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 in IVS-R1 and -R4 sessions. Firstly, we determine the linear trend (velocity vectors of the antenna coordinates) due to e.g. plate tectonics. The trends of the coordinate time series are estimated by Least Squares (LS), fitting the coefficients of a linear regression function. After removing the linear trend from the series, sinusoidal variations of the series, if they exist, are determined by estimating the amplitudes and phase of the Fourier series based on the frequency of the maximum power spectral density in the respective spectra plot (periodogram). In order to sample the data, evenly linear interpolation is used. The spectral density of the data is produced by Fast Fourier Transform (FFT). For most of the investigated radio telescope time series, harmonic variations are not found. The significant periods of the up components ranges from ≈ 50 to ≈ 450 days and differ for each antenna. The amplitudes of the detected variations are small, in ranges between 0.4 - 0.1 mm. Many geophysical models had been applied to the data (daily sinex normal equations of VLBI sessions were provided by Deutsches Geodatisches Forschungsinstitut (DGFI)) except the models of atmosphere loading and thermal deformation.

Keywords. VLBI radio telescope coordinate time series, harmonic analysis, IVS -R1 and -R4 sessions.

1 Introduction

Several studies have been performed in the last ten years to individuate harmonic site position variations by VLBI (Titov & Yakovleva, 1999; Petrov & Ma, 2003; Tesmer et al., 2007). All these studies detected annual signals in VLBI baseline length time series and also a semiannual signature has been determined on some baselines. A more complete study has been published by Collilieux et al., 2007 comparing ITRF2005 input data that come from VLBI, GPS, and SLR. In this work, on co-located sites, the GPS height annual signal has been confirmed by VLBI and SLR measurements, however no significant signal at lower periods has been confirmed neither by VLBI nor by SLR.

With in this study we start to investigate on these inconsistencies using IVS-R1 and -R4 experiments that have a high density of sessions respect to other standard VLBI experiments. On the whole, 17 radio telescope sites which have continuously taken part in most of the IVS-R1 and -R4 daily sessions from the beginning of 1994 to the end of 2008 are included in our study. The a priori coordinates of these VLBI stations provided from Deutsches Geodatisches Forschungsinstitut (DGFI), estimated by introducing No Net Rotation (NNR) and No Net Translation (NNT) conditions with the ITRF2000 coordinates of 25 globally distributed VLBI antennas. The corrections to the apriori coordinates are estimated with LS adjustment from the daily sinex normal equations (minimum constrained) of IVS-R1 and -R4 sessions.

2 VLBI radio telescope coordinate time series analysis

After the estimate of the adjusted coordinates of the antennas at their respective time epochs, coordinate time series of each antenna are produced. The determination and removal of the yearly trends (velocities) from the radio telescope coordinates is carried out by LS fit to the linear function

$$X_t - X_{mean} = a_1(t - t_1) + \epsilon_t \ , \qquad (1)$$

where X_{mean} is the yearly mean value of the coordinate series, a_1 is the trend (velocity vector, cartesian components) of the year (estimated values) and ϵ_t are the residuals. 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 and f is the degrees of freedom. Simply stated, the test statistic is

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

where S is the standard deviation of the parameter (Wolf & Ghilani, 1997). Offsets (yearly mean values of the coordinate series) and statistically significant yearly trends are removed from the time series of the antenna coordinates. The residual parts (ϵ_t) of the coordinates are then transformed to the local topocentric coordinates as follows

$$\begin{bmatrix} North \\ East \\ Up \end{bmatrix} = T * \begin{bmatrix} \epsilon_{X(t)} \\ \epsilon_{Y(t)} \\ \epsilon_{Z(t)} \end{bmatrix} \ , \qquad (3)$$

with

$$T = \begin{bmatrix} -sin\varphi\, cos\lambda & -sin\varphi\, sin\lambda & cos\varphi \\ -sin\lambda & cos\lambda & 0 \\ cos\varphi cos\lambda & cos\varphi sin\lambda & sin\varphi \end{bmatrix} \ , \qquad (4)$$

where φ is the latitude and λ is the longitude of the station. The related co-variances of the station coordinates are transformed to local topocentric system as follows

$$Q_{NEU} = \begin{bmatrix} q_{NN} & q_{NE} & q_{NU} \\ q_{NE} & q_{EE} & q_{EU} \\ q_{NU} & q_{EU} & q_{UU} \end{bmatrix} = TQ_xT^T \ . \qquad (5)$$

The resulted series in the local topocentric system are analysed by means of detecting cyclicities (harmonics). This single spectral analysis approach, known as auto spectral analysis (autospectrum, or periodogram), is 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).

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

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

where ω is called as angular frequency, R is the amplitude, ϕ is the phase and Z_t denotes a stationary series. Since $cos(\omega + \phi) = cos\omega\, cos\phi - sin\omega\, sin\phi$, Eq. (6) can be expressed as

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

where $a_p = R_p cos\phi_p$ and $b_p = -R_p sin\phi_p$. The amplitude and phase of the variation ($p^{th} harmonic$) are

$$R_p = \sqrt{a_p^2 + b_p^2} \ , \quad \phi_p = tan^{-1}(-b_p/a_p) \ . \qquad (8)$$

If we are interested in variation at low frequency of 1 cycle per year, then we should have at least 1 year's data in which case the lowest 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 Nyquist frequency is the highest frequency for which we can get meaningful information from a set of data. The Fourier series representation of the data is normally evaluated at the frequencies of $\omega_p = 2\pi p/N$ provided from the fundamental ($2\pi/N$) frequency by multiplying the integers $p = 1, 2, ..., N/2$, called as harmonics (Chatfield, 2004; Trauth, 2007). The procedures that is done to analyse the coordinate time series of VLBI radio telescope coordinates are itemized below:

- The normal equation matrices' sinex files of the sessions IVS-R1 and -R4 are downloaded from the DGFI database. The corrections to the antennas' a priori ITRF2000 coordinates are estimated at their session time epochs with LS (step 1).
- Firstly, yearly mean values of the coordinate series are removed (Eq. 1). Then, the yearly linear trends (velocities) of each antenna are estimated (Eq. 1) with LS. All the significant (Eq. 2) linear trends from the series are removed resulting in the stationary series (the series without any trend). The residual stationary series with their covariance matrices are transformed to local topocentric coordinate system (Eq. 3 and 4) (North, East, and Up) (step 2).

- ◦ In order to produce the data evenly distributed a linear interpolation is introduced to the real data (as to make use of FFT to plot spectral density of the series). By the linear interpolation the same number of artificial data with the real data which are all in the range of the real data are produced (step 3).
- ◦ The maximum power of the spectral density and its frequency is computed with FFT (step 4).
- ◦ The coefficients of the Fourier series (Eq. 7) are estimated with LS based on the frequency of the maximum power (step 5).
- ◦ The amplitude and phase of the first largest cycle are calculated (Eq. 8) with these coefficients of the Fourier series (step 6).
- ◦ In case the amplitude is larger then 0.1 mm then the harmonic effect is removed from the respective series then the iteration procedure from step 4 is repeated again for the same series (step 7).
- ◦ In case the estimated amplitude is smaller then 0.1 mm the loop is finished for this series (step 8).
- ◦ The same procedure is applied for the north, east and up components of each antenna (step 9).

3 Results of the analysis

Table 1 shows a comparision between our estimates of yearly significant velocities from the IVS-R1 and -R4 sessions and retrieved velocities from the combined solution of the Terrestrial Reference Frame (TRF) of International Earth Rotation and Reference Systems Service (IERS), ITRF2000 at epoch 1997.0, in local topocentric coordinates. The series are unevenly spaced. Averages of the sampling intervals are used for producing the Nyquist frequencies. To form evenly spaced data linear interpolation is applied. For the unevenly spaced data it seems to be impossible to prevent artefacts and spurious effects on the interpolation results. The power spectral density of the time series is computed by FFT and plotted e.g. for the Wettzell antenna coordinate series of the up component given in Figure 2. The coefficients of Fourier series (a_p and b_p) given in Eq. (7) are estimated with least squares according to the period of the maximum power produced by the power spectral density plots. With the coefficients of the Fourier series amplitude and phase of the maximum harmonic variation (spectra) is computed with Eq. 8. Iteratively, cyclicities are removed from the data, based on the frequency of maximum power (Schuh, 1981). The iterations are stopped when the amplitudes are found out below the value of 0.1 mm. Harmonic behaviour of the up component of the Wettzell antenna from 1994.01 is shown in Figure 1. Significant harmonics (amplitude, phase, and period) of the VLBI antenna coordinates are given in Table 2.

4 Conclusions and prospects

After removing the linear trend from the series, sinusoidal variations of the series are determined by estimating the amplitudes and phase of the Fourier series based on the frequency of the maximum power spectral density in the respective spectra plot (autospectrum). The significant periods of the up components ranges from $\approx$ 50 to $\approx$ 450 days and differ for each antenna. The amplitudes of the detected variations are small, in ranges between 0.4 - 0.1 mm (Table 2). The retrieved 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. This may be caused by the artefacts of the data interpolation carried out linearly or the data itself because of the un-modeled geophysical parts of the a priori coordinates derived.

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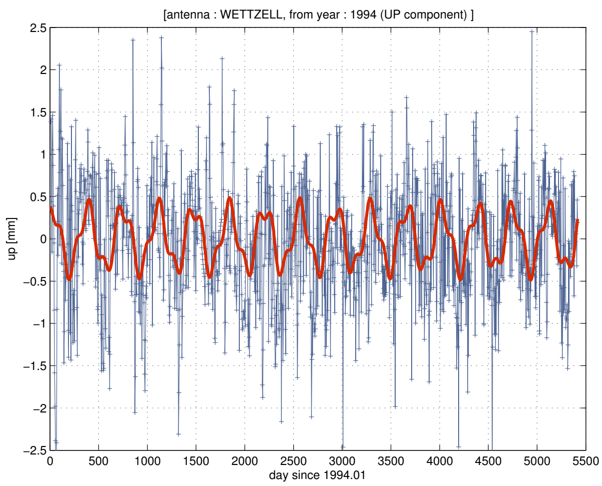

Figure 1. Harmonic behaviour of the antenna Wettzell - up component from 1994.01

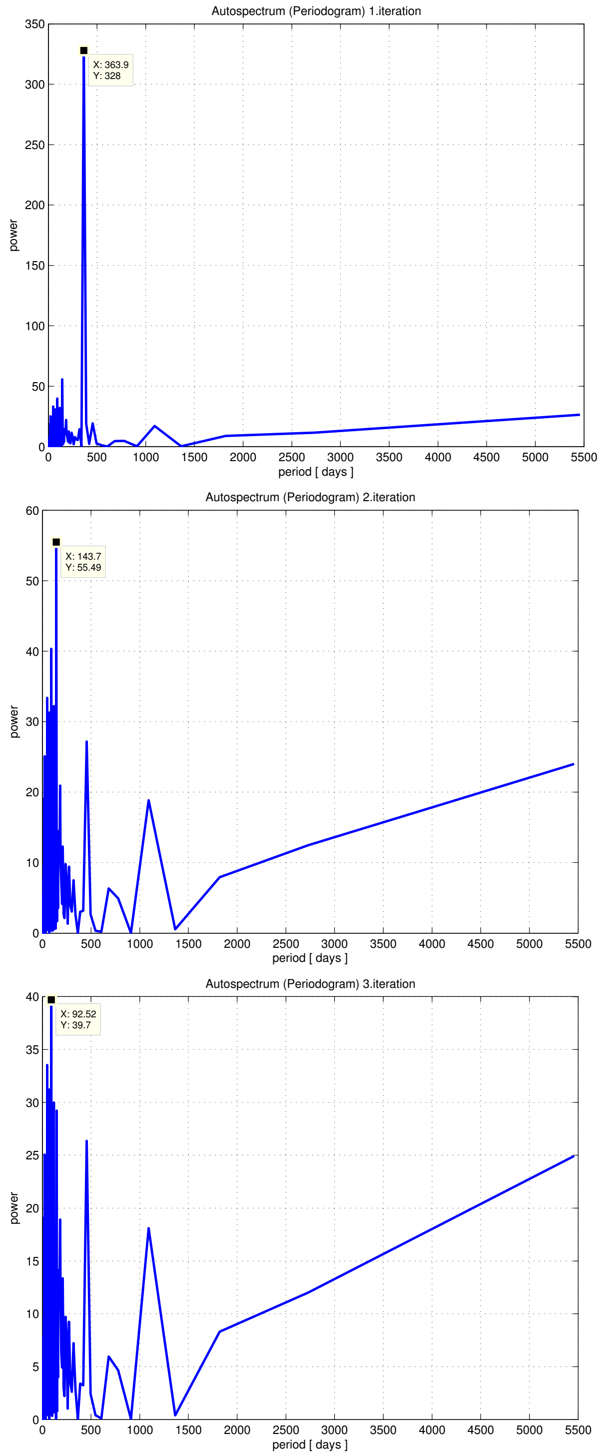

Figure 2. Spectra plot of the time series of the up component of the antenna Wettzell for the first three iterations

Table 1. The velocity vectors derived from ITRF2000 at epoch 1997.0 and IVS-R1 and -R4 Sessions

	ITRF2000			IVS-R1 and -R4		
	v_{north} (cm)	v_{east} (cm)	v_{up} (cm)	v_{north} (cm)	v_{east} (cm)	v_{up} (cm)
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. Significant harmonics of the antenna coordinates

Algopark (time interval : 2002.01 - 2006.53, number of data : 262)												
	Up				East				North			
Iteration	Amp. (mm)	Phase (°)	Per. (day)	Iter.	Amp.	Phase	Per.	Iter.	Amp.	Phase	Per.
1	0.21	59.4	411.2	1	0.30	-4.76	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 : 1990.02 - 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	363.9	1	0.18	-53.1	1819.6	1	0.24	-36.6	5458.9
2	0.13	54.9	143.7	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	-	-	-	-