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Establishment of a global three-dimensional kinematic reference frame using VLBI and DORIS data

The main aim of this paper is to provide an algorithm to combine VLBI (Very Long Baseline Interferometry) and DORIS (Doppler Orbitography and Radio positioning Integrated by Satellite) data sets into the same kinematics reference frame. In a first stage of computation the VLBI and DORIS networks are knitted together using the velocities of each station with their covariance matrices that were obtained from individual solutions. A sequential least squares adjustment was used. In a second stage of computation a method of iterative weighted similarity transformation has been elaborated. In order to fix the three-dimensional kinematic reference frame (KRF), a system of constraints or datum equations based on vertical component of some quasi-stable reference stations are used. This strategy provides a datum that is robust to unstable reference points and gives less distorted displacements. This method has been applied to the VLBI and DORIS data collected during the last decades. Without survey ties available, and consequently without relative velocities between collocated VLBI and DORIS points, we forced the velocities of collocated sites to the same value and constrained their root mean squares to be equal to zero. As VLBI information is formally for some stations ten times more precise than the DORIS information, reference frame and precision of the VLBI stations were practically not affected by this computation. But precision of DORIS station velocities of the joint network is improved by almost 15% and fairly close agreement between ITRF2000 solution, NNR Nuvel-1A model predictions, and our solution has been found. The technique presented provides a method to define KRF without any information from a geological plate motion model. It is thus possible to verify any geological model using only geodetic information itself.

Key words: *linear transformations, matrix inversion, general inversion, kinematic reference frame, NNR NUVEL-1A plate model, VLBI, DORIS, ITRF2000*

1. Introduction

Difficulties in establishing a kinematic reference frame (KRF) fixed to the Earths' interior complicate the study of the plate motions of the Earths' surface. The aim of this paper is to establish a KRF by processing only VLBI and DORIS data. Such KRF must be totally free of any kind of tectonic plate motion model or of any geological assumption that could lead to significant

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changes of the site velocities depending on the choice of the sites that were constrained. These effects are due to the hidden errors coming from the uncertainties of the reference plate motion model, ignoring errors in the survey data of selected points as reference stations, and the misfit between the measurements and the model predictions. Our method avoids effects of a-priori values of fixed velocities component on the estimated KRF. However, the quality of the plate motion define by this kind of KRF can be assessed through comparison with NNR Nuvel-1A model and ITRF (International Terrestrial Reference Frame). That is why the problem of fixing reference frame has not a theoretical but a practical importance as well, because "geophysical information inferred from this frame, such as tectonic plate motions, allows meaningful comparisons with existing geological models, such as NUVEL-1A"[1].

It should be noted, that even ITRF2000 is not free from tectonic plate motions model. As noted in [1] , "The ITRF2000 origin is defined by the Earth center of mass sensed by satellite laser ranging (SLR)and its scale by SLR and VLBI. Its orientation is aligned to the ITRF97 at epoch 1997.0, and its orientation time evolution follows, conventionally, that of the no-net-rotation NNR-NUVEL-1A model". Our KRF is totally free from any tectonic plate motions model. Moreover, the densified VLBI and/or SLR and not so precise but more inexpensive DORIS and/or GPS space geodetic nets will provide a vast velocity field permitting detailed and localized crustal deformation evaluation in plate interiors as well as along plate boundaries.

Nevertheless, a large amount of literature exists about how to fix coordinate frame without external information, using geodetic data only. Such method which is known as free network adjustment with general inversion of matrix has shortcomings in classical formulation. First of all, few of the geodetic sites are located on the Eurasia and North America plates. Secondly, all plates have different sizes and velocities. These lead to some bias in mean velocities of these plates when using the classical formulation of the free network adjustment based on space geodetic measurements. It is the main reason why this approach gives unreliable results. These shortcomings of the classical approach are overcome by only restricting vertical components of few quasi-stable geodetic stations [14].

The classical methods of computation have also problems that may be tied with an ill-conditioned solution. A method for overcoming this problem is given in [11, 12]. Few questions may arise if incorporating additional errors into stochastic model [e.g., 2, 8, 15]. These approaches are identical to the well-known method of regularization solution of linear equation system which is applied to overcome the ill-conditioned problem.

2. Algorithm of calculation

A proposed algorithm can be divided into two stages. In the first stage we use for DORIS and VLBI stations two sets of vectors $\delta X'_D$, $\delta X'_V$ of three-dimensional Cartesian velocities with their covariance matrices K'_D, K'_V.

The relative velocities d_i^c between VLBI and DORIS monuments with their root mean squares m_i can be taken from terrestrial geodetic observations when available. If they are absent, (for collocated VLBI and DORIS sites without survey tie for velocities) d_i^c and m_i were put to zero. We have introduced a covariance matrix $Q = P^{-1}$, where P is the weight matrix for sites with a-priori information on d_i^c in three directions. These new additional observations are uncorrelated with the existing VLBI and DORIS observations. Their effect is adding to the previous solutions using algorithms [9, 10]. The result will be an integrated network in which VLBI and DORIS velocity vectors δX are expressed in a common reference frame with their associated covariance matrix $K_{\delta X}$.

Theoretically for every collocated site we can write

$$\delta x_{V,i}^c - \delta x_{D,i}^c - d_i^c = l_i \tag{1}$$

where $\delta x^c_{V,i}$ and $\delta x^c_{D,i}$ are VLBI and DORIS velocities, obtained from individual solutions, and l_i is the misclosure. We thus can write a set of condition equations in the form proposed by Gerasimenko [9]

$$B\delta - V + L = 0 \tag{2}$$

where L is the vector of misclosures, δ is the vector of corrections to the vector $\delta X' = \binom{\delta X'_V}{\delta X'_D}$ with covariance matrix $K'_{\delta X} = \begin{pmatrix} K'_{\delta X_V} & 0 \\ 0 & K'_{\delta X_D} \end{pmatrix}$, V is the vector of corrections to relative velocities for collocated VLBI and DORIS sites .

Matrix B in equation (2) is known as the design matrix. Every line of this matrix contains only two nonzero elements $+1$ and -1. The least squares solution of equations (2) gives the vector

$$\delta = -K'_{\delta X} B^T N^{-1} L \tag{3}$$

and displacement vector in common reference frame

$$\delta X = \delta X' + \delta \tag{4}$$

with its associated covariance matrix

$$K_{\delta X} = K'_{\delta X} - K'_{\delta X} B^T N^{-1} B K'_{\delta X} \tag{5}$$

where normal matrix

$$N = B K'_{\delta X} B^T + P^{-1} \tag{6}$$

It should be noted that instead of simultaneous solution of equations (2) it is useful to use the known sequential approach [6, 9] if the measured velocities between VLBI and DORIS monuments are uncorrelated. The results must be the same as in algorithm (2)-(6).

In the second stage of calculation we fixed the KRF with respect to datum equations (this is a system of constraints in which there is an equation for each datum defect of the network)

$$B_H \delta X = 0 \tag{7}$$

through iterative weighted similarity transformation (S-transformation) under condition that vertical motion dH of every reference (quasi-stable) station do not exceed few mm/year. In our solution we take $|dH| < 4$ mm/yr in order to compare our solution with the VLBI solution Gerasimenko and Kasahara [13]. The construction of matrix B_H is carried out by the algorithm described by Gerasimenko and Kato [14]. In this algorithm only vertical components of quasi-stable site velocities for every X, Y, Z direction are used in order to fix the KRF.

Transformation of the displacement vector δX and its covariance matrix $K_{\delta X}$ from iteration i to iteration $i+1$ is performed using equations

$$\delta X^{(i+1)} = S^{(i)} \delta X^{(i)}, \tag{8}$$

$$K_{\delta X^{(i+1)}} = S^{(i)} K_{\delta X^{(i)}} {S^{(i)}}^T \tag{9}$$

with transformation matrix [5, 19]

$$S = I - G(B_H^T W G)^{-1} B_H^T W \tag{10}$$

where matrix W can be interpreted as a weight matrix in the definition of the datum and therefore equations (8) and (9) is called a weighted similarity transformation. It should be noted that many authors have written on this subject. But in all the geodetic literature almost nothing has been said about the proper choice of the weight matrix W, excluding the papers [5, 19].

The matrix G^T being known as eigenvectors to the zero eigenvalues of the normal matrix of the whole network. Its construction has no any problem and is described in known geodetic literature (see, e.g., 5, 24, etc).

We take the weight matrix as diagonal

$$W = diag(1/\sigma^2_{dH^{(j)}}), \tag{11}$$

where $\sigma_{dH^{(j)}}$ is the root mean square of the vertical displacement dH_j of corresponding station j. The choice of such weight matrix is based on the fact that we only used vertical components in the three directions for the datum equations (7).

3. Data and Results

The above depicted concept has been applied to the S2001 VLBI solution [13] and a DORIS solution computed by LEGOS/CLS analysis center. The solution S2001 was obtained using NASA Goddard Space Flight Center's VLBI terrestrial reference frame solution number 1122, calculated in 1999 June. The DORIS solution is based on 9 years of data from satellites Topex/Poseidon (T/P), Spot-2, Spot-3 and Spot-4. The DORIS system was developed in the early 1990s to be placed onboard the altimeter satellite T/P launched in 1992. In order to reach the performance initially expected for its first mission, a worldwide network of permanent transmitting beacons has been deployed. The DORIS system allows the orbit of T/P to be computed with a precision of 1-2 cm [18]. DORIS is also used for absolute positioning of the ground beacons. Since the launch of Spot-2 in 1990, the DORIS performances for absolute positioning have been regularly improved, from a precision of 10 to 20 cm obtained during the first year of the system life time to 1 cm nowadays. The processing of DORIS data was performed by the GINS/DYNAMO software based on a semi-dynamical method developed at GRGS (Groupe de Recherche de Géodésie Spatiale). It consists of computing the satellite's orbit, beacons positions and velocities, and Earth orientation parameters, in a single inversion, together with selected parameters required to improve the acceleration models (used to describe the satellite orbit) and the measurement corrections. It is thus used to deduce horizontal and vertical movements at the surface of the Earth with a precision in the range of 2-3 mm/year in average [3, 4, 7, 17, 20, 21, 22]. The S2001 and DORIS solutions give two sets of rates of changes of three-dimensional Cartesian coordinates in X, Y, Z directions with their covariance matrices. These quantities were used in order to obtain the three-dimensional KRF. The 49 DORIS and 59 VLBI stations were used to calculate point motion of the Earth surface.

In the first stage of computation we have knitted VLBI and DORIS networks by equating the velocities of collocated sites as depicted in section 2. The collocated DORIS and VLBI sites are respectively: ORRA - 1545, KOKA - 7298, and 1311, RIDA - 7219, SANA - 1404, SPIA - 7331, HBLA - 7232, YELA - 7296, GOMA - 1515, FAIA - 7225. Practically we constrained the velocities of mutual site to the same values and their root mean squares to zero because we had no geodetic information about their relative movement. As the VLBI information is much more precise than the DORIS information, VLBI station velocities did not differ from the results of Gerasimenko and Kasahara [13] by more than 0.5 mm/yr. 72 quasi-stable stations were selected in a process of successive joint S-transformations of VLBI and DORIS solutions and a subsequent analysis of its results in order to fix the KRF. Stations were considered as quasi-stable when their vertical displacements did not exceed 4 mm/yr. Table 1 lists 39 quasi-stable as well as 20 mobile (free) VLBI stations and their topocentric velocities dB, dL, dH (north, east, up) deduced from the ITRF2000 reference frame and NNR NUVEL-1A model.

Table 1. Velocities and their RMS of VLBI stations (in mm/yr)

Station name	VLBI solution S2003						NNR NUVEL-1A		Solution ITRF2000		
and	North		East		Up		North	East	North	East	Up
number	dB	σ	dL	σ	dH	σ	dB	dL	dB	dL	dH
7282 ALGOPARK	2.6	.2	-17.9	.1	3.2	.3	3.2	-17.0	1.3	-16.6	2.3
7614 BR-VLBA	-9.5	.2	-14.7	.2	-4.3	.4	-12.7	-14.8	-10.8	-12.9	-5.1
7332 CRIMEA	11.3	.4	24.0	.6	2.5	1.4	9.1	23.9	11.1	24.7	.7
1515 DSS15	-4.6	.4	-19.7	.3	.1	.7	-11.8	-12.2	-5.3	-17.0	-1.3
1545 DSS45	54.2	.3	18.3	.3	.6	.6	53.7	17.7	54.9	18.4	1.2
1565 DSS65	15.5	.2	18.1	.2	1.3	.4	15.7	18.6	15.7	19.0	1.5
7203 EFLSBERG	14.9	.2	19.0	.2	5.2	.7	14.4	19.0	14.7	19.5	-2.1
7613 FD-VLBA	-5.3	.2	-13.8	.2	.4	.4	-7.1	-11.9	-7.2	-12.1	-.6
7266 FORT ORD	24.0	1.4	-41.3	1.1	5.5	6.6	24.5	-38.5	22.9	-41.1	8.3
7297 FORTLEZA	12.9	.2	-6.6	.2	.7	.3	11.7	-5.5	12.2	-4.3	.9
7108 GGAO7108	3.1	.6	-16.2	.6	-2.7	2.7	3.6	-15.0	2.8	-14.4	-1.9
7225 GILCREEK	-21.7	.1	-10.1	.2	1.6	.1	-20.2	-10.3	-22.6	-8.9	.4
7232 HARTRAO	16.2	.2	16.3	.2	-1.8	.4	20.1	20.7	17.9	18.1	.4
7218 HATCREEK	-6.9	.3	-21.3	.3	1.9	1.0	-13.3	-12.9	-8.8	-20.2	-1.9
7205 HAYSTACK	5.9	.3	-16.5	.3	-.8	.6	5.7	-15.7	4.4	-15.2	-1.0
7618 HN-VLBA	6.2	.3	-15.5	.3	-.7	.6	5.6	-15.9	4.5	-14.7	.2
7242 HOBART26	55.0	.3	14.4	.2	.0	.5	54.4	12.9	55.4	13.9	1.1
7263 JPL MV1	8.9	1.1	-38.7	.9	6.3	6.1	23.1	-40.0	11.2	-37.1	-1.6
1857 KASHIM34	-11.5	.4	-4.5	.3	-8.2	.9	-16.7	8.4	-11.6	-3.8	-4.1
1856 KASHIMA	-11.3	.2	-4.6	.2	-2.2	.3	-16.7	8.4	-11.6	-3.8	-4.1
1311 KAUAI	34.4	.2	-64.2	.2	.5	.2	32.3	-58.3	32.5	-62.4	-.8
7278 KODIAK	-15.8	1.1	-15.4	1.1	-1.5	5.4	-21.0	-8.2	-11.3	-12.6	11.0
7298 KOKEE	34.4	.2	-64.2	.2	.5	.2	32.3	-58.3	32.5	-62.4	-.8
7610 KP-VLBA	-7.6	.2	-14.4	.2	-1.2	.5	-9.9	-11.8	-9.3	-12.4	-.9
4968 KWAJAL26	25.9	1.5	-73.1	1.2	-3.4	3.8	28.1	-65.4	26.3	-71.5	1.4
7611 LA-VLBA	-5.6	.2	-15.2	.2	-1.9	.3	-8.0	-13.4	-7.4	-13.5	-2.1
7243 MATERA	18.4	.1	22.8	.2	-.9	.2	12.8	22.0	18.1	23.7	-1.0
7230 MEDICINA	17.3	.1	21.5	.2	-2.3	.3	13.6	20.8	16.1	23.4	-4.1
7617 MK-VLBA	33.3	.3	-65.2	.3	-3.2	.4	32.1	-58.5	32.6	-63.0	-3.1
7222 MOJAVE12	-3.2	.2	-18.1	.2	-1.2	.3	-11.8	-12.2	-5.3	-17.0	-1.3
7274 MON PEAK	14.7	.7	-45.5	.6	-4.9	3.0	22.4	-40.9	17.2	-38.8	.2
7612 NL-VLBA	-.1	.2	-16.6	.2	-3.9	.5	-2.2	-15.9	-2.4	-15.1	-2.9
7547 NOTO	19.0	.2	21.0	.2	-1.5	.4	20.5	19.8	18.0	21.3	-1.7
7204 NRAO 140	2.7	.3	-16.5	.3	-.3	1.1	2.5	-14.9	1.6	-14.5	-1.0
7208 NRAO20	4.3	.2	-15.9	.2	3.5	.5	2.5	-14.9	1.6	-14.5	-1.0
7331 NYALES20	14.2	.2	10.9	.2	5.1	.4	13.6	12.9	14.0	10.4	6.4
7245 OHIGGINS	10.0	1.2	11.5	1.0	6.4	2.8	10.2	16.3	10.2	14.4	9.5
7213 ONSALA60	14.1	.1	17.1	.2	3.4	.2	13.6	18.6	13.6	17.2	2.6
7616 OV-VLBA	-4.8	.2	-20.5	.2	-3.8	.5	-12.3	-12.5	-6.0	-19.0	-3.7
7207 OVRO 130	-3.3	.3	-20.5	.3	-2.7	1.0	-12.3	-12.5	-6.0	-19.0	-3.7
7234 PIETOWN	-7.7	.2	-15.4	.2	.4	.3	-8.7	-12.8	-9.8	-13.8	-.5
7256 PINFLATS	6.4	.8	-31.3	.7	-5.2	6.3	22.4	-40.2	9.1	-28.5	-.8
7258 PLATTVIL	-7.8	.5	-17.0	.6	3.4	3.1	-7.4	-14.8	-7.3	-15.2	-3.3
7252 PRESIDIO	10.9	.8	-33.4	.8	-11.7	4.1	-13.7	-12.1	9.7	-32.0	-7.3
7251 PT REYES	21.4	.7	-37.4	.6	7.1	3.3	24.9	-37.4	19.2	-35.6	13.5
7221 QUINCY	-5.4	.6	-23.6	.6	4.0	3.6	-13.2	-12.8	-6.3	-21.1	-.9
7219 RICHMOND	2.3	.2	-11.9	.2	-1.3	.3	2.2	-10.7	1.3	-9.8	.3
1404 SANTIA12	18.8	.4	17.0	.4	5.0	.9	9.4	-.9	16.3	18.9	4.7
7615 SC-VLBA	13.9	.3	9.1	.3	5.1	.7	10.3	3.8	12.4	10.8	.9
7227 SESHAN25	-14.5	.3	31.1	.3	-.4	.7	-13.3	22.3	-14.7	32.1	-1.5
7280 SNDPOINT	-19.2	1.7	-11.1	1.3	-23.8	6.6	-22.1	-5.6	-22.0	-10.5	-.3
7602 TROMSONO	13.8	1.4	27.7	1.0	8.5	5.0	12.4	17.2	14.5	13.9	2.6
7330 URUMQI	4.4	1.3	30.1	2.3	-11.6	4.3	-5.5	25.3	4.6	30.3	-5.3
7223 VNDNBERG	24.0	.3	-43.2	.3	2.7	1.1	24.0	-40.2	21.7	-42.1	2.9
7209 WESTFORD	5.8	.2	-16.7	.1	-.6	.1	5.7	-15.7	4.4	-15.2	-1.0
7224 WETTZELL	14.8	.1	19.8	.2	-1.0	.1	13.5	20.3	14.4	20.3	-.9
7333 YEBES	14.8	.7	15.4	.5	-16.5	2.2	15.6	18.8	15.4	18.6	-1.6
7296 YLOW7296	-10.5	.3	-18.8	.3	5.3	.7	-10.9	-18.3	-11.6	-17.1	5.0
7894 YUMA	-8.6	1.1	-14.8	1.0	16.0	7.1	-10.9	-11.8	-9.9	-12.0	15.6

It allows us to compare our solution (titled as S2003) and to determine its quality. Table 2 contains a statistics of velocity differences in Cartesian X, Y, Z and topocentric B, L, H coordinates between our solution S2003, ITRF2000 and NNR NUVEL-1A for all VLBI stations. It should be noted that there are no root mean squares (RMS) of topocentric velocities for ITRF2000 solution in file *ITRF*2000 [16]. That's why we put equal weights for all of these velocities. This should lead to some errors on the statistics given on the fourth column of Table 2 for B, L, H directions. For this reason we did not calculate the statistics of topocentric velocity differences between S2003 and ITRF solutions.

Table 2. Statistics of differences between VLBI solution S2003, ITRF2000 and NNR NUVEL-1A model for all VLBI stations

	S2003–NUVEL-1A		ITRF2000–NNR NUVEL-1A		S2003–ITRF2000
	X, Y, Z	B, L, H	X, Y, Z	B, L, H	X, Y, Z
WRMS (mm/yr)	3.36	3.51	2.69	5.12	1.38
	3.45	4.50	2.87	5.62	1.36
	2.37	1.99	2.66	4.29	1.78
Weighted mean (mm/yr)	-0.75	1.83	0.28	1.00	-1.06
	0.91	-2.04	0.44	-0.83	0.11
	1.33	0.10	-0.07	0.31	1.25

Table 2 shows that S2003 solution is practically as good as ITRF2000 solution with respect to NNR NUVEL-1A plate model although ITRF2000 solution covers the largest set of globally distributed VLBI, SLR, DORIS and GPS terrestrial space geodesy stations. Moreover site velocities are determined more reliably by space tracking data rather than by geological data. It confirms that KRF can be fixed exclusively using space based measurements itself. This was already shown in [13] and [14] with VLBI data alone.

We have also transformed the solution S2001 without DORIS information by algorithm (7)-(11). The results of this separate S-transformation showed that all velocities differ from the results of the Table 1 in the limit of 0.8 mm/yr, excluding the point 1311 for which the difference was 1.8 mm/yr in the north direction. The precision of all velocities are practically the same as in the solution S2003. It indicates that DORIS data did not significantly influence the process of fixing KRF in the solution S2003.

We compared solution S2003 with the solution S2001. First of all the precision of VLBI velocities are globally better in S2003 than in S2001. Secondly, statistics of differences between solution S2003, ITRF and NNR NUVEL-1A are better as well. It can be seen by comparison of Table 2 and Table 3.

Table 3. Statistics of differences between VLBI solution S2001, ITRF97 and NNR NUVEL-1A model for all VLBI stations (by Gerasimenko and Kasahara, 2002)

	S2001–NUVEL-1A		ITRF1997–NNR NUVEL-1A		S2001–ITRF1997
	X, Y, Z	B, L, H	X, Y, Z	B, L, H	X, Y, Z
WRMS (mm/yr)	4.54	4.55	3.99	5.65	1.94
	4.97	6.26	3.89	6.27	2.81
	3.59	2.41	2.66	4.61	4.03
Weighted mean (mm/yr)	-0.88	3.06	0.23	-0.69	-1.48
	2.32	-2.41	0.54	-0.53	1.84
	2.74	0.40	-1.06	0.35	3.77

We made an analogous statistics for velocity differences of 47 stations between our solution S2003, ITRF2000 and NNR NUVEL-1A for the quasi-stable stations that are supposed to be far enough from plate boundaries and intraplate deformations. The stations chosen must have velocities that differ by less than 10mm/yr from NNR NUVEL-1A predictions. These velocity differences show high agreement of solutions (see Table 4). The statistics of velocity differences of solution S2003 and ITRF2000 in Table 4 remained practically the same as in Table 2. These results reconfirm the conclusion made by Takahashi [23] that the stations near the plate boundaries are supposed to change their positions to the effect of the neighboring plates‘ motion and/or are situated in unstable regions because their motion are essentially different from the motion of NNR NUVEL-1A model.

Table 4. Statistics of differences between VLBI solution S2003, ITRF2000 and NNR NUVEL-1A model for 47 stations located in stable plate interior

	S2003–NUVEL-1A		ITRF2000–NNR NUVEL-1A		S2003–ITRF2000
	X,Y,Z	B,L,H	X,Y,Z	B,L,H	X,Y,Z
WRMS (mm/yr)	2.19	3.09	1.64	3.03	1.35
	3.18	3.37	2.58	3.28	1.16
	2.29	1.88	2.33	3.83	1.74
Weighted mean (mm/yr)	-1.23	1.64	0.13	0.51	-1.08
	0.68	-1.73	0.28	-0.58	0.08
	1.27	0.18	-0.20	0.46	1.29

Similar statistics of velocity differences of DORIS stations are submitted in Table 5-7. Although precision of DORIS velocities are not as good as for VLBI velocities, as can be seen from comparison of Table 1 and Table 7, the DORIS velocity differences statistics in Table 5 and Table 6 are much closed to the VLBI values.

Table 5. Statistics of differences between S2003, ITRF2000 and NNR NUVEL-1A for all DORIS stations

	S2003–NUVEL-1A		ITRF2000–NNR NUVEL-1A		S2003–ITRF2000
	X,Y,Z	B,L,H	X,Y,Z	B,L,H	X,Y,Z
WRMS (mm/yr)	3.17	2.52	5.57	6.83	1.55
	3.77	4.11	3.40	11.47	1.47
	2.08	1.92	3.53	3.65	1.57
Weighted mean (mm/yr)	-0.81	-0.13	0.75	0.47	-1.15
	-0.31	-1.01	-0.70	-1.63	0.38
	0.77	1.25	1.31	0.43	0.72

Table 6. Statistics of differences between S2003, ITRF2000 and NNR NUVEL-1A for 37 DORIS stations located in stable plate interior

	S2003–NUVEL-1A		ITRF2000–NNR NUVEL-1A		S2003–ITRF2000
	X,Y,Z	B,L,H	X,Y,Z	B,L,H	X,Y,Z
WRMS (mm/yr)	1.59	1.91	4.02	3.20	1.52
	3.76	2.94	2.61	5.17	1.43
	1.92	1.84	3.05	3.55	1.42
Weighted mean (mm/yr)	-1.20	-0.40	0.44	-0.13	-1.14
	-0.26	-1.51	-0.50	-0.86	0.43
	0.69	1.22	0.98	0.56	0.65

Table 7. Velocities and their RMS of DORIS stations (in mm/yr)

Station name	VLBI solution S2003						NNR NUVEL-1A		Solution ITRF2000		
and	North		East		Up		North	East	North	East	Up
number	*dB*	σ	*dL*	σ	*dH*	σ	*dB*	*dL*	*dB*	*dL*	*dH*
1 TLSA	14.8	6.0	18.9	11.6	-4.0	8.9	14.8	18.8	15.3	19.0	-3.3
2 REYA	22.3	5.4	-12.2	7.7	-3.8	7.0	21.1	-9.6	19.1	-9.2	-1.2
3 SPIA	14.2	0.2	11.0	0.2	5.1	0.4	13.4	12.7	14.0	10.4	6.4
4 META	14.7	3.9	18.0	6.1	1.9	5.3	11.1	20.1	11.7	20.2	3.5
5 SAKA	-22.7	5.7	25.1	10.2	31	8.3	-15.7	16.5	-19.5	15.5	1.0
6 KITA	4.8	6.3	21.9	13.8	-11.1	9.5	0.2	25.5	4.1	28.0	-1.5
7 BADA	-7.2	3.2	26.9	5.3	1.5	4.3	-9.3	22.6	-8.4	25.0	2.1
8 DIOA	-8.0	4.2	3.0	9.7	-3.5	6.9	11.2	22.7	-11.6	3.5	1.1
9 EVEB	25.7	4.1	34.1	10.2	0.2	6.5	-5.3	24.5	22.9	32.4	3.2
10 PURA	-14.2	4.3	31.0	9.8	-5.5	6.7	-12.6	22.1	-13.6	27.3	7.6
11 MANA	-1.2	4.2	-34.1	10.2	-5.0	6.1	-13.0	21.5	2.0	-31.3	-3.3
12 CIBB	-5.7	4.8	20.4	11.6	1.3	7.2	-10.2	18.1	-5.8	23.9	-8.4
13 COLA	32.8	4.5	47.9	10.8	-1.1	6.4	42.0	42.0	30.3	48.5	1.4
14 HBLA	16.2	0.2	16.3	0.2	-1.8	0.4	19.9	20.4	17.9	18.1	0.4
15 MARA	1.9	6.9	5.3	13.3	-3.4	10.6	5.3	8.3	-0.5	5.4	-3.2
16 TRIA	23.4	3.5	19.1	7.0	3.7	4.9	17.9	25.4	22.4	19.9	2.3
17 HELA	21.4	12.2	25.0	32.3	5.6	20.4	18.8	25.8	21.4	16.9	1.3
18 LIBA	20.3	6.3	16.5	16.1	-1.0	9.9	20.2	24.6	17.7	14.9	-5.1
19 ARMA	17.5	15.5	17.5	42.0	-3.5	25.6	20.1	22.3	20.1	24.6	-4.4
20 DAKA	19.3	4.4	20.0	11.1	2.4	6.3	16.9	21.0	15.9	18.8	-1.2
21 DJIA	19.4	4.1	26.9	9.6	-2.2	5.8	18.0	26.0	19.3	27.0	2.4
22 OTTA	3.7	28.1	-29.2	60.3	-3.2	47.2	4.2	-17.0	11.3	-17.9	2.0
23 YELA	-10.5	0.3	-18.8	0.3	5.3	0.7	-11.2	-18.6	-11.6	-17.1	5.0
24 GOMA	-4.6	0.5	-19.7	0.3	0.1	0.7	-12.0	-12.3	-5.3	-17	-1.3
25 FAIA	-21.7	0.1	-10.1	0.1	1.6	0.1	-20.6	-10.5	-22.6	-8.9	0.4
26 KOKA	34.4	0.2	-64.2	0.2	0.5	0.2	32.3	-58.3	32.5	-62.4	-0.8
27 RIDA	2.3	0.2	-11.9	0.2	-1.3	0.3	2.3	-10.9	1.3	-9.8	0.3
28 SODA	46.6	13.1	-59.5	31.7	-31.1	20.8	20.1	-52.0	14.8	-48.2	-10.4
29 RIOA	13.3	4.8	6.3	8.0	2.0	6.7	9.6	1.8	11.7	3.4	5.1
30 CACB	16.4	3.7	-5.1	9.0	-0.2	5.0	11.4	-4.3	11.5	-0.8	6.7
31 EASA	-9.3	3.0	74.3	6.8	8.0	4.2	-8.9	79.6	-7.5	66.5	0.2
32 SANA	18.9	0.4	16.9	0.4	5.0	0.9	9.4	-0.9	16.4	18.9	4.7
33 GALA	10.6	4.5	51.3	11.8	-3.5	7.0	10.2	62.3	8.8	49.2	-1.1
34 AREA	6.2	4.8	1.8	11.9	-5.3	6.9	9.3	-3.3	14.5	10.9	0.6
35 ORRA	54.2	0.3	18.3	0.3	0.4	0.6	54.1	17.6	54.9	18.5	1.0
36 YARA	54.7	5.2	39.9	11.1	6.0	7.6	59.6	39.2	55.9	39.1	0.1
37 GUAB	0.5	4.8	-11.2	11.4	-0.5	6.6	-2.2	-43.5	2.3	-11.0	3.2
38 MORA	53.7	4.4	35.4	10.6	3.4	6.3	54.9	35.7	54.3	32.4	1.7
39 SYOB	2.3	5.3	-11.0	5.7	-0.5	6.2	5.1	-1.7	1.3	-3.6	2.1
40 ROTA	10.8	2.5	16.2	3.2	0.7	3.0	9.0	16.5	8.2	13.4	1.2
41 KERA	-4.7	5.1	2.4	9.0	0.0	7.0	-1.3	6.4	-3.1	5.9	5.0
42 AMSA	-12.9	10.3	-9.8	22.1	-11.0	16.1	-2.8	11.6	-14.5	-12.5	-1.9
43 ADEA	-13.1	2.1	11.2	2.9	-2.7	2.4	-11.7	6.7	-8.1	11.6	-0.9
44 PAPB	35.3	11.3	-71.1	27.7	-8.2	17.7	24.8	-58.4	31.7	-61.9	3.6
45 RAQB	31.2	7.1	-67.7	16.5	-5.1	11.5	30.7	-60.9	29.6	-71.3	-7.0
46 NOUA	42.3	5.9	24.3	14.5	0.1	9.1	43.8	21.8	44.9	18.6	0.1
47 WALA	28.2	5.1	-63.8	12.5	-0.3	7.8	31.4	-60.1	33.1	-61.2	-2.7
48 KRVB	15.7	3.2	-8.6	7.4	2.2	4.3	11.0	-5.7	12	-4.5	2.5
49 REUA	12.8	5.4	14.1	13.1	-5.1	8.0	15.7	18.3	13.0	11.5	0.4

4. Conclusion

Site velocities are determined more reliably by space tracking data rather than by geological data. Moreover, the KRF can be fixed by our algorithm exclusively using space based geodetic data and completely independent from any plate motion model. Besides, we can analyze plate motion model such as NNR NUVEL-1A using only geodetic information itself. Differences between DORIS reference frame with NNR NUVEL-1A model and ITRF2000 are very similar to those obtained when comparing NNR NUVEL-1A and ITRF2000 to VLBI reference frame, although the DORIS data are not as precise as VLBI data. But KRF might be fixed by VLBI data only because of the precision of DORIS data is not adequate for this aim.

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Gerasimenko M.D., Kolomiets A.G., Kasahara M., Crétaux J.-F., Soudarin L. Establishment of a global three-dimensional kinematic reference frame using VLBI and DORIS data.. Far Eastern Mathematical Journal. 2005. V. 6. № 1–2. P. 3–13.

ABSTRACT

The main aim of this paper is to provide an algorithm to combine VLBI (Very Long Baseline Interferometry) and DORIS (Doppler Orbitography and Radio positioning Integrated by Satellite) data sets into the same kinematics reference frame. In the first stage of computation the VLBI and DORIS networks are knitted together using the velocities of each station with their covariance matrices that were obtained from individual solutions. A sequential least squares adjustment was used. In the second stage of computation a method of iterative weighted similarity transformation has been elaborated. In order to fix the three-dimensional kinematic reference frame (KRF), a system of constraints or datum equations based on vertical component of some quasi-stable reference stations are used. This strategy provides a datum that is robust to unstable reference points and gives less distorted displacements. This method has been applied to the VLBI and DORIS data collected during the last decades. Without survey ties available, and consequently without relative velocities between collocated VLBI and DORIS points, we forced the velocities of collocated sites to the same value and constrained their root mean squares to be equal to zero. As VLBI information is formally for some stations ten times more precise than the DORIS information, reference frame and precision of the VLBI stations were practically not affected by this computation. But precision of DORIS station velocities of the joint network is improved by almost 15% and fairly close agreement between ITRF2000 solution, NNR Nuvel-1A model predictions, and our solution has been found. The technique presented provides a method to define KRF without any information from a geological plate motion model. It is thus possible to verify any geological model using only geodetic information itself.

Key words: *linear transformations, matrix inversion, general inversion, kinematic reference frame, NNR NUVEL-1A plate model, VLBI, DORIS, ITRF2000*