On the role of space geodetic measurements for global changes monitoring

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One of the most important and unique task of space geodesy is a development and control of the global terrestrial reference coordinate frame – ITRF, accurate and stable within millimeter level. Small movements of the ITRF origin (geocenter), which conventionally coincides with the Earth's center of mass, provide important information about mass redistribution in the Earth system. An accuracy of the geocenter position estimation is strongly dependent on the geodetic network size and stations distribution over the Earth's surface. From this point of view Doppler Orbit determination and Radiopositioning Integrated on Satellites (DORIS) system has an advantage, as its ground network of beacons consists of about 70 sites, equally distributed over the Earth's surface. The IDC Analysis Center of the Institute of astronomy, RAS, performs DORIS data analysis since 1995. Estimated amplitudes of annual and semiannual variations of the geocenter positions are in the limits of 2–10 mm for horizontal components and 8–30 mm for vertical component. The first attempt to develop a mathematical model of the geocenter motion has been made with the use of Dynamic Regression Modelling approach for spectral analysis of the long set (16 years) of geocenter coordinates, estimated by DORIS measurements at the Institute of Astronomy of the Russian Academy of Sciences (INASAN). In the issue of these studies a possibility to predict the preliminary geocenter positions with the accuracy about 2–4 mm seems feasible over time period up to 10 weeks by the use of mathematical models. Further improvement of the contemporary ITRF could be possible only with dense and equally distributed tracking networks equipped with different measurement techniques. A development of the precise fundamental geodetic network, based on the combined use of GNSS, SLR and VLBI measurements, is now carried out in Russia. Monitoring of secular movements (velocities) of the permanent GPS-stations, located in Russia, already provided an improvement of the reference coordinate frame for North Eurasia. Studies of the seismic belts of Eurasia and velocities of the crust movement, estimated with the use of GPS measurements, showed that only a northern part of the continent could be classified as an indivisible lithosphere plate. It could be named the North Eurasian Plate unlike the Eurasian Plate, which doesn't exist now as an indivisible tectonic block. *KEYWORDS: ITRF origin estimation; space geodesy; monitoring tectonic movements.*

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1. Introduction

During the last decades plenty of new information about the Earth and its environment has been obtained as a result of data processing of systematic earth-based observations of special artificial satellites. The detailed analysis of their orbital parameters variations makes possible to understand physical and dynamic properties of the Earth as a planet. The important advantage of this new space branch in the field of Earth's sciences, named satellite or space geodesy, is its global nature in particular.

The considerable increasing of satellite laser ranging accuracy and fast development of satellite radio navigation and positioning systems such as GPS, GLONASS and Doppler Orbit determination and Radiopositioning Integrated on Satellites (DORIS) [*Dow et al.*, 2008; *Noll,* 2010] has fully

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changed the approach to problems of determination of a large scope of physical and dynamic parameters of the Earth as a planet.

The recent detailed model of the Earth's gravity field EGM2008, obtained with the use of space missions CHAMP, GRACE, GOCE, contains spherical harmonic coefficients up to degree 2190 and order 2159 [*Schlüter, Behrerd*, 2007]. These models allow discovering fine peculiarities of the Earth's tectonic structure, which are the consequence of various geophysical processes in active tectonic zones of subduction, collision and plate expansion such as, for instance, the Himalayan-Tibetan Region and the Middle-Atlantic Ridge [*Dick, Richter*, 2002]. Till now the detailed peculiarities of the tectonic structures could be discovered only with the use of very expensive local gravimetric measurements by means of land-based facilities or from sea vessels. Similar space missions will open new ways to study the Earth's gravity field, its internal structure and time changes of the Earth's physical and dynamic parameters. Most users in space geodesy find their needs covered by a truncated version of the gravity model, on condition that this truncated level will provide a 3-dimensional orbit accuracy of better than 0.5 mm for the indicated satellites. Thus for DORIS type satellites it is sufficient to use 90 coefficients, for high orbital satellite LAGEOS – about 20 coefficients and for GNSS orbits – only 12 coefficients are usually used.

The relative coordinates of the ground-based points and the base lengths at distances of hundreds or thousands kilometers could be determined with errors of few mm horizontally and less than 1.0 cm vertically.

An important problem, being solved currently only by means of satellite observations and very long baseline radio-interferometry – VLBI [*Petit, Luzum*, 2010], is a registration and monitoring of short-period variations of the Earth's rotation speed and its orientation in the Space, since these parameters determine the Universal Time and are required to connect the inertial (celestial) coordinate frame with geocentric (terrestrial) frame. The International Earth Rotation and Reference Systems Service (IERS) [*Rummel, Foeldvary*, 2006] regularly determines and publishes information about the Earth's orientation parameters to within 0.1–0.2 ms of the arc (1 cm) in the pole position and about 0.3 ms in time with resolution of 1 day and less.

Coefficients of nutation (characterizing movement of the Earth's rotation axis in the inertial frame) have been determined to high precision that is necessary to study the Earth's internal structure and free nutation of its liquid external core. Interpretation of long-period fluctuations of the Earth's rotation velocity (day duration) and periodical movements of the Earth's center of masses must be probably connected with generation of perfect models of the planet internal structure. These researches go on as observed material is accumulated.

To study mechanisms of destructive geodynamic phenomena including determination of places of possible severe earthquakes, volcano eruptions and some other natural hazards, it is important to have means to evolve areas where maximum changes of the displacement velocities and the terrestrial crust vertical movements are possible. Since these displacements appear at the level of centimeters or even millimeters then the measurement accuracy has to be the proper one. The experience of the last years has showed that currently only satellite geodesy techniques are the most effective (as for accuracy and cost-effectiveness) for research activities in this field.

In this connection, one of the most important and unique task of space geodesy is a development and control of the global terrestrial reference coordinate frame, accurate and stable within millimeter level.

2. Definition of the International Terrestrial Reference Frame

According to the IERS Conventions-2010 [*Schlüter, Behrerd*, 2007], the International Terrestrial Reference Frame (ITRF) is a spatial reference coordinate system co-rotating with the Earth in its diurnal motion in space. In such a frame, positions of points attached to the Earth's crust have coordinates, which undergo only small variations with time due to geophysical effects: tectonic and tidal deformations. The current ITRF model is linear and geocentric. Its origin, conventionally, is defined to be at the center of mass (CM) for the whole Earth, including atmosphere and oceans. A realization of the terrestrial reference frame is achieved by the set of physical points with the coordinates, precisely determined by the use of modern space geodetic techniques. A number of reference points is growing up with time and the last realization of the International Terrestrial Reference Frame (ITRF 2008) is based on the network, containing 580 sites. For the ITRF 2008 solution the reprocessed data of four space geodesy techniques VLBI, SLR, GPS and DORIS, spanning 29, 26, 12.5 and 16 years respectively, were used. Majority of sites (463) are located in the northern hemisphere and 117 sites are in the southern hemisphere.

In the base of all space geodetic methods (except of VLBI) there is an accurate determination of the observable satellites orbits, which are moving relative to the center of mass (CM) of the entire Earth. However, in reality the sites of the ITRF network are fixed to the solid Earth crust and its origin coincides with the center of the solid Earth surface figure (CF). Studies of the ITRF precision and stability, carried out at the different research centers [*Blewitt*, 2003; *Boucher, Sillard*, 1999], show that the origin of the terrestrial coordinate system (CF), attached to the rigid crust-fixed frame, is moving relatively to the center of satellite orbits, which is CM. This motion is known as "geocenter motion", and is estimated at the level of a few millimeters to centimeter for the periods from diurnal to seasonal. In accordance with the IERS Conventions the origin of the ITRF is considered as the mean Earth center of mass, averaged over time span of the SLR observations and modeled as a linear function of time. But for analysis of the local geodetic measurements an instantaneous geocentric site position may be required, then it should be computed as

$$\mathbf{X} = \mathbf{X}_{\mathrm{ITRF}} - \mathbf{R}_G$$

where $\mathbf{R}_G$ is the motion of the ITRF origin.

The center of mass variations must be properly accounted for in the realization of the tracking stations positions within the reference frame, as the accuracy of the vertical component is very sensitive to the stability of its origin. This is important when the ocean tides loading effect on the height component of the coordinate is evaluated, especially for the coastal sites. This effect may reach 5–6 mm [*Cretaux et al.*, 2002].

Accurately determined geocenter variations and a full understanding of the observed geocenter motions provide important information about mass redistribution in the Earth system and should provide observational constraints on mass budgets in global atmospheric and hydrological models, especially those of the snow/ice fields in the Antarctic, Arctic and Greenland, as well as mean sea level variations, which are of great interest for global climate studies. It should be noted, that an accuracy of the geocenter position estimation is strongly dependent on the geodetic network size and stations distribution over the Earth's surface [*Dong et al.*, 2003; *Tatevian et al.*, 2004]. From this point of view DORIS system has an advantage, as its ground network of beacons consists of about 70 sites, equally distributed over the Earth's surface.

3. Estimation of the Geocenter Motion With DORIS Data

3.1. DORIS, General Features

DORIS is a satellite system, developed to support high accuracy orbit determination for altimetry measurements of the sea level and ground beacon positioning. It is an uplink radio-electrical system based upon Doppler measurements and dual-frequency to correct for ionosphere effects [*Willis et al.*, 2006].

The objectives of the global navigation satellite systems GNSS and DORIS are different. DORIS receivers are installed on research satellites mainly for precise orbit determination (POD) for altimeter mission and for some other scientific objectives [*Willis et al.*, 2010]. The tracking data are also used by the geodetic community. The space segment now is accounted for 6 satellites. Precise beacon positioning reaches the centimeter accuracy and stability in reference frame. For the best geodetic results of better than 10 mm in all 3D components, the number of satellites should be greater than four and fly at significantly different inclinations [*Willis*, 2007]. Due to efforts of the International Doris Service (IDS), National Space Committee of France (CNES) takes this requirement into account and several new satellite missions are planned through 2016 year in cooperation with Italy, China, USA and ESA.

The DORIS data from all ground beacons are first archived at the IDS data centers [*Noll, Soudarin*, 2006] and then are used by seven Analysis Centers, which generate time series of station coordinates, Earth Orientation Parameters (EOP) and orbital parameters of the DORIS satellites.

3.2. Analyses of the DORIS Network Measurements

The IDC Analysis Center (INA) of the Institute of astronomy, RAS, performs DORIS data analysis since 1995. For that GIPSY/OASIS2 software, developed by Jet Propulsion Laboratory (JPL) [*Webb, Zumberge*, 1997] and significantly expended for DORIS applications by joint IGN (Institute Geographique National)/JPL cooperation is used [*Willis et al.*, 2005]. The detailed description of the methods applied for data processing has been described in [*Kuzin, Tatevian*, 2000, 2002; *Kuzin et al.*, 2010]. Stations coordinates, estimated on daily basis using all available satellites with DORIS equipment, are combined into weekly solutions, projected (removing of the indetermination due to a loosely definition of the terrestrial reference frame) and transformed to a well-defined reference frame with the use of 7 parameters of Helmert transformation.

Taking into account recommendations of the IERS and International DORIS service (IDS), a reprocessing of the all available DORIS data since 1993.0 are performed aiming to obtain a unified coordinated solution of the IDS analysis centers for the submission to the new version of the Terrestrial Reference System – ITRF 2008 and to the IDS data center. For these solutions the next standards have been recommended by the IDS: gravity model – GGM02C [*Tapley et al.*, 2005]; atmospheric gravity – not applied; ocean tides – CSR3; atmospheric density – DTM2000 [*Bruinsma, Thvillier*, 2000]; drag paramete rization – Cd/1 hrs; troposphere mapping function – Niell [*Niell*, 1996].

The weekly solutions of coordinates of all 71 DORIS ground sites and EOP have been estimated with the use of new improved satellite surface models, submitted by CNES, and with measurement data of the satellites SPOT2, SPOT3, SPOT4, SPOT5, TOPEX, and ENVISAT.

Weekly coordinates of the DORIS network were estimated with the internal precision at the level of 0.5–20.0 mm for the majority of stations. In our solutions we evaluated simultaneously 4 EOP parameters per day (X-pole, Y-pole coordinates and their rates). Mean square residuals of pole coordinates for the period 2000–2009 are estimated as 2.60 mas and 1.70 mas, respectively, with refer to IERS C04 solution [*Altamimi, Collilieux*, 2010]. A comparison of orbit estimations, made by INA center and other IDS centers, showed inter-orbit consistency at the level 1–2 cm in all directions.

It was approved, that DORIS positioning accuracy strongly depends on the number and constellation of satellites used in the solutions. The systematic errors in the solutions may be caused by incomplete models used for orbit determination [*Gobinddass et al.*, 2009a, 2009b]. The solar radiation pressure affects significantly the orbital movement of the DORIS satellites, because of a complex shape and varying optical properties of the different surfaces of the spacecrafts. The shortcoming modeling of this effect can produce periodic Z shifts at the draconic period.

Table 1. Periodical variations of the geocenter movements

	Coordinates	Interval of processing	Annual period		Semiannual period	
	(3 components)	Years	A, mm	Phase, degrees	A, mm	Phase, degrees
X	DORIS (INA)	1993.00–2011.50	5.32 ± 0.22	100.91 ± 3.54	8.04 ± 0.27	356.94 ± 2.11
Y	DORIS (INA)	1993.00–2011.50	4.26 ± 0.02	313.16 ± 6.20	8.43 ± 0.28	351.68 ± 2.51
Z	DORIS (INA)	1993.00–2011.50	2.64 ± 1.04	268.90 ± 21.67	31.46 ± 0.98	357.94 ± 1.92

3.3. Determination of the Geocenter Positions

A set of translation parameters, derived in the process of transformation the free network weekly solutions for coordinates into well-defined reference frame (ITRF 2005), was analyzed with a view to study variations of the geocenter movements. Three translations parameters and scale factor are more significant as compared with 3 rotational ones, as they provide information on the position of the reference terrestrial network origin (geocenter). This method of the geocenter estimation is often named as the "geometrical".

In order to estimate linear trend, amplitudes, periods and phases of geocenter variations the linear regression analysis has been applied. For analysis the next approximation was used:

$$J(t) = a_0 + b_0 t + A_0 \sin\left(\frac{2\pi}{P}(t - t_0)\right) + \varphi_0 \tag{1}$$

A_0 – amplitude of the signal; P – period of the signal (in years); φ_0 – initial phase of the signal; a_0 – offset; b_0 – trend; t – time; t_0 – arbitrary initial time (we take t_0 – 1-st January).

The amplitudes and phases of the periodical annual and semiannual variations of the geocenter components X, Y, Z (with respect to 2005.0) are presented in Table 1.

Estimated annual geocenter variations were derived by least square method. Evaluated amplitudes are: 5.32 mm, 4.26 mm, 2.64 mm for X, Y, Z components respectively. Amplitudes of the semiannual variations are estimated as 8.64 mm, 8.43 mm, 31.46 mm for X, Y, Z components. A low linear trend of Z component was recorded in the analyzed set of DORIS data (Table 2).

Amplitudes of annual and semi annual geocenter variations, evaluated by the analyses of DORIS data, are significantly 4–6 times as much as those, derived from the GPS and SLR measurements, mainly in the geocenter Z-component [*Bouille*, 2000; *Lavallee et al.*, 2006]. Systematic errors in geocenter estimation by DORIS measurements are satellite dependent, and improved satellites orbital modeling has to be applied to avoid the discrepancies between different geocenter solutions. Nevertheless we assume that general behavior of the geocenter motion, estimated with the use of multi-years DORIS time series, more or less coincide with its real motion.

3.4. Mathematical Modeling of the Geocenter Motion

The first attempt to develop a mathematical model of the geocenter motion has been made with the use of Dynamic Regression Modelling approach [*Valeev*, 1991] for spectral analysis of the same long set (16 years) of geocenter coordinates, estimated by DORIS measurements at the INASAN Analysis center. The analysis of time series with DRM method includes:

- the graphic representation and the description of time series behavior;
- studies of time series with the help of correlation, spectral and wavelet analysis;
- removal of nonrandom trend component;
- estimation of harmonic components;
- analysis of the time series random component, which remained after removal of items listed above.

Amplitudes of annual and semi-annual variations of geocenter, derived with the use of two different methods of spectral analysis are in very good agreement between each other [*Kuzin*, 2010]. By the use of dynamic regression modelling several other harmonics with periods of 1, 2 months and 2, 3 years, but with very small (as compared with noise) amplitudes were found out. For comparison geocenter time series, derived from the GPS daily coordinate solutions at JPL (ftp://sideshow.jpl.nasa.gov/pub/usrs/mbh) for the time period 1992.5–2007.6 has been examined with DRM analysis as well [*Valeev et al.*, 2011]. For both DORIS and GPS data, annual and semiannual harmonics have more significant amplitudes, but there are other common harmonics with smaller amplitudes and with periods 1 month, 118 days and 1190 days (only for dx component of the geocenter).

Two types of mathematical models: complete (all harmonics) and truncated (only annual, semi-annual and 118

Table 2. Linear trend of the geocenter coordinates (X, Y, Z)

SOLUTION	X, mm/y	Y, mm/y	Z, mm/y
DORIS/INA	0.29 ± 0.04	-0.07 ± 0.05	2.62 ± 0.16

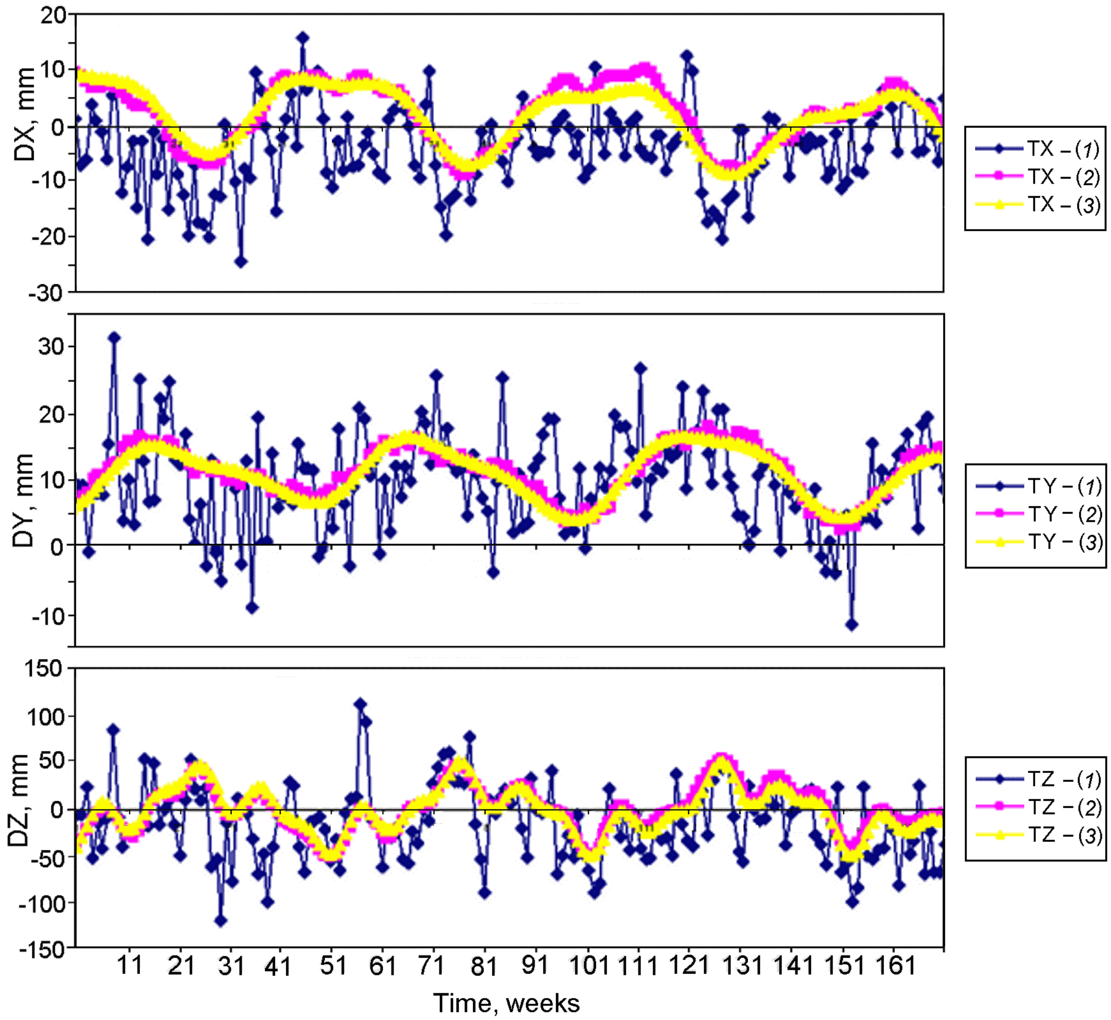

Figure 1. Diagrams of geocenter positions, estimated by the truncated (*1*), complete (*2*) mathematical models and by the real DORIS observations (*3*).

days), developed by the use of DORIS data, have been compared with observable geocenter positions on the time interval 1190 days (Figure 1). In the issue of our studies a possibility to predict the preliminary geocenter positions with the accuracy about 2–4 mm seems feasible over time period up to 10 weeks with the use of truncated models, as the differences between complete and truncated modeling are in the limit of 1–4 mm. That is comparable with the accuracy of a complete mathematical modeling of the geocenter motion.

4. Monitoring of the Tectonic Movements of the Northern Eurasia

The current procedure used in the ITRF elaboration is to form a secular frame with linear velocities of the core stations. Times series of station positions allow to monitor any non-linear motion or drift. Further improvement of the contemporary ITRF could be possible only with dense and equally distributed tracking networks equipped with different measurement techniques.

A development of the precise fundamental geodetic network, based on the combined use of GNSS, SLR and VLBI measurements, is now carried out in Russia [*Demianov, Tatevian*, 2000]. This network will fix the national coordinate system all over the country with mean square errors at the level of 2–3 cm for absolute coordinates and for relative positioning within errors of 1 cm. (Figure 2)

At present the new regional reference network consists of 33 permanent stations in 700–800 km distance each other. All sites are equipped with dual GPS/GLONASS receivers, and several fundamental stations are collocated with the existing on the Russian territory sites of the international IGS network, satellite Laser ranging stations and VLBI observatories (“QUASAR” network) [*Finkelstein*, 2001]. All these collocated sites will provide connection of the regional geodetic system to the global ITRF.

Figure 2. Permanent GPS/GLONASS sites in Russia.

Monitoring of secular movements (velocities) of the permanent GPS-stations, located in Russia, already allowed to improve the reference coordinate frame for North Eurasia so far as this network provides representative covering of the largest stable areas (the Siberian and the East European) of the Eurasian plate [*Kogan, Steblov*, 2008]. Analysis of the average values of the GPS sites velocities shows that the general movement direction of the European part of the continent is the north-eastern one. However, as moving eastward, the northern movement component decreases and approximately at the longitude of Novosibirsk the direction changes to the southeast. Movement of the outermost points of the continent (Magadan and Petropavlovsk-Kamchatsky) has strongly pronounced the south-western direction, i.e. there is a rotation of the Eurasian continent.

An establishment the present-day heterogeneity of the Eurasia was one of the most significant achievements of regional geodynamics during last decade. Studies of the seismic belts of Eurasia and velocities of the crust movement, estimated with the use of GPS measurements, showed that only a northern part of the continent could be classified as an indivisible lithosphere plate [*Gatinsky*, 2005] It could be named the North Eurasian Plate unlike the Eurasian Plate, which doesn't exists now as an indivisible tectonic block. Along its southern border, there is a zone consisting of a great number of microplates, surrounding the South-Eurasian stable plate (Figure 3). Interaction of these small plates and blocks influences distribution of seismic stresses in internal parts of the continent that is confirmed by the highest seismic activity of the triangle bordered by thrusts of the Himalayas and faults of the Pamirs, the Tien-Shan, the Baikal lake and the North-Eastern China.

5. Summary

Precise measurements and control of the relatively small changes induced by mass transfer in the Earth's system are essential for a variety of applications, as well as for tectonic studies and understanding the behavior of the Earth's interior and its influence on volcanic and seismic activities. Geocenter movements relative to the ITRF origin (at the level of 1–5 mm) directly affect estimates of all space geodetic measurements that use the ITRF as a reference system. Mainly this refers to vertical components of the ground stations, which are very sensitive to the stability of the ITRF origin. In the issue of our studies a possibility to predict the preliminary geocenter positions with the accuracy about 2–4 mm seems feasible over time period up to 10 weeks by the use of truncated mathematical models, as the differences between complete and truncated modeling are in the limit of 1–4 mm.

Amplitudes of the geocenter variations, estimated by DORIS data are significantly 4–6 times as much as those, derived from the GPS and SLR measurements due to systematic errors in satellites orbital modeling. According to the IERS Conventions-2010 the origin of the ITRF is considered as the mean Earth center of mass, averaged over multiyear time span of the optical SLR observations, as the SLR data allow access to the Earth center of mass (a natural ITRF origin), the point around which the satellites orbit.

With understanding, that a further improvement of the global terrestrial reference coordinate frame, accurate and stable within one mm level could be possible only through the long-term worldwide cooperative efforts, the Interna-

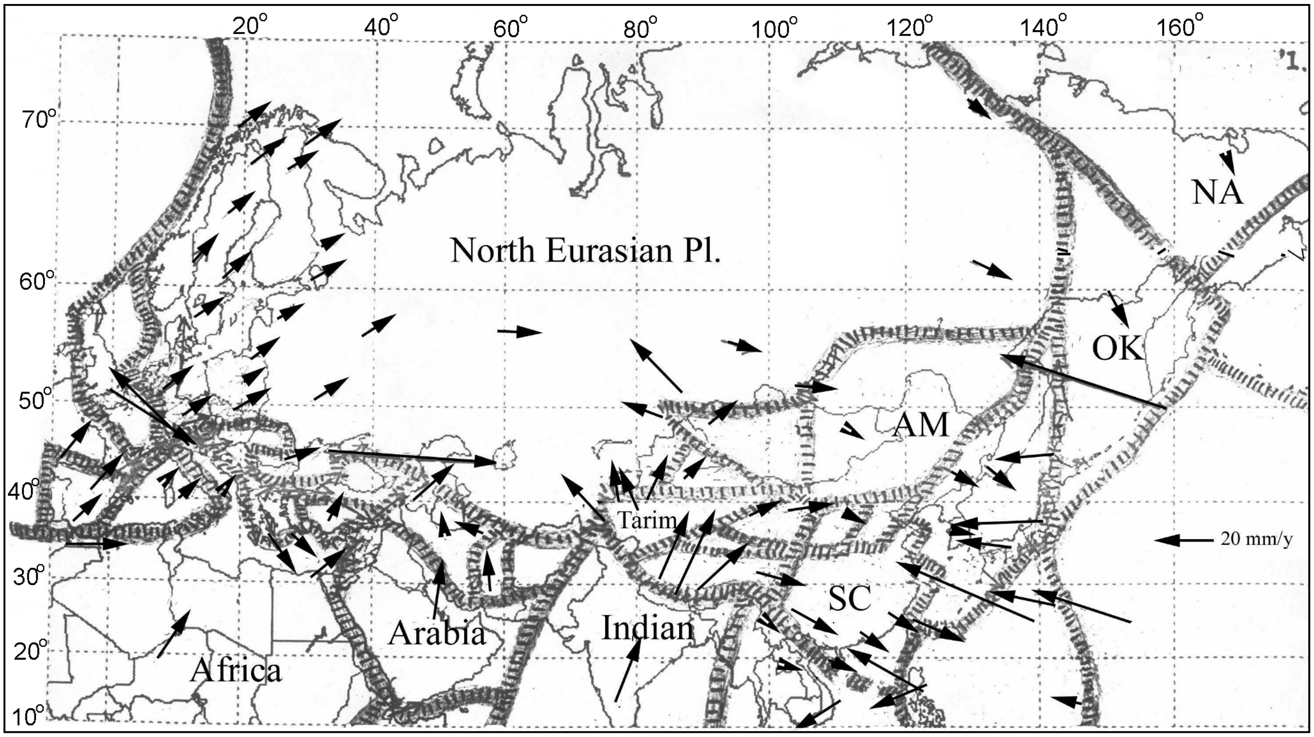

Figure 3. Southern border of the Eurasian tectonic plate (micro plates and tectonic blocks).

tional Association of Geodesy initiated a new project on the establishment (by 2020) of the Global Geodetic Observing System (GGOS) [*Plag*, 2009]. GGOS will integrate different geodetic techniques and satellites, different geophysical models, different ideas and methods in order to ensure a long-term monitoring of the geodynamic phenomena and geophysical parameters. GGOS will consist of about 40 permanent ground tracking sites, equipped with different types of modern instruments for minimizing systematic errors, characteristic for every usable technique, space segment of special research satellites and centers of merging, storage and analyses of the data.

In the frame of GGOS, the Earth system is viewed as a whole including the solid Earth as well as the fluid components (atmosphere, oceans, ground waters), the static as well as time-varying quantities.

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