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ITRS, PZ-90 and WGS 84: current realizations and the related transformation parameters

C. Boucher[1], Z. Altamimi[2]

[1] Institut Geographique National, DAEI, 2 Avenue Pasteur, 94160 Saint-Mandé, France
e-mail: cboucher@club-internet.fr; Tel.: +33-1-43-98-83-27; +33-1-43-98-84-88
[2] Institut Géographique National, ENSG/LAREG, 6–8 Avenue Blaise Pascal, 77455 Marne-la-Vallée, France
e-mail: altamimi@ensg.ign.fr; Tel.: +33-1-64-15-32-55; Fax: +33-01-64-15-32-53

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Abstract. The first results of the International GLONASS Experiment 1998 (IGEX-98) campaign have provided significant material to illustrate the mutual benefits of the GLONASS system and the realization of the International Terrestrial Reference System (ITRS). A specific aspect, namely the relationship between the World Geodetic System 1984 (WGS 84) and the PZ-90 system using ITRS as a primary standard, is investigated. A review of current works is carried out. A transformation strategy is proposed for the three systems based on recent results from IGEX-98 and an independent set of transformation parameters derived by the Jet Propulsion Laboratory from ITRF97 and PZ-90 coordinates for 16 global stations.

Key words: Terrestrial reference systems – International terrestrial reference system – World geodetic system 84 – PZ-90

1 Introduction

The rapid development and use of global satellite navigation systems has made the concept of terrestrial reference systems (TRS) a very important and somewhat sensitive issue. Comparisons between positions derived from these navigation systems and existing maps, either on land or at sea, exhibit noticeable discrepancies caused by different coordinate systems, in particular different TRSs.

The two currently operational global satellite navigation systems, namely the global positioning system (GPS) developed by the USA and the Global Navigation Satellite System (GLONASS) system developed by Russia, have made this point clear in their various official publications: GPS uses WGS 84 as its reference TRS, while GLONASS uses PZ-90.

Biases between satellite-derived positions and map positions currently reach several hundreds of meters and are therefore visible most of the time, even in the case of GPS with selective availabilty (SA). But biases between GPS-derived and GLONASS-derived positions are less clear. Nevertheless, many users have identified systematic discrepancies by collocating receivers of each type. Knowledge of the difference between World Geodetic System (WGS) 84 and PZ-90 was therefore essential to better understand such comparisons, and better separate the reference system effect from other sources of discrepancies. Moreover, the simultaneous availability of both systems and their technical similarities have encouraged the development of mixed receivers. The increased number of simultaneously tracked satellites is a key factor in improving the quality of positioning, not only for accuracy, but also for availability or reliability. Therefore it is of great interest to use both GPS and GLONASS measurements in such a process, but it is required that any reference system discrepancies are corrected when the broadcast navigation information of each system is used. This last point gave an impetus to recent investigations on the WGS 84/PZ-90 transformation performed mainly by the navigation community.

This paper reviews some of these estimates, including the significant progress realized thanks to the IGEX-98 campaign, which provided for the first time a remarkable data set of GLONASS satellites in conjunction with GPS and laser networks. (Willis et al. 1999a, b). It also reviews some basic points which better explain the apparent diversity of transformation parameter estimates.

2 The basic concepts and their uses

These concepts were redefined extensively in the 1980s by the astronomical and geodetic communities (see e.g. Kovalevsky et al. 1989).

An ideal TRS is defined as a three-dimensional (3-D) reference frame (in the mathematical sense) close to the

Correspondence to: C. Boucher

Earth and co-rotating with it. In the Newtonian framework, the geometry of the physical space considered as a Euclidian affine space of dimension 3 provides a standard and rigourous model of such a system through the selection of an affine frame. A *geocentric* TRS has its origin close to the geocenter and its orientation equatorial (Z axis is the direction of the pole). We further distinguish two types, depending on the method used (classical terrestrial or space techniques) to establish and realize such systems.

1. (Really) geocentric, which means that realizations will be close to the geocenter (a few meters in the early days of satellite geodesy, nowdays a few centimeters) and the zero meridians of the equatorial orientations will be almost identical (currently expressed using the name of the Greenwich meridian, for historical reasons).

2. Quasi-geocentric, for systems established with terrestrial geodetic techniques usually using a fundamental station. In such cases, the origin may be offset from the geocenter by several hundred meters. Notice also that these systems currently use a zero meridian linked to some astronomical observatory and therefore should be realigned to the conventional Greenwich origin by adopting a longitude for this zero meridian with respect to Greenwich. For instance, in Europe, several conventional origins are still in use for mapping purposes (e.g. Paris, Rome, Madrid).

Under these restrictions, the general transformation of the Cartesian coordinates (X) of any point close to the Earth from any one TRS to any other one will be given by a tri-dimensional similarity transformation (T is a translation vector, λ a scale factor and R a rotation matrix) as follows:

$$X^{(1)} = T_{1,2} + \lambda_{1,2} \cdot R_{1,2} \cdot X^{(2)}$$

For practical use, we adopt the convention currently used by IERS and in Boucher and Altamimi (1996). The parameters for transforming an X system into an X_S system are denoted $T1$, $T2$, $T3$, D, $R1$, $R2$, and $R3$:

$$\begin{pmatrix} Xs \\ Ys \\ Zs \end{pmatrix} = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} + \begin{pmatrix} T1 \\ T2 \\ T3 \end{pmatrix} + \begin{pmatrix} D & -R3 & R2 \\ R3 & D & -R1 \\ -R2 & R1 & D \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

It must be noted that the sign convention for rotation angles often found in the literature is the opposite of this.

A conventional TRF is defined as a set of physical points with precisely determined coordinates in a specific coordinate system that is the realization of an ideal TRS. Such frames are currently classified as of dynamical or kinematical type, depending on whether or not a dynamical model is applied in the determination process of these coordinates.

The example of a dynamical TRF of specific interest in this paper is the ephemerides of artificial satellites. The ephemerides derived from the navigation message either from GPS or GLONASS, or those computed by analysis centers processing space geodetic data, are of this type. We shall categorize these as 'E-frames' in this paper. It is important to note that what we label E-frames are satellite ephemerides expressed in an Earth-fixed geocentric system, not ephemerides in a quasi-inertial frame. This implies in particular that they are sensitive to the Earth orientation parameter (EOP) values adopted in computations generating the satellite ephemerides.

However, kinematical TRFs are the most user oriented type. We can again distinguish between two types in this study.

1. 'T-frame' will designate a set of coordinates (and possibly velocities) of a tracking network of stations used to produce ephemerides by dynamical processing.
2. 'N-frame' will designate a network of points with coordinates (and possibly velocities) determined by processing tracking data of the satellite systems considered here (GPS or GLONASS).

Some fundamental remarks must be made at this point to illustrate the relative complexity of the consistency of the various realizations of a TRS.

To some extent, transformation parameters have to be understood as representing the transfer of any systematic changes which fit with some part of this similarity transformation (shift, scale, or rotation). The values of these parameters are determined by an estimation process [usually least squares (LS)], based on two frames with corresponding points. This can therefore be done for T-, E- or N-frames. A more theoretical presentation of this can be found, for example, in Sillard and Boucher (submitted).

In the case of operational orbit computations, as done for generating broadcast messages for each satellite system, we can easily understand that a transformation of the T-frame used in this computation will map, to some extent, especially in orientation into the resulting E-frame, a dynamical law such as Kepler's third law introducing constraints on origin and scale, depending on orbital arc length. It is important to note that there is not a simple law presently available to describe this transfer function between T-frames and E-frames. It certainly depends upon tracking network geometry, orbital arc characteristics, type of orbit, the arc length, and the number of simultaneously observed satellites). For instance, recent investigations on the DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) system showed results on this specific topic using numerical simulations in the case of the Topex/Poseidon mission (Morel 2000). In the case of the GPS type configuration, the current findings of analysis done by the International GPS Service (IGS) indicate a T- to E-frame transfer only significant in rotations (Kouba personal communication). In addition, we must also understand that other error sources can infer systematic biases in the E-frame which are not in the T-frame (this was the case for uncorrected antenna offsets of satellites).

In the case of N-frames generated by point positioning of ground networks, the E-frame will generally map directly into the resulting N-frame if the orbits are not readjusted. This may not be true if strong constraints are placed on a priori values, if the adopted satellite clock data affect the origin (Kouba personal communication), or if there are constraints on some station positions, as is often the case (see example below).

3 Description of the three systems and history of their realizations

3.1 The International Terrestrial Reference System (ITRS)

The International Earth Rotation Service (IERS) is presently responsible for the realization, use and promotion of the International Terrestrial Reference System (ITRS) as defined by the International Union of Geodesy and Geophysics (IUGG) resolution No. 2 adopted in Vienna in 1991 (Geodesist's Handbook 1992, Bulletin Géodésique 66).

The ITRS definition fulfills the following conditions.

1. It is geocentric, the center of mass being defined for the whole Earth, including oceans and atmosphere.
2. The unit of length is the meter (SI). This scale is consistent with the TCG (Geocentric Coordinate Time) time coordinate for a geocentric local frame, in agreement with the International Astronomical Union (IAU) and IUGG (1991) resolutions. This is obtained by appropriate relativistic modeling.
3. Its orientation was initially given by the Bureau International de l'Heure (BIH) orientation at 1984.0. The IERS Reference Pole (IRP) and Reference Meridian (IRM) are consistent with the corresponding BIH reference directions to within $+/-$ 0.005″. The BIH reference pole was adjusted to the Conventional International Origin (CIO) in 1967; it was then kept stable independently until 1987. The uncertainty of the tie of the IRP with the CIO is $+/-$ 0.03″.
4. The time evolution of the orientation is ensured by using a no-net-rotation condition with regard to horizontal tectonic motions over the whole Earth.

[See IERS Conventions (McCarthy 1996) for a detailed description of the ITRS.]

Realizations of the ITRS are produced by the Terrestrial Frame Section of the IERS Central Bureau under the name International Terrestrial Reference Frames (ITRF). These consist of lists of coordinates (and velocities) for a selection of IERS sites (tracking stations or related ground markers) that are obtained by combining the results of several space techniques, currently: very long baseline interferometry (VLBI), lunar laser ranging (LLR), GPS, satellite laser ranging (SLR), and DORIS. General documentation on terrestrial reference systems and frames is available at http://lareg.ensg.ign.fr/ITRF/.

Almost every year since the beginning of the Service, a new global solution has been performed and published, replacing the previous solutions. The most recent solutions are ITRF94, ITRF96, and ITRF97, which is the current one (a new solution is in progress and will be published as ITRF2000).

Each such solution is an N-frame realizing ITRS.

In addition, the IGS has adopted the ITRS as its reference system. Consequently the IGS products are all referred to this system. The GPS precise ephemerides produced by the IGS (either precise, rapid, or predicted) are therefore E-frames in the ITRS for all GPS satellites.

3.2 The World Geodetic System 1984 (WGS 84)

WGS 84 is a complete standard for georeferencing and was established by the US Department of Defense (National Imagery and Mapping Agency, formerly Defense Mapping Agency). A TRS was of course adopted for WGS 84. However, it must be understood that WGS 84 as a TRS has had several successive realizations, improving its geometric quality from the meter level to the centimeter level (Malys and Slater 1994; Slater and Malys 1998). The initial realizations used the Transit satellite navigation system (Satellite Doppler), where various residual errors were contributing to limit its final accuracy to meter level. For instance, ionospheric residual error caused significant height biases (Sillard and Boucher 1996).

The GPS broadcast orbits represent the basic realization of WGS 84 for modern users. According to the present terminology, this is an E-frame. As already stated, any improvement in processing strategy may produce systematic changes that map into the similarity transformation parameters. Numerically the corresponding frame will change accordingly. This is particularly true for the effect of the T-frame on the generation of GPS broadcast orbits. The operational GPS tracking station network (five OCS stations) is small and any change in adopted positions for these stations will map to some extent into the broadcast orbits. As reported by Malys and Slater (1994), changes at the meter level have occurred. Since January 1997, the T-frame labeled WGS 84 (G873), which has been adopted for OCS and broadcast orbits, is consistent with ITRS to better than a decimeter. This T-frame was derived from a global GPS solution for the combined network of OCS and NIMA GPS tracking stations. [See also the recent paper by Malys and Slater (1998)].

3.3 The PZ-90 system

The PZ-90 system is a global system developed by Russia, similar to WGS 84, and used as the nominal system for GLONASS navigation. It was realized by positioning 26 ground stations established from observations of the Geo-IK geodetic satellite, including photographing it against a star background, Doppler measurements, laser ranging, and satellite altimetry. It also included electronic and laser range measurement of GLONASS and Etalon satellites. A subset of these stations is used to generate the broadcast PZ-90 GLONASS orbits (Boykov et al. 1993; Mitrikas et al. 1998).

4 Review of previous determinations of transformation parameters between PZ-90 and other systems (WGS 84 or ITRS)

Several investigations have been published about the transformation between PZ-90 and WGS 84. We mention briefly some of them for which we have information, giving for each a short summary and a critical comment.

4.1 Misra et al. (1996)

Summary:

Purpose: link between PZ-90/WGS 84 E-frames.
Method: comparison of E-frames for GLONASS satellites 63 and 67.
Period: 1995–1996.
E-frame in PZ-90: from broadcast message, estimated by authors at 20-m accuracy level.
E-frame in WGS 84: estimated by laser tracking using a global network. Accuracy estimated at 10-m level.

Comment:

It is difficult to guarantee this estimate to better than a few meters.

4.2 Rossbach et al. (1996)

Summary:

Purpose: link between PZ-90/ITRS N-frames.
Method: comparison of two N-frames located in Europe. The network included six stations (Herstmonceux, Madrid, Wettzell, Metsahovi, Maspalomas, and Zvenigorod).
Period: 1996.
N-frame in PZ-90: determined with the Bernese software GLONASS data with broadcast orbits.
N-frame in ITRS: IGS values of the stations in ITRS.

Comments:

The resulting transformation is valid at better than meter level for Europe and the epoch 1996. Extrapolation in time or in other geographical areas cannot guarantee this level of accuracy.

4.3 Mitrikas et al. (1998)

Summary:

Purpose: link between PZ-90/ITRS E-frames.
Method: comparison of E-frames for GLONASS satellites 63 and 67.
Period: 1995–1997.
E-frame in PZ-90: from broadcast message.
E-frame in ITRS: orbit computation using laser data expressed in ITRF94.

Comments:

This transformation is globally valid but shows instabilities and time variations of the PZ-90 E-frame for GLONASS with regard to the computed ITRS E-frame derived by laser data. Its quality is at best at the 1-m level.

4.4 Bazlov et al. (1999)

Summary:

Purpose: link between PZ-90/ITRS N-frames.
Method: comparison of two N-frames located in Russian territory.
Period: 1997.
N-frame in PZ-90: original PZ-90 positions derived from Geo-IK data.
N-frame in ITRS: GPS positioning at the stations, computed in ITRS.

Comments:

This formula is valid for the Russian territory and based on an N-frame not related to GLONASS.

5 Contribution of the IGEX-98 campaign

5.1 Analysis done at the IERS Terrestrial Frame Section

The IERS Terrestrial Frame Section issued a call for results among the analysis centers participating in the IGEX-98 campaign. Two centers provided results in response to this call.

5.1.1 GeoForschungsZentrum, Potsdam (GFZ) solutions

GFZ provided 11 weekly SINEX files corresponding to GPS weeks 991 to 1001. These solutions were derived with the following properties.

1. GLONASS as well as GPS data for mixed dual-frequency receivers were used.
2. GPS orbits from the IGS final solution were introduced and fixed (except eclipsing GPS satellites).
3. Earth rotation parameters were fixed to the estimated values of the IGS.
4. Coordinates of only one station were fixed to their initial values in the determination of orbits.

5.1.2 Jet Propulsion Laboratory, Pasadena (JPL) solutions

The JPL provided two types of daily solutions using over 100 days of data.

1. Station precise point positioning (PPP) solutions computed from GPS dual-frequency tracking data by fixing the GPS satellite orbit and clock to the IGS/FLINN solution. The reference frame for this set of solutions is the one defined by IGS/FLINN orbit solution, i.e. ITRF96. In this solution, station position,

receiver clock and tropospheric delay for each individual site are solved for, station by station.

2. Station PPP solutions computed from GLONASS dual-frequency tracking data by fixing the GLONASS satellite orbit and clock to the broadcast ephemeris and clock values; the reference frame for this set of solutions is the one defined by the GLONASS broadcast orbit, which is PZ-90. In this solution, the broadcast orbit is first smoothed by a dynamic fit (trajectory fit) to remove outliers and gross errors. The 3-D RMS error of the fit is around 5 m. Station position, receiver clock and tropospheric delay are then solved for individual sites by fixing the orbit to the smoothed orbit file and fixing the satellite clock to the broadcast clock values.

The results of these data were presented at the IGEX Workshop held in Nashville in September 1999 (Altamimi and Boucher 1999).

5.1.3 Use of GFZ data

The GFZ data are N-frames with some constraints on station positions. The way they were processed indicates they are realizations of ITRS. We checked their N-frame with regards to ITRF97. We found an agreement to better than 3 cm for each weekly solution. Consequently, the corresponding E-frame for GLONASS satellites is in ITRS and could be compared with the broadcast message. Unfortunately these data were not available to us for this study.

5.1.4 Use of JPL data

The JPL provided data which could be used to compute transformation parameters on N-frames.

1. One hundred daily N-frames in PZ-90 using point positioning of mixed receivers with GLONASS phase data and GLONASS broadcast orbits. The comparison between each daily solution in PZ-90 and ITRF97 was presented at the Nashville (Altamimi and Boucher 1999) Workshop. The mean values of the 100 sets of transformation parameters are given in Table 1, item (A).

2. The 100 daily solutions were combined together to provide an additional N-frame in PZ-90. The transformation between the cumulated N-frame in PZ-90 and ITRF97 is given in Table 1, item (B). The RMS residual over 16 stations is 46 cm. The parameters refer to the central epoch of the data span, namely 1999.5. Figure 1 shows the distribution of the 16 common stations.

We can conclude from the consistency of both methods (A) and (B) that the precision of the resulting transformation is better than 0.1 m, resulting in the following findings.

1. The agreement between (A) and (B) is of the order of 10 cm.
2. The standard deviation of the parameters of the regression lines computed in (A) are at the 10 cm level (largest one 16 cm). This includes the network geometric effect (Fig. 1), which is not negligible. We estimated it by comparing the JPL daily ITRF96 solution for the 16 stations to ITRF97 and performed a similar regression. The resulting mean transformation exhibits an agreement better than 5 cm.

Table 1. Results using IGEX-98 data

X	*XS*	*T*1 (cm)	*T*2 (cm)	*T*3 (cm)	*D* (ppb)	*R*1 (mas)	*R*2 (mas)	*R*3 (mas)	
ITRS	PZ-90	−30	10	90	0	3	13	−355	(A)
		−24	15	77	31	3	19	−353	(B)
		3	2	45	−13	37	−10	−350	(C)
		0	0	110	−9	16	4	−357	(D)

3. In case B the residuals of 40 cm at each of the 16 stations are consistent with $40/\sqrt{16} = 10\,\mathrm{cm}$ for transformation parameters.

5.2 Other analysis using IGEX-98 data

Two other recent results benefiting from the IGEX campaign are available.

1. The group from the University of Bern (Ineichen et al. 1999) computed daily transformation parameters between E-frames in PZ-90 from GLONASS broadcast and the ITRS using their processing of GLONASS phase data with the Bernese software and T-frame in ITRF96. The resulting average transformation is labeled (C) in Table 1. A recent report by Habrich (1999) that uses a similar analysis of IGEX data confirms these numbers.

2. A Russian group from the GEO-ZUP Company and the Russian Mission Control Center (Mitrikas et al. 1999) has computed orbits using the laser tracking data from eight GLONASS satellites collected during IGEX-98, based on a T-frame expressed in ITRF94. The resulting E-frame in the ITRS was compared to the E-frame from the GLONASS broadcast ephemerides and to the E-frame based on an averaged post-processed orbit determined from ranging measurements. The corresponding formula is labeled (D) in Table 1. Mitrikas et al. (1999) also noted that transformation rotations about the x and y axes (R1, R2) are correlated with polar motion because of the way that the GLONASS Satellite Control Segment computes the broadcast ephemeris predictions.

Table 1 shows that all results agree at the few decimeter to 1-m level.

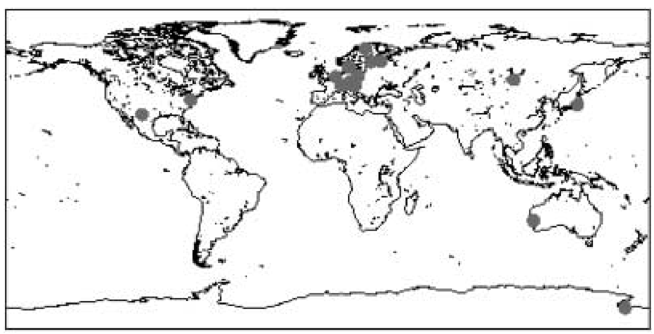

Fig. 1. Distribution of the 16 common stations between ITR97 and the PZ-90 realization obtained by cumulating 100 JPL solutions

6 Critical results

In order to summarize in a compact way the evolution of the estimates, we have collected transformation parameters standardized as PZ-90 to WGS 84. None of the studies [except (1)] used a direct realization of WGS 84, but a realization of the ITRS. We have seen that, since 1997, the WGS 84 GPS broadcast ephemerides T-frame is consistent with the ITRS at better than the 5-cm level. This may not be completely true for earlier epochs. Furthermore, as mentioned previously, the WGS 84 broadcast E-frame will have larger discrepancies. The IGS is monitoring daily the WGS 84 E-frame for GPS satellites, by comparing it with IGS E-frames (expressed in the ITRS). Their RMS variations are currently 2–3 m with biases of several decimeters (see IGS Analysis Coordinator Reports, e.g. Kouba and Mireault 1999).

Table 2 presents the values.

At this level, we must now undertake a critical review.

1. First, the last three determinations show an agreement at the decimeter level (maximum disagreement of 45 cm). They all use IGEX data and therefore the same epoch (1999).
2. (1) shows disagreement at the 2-m level, which is acceptable considering its intrinsic value.
3. Same remark for (2) at 1-m level.
4. (5) is an extension of (3) using more data, especially IGEX laser tracking. The disagreement is at the 1-m level. Their paper has, moreover, clearly shown the time variation of the E-frame transformations computed using laser data. But (5) shows a fairly good agreement with (6)–(8), better than 50 cm.

We therefore select as useful estimates (5), (6), and (8). They are relevant to the present epoch through IGEX data, the first two are E-frames using laser and phase data respectively, the last is a N-frame of the global IGEX network. The other determinations are of less interest, all being compatible considering their intrinsic qualities.

7 Conclusion: recommendations on transformation strategy

Before concluding on the choice of a transformation formula, we can make some general recommendations, as follows.

1. The best simultaneous use of GPS and GLONASS data should be based on IGS products, where GPS and GLONASS precise ephemerides are available in the ITRS. Moreover, accurate clock information is also provided, consistent with these E-frames.

2. Although the IGS is providing progressively real time products, broadcast ephemerides for both GPS and GLONASS will still be used for many applications. The most useful information is therefore to obtain the instantaneous transformation between the two E-frames. Again, the IGS is a reference source for these data. Comparisons between IGS orbits and broadcast messages are being disseminated for both GPS and GLONASS. The IGS now makes this information widely available, through the IGS Rapid combination summaries for GPS and through IGLOS (International GLONASS Pilot Project) information for GLONASS.

3. It may nevertheless be useful to adopt a reference transformation when previous data are not available to a particular user.

This is why we suggest adopting the following values based on an average of the three determinations (5), (6), and (8), which agree to better than 50 cm with each other. At this level, we consider this formula a viable reference, considering the previous remarks.

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{\mathrm{WGS84}} = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{\mathrm{PZ\text{-}90}} + \begin{pmatrix} 0.07\,\mathrm{m} \\ -0.0\,\mathrm{m} \\ -0.77\,\mathrm{m} \end{pmatrix} + \begin{pmatrix} -3\,\mathrm{ppb} & -353\,\mathrm{mas} & -4\,\mathrm{mas} \\ 353\,\mathrm{mas} & -3\,\mathrm{ppb} & 19\,\mathrm{mas} \\ 4\,\mathrm{mas} & -19\,\mathrm{mas} & -3\,\mathrm{ppb} \end{pmatrix} \begin{pmatrix} X_{90} \\ Y_{90} \\ Z_{90} \end{pmatrix}$$

Ultimately, such a reference formula should be approved by the relevant organizations, in particular the scientific services of the IERS and IGS.

As a final recommendation, we again draw attention to the fact that the various realizations of WGS 84 and PZ-90 transformations remain inconsistent at the meter

Table 2. Transformation parameters from PZ-90 to WGS 84

$T1$ (cm)	$T2$ (cm)	$T3$ (cm)	D (ppb)	$R1$ (mas)	$R2$ (mas)	$R3$ (mas)	Frame type	Epoch	
0	250	0	0	0	0	392	E	95–96	(1)[a]
0	0	0	0	0	0	330	N Europe	95	(2)
−47	−51	−200	22	2	1	356	E	95–97	(3)
−110	−30	−90	−120	0	0	169	N Russia		(4)
0	0	−110	9	−16	−4	357	E	96–99	(5)
−3	−2	−45	13	−37	10	350	E	99	(6)
30	−10	−90	0	−3	−13	355	N IGEX	99	(7)
24	−15	−77	−31	−3	−19	353	N IGEX	99	(8)

[a] (1) Misra et al. (1996); (2) Rossbach et al. (1996); (3) Mitrikas et al. (1998); (4) Bazlov et al. (1999); (5) Mitrikas et al. (1999) [(D) values of Table 1], assuming identity between ITRS and WGS 84; (6) Ineichen (1999) [(C) values of Table 1]; (7) Altamimi and Boucher (1999) [(A) values of Table 1]; (8) This paper [(B) values of Table 1, using JPL point positioning solution]

level. Thus, such transformations should be considered as 'conventional'. In particular, as mentioned before, the best way to remove systematic biases between the WGS 84 E-frame (GPS brodcast ephemerides) and PZ-90 E-frame (GLONASS broadcast ephemerides) is presently to combine the daily transformation parameters between each of these E-frames and the ITRS E-frames provided by IGS ephemerides (for GPS and GLONASS satellites respectively).

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References

Altamimi Z, Boucher C (1999) GLONASS and the International Terrestrial Reference System. IGEX-98 Workshop, Nashville, 13–14 September, pp 37–46

Bazlov YA, Galazin VF, Kaplan BL, Maksimov VG, Rogozin VP (1999) GLONASS to GPS, a new coordinate transformation. GPS world January

Boucher C, Altamimi Z (1996) International Terrestrial Reference Frame. GPS World 7(9): 71–74

Boucher C, Altamimi Z, Sillard P (1999) The 1997 International Terrestrial Reference Frame (ITRF97). IERS tech note 27. Observatoire de Paris

Boykov VV, Galazin VF, Kaplan BL, Maksimov VG, Bazlov YA (1993) Experience in developing the PZ-90 Geocentric Coordinate System. Geod Kartogr 11: 17–21

Geodesist's Handbook (1992) J Geod 66

Habrich H (1999) Geodetic applications of the Global Navigation Satellite System (GLONASS) and GLONASS/GPS Combinations. PhD dissertation, Astronomical Institute, University of Bern

Ineichen D, Rothacher M, Springer T, Beutler G (1999) Computation of precise GLONASS orbits for IGEX-98. In: Schwarz (ed) Geodesy beyond 2000. International Association of Geodesy Symposia, vol 121. Springer, Berlin, Heidelberg New York, pp 26–31

Kouba J, Mireault Y (1999) 1998 Analysis coordinator report. 1998 IGS tech rep. IGS Central Bureau, Pasadena

Kovalevsky J, Mueller II, Kolacek B (1989) Reference frames in astronomy and geophysics. Kluwer Academic, Dordrecht

Malys S, Slater J (1994) Maintenance and enhancement of the World Geodetic System 1984. Proc ION-94 Salt Lake City, September

McCarthy D (ed) (1996) IERS Conventions. IERS tech note 21. Observatoire de Paris

Misra P, Abbot R, Gaposhkin E (1996) Integrated use of GPS and GLONASS: transformation between WGS 84 and PZ-90. Proc ION GPS96, pp 307–314

Mitrikas VV, Revnivykh SG, Bykhanov EV (1998) WGS 84/PZ-90 transformation parameters determination based on laser and ephemeris long-term GLONASS orbital data processing. Proc ION GPS98, pp 1625–1635

Mitrikas VV, Revnivykh SG, Glotov VD, Zinkovski MV (1999) PZ-90 GLONASS to ITRF transformation as a result of IGEX-98 laser tracking campaign. IGEX-98 Workshop, Nashville, 13–14 September

Morel L (2000) Références Géodésiques pour les futures missions altimétriques: application à la mission JASON. PhD dissertation, Paris Observatory

Rossbach U, Habrich H, Zarraoa N (1996) Transformation parameters between PZ-90 and WGS 84. Proc ION GPS96, pp 279–285

Slater JA, Malys S (1998) WGS 84 – past, present and future. In: Brunner FK (ed) advances in positioning and reference frames. International Association of Geodesy Symposia, vol 118. Springer, Berlin Heidelberg New York

Sillard P, Boucher C (1996) Improvement of the transformation between ITRF and Doppler-realized WGS 84. J Geod 70: 768–780

Sillard P, Boucher C (submitted) A review of algebraic constraints in terrestrial reference frame datum definition. J Geod

Willis P, Beutler G, Gurtner W, Hein G, Neilan RE, Noll C, Slater JA (1999a) IGEX, International GLONASS Experiment – scientific objective and preparation. Adv Space Res 23(4): 659–664

Willis P, Slater JA, Beutler G, Gurtner W, Noll C, Weber R, Neilan RE, Hein G (1999b) The IGEX-98 campaign: highlights and perspectives. IAG General Assembly, Birmingham, pp 22–25