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Analyses on the Time Series of the Radio Telescope Coordinates of the IVS-R1 and -R4 Sessions

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ABSTRACT: In this study, we investigate the coordinate time series of the radio telescopes which regularly take part for IVS-R1 and –R4 sessions. Firstly, we determine the deterministic parts of the series such as linear trend (velocity vectors of the antenna coordinates) due to e.g. crustal movements. Linear trends of the coordinate time series are estimated by least square (LS), fitting the coefficients of a linear regression function. After removing the linear trend from the series, sinusoidal (harmonic) variations of the series if they exist are determined by estimating the amplitude and phase of the Fourier series based on the frequency of the maximum spectral density (power) in the respective spectra plot (periodogram). To sample the data evenly linear interpolation is used. The spectral density of the data is produced by Fast Fourier Transform based on Discrete Fourier Transform. Most of the antennas harmonic variations are not found. Also, the amplitudes of the detected variations are small in ranges between 0.4 - 0.1 mm. This may be caused by the artifacts of the data interpolation or the data it self may not consist any harmonic variations. Because the geophysical models are already applied to the downloaded data (daily sinex normal equations of VLBI sessions provided by Deutsches Geodatisches Forschungsinstitut (DGFI)) except the models of atmosphere loading and thermal deformation.

The determination and removal of the offsets and linear trends (velocities) of coordinates is carried out by LS fit to the linear function.

$$X_t = a_0 + a_1(t - t_0) + \varepsilon_t \qquad (1)$$

where a_0 is the offset with respect to the mean coordinate value of the year, and a_1 is the trend and ε_t are the residuals (Chatfield, 2004). The estimated parameters are divided by their standard deviations represent a $t-$ statistics with f degrees of freedom. If a parameter is to be judged as statistically different from zero, and thus significant, the computed t value (the test statistic) must be greater than $t_{1-\alpha,f}$, where $1-\alpha$ is the level of confidence. Simply stated, the test statistic is

$$t = \frac{|parameter|}{S} \qquad (2)$$

where S is the standard deviation of the parameter. Table 1 shows the site velocities (trends) for the sites of which have adequate estimates (about 50 coordinate estimates per year) also for detecting annual and semi-annual tidal variations.

Sitename	Year	V_{north}(cm)	V_{east}(cm)	V_{up}cm)	mvn(cm)	mve(cm)	mvu(cm)	num_est	Test(N)	Test(E)	Test(U)	t	Significance
ALGOPARK	2001	0.32	-1.68	0.31	0.04	0.02	0.01	57	8.86	77.76	24.47	1.67	+ + +
ALGOPARK	2002	-0.04	-1.76	0.23	0.05	0.03	0.02	67	0.72	59.59	14.43	1.67	- + +
ALGOPARK	2003	0.16	-1.62	0.24	0.04	0.03	0.02	55	3.73	51.45	10.10	1.67	+ + +
ALGOPARK	2005	0.17	-1.61	0.28	0.04	0.03	0.02	68	4.16	54.82	14.15	1.67	+ + +
FORTLEZA	1995	1.19	-0.42	0.01	0.04	0.05	0.03	56	33.02	8.86	0.25	1.67	+ + -
FORTLEZA	1996	1.25	-0.49	-0.04	0.05	0.05	0.03	59	22.88	9.53	1.32	1.67	+ + -
FORTLEZA	1998	1.29	-0.58	-0.05	0.08	0.06	0.04	53	15.79	8.93	1.26	1.68	+ + -
FORTLEZA	1999	1.12	-0.48	0.01	0.05	0.04	0.03	60	23.12	10.95	0.47	1.67	+ + -
FORTLEZA	2001	0.89	-0.29	0.12	0.05	0.05	0.03	59	17.15	5.32	4.08	1.67	+ + +
FORTLEZA	2003	1.11	-0.43	-0.00	0.06	0.06	0.04	49	17.24	7.03	0.00	1.68	+ + -
FORTLEZA	2005	1.18	-0.27	0.01	0.07	0.10	0.06	52	17.10	2.77	0.20	1.68	+ + -
FORTLEZA	2006	1.03	-0.20	0.11	0.07	0.09	0.04	59	14.91	2.25	2.72	1.67	+ + +
FORTLEZA	2007	1.28	-0.27	-0.01	0.04	0.07	0.03	72	30.48	3.82	0.32	1.67	+ + -
FORTLEZA	2008	1.16	-0.48	0.08	0.07	0.09	0.06	56	16.00	5.22	1.40	1.67	+ + -
GILCREEK	1994	-2.07	-0.93	0.25	0.05	0.04	0.05	64	41.44	23.94	5.25	1.67	+ + +
GILCREEK	1996	-2.30	-0.67	-0.02	0.07	0.06	0.07	66	34.02	11.51	0.30	1.67	+ + -
GILCREEK	1997	-2.12	-0.76	0.17	0.07	0.04	0.07	59	29.65	17.53	2.42	1.67	+ + +
GILCREEK	1998	-2.02	-0.93	0.16	0.06	0.04	0.05	75	34.69	23.51	3.22	1.67	+ + +
GILCREEK	1999	-1.83	-0.80	0.36	0.09	0.05	0.06	59	20.71	17.29	5.57	1.67	+ + +
GILCREEK	2001	-2.08	-0.78	0.25	0.08	0.05	0.08	63	26.65	16.79	3.13	1.67	+ + +
GILCREEK	2002	-5.42	0.94	1.28	0.45	0.18	0.13	101	12.00	5.11	9.78	1.66	+ + +
GILCREEK	2003	-2.57	-0.72	-0.03	0.02	0.01	0.02	99	130.21	57.37	1.27	1.66	+ + -
GILCREEK	2004	-2.13	-0.72	0.24	0.05	0.05	0.06	82	41.25	15.20	4.04	1.66	+ + +
GILCREEK	2005	-2.39	-0.86	0.15	0.04	0.03	0.04	96	62.91	29.70	3.43	1.66	+ + +
KOKEE	1994	3.21	-6.29	-0.02	0.08	0.04	0.06	52	41.31	145.14	0.33	1.68	+ + -
KOKEE	1995	3.30	-6.46	0.03	0.05	0.07	0.07	61	62.26	87.69	0.43	1.67	+ + -
KOKEE	1996	3.08	-5.95	-0.21	0.08	0.10	0.07	90	39.33	59.24	3.04	1.66	+ + +
KOKEE	1997	3.04	-6.17	-0.01	0.11	0.09	0.10	62	27.77	70.19	0.12	1.67	+ + -
KOKEE	1998	3.15	-5.95	-0.20	0.06	0.07	0.05	70	48.55	81.61	3.92	1.67	+ + +
KOKEE	1999	3.36	-6.17	-0.15	0.09	0.09	0.08	79	35.69	68.45	1.91	1.66	+ + +
KOKEE	2000	3.28	-6.36	0.02	0.20	0.11	0.17	57	16.16	55.90	0.13	1.67	+ + -
KOKEE	2001	3.25	-6.24	-0.14	0.06	0.05	0.05	89	52.60	137.26	2.63	1.66	+ + +
KOKEE	2002	3.19	-6.24	-0.05	0.07	0.03	0.05	79	44.27	179.32	1.01	1.66	+ + -
KOKEE	2003	3.44	-6.32	-0.06	0.08	0.04	0.06	78	40.87	141.07	1.08	1.67	+ + -
KOKEE	2004	3.27	-6.29	-0.04	0.14	0.08	0.10	62	22.80	79.71	0.38	1.67	+ + -
KOKEE	2005	3.43	-6.22	-0.10	0.06	0.05	0.04	95	53.16	121.40	2.52	1.66	+ + +
KOKEE	2006	3.61	-6.19	-0.14	0.13	0.08	0.08	79	26.97	74.77	1.77	1.66	+ + +
KOKEE	2007	3.51	-6.35	-0.09	0.06	0.05	0.05	92	63.36	137.82	1.79	1.66	+ + +
KOKEE	2008	3.29	-6.28	-0.20	0.08	0.06	0.05	86	42.58	104.90	3.85	1.66	+ + +
MATERA	2002	1.79	2.26	-0.08	0.04	0.03	0.02	62	40.31	74.56	3.67	1.67	+ + +
MATERA	2003	1.81	2.36	-0.11	0.04	0.02	0.02	68	50.09	120.29	6.41	1.67	+ + +
NYALES20	2001	1.54	1.03	0.78	0.04	0.02	0.07	74	42.97	44.64	11.63	1.67	+ + +
NYALES20	2002	1.54	1.00	0.70	0.01	0.01	0.04	93	103.10	79.07	17.66	1.66	+ + +
NYALES20	2003	1.46	1.14	0.88	0.02	0.02	0.07	58	65.73	72.95	12.77	1.67	+ + +
NYALES20	2004	1.52	1.04	0.85	0.04	0.02	0.11	60	42.64	48.41	8.07	1.67	+ + +
NYALES20	2005	1.54	1.16	0.87	0.03	0.01	0.07	79	61.71	102.45	13.26	1.66	+ + +
NYALES20	2006	1.59	1.06	0.76	0.04	0.03	0.08	52	39.11	40.52	10.10	1.68	+ + +
NYALES20	2007	1.50	1.11	0.70	0.04	0.02	0.08	53	41.64	66.67	8.82	1.68	+ + +
NYALES20	2008	1.36	1.19	0.35	0.06	0.05	0.15	56	24.77	25.52	2.37	1.67	+ + +
SVETLOE	2005	0.94	2.02	0.07	0.07	0.05	0.06	51	13.17	39.51	1.24	1.68	+ + -
TIGOCONC	2003	1.76	3.16	0.21	0.09	0.05	0.05	82	19.56	61.73	4.16	1.66	+ + +
TIGOCONC	2004	1.98	3.46	-0.10	0.16	0.07	0.09	58	12.33	46.30	1.04	1.67	+ + -
TIGOCONC	2005	2.13	3.57	-0.46	0.14	0.06	0.07	92	15.69	60.37	6.95	1.66	+ + +
TIGOCONC	2006	1.91	3.54	-0.20	0.06	0.04	0.03	91	34.23	91.25	6.02	1.66	+ + +
TIGOCONC	2007	1.80	3.36	-0.13	0.07	0.05	0.03	90	24.25	66.88	4.09	1.66	+ + +
TIGOCONC	2008	1.47	3.43	-0.14	0.12	0.10	0.08	67	12.51	35.46	1.80	1.67	+ + +
WESTFORD	2001	0.19	-1.57	-0.03	0.06	0.06	0.04	52	3.43	24.26	0.70	1.68	+ + -
WESTFORD	2002	0.24	-1.59	-0.06	0.03	0.02	0.01	74	7.29	96.46	5.46	1.67	+ + +
WESTFORD	2003	0.35	-1.53	-0.04	0.05	0.02	0.02	65	7.78	64.60	2.19	1.67	+ + +
WESTFORD	2004	0.27	-1.51	-0.06	0.04	0.03	0.03	59	6.09	49.66	2.49	1.67	+ + +
WESTFORD	2005	0.19	-1.56	0.06	0.06	0.05	0.03	63	2.87	31.40	1.91	1.67	+ + +
WESTFORD	2006	0.22	-1.59	-0.04	0.08	0.04	0.03	55	2.69	36.68	1.09	1.67	+ + -
WESTFORD	2007	0.24	-1.53	-0.00	0.04	0.03	0.02	50	6.70	50.52	0.09	1.68	+ + -
WESTFORD	2008	0.28	-1.51	-0.03	0.06	0.04	0.04	53	4.44	34.77	0.82	1.68	+ + -
WETTZELL	1994	1.55	1.94	-0.14	0.04	0.03	0.03	67	39.89	71.17	4.63	1.67	+ + +
WETTZELL	1995	1.20	1.93	-0.17	0.06	0.06	0.03	66	19.15	33.87	5.89	1.67	+ + +
WETTZELL	1996	1.46	2.26	-0.10	0.04	0.06	0.02	87	35.36	37.00	4.88	1.66	+ + +
WETTZELL	1997	1.43	2.16	-0.06	0.04	0.03	0.03	57	37.54	72.80	2.36	1.67	+ + +
WETTZELL	1998	1.46	2.05	-0.14	0.05	0.04	0.03	53	27.76	58.46	4.34	1.68	+ + +
WETTZELL	1999	1.29	1.97	-0.17	0.08	0.05	0.04	60	16.94	36.39	4.73	1.67	+ + +
WETTZELL	2000	1.35	2.01	-0.16	0.07	0.04	0.05	61	18.78	45.80	3.34	1.67	+ + +
WETTZELL	2001	1.40	2.04	-0.13	0.03	0.02	0.02	93	46.71	96.46	5.62	1.66	+ + +
WETTZELL	2002	1.38	2.02	-0.09	0.02	0.01	0.01	118	84.77	192.98	7.72	1.66	+ + +
WETTZELL	2003	1.38	2.14	-0.00	0.02	0.01	0.01	116	87.68	234.89	0.19	1.66	+ + -
WETTZELL	2004	1.44	2.14	-0.07	0.03	0.02	0.02	105	44.55	121.51	3.89	1.66	+ + +
WETTZELL	2005	1.48	2.08	-0.04	0.02	0.01	0.01	131	70.09	151.95	3.45	1.66	+ + +
WETTZELL	2006	1.53	2.03	-0.04	0.02	0.01	0.01	119	78.05	140.71	3.54	1.66	+ + +
WETTZELL	2007	1.41	2.02	-0.13	0.02	0.01	0.01	110	82.89	223.09	11.48	1.66	+ + +
WETTZELL	2008	1.37	2.02	-0.07	0.02	0.01	0.01	112	76.10	135.74	6.64	1.66	+ + +
ZELENCHK	2006	1.11	2.61	0.63	0.10	0.05	0.03	51	11.42	51.35	21.69	1.68	+ + +
ZELENCHK	2008	0.76	2.48	0.55	0.07	0.07	0.03	56	10.29	35.30	17.73	1.67	+ + +

Table 1. Velocities

In total, 17 radio telescope sites which have consistently taken part in most of the sessions from the beginning of 1994 to end of 2008 are included in our study. In Figure 1, the 17 VLBI sites that participated in the IVS-R1 and IVS-R4 24 hour (daily) sessions are shown. Figure 2 shows north, east and up components of the yearly site velocities and respective years are plotted.

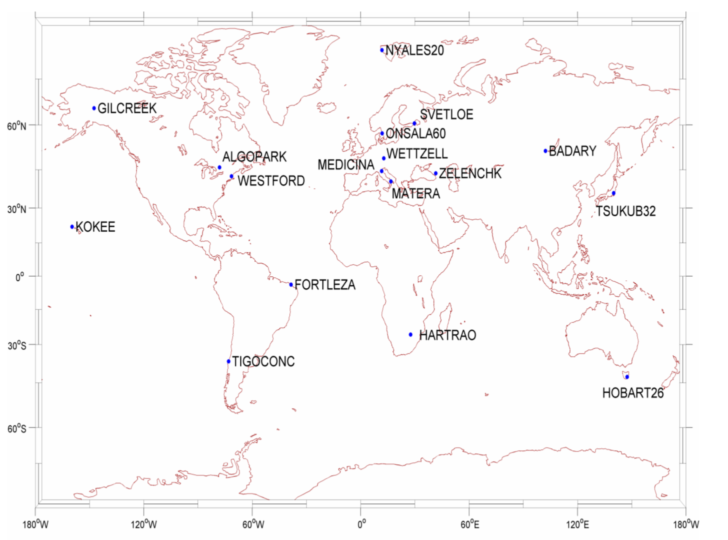


Figure 1. VLBI radio telescopes of IVS-R1 and R4 sessions

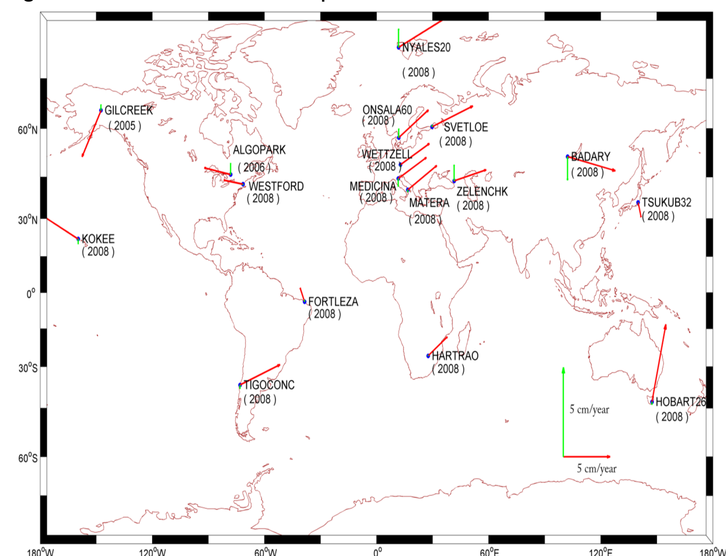


Figure 2. Site velocities

The velocities estimated in this study are almost equal to the ITRF 2005. Table 2 shows the north, east and up components of the some antenna velocities of ITRF 2000 at epoch 1997.0 .

Site name	ITRF 2000 at epoch 1997.0 v_{north} [cm]	v_{east} [cm]	v_{up} [cm]	from IVS-R1 and -R4 sessions v_{north} [cm] (year)	v_{east} [cm] (year)	v_{up} [cm] (year)
Algopark	0.13	-1.66	0.23	0.17 (2005)	-1.61 (2005)	0.23 (2002)
Fortaleza	1.21	-0.43	0.09	1.16 (2008)	-0.48 (2008)	0.11 (2006)
Kokee	3.24	-6.24	-0.08	3.29 (2008)	-6.46 (1995)	-0.09 (2007)
Matera	1.81	2.37	-0.10	1.81 (2003)	2.36 (2003)	-0.11 (2003)
Wettzell	1.44	2.03	-0.09	1.37 (2008)	2.02 (2008)	-0.07 (2008)

Table 2. Comparison between ITRF2000 and estimated velocity vectors

The Earth Centred Earth Fixed (ECEF) coordinates of the radio telescopes are estimated with minimum constrained Least Squares adjustment from the daily sinex normal equations of VLBI sessions provided by Deutsches Geodatisches Forschungsinstitut (DGFI). The respective a priori station coordinates are computed from the coordinates of 25 globally distributed stations constrained to have NNR and NNT w.r.t. ITRF2000.

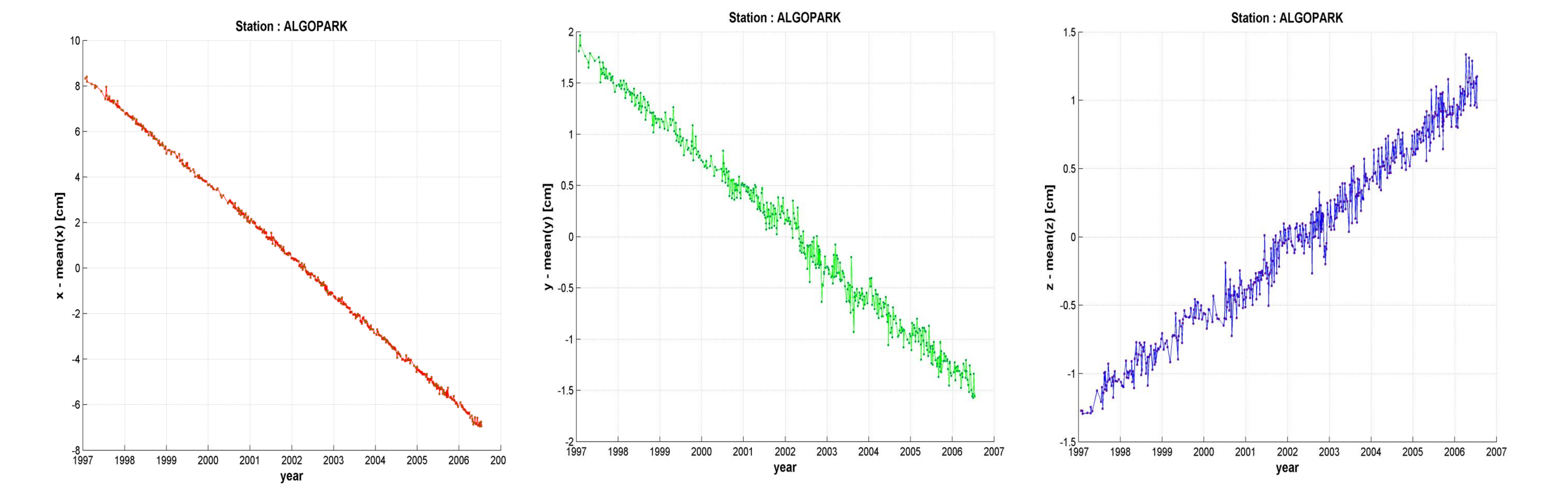


Figure 3. Time series of the station coordinates of Algopark

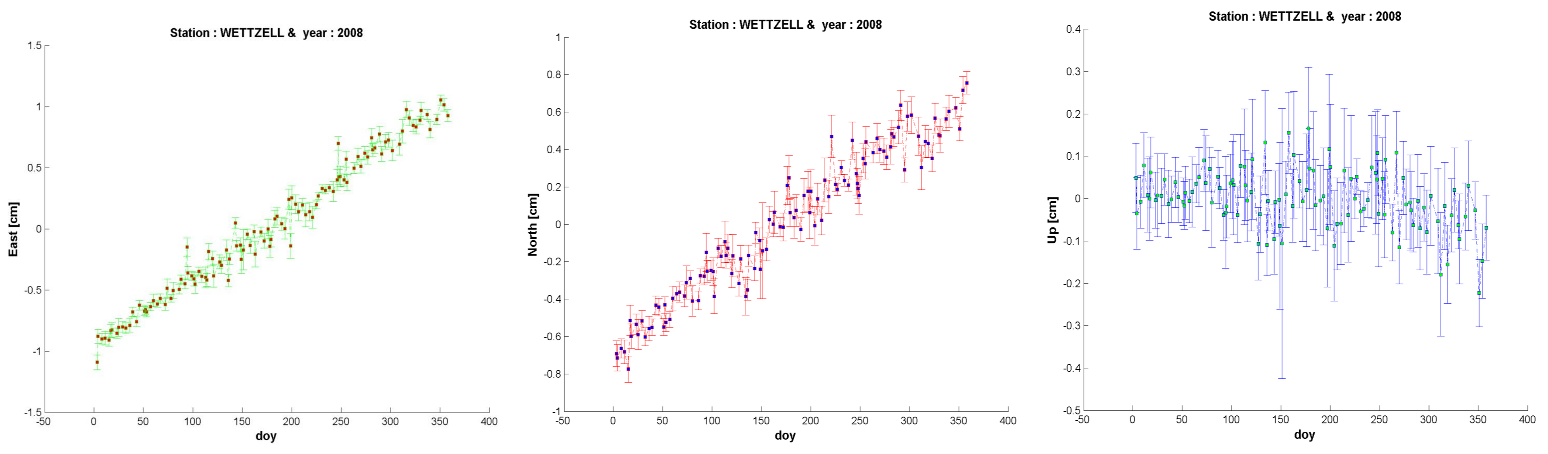
The adjusted ECEF (ITRF2000) coordinates are transformed to the local topocentric coordinates as:

$$\begin{bmatrix} N \\ E \\ U \end{bmatrix} = T * \begin{bmatrix} X - X_{mean} \\ Y - Y_{mean} \\ Z - Z_{mean} \end{bmatrix} \quad (4) \qquad T = \begin{bmatrix} -\sin\varphi\cos\lambda & -\sin\varphi\sin\lambda & \cos\varphi \\ -\sin\lambda & \cos\lambda & 0 \\ \cos\varphi\cos\lambda & \cos\varphi\sin\lambda & \sin\varphi \end{bmatrix} \quad (5)$$

estimation of respective covariances

$$Q_{NEU} = T * Q_X * T^T \qquad Q_{NEU} = \begin{bmatrix} q_{NN} & q_{NE} & q_{NU} \\ & q_{EE} & q_{EU} \\ & & q_{UU} \end{bmatrix}$$

λ : longitude of station $\qquad \varphi$: latitude of station



For further investigations of the coordinates to examine if they contain any sinusoidal variations after the removal of the significant trends from series spectral analysis should be carried out. However, in Figure 5 from the time series of local topocentric coordinates of the site Svetloe, for year 2008 there is no significant trend in the up direction which means that directly cyclic variations should be investigated for these kinds of series without removing the insignificant trend estimate.

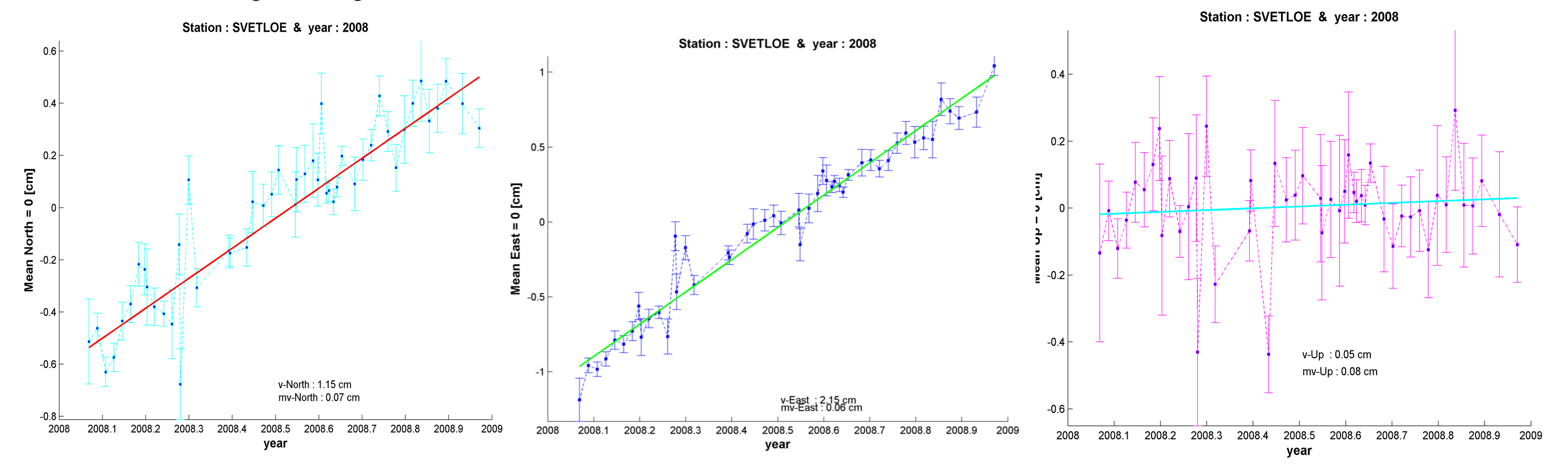


Figure 5. Time series of local topocentric coordinates of the site Svetloe

TIME SERIES ANALYSIS OF COORDINATES:

After reduction linear trend the resulted stationary series are analysed by means of detecting harmonics. This single spectral analysis approach known as auto spectral analysis based on the detection of the maximum power and respective frequency. The procedure is carried out iteratively eliminating the maximum amplitude up to reaching noise floor (Schuh, 1981).

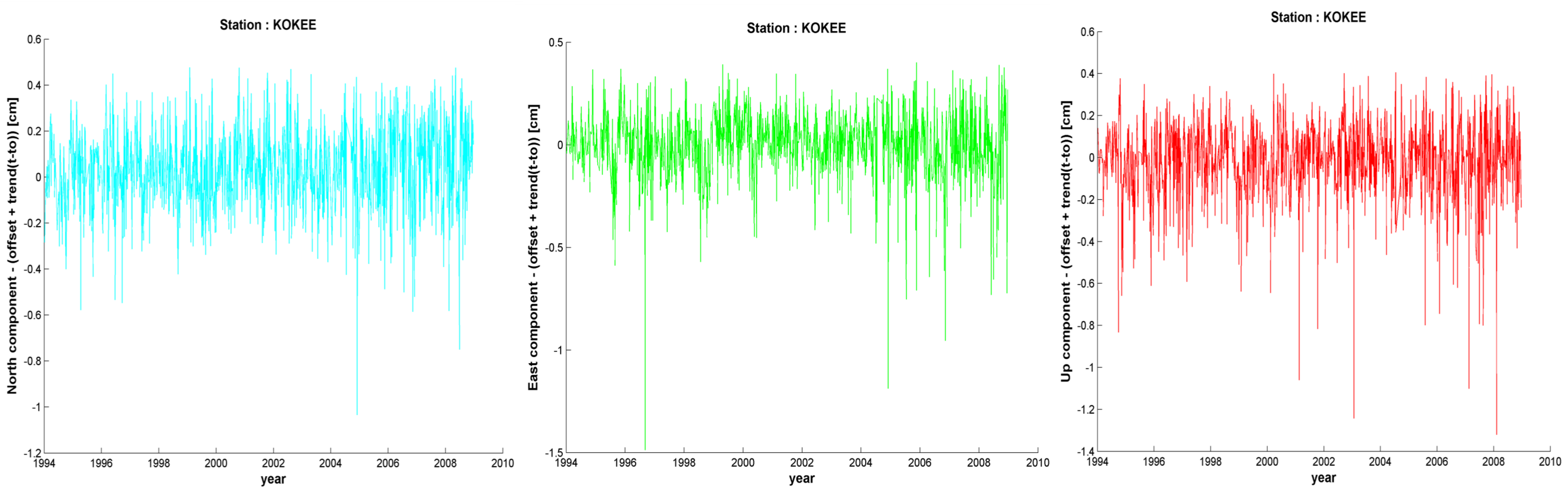


Figure 5. Kokee radio telescope coordinate series cleaned from trends

In case a time series contains a periodic sinusoidal component with a known wavelength (frequency) the model will be

$$X_t = \sum_{p=1}^{k} R_p \cos(\omega_p t + \Phi_p) + Z_t \qquad (6)$$

ω : the sinusoidal variation; R : amplitude of the variation; Φ : phase; $\{Z_t\}$ stationary random series

$$\cos(\omega + \Phi) = \cos\omega t \cos\Phi - \sin\omega t \sin\Phi \qquad b_p = -R_p \sin\Phi_p \qquad a_p = R_p \cos\Phi_p$$

$$X_t = \sum_{p=1}^{k} (a_p \cos\omega_p t - b_p \sin\omega_p t) + Z_t \qquad (7)$$

$$R_p = \sqrt{a_p^2 + b_p^2} \qquad \Phi_p = \tan^{-1}(-b_p / a_p) \qquad (8)$$ amplitude and phase of the variations of p th harmonics

If we are interested in variation at low frequency of 1 cycle per year, then we should at least 1 year's data in which case the lowest (fundamental) frequency we can fit is at 1 cycle per year. In other words, the lowest frequency covers the longest time period over the data. The lowest frequency depends on N which is the total number of the pairs of amplitudes of the harmonic analysis. The Nyquist frequency is the highest angular frequency (π) about which we can get meaningful information from a set of data. The Fourier series representation of the data is normally evaluated at the frequencies ($2\pi/N$) of provided from the fundamental ($\omega_p = 2\pi p/N$) frequency by multiplying the integers, $p = 1,...,N/2$ called as Harmonics (Chatfield, 2004).

The coordinate time series of the VLBI antennas produced from the daily sinex normal equations of IVS-R1and -R4 sessions are unevenly spaced. As an example, sampling intervals are shown in Figure 6 for the antenna Wettzell. The mean of the sampling interval (e.g. antenna Wettzell up component 4 days) is used for producing the fundamental frequency (the maximum period data can produce).

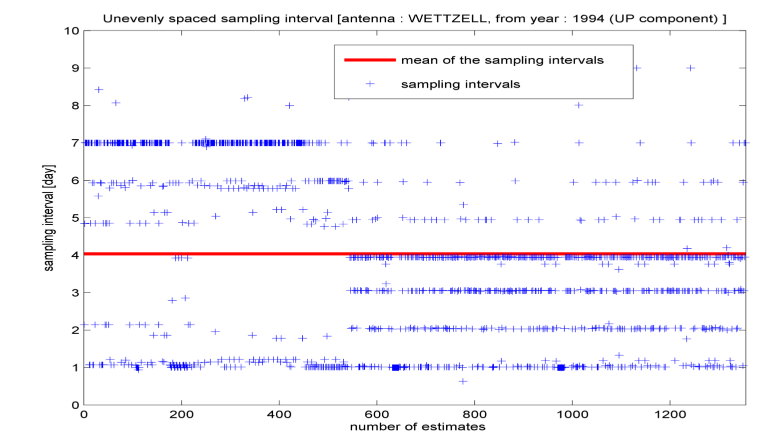


Figure 6. sampling interval of the antenna Wettzell coordinate timeseries

To form evenly spaced data linear interpolation (Trauth, 2007) is applied depending on the evenly-spaced (mean of the sampling interval) time axis (Figure 7). For the unevenly spaced data it seems to be impossible to prevent artifacts and spurious cycyles on the results to some extend since it is not possible to stay with in the range of the original data with any interpolation method..

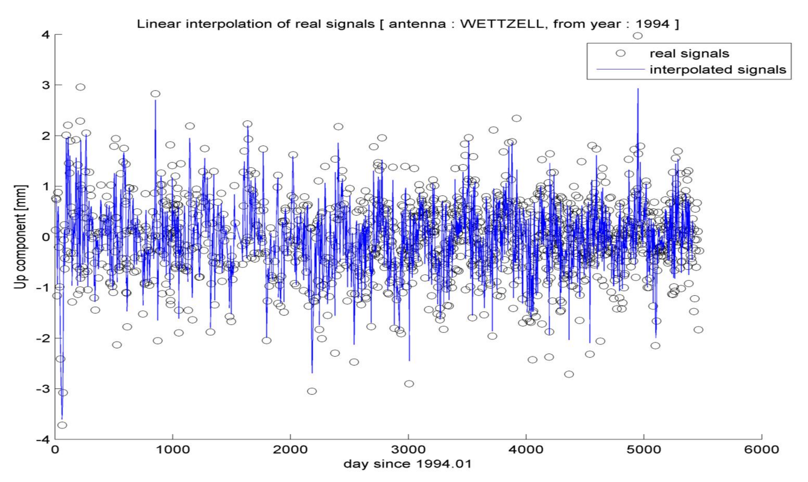


Figure 7. Resampling the data

The power spectral density of the time series is computed by Fast Fourier Transform (Brigham, 1988) and ploted in Figure 8.

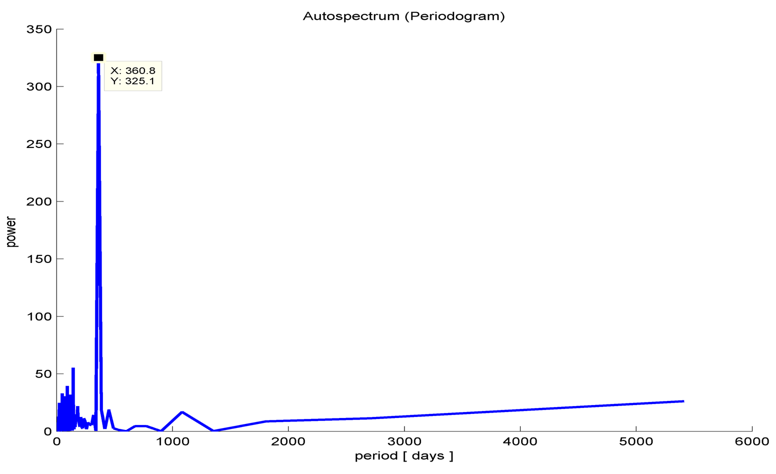


Figure 8. Autospectrum on the time series of the up component of the antenna Wettzell for the first iteration

The Fourier series (Eq.7) coefficients are estimated according to the period (360.8 days (fs = 0.00277)) of maximum power with least squares. With the coefficients of the Fourier Series amplitude and phase of the maximum cyclic variation is provided (Eq.8). The amplitude and phase are found out 0.35 mm and -45.21°, respectively for the Wettzell up component. The Fourier series and the signal is shown in Figure 9.

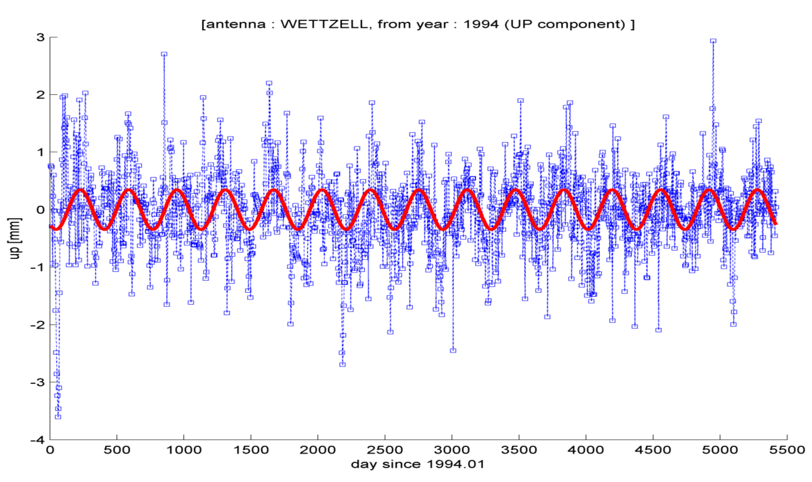


Figure 9. The Fourier Series of the cyclic component that have the maximum power

After the removal of the sinusoidal component from data (Figure 10) depending on the new period (360.8 days) the spectra of the residual is produced again (Figure 11). In every step harmonics are removed from the data based on the frequency of maximum power.

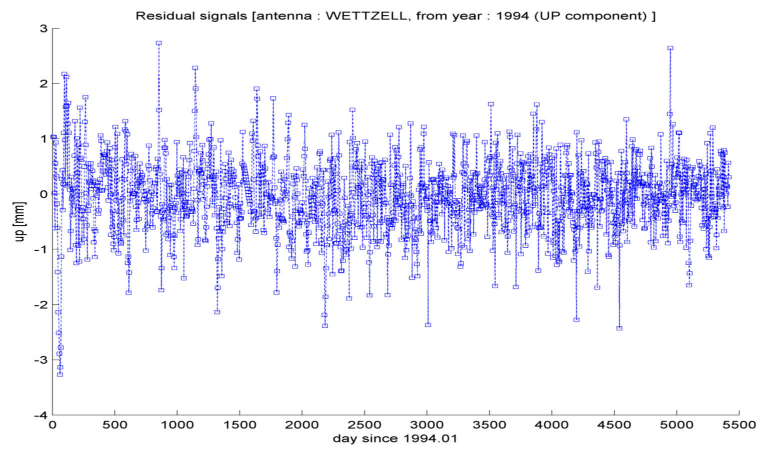


Figure 10. The remaining part of the time series - up component of the station Wettzell after eliminating the sinusoid of the first iteration

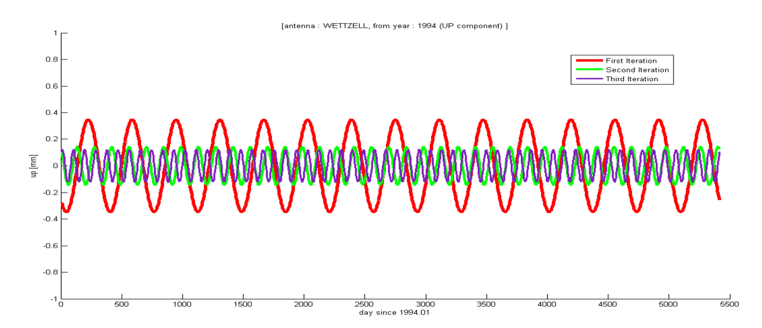


Figure 11. The significant sinusoids on the up component of Wettzell

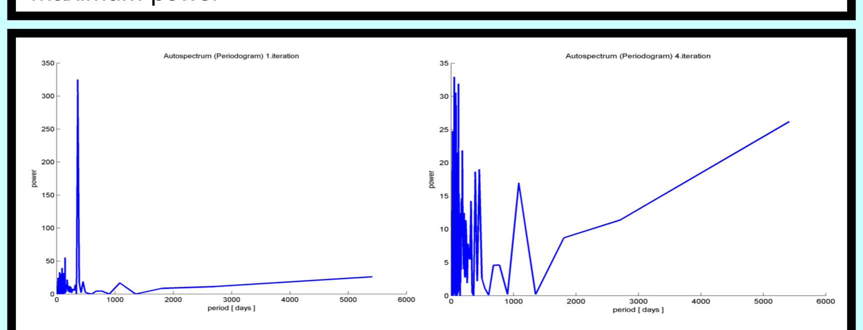


Figure 12. Spectra of first and last iteration for antenna Wetzell up component

Iteration (Up)	Amplitude (mm)	Phase (°)	Period (day)	Iteration (East)	Amplitude (mm)	Phase (°)	Period (day)	Iteration (North)	Amplitude (mm)	Phase (°)	Period (day)
Algopark (time interval : 2002.01 – 2006.53, number of data : 262)											
1	0.21	59.4	411.2	1	0.30	-47.6	205.6	1	0.21	-1.1	234.9
2	0.25	72.9	328.9	-	-	-	-	2	0.17	-25.9	31.0
Fortaleza (time interval : 1999.02 – 2008.9, number of data : 525)											
-	-	-	-	1	0.13	-37.2	325.8	1	0.12	24.3	155.8
Kokee (time interval : 1994.01 – 2008.9, number of data : 1129)											
1	0.17	-50.2	454.5	-	-	-	-	-	-	-	-
Nyales20 (time interval : 1996.03 – 2008.9, number of data : 723)											
1	0.16	6.05	196.4	-	-	-	-	-	-	-	-
Westford (time interval : 2002.0 – 2008.9, number of data : 417)											
1	0.25	-19.1	360.9	1	0.21	76.9	210.6	1	0.66	-41.9	360.9
2	0.21	13.8	148.6	-	-	-	-	2	0.43	-27.4	2526.9
3	0.16	76.7	84.2	-	-	-	-	3	0.25	-30.5	93.6
4	0.12	72.2	126.3	-	-	-	-	-	-	-	-
5	0.11	-48.7	53.8	-	-	-	-	-	-	-	-
Wettzell (time interval : 1994.0 – 2008.9, number of data : 1353)											
1	0.35	-45.2	360.8	1	0.18	-53.1	1819.6	1	0.24	-36.6	5458.9
2	0.13	54.9	143.6	2	0.14	-33.7	341.2	-	-	-	-
3	0.04	20.0	92.5	3	0.13	72.8	779.8	-	-	-	-
-	-	-	-	4	0.12	41.0	1364.7	-	-	-	-

Table 3. Significant harmonics of the antenna coordinates

CONLUSIONS:

- VLBI antenna coordinate velocities produced from IVS-R1 and –R4 sessions are approximately the same with the ITRF 2000 velocities of the same sites.
- After removing the linear trend from the series, sinusoidal (harmonic) variations of the series (tidal variations of the antenna coordinates) if they exist are determined by estimating the amplitudes and phase of the Fourier series based on the frequency of the maximum spectral density (power) in the respective spectra plot (periodogram).
- In most of the antennas harmonic variations are not found.
- The amplitudes of the detected variations are small in ranges between 0.4 - 0.1 mm. This may be caused by the artifacts of the data interpolation carried out linearly or the data itself because of the un-modeled geophysical parts of the a priori coordinates derived.
- The derived data daily sinex normal equations of VLBI sessions provided by DGFI has already been modeled as a priori by certain geophysical models (e.g. troposphere, solid Earth tide, ocean loading, and pole tide) except atmosphere loading and thermal deformation.

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