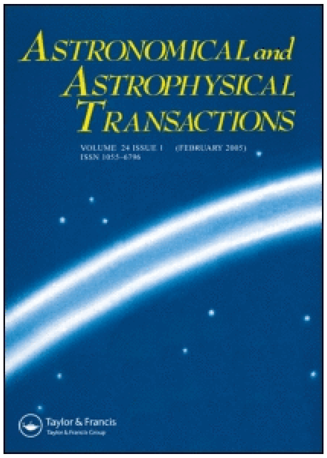

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Seasonal variations in radial components of VLBI stations

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SEASONAL VARIATIONS IN RADIAL COMPONENTS OF VLBI STATIONS

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We consider seasonal variations of baselength from global VLBI data adjustment. Spectral analysis of the baselength time series showed that annual and semiannual signals are significant. Estimates of the signal amplitudes and phases as well as relative rates are represented for 35 independent baselines. This allows us to determine the seasonal variations in radial components of 14 individual VLBI sites. The typical estimate is 4–7 mm for annual and 1–3 mm for semiannual harmonic. Possible reasons of the effect are discussed. This must be included into the routine procedure of observational VLBI adjustment to avoid possible bias of other parameter estimates.

KEY WORDS VLBI data adjustment, atmospheric loading, seasonal deformation of the Earth's surface, tectonic motion

1 INTRODUCTION

In accordance with the conventional model of tectonical plate motion NNR-NUVEL1 the variations of baselengths should be straight lines (Argus *et al.*, 1994), but at the beginning of the 1990s some scientists found seasonal signatures in a few baselines time series (MacMillan *et al.*, 1994a; 1994b; Herring anf Dong, 1991). More recently the various deviations from linear dependence were described by Zarraoa (1995), but they have not yet been explained. The problem becomes complicated due to the fact that the detected seasonal variations can arise from inaccuracies of other natural effect modelling. For example, Niell (1991) showed that the seasonal variations into both horizontal and vertical components can be affected by incompleteness of mapping function simulation. Therefore one should be more careful during the interpretation of the effect.

Interesting results on annual variations of the Earth's surface were published in the papers about the atmospheric pressure loading effect on VLBI station component displacement (Stolz and Larden, 1979; Rabbel and Zschau, 1985; Manabe *et al.*, 1991). In spite of different approaches for modelling, similar estimates of the annual shift of vertical components (1–2 cm) were obtained. Therefore there is reason to assert that the variations under study arise from seasonal movement of large air masses. McMillan and Ma (1994a) reached the same conclusion from an analysis of VLBI data adjustment with a different meaning of elevation angle cutting.

As usual scientists pay more attention to high-frequency ($\sim$ 2 weeks) variations of atmospheric pressure and VLBI site components than to seasonal ones (vanDam and Herring, 1994; MacMillan and Gipson, 1994b). The authors have been trying to explain fast changes of baselength estimates which were discovered using observational VLBI data. They obtained correlation coefficients from -0.6 to -0.3 mm/mbar (vanDam and Herring, 1994) and from -0.6 to -0.2 mm/mbar (MacMillan and Gipson, 1994b). Manabe *et al.* (1991) and vanDam and Herring (1994) studied the presence of the annual signal as well, but the spectral analysis has not been applied for baselength time series processing although some baselines have a few hundred observations. Therefore up to now there has been no evidence that the period of seasonal signature is equal to one year.

In this paper the seasonal variations of baselengths are considered. Daily estimates of baselengths for the time period from 1982 till 1995 have been taken from current publications of GSFC (Ma and Ryan, 1995). It is the most complete database of global VLBI adjustment results. Therefore an application of spectral analysis will allow us to catch signatures in the range from some days to some years.

2 RESULTS OF ANALYSIS

The baselength estimates have been calculated by the Goddard Space Flight Centre (GSFC, NASA) using CALC/SOLVE software (Ma and Ryan, 1995). The code takes into account the stochastic nature of both clock parameters and wet troposphere delays. Results of the analysis are available electronically. We have chosen a set of 35 baselines which have a long observational history or have been operating actively during recent years (Table 1). The length range is from 500 km to 11 000 km; the 17 VLBI stations are located on different continents as well as latitude zones. The choice allows us to extract both regional and global natural phenomena.

The baselength estimate time series are not equidistant because the VLBI stations have been participating in different programmes with special observational schedules. Therefore we have applied the approach of Barning for spectral analysis. It appears that the annual signature is present in almost all 35 time series. Figure 1 demonstrates the Westford–Wettzell baseline evolution from 1990 till 1995. The corresponding power spectrum density is shown in Figure 2. Obviously the annual signature predominates. Moreover, there is a small peak near the period of 100 days. In reality there are two close peaks with periods $\sim$ 95 and $\sim$ 107 days.

For a few baselines a meaningful semiannual signature has been discovered. Figure 3 demonstrates the time variations of the Gilcreek–Wettzell baseline, and Figure 4 shows the corresponding power spectra density.

Table 1. Information about baselines. The symbol 'i' means that the baseline contains inland sites only; 'c' means that one or both sites are close to ocean coast

No.		*Baseline*	*Length (km)*	*Number of points*	*Time span of observations*
1	i	Wettzell–Medicina	522	38	04.04.87–09.06.95
2	c	Wettzell–Onsala	920	226	17.11.83–29.06.95
3	c	Wettzell–Matera	990	77	21.12.90–09.06.95
4	c	Richmond–Westford	2045	563	05.01.84–19.08.92
5	c	Richmond–HRAS085	2363	350	05.01.84–30.10.90
6	i	Westford–HRAS085	3135	375	04.01.85–17.06.89
7	c	Richmond–Mojave12	3595	221	05.01.84–11.08.92
8	i	Gilcreek–Mojave12	3816	284	08.07.84–01.09.92
9	i	Westford–Mojave12	3904	445	29.06.83–01.09.92
10	c	Gilcreek–Kokee	4728	146	09.09.93–26.07.95
11	c	Gilcreek–Kauai	4728	368	08.07.84–15.03.94
12	i	Gilcreek–NRAO85 3	5035	378	20.02.89–26.07.95
13	i	Gilcreek–Westford	5040	290	29.08.84–29.06.95
14	c	Gilcreek–Kashima	5427	152	30.07.84–25.07.95
15	c	Westford–Onsala	5601	212	18.03.82–29.06.95
16	i	Wettzell–Westford	5998	822	17.11.83–29.06.95
17	c	Fortleza–NRAO85 3	6074	115	07.07.93–19.07.95
18	c	Wettzell–Algopark	6155	51	02.07.90–15.06.95
19	i	Wettzell–NRAO85 3	6726	186	20.11.91–26.07.95
20	i	Wettzell–Gilcreek	6858	290	31.08.84–26.07.95
21	c	Kokee–NRAO85 3	7208	118	09.06.93–26.07.95
22	c	Kauai–NRAO85 3	7208	227	20.02.89–15.03.94
23	c	Wettzell–Fortleza	7215	123	22.04.93–19.07.95
24	c	Matera–NRAO85 3	7356	91	05.10.90–20.12.94
25	c	Wettzel–Richmond	7588	534	25.01.84–19.08.92
26	c	Gilcreek–Matera	7660	84	05.10.90–24.01.95
27	i	Wettzell–Hartrao	7832	98	10.01.86–18.07.95
28	i	Wettzell–HRAS085	8418	415	17.11.83–30.10.90
29	i	Wettzell–Mojave12	8589	266	31.08.84–01.09.92
30	i	Hartrao–Hobart26	9168	99	21.12.89–25.07.95
31	c	Gilcreek–Fortleza	9865	82	07.07.93–12.07.95
32	c	Wettzell–Kokee	10357	148	09.06.93–26.07.95
33	i	Westford–Hartrao	10659	85	10.01.86–04.04.95
34	i	Gilcreek–Hobart26	10953	78	27.09.89–25.07.95
35	c	Fortleza–Kokee	11064	100	14.07.93–19.07.95

Using the preliminary results the following parametric model for baselength time series approximations has been chosen:

$$L(t) = a + bt + c\left[\cos\left(\frac{2\pi}{P}t + \varphi\right)\right] + d\left[\cos\left(\frac{4\pi}{P}t + \theta\right)\right] + w\,, \tag{1}$$

where t is the epoch of observations; $L(t)$ is the baselength; a, b are the linear trend parameters; P is the period of the Earth's rotation in its orbit; c, φ are the amplitude and phase of the annual signature; d, θ are the amplitude and phase of the semiannual signature; and w is the random error.

In spite of the presence of other signatures we have not included them into model (1), because their origin is still unclear. They change from baseline to baseline, so

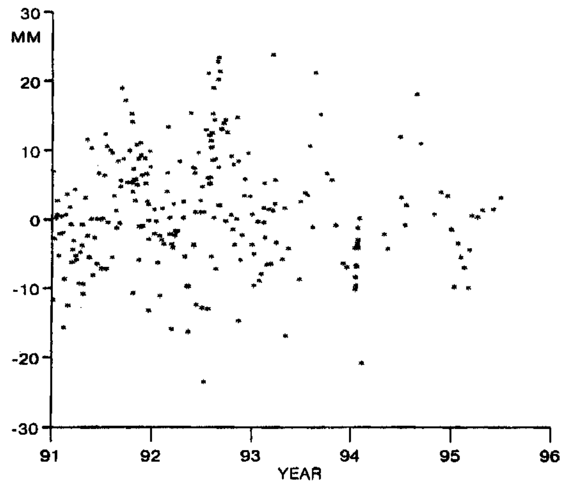

Figure 1 Evolution of the Westford–Wettzell baseline. There are significant seasonal variations.

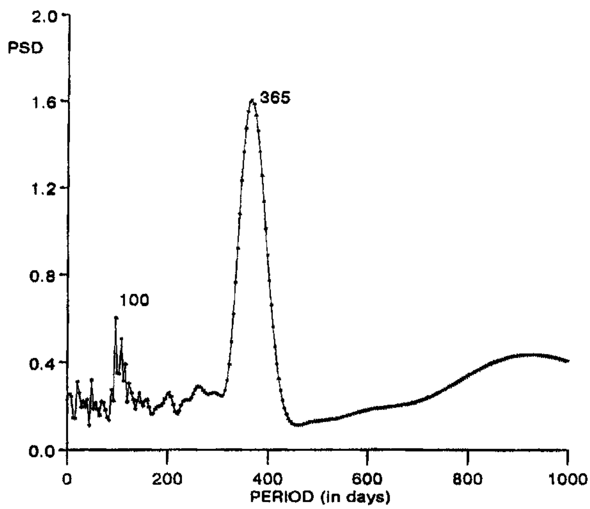

Figure 2 Spectrum of the Westford–Wettzell baseline variations. The largest harmonic is an annual one. There is no semiannual harmonic.

that there is no possibility of supposing that the variations are global. Sometimes the signatures can be caused by local effects (for example, seasonal thermic deformation of antenna). A detailed special investigation needs to be made for final identification.

After adjustment with parametric model (1) we obtained estimates of the six parameters. Table 2 contains the linear trend coefficients as well as amplitudes and phases of annual and semiannual signatures with standard deviations. Figure 5

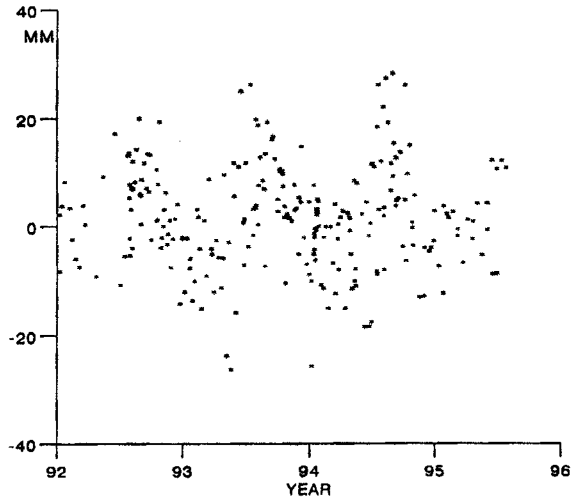

Figure 3 Evolution of the Gilcreek–Wettzell baseline. There are significant seasonal variations.

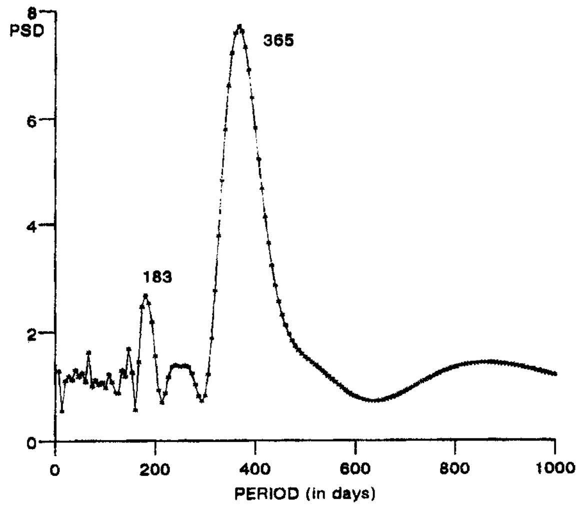

Figure 4 Spectrum of the Gilcreek–Wettzell baseline variations. There are both annual and semiannual harmonics.

shows the 'baselength versus amplitude of signal' relation for all 35 baselines; and, separately, for baselines from both inland and one or two coastal stations in order to evaluate the influence of the ocean on the seasonal variations. Table 3 contains the regression parameters. The coefficients are practically equal to each other, therefore one can draw the conclusion that the power of the annual variations does not depend on the location of the VLBI station relative to a large mass of water.

Table 2. Results of estimation with parametrical model (1). Titles of sites are abbreviated

Baseline	*Rate (mm/year)*	*c (mm)*	*φ (degrees)*	*d (mm)*	*θ (degrees)*
Wett–Med	−2.3±0.3	1.0±0.9	35±53	2.7±1.5	200±17
Wett–Ons	−0.6±0.1	0.7±0.4	124±30	0.3±0.4	193±65
Wett–Mat	−3.7±0.4	2.8±0.6	117±13	1.3±0.5	276±25
Rich–West	−0.3±0.1	0.7±0.4	187±32	0.9±0.4	300±25
Rich–HRAS	2.0±0.3	1.0±0.8	150±42	0.5±0.7	33±86
West–HRAS	5.2±0.3	3.1±0.6	140±11	1.2±0.6	227±28
Rich–Moj12	5.1±0.6	2.2±0.7	165±20	0.5±0.8	156±79
Gilc–Moj12	−10.7±0.2	3.1±0.5	98±10	2.6±0.5	336±11
West–Moj12	0.7±0.2	3.4±0.4	126±8	0.7±0.5	251±37
Gilc–Kok	−43.9±0.9	5.2±0.7	99±7	1.8±0.8	287±22
Gilc–Kau	−45.5±0.2	4.1±0.6	121±8	1.3±0.6	304±25
Gilc–NRAO	−1.9±0.3	4.9±0.5	120±6	2.2±0.5	223±15
Gilc–West	−0.3±0.1	3.1±0.4	136±8	1.1±0.4	243±21
Gilc–Kash	1.7±0.4	7.8±1.4	129±10	2.4±1.3	289±35
West–Ons	17.4±0.2	6.5±0.8	167±7	0.6±0.8	193±77
Wett–West	17.4±0.1	5.5±0.4	119±4	1.9±0.4	205±12
Fort–NRAO	4.6±1.7	4.4±1.3	132±17	1.7±1.2	96±40
Wett–Alg	17.6±1.5	10.5±9.0	114±33	6.0±4.7	53±44
Wett–NRAO	15.6±0.8	7.4±0.9	142±7	1.4±0.9	201±38
Wett–Gilc	10.0±0.4	5.4±0.7	111±7	3.4±0.7	257±11
Kok–NRAO	15.6±1.6	6.3±1.3	147±12	1.4±1.2	174±53
Kau–NRAO	13.8±0.9	6.3±1.4	135±12	1.0±1.4	182±80
Wett–Fort	18.6±2.2	5.1±1.7	120±17	0.9±1.5	250±101
Mat–NRAO	14.1±1.5	11.9±1.8	133±9	2.9±1.8	306±36
Wett–Rich	14.8±0.3	3.6±0.9	138±15	1.4±0.9	143±37
Gilc–Mat	2.3±1.6	9.2±1.8	129±12	3.2±1.8	287±31
Wett–Hart	−2.9±0.8	3.0±2.9	100±48	3.7±2.7	206±41
Wett–HRAS	14.0±0.7	7.9±1.7	167±11	0.9±1.6	148±99
Wett–Moj12	8.3±0.6	7.4±1.1	114±8	1.0±1.1	85±62
Hart–Hob26	32.9±2.7	13.1±5.1	323±23	2.4±5.3	112±125
Gilc–Fort	12.1±3.3	9.7±2.7	93±14	3.7±2.4	334±37
Wett–Kokee	−20.0±2.2	11.3±1.8	113±8	3.5±1.8	267±26
West–Hart	13.0±1.5	9.3±5.8	89±31	7.8±5.4	207±38
Gilc–Hob26	−34.9±1.9	8.4±5.0	319±35	16.4±4.8	335±17
Fort–Kokee	36.2±4.1	8.5±3.0	83±19	3.3±2.8	333±49

The semiannual signature does not show so obvious a correlation between amplitude and baselength. Moreover, for 10 baselines from the set under study the amplitude estimates are not meaningful. Figure 5 (right, bottom) shows the 'baselength–semiannual signature amplitude' plot and the last column of Table 3 contains the regression coefficients. It seems that the semiannual signature amplitude increases proportionally to the baselength too, but the dependence is not so clear as for the annual one. Probably, the effect is larger for high-latitude stations. For example, semiannual signatures are meaningful for all baselines with the Gilcreek station (latitude 64°). For the Gilcreek–Hobart26 baseline which has the largest latitude angular distance (106°) the effect exceeds 15 mm! The corresponding point is too far from the linear trend in Figure 5.

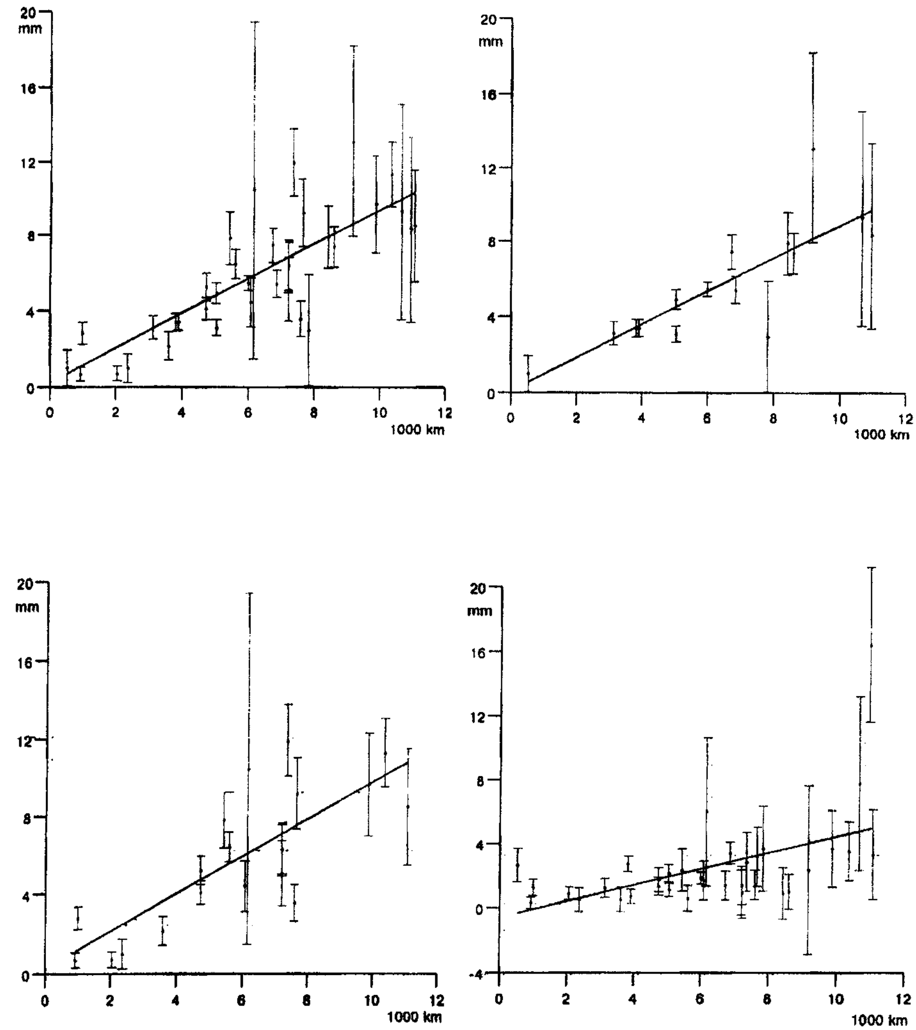

Figure 5 Baselength versus amplitude of annual signature for all 35 baselines (left, top), 15 baselines from inland sites only (right, top), 20 baselines with coastal stations (left, bottom) and of semiannual signature for 35 baselines (right, bottom). Error bars and linear trend are shown. The parameters of the linear trend are in Table 3.

It is important to determine the seasonal effects for individual VLBI site for a more thorough analysis. Unfortunately to do this research using original estimates of radial component variations from observational data is impossible due to the unexpected motion of the terrestrial reference system. Therefore we make use of the amplitudes and phases from Table 2 for this purpose. It is known that the radial components of a VLBI site are much more sensitive to atmospheric loading then horizontal ones. This allows us to make the hypothesis that the baselength variation

Table 3. Results of the parameter estimation linear trend $A(L) = c + kL$. A is the amplitude of the annual or semiannual signature; L is the baselength

Coefficient	*annual* *35 baselines*	*annual* *15 baselines* *(inland)*	*annual* *20 baselines* *(coast)*	*semiannual* *35 baselines*
c (mm)	-0.09 ± 0.40	0.15 ± 0.68	-0.17 ± 0.54	0.53 ± 0.20
k (mm/1000 km)	0.88 ± 0.09	0.83 ± 0.13	0.92 ± 0.14	0.21 ± 0.06

is a manifestation of the VLBI site radial motion only. This assumption distorts our estimates by little more than 2–3 mm. We describe below the mathematical approach in detail.

The baselength is given by

$$L^2 = r_2^2 + r_1^2 - 2r_2 r_1 \cos\psi \,, \tag{2}$$

where ψ is the angular distance from the Earth's centre between the directions of station 1 and station 2 (with radial components r_1 and r_2, respectively). The formula (2) helps us to separate the radial and horizontal components. Under the assumption that the seasonal variations in baselines arise from radial component instability only, we will accept that the angular distance ψ does not change. Small changes Δr_1 and Δr_2 will result in a correction ΔL to the baselength as follows:

$$\Delta l = \frac{1}{L}[(r_2 - r_1 \cos\psi)\Delta r_2 + (r_1 - r_2 \cos\psi)\Delta r_1] \,. \tag{3}$$

Let us accept in (3) that r_1 is approximately equal to r_2 and $r_1 \approx r_2 \approx r$, where r

Table 4. Amplitudes and phases for annual (h, φ) and semiannual (g, θ) harmonics. The symbol # means that the corresponding amplitude is not significant

Station	h (mm)	φ (degrees)	g (mm)	θ (degrees)
Wettzell	6.9±1.9	122±12	2.4±1.7	238±31
Gilcreek	4.6±3.0	98±14	3.3±1.9	304±32
Westford	5.8±2.0	138±20	3.0±2.2	207±31
Fortleza	4.4±2.5	83±12	1.7±2.9#	24±65
Kokee	6.4±2.6	103±15	2.0±2.6#	287±43
NRAO85 3	7.1±1.9	156±19	3.2±1.8	160±38
Onsala	6.0±2.3	172±31	2.2±3.8#	129±58
Matera	20.3±3.7	123±8	8.7±3.5	279±15
Richmond	2.3±2.7#	245±43	0.8±2.2#	28±73
HRAS085	5.7±2.4	168±29	1.0±2.8#	97±78
Mojave12	4.9±2.6	114±23	1.9±2.6#	27±55
Hartrao	4.9±2.9	30±20	7.8±2.2	174±22
Hobart26	15.3±4.0	307±14	11.1±2.4	352±19
Kauai	6.0±3.8	123±29	0.9±3.8#	317±77

is the radius of the Earth. Then

$$\Delta L = \frac{1}{L}[r(1-\cos\psi)\Delta r_2 + r(1-\cos\psi)\Delta r_1]\,. \tag{4}$$

Combining (2) and (4):

$$\Delta L = \frac{r(1-\cos\psi)}{r[2(1-\cos\psi)]^{1/2}}(\Delta r_1 + \Delta r_2) = \left(\frac{1-\cos\psi}{2}\right)^{1/2}(\Delta r_1 + \Delta r_2)\,. \tag{5}$$

In accordance with our assumption that the values Δr_1, and Δr_2, are oscillating functions of time

$$\Delta r_1 = h_1 \cos\left(\frac{2\pi}{P}t + \varphi_1\right) + g_1 \cos\left(\frac{4\pi}{P}t + \theta_1\right)\,, \tag{6a}$$

and

$$\Delta r_2 = h_2 \cos\left(\frac{2\pi}{P}t + \varphi_2\right) + g_2 \cos\left(\frac{4\pi}{P}t + \theta_2\right)\,, \tag{6b}$$

Therefore for every individual value ΔL from (5)

$$\begin{aligned} \Delta L &= \left(\frac{1-\cos\psi}{2}\right)^{1/2} \Big[(h_1\cos\varphi_1 + h_2\cos\varphi_2)\cos\frac{2\pi}{P} \\ &- (h_1\sin\varphi_1 + h_2\sin\varphi_2)\sin\frac{2\pi}{P} + (g_1\cos\theta_1 + g_2\cos\theta_2)\cos\frac{4\pi}{P} \\ &- (g_1\sin\theta_1 + g_2\sin\theta_2)\sin\frac{4\pi}{P}\Big]\,. \end{aligned} \tag{7}$$

Using expressions (1) and (7) one can establish the relationship between the parameters of the baseline and the radial components variations.

$$\begin{aligned} c\cos\varphi &= \left(\frac{1-\cos\psi}{2}\right)^{1/2}(h_1\cos\varphi_1 + h_2\cos\varphi_2)\,, \\ c\sin\varphi &= \left(\frac{1-\cos\psi}{2}\right)^{1/2}(h_1\sin\varphi_1 + h_2\sin\varphi_2)\,, \\ d\cos\theta &= \left(\frac{1-\cos\psi}{2}\right)^{1/2}(g_1\cos\theta_1 + g_2\cos\theta_2)\,, \\ d\sin\theta &= \left(\frac{1-\cos\psi}{2}\right)^{1/2}(g_1\sin\theta_1 + g_2\sin\theta_2)\,. \end{aligned} \tag{8}$$

The left side in (8) are the parameters of the seasonal baseline variation which have already been estimated in Table 2. For a single baseline we have eight unknowns on the right side of (8) and only four equations from the left side. Fortunately, in Table 2 there are enough baselines with common stations, therefore we are able to construct the system like (8) where the number of unknowns will be less than the number of equations and we can solve the system using conventional least squares methods.

The estimates of amplitudes and phases for both annual and semiannual harmonics are represented in Table 4. To decrease the effect of random error we do not save in (7) those stations which are part of the only baseline in Table 2. So results on 14 VLBI stations in Table 4 (Algopark, Kashima, and Medicina are not included) are shown.

3 DISCUSSION

Increasing both seasonal signatures proportionally to the baselength means that they are affected by variations of the site radial components (Figure 5). A similar conclusion has been reached for high-frequency baselength variations as well (vanDam and Herring, 1994; MacMillan *et al.*, 1994). But contrary to the latter, amplitudes of annual and semiannual signatures do not depend on the distance from the ocean coast. Therefore the inverted barometric effect (which reduces the contribution of high-frequency atmospheric pressure variations to total load) has no influence on the seasonal effect. It is known that the high-frequency displacements of the Earth arise mostly from variations of atmospheric pressure on the site and adjacent area (1000–2000 km) (vanDam and Herring, 1994). This means that there is a natural phenomenon causing the seasonal effects at distant places on the Earth's surface simultaneously.

This conclusion is confirmed by the distribution of annual signature phases from Table 4. For the majority of them (11 out of 14) the phase estimates are in the range 80–180° with a concentration in the range 120–130°. Due to the facts that Richmond does not show significant annual harmonic and Hartrao and Hobart26 are located in the Southern hemisphere one can deduce that all VLBI sites in the Northern hemisphere (including Fortaleza with latitude −4°) are lowered in the first part of the year and rise in the second part.

Amplitudes of the annual variations change from 4.4 to 7.1 mm exception Richmond (2.3 mm) and two stations which show surprisingly large estimates: Hobart26 (15.3 mm) and Matera (20.3 mm). It seems that an amplitude of 5–6 mm is the most typical value for annual deformation of vertical components. Two large estimates for Hobart26 and Matera should be studied thoroughly in the future. Perhaps, there are local reasons for increasing annual signal amplitude. The small value for Richmond can be explained by the non-standard mounting of the antenna system.

The presence of a semiannual signal is not so obvious in Table 4 because for seven stations (50%) the amplitude estimates are not significant. Matera and Hobart26 again show extremely large amplitude. It seems that the typical amplitude of the semiannual harmonic (1–3 mm) is less than the annual one and cannot always be found on the modern level of observational precision. Nevertheless, any theoretical model will have to explain the existence of both annual as well as semiannual signals in the spectrum of vertical component variations.

Formal errors of amplitude estimates in Table 4 do not exceed 4 mm. A typical value of the error is 2–3 mm and corresponds to our assumption about the stability of the VLBI station horizontal components. Thus the accuracy level is the limit of our approach under the accepted assumptions.

Let us to consider briefly three alternative explanations of the seasonal variations.

1. *Snow loading.* Recently it has been shown that snow cover with a height of more than 30 cm and a radius of 100 km around the site of observations reduces the quasi-geoid level by up to 12 mm (Bakulevich and Dvulit, 1995). It seems that the effect should be taken into account for VLBI stations at middle- and high-latitudes. But it does not explain the displacement of stations close to equatorial zones.

2. *Vertical motion of the concrete tower due to seasonal variations of the surrounding air temperature.* For example, since summer 1996 special devices for monitoring of concrete tower temperature have been installed in the Onsala VLBI station. Observations show that the amplitude of yearly variations could reach 5 mm with a maximum in July (temperature +30 °C) and a minimum in January (−10 °C) (Elgered, 1996). The result is in a good accordance with information about the station from Table 4. However, some VLBI stations with similar amplitudes of vertical deformation are located in regions where there is not so large a temperature change from winter to summer (Fortaleza, for example).

3. *Insufficiency of tropospheric model.* It is known that geodetic VLBI results are affected by dry and wet components of the tropospheric model (for example, Fisher *et al.*, 1987). Moreover, errors at low elevation angles may be a reason for seasonal variations of vertical VLBI site components. The effect could reach 35 mm for Gilcreek (Niell, 1991). It is obvious that the insufficiency of the tropospheric model does not depend on the latitude of the VLBI site and the adjacency of a large mass of water, therefore, it could be a strong alternative for the appearance of a global seasonal effect in vertical VLBI site components. Niell (1996) constructed an advanced mapping function which takes into account both latitude and seasonal dependencies. Implementation of the model in packages for VLBI data analysis will help to check the suggestion against the alternative.

4 CONCLUSION

Applying spectral analysis to the set of 35 baselines we have found variations of their lengths with periods 1 and 0.5 year. Variations of VLBI site radial components are responsible for the effect because the amplitudes of the seasonal variations increase with baselength. The following expression introduces the 'baselength-annual signature amplitude' slope:

$$A(L) = -0.09 + 0.88L\,. \tag{9}$$

The estimated coefficients of the linear trend do not depend essentially on the distance of an individual station from the ocean coast. Therefore the inverted barometer effect is not likely to reduce the contribution of annual pressure variations to the station displacement. Moreover, the phase estimates concentrate in a very narrow span for VLBI sites in the Northern hemisphere. These results indicate that the annual signature is affected by any global natural process.

As to the semiannual signature there is not so strong confidence that it is a global effect. However it is powerful enough for a few baselines, especially. The corresponding relationship like (9) is given by

$$A(L) = 0.53 + 0.21L\,. \tag{10}$$

To point out now a reason of the seasonal variations in baselengths is still difficult. The annual signal could have arisen from a variety natural phenomena with period 1 year which are able to contribute to the total loading effect. Fortunately, the discovery of a semiannual signal indicates that any theoretical hypothesis should predict the occurrence of a signal with period 0.5 year. It seems that seasonal transferring of atmospheric mass is the most appropriate explanation of the effect. However, concrete tower temperature variations as well as snow loading could make an essential contribution to total load for stations at middle and high latitudes. Probably, several natural phenomena mix together in order to initiate the effect under study. Therefore we cannot say that the estimates from Table 4 reflect any separate natural process.

Actually, the parameters of seasonal variations for individual VLBI sites change from year to year. Following our approach the amplitudes and phases from Table 4 are smoothed or 'averaged' on the whole time span. Therefore it is too early to recommend them for reduction calculations during observational data processing. Nevertheless, they could be very useful for checking and interpretation of other observational results.

We conclude that the seasonal variations of VLBI site radial components as well as baselengths are real. They should be taken into account when the motion of tectonic plates is analysed. Otherwise, the estimates of VLBI site velocities can be biased, especially, for sparse time series.

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