.380534684051D-09
	i	0.953438168082D+00	0.812398654315D-09
	Ω	-0.206441240867D+00	0.118577279207D-08
	ω	-0.379159495544D+01	0.774692915936D-07
	T_0	0.512863324524D+06	0.531342394910D-03
	p_D	0.889938730207D-07	0.397326206045D-11
	p_Y	0.573534208408D-09	0.874416180086D-12
26	a	0.265613917719D+08	0.244463635185D-02
	e	0.813334329259D-02	0.473302300665D-09
	i	0.960425570394D+00	0.839415055546D-09
	Ω	-0.125062299656D+01	0.114259342044D-08
	ω	-0.148552570466D+01	0.767525925045D-07
	T_0	0.507112568271D+06	0.533697426785D-03
	p_D	0.944801642008D-07	0.150778959645D-10
	p_Y	0.145451863107D-08	0.570831511607D-12
28	a	0.265607025357D+08	0.202382991847D-02
	e	0.764271346944D-02	0.719662917627D-09
	i	0.963194568502D+00	0.698672292662D-09
	Ω	0.189602901154D+01	0.112527502864D-08
	ω	0.271910173495D+01	0.529817387416D-07
	T_0	0.532739900432D+06	0.357536684379D-03
	p_D	0.894786420661D-07	0.634459614604D-11
	p_Y	0.824637879137D-09	0.611346625107D-12

APPENDIX IX

DAILY SOLUTION SAMPLE FOR JULY 25

(STRATEGY-3)

************ ITERATION LOOP 1 *************

Re-Evaluation of Nuisance Parameters

Part 1 Station Coordinate Corrections (meter):

ST: AB	0.0000E+00	0.0000E+00	0.0000E+00
ST: AL	0.5397E-06	0.2829E-07	-0.4376E-06
ST: FA	0.7850E-06	0.1740E-05	0.1304E-05
ST: GO	0.0000E+00	0.0000E+00	0.0000E+00
ST: GR	0.0000E+00	0.0000E+00	0.0000E+00
ST: HA	-0.5950E-07	0.1809E-07	0.1523E-06
ST: HE	-0.1496	-0.2281E-01	-0.2204E-01
ST: JP	0.0000E+00	0.0000E+00	0.0000E+00
ST: KK	0.1603E-06	0.6916E-06	-0.1343E-05
ST: KO	-0.7673E-06	-0.3566E-05	0.3148E-05
ST: MA	0.2049E-05	0.3665E-05	-0.3905E-05
ST: MC	0.0000E+00	0.0000E+00	0.0000E+00
ST: MD	0.0000E+00	0.0000E+00	0.0000E+00
ST: ME	-0.1154	-0.2072	-0.2551
ST: MP	0.7498E-01	0.1021E-01	0.1246
ST: NY	0.0000E+00	0.0000E+00	0.0000E+00
ST: ON	-0.2135E-06	0.1576E-05	-0.9187E-06
ST: PA	-0.5821	-0.3973	0.4989E-02
ST: PE	-0.2569E-01	-0.1619E-01	0.6182E-02
ST: PI	-0.1243	-0.2341E-01	0.8561E-01
ST: SA	-0.2022	-0.6415E-01	-0.1866
ST: ST	0.2663E-01	0.4432E-01	-0.4314E-01
ST: TI	0.0000E+00	0.0000E+00	0.0000E+00
ST: TR	-0.3310E-06	-0.1197E-05	0.1878E-05
ST: TW	0.3522	-0.7186	0.1406
ST: US	0.0000E+00	0.0000E+00	0.0000E+00
ST: WT	-0.1224E-01	-0.2424E-01	0.1012E-01
ST: YA	-0.1323E-06	-0.2863E-06	-0.3153E-06
ST: YE	-0.1604E-05	-0.2397E-05	0.1525E-06

Observation Window 1

Part 2 Tropospheric Scale Corrections & Zenith Delay Corrections (in mm)

Notice: Zenith Delay Computed from Default Met. Data by using

SR. HOPF Default Met. Data :

Pres. = 1000.00 mbar Temp. = 0.00°C Rel. Huml. = 50.00%

Stations	Corrections			
	Scale	& rms	Zenith Delay, in mm	rms
AL	0.0344	0.000	79	0
FA	0.0653	0.000	151	0
HA	0.1014	0.001	234	1
HE	0.0609	0.001	140	1
KK	0.1048	0.000	242	0
KO	0.0814	0.000	188	0
MA	0.0812	0.000	187	0
ME	0.0473	0.000	109	0
MP	0.0417	0.001	96	1
ON	0.0559	0.000	129	0
PA	0.1379	0.001	319	1
PE	0.0731	0.000	169	0
PI	0.0437	0.000	101	0
SA	0.0376	0.001	86	3
ST	0.0524	0.000	121	1
TR	0.0659	0.000	152	0
TW	0.1446	0.002	334	3
WT	0.1044	0.000	241	0
YA	0.0567	0.001	131	2
YE	0.0330	0.000	76	0

```
AMBIGUITY   3 :                            227.17    +/-   0.51
AMBIGUITY  17 :                            109.28    +/-   0.45
AMBIGUITY  46 :                            262.78    +/-   0.63
AMBIGUITY  28 :                            -41.61    +/-   0.37
AMBIGUITY  83 :                            548.15    +/-   0.43
AMBIGUITY  51 :                            265.62    +/-   0.36
AMBIGUITY  11 :                             66.43    +/-   0.28
AMBIGUITY  15 :                            -43.63    +/-   0.22
AMBIGUITY  62 :                            148.55    +/-   0.36
AMBIGUITY  55 :                            247.03    +/-   0.37
AMBIGUITY  73 :                            146.45    +/-   0.29
AMBIGUITY  48 :                            205.37    +/-   0.26
AMBIGUITY  84 :                            142.51    +/-   0.41
AMBIGUITY  49 :                            437.40    +/-   0.33
AMBIGUITY  76 :                            169.10    +/-   0.48

OBSERVATION /T1212X.PREDD.CIGNET.OUT.JULY25(YAHAGP3)
STATIONS:   YA HA

AMBIGUITY WRT REFERENCE SATELLITE :   18
AMBIGUITY  74 :                            443.98    +/-   6.75
AMBIGUITY  13 :                             69.96    +/-   4.56
AMBIGUITY  24 :                           -391.39    +/-   5.17

OBSERVATION /T1212X.PREDD.CIGNET.OUT.JULY25(YAHAGP4)
STATIONS:   YA HA

AMBIGUITY WRT REFERENCE SATELLITE :   16
AMBIGUITY  54 :                            355.13    +/-   3.83

OBSERVATION /T1212X.PREDD.CIGNET.OUT.JULY25(YAHAGP6)
STATIONS:   YA HA

AMBIGUITY WRT REFERENCE SATELLITE :   42
AMBIGUITY  20 :                           -107.58    +/-   4.91

OBSERVATION /T1212X.PREDD.CIGNET.OUT.JULY25(YAHAGP7)
STATIONS:   YA HA

AMBIGUITY WRT REFERENCE SATELLITE :    3
AMBIGUITY  50 :                           -192.34    +/-   3.95
AMBIGUITY  25 :                           -218.87    +/-   4.01

OBSERVATION /T1212X.PREDD.CIGNET.OUT.JULY25(YAHAGP10)
STATIONS:   YA HA

AMBIGUITY WRT REFERENCE SATELLITE :   58
AMBIGUITY  11 :                              9.03    +/-   7.47

OBSERVATION /T1212X.PREDD.CIGNET.OUT.JULY25(YAHAGP11)
STATIONS:   YA HA

AMBIGUITY WRT REFERENCE SATELLITE :   15
AMBIGUITY  41 :                           -224.58    +/-   6.35
AMBIGUITY 104 :                            -52.25    +/-   5.16
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Part 5 Satellite Orbit Results

(Referenced to initial epoch: GPS week 654 and GPS time 518400.00000 seconds)

PRN	Semi-major axis Arg. of Perigee	Eccentricity To	Inclination Direct Radiation	R.A. of Ascending node Y-Bias
Correction				
2	-0.199487583197D-02	0.462496844275D-10	0.788722531479D-10	-0.718260500607D-10
	-0.128532269056D-08	-0.652448790386D-05	0.122800271824D-11	0.581252494600D-11
3	-0.710884669399D-03	-0.266819766578D-10	0.276923922013D-10	-0.101647420134D-09
	0.230605662312D-08	0.167762359514D-04	0.628572153363D-12	0.165996472174D-11
11	-0.210556529143D-02	0.940834773109D-10	0.600760630095D-10	-0.182938465974D-09
	0.401366401993D-08	0.315405089980D-04	0.137636835391D-11	0.326318690939D-11
12	0.179939811737D-02	0.481301161550D-10	0.710267851065D-10	-0.362673563556D-10
	0.922217672458D-08	0.604280788243D-04	0.774227348567D-11	0.865374225931D-11
13	-0.220008268858D-02	-0.167572366881D-10	0.168327482522D-09	-0.259560011032D-09
	-0.119669566155D-07	-0.782019017911D-04	-0.349948307314D-11	0.363264601117D-11
14	-0.921986576154D-02	-0.313198444728D-10	-0.176348347327D-10	-0.118909504311D-09
	0.152409237724D-07	0.122273078893D-03	0.806837765021D-11	-0.149906810152D-10
15	0.590653689122D-02	-0.490685255217D-10	-0.142608048059D-09	0.137836672065D-09
	-0.163340377737D-07	-0.122367370641D-03	0.500529739636D-11	0.327940578839D-10
16	0.189092030864D-02	-0.126840867334D-09	0.121452094948D-09	-0.954025873812D-10
	-0.984007128782D-07	-0.673787308369D-03	-0.103944073920D-10	0.352585141365D-11
17	0.425035090748D-02	0.103177547095D-09	0.753990600263D-10	-0.526183361261D-10
	0.153400658261D-07	0.104128909768D-03	-0.701416046862D-11	0.900214829499D-11
18	0.236245769234D-02	-0.806720443754D-10	0.282388822031D-09	-0.475425927985D-10
	-0.198165530820D-07	-0.140767323530D-03	-0.206872999824D-10	0.335081493461D-11
19	-0.106789207735D-01	0.626062509883D-09	0.113370915004D-09	-0.256123938120D-09

	-0.106121676117D-05	-0.724837541208D-02	-0.809245146680D-10	-0.686852815666D-11
20	0.149226522875D-02	-0.107750781970D-10	0.112242815949D-09	-0.821542119026D-10
	-0.157652209278D-07	-0.111063806240D-03	0.252467559638D-11	-0.300378311016D-11
21	0.222418043125D-02	-0.371687799745D-10	0.126258422423D-09	-0.573306446968D-10
	0.562941634387D-09	0.502919758084D-05	0.278693741831D-12	0.372814436226D-11
23	0.296996372651D-02	-0.584964563204D-10	0.707540580918D-10	-0.351222682642D-12
	0.561858097815D-09	-0.953884796591D-06	-0.241978729481D-11	0.465714639445D-11
24	0.211437811601D-02	0.197644717628D-10	0.141999134679D-09	-0.316353526184D-09
	-0.422030516422D-07	-0.289279654982D-03	-0.110146465152D-10	-0.151425083655D-10
25	0.636619884209D-03	-0.220603885628D-10	0.114294242754D-09	-0.844784018083D-10
	0.584879411210D-08	0.399494976675D-04	-0.181500020034D-11	0.355474975696D-12
26	0.803249588982D-03	-0.108284580624D-11	0.417724100911D-10	-0.796844290912D-10
	-0.244117026534D-08	-0.183414248667D-04	0.308741395755D-11	0.548603096061D-12
28	-0.428111320336D-02	-0.107030665041D-09	0.935251108661D-10	-0.335886994274D-10
	0.143775160580D-07	0.979172167188D-04	0.111133588707D-11	0.910401770754D-11

Final Results

2	0.265613693816D+08	0.108332498834D-01	0.958152542096D+00	0.830997372167D+00
	-0.290973217500D+01	0.501875507355D+06	0.957575524194D-07	0.869532573602D-09
3	0.265579632693D+08	0.128454385566D-01	0.112236399162D+01	0.222383015038D+01
	0.249371167492D+01	0.522461186766D+06	0.814501773459D-07	0.277951759986D-09
11	0.265620655831D+08	0.134281167226D-01	0.111343008889D+01	0.221274978736D+01
	-0.225303811548D+01	0.503795468040D+06	0.825604017494D-07	-0.938209192988D-09
12	0.265581862905D+08	0.122737348954D-01	0.109600325055D+01	0.686150190973D-01
	-0.334985797505D+00	0.526992871605D+06	0.807858434469D-07	-0.363289061786D-08
13	0.265595874123D+08	0.384984158613D-02	0.110908206300D+01	0.219546767094D+01
	-0.251595428609D+01	0.517188027334D+06	0.857277197499D-07	-0.963138806332D-10
14	0.265612414377D+08	0.419352293022D-02	0.960520866392D+00	-0.226728979282D+01
	-0.332698522963D+01	0.512978044070D+06	0.960103288159D-07	0.618188724517D-09
15	0.265589229134D+08	0.722739423828D-02	0.961959528594D+00	0.298395609261D+01
	-0.437923384998D+01	0.497345022991D+06	0.916000834344D-07	0.541435794006D-08

16	0.265591729759D+08	0.118189851946D-02	0.957675288505D+00	-0.225448636521D+01
	0.332292755831D+01	0.530549473824D+06	0.944387509330D-07	0.549212601652D-09
17	0.265597328263D+08	0.682663419100D-02	0.963412425079D+00	0.301677999963D+01
	0.144392443352D+01	0.521687179448D+06	0.900792181418D-07	0.377044221470D-08
18	0.265598138779D+08	0.474245473687D-02	0.945627434848D+00	-0.126184619188D+01
	0.109843711916D+01	0.511234650852D+06	0.934313659881D-07	0.197750489577D-08
19	0.265589909850D+08	0.147602732558D-02	0.943693773304D+00	-0.200553422668D+00
	-0.462078820127D+00	0.507610783233D+06	0.963724193492D-07	0.473176877942D-09
20	0.265618080614D+08	0.416017505134D-02	0.963908322007D+00	0.836447780697D+00
	-0.467061547855D+01	0.506630775359D+06	0.972677708015D-07	0.479571796345D-09
21	0.265607001428D+08	0.100921585420D-01	0.954318187801D+00	-0.229293398706D+01
	0.244498862638D+01	0.539648127577D+06	0.961670316773D-07	0.569997916504D-09
23	0.265617842047D+08	0.604785367189D-02	0.958123554467D+00	-0.226261988153D+01
	-0.248899750966D+01	0.501997200624D+06	0.754820968535D-07	0.112725467256D-08
24	0.265607174474D+08	0.410246171731D-02	0.967240552501D+00	0.293784212056D+01
	0.386735141104D+01	0.525896197025D+06	0.839066988315D-07	0.133043103212D-08
25	0.265618269945D+08	0.625710599065D-02	0.953438183428D+00	-0.206441256377D+00
	-0.379159071917D+01	0.512863353790D+06	0.884254231241D-07	-0.223515772308D-10
26	0.265613914489D+08	0.813337136459D-02	0.960425541104D+00	-0.125062299386D+01
	-0.148553446488D+01	0.507112507539D+06	0.967408244509D-07	0.269289017647D-09
28	0.265607012029D+08	0.764268292830D-02	0.963194594391D+00	0.189602902371D+01
	0.271909722439D+01	0.532739870158D+06	0.923260206130D-07	0.337956072858D-08

Standard deviations for final results

2	0.339267508359D-01	0.138153200523D-08	0.992914317239D-09	0.160075138961D-08
	0.600137606937D-07	0.446608390573D-03	0.816637241050D-10	0.121730202440D-09
3	0.124422947245D-01	0.746813877687D-09	0.800830365716D-09	0.121191191799D-08
	0.319917772698D-07	0.217179824311D-03	0.450588954704D-10	0.225592624904D-10
11	0.182180044389D-01	0.462917609496D-09	0.780859124357D-09	0.960792137662D-09
	0.513674443847D-07	0.373425024694D-03	0.526226919532D-10	0.398357293079D-10
12	0.262965617458D-01	0.740307159022D-09	0.784474671785D-09	0.134553160485D-08
	0.849446330147D-07	0.571763596156D-03	0.554045423820D-10	0.110459337722D-09

13	0.213617601215D-01	0.485565990158D-09	0.824124689524D-09	0.114177927195D-08
	0.234372723394D-06	0.161598756991D-02	0.507049436359D-10	0.468687698681D-10
14	0.234838053629D-01	0.497923409443D-09	0.691080580637D-09	0.131813771307D-08
	0.323363446924D-06	0.222295535689D-02	0.879692620173D-10	0.416785481261D-10
15	0.924092470120D-02	0.709147532578D-09	0.109334348159D-08	0.141743232014D-08
	0.541138492717D-07	0.366497042729D-03	0.364402394923D-10	0.168965474102D-09
16	0.134579099358D-01	0.654961107311D-09	0.826536071557D-09	0.141782861945D-08
	0.720871886843D-06	0.493928057656D-02	0.580305161740D-10	0.252162777346D-10
17	0.812797277275D-02	0.566221652758D-09	0.974273511684D-09	0.142271458545D-08
	0.573052064525D-07	0.386138197506D-03	0.455276628628D-10	0.183530897553D-09
18	0.197753681066D-01	0.475238956655D-09	0.673284099808D-09	0.143927952141D-08
	0.224851944707D-06	0.153301682928D-02	0.167462590677D-09	0.272605942469D-10
19	0.192867573637D-01	0.590451435835D-09	0.842490787843D-09	0.128508472071D-08
	0.966992498910D-06	0.660492443761D-02	0.782744202459D-10	0.366282595407D-10
20	0.262676888391D-01	0.580020331861D-09	0.801998886511D-09	0.133704425961D-08
	0.247953903957D-06	0.172949140523D-02	0.559112025723D-10	0.794057481731D-10
21	0.244697992961D-01	0.435218524652D-09	0.851519768591D-09	0.120476746950D-08
	0.802631508179D-07	0.540486907276D-03	0.758749185533D-10	0.422901978989D-10
23	0.154606359844D-01	0.519435008365D-09	0.873324890291D-09	0.121425094367D-08
	0.891442576065D-07	0.631605414571D-03	0.509675513329D-10	0.261791369589D-10
24	0.227979156439D-01	0.614884358039D-09	0.128099311893D-08	0.264075401162D-08
	0.247973300414D-06	0.170295654071D-02	0.449104743023D-10	0.180250310834D-09
25	0.141784192945D-01	0.507546567036D-09	0.823963495227D-09	0.112985492306D-08
	0.101237347884D-06	0.696702483076D-03	0.487126934191D-10	0.338517011627D-10
26	0.276194690530D-01	0.112516497519D-08	0.863902896424D-09	0.103078297902D-08
	0.867911867914D-07	0.608927331363D-03	0.163651757852D-09	0.476350435856D-10
28	0.474561693290D-01	0.179289719376D-08	0.893192836398D-09	0.106247087187D-08
	0.513687235881D-07	0.347543045490D-03	0.136130579746D-09	0.975473261984D-10

Part 6 A Priori & A Posteriori Station Coordinates (Geodetic & Cartesian) and Their Discrepancies

(Reference Ellipsoid: a_e = 6378137.0 f-1 = 298.2572, x_e = 0.0, y_e = 0.0, z_e = 0.0)

Stations	Latitude : degree , minute , second Longitude: degree , minute , second Height : meter Cartesian: meter X , Y , Z PRIORI	Posteriori	RMS(mm)	Discrepancy in Coord. Components & Position mm
AL	45 57 20.87985	45 57 20.87985	0	0
	- 78 4 16.91374	- 78 4 16.91374	0	0
	200.877	200.877	0	0
	918129.616	918129.616	0	0
	-4346071.224	-4346071.224	0	0
	4561977.800	4561977.800	0	0
				0
FA	64 58 40.80813	64 58 40.80813	0	0
	-147 29 57.25544	-147 29 57.25544	0	0
	319.007	319.007	0	0
	-2281621.327	-2281621.327	0	0
	-1453595.775	-1453595.775	0	0
	5756961.976	5756961.976	0	0
				0
HA	- 25 53 13.57501	- 25 53 13.57501	0	0
	27 42 27.93449	27 42 27.93449	0	0
	1555.358	1555.358	0	0
	5084625.404	5084625.404	0	0
	2670366.499	2670366.499	0	0
	-2768494.039	-2768494.039	0	0
				0
HE	50 52 2.31818	50 52 2.32149	1	102
	0 20 10.56719	0 20 10.56607	2	-22
	76.836	76.724	4	-112
	4033470.603	4033470.453	3	-150
	23672.692	23672.669	2	-23
	4924301.360	4924301.338	3	-22
				153
KK	22 7 34.53228	22 7 34.53228	0	0
	-159 39 53.71399	-159 39 53.71399	0	0
	1167.363	1167.363	0	0
	-5543838.080	-5543838.080	0	0
	-2054587.522	-2054587.522	0	0
	2387809.570	2387809.570	0	0
				0

	52 10 42.32860	52 10 42.32860	0	0
	5 48 34.70755	5 48 34.70755	0	0
	96.868	96.868	0	0
KO				
	3899225.347	3899225.347	0	0
	396731.759	396731.759	0	0
	5015078.296	5015078.296	0	0
				0
	40 38 56.86530	40 38 56.86530	0	0
	16 42 16.04164	16 42 16.04164	0	0
	535.660	535.660	0	0
MA				
	4641949.814	4641949.814	0	0
	1393045.203	1393045.203	0	0
	4133287.266	4133287.266	0	0
				0
	60 13 2.89136	60 13 2.89261	1	39
	24 23 43.14837	24 23 43.13921	1	-141
	74.199	73.883	3	-316
ME				
	2892561.789	2892561.674	2	-115
	1311839.284	1311839.077	1	-207
	5512616.288	5512616.033	3	-255
				347
	27 45 49.78076	27 45 49.78329	2	78
	- 15 37 59.80322	- 15 37 59.80212	3	30
	198.659	198.779	6	120
MP				
	5439189.116	5439189.191	5	75
	-1522054.921	-1522054.911	3	10
	2953464.053	2953464.178	4	125
				146
	57 23 43.06867	57 23 43.06867	0	0
	11 55 31.85109	11 55 31.85109	0	0
	45.557	45.557	0	0
ON				
	3370658.757	3370658.757	0	0
	711876.989	711876.989	0	0
	5349786.812	5349786.812	0	0
				0
	- 17 34 0.26940	- 17 34 0.26234	4	217
	-149 34 28.31569	-149 34 28.31407	9	48
	337.342	338.011	9	669
PA				
	-5245194.620	-5245195.202	10	-582
	-3080472.227	-3080472.624	9	-397
	-1912825.489	-1912825.484	3	5
				704
	49 19 21.43297	49 19 21.43245	1	-16
	-119 37 29.92711	-119 37 29.92782	2	-14

	541.926	541.948	3	22
PE				
	-2059164.607	-2059164.633	2	-26
	-3621108.420	-3621108.436	2	-16
	4814432.463	4814432.469	2	6
				31
	33 36 43.75566	33 36 43.75660	1	29
	-116 27 29.36107	-116 27 29.36498	2	-101
	1256.156	1256.267	3	111
PI				
	-2369510.370	-2369510.494	2	-124
	-4761207.237	-4761207.260	3	-23
	3511396.079	3511396.165	2	86
				152
	- 33 9 1.04080	- 33 9 1.04598	8	-160
	- 70 40 6.81203	- 70 40 6.82021	15	-212
	723.087	723.184	18	97
SA				
	1769693.087	1769692.885	15	-202
	-5044574.287	-5044574.351	16	-64
	-3468321.035	-3468321.222	11	-187
				282
	47 35 42.85757	47 35 42.85709	1	-15
	- 52 40 39.88506	- 52 40 39.88276	2	48
	152.878	152.833	4	-45
ST				
	2612631.411	2612631.438	2	27
	-3426806.997	-3426806.953	3	44
	4686757.781	4686757.738	3	-43
				67
	69 39 45.88758	69 39 45.88758	0	0
	18 56 17.97279	18 56 17.97279	0	0
	132.450	132.450	0	0
TR				
	2102940.451	2102940.451	0	0
	721569.379	721569.379	0	0
	5958192.072	5958192.072	0	0
				0
	25 1 16.79394	25 1 16.80903	15	464
	121 32 11.53789	121 32 11.54059	39	76
	43.968	43.305	26	-662
TW				
	-3024781.762	-3024781.410	31	352
	4928936.957	4928936.238	37	-719
	2681234.453	2681234.594	9	141
				812
	49 8 39.20448	49 8 39.20511	0	20
	12 52 44.03976	12 52 44.03873	1	-21
	666.061	666.057	2	-4
WT				
	4075578.683	4075578.671	1	-12

	931852.634 4801569.980	931852.610 1 4801569.990 1	-24 10 28
YA	- 29 2 47.61947 115 20 49.09873 241.281 -2389025.331 5043316.830 -3078530.926	- 29 2 47.61947 0 115 20 49.09873 0 241.281 0 -2389025.331 0 5043316.830 0 -3078530.926 0	0 0 0 0 0 0 0
YE	62 28 51.22388 -114 28 50.50947 180.814 -1224452.369 -2689216.048 5633638.286	62 28 51.22388 0 -114 28 50.50947 0 180.814 0 -1224452.369 0 -2689216.048 0 5633638.286 0	0 0 0 0 0 0 0

A POSTERIORI VARIANCE FACTOR : 1.8148

CROSS-CORRELATION BETWEEN STATIONS
ALL |CROSS-CORRELATION VALUES| SMALLER THAN 1.00

CROSS-CORRELATION BETWEEN COORDINATES

STATION NAME : AL

ALL |CROSS-CORRELATION VALUES| SMALLER THAN 1.00

CROSS-CORRELATION BETWEEN COORDINATES
ALL |CROSS-CORRELATION VALUES| SMALLER THAN 1.00

STATION NAME : FA

ALL |CROSS-CORRELATION VALUES| SMALLER THAN 1.00

CROSS-CORRELATION BETWEEN COORDINATES
ALL |CROSS-CORRELATION VALUES| SMALLER THAN 1.00

STATION NAME : HA

ALL |CROSS-CORRELATION VALUES| SMALLER THAN 1.00

CROSS-CORRELATION BETWEEN COORDINATES
ALL |CROSS-CORRELATION VALUES| SMALLER THAN 1.00

STATION NAME : HE

ALL |CROSS-CORRELATION VALUES| SMALLER THAN 1.00

CROSS-CORRELATION BETWEEN COORDINATES
ALL |CROSS-CORRELATION VALUES| SMALLER THAN 1.00

STATION NAME : KK

ALL |CROSS-CORRELATION VALUES| SMALLER THAN 1.00

CROSS-CORRELATION BETWEEN COORDINATES
ALL |CROSS-CORRELATION VALUES| SMALLER THAN 1.00

STATION NAME : KO

ALL |CROSS-CORRELATION VALUES| SMALLER THAN 1.00

CROSS-CORRELATION BETWEEN COORDINATES
ALL |CROSS-CORRELATION VALUES| SMALLER THAN 1.00

STATION NAME : MA

ALL |CROSS-CORRELATION VALUES| SMALLER THAN 1.00

CROSS-CORRELATION BETWEEN COORDINATES
ALL |CROSS-CORRELATION VALUES| SMALLER THAN 1.00

STATION NAME : ME

ALL |CROSS-CORRELATION VALUES| SMALLER THAN 1.00

CROSS-CORRELATION BETWEEN COORDINATES
ALL |CROSS-CORRELATION VALUES| SMALLER THAN 1.00

STATION NAME : MP

ALL |CROSS-CORRELATION VALUES| SMALLER THAN 1.00

CROSS-CORRELATION BETWEEN COORDINATES
ALL |CROSS-CORRELATION VALUES| SMALLER THAN 1.00

STATION NAME : ON

ALL |CROSS-CORRELATION VALUES| SMALLER THAN 1.00

CROSS-CORRELATION BETWEEN COORDINATES
ALL |CROSS-CORRELATION VALUES| SMALLER THAN 1.00

STATION NAME : PA

ALL |CROSS-CORRELATION VALUES| SMALLER THAN 1.00

CROSS-CORRELATION BETWEEN COORDINATES
ALL |CROSS-CORRELATION VALUES| SMALLER THAN 1.00

STATION NAME : PE

ALL |CROSS-CORRELATION VALUES| SMALLER THAN 1.00

CROSS-CORRELATION BETWEEN COORDINATES
ALL |CROSS-CORRELATION VALUES| SMALLER THAN 1.00

```
STATION NAME : PI
-----------------
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

CROSS-CORRELATION BETWEEN COORDINATES
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

STATION NAME : SA
-----------------
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

CROSS-CORRELATION BETWEEN COORDINATES
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

STATION NAME : ST
-----------------
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

CROSS-CORRELATION BETWEEN COORDINATES
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

STATION NAME : TR
-----------------
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

CROSS-CORRELATION BETWEEN COORDINATES
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

STATION NAME : TW
-----------------
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

CROSS-CORRELATION BETWEEN COORDINATES
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

STATION NAME : WT
-----------------
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

CROSS-CORRELATION BETWEEN COORDINATES
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

STATION NAME : YA
-----------------
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

CROSS-CORRELATION BETWEEN COORDINATES
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

STATION NAME : YE
-----------------
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

CROSS-CORRELATION BETWEEN COORDINATES
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00
```

Part 7 Baseline Components Summary

Baseline Name	Baseline Length & its rms			
	azimuth 1'st to 2'nd		azimuth 1'st to 2'nd	
* Priori	Posteriori(Geodetic &		Cartesian & rms(mm)	
Latitude	Latitude		X (m)	
Longitude	Longitude		Y (m)	
Height (m)	Height (m)		Z (m)	
AL ST	1931826.4044	m +/-	2	
	- 75 23 44.418	0.000	85 57 21.981	0.000
1 38 21.97773	1 38 21.97724	1	-1694501.8216	2
25 23 37.02869	25 23 37.03099	2	-919264.2713	3
-47.99884	-48.0436	4	-124779.9379	3
FA KK	4728047.9226	m +/-	0	
	163 30 59.340	0.000	7 27 48.941	0.000
- 42 51 6.27585	- 42 51 6.27585	0	3262216.7530	0
- 12 9 56.45855	- 12 9 56.45855	0	600991.7470	0
848.35550	848.3555	0	3369152.4060	0
HA SA	8426081.4151	m +/-	17	
	123 19 18.837	0.000	116 11 33.893	0.000
- 7 15 47.46579	- 7 15 47.47097	8	3314932.5192	15
- 98 22 34.74652	- 98 22 34.75470	15	7714940.8501	16
-832.27070	-832.1740	18	699827.1826	11
HE KO	406737.3713	m +/-	2	
	- 66 51 55.631	0.001	108 50 53.301	0.001
1 18 40.01042	1 18 40.00711	1	134245.1064	3
5 28 24.14036	5 28 24.14148	2	-373059.0898	2
20.03201	20.1436	4	-90776.9580	3
KK PA	4431375.5968	m +/-	4	
	-165 7 34.757	0.000	14 26 45.006	0.000
- 39 41 34.80168	- 39 41 34.79462	4	-298642.8779	10
10 5 25.39830	10 5 25.39992	9	1025885.1023	9
-830.02067	-829.3518	9	4300635.0540	3
KO ON	700520.4827	m +/-	0	
	- 31 39 0.745	0.000	143 20 46.653	0.000
5 13 0.74008	5 13 0.74007	0	528566.5900	0
6 6 57.14354	6 6 57.14354	0	-315145.2300	0
-51.31136	-51.3114	0	-334708.5160	0
MA HA	7032929.4432	m +/-	0	
	-169 12 36.134	0.000	9 5 39.371	0.000
- 66 32 10.44031	- 66 32 10.44031	0	-442675.5900	0
11 0 11.89285	11 0 11.89285	0	-1277321.2960	0
1019.69799	1019.6980	0	6901781.3050	0
MA MP	3244284.4847	m +/-	3	
	105 39 22.468	0.000	55 42 46.681	0.000
- 12 53 7.08455	- 12 53 7.08201	2	-797239.3770	5
- 32 20 15.84486	- 32 20 15.84377	3	2915100.1138	3

-337.00035	-336.8808	6	1179823.0884	4
MA WT	989988.2218	m +/-	0	
	16 24 57.408	0.000	160 52 33.309	0.000
8 29 42.33917	8 29 42.33981	0	566371.1432	1
- 3 49 32.00189	- 3 49 32.00292	1	461192.5932	1
130.40080	130.3971	2	-668282.7241	1
ON ME	784247.8455	m +/-	1	
	- 61 10 42.629	0.000	108 8 24.141	0.000
2 49 19.82268	2 49 19.82394	1	478097.0834	2
12 28 11.29729	12 28 11.28813	1	-599962.0878	1
28.64288	28.3267	3	-162829.2209	3
PE AL	3074668.3475	m +/-	2	
	- 80 52 2.434	0.000	67 47 54.791	0.000
- 3 22 0.55313	- 3 22 0.55260	1	-2977294.2487	2
41 33 13.01337	41 33 13.01408	2	724962.7878	2
-341.04899	-341.0711	3	252454.6692	2
PE PI	1758989.3388	m +/-	1	
	-170 17 29.932	0.000	7 35 28.119	0.000
- 15 42 37.67731	- 15 42 37.67584	1	310345.8616	2
3 10 0.56604	3 10 0.56284	2	1140098.8242	2
714.23063	714.3195	3	1303036.3046	2
AL YE	2912779.2285	m +/-	0	
	38 12 6.979	0.000	111 37 18.893	0.000
16 31 30.34403	16 31 30.34403	0	2142581.9850	0
- 36 24 33.59573	- 36 24 33.59573	0	-1656855.1760	0
-20.06256	-20.0626	0	-1071660.4860	0
PI KK	4320253.7964	m +/-	3	
	95 19 29.602	0.000	63 35 49.239	0.000
- 11 29 9.22338	- 11 29 9.22432	1	3174327.5857	2
- 43 12 24.35292	- 43 12 24.34901	2	-2706619.7384	3
-88.79341	-88.9044	3	1123586.5946	2
SA PA	7448886.9944	m +/-	14	
	99 19 58.170	0.000	119 49 56.597	0.000
15 35 0.77140	15 35 0.78364	8	7014888.0869	14
- 78 54 21.50366	- 78 54 21.49386	17	-1964101.7268	16
-385.74477	-385.1726	22	-1555495.7376	11
TR ME	1081877.0715	m +/-	1	
	-163 43 41.599	0.000	11 18 39.552	0.000
- 9 26 42.99623	- 9 26 42.99497	1	-789621.2226	2
5 27 25.17558	5 27 25.16642	1	-590269.6978	1
-58.25018	-58.5663	3	445576.0391	3
TW YA	5795875.0463	m +/-	9	
	173 17 50.201	0.002	6 56 49.189	0.002
- 54 4 4.41341	- 54 4 4.42850	15	-635756.0788	31
- 6 11 22.43916	- 6 11 22.44185	39	-114380.5916	37
197.31370	197.9761	26	5759765.5196	9
WT KO	602528.5192	m +/-	1	

```
||                  |  53 16 15.904  0.000|  121 15 24.359  0.000||
||    3  2  3.12412|   3  2  3.12349      0|    176353.3238      1 ||
|| -  7  4  9.33221|-  7  4  9.33118      1|    535120.8508      1 ||
||    -569.19269    |     -569.1890       2|   -213508.3059      1 ||
||__________________|______________________|_______________________||
||     YA      HA   |    7847449.9969   m +/-      0               ||
||                  | 112  2 38.570  0.000|  115 43 17.566  0.000||
||    3  9 34.04446|   3  9 34.04446      0|  -7473650.7350      0 ||
|| - 87 38 21.16424|- 87 38 21.16424      0|   2372950.3310      0 ||
||    1314.07656    |     1314.0766       0|   -310036.8870      0 ||
||__________________|______________________|_______________________||
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CROSS-CORRELATION BETWEEN BASELINE COMPONENTS

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BASELINE OF STATIONS : AL &  ST
-----------------------------------
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

BASELINE OF STATIONS : FA &  KK
-----------------------------------
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

BASELINE OF STATIONS : HA &  SA
-----------------------------------
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

BASELINE OF STATIONS : HE &  KO
-----------------------------------
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

BASELINE OF STATIONS : KK &  PA
-----------------------------------
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

BASELINE OF STATIONS : KO &  ON
-----------------------------------
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

BASELINE OF STATIONS : MA &  HA
-----------------------------------
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

BASELINE OF STATIONS : MA &  MP
-----------------------------------
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

BASELINE OF STATIONS : MA &  WT
-----------------------------------
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00
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ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

BASELINE OF STATIONS : ON &  ME
-----------------------------------
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

BASELINE OF STATIONS : PE &  AL
-----------------------------------
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

BASELINE OF STATIONS : PE &  PI
-----------------------------------
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

BASELINE OF STATIONS : AL &  YE
-----------------------------------
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

BASELINE OF STATIONS : PI &  KK
-----------------------------------
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

BASELINE OF STATIONS : SA &  PA
-----------------------------------
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

BASELINE OF STATIONS : TR &  ME
-----------------------------------
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

BASELINE OF STATIONS : TW &  YA
-----------------------------------
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

BASELINE OF STATIONS : WT &  KO
-----------------------------------
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00

BASELINE OF STATIONS : YA &  HA
-----------------------------------
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00
ALL |CROSS-CORRELATION VALUES| SMALLER THAN  1.00
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Part 8 Baseline Discrepancies in Latitude, Longitude, Height and Length

Baseline	Length (in m)	Discrepancies (in mm) North	East	Height	Length
AL ST	1931826.404	15	-48	45	-42
FA KK	4728047.923	0	0	0	0
HA SA	8426081.415	160	212	-97	-154
HE KO	406737.371	102	-21	-112	24
KK PA	4431375.597	-217	-48	-669	-48
KO ON	700520.483	0	0	0	0
MA HA	7032929.443	0	0	0	0
MA MP	3244284.485	-78	-30	-120	36
MA WT	989988.222	-20	21	4	-25
ON ME	784247.845	-39	141	316	141
PE AL	3074668.347	-16	-15	22	-22
PE PI	1758989.339	-45	83	-89	37
AL YE	2912779.228	0	0	0	0
PI KK	4320253.796	29	-112	111	54
SA PA	7448886.994	-376	-289	-572	-310
TR ME	1081877.072	-39	141	316	92
TW YA	5795875.046	465	73	-662	-115
WT KO	602528.519	20	-20	-4	29
YA HA	7847449.997	0	0	0	0

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