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地球参考系研究进展

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提要

本文简要阐述了地球参考系的定义、实现和相互变换；评述了地球参考系在近十几年来的研究进展，并结合90年代对地球参考系的毫米级要求，讨论了目前存在的问题和可能的改进设想。

Progress in the Research of Conventional Terrestrial Reference System

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Abstract

Firstly, the definition, realization and transformation of Conventional Terrestrial Reference System (CTRS) are described. Secondly, the recent progress of the CTRS research is reviewed. Finally, we discuss the problems and possible improvements for CTRS with millimeter accuracy in the 1990' s.

1. Introduction

In order to describe various phenomena of kinematics and dynamics occurred in the deforming Earth, an appropriate terrestrial reference system is needed.

The establishment of the CTRS with high accuracy has become possible because of the development of space geodetic techniques such as Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Lunar Laser Ranging (LLR), Global Positioning System (GPS), and so on. The great progress achieved by these techniques in recent more than 10 years, has not only greatly improved the accuracy of the CTRS, but also revised the concept of the CTRS. The main difference in concept is that the observing stations on the surface of the Earth are no longer assumed motionless with respect to each other and time has been a non-negligible reference ele-

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ment. The three-dimensional CTRS has been substituted by the four-dimensional CTRS. Furthermore, at the end of the 1980' s, the motions of the observing stations only contain the horizontal velocities predicted from geological plate motion observations, but now they must contain not only the horizontal velocities predicted from geological observations, but also the horizontal and even vertical velocities from space geodetic observations. This paper presents the progress in the research of the CTRS.

2. Definition of the CTRS

1. Ideal Terrestrial Reference System

An ideal terrestrial reference system should be such a system fixed to the Earth[1,31]: relative to which the Earth should only have deformations(i. e. no global rotation and translation); relative to the celestial reference system which only represents the global motions of the Earth, such as orbit motions and rotation of the Earth. Theoretically, to define such a system, one usually uses the Tisserand condition[2,3], which can be expressed mathematically as

$$\begin{cases} \int_D \mathbf{V} \cdot \mathrm{d}m = 0 \\ \int_D \mathbf{R} \times \mathbf{V} \cdot \mathrm{d}m = 0 \end{cases} \tag{2.1}$$

where D is the domain considered as the whole Earth; **R** is the position vector of dm in the reference frame; dm is a mini-mass element at **R**; **V** is the velocity vector of dm.

2. Conventional Terrestrial Reference System

The preceding theoretical definition only specify the manner of the CTRS fixed to the Earth. One must define its origin, scale, and orientation in practical application. The definition of the CTRS given by Boucher et al. is as follows[4,6]:

(a) It is geocentric, the center of mass being defined for the whole Earth, including oceans and atmosphere.

(b) Its scale is that of a local Earth frame, in the meaning of a relativistic theory of gravitation.

(c) Its orientation is defined by the Earth Rotation Parameter at a certain reference epoch.

(d) Its time evolution in orientation will create no residual global rotation and translation with respect to the crust.

If D in formula (2.1) is only considered as the crust, obviously, (d) is equivalent to the approximate Tisserand condition. It is worthy of mention that the premise of the definition like this is that the crust has no net rotation and translation relative to the deep mantle, if not, this definition would not be rigious.

The so called "conventional" means that the origin, scale and orientation of the CTRS is usually defined in agreement with the conventional standards given by international organizations.

3. Conventional Terrestrial Reference Frame

Once a CTRS is chosen, the coordinates of a certain number of fiducial points on the Earth' s surface can be determined in the CTRS from observations, and the set of points should be numerous enough and accessible to observation so as to allow the coordinates of the other points to be determined with respect to them. Then, the set of fiducial points and their coordinates make up a conventional terrestrial reference frame(CTRF). The purpose of realizing a CTRF is to provide a means to materialize a CTRS so that it can be used for the quantitative description of positions and motions on the Earth. The CTRS is a general concept, and practically the CTRF is used more often than the CTRS.

4. Time References

According to the modern concept of CTRS, the points on the Earth' s surface should not be considered motionless. The drift of the points with time would cause deformation of the CTRF, and therefore time has to be considered. The CTRF with high accuracy should include not only the coordinates of the points, but also a reference epoch and a drift velocity field of the points.

3. Realization of the CTRS

1. The Establishment of the CTRF

Currently, the establishment of the CTRF is mainly based upon VLBI, SLR, and GPS techniques[9,11]. The Doppler technique was no longer in use after 1988 because of its low accuracy, LLR has little contribution to the CTRF because there are only a few LLR observing stations. A recent breakthrough in GPS has made itself very important in the establishment of the CTRF.

The ideal distribution of the observing stations in the CTRF should constitute a polyhedron[2]. In reality it is not possible, but the distribution of the stations should satisfy the following requirements as far as possible[25]: (i) There are a sufficient number of stations on most of the major plates to provide the necessary statistical strength; (ii) The stations lie on relatively stable parts of the plates so as to reduce the possibility that the tectonic deformation affects the configuration of the CTRF. Figure 5-1 shows the distribution of the observing stations currently in operation. Obviously, the requirements above are far from satisfactory.

The geometric origin of the CTRF is defined at the center of mass of the Earth (geocenter) by satellite-based dynamical techniques. The ephemeris used in these techniques is related to the geocenter, so the station coordinates determined by them is geocentric coordinates. Because of errors in observations and ephemeris, the real origin of the CTRF can not be rigiously determined at the geocenter, therefore, translation of the origin of the CTRF should be considered when comparison or transformation between any two different CTRF is performed. The scale of the CTRF is usually fixed by adopting the velocity in vacuum of electromagnetic waves (c), the suitable relativistic correction models, and the gravitational constant of the Earth (GM). Adopting different models and constants may cause different scales. The orientation of the CTRF is often defined by adopting Earth Rotation Parameter (ERP) at a certain epoch. Earth Rotation Parameters at different epochs will give different orientation. The time evolution constraint in orientation of the CTRF may be realized in two ways: (i) adopting a no-net-rotation plate motion model (e. g. AM0-2 or NNR-NUVEL1); (ii) adopting the discrete Tisserand condition:

$$\begin{cases} \sum_{k} \mathbf{V}_k = 0 \\ \sum_{k} \mathbf{R}_k \times \mathbf{V}_k = 0 \end{cases} \tag{3.1}$$

Because the distribution of the stations would possiblly affect the orientation of the CTRF when the second way is adopted, so one usually adopts the first way.

Space geodetic techniques provide a large variety of data, the complex analysis of these data is performed by various data analysis centers. One of the tasks of these centers is to establish the CTRF based on these techniques. The main characteristics of these CTRF are described as follows[3]:

(a) VTRF, a CTRF series realized by VLBI techniques. Very Long Baseline Interferometry, in its geodetic use, provides relative position between two ground stations, by measuring the relative propagation delays of a radio signal from a compact extragalactic radio source. The extragalactic radio sources form approximately an ideal inertial celestial reference frame, and VTRF can be attached to this frame directly. The geocentric coordinates of VLBI stations can not be obtained directly, however, because VLBI observations are not sensitive to the geocenter. Conceptionally, one can not establish a CTRF whose origin locates at the geocenter only by VLBI. In practice, the origin of VTRF is usually fixed by adopting SLR geocentric coordinates of a VLBI-SLR co-location station (e. g. Westford station in U. S. A.)[21,23]. The disadventage is that the error in initial coordinate would result in a drift of the whole VTRF.

(b) STRF, a CTRF series realized by SLR techniques. Satellite Laser Ranging provides laser ranging data from several tens of ground stations to properly equipped satellites such as STARLETTE, AJIKAIE, and especially LAGEOS. One can obtain the geocentric coordinates of SLR stations directly from SLR observations because they are sensitive to the geocenter. The origin of STRF can be defined at the geocenter by putting to zero, the three first coefficients of the spherical harmonic expansion of the geopotential, therefore, STRF is indeed a geocentric CTRF. Its disadventage is that it can not be directly attached to a radio source celestial reference frame.

(c) LTRF, a CTRF series realized by LLR techniques. LTRF is simlar to STRF, but its accuracy is lower, and the number of its observing stations is smaller.

(d) GTRF, a CTRF series realized by GPS techniques. Global Positioning System determines the positions of the observing stations by receiving radio signals from satellites. GPS can provide two kinds of positioning ways: (i) Absolute positioning way, which can realize a geocentric CTRF, but its positioning accuracy is very low, and has no contribution to the CTRF with high accuracy; (ii) Relative positioning way, which is simlar to VLBI, thus GTRF realized by this way is also simlar to VTRF.

(e) BTS/ITRF, a CTRF series established by international service orgnization, because of the limitation of the CTRFs realized by various single techniques, for example, VTRF and GTRF are not really geocentric CTRF, STRF and LTRF can not link to a ideal radio source celestial reference frame directly, thus, it is necessary to establish an optimistic CTRF by combining the adventages of various techniques. BTS and ITRF series are this kind of CTRF and have been in use for international service.

2. The Maintenance of the CTRF

The Earth is not a rigid body, and various deformations are occurring in the Earth. In order to maintain stability of the CTRF in the deforming Earth, one must model and correct these deformations. Considering the effect of these deformations, coordinates of a point on the Earth's surface at epoch t can be expressed as

$$\begin{cases} \mathbf{R}(t) = \mathbf{R}_0 + \mathbf{R}(t - t_0) \times \sum\limits_k \Delta\mathbf{R}_k(t) \\ \mathbf{R} = \mathbf{V}_P + \mathbf{V}_i + \mathbf{V}_r \end{cases} \tag{3.2}$$

where $\mathbf{R}_0$ and $\mathbf{R}$ are the coordinate and coordinate velocity of the point at epoch t_0 respectively; $\mathbf{V}_P$ is the horizontal velocity caused by plate motion; $\mathbf{V}_i$ is the vertical velocity caused by post-glacial crust rebound; $\mathbf{V}_r$ is the resi dual velocity except $\mathbf{V}_P$ and $\mathbf{V}_i$ caused by regional deformations; $\sum\limits_k \Delta\mathbf{R}_k(t)$ are corrections to the deformations caused by short-term and short-period geodynamical phenomena such as solid Earth tide, ocean loading, and atmosphere loading. Further corrections could be added if they are at mm level and can be computed by a suitable model.

The Effect of Plate Motions: Large-scale plate motions occurring in the Earth would cause drifts of the stations in the CTRF, and the drift velocity is about 1—10 cm. yr^{-1}. Now the observing results from VLBI and SLR have confirmed this kind of drifts, and the drift velocity from VLBI and SLR is roughly consistent with those from geological information. Therefore, in order to maintain stability of the CTRF, one often use an appropriate plate motion model to correct the coordinate drifts. The plate model can provide the Euler vector of each plate, $\vec{\omega}$. Let $\mathbf{R}_0$ be a position vector of a point in k plate at epoch t_0, its drift velocity would be

$$\mathbf{V}_P = \vec{\omega}_k \times \mathbf{R}_0 \tag{3.3}$$

The plate model AM0-2[15] was widely adopted before 1991, but now, the new model NNR-NUVEL1[15,17] is recommended to replace AM0-2 in IERS standards (1992)[13].

The Effect of Regional Deformations: The plates are assumed as rigid bodies when a global plate motion model is established, but in reality, deformations are occurring in boundaries and even central parts of the plates[22]. The stations which locate in deformation zones would not follow completely the motions of the rigid plates, they would move at the combining velocities of plate motions ($\mathbf{V}_P$) and regional deformations ($\mathbf{V}_r$). The effect of this kind of deformations on the station coordinates could be corrected by establishing the regional deformation models.

The Effect of Post-glacial Crust Rebound: The vertical motions of stations are mainly caused by post-glacial rebound, which only occurs in some formerly glacier-covered regions, for instance, Hudson Bay and Fennoscandia, where the maximum rebound velocity is up to 14 mm·yr^{-1}. Tushingham and Peltier(1991)[26] inferred a new global model of late Pleistocene deglaciation based upon geophyical predictions of post-glacial relative sea level change, referred to as ICE-3G, which can be used to compute the vertical motions of the stations[10].

The Effect of Short-term and Short-Period Deformations: The solid Earth tide can cause periodic displacement of the ground stations (long term displacement is also considered). The level of the displacement may be up to several tens of cm. The theory of Wahr (1981)[28] was recommended in IERS standards (1992) to compute corrections to the solid Earth tide displacement, and the precision of correction is 1 cm. In addition, the ocean and atmosphere loading may also cause the displacement of the ground stations, and the corresponding correction models are given in IERS standards (1992). With the improvement of accuracy of the CTRF, more and more deforming sources should be considered.

The Effect of Suddenly Occurred Deformations such as the Earthquakes: Some suddenly occurred deformations, such as the earthquakes, would significantly change the coordinates of the stations which locate at nearby deformation zones. One should replace the old station coordinates by the new values after the deformations happen.

4. Transformation of the CTRS

1. Transformation Between Any Two CTRFs

As mentioned above, different techniques, models, constants and analysing methods, would result in different CTRFs, such as VTRF, STRF, GTRF, ITRF, and so on, and therefore their origin, scale, and orientation may not be rigiously consistent with each other. In practical application, coordinates of some points often need to be transfomed from a CTRF into another. There are many models which can be used to perform the transformation. For any two Cartesian systems, the seven-parameter similarity tranformation model is usually adopted and also recommended in IERS standards (1992)[29]:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} + (1+\delta s) \begin{bmatrix} 1 & \delta\omega & -\delta\psi \\ -\delta\omega & 1 & \delta\epsilon \\ \delta\psi & -\delta\epsilon & 1 \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix} \tag{4.1}$$

where Δx, Δy, Δz are coordinates of the origin of the frame (u, v, w) in the frame (x, y, z); $\delta\epsilon$, $\delta\psi$, $\delta\omega$ are differential rotations respectively, around the axes (u, v, w) to establish parallelism with the (x, y, z) frame; and δs is differential scale change.

In order to perform transformation between any two CTRFs, co-location observing stations with different techniques are necessary. The transformation parameters can be estimated from these co-location observations. Currently, there are 32 co-location stations on the Earth[14]: 5 VLBI-SLR-GPS, 3 VLBI-SLR-LLR, 15 VLBI-SLR, 6 VLBI-GPS, and 3 SLR-GPS. Except SLR-GPS, any two techniques have more than 3 co-location stations, so they can be transformed to each other satisfactorily.

For each new ITRF for global service established by IERS, IERS gives both the transformation parameters between the ITRF and the other CTRFs and the previous BTS/ITRF frames[7,8]. One can use these parameters to perform transformation between any two CTRFs easily. Due to the drifts of the station coordinates, each CTRF has a reference epoch, and the transformation parameters between two CTRFs with different epoches are different, therefore, IERS gives not only the transformation parameters at a certain epoch, but also the rate of change of these parameters (the scale is considered unchangeable with time). For the transformation parameters

$T(t_0)$ and its rate of change $\dot{T}$ at epoch t_0, the transformation parametrs at epoch t would be

$$T(t)=T(t_0)+\dot{T}(t-t_0) \tag{4.2}$$

2. Comparison Between Any Two CTRFs

For a CTRF realized by a single technique, its precision is only internal consistency. In order to evaluate the real accuracy of the CTRF, one should combine different techniques. Because of the systematic differences between the two kinds of CTRF, comparison can not be performed directly. For a comparison, two sets of coordinates of the co-location stations should be transformed to a same frame, and the coordinate differences in the frame could be used to evaluate the realizing accuracy of the CTRF. Ray et al. (1991)[30] adopted the geocentric coordinates of 18 pairs of VLBI-SLR stations to compare VTRF with STRF. After seven-parameter frame adjustment, the two coordinate sets have weighted rms of 15, 22, and 22 mm for x, y, and z, respectively, indicating that the accuracy of geocentric coordinates determined by VLBI and SLR techniques is within 30 mm level.

5. Progress of the CTRS

Since the NASA Crustal Dynamics Program began, the relevant techniques (e. g. VLBI, SLR, LLR, GPS) have changed profoundly. Various relevant dynamical models and data processing methods have become more and more refined, and the new observing stations have also largely increased. All of these improvements have greatly promoted the research and service of the CTRS. The accuracy of the CTRS have been raised from the early tens of centimeters level to sub-centimeter level at present, and the three-dimensional CTRS has been substituted by the four-dimensional CTRS, here we present the progress of the CTRS in the following aspects.

1. Increase of the Observing Stations and Improvement of the Observing Accuracy

Because of the adoption of VLBI Mark Ⅲ data acquisition system, the observing precision of VLBI system has been raised from tens of cm in the 1970's to a few cm in the 1980's. Moreover, with the improvement of the sensitivity of the receiver and the stability of the atmotic clock, and refinement of data processing methods, the observing precision of VLBI system has been raised to sub-cm level at the end of 1980' s and the early 1990's. Now the precision of VLBI baseline (24 hours observation) is 5.1mm + 2.2ppb[32]. Meanwhile, the number of VLBI stations for astrogeodynamics has been increased from about 10 at the early 1980's to 87 (36 fixed stations, 51 mobile ones) at present. The distribution of VLBI stations is shown in figure 5-1 and table 5-1.

SLR technique has been largely upgraded in the last 10 years. The third generation laser ranging intruments have raised the ranging precision from the early tens of cm to 5cm, moreover, with further improvement of the instruments and refinement of data processing methods, the ranging precision has now reached 3cm. In addition, the number of SLR stations has also been increased from the early about 20 to the present more than 70. The distribution of SLR stations is shown in figure 5-1 and table 5-1.

There are only 3 LLR stations, and the LLR station in Hawaii stopped operation in 1991. But its ranging precision has been largely raised and is now better than 6 cm.

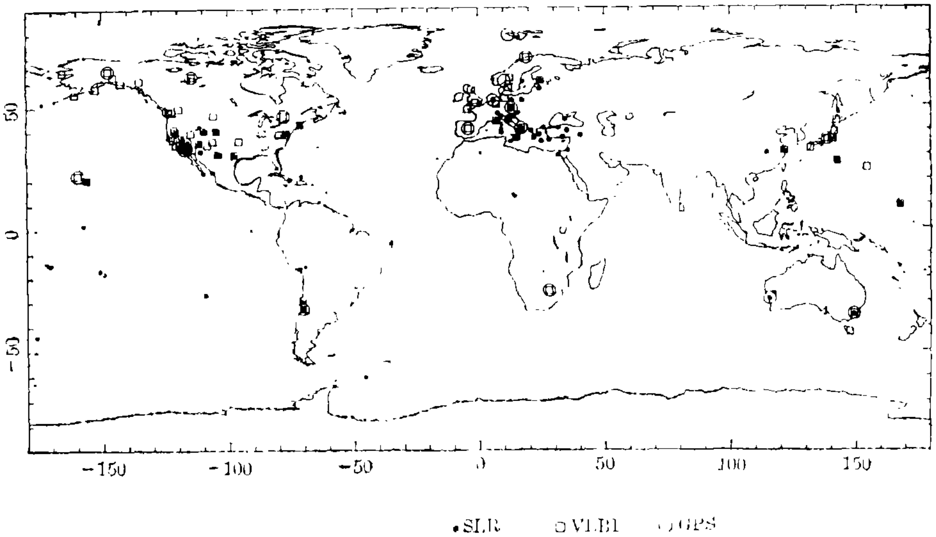

Figure 5-1 The Global Distribution of the Observing Stations in ITRF 91

Table 5-1 The Distribution of the Existing Observing Stations at Present and the Observing Stations Planned in the 1990's in Global Plates

	Stations	NOAM	EURA	PCFC	AUST	SOAM	AFRC	INDI	ANTA	NAZC	COCO	CARB	ARAB	PHIL
VLBI	Existing	51	17	15	2	1	1							1
	Planned	5	3	3	1	1		1	2					
SLR	Existing	24	33	4	2	4	2			1				1
	Planned	3	4											
LLR	Existing	1	1	1										
	Planned	1	2		1									
GPS	Existing	9	7	1	2	1	1							
	Planned	≥3	≥3	≥3	≥3	≥3	≥3	≥3	≥3	≥3	≥3	≥3	≥3	≥3

Table 5-2 Evolution of the CTRF Realized by BIH and IERS(1984-1991)

Organization	Characteristics		NAME	Techniques	Motion Model	Epoch	Number of Stations
BIH	3-Dimensional		BTS84	VLBI, SLR, LLR, Doppler			34
			BTS85	VLBI, SLR, LLR, Doppler			94
	4-D	2-D Velocity Field	BTS86	VLBI, SLR, LLR, Doppler	AMO-2	1984.0	123
			BTS87	VLBI, SLR, LLR, Doppler	AMO-2	1984.0	140
IERS			ITRF88	VLBI, SLR, LLR	AMO-2	1988.0	96
			ITRF89	VLBI, SLR, LLR	AMO-2	1988.0	115
			ITRF90	VLBI, SLR, LLR,	AMO-2	1988.0	124
		3-D Velocity Field	ITRF91	VLBI, SLR, LLR, GPS	ESTIMATES/ NNR-NUVEL1	1988.0	130
			ITRF92				

GPS technique has achieved breakthrough in recent several years in its geodynamical applications, especialy in establishing the CTRF with high accuracy. Its ability of measuring short baseline (tens of km) at mm precision and long baseline (thousands of km) at cm precision has been testified successfully in the first GPS Internationl Geodynamics Test (GIG' 91) orgnized by International GPS Geodynamics Service (IGS) in 1991. The measuring results of GPS baselines in global scale from GIG' 91 are as follows[33]. The repeating rate of baseline length in an observing day is 3mm + 3ppb. The fitting degree with the corresponding VLBI results is 2.5ppb. The precision of the three-dimensional geocentric coordinates of GPS stations from GIG' 91 has also reached 3cm level[33]. Therefore, GPS technique will contribute greatly to the establishment of the CTRF with high accuracy in the future. According to the measuring results from GIG' 91, JPL GPS data analysis center has established the first GTRF, which has been used to establish the ITRF91 by IERS[12]. The GTRF contains 21 permanent GPS stations. The distribution of them is shown in figure 5-1 and table 5-1.

2. Improvement of Plate Motion Model

A series of plate motion models have been published since the plate tectonics was formed. Among them the plate model RMZ[15] was widely accepted and adopted. AMO-2 was derived from the RM2 model under condition of no-net-rotation constraint[15]. AM1-2[15], which minimizes the motion of a set of hotspots, was also derived from RM2. This two absolute motion models are usually adopted in data analysis. AMO-2 depends only on the contour of plate boundaries, whereas AM1-2 depends on the selection of the hotspots which are more subject to uncertainties. On the other hand, AMO-2 corresponds to the type of time evolution constraints that one wants to give to the terrestrial reference frames (see section Ⅱ). and has been consequently adopted by MERIT standards (1983)[27] and IERS standards (1989)[5]. Nevertheless, AM1-2 leads to a system linked to the mantle which is needed to express a geopotential model. Therefore it is favoured by groups which perform dynamical analysis of satellite tracking data. With the deep going research on plate tetonics and kinematics in the 1980's, many new results were discovered, and some disadventages in RM2 were revealed. These new results provide a possibility of establishing a new plate model. Afterwards DeMets et al.(1990)[16] derived a new plate relative motion model, known as NUVEL-1. NUVEL-1 is better than RM2 in several major aspects[15,16]: (i)The NUVEL-1 data set is much better than the RM2 one in quantity, distribution, and accuracy; (ii)The India-Australia plate is devided into two plates: India plate and Australia plate, which overcome the disagreement of RM2 with the observing data set in the India Ocean; (iii) Plate motions predicted by NUVEL-1 are more accurate than RM2, it has been confirmed by observational results[20,21]. Thus, when NUVEL-1 was published, it was accepted and adopted immediately. Thereafter, Gripp and Gordon(1990)[18] derived an absolute plate motion model, HS2-NUVEL1, from NUVEL-1 by minimizing the motions of the same set of hotspots as those adopted by AM1-2. Argus and Gordon (1991)[17] derived another absolute model, NNR-NUVEL1, from NUVEL-1 by applying a no-net-rotation condition. Based on same reason as above, NR-NUVEL1 has been adopted by IERS standards(1992)[13] instead of AMO-2.

The plate motions predicted from the geological models are the average of plate motions over recent several million years[16]. Although they are generally in agreement with the observational plate motions in many regions, significant differences still exist in some regions, for example, the rate of change of the baselines over the Atlantic Ocean from space geodetic observations is significantly smaller than that predicted from the geological models[20]. These differences may imply that the plate motions have changed. Therefore, an instantaneous plate motion model should be established by space geodetic observations. Ward (1990), Argus and Gordon (1990)[19,20] have done some work in this aspect. The Euler vector of Pacific-North America plate motion derived from the rates of change of VLBI baselines is consistent with the corresponding Euler vector given by NUVEL-1, whereas the Euler vector of Eurasia-North America from VLBI has big difference with the corresponding Euler vector from NUVEL-1, and its precision is very low. Possiblly it is either because the poor distribution of the VLBI stations in Eurasia plate (see figure 5-1) can not give the Euler vector a strong contraint, or because the plate motion has changed significantly. Thus further research is needed to confirm it.

3. The Velocity Field of the CTRF

Variation of plate motion and regional crust deformation would affect the velocities of the stations, so it would be difficult to maintain the stablity of CTRF only by adopting geological model. Currently, because of the lack of sufficient observations, one can not establish a perfect global plate instantaneous motion model. Therefore, for those observing stations which have sufficient observations, their velocities will contain not only the velocities from geological model, but also the velocities from observations[12], their coordinates could be transfered from an epoch to another epoch by using the combining velocities; for other stations whose observations are not enough to estimate the instantaneous velocities, their velocities are still given by geological model. So far the vertical velocities of the observing stations from the observations have poor accuracy due to the effect of atmosphere, and the post-glacial rebound model is not perfect enough, so the vertical velocities of stations were not considered before 1991. However, beginning from 1991, the vertical velocities of the observing stations have been considered at the observing stations having sufficient observations, and their vertical velocities were derived from observations. For other stations, their vertical velocities are fixed to zero[12]. In ITRF91, each observing station has 3 velocity elements in horizontal and vertical directions, which form a three-dimensional velocity field.

4. The Progress in International CTRF Service

The international CTRF service based on space geodetic techniques began in 1984, the BIH combined the observations from VLBI, SLR, LLR, and Doppler techniques to establish a series of the BIH terrestrial reference systems(i.e. BTS84-BTS87)[4,6]. Thereafter, the IERS was established in 1987 by IAU and IUGG, and it started operation on January 1st, 1988. It replaces the IPMS and the earth-rotation section of the BIH, and one of its tasks is to define and maintain a Conventional Terrestrial Reference System based on the observing stations that use the high-precision techniques in space geodesy. The IERS combined the observations from VLBI, SLR, LLR, and GPS to establish a series of the IERS Terrestrial Reference Frames (i. e. ITRF 88-ITRF91)[7,8,12]. From ITRF88 to ITRF90, IERS only adopted VLBI, SLR, LLR techniques to establish the ITRF. Recently, the progress in GPS techniques let it have the ability to participate in the CTRF service of IERS[8]. Now it has been used in ITRF91. Figure 5-1 shows the distribution of the stations in ITRF91. Table 5-2 shows the evolution of the CTRF realized by BIH and IERS. From BTS84 to BTS85, the station velocities were not considered; from BTS86 to ITRF90, the station velocities followed a two-dimensional velocity field predicted from AMO-2; beginning from ITRF91, the station velocities would follow a three-dimensional combined velocity field predicted from NNR-NUVEL1 and space geodetic observations.

6。Problems and Prospects

Although a great progress has been achieved in the research of the CTRS, for the requirement in the research of astrogeodynamics at mm accuracy level in the 1990's there are still many problems. In the following, we discuss the problems and the approaches to solving them.

(a) The distribution of the observing stations in global plates is still poor[25]. Currently, most of the stations lie on the western Europe, the North America, and the central Pacific Ocean (see Figure 5-1). Only a few stations lie on the other plates, which make the configuration of the CTRF very poor and difficult to work globally. The only way to change this status is to add new observing stations. In the 1990's, a Fiducial Laboratory International Nature Science Networks (FLINSN) will be established by international orgnizations, which will be used to the research of solid earth dynamics. The FLINN will be constituted by more than 200 fiducial observing stations which lie on the continents and islands with a separation of about 1 000 km as uniform as possible, and each major plate has at least 3 stations. The co-location stations of various techniques should also distribute uniformly on the Earth and have sufficient quantity so as to provide an optimistic match of various techniques. These stations will form a very good terrestrial reference frame. This future CTRF would mainly based upon VLBI, SLR, and GPS techniques, in which, VLBI provides a quasi-inertial celestial reference system linked to the radio sources; SLR provides the position of the geocenter and relates to a gravitational field of the Earth; whereas GPS is mainly used to promote the spacial and temporal resolutions of the CTRF by densification. Once this CTRF with mm accuracy is established, the accuracy of the coordinate of any point on the Earth predicted from GPS observations in one day will be better than 1 cm[33]. It will provide a very important reference for the measurement and research of the kinematical variations of the Earth. Table 5-1 shows the distribution of the new stations which will be established in the 1990's,

(b) At present, although the observing techniques have been at cm precision, significant improvement is required for mm presision[24]. VLBI technique will be improved by adopting the new Mark Ⅳ data acquisition system with wider bandwidth of RF and etc. to reach mm precision. GSFC and NRAO in U. S. A. have performed a test of feasibility. The result is that after the above-mentioned improvements, the rms of baseline is 1 mm in horizontal direction and 7 mm in vertical direction; the rms of delay is 20 ps[32]. The laser techniques (SLR, LLR) will be improved by adopting two-color laser ranging instrument to reach mm precision. The test of feasibility began at the end of the 1980's, we hope that it can be used at the mid-1990's. For the GPS technique, the refraction of radio wave in ionosphere and tropsphere are the major causes to degrade the observing precision, while the solution for initial phase ambiguity, and the resolution and revison of cycle slip are two difficult problems in data analysis. Moreover, the GPS policy of American government also limits its applications. Thus, the improvement of the precision of GPS will face much more difficulities. Currently, some countries are establishing the GPS tracking network so as to provide the precise ephemeris, and engaged in solving above-mentioned problems.

(c) The absolute reference frame of plate motions still has doubts. Now there are two kinds of absolute reference frames: the hotspot (HS) reference frame and the no-net-rotation (NNR) reference frame. If both of them are based upon the dynamically correct premises, they should have no relative rotation with respect to each other. But in reality, there is a right-handed rotation of 0.33°/Myr., about 49° S, 65° E between them[17], this is a very significant difference. The biggest velocity difference on the Earth's surfaec between NNR-NUVEL1 and HS2-NUVEL1 is 37 $\mathrm{mm \cdot yr^{-1}}$. Consequently, a question has been put forward. Which one is correct? If the NNR reference frame is correct, then the hotspots may have coherent motion relative to deep mantle. However it is difficult to explain this kind of motion in geodynamics. Alternatively, if the HS reference frame is correct, then the difference between the two frames may show that the NNR reference frame is based on a dynamically incorrect premise. Argus and Gordon (1991) thought that it is more likely that the HS reference frame is the more appropriate frame. If that is true, the definition of the CTRS in section Ⅱ would be incorrect because the crust may have net rotation relative to the deep mantle, and it would be unsuitable that adopting AM0-2 or NNR-NUVEL1 to maintain the stablity of CTRF. Obviously, one should adopt the models based on hotspots such as AM1-2 or HS2-NUVEL1. No definite conclusion has been reached so far because of the complexity of the problem. To solve for the problem, further research is needed. Meanwhile, the exploration of a new and more appropriate absolute reference frame of plate motions never stops.

(d) because of the limitations of the distribution of the observing stations and the quantity of observations, one cannot establish a global plate instantaneous motion model only based upon space geodetic observations at present, and the geological model still have to be adopted in a period of time. Therefore, for some stations on the region where plate motion may have changed, the geological model will give incorrect station velocities. One should improve the geological model gradually by space geodetic observations, and finally establish a global model completely based upon space geodetic observations.

(e) The secular term in the motions of the stations in vertical direction is mainly the post-glacial rebound. This term has not been considered up to now due to the uncertainties in its models, thus, to refine the rebound models will be an important work in the future. Space geodetic observations with more accuracy for vertical motions are still needed.

(f) The correction accuracy of some deformations, such as solid Earth tide displacement, is now cm level. In order to realize the CTRF with mm accuracy, one should refine these models with mm level, and consider much more deformations in mm level also.

References

[1] Kovalevsky, J. and Mueller, I. I. in Reference Frames, ed. by Kovalevsky, J. and I. I. Muller, p. 1,(1989).
[2] Mueller, I. I., in Reference Framens, ed. by J. Kovalevsky, and I. I. Muller, p. 163, (1989).
[3] Boucher, C., in Reference Frames, ed. by J. Kovalevsky, and I. I. Muller, p. 327, (1989).
[4] Boucher, C. and Altamimi, Z., IERS Technical Note 1, (1989).
[5] Mc Carthy, D. D. (ed.), IERS Technical Note 3, (1989).
[6] Boucher, C. and Altamimi, Z., IERS Technical Note 4, (1990).
[7] Boucher, C. and Altamimi, Z., IERS Technical Note 6, (1991).
[8] Boucher, C. and Altamimi, Z., IERS Technical Note 9, (1991).
[9] Boucher, C. and Altamimi, Z., IERS Technical Note 10, (1992).
[10] Mc Carthy, D. D. (ed.), IERS standards (draft) (1992).
[11] Charlot, P. (ed.), IERS Technical Note 11, (1992).
[12] Boucher, C. et al., IERS Technical Note 12, (1992).
[13] Mc Carthy, D. D. (ed.), IERS Technical Note 13, (1992).
[14] IERS, Annual Report for 1991, (1992).
[15] Minster, J. B. and Jordan, T. H. *J. Geophys, Res.*, 83 (1978), 5331.
[16] DeMets, C. et al., *Geophys. J. Int.*, 101 (1990), 425.
[17] Argus, D. F. and Gordon, R. G., *Geophys. Res. Lett.*, 18 (1991), 2039.
[18] Gripp, A. E. and Gordon, R. G., *Geophys. Res. Lett.*, 17 (1990), 1109.
[19] Argus, D. F. and Gordon, R. G., *J. Geophys. Res.*, 95 (1990), 17315.
[20] Ward, S. N., *J. Geophys. Res.*, 95 (1990), 21965.
[21] Caprette, D. S. et al., Crustal Dynamics Project Data Analysis-1990, (1991).
[22] Jordan, T. H. and Minster, J. B., in IAU Symposium No. 129, p. 341, (1988).
[23] Papo, H. B. and Saleh, J., in IAU Symposium No. 129, p. 423, (1988).
[24] Carter, W. E. and Robertson, D. S., in IAG Symposium No. 105, p. 115, (1989).
[25] Kosek, W. and Kolaczek, B., in IAG Symposium No. 105, p. 138, (1989).

[26] Tushingham, A. M. and Peltier, W. R. *J. Geophys. Res.*, 96 (1991), 4497.

[27] Melbourne, W. (ed.), MERIT Standards (1983).

[28] Wahr, J. M., *Geophys. J. Roy. Astron. Soc.*, 64 (1981), 705.

[29] Soler, T. and Hothern, T. D. *J. Surv. Engrg.*, 115 (1989), 414.

[30] Ray, J. R. et al., *Geophys. Res. Lett.*, 18 (1991), 231.

[31] Zhao Ming and Song Guoxuan (ed.), Astrogeodynamics, (1989).

[32] Qian Zihan, The applications of Chinese VLBI network in the measurement of Chinese crustal motions and the establishment of CTS and CIS (1992).

[33] Zhu Wenyao, The applications and progress of GPS in geodynamics (1992).