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COORDINATE SYSTEMS AND COORDINATE TRANSFORMATIONS IN AIR NAVIGATION TASKS

Main types of coordinate systems used for solving air navigation tasks that are connected with the provision of aeronautical flight control and landing are examined in the article. The main requirements for coordinate systems are given.

Local (orthogonal, cylindrical and spherical) coordinate systems were studied, their advantages and disadvantages as well as areas of their application were highlighted. Direct and backward coordinate transformations between the local coordinate systems were shown.

The author shows distinctive features of global coordinate systems application which are connected with choosing the Earth's figure model and its mathematical description problems. Basic information about the global terrestrial ellipsoids and their parameters is presented. The need to shift to the global terrestrial ellipsoid and global reference systems is demonstrated. Basic information about the ITRS and ITRF is given. Differences in determining an object's space coordinates in these reference systems are described. Differences in the areas of application of PZ-90 and SK-2011systems as well as their prototypes WGS-84 and NAD-83 are specified.

The author considers peculiarities of global geodesic and geospheric (great-circle) coordinate systems, their advantages and disadvantages. Direct and backward coordinate transitions for global coordinate systems as well as expressions that link geocentric and topocentric coordinate systems are illustrated.

Key words: coordinate system, geoid, global terrestrial ellipsoid, coordinate transformations, a local coordinate system, a geodetic coordinate system, air navigation.

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СИСТЕМЫ КООРДИНАТ И КООРДИНАТНЫЕ ПРЕОБРАЗОВАНИЯ В ЗАДАЧАХ АЭРОНАВИГАЦИИ

В статье рассмотрены основные типы систем координат, используемых для решения задач воздушной навигации. Приводятся основные требования, предъявляемые к выбору системы координат.

Рассмотрены локальные системы координат - прямоугольная, цилиндрическая и сферическая, указаны их достоинства и недостатки, области применения. Приведены прямые и обратные преобразования координат между локальными системами координат.

Показаны особенности применения глобальных систем координат, связанные с выбором модели фигуры Земли и проблемами ее математического описания. Даны основные сведения об общеземных эллипсоидах и их параметрах. Показана необходимость перехода к общеземному эллипсоиду и глобальным системам отсчета и этапы такого перехода. Приведены общие сведения о Международной системе отсчета ITRS и Международной земной отсчетной основе ITRF. Указаны отличия в областях применения систем ПЗ-90 и СК-2011 и их аналогов WGS-84 и NAD-83.

Рассмотрены особенности глобальных геодезической и геосферической (ортодромической) систем координат, их достоинства и недостатки. Приведены

прямые и обратные координатные преобразования для глобальных систем координат, а также выражения, устанавливающие связь между геоцентрическими и топоцентрическими системами координат.

Ключевые слова: система координат, геоид, общеземной эллипсоид, координатные преобразования, локальная система координат, геодезическая система координат, аэронавигация.

For the aircraft's position and motion parameters determination as well as the mathematical description of navigation processes, a reference system - coordinate system, should be specified.

The chosen coordinate system must meet the number of requirements [Скрыпник, 2014]:

navigation tasks solving with the required accuracy;

coverage of necessary earth surface territory square or the air space capacity, in the range of which the navigation tasks are solved;

visibility and simplicity of information display and perception regarding the object's position in the axis system;

getting the simplex mathematical correlations that describe the aircraft's motion process.

Requirements listed above are controversial. Thus, the coordinate systems' choice, being the same for the whole earth surface, inevitably brings to complicated mathematical correlations, and the coordinate systems that allow to solve navigation tasks using relatively simple mathematic dependencies, provide the acceptable accuracy only in limited area of space. That is why in practice different coordinate systems can be used, each of which provides the most effective solution of specific navigation tasks.

Coordinate systems used in air navigation can be classified by the following features [Скрыпник, 2014]:

by the amount of earth's surface or spatial region coverage (local, global).

by the position of coordinate system's origin (geocentric - the origin matches the Earth center of mass, topocentric - the origin is in the point on the earth surface and also the coordinate systems connected with an aircraft and moving together with it toward the earth surface).

by plane's reference orientation (horizontal, equatorial, orbital).

Local coordinate systems cover limited area of earth surface and are used at aircraft's movements to the distances up to 400-450 km, when the earth curvature can be neglected for navigation task solution's accuracy. In such coordinate systems, landing systems (ILS) and short range navigation systems VOR/DME, TACAN are used.

Local coordinate systems include cylindrical, spherical and orthogonal Cartesian (*fig*.1) [Корн, 1974] which origins are situated in a point on the earth surface. These are topocentric systems.

In these coordinate systems *M* point coordinates are: in Cartesian system (*fig*.1, a) - *x, y, z* coordinates; in cylindric (*fig*.1, b) - *r* projection onto the horizontal plane of radius-vector ρ, traced from the coordinate system's origin to *M* point, azimuth Θ, height *z*; in spheric (*fig*.1, c) - distance ρ (radius-vector) to the *M* point from the coordinate system's origin, azimuth Θ, angle of β. Spheric coordinate system is also called "rho-theta" system.

Azimuth is reckoned from the *OX* axis direction in horizontal plane, which as a rule is oriented to the magnetic north direction, till the radius-vector *r* projection onto the horizontal plane. *OZ* axis is oriented to earth surface in *O* point on the normal.

Local coordinate systems are widely used in short range flights (up to 500 km), aircraft control on all taking off and landing phases and aircraft position determination toward the landmarks.

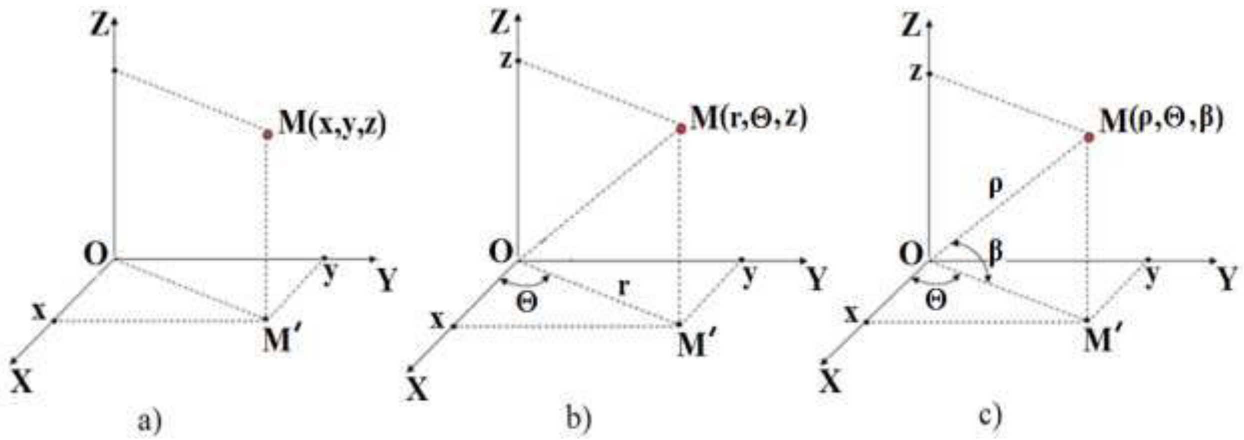

Fig.1. Local coordinate systems

There are pretty elementary mathematic correlations (transformational coordinates) that allow to re-count the coordinates of a point from one coordinate system to another. Transformation from the cylindrical to Cartesian system is written as [Корн, 1974]

$$x = r\cos\Theta, \qquad y = r\sin\Theta, \qquad z = z.$$

and reversed transformation is written as

$$r = \sqrt{x^2 + y^2}, \qquad \Theta = arctg\frac{y}{x}, \qquad z = z.$$

Transformation from spherical into the Cartesian System is written as

$$x = \rho\cos\beta\cos\Theta, \qquad y = \rho\cos\beta\sin\Theta, \qquad z = \rho\sin\beta,$$

and reversed transformation is written as

$$\rho = \sqrt{x^2 + y^2 + z^2}\,, \qquad \Theta = arctg\,\frac{y}{x}\,, \qquad \beta = arctg\,\frac{z}{\sqrt{x^2 + y^2}}\,.$$

The advantages of described coordinate systems include pretty elementary mathematical correlations that describe aircrafts' motion processes, visibility and simplicity of display and perception of information about object's position toward the origin of coordinate system, simple and accurate coordinate transformations from one system to another. Main disadvantage of these systems includes small fraction of earth surface's parts coverage.

Global coordinate systems cover the whole Earth's surface. Earth's figure and therefore its surface has an irregular shape (*fig*.2, a). Unfortunately, there is no such coordinate system that considers the Earth's figure absolutely accurate while describing the navigation processes toward the earth surface in any of its area. That is why various approximations of Earth's figure are used for meeting the accuracy requirements when solving geodesic, cartographic and navigation tasks.

The usage of modern technologies in Earth's parameters measurements, satellite navigation development and also the requirements of air space interoperability caused significant changes in approach to describing the Earth's figure and this description accuracy. As a result, today such coordinate systems are used for geodesic and cartographic, as well as for air and cosmic navigation tasks solving.

Systems of the first type that are used for quite a long period of time, are oriented on the separated determination of objects' position on the Earth surface (horizontal 2D space) and vertically (orthometrical altitude which is reckoned from the mid sea level (MSL)) and systems of the second type - on the objects' position determination in the 3D space. In both cases, more accurate approximation of Earth's figure and its surface is required [Постановление Правительства Российской Федерации от 28.12.2012 №1463].

Geoid is the closest in shape to the Earth's surface. Geoid (*fig*.2, b) is the geopotential surface of the Earth's gravity field, matching the MSL's surface in its calm state. Due to effects, such as atmospheric pressure, temperature, prevailing winds and currents, and salinity variations, MSL will depart from this level surface by a meter or more.

Although the geoid surface is flat in comparison to the physical surface of Earth, it still has irregular shape. This is caused by erratic positions of gravitational masses in the Earth's body, causing the plumb-lines deviation. Geoid is the surface toward which the heights reference to MSL is being reckoned from.

To create the global geoid, the Earth Gravitational Model was developed in 1996 - EGM96 and geoid WGS-84 (EGM96) passed that provides the accuracy of as well as 1 m in the points where gravitation was measured. The WGS-84 Earth Gravitational Model 2008 (EGM2008) is the latest, most accurate and complete gravitational model from which a global geoid is derived [Doc 9674 AN/946. World Geodetic System - 1984 (WGS-84) Manual]. This supersedes EGM96 which is the previous model.

Geoid cannot be mathematically described, that is why for the practical tasks solving on the Earth's surface, it is showed up as mathematically described geometric figure - ellipsoid (*fig*.2, c).

Any rotating liquid homogenous body of big mass can take ellipsoid shape under inner gravity and centrifugal forces. By picking the ellipsoid parameters, it can be more or less moved closer to the geoid in its different parts.

This may mean that the geoid does not fit the actual Earth in another part of the world. The differences in heights referenced to the geoid versus heights referenced to the ellipsoid can be as much as 100 m [Moritz, URL: http:// geodeticscience.org/course/refpapers/00740128.pdf].

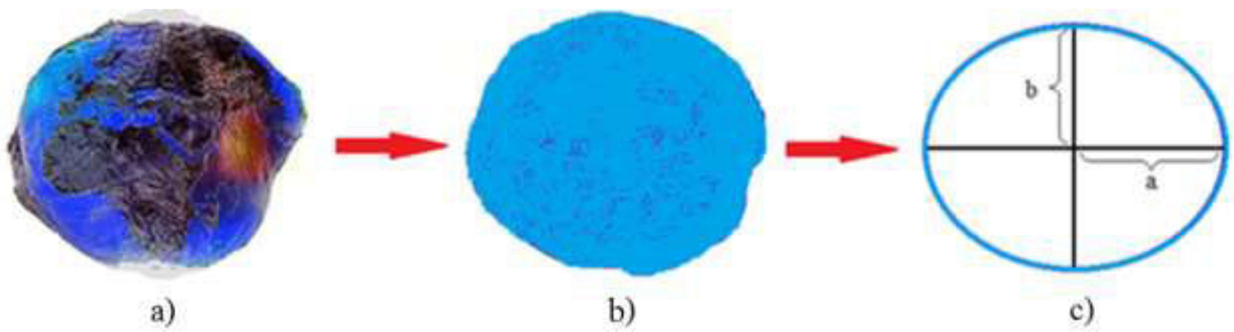

Fig.2. Earth figure approximations

Till 1964 every country selected the parameters of an ellipsoid that was close to the geoid within the territory of that country. Such ellipsoid was named the Local Ellipsoid. Normally, local ellipsoids were taken for legislatively geodesic measurements' processing. Historically, different ellipsoids were taken and legislated at different periods of time in various countries and their parameters didn't coincide.

In Russia/USSR the Krasovsky ellipsoid was used with the following parameters: big semiaxis a=6378245 m, small semiaxis b=6356863 m, compression ratio 1:298,3. In the USA and Canada the Clarke ellipsoid (Clarke 1880) was used with the following parameters: big semiaxis a=6378249 m, compression ratio 1:295,0. In many Western Europe and some Asian countries Hayford ellipsoid was taken, while in former British colonies such as India and Southern Asia counties, the Everest ellipsoid was used [Doc 9674 AN/946. World Geodetic System - 1984 (WGS-84) Manual].

Aircrafts' flight distances increase, global navigation satellite systems' introduction as well as the flight management systems' development (FMS) detected the number of critical problems when using local ellipsoids, e.g. measured coordinates' kicks when passing different countries' air space. That is why the work has been carried out to set the global ellipsoid which would be suitable for all countries. As a result, the geodesic reference system 1980 (GRS-80) ellipsoid was adopted [Moritz, URL: http:// geodeticscience.org/course/refpapers/00740128.pdf].

Geodesic positions referenced to the Earth are defined in the general context of a terrestrial reference system and with respect to a specific terrestrial reference frame. The reference system defines the physical constants (gravitational constant, the semi-major axis of the Earth's best fitting ellipsoid, the speed of light), models and coordinate system needed to unambiguously and consistently define the coordinates of a point.

As an example, the coordinate system can be defined as a 3-dimensional Cartesian system (*OXYZ*) with its origin *O* point at the Earth's center of mass and the three coordinate axes aligned with the equator and the rotational axis of the Earth, and rotating with the Earth's crust.

The scientific standard for the terrestrial reference system is the International Terrestrial Reference System (ITRS). The ITRS embodies a set of conventions that represent the state-of-the-art for referencing geodesic positions to the Earth. These conventions are established by the International Earth Rotation and Reference Systems Service (IERS) [ITRF 2008. URL: http://itrf.ensg.ign.fr/ITRF_solutions/2008/].

In ITRS it is convenient to describe the navigation processes using the Inertial Reference Systems (IRS) and satellite navigation systems, since the measurements in the first case are performed in inertial space, in the second case - toward the objects, which are not connected with the earth's surface.

The physical realization of this system represents a global network of ground stations (on the Earth’s crust) whose three-dimensional coordinates and linear velocities are derived from space-based observations. This station set defines the International Terrestrial Reference Frame (ITRF). The ITRF is periodically modified and applies any changes that have been adopted in the ITRS. The current version of the reference frame is ITRF-2008.

The USA's terrestrial reference system is WGS-84. WGS-84 constitutes an Earth-centered and Earth-fixed coordinate system and a prescribed set of constants, models and conventions that are largely adopted from the ITRS. Its big semiaxis a=6 378 137 m, small semiaxis b=6356777 m, compression ratio 1: 298,257.

The WGS-84 reference frame is defined by a global network of GPS stations which coordinates are closely aligned with the ITRF. The operational reference frame for GPS is WGS-84 also. Ensuring that the WGS-84 frame is consistent with ITRF supports GPS interoperability with other GNSS.

As with the ITRF, the WGS-84 reference frame is periodically updated and designated by the GPS. WGS-84 (G1762) is the current reference frame and is aligned to ITRF2008.

In the USSR, the state terrestrial reference system "Parametry Zemlu" (earth parameters) 1990" (PZ-90) was introduced. In November 2007, the system was modified and named PZ-90.02. Its parameters were modified for some metres at once and it started to match WGS-84 (big semiaxis a=6378136 m, small semiaxis b=6356777 m, compression ratio 1:298, 258). The current version of the Russia terrestrial reference system is PZ-90.11, set in 2012. Ellipsoid's PZ-90.11 surface is taken as a vertical reference in this coordinate system [Параметры Земли 1990 года].

The WGS-84 reference ellipsoid is, for most practical purposes, identical to the GRS-80 ellipsoid. Both ellipsoids have the same semi-major axis and orientation but unique with respect to the ITRF and their flattening agree to 8 significant digits. The ITRS does not directly adopt a reference ellipsoid in its definitions but recommends GRS-80 to transform from ITRF Cartesian coordinates to geodesic coordinates. This relationship between the ellipsoid and the terrestrial reference system constitutes the datum definition.

In the U.S., the North American Datum 1983 (NAD-83) is the standard geodetic reference system that defines three-dimensional control for the country. The GRS-80 ellipsoid was adopted as the reference surface. Ellipsoid heights are also associated with the traditional horizontal control points to define a rigorous set of 3-D coordinates.

In Russia SK-2011 (Sistema Koordinat-2011) is the current version of standard geodesic reference system since 2012. The GRS-80 ellipsoid was adopted as the reference surface for it. Its previous versions SK-42 and SK-95, in which the Krasovsky ellipsoid was used as the reference surface. Its previous versions, SK-42 and SK-95, where the Krasovsky ellipsoid was used as the reference surface.

NAD-83 and SK-2011 are made for performing geodesic and cartographic works. These systems are convenient for aircraft's navigation toward the Earth stations and landmarks, which coordinates are pegged to the Earth's surface.

ICAO has adopted WGS-84 as the world standard and designated the use of the WGS-84 as the universal datum. Since then, the horizontal features have been used on WGS-84 or in other geodesic reference systems which are compatible, such as the NAD-83 or the ITRF combined with the GRS-80 ellipsoid.

Vertical data is traditionally associated with MSL. All elevations on land are referenced to this zero value.

Many national and regional vertical data are tied to a local mean sea level (LMSL), which may significantly differ from global MSL due to local effects such as river runoff and extremes in coastal tidal effects. Thus, national and regional vertical data around the world, which are tied to LMSL, will significantly differ from one another when considered on a global basis. In addition, due to the ways the various vertical data are realized, other departures at the meter level or more will be found when comparing elevations to a global geoid reference.

In the USA, the North American Vertical Datum 1988 (NAVD 88) is used for the altitude reference (the single tide gauge elevation at Point Rimouski, Quebec, Canada, as the continental elevation reference point and essentially references all other elevations in the U.S. to this).

In Russia, all altitudes take their origin from the Baltic Sea level (from the zero-point of flagstaff located in Kronstadt, Saint-Petersburg). Today, the Baltic Sea heights' system of 1977 is used.

For the U.S., a hybrid geoid model, GEOID12A, has been developed to directly relate ellipsoid heights from the NAD-83 datum to the NAVD-88 orthometric heights.

In order to express coordinates in geodetic terms as longitude B, latitude L and ellipsoid height H, a two-parameter oblate reference ellipsoid is defined. For geocentric terrestrial reference systems (*fig*.3), this ellipsoid is selected so that its center (O point) coincides with the Earth’s center of mass, its axes are oriented and fixed to the ITRS coordinate axes, and its semi-major a and semi-minor b axes and rotation rate approximate those of the Earth. The semi-major axis of the ellipsoid coincides with the OZ-axis of the ITRF while the OX- and OY-axes of the ITRF are fixed to the ellipsoid on its equatorial plane. The OZ-axis is rotating at a rate that approximates that of the Earth.

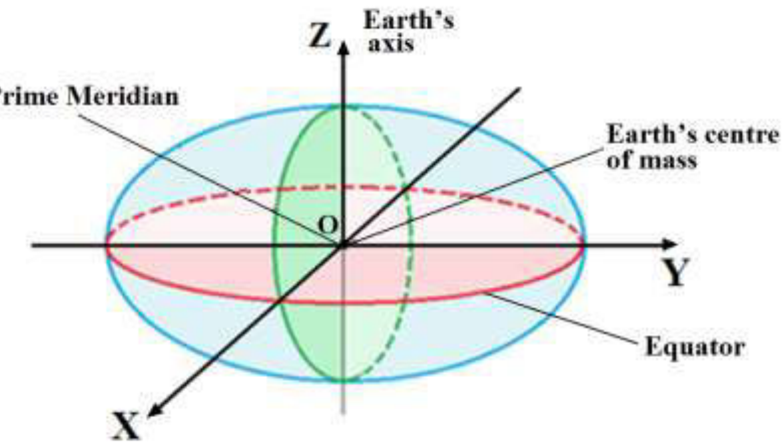

Fig.3. Geocentric terrestrial reference systems

Geodesic Latitude of *M* point is the angle between the normal line to the ellipsoid's surface in this point and the equator's surface (*fig*.4, a, c). This normal line does not necessarily pass through the centre of the ellipsoid.

Geodesic Longitude of *M* point is the dihedral angle between the Greenwich meridian planes and the meridian passing through the *M* point (*fig*.4, b, c).

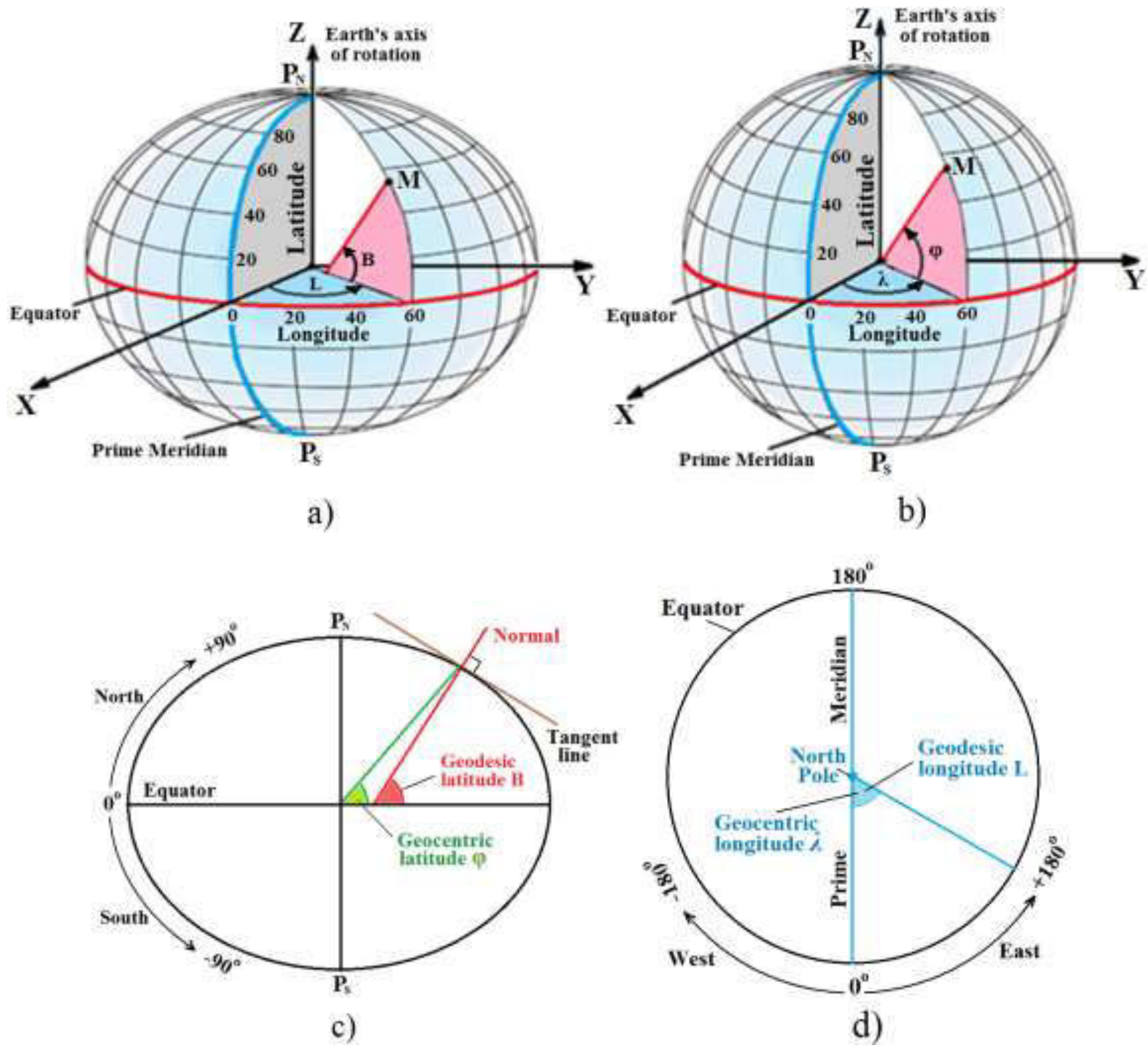

Fig.4. Global geocentric coordinate systems

Geodesic (orthometric) H altitude of M point is the distance on the normal from the ellipsoid's surface to the M point.

Ellipsoid's surface has strict mathematical description and allows to get the formulas for navigation tasks solving with high accuracy. However, these formulas are pretty complicated and are realized in practice only in modern FMS's computers.

Connection between the object's coordinates in Cartesian system $OXYZ$ and geodesic (spatial ellipsoidal) coordinates is determined by the following expressions

$$x=(N+H)\cos B\cos L, \qquad y=(N+H)\cos B\sin L, \qquad z=(N+H-e^2N)\sin B,$$

where H is the height above ellipsoid's surface, $e=\frac{\sqrt{a^2-b^2}}{a}$ - eccentricity of a ground ellipsoid, $N=a\cdot(1-e^2\sin^2 B)^{-1/2}$ - radius of the first vertical's curvature.

Coordinates' transformation from Cartesian system $OXYZ$ into geodesic (spatial ellipsoidal) is performed using the following expressions:

$$B=arctg\frac{z}{\sqrt{(x^2+y^2)}}\left(1-e^2\frac{N}{N+H}\right)^{-1}, \qquad L=Arctg\frac{y}{x}, \quad [-\pi,\pi],$$

$$H=\frac{\sqrt{x^2+y^2}}{\cos B}-N,$$

where $Arctg\ (*)$ is a circular value of an anti-tangent considering the quadrants.

It is important to know that this transformation is performed using the iterational method and the convergence is fastly achieved.

For the objects' coordinates translation into the local topocentrical coordinate system ($OX_{Loc}Y_{Loc}Z_{Loc}$), being geodesically connected to the predefined Earth's point (B_0, L_0, H_0) (*fig*.5), first the translation is performed from geodesic coordinates (B, L, h) into the geocentric rectangular coordinates (x, y, z), connected to the Earth's center, and then the transformation is performed [Скрыпник, 2010]

$$\begin{vmatrix} x_{Loc} \\ y_{Loc} \\ z_{Loc} \end{vmatrix} = \bar{M}\cdot\begin{vmatrix} x - x_0 \\ y - y_0 \\ z - z_0 \end{vmatrix},$$

where x_0, y_0, z_0 are geocentrically orthogonal coordinates of the local coordinates system's origin, $\bar{M} = \begin{vmatrix} -sinL_0 & cosL_0 & 0 \\ -cosL_0 sinB_0 & -sinL_0 sinB_0 & cosB_0 \\ cosL_0 cosB_0 & sinL_0 \cos B_0 & sinB_0 \end{vmatrix}$ - transformation matrix.

Fig.5. Topocentrical local Cartesian System

Reversed translation of local coordinates ($OX_{Loc}Y_{Loc}Z_{Loc}$) into the geocentrical coordinate system ($OXYZ$) is performed according to the expression

$$\begin{vmatrix} x \\ y \\ z \end{vmatrix} = \bar{M}^T \begin{vmatrix} x_{Loc} \\ y_{Loc} \\ z_{Loc} \end{vmatrix} + \begin{vmatrix} x_0 \\ y_0 \\ z_0 \end{vmatrix},$$

where $\bar{M}^T$ - is the transponded matrix.

For simplifying the mathematical description of navigation processes, ellipsoid is replaced by the sphere and geospherical coordinate system is applied (*fig*.4,b). The M point position on its surface is determined by geospherical coordinates - latitude φ and longitude λ.

Yet, the geospherical (geocentric) latitude of M point is the angle between the radius-vector, lined from the spheric center to the M point, and the equatorial plane.

Concepts and the way of geospherical λ and geodesic longitude L reckoning match.

When solving the navigation tasks in geospherical coordinate system, methodical errors of determining the object's position appear which are caused by the approximation of Earth figure by the sphere. The maximum difference between geocentric and geodesic latitudes is most significant in mid-latitudes (at approx. *45°N/S*) and makes $(B-\varphi)_{max}$=11.6 minutes of arc and decreases while approaching the poles or equator. Upon that, geospherical latitude is always less than geodesic one (except for the poles and equator) and geodesic and geospherical longitudes' points match.

The geodesic latitude re-counting into the geospherical one can be performed using the approximate formula

$$\varphi = B - 8'39''\sin 2B.$$

For the point being on the Earth's sphere surface, coordinatial transformations from geospherical coordinate system into the Cartesian System *OXYZ* are written as

$$x = R\cos\varphi\cos\lambda, \qquad y = R\cos\varphi\sin\lambda, \qquad z = R\sin\varphi,$$

and vice versa are written as

$$R = \sqrt{x^2 + y^2 + z^2}, \qquad \varphi = arctg\frac{z}{\sqrt{x^2 + y^2}}, \qquad \lambda = arctg\frac{y}{x}.$$

For navigation parameters measurement with the help of onboard technical aids which antennas system directional patterns are oriented to the construction lines of an aircraft, connected coordinate systems are used. Cartesian System $OX_{ac}Y_{ac}Z_{ac}$ is normally used, which origin is combined with the aircraft's center of mass, OX_{ac} axe matches its longitude axe, OZ_{ac} axe is directed to the right semi-plane side, OY_{ac} axe is directed upward. Such coordinate system is called airframe and is moving in space according to aircraft's evolutions.

For solving the navigation tasks towards the Earth surface this method turns out to be inconvenient in the number of cases, so the horizontal coordinate system $O_{hor}X_{hor}Y_{hor}Z_{hor}$ is used (fig.6) that is connected to an aircraft where the $X_{hor}O_{hor}$-Z_{hor} surface keeps horizontal position at aircraft's evolutions.

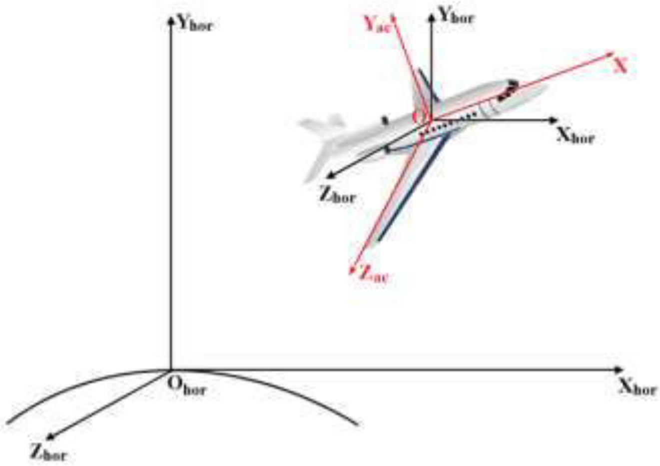

Fig.6. Connected coordinate systems.

For re-counting of measured navigation parameters from the aircraft's into horizontal coordinate system the information about aircraft's roll and pitch is required.

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