

# On comparison of the Earth orientation parameters obtained from different VLBI networks and observing programs

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**Abstract** In this paper, a new geometry index of very long baseline interferometry (VLBI) observing networks, the volume of network  $V$ , is examined as an indicator of the errors in the Earth orientation parameters (EOP) obtained from VLBI observations. It has been shown that both EOP precision and accuracy can be well described by the power law  $\sigma = aV^c$  in a wide range of the network size from domestic to global VLBI networks. In other words, as the network volume grows, the EOP errors become smaller following a power law. This should be taken into account for a proper comparison of EOP estimates obtained from different VLBI networks. Thus, performing correct EOP comparison allows us to investigate accurately finer factors affecting the EOP errors. In particular, it was found that the dependence of the EOP precision and accuracy on the recording data rate can also be described by a power law. One important conclusion is that the EOP accuracy depends primarily on the network geometry and to lesser extent on other factors, such as recording mode and data rate and scheduling parameters, whereas these factors have a stronger impact on the EOP precision.

**Keywords** VLBI · Earth orientation parameters (EOP) · EOP errors · Network geometry

## 1 Introduction

Very long baseline interferometry (VLBI) is a unique technique to determine the Earth orientation parameters (EOP), because it is the only method, which can provide the complete set of five EOP: terrestrial pole coordinates  $X_p$  and

$Y_p$ , Universal Time  $UT1$ , and celestial pole coordinates  $X_c$  and  $Y_c$ , with highest accuracy. Therefore, investigation of various influences on the errors in EOP derived from the VLBI observations is important for improving the results. One of the main factors affecting the EOP results is the network geometry.

Evaluation of the dependence of the EOP errors on the network geometry is important for many practical tasks, such as comparison of EOP estimates obtained on different VLBI networks, observation scheduling, design of VLBI experiments and networks, optimal use of the existing VLBI stations for the determination of EOP. For this reason, an analysis of the differences in EOP values and errors obtained from different observing programs and networks is one of the most actual topics in geodetic VLBI, and many authors have contributed to these studies, e.g. MacMillan and Ma (2000), Sokolskaya and Skurikhina (2000), Johnson (2004), Lambert and Gontier (2006), and Searle (2006). However, the authors of these papers did not investigate directly the immediate connection between EOP and the quantitative parameters of the network geometry.

As follows from the basic principles of VLBI measurements, errors in geodetic and astronomical parameters derived from the VLBI observations directly depend on the number and the length of the baselines involved. Let us have a look at the basic VLBI equation, keeping the main terms in the geometric delay:

$$c\tau = \mathbf{r} \cdot (\mathbf{Q} \mathbf{e}_s) = r (\mathbf{e}_r \cdot (\mathbf{Q} \mathbf{e}_s)), \quad (1)$$

where  $\mathbf{r} = r \mathbf{e}_r$  is the station geocentric vector in the terrestrial coordinate system,  $r$  and  $\mathbf{e}_r$  are its length, and corresponding unit vector,  $\mathbf{e}_s$  is a unit geocentric vector in the celestial coordinate system in the direction of the radio source,  $\mathbf{Q}$  is the rotation matrix for the transformation from celestial to terrestrial coordinate system. To get a corresponding equation

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of condition to be used in a parameter solution, one has to compute the partial derivatives of Eq. (1) with respect to the parameters to be solved. In the case of EOP, the partial derivatives are given as

$$\frac{\partial \tau}{\partial p} = c^{-1} r \left( \mathbf{e}_r \cdot \left( \frac{\partial \mathbf{Q}}{\partial p} \mathbf{e}_s \right) \right), \quad (2)$$

where  $p$  is one of the Earth rotation parameters.

As one can see from Eq. (2), the partial derivatives of the interferometric delay with respect to EOP are proportional to the baseline length. This means that a longer baseline yields smaller EOP errors. It should be mentioned, however, that since we consider the VLBI observations carried out on the real near-spherical Earth, the longest baselines compatible with the Earth's diameter in practice do not necessarily have smallest EOP error due to the problem of the common visibility of radio sources from the two ends of the baseline. For this reason, an optimal baseline length can be found for every specific geodetic or astronomical task, but this analysis is out of the scope of this paper.

To perform a more detailed analysis of the dependence of the EOP errors on the baseline orientation, one can rewrite Eq. (1) as

$$c\tau = r_e \cos \delta \cos h + r_p \sin \delta, \quad (3)$$

where  $r_e$  and  $r_p$  are the equatorial and polar components (projections) of the station vector  $\mathbf{r}$ , respectively,  $\delta$ ,  $h$  being the source declination and hour angle, respectively. Detailed consideration of this equation which can be found, e.g. in [Dermanis and Mueller \(1978\)](#), [Ma \(1978\)](#), [Nothnagel et al. \(1994\)](#), and [Schuh \(2000\)](#), along with a joint analysis of the set of Eq. (3) written for all baselines of the given station network, allows us to conclude that larger baseline equatorial component yields smaller  $UT1$  error, and larger both polar and equatorial projections are needed to get a better separation and less errors in  $X_p$ ,  $Y_p$ ,  $X_c$ , and  $Y_c$ . It is also important that errors in the pole coordinates  $X_p$  and  $Y_p$  may depend on the network longitudinal orientation in the case of a moderate longitude span of the network.

In general, one can expect that the sought-for dependence of the EOP errors on the network geometry is a function of several indices, such as:

- the network span in various directions, e.g. geodetic (latitude  $\Delta\varphi$ ,  $\Delta\lambda$ ) or Cartesian ( $\Delta X$ ,  $\Delta Y$ ,  $\Delta Z$ ) coordinates;
- the network orientation, e.g. central longitude, prevailing baselines directions;
- the number of stations or baselines.

All these factors definitely influence, to a greater or lesser extent, the EOP results obtained from VLBI observations.

Hence, they should be accounted for to provide more rigorous comparison of the EOP derived from different networks and separate the impact of the network geometry and other factors, such as recording data rate and scheduling parameters, on the EOP errors. However, a large number of the network parameters make it difficult to develop a practical method of comparison of EOP. Therefore, it would be useful and convenient to have a generalized index of the network geometry which could serve as an argument of a simple enough but sufficiently accurate function describing the dependence of the EOP errors on the network geometry, and could be used in the comparative studies.

In this paper, continuing the previous study ([Malkin 2007](#)), such a generalized index of the VLBI network geometry is considered, namely, the volume of network, more precisely the volume of the polyhedron with the network stations at the vertices. In Sect. 2, the dependence of the EOP errors on the network volume has been investigated, and in Sect. 3, this dependence will be applied to a more rigorous comparison of the EOP errors obtained from different VLBI networks.

It is important to distinguish between two kinds of errors, namely, precision, which is a measure of the repeatability (reproducibility) of estimates, and accuracy, which refers to the agreement between our estimates and the true value (veracity). Hereafter, it is considered that the EOP precision can be characterized by the formal error (uncertainty) of the EOP estimates computed making use of a data processing software. To assess the EOP accuracy, one can compare the EOP obtained from VLBI observations with an independent EOP series provided by another space geodesy technique. In this paper, like in other similar studies (e.g. [Vennebusch et al. 2007](#)), we used the EOP series provided by the International GNSS Service (IGS, [Dow et al. 2005](#)) for comparison. The term 'error' is used here as a collective name for precision and accuracy in the case when both precision and accuracy are considered.

For completeness, mention may be made of another measure of the EOP quality, the Allan deviation, which may be used either in its original formulation ([Gambis 2002](#)) or with extensions developed in [Malkin \(2008\)](#) for analyzing unequally weighted and multidimensional observations, e.g. both pole coordinates simultaneously. This method was not used in this work, although it may be worth trying for supplement analysis.

For our computations, the VLBI observations were used, collected on the global and regional networks in the framework of observing programs coordinated by the International VLBI Service for Geodesy and Astrometry (IVS, [Schlüter and Behrend 2007](#)), and stored in the IVS Data Centers.<sup>1</sup>

<sup>1</sup> <http://ivscc.gsfc.nasa.gov/products-data/data.html>.

## 2 Dependence of the EOP errors on the network volume

This study begins with the computation of an about 10.7-year EOP series for the period from July 1996 till February 2007, 1,440 24-h sessions in total. The start epoch of the investigated time series was chosen to be the same as the start epoch of the IGS EOP series *igs00p03.erp* used hereafter for accuracy assessment of the VLBI terrestrial pole coordinates.

During the session processing, the volume of the session network was computed simultaneously with EOP in the following way:

1. Compute the tetrahedron mesh for the network polyhedron by means of the Delaunay triangulation making use of the GEOMPACK package by Joe (1991).
2. Compute the volume of each tetrahedron as a scalar triple product:

$$|(\mathbf{r}_2 - \mathbf{r}_1) \cdot ((\mathbf{r}_3 - \mathbf{r}_1) \times (\mathbf{r}_4 - \mathbf{r}_1))| / 6, \tag{4}$$

where  $\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3, \mathbf{r}_4$  are the geocentric station vectors.

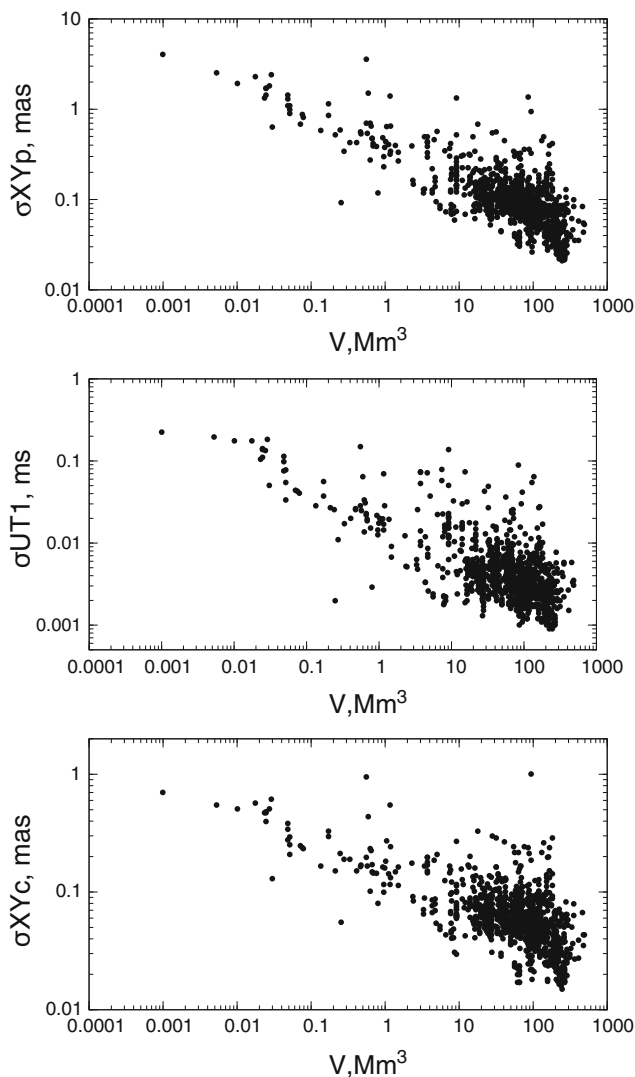
3. Compute the total network volume as the sum of the volumes of all the tetrahedrons.

Some examples of the volume of different IVS observing networks processed in this work are presented in Table 1, where the smallest and the largest IVS networks are shown. The first column of the table contains the IVS session name. The smallest IVS networks are typical of Japanese (JADE) and European (EUROPE) regional sessions. The largest networks were observed in T2 experiments primarily aimed at the improvement of the terrestrial reference system. One can see from Table 1 that the volume of IVS networks differ from each other by several orders of magnitude. For comparison, the volume of the Earth is  $1,083 \text{ Mm}^3$ .

Now, if we plot the EOP precision as a function of the network volume, as shown in Fig. 1, a clear linear (in log–log scale) dependence between these values can be seen.

**Table 1** The volume of the smallest and largest IVS networks

Session	Volume, $\text{Mm}^3$
JADE-0610	9.925E-04
EUROPE-35	5.285E-03
JADE-0601	1.008E-02
EUROPE-56	1.761E-02
...	
T2037	4.607E+02
T2038	4.723E+02
T2041	4.816E+02
T2043	4.871E+02



**Fig. 1** Dependence of the EOP precision on the network volume  $V$ . Downward, average formal error in the terrestrial pole coordinates  $X_p$  and  $Y_p$ , Universal Time  $UT1$ , and celestial pole coordinates  $X_c$  and  $Y_c$  are depicted (logarithmic scales on both axes)

To investigate the dependence of the EOP errors on the network volume in detail, the following computations were performed.

1. The EOP series mentioned above was arranged in nine groups by the network volume  $V$  in  $\text{Mm}^3$ :  $V < 0.1$ ,  $(\sqrt{10})^k \leq V < (\sqrt{10})^{k+1}$ ,  $k = -2, \dots, 5$ ;
2. For the sessions fallen into each group the following quantities were calculated:
  - the average network volume;
  - the average formal errors in  $X_p, Y_p, UT1, X_c$  and  $Y_c$  regarded as EOP precision;
  - weighted root-mean-square (WRMS) of the differences in  $X_p, Y_p$  between the computed EOP

**Table 2** Results of splitting of the VLBI EOP series into nine groups by the network volume  $V$

V range, Mm <sup>3</sup>	N	V, Mm <sup>3</sup>	EOP precision					EOP accuracy	
			$X_p$	$Y_p$	UT1	$X_c$	$Y_c$	$X_p$	$Y_p$
$V < 0.1$	20	0.001	0.505	0.661	0.335	0.131	0.128	3.118	3.033
		0.079	5.213	3.230	2.231	0.629	0.780		
		0.037	1.599	1.500	1.109	0.383	0.404		
$0.1 \leq V < 0.316$	7	0.134	0.115	0.068	0.020	0.056	0.055	0.415	0.385
		0.276	0.889	1.415	0.564	0.346	0.315		
		0.209	0.516	0.667	0.268	0.209	0.190		
$0.316 \leq V < 1$	21	0.333	0.138	0.096	0.029	0.080	0.080	0.726	0.491
		0.992	3.451	3.735	1.495	0.910	0.979		
		0.667	0.608	0.686	0.286	0.208	0.207		
$1 \leq V < 3.16$	13	1.01	0.149	0.119	0.051	0.084	0.085	0.481	0.482
		2.40	1.229	1.599	0.691	0.617	0.487		
		1.48	0.431	0.482	0.189	0.191	0.180		
$3.16 \leq V < 10$	59	3.33	0.052	0.067	0.018	0.031	0.025	0.251	0.237
		9.24	1.380	1.282	1.363	0.267	0.272		
		6.98	0.232	0.228	0.195	0.095	0.094		
$10 \leq V < 31.6$	188	10.6	0.052	0.047	0.013	0.030	0.032	0.221	0.188
		31.2	0.835	0.627	0.744	0.303	0.353		
		22.1	0.136	0.120	0.059	0.075	0.076		
$31.6 \leq V < 100$	698	32.0	0.026	0.026	0.010	0.017	0.017	0.186	0.173
		99.9	2.355	0.905	0.890	1.000	0.995		
		65.4	0.114	0.094	0.049	0.065	0.065		
$100 \leq V < 316$	422	101	0.021	0.020	0.009	0.015	0.015	0.116	0.129
		313	0.678	0.402	0.642	0.285	0.287		
		170	0.072	0.069	0.035	0.049	0.049		
$316 \leq V < 1000$	12	325	0.030	0.034	0.015	0.027	0.027	0.106	0.080
		487	0.091	0.110	0.058	0.079	0.079		
		399	0.055	0.061	0.037	0.047	0.043		

For each  $V$  range, number of sessions  $N$  is given, and for each parameter, minimal, maximal and average values are shown downward. Unit for  $X_p$ ,  $Y_p$ ,  $X_c$ ,  $Y_c$ : mas, unit for UT1: 0.1 ms

and the IGS combined series `igs00p03.erp`<sup>2</sup> after removing the constant bias between the VLBI and IGS EOP series regarded as EOP accuracy.

Details and results of computation are shown in Table 2 and Figs. 2 and 3. The nine averaged points thus obtained were then used to compute the parameters of a power law fitting best to the data

$$\sigma = aV^c, \quad (5)$$

where  $\sigma$  is an EOP error, i.e. can stand for precision or accuracy. For actual computation, this dependence was transformed to the linear form

$$\log \sigma = b + c \log V, \quad (6)$$

where  $b = \log a$ . The parameters  $b$  and  $c$  were computed by means of the least-squares linear fit with weights dependent

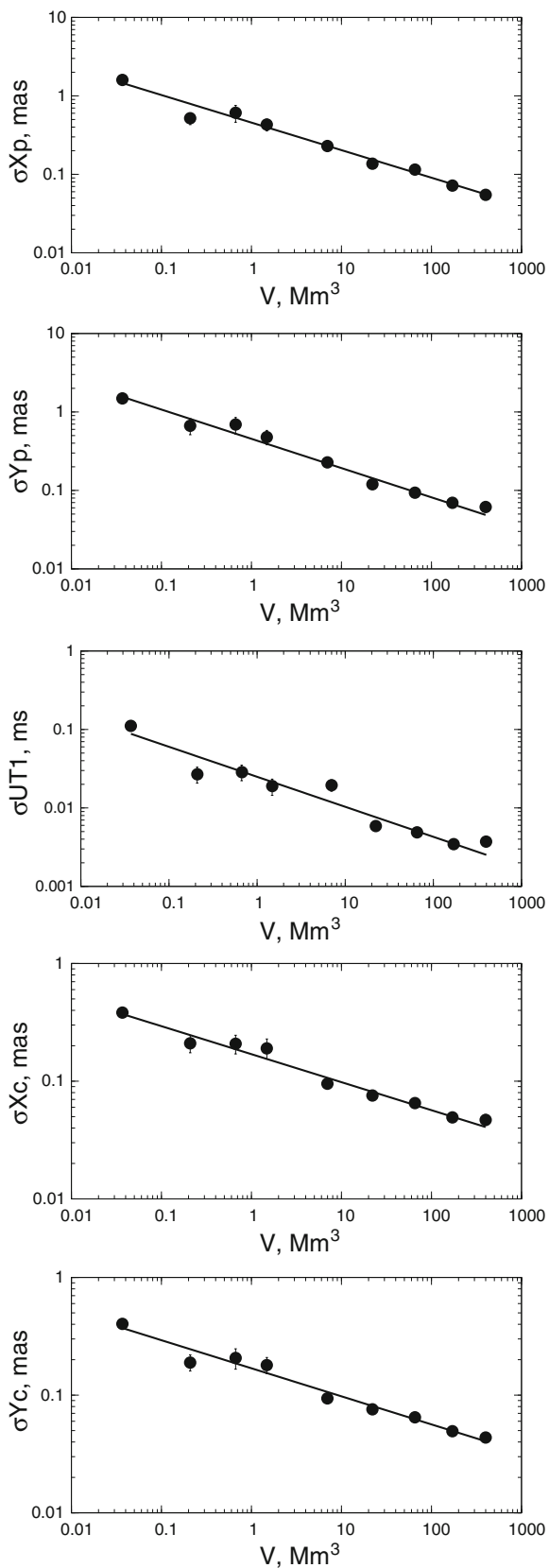
on the number of sessions fallen into each group. The results are presented in Tables 3 and 4, and depicted as the regression lines in Figs. 2 and 3. One can see that the dependence of both EOP precision and accuracy on the network volume can be nicely described by a power law.

Generally speaking, it is natural that the EOP precision improves with larger network size (volume) since a large network has larger projections of the network baselines on the rotation axes. More interesting and less evident is that the EOP accuracy follows the same power law with practically the same exponent  $c$  but with a different factor  $a$ .

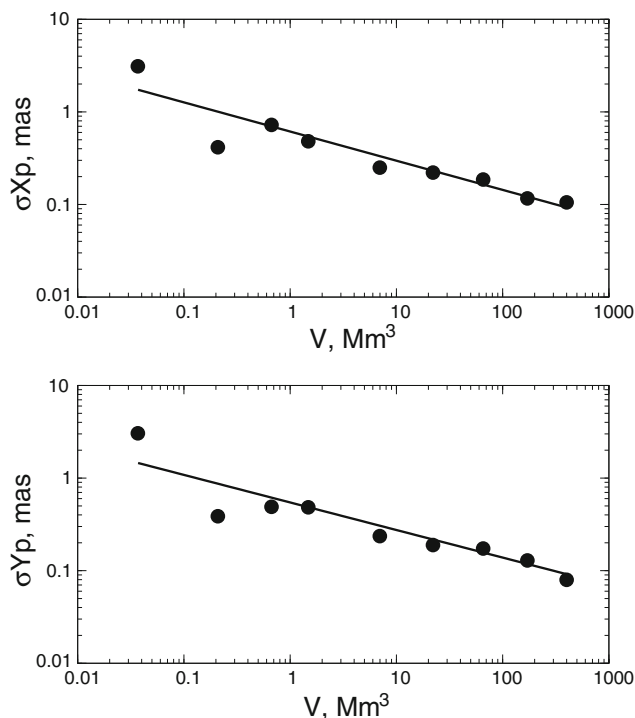
### 3 Comparison of observing programs

In this section, an application of found dependence of the EOP errors on network geometry to a comparison of EOP obtained from different IVS observing programs will be considered.

<sup>2</sup> <ftp://cddis.gsfc.nasa.gov/gps/products/>.



**Fig. 2** Dependence of the EOP precision (mean formal errors for the nine groups of volume) on the network volume  $V$  (logarithmic scales on both axes). *Solid line* corresponds to the power law (Table 3)



**Fig. 3** Dependence of the EOP accuracy (WRMS of the differences with respect to IGS EOP for the nine groups of volume) on the network volume  $V$  (logarithmic scales on both axes). *Solid line* corresponds to the power law (Table 4)

**Table 3** Representation of the EOP precision by a power law  $\log \sigma = b + c \log V$

EOP	Unit	$b$	$c$
$X_p$	mas	$-0.340 \pm 0.022$	$-0.351 \pm 0.018$
$Y_p$	mas	$-0.342 \pm 0.023$	$-0.373 \pm 0.019$
$UT1$	ms	$-0.0603 \pm 0.0043$	$-0.0382 \pm 0.0036$
$X_c$	mas	$-0.771 \pm 0.016$	$-0.238 \pm 0.013$
$Y_c$	mas	$-0.772 \pm 0.016$	$-0.238 \pm 0.013$

**Table 4** Representation of the EOP accuracy by a power law  $\log \sigma = b + c \log V$

EOP	Unit	$b$	$c$
$X_p$	mas	$-0.212 \pm 0.045$	$-0.315 \pm 0.038$
$Y_p$	mas	$-0.263 \pm 0.049$	$-0.298 \pm 0.041$

To investigate the dependence of the EOP errors on the observing program, we have performed the same computations as described in the previous section, with the only difference that EOP results were arranged in 13 groups by the IVS observing programs: 11 global networks R1, R4, RD, RDV, NEOS-A, CORE-A, CORE-B, CONT02, CONT05, T2, E3, and 2 regional networks EURO, JADE. Although the last two programs are primarily intended for geodesy researches



**Table 5** Characteristics of IVS observing programs

Program	Observation period	Number of sessions	Number of stations	Number of observations	Network volume, Mm <sup>3</sup>	Data rate, Mbps
R1	2002–2007	261	4–8 (6.2)	700–4800 (2000)	2.4–320 (140)	256
R4	2002–2007	258	4–8 (6.3)	400–3200 (1300)	7.7–273 (84)	56–128
RD	2004–2006	18	5–7 (6.1)	1200–3100 (2300)	16–27 (22)	1024
RDV	1997–2007	55	14–20 (17.5)	7600–29300 (17500)	28–313 (160)	128
NEOS-A	1996–2001	283	4–6 (5.1)	300–2000 (1100)	4.7–117 (54)	56
CORE-A	1997–2000	79	4–6 (5.5)	400–2000 (1300)	1.0–187 (94)	56
CORE-B	1997–2001	53	4–8 (6.2)	400–3500 (1600)	0.3–235 (76)	56
CONT02	2002	15	7–8 (7.9)	2300–3500 (3000)	91–92 (92)	256
CONT05	2005	15	10–11 (10.9)	5600–6500 (6000)	263–265 (265)	256
T2	2002–2006	41	5–15 (9.0)	300–5600 (1800)	11–487 (219)	64–128
E3	2002–2006	31	4–6 (4.5)	200–800 (400)	1.0–88 (25)	128
EURO	1996–2006	36	4–9 (6.6)	400–5400 (2800)	0.01–1.4 (0.6)	64–128
JADE	1999–2006	12	4–6 (5.1)	700–2100 (1400)	0.001–0.05 (0.03)	128

Only the programs and observations used in this paper are shown. In some columns, the average value is given in parentheses

in relatively small geographic regions, and are not supposed to obtain scientifically useful EOP results, they are included in this study for the following reasons:

- including the relatively small regional networks in this study provides significantly larger range of the network volume, and thus allows us to get more reliable estimates for the slope of the log–log regression line corresponding to the power law discussed above;
- some IVS analysis centers include EURO, and sometimes JD sessions in their EOP series.

The results shown in the previous section show that taking the small networks into consideration does not corrupt the estimates of the parameters of the power law describing the dependence of the EOP errors on the network volume, which can be seen in Figs. 2 and 3.

A detailed description of different IVS observing programs can be found at the IVS website,<sup>3</sup> and their main relevant characteristics are shown in Table 5. Note that in further computation the average value of the extremes was taken for observing programs with changing data rate.

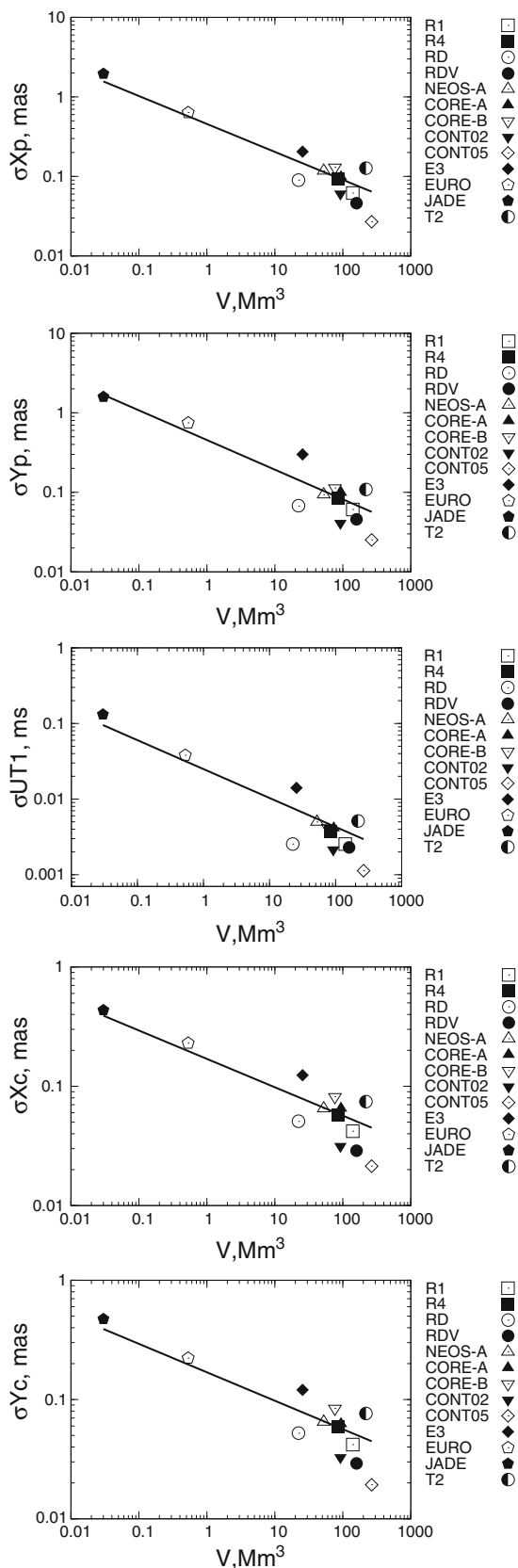
For all the observing programs listed above, except RD (Research and development experiments), all the sessions observed during the used time span were included in this study. As to the RD program, only 18 sessions observed with the recording data rate 1 Gbps were used. It is worth mentioning that CONT02 and CONT05 programs were special 2-week continuous observing campaigns primarily aimed at the highest EOP quality. It can also be mentioned that all observing programs were observed with the Mark IV terminal developed in the USA (Whitney 1998), except E3

sessions observed with the S2 terminal developed in Canada (Wietfheldt et al. 1996), and JADE sessions observed with the K4 terminal developed in Japan and compatible with Mark IV (Kiuchi et al. 1997). An overview and comparison of VLBI terminals can be found, e.g. in Petrachenko (2000). The S2 terminal provides maximum recording rate of 128 Mbps, whereas the other terminals use the recording rate of 256 Mbps for regular experiments and up to 1 Gbps in RD sessions, as can be seen in Table 5.

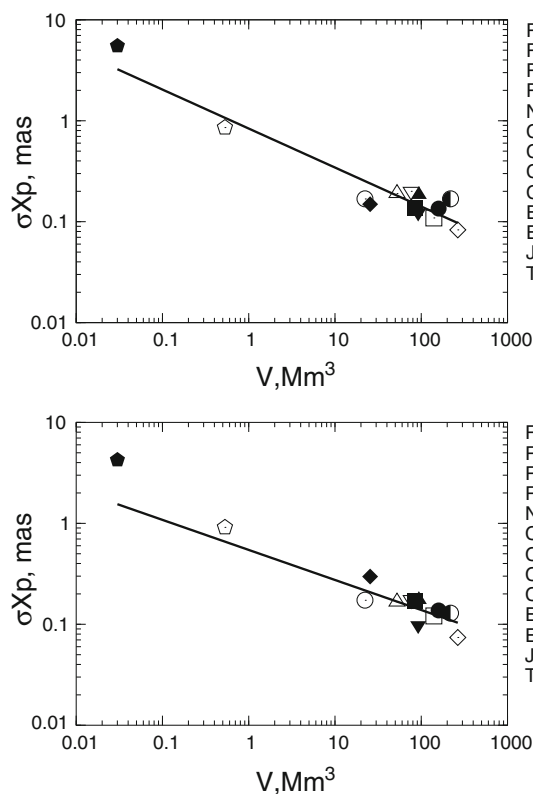
The results of computations are presented in Figs. 4 and 5, where the solid lines correspond to the power law with the parameters given in Tables 3 and 4 for EOP precision and accuracy, respectively. When comparing these results with those presented in the previous section, one can see that the scatter of the points with respect to the regression line in Figs. 4 and 5 is greater than that in Figs. 2 and 3, which can be explained by the fact that, as a rule, networks of different sizes participated in the same observing program, which can be clearly seen from Table 5. Besides, the differences in some scheduling options, such as optimization, recording mode and source selection, also influence the EOP errors and cause their deviation from the common (average) law.

Collating the results obtained above for the EOP precision and accuracy one can see that the scatter (WRMS of the residuals) of the EOP accuracy with respect to the regression line (0.033 mas) is much less than that of the EOP precision (0.054 mas). The difference becomes even larger if the WRMS is scaled to the magnitude of the accuracy and precision, respectively, more precisely to the  $a$  factor in Eq. (5)—0.039 versus 0.108. This may mean that the EOP accuracy follows more strongly a power law than the EOP precision. In other words, one can conclude that the EOP accuracy depends primarily on the network geometry and to less extent on other factors, which have stronger impact on the EOP precision.

<sup>3</sup> <http://ivscc.gsfc.nasa.gov/program/descrip.html>.



**Fig. 4** Dependence of the EOP precision on the average network volume  $V$  for different observing programs (logarithmic scales on both axes). *Solid line* corresponds to the power law (Table 3)



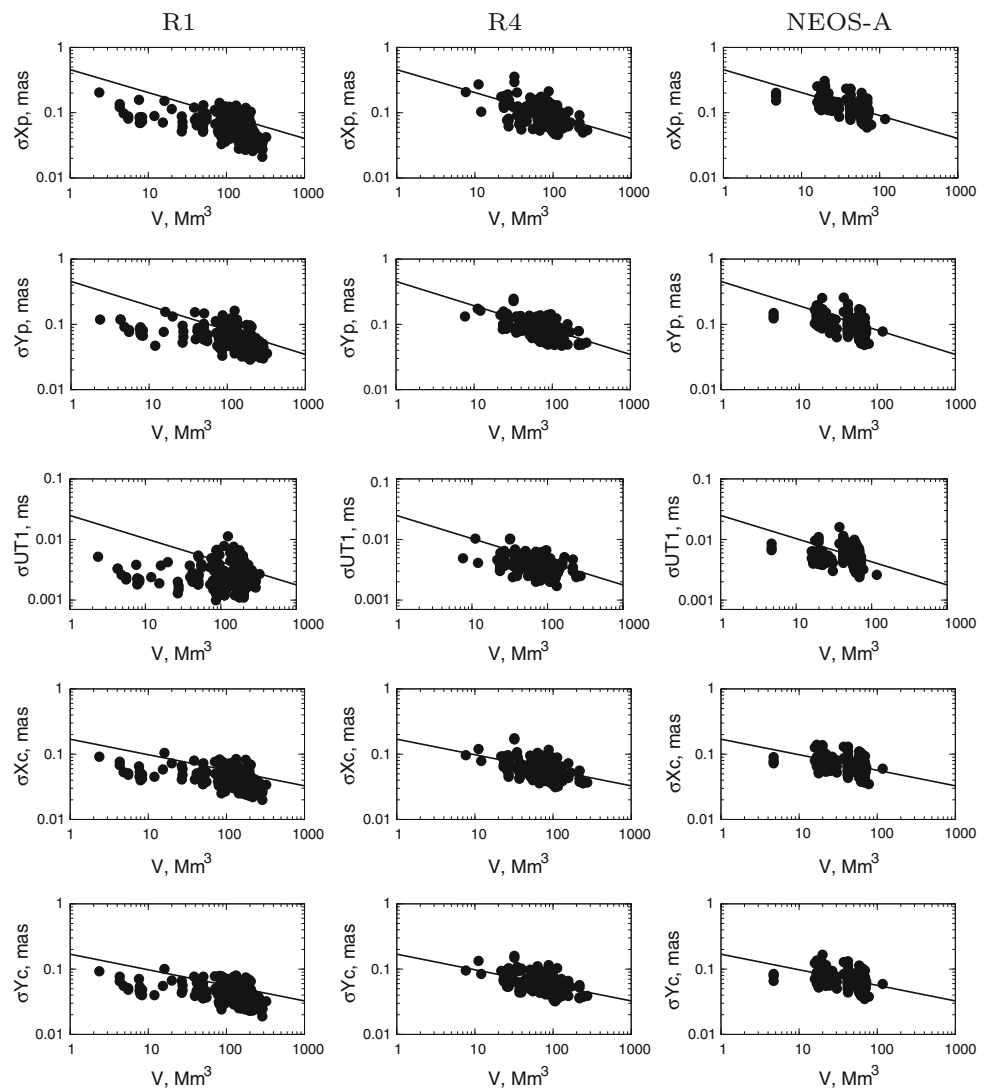
**Fig. 5** Dependence of the EOP accuracy on the average network volume  $V$  for different observing programs (logarithmic scales on both axes). *Solid line* corresponds to the power law (Table 4)

An analysis of the data presented in Table 5 and Figs. 4 and 5 allows us to make some interesting perceptions. Here are two examples.

- The known fact of smaller errors of the EOP obtained from the R1 observations with respect to the R4 program can be mainly explained by the difference between the average volume of the R1 and R4 networks, 140 and 84  $Mm^3$ , respectively.
- The observations made in the framework of the E3 program, using S2 terminal, involving relatively small number of stations, and delivering relatively small number of observations, show relatively bad precision. However, the accuracy of the E3 EOP, after accounting for the network size, is at a level of the accuracy of other observing programs involving more stations, using higher recording data rate, and collecting much more observations.

It is interesting to see how the general law derived from the whole data set works for separate IVS observing programs. For this comparison, three observing programs were selected, R1, R4, and NEOS-A, each having a large number of sessions and a large range of network volume. All the three programs are designed for the highly accurate EOP

**Fig. 6** Dependence of the EOP precision on the average network volume  $V$  for three IVS observing programs R1, R4 and NEOS-A (logarithmic scales on both axes). *Solid line* corresponds to the power law (Table 3)



determination and use Mark IV terminals, with different recording data rate, however, as can be seen from Table 5. Results of computations are presented in Fig. 6.

In these plots, one can see that the three compared observing programs show similar slope in the dependence of the formal errors on the network volume, and this slope is close to the general power law derived from the whole data set. The small discrepancies in the slope between the separate observing programs among them and with the general slope given in Table 3 can be evidently explained by the difference in the number of observations and the range of the network size. Indeed, finer dependencies of the EOP errors on the network geometry may contribute to these discrepancies. One can also see in Fig. 6 that session points for R4 and NEOS-A are laying practically on the general regression line, whereas R1 sessions are shifted down with respect to the general law, which corresponds to the averaged program points in Fig. 4. One of the possible reasons of a better precision of the R1

EOP may be a higher recording data rate of 256 Mbps as compared with 56–128 Mbps used during NEOS-A and R4 sessions. However, possible dependence of the EOP errors on the recording data rate is definitely a finer effect than the dependence on the network volume.

Thus, it is clear from the results presented above that to compare correctly the errors in EOP obtained from different VLBI networks it is necessary to properly account for the network size. This can be done by the following method. Before comparing different observing programs, corresponding EOP errors should be reduced to the unit volume. To do so, the errors are to be modified as follows:

$$\sigma_m = \sigma/V^c, \quad (7)$$

where  $\sigma$  is the original error (precision or accuracy), and  $\sigma_m$  is the modified error. Original and modified errors in pole coordinates (average for  $X_p$  and  $Y_p$ ) computed using Eq. (7) are

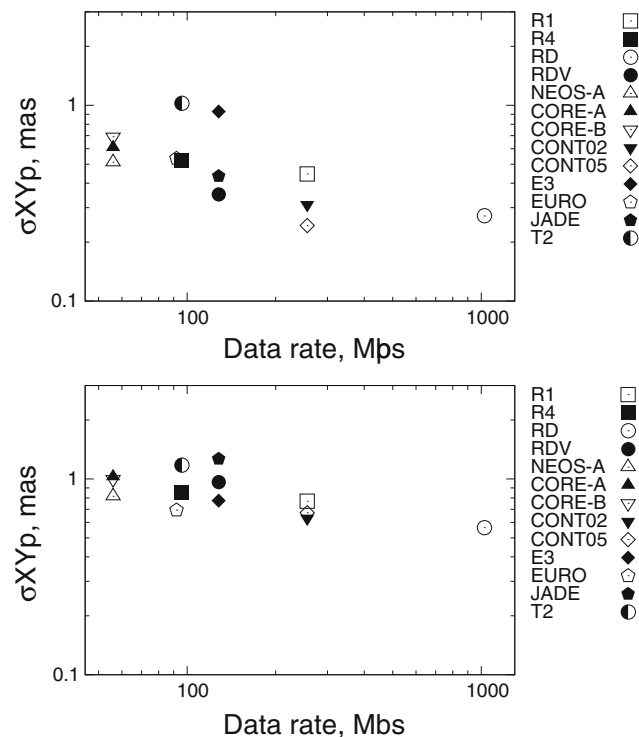


**Table 6** Original ( $\sigma$ ) and modified ( $\sigma_m$ ) errors in pole coordinates (average of  $X_p$  and  $Y_p$ ) (Unit: mas)

Program	Precision, mas		Accuracy, mas	
	$\sigma$	$\sigma_m$	$\sigma$	$\sigma_m$
R1	0.061	0.446	0.115	0.770
R4	0.088	0.520	0.155	0.853
RD	0.079	0.272	0.170	0.564
RDV	0.046	0.352	0.137	0.961
NEOS-A	0.105	0.512	0.178	0.816
CORE-A	0.099	0.609	0.179	1.027
CORE-B	0.121	0.691	0.188	0.998
CONT02	0.051	0.311	0.111	0.630
CONT05	0.026	0.243	0.079	0.672
T2	0.118	1.021	0.148	1.178
E3	0.253	0.929	0.223	0.775
EURO	0.691	0.535	0.885	0.693
JADE	1.771	0.435	4.884	1.267

shown in Table 6. These results give a quantitative confirmation of the preliminary conclusions made from Figs. 4 and 5.

Comparison of the data presented in Tables 5 and 6 allows us to make a conclusion on the dependence of the EOP errors on the recording data rate, which is depicted in Fig. 7. From these data, one can see that the dependence of the errors in pole coordinates on the recording data rate can also be



**Fig. 7** Dependence of the modified EOP precision (*top*) and accuracy (*bottom*) on the recording data rate (logarithmic scales on both axes)

represented by the power law:  $\log \sigma = (0.437 \pm 0.041) - (0.352 - \pm 0.121) \log R$  for the pole coordinates precision and  $\log \sigma = (0.338 \pm 0.023) - (0.194 - \pm 0.068) \log R$  for the accuracy, where  $R$  is the recording data rate in Mbps. Again, like the case of dependence of the EOP errors on the network volume, the EOP accuracy shows stronger dependence on the registration data rate than the EOP precision. This can be seen from comparison of the ratio between the largest and smallest modified values of precision and accuracy.

### 4 Conclusion

The volume of a VLBI network, i.e. the volume of a polyhedron formed by the network stations, can serve as a generalized index of network geometry. A comparison of EOP obtained on different observing networks allowed us to show that both EOP precision (formal errors) and accuracy (WRMS with IGS EOP series) strongly follow a power law with respect to the network volume in a wide range of the network size, from regional to global one. Thus, the network volume seems to be a governing factor of the errors in the VLBI EOP.

Indeed, the dependence found in this paper cannot predict errors in EOP derived from a particular VLBI session, which depend on many reasons, such as details of the network geometry and baseline orientation, scheduling parameters (optimization, recording mode and data rate, source selection), station operation quality, etc., and may differ from the computed value by a factor of 2–3, as can be seen from Fig. 1. It is intended for overall comparison of the observing networks.

On the basis of this result, the method is proposed to compare correctly the EOP errors, both precision and accuracy, for different VLBI networks and observing programs. Following this method, the errors should be compared after a reduction to the unit volume in accordance with Eq. (7). After that, comparison of the modified EOP errors obtained from observations on different networks (observing programs) does not depend on the network size anymore, which allows us to estimate the influence of other factors on EOP results. In particular, dependence of the EOP errors on the recording data rate was derived from an analysis of the observations made in the framework of several IVS observing programs. It was found that this dependence can also be described by a power law.

It is remarkable that dependence of the EOP accuracy on both the network volume and the recording data rate is described by a power law more accurately than that for the EOP precision. This may show evidence that the EOP accuracy depends mainly on the network geometry, and the EOP precision depends to greater extent on other factors mentioned earlier.

The results obtained in this paper can also be used for planning geodetic VLBI campaigns, optimal use of the existing IVS network and for designing new VLBI networks, such as VLBI2010 (Petrachenko et al. 2004) and GGOS (Global Geodetic Observing System, Pearlman et al. 2006, 2007).

Of course, the proposed method of accounting for the network geometry is applicable only for the networks comprising four and more stations, but this does not seem to be a serious limitation since the most valuable scientific VLBI results are obtained on ramified networks.

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