（双语教程）

# 大地测量学基础

Foundation of Geodesy: Bilingual Reading Book

张西光 吕志平 李健 曲云英 等 编著

测绘出版社

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·北京·

## 内容提要

本书为测绘类专业本科《大地测量学基础》（普通高等教育“十一五”国家级规划教材，吕志平，乔书波编著，测绘出版社，2010.3）的英语辅助教材，目的是使学生在学习《大地测量学基础》课程的同时，学习掌握该课程的基本概念、基本理论在英文中的表达和描述，为以后阅读英文专业文献，撰写专业论文打下良好的基础。

本书可作为高等院校测绘类各专业本科生的通用教材，对于从事与测绘工程有关的技术人员也是一本值得推荐的基础性参考书。

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# 前　言

通过阅读专业英文文献，获取知识，进而进行科学研究和学术交流，是英语教育的一项重要目标。从通用英语的学习，过渡到使用英语学习专业课程，并非简单、自然完成的，通常需要一个过程。大地测量学基础课程通常开设在第四或第五学期，编写一本双语教程，加强学生在这方面的训练，顺利实现这一过渡，是一件很有意义的工作。

编写本书的目的在于，使学生在学习《大地测量学基础》（普通高等教育“十一五”国家级规划教材，吕志平，乔书波编著，测绘出版社，2010.3）课程的同时，学习掌握该课程的基本概念、基本理论在英文中的表达和描述，为以后阅读英文专业文献，撰写英文专业论文打下良好的基础。这也是本课程与专业英语课程的教学内容定位不同之处。

本书的英文教学内容，取材于英、美和加拿大等国的测绘类专著、科技论文和科技词典，以选取原文为主，部分内容略加变动，符号改为我国惯用符号。在选材时，除了注重内容的原汁原味，还注重把握下面四条原则。第一，选取的内容能够激发学生阅读专业英文文献的兴趣，例如，给出了大地测量学的四个定义，从不同角度出发阐释，引发学生思考；关于大地测量学历史的回顾，与中文教材上的内容略有不同，从不同侧面审视大地测量学的发展。第二，选取的内容与大地测量学基础课程的内容既互为对照，又互为补充，可作为课外学习的延伸，例如，大地问题解算的逐点积累法，本书选择了编程实现该方法的内容；再如，关于WGS-84坐标系和ITRF坐标系的内容，本书选取了较多材料，便于课后扩展学习。第三，所选专业内容在科技文献中表达的典型性，从中学习各种表达方式和技巧，例如，选取的内容包括术语的定义，公式推导，某领域综述及总结，等等。第四，选取的内容很多出自著名大地测量学家之手，其科学性自不必多言，更重要的是学习到他们对问题的认识，例如，关于时间系统的描述极为简洁；关于板块构造运动的描述特别形象，给人以深刻印象。此外，为方便学生自学，增加了专业词汇表和参考译文。

本书在编写的过程中，得到信息工程大学测绘学院训练部张晓森部长、郭延斌主任，一系李广云主任和一系大地测量教研室全体同仁的大力支持。宋力杰教授、柴洪洲教授审阅了全书，并提出了许多宝贵意见，刘长建副教授、赵冬青副教授和乔书波副教授在搜集素材，文献翻译中提供了很大的帮助，在此表示衷心感谢。本书的出版还要感谢测绘学院“2110学科建设”的资助。

由于编者水平有限，经验不足，书中存在的缺点和错误，恳请读者批评、指正，以促进本课程建设的不断发展。

# Contents

## 参考译文

earth must be considered. In **plane surveying** ( topographic survey, engineer survey, cadastral survey), the details of the land surface are obtained, the horizontal plane is in general sufficient as a reference surface.

There is close interaction between global geodesy, control surveying and plane surveying. The control survey adopts the parameters determined by measurements of the earth, and its own results are available to those who measure the earth. The plane surveys, in turn, are generally tied to the control points of the control surveys and serve then particularly in the development of national map series and in the formation of real estate cadastres.

With the corresponding classifications in the realms of the English and French languages, the concept of "GEODESY" is to be referred only to global geodesy and control surveying.

## 1.3 Aim of Geodesy

Practical aim of geodesy:

Using the results of scientific geodesy, carry out the measurements and computations needed for making accurate and reliable maps of the earth's surface.

Scientific aim of geodesy:

To determine the size and shape of the earth, and in cooperation with other sciences, study its gravitational field and to some extent the internal structure.

## 1.4 Historical Introduction

Since about 150 years, geodesy can be regarded as an independent discipline of science. Baeyer's memorandum about the size and figure of the earth "Über die Größe und Figur der Erde" (1861) may be seen as a starting point, even though important geodetic work had been done before by famous scientists such as Newton, Laplace, Gauss, Bessel. But their work was not referred to as geodesy and they did not regard themselves as geodesists. Baeyer's initiative resulted in an extension and unification of existing triangulation and leveling networks covering central Europe. This work was then expanded to the whole of Europe, before its transition to an international effort with the aim to determine the global figure of the earth. It was one of the first international projects in science and the root of what is today the International Association of Geodesy (IAG).

**In 2007, 50 years of space age was celebrated.** With the launch of Sputnik 1 on October 4, 1957 (and shortly after of Sputnik 2) modern space age began. Already these two satellites had a fundamental effect on geodesy. Almost instantaneously, a large part of 100 years of diligent geodetic work dedicated to the determination of the figure of the earth became out-dated. From measuring the precession of satellite orbits, the earth's flattening could be determined much more accurately than with classical astro-geodetic work. Satellites opened new horizons for geodesy and no other discipline is known to me that has benefited more profoundly from space techniques. Positioning, gravity field determination, earth rotation monitoring and geodetic remote sensing can be done much more accurately, completely and efficiently from space. Geodesy became truly global and three-dimensional. Oceans, a "terra incognita" of the classical times turned with satellites into an area of great geodetic activity. Classical geodetic techniques did not allow the accurate measurement of zenith angles, due to atmospheric refraction. From space, the vertical dimension of the earth's surface can be determined almost as accurately as the horizontal components. Progress of space geodesy was fast and had a great impact. Hand in hand with the rapid development of geodetic space techniques geosciences became more and more interested in geodetic work.

## 1.5 Recent Developments of Space Geodesy

In recent years, the general emphasis of earth sciences has moved towards **Climate Change and Earth System Science**. Awareness grew that we need a much better understanding of the earth as a system, of solar radiation as its driving force, of the thermal back radiation and how it is affected by even tiny changes in chemical composition of the atmosphere, and last not least, of the impact of man. One fundamental deficiency became particularly evident in the course of the preparation of the last report of the Intergovernmental Panel on Climate Change (Climate Change, 2007) and has been addressed in several articles in Science and Nature: There is a clear lack of observations. Space geodesy is able to provide important new and unique data to Global Change research by measuring mass and energy transport processes in the earth system. Ben Chao (2003) wrote: "After three decades and three orders of magnitude of advances, space geodesy is poised for prime time in observing the integrated mass transports that take place in the earth system, from the high atmosphere to the deep interior of the core. As such space geodesy has become a new remote sensing tool, in monitoring climatic and geophysical changes with ever increasing sensitivity and resolution." One can claim that geodesy, by merging geometry, earth rotation, gravity and geoid, is in a position to provide "metric and weight" to earth system research. Before this background, the establishment of the Global Geodetic Observing System (GGOS) is the right step at the right time. The underlying concept is simple and well described by the scheme shown in Fig. 1.1 and due to Rothacher.

GGOS will combine the **three fundamental pillars of geodesy:** the measurement of the shape of the earth, earth rotation and the earth's gravity field and geoid. The objective is to realize this with a relative precision level of $10^{-9}$ in one unified earth fixed reference system and to keep this system stable over decades. Where does such a demanding requirement come from? In geosciences, one usually deals with estimates accurate to only a few percent. Global change parameters are small and their temporal changes are slow and even smaller. In general, they cannot be observed directly but have to be derived from a combination of several measurement systems and models. In order to be able to analyze them as a global process they have to be scaled relative to the dimension of the earth. Let us take an example. Sea level at an arbitrary tide gauge may vary by a few meters, due to tides and storm surges. Measurement of sea level change with a precision of a few mm requires therefore a relative precision of $10^{-3}$ at this particular station. Local sea level monitoring can be transformed into a global monitoring system by satellite systems such as altimetry and GPS. Only then, a global process can be deduced from local tide gauge records. In order to achieve cm-or mm-precision with satellite systems globally, orbit determination and altimetric measurements have to be delivered with a relative precision of 1 ppb.

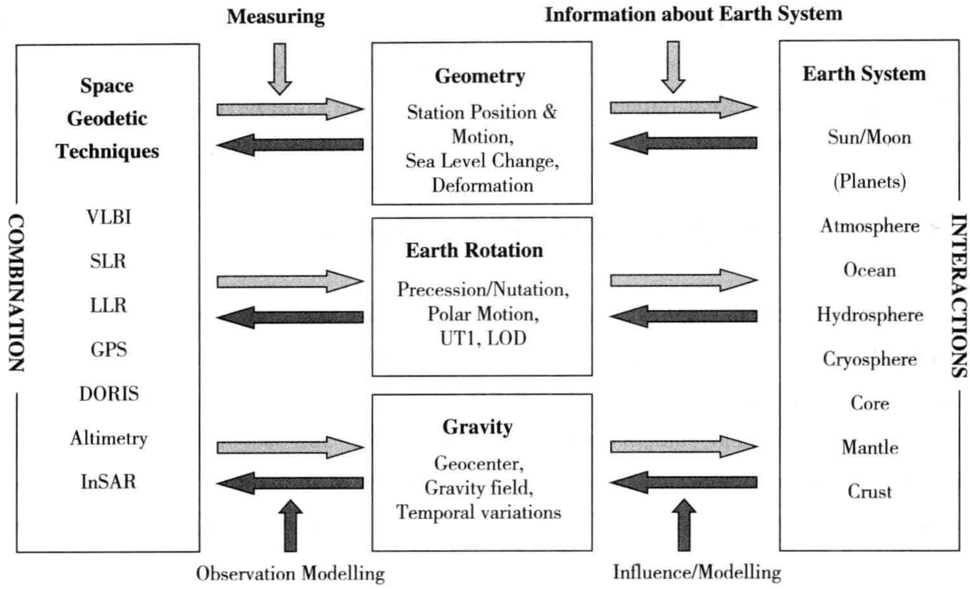

Fig. 1.1 Combination of the space geodetic techniques, the three pillars of space geodesy, and the interaction with the components of the earth's system

In order to meet the goals set for GGOS a series of rather fundamental geodetic problems have to be dealt with. The three pillars of geodesy, geometry, earth rotation and gravity have to be expressed in one and the same earth fixed reference system with millimeter precision and stability (of the frame) has to be guaranteed over decades. This requires the space as well as the ground segments to function as one homogeneous entity as if all observations were done in one observatory encompassing the earth. Each observation contains a superposition of a variety of effects, related to ionosphere, atmosphere, oceans, ice shields and solid earth. In order to employ them for earth system research strategies have to be developed for their separation and quantification by analyzing their spatial, temporal and spectral characteristics. Satellite measurements represent time series along their orbit. Via the earth's rotation and the choice of the satellite orbit elements these time series are related to a spatial and temporal sampling of the earth. The reconstruction of the temporal and spatial geophysical phenomena poses a complicated problem of aliasing and inversion. The current investigations of the global water cycle or of the ice mass balance in Greenland and Antarctica from GRACE gravimetry are exactly problems of this type. The inclusion of terrestrial and airborne data, such as surface loading, ocean bottom pressure, tide gauges, gravimetry or altimetry may certainly help. However, this step is not easy either, because terrestrial measurements are affected by local influences and exhibit a spectral sensitivity quite different from that of satellite observations. Probably the most effective support to de-aliasing and separation of geophysical phenomena is the inclusion of prior information, such as models of solid earth and ocean tides, atmosphere, oceans, ice, hydrology or glacial isostatic adjustment, however only if they are introduced consistently for all techniques of the observing system. Important work towards these goals is currently underway and we see geodetic techniques used much more widely in the various earth disciplines.

Wegener developed over the years from an almost mono-disciplinary project to regional multi-disciplinary activity combining a large variety of geodetic and non-geodetic measurements techniques and involving all geo-disciplines relevant to its objectives. It is therefore an excellent example on how GGOS could operate on a global scale.

## Vocabulary

altimetry /ælˈtimitri/ *n.* 测高学，高度测量法(以海平面为基准)
celestial /səˈlestʃəl/ *adj.* 天的，天空的
curvature /ˈkəːvəˌtʃʊə, －tʃə/ *n.* 曲率，弯曲
earth rotation /əːθ rəuˈteiʃən / 地球自转
figure of the earth /ˈfiɡə ɔv ði əːθ/ 地球形状
flattening /ˈflætniŋ/ *n.* 扁率
geodesy /dʒiːˈɔdisi/ *n.* 大地测量学
geoid /ˈdʒiːɔid/ *n.* 大地水准面
gravity field /ˈɡræviti fiːld/ 重力场
leveling /ˈlevəliŋ/ *n.* 水准测量
leveling network /ˈlevəliŋ ˈnetwəːk/ 水准网
network /ˈnetwəːk/ *n.* (控制)网
precession /priˈseʃən/ *n.* 岁差，进动
triangulation /traiˌæŋɡjuˈleiʃən/ *n.* 三角测量
zenith /ˈziːniθ/ *n.* 天顶

# 2 Reference System

## 2.1 Time Systems

In the context of this book, time is regarded as absolute and independent of space. In reality, time keeping, and satellite measurements in general, are so accurate nowadays that adequate modeling requires the use of special and general theory of relativity for practical reason.

Time keeping requires a **periodic process**, a **counter** ( in order to count the number of periods) and an **origin** where the counting starts. In addition, in order to be able to keep the same time at different locations **some means of transfer/transport of time** has to be available. There exist a number of natural "clocks" that produce very stable periodic oscillations: the orbit of the earth about the sun, of the moon about the earth and earth rotation. Their fundamental periods, year, month and day, are closely related to natural processes such as seasons that affect our living conditions and these periods define the basic structure of our life. From these fundamental periods the basic long term counting structure has been deduced, our **calendars** ( we use the Gregorian calendar, adopted in 1582 ). In scientific work a continuous counting is preferable to the complicated structure of counting with months or year of varying length. For this purpose the **Julian date ( JD)** has been invented with 36525 days per century.

The adopted reference date is

J2000. 0 = 2000 Jan 1. 5 = January 1, 2000 at 12h

where it is

JD 2451545. 0.

For a long time the natural period day, and even more the revolution of the moon, were superior in terms of stability to any artificial clock. Only with the advent of quartz and atomic oscillators, artificial clocks were created that meanwhile surpassed the precision and stability of natural clocks. Our current definition of the unit of second is based on the oscillation period of a cesium clock. In 1984 **atomic time**( Temps Atomique International = **TAI**) has been introduced as official, internationally adopted time. It has a constant off-set of 32s. 184 with respect to the **terrestrial dynamic time ( TDT)**. The latter is derived from models of planetary motion and based on the theory of relativity. TAI has a constant off-set of 19s with respect to **GPS-time**.

Civilian time is related to the rhythm of day and night, i. e. to the rise and fall of the sun. Because of the complicated deviations of the apparent motion of the sun, some model or mean solar motion has been conceived. It refers to the Greenwich meridian and is denoted **universal time ( UT)**. From UT standard zonal times have been deduced. earth rotation—and therefore UT—exhibits a drift and small irregular fluctuations ( changes in LOD) with respect to TAI. In order to circumvent this, a coordinated universal time (**UTC**) has been conceived, which on the one hand is kept synchronous with respect to TAI and on the other hand, through regular corrections (leap seconds), is kept within small bounds to follow the actual angular rate of the earth. The actual and uncorrected universal time is denoted **UT1**. It represents the actual phase angle of the rotating earth. The difference UT1-UTC is provided in monthly tables and provided as coded message in broadcasted time signals. If the difference UT1-UTC exceeds the size of 0.9 s a leap second is introduced. **UT0** completes the system of universal times. It contains all variations in rotation due to polar motion.

Finally, **sidereal time** is the angle of a terrestrial meridian (rotating with the earth) with respect to vernal equinox. The most prominent types of sidereal time are Greenwich Mean Sidereal Time (GMST) $\bar{\Theta}$ and Greenwich Apparent (or true) Sidereal Time (GAST) $\Theta$.

GMST is corrected for fluctuations caused by nutation. It is

$$\Theta = \bar{\Theta} + \Delta n = \bar{\Theta} + \Delta\psi \cdot \cos\varepsilon + 0.002\,64'' \cdot \sin\Omega + 0.000\,063'' \cdot \sin 2\Omega \qquad (2.1)$$

and $\Omega$ the mean node of the moon. Greenwich Apparent Sidereal Time is needed for the transformation from earth-fixed to space-fixed.

Since sidereal time is measured with respect to vernal equinox, while universal time is a solar time and counted with respect to the apparent pass of the sun through the meridian at Greenwich the length of the year is different by one day: tropical year

in solar days: 365.24220
in sidereal days: 366.24220.

This difference has to be accounted for when transforming UT1 to GMST. It holds

$$\mathrm{GMST} = \mathrm{UT1} + \alpha(\Theta) - 12^{h} \qquad (2.2)$$

with the right ascension of the sun:

$$\alpha(\Theta) = 12^{h} + (24\,110.548\,40^{s} + 8\,640.812\,866^{s} \cdot t + 0.093\,104^{s} \cdot t^{2} - 6.2^{s} \cdot 10^{-6} \cdot t^{3}) \qquad (2.3)$$

and

$$t = (T - \mathrm{J2000.0})/36\,525.0 \qquad (2.4)$$

with $T$ Julian Date at epoch and J2000.0 = JD2451545.0.

## 2.2 International Earth Rotation Service

The International Earth Rotation Service (IERS) is in charge of **providing and maintaining conventional celestial and terrestrial reference frames**. These frames are a realization of the reference systems recommended by the International Astronomical Union (IAU) and the International Union of Geodesy and Geophysics (IUGG). IERS is also responsible for **the determination of the orientation parameters of the earth as functions of time**, which relate the two frames to each other.

Established by the IAU and IUGG, the IERS has operated since January 1, 1988. It collects, analyzes, and models observations of a global network of astronomic and geodetic stations (about 300 sites in 1996), operating either permanently or for a certain time span. Observation techniques include VLBI, LLR, SLR, GPS, DORIS.

The different types of observations are evaluated at the respective IERS coordinating centers and then combined by an adjustment at the IERS Central Bureau. The results include the positions (coordinates) of both the extragalactic radio sources and the terrestrial stations, the earth orientation parameters (EOP), and other information. With respect to the EOP, VLBI provides information about precession, nutation, polar motion, and UT1. Satellite techniques contribute to the daily interpolation of UT and to the determination of polar motion. The results are disseminated through bulletins, annual reports, and technical notes. The evaluation of the observations is based on the IERS Conventions, which are consistent with the IAU and IUGG/IAG recommendations for reference systems.

## 2.3 Celestial Reference System

An inertial system is needed in order to describe the motions of the earth and other celestial bodies in space, including those of artificial satellites. Such a system is characterized by Newton's law of motion; it is either at rest or in the state of a uniform rectilinear motion without rotation. A space-fixed system (celestial reference system) represents an approximation to an inertial system and can be defined by appropriate conventions: Conventional Inertial System (CIS). The coordinate frame for such a system is provided by spherical astronomy. The spatial orientation of this frame varies with time, and therefore, modeling of the variations is required. The International Celestial Reference Frame represents the realization of the celestial reference system.

### 2.3.1 Equatorial System of Spherical Astronomy

The coordinates of the celestial reference system are **defined by the equatorial system of spherical astronomy**. We introduce a three-dimensional Cartesian coordinate system with the origin at the center of mass of the earth (geocenter). The $Z$-axis coincides with the rotational axis of the earth. The $X$ and $Y$-axes span the equatorial plane, with the $X$-axis pointing to the vernal equinox and the $Y$-axis forming a right-handed system (Fig. 2.1).

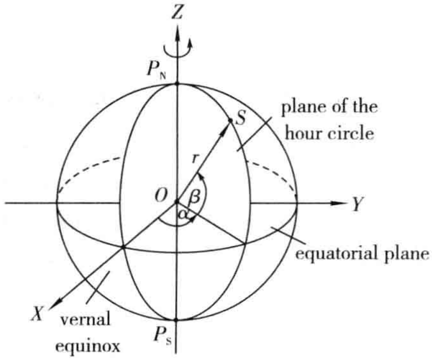

Fig. 2.1 Astronomic equatorial system

We circumscribe the unit sphere (celestial sphere) about the earth. The rotational axis meets the sphere at the celestial north and south poles $P_N$ and $P_S$. The great circles perpendicular to the celestial equator, which contain the celestial poles, are called **hour circles**, and the small circles parallel to the equator are termed **celestial parallels**.

The **right ascension** $\alpha$ is the angle measured in the plane of the equator between the planes of the hour circles passing through the vernal equinox and the celestial body $S$; it is reckoned from the vernal equinox anticlockwise. The **declination** $\delta$ is the angle measured in the plane of the hour circle between the equatorial plane and the line $OS$ (positive from the equator to $P_N$ and negative to $P_S$).

The position of a celestial body $S$ can be described either by the Cartesian coordinates $X, Y, Z$, or by the spherical coordinates $\alpha, \delta, r$ ($r$ = distance from the origin $O$). We have the transformation

$$\boldsymbol{r} = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = r \begin{pmatrix} \cos\alpha\cos\delta \\ \sin\alpha\cos\delta \\ \sin\delta \end{pmatrix} \tag{2.5}$$

In geodesy, only directions are important for stars and extragalactic sources. With $r = 1$, $\alpha$ and $\delta$ describe the position of $S$ on the unit sphere. They can also be expressed by the lengths of the corresponding arcs on the equator and the hour circle.

We introduce the local meridian plane of the observer, spanned by the local vertical (direction of the plumb line) and the rotational axis, after a parallel shift from the geocenter to the topocenter. The zenith point $Z$ is the intersection of the vertical with the unit sphere, and the celestial meridian is the great circle through $Z$ and the poles (Fig. 2.2). The **hour angle** $h$ is measured in the equatorial plane between the celestial meridian through $Z$ and the hour circle of $S$, reckoned from the upper meridian toward west. Because of the earth's rotation, the hour angle system ($h, \delta$) depends on time. The $h, \delta$-system is rotated, with respect to the $\alpha, \delta$-system, about the polar axis by the angle of sidereal time LAST. We have the relation

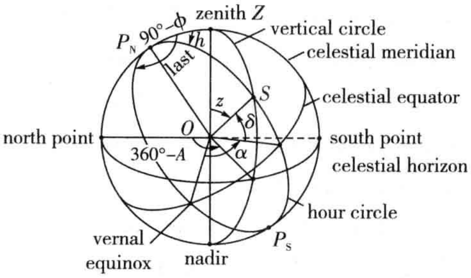

Fig. 2.2 Astronomic equatorial and horizon system

$$\text{LAST} = h + \alpha \tag{2.6}$$

which is used with time determination.

## 2.3.2 Precession and Nutation

The earth's axis of rotation, which has been introduced as the $Z$-axis, changes its spatial orientation with time. As a consequence, the position ($\alpha, \delta$) of a celestial body varies, with a superposition of long and short-periodic effects.

The **lunisolar precession** is a long-periodic effect caused by the gravitation of the moon and the sun on the equatorial bulge of the earth. This creates a force couple (torque) which tends to turn the equatorial plane into the plane of the ecliptic (Fig. 2.3). In combination with the moment of the earth's rotation, the earth's axis describes a gyration of a cone with a generating angle of 23.5° (corresponding to the obliquity of the ecliptic $\varepsilon$), about the northern pole of the ecliptic $E_N$. The vernal equinox moves clockwise along the ecliptic at a rate of 50.3″/year, making a complete revolution in about 25 800 years. The gravitation of the planets causes a slow dislocation of the earth's orbit and thereby an additional migration of the vernal equinox along the equator and a change in $\varepsilon$: **planetary precession**. The sum of the lunisolar and the planetary precession is termed general precession.

The precession is superimposed by short-periodic effects known as **nutation**, which has periods between 5 days and 18.6 years. These periods are mainly due to the time variations of the inclination of the moon's orbit with respect to the ecliptic (appr. 5°). Other components have semiannual and semimonthly periods and stem from the oscillations of the sun and moon between the earth's northern and southern hemisphere.

Precession and nutation can be modeled as a function of time using the ephemeredes of the moon, the sun, and the planets. The IAU (1976) theory of precession provides three time-dependent Eulerian rotation angles for reducing the positions of celestial bodies to a common reference. For the reference epoch J2000.0, we have the fundamental constants "general precession in longitude at the ecliptic" (5 029.096 5″/century) and "obliquity of the ecliptic" (23°26′21.412″).

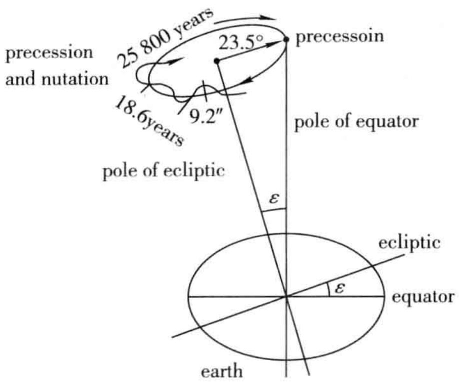

Fig. 2.3 Precession and nutation

The IAU (1980) theory of nutation describes this effect by a rotation about the cone of precession. The deviation of the true pole from the mean pole is modeled by two time-dependent parameters. Hereby, the earth is regarded as an elliptical, rotating, elastic, and ocean-free body with solid inner and liquid outer cores. For the epoch J2000.0 the constant of nutation is 9.202 5″.

The IAU models for precession and nutation define the reference pole for the international celestial reference frame (Celestial Ephemeris Pole CEP). CEP is free of diurnal or quasidiurnal nutation terms (amplitudes <0.001″) with respect to the space- or earth-fixed coordinate systems. It is also referred to as the pole of the instantaneous equatorial system.

The IAU models for precession and nutation provide a precision of ±0.001″at 5 to 7 days resolution. An improved theory has been developed at the IERS based on recent VLBI and LLR data. Larger offsets (<0.02″) of the celestial pole from CEP have been found; these are published regularly by IERS.

The instantaneous position of a celestial body is called true position at the epoch *t*. By accounting for nutation, we obtain the mean position at epoch *t*, which refers to the mean celestial equator and the mean vernal equinox. If precession is also taken into account, we get the mean position at the reference epoch J2000.0.

### 2.3.3 International Celestial Reference Frame

The International Celestial Reference System (ICRS), as recommended by IAU, is based on the general theory of relativity, with the time coordinate defined by the international atomic time. **ICRS approximates a space-fixed conventional inertial-system (CIS) with the origin at the barycenter of the solar system**. It is assumed that no global rotation of the system exists. This implies that the defining sources are either free from proper motion (component of spatial motion