AN INFLUENCE OF WIDE-BAND OSCILLATIONS IN POLE COORDINATES CAUSED BY ATMOSPHERIC, OCEAN AND HYDROLOGY EXCITATION FUNCTIONS ON THEIR PREDICTION ERRORS

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1. INTRODUCTION

Increase of accuracy of space geodetic techniques during the last decades caused increase of determination accuracy of Earth orientation parameters (EOP) which are x, y pole coordinates, universal time UT1-UTC and celestial pole offsets as precession-nutation model corrections. The exact knowledge of the EOP is important for many investigations in astronomy and geodesy. For some tasks also real-time and even future EOP data are needed. Within the IERS operational predictions are provided each day by the International Earth Rotation and Reference Systems Service (IERS) Rapid Service/Prediction Centre (RS/PC) at United States Naval Observatory (USNO), Washington DC. The UT1-UTC data are predicted using the algorithm which incorporates axial component of atmospheric angular momentum (Johnson et al., 2005; Wooden et al., 2005) and since January 25th 2007 the x, y pole coordinates data are predicted using the combination of the least-squares (LS) extrapolation and autoregressive (AR) prediction algorithm (Kosek et al., 2004; Stamatakos et al., 2008; USNO, 2007). These predictions enable computation of real time transformation between the International Celestial and Terrestrial Reference Frames. Such real-time transformation is very important for the NASA Deep Space Network (DSN), which is an international network of antennas that supports interplanetary spacecraft missions and radio and radar astronomy observations for the exploration of the solar system and the universe. The network also supports selected Earth-orbiting missions. The DSN currently consists of three deep-space communications facilities placed approximately 120 degrees apart around the world: at Goldstone, in California's Mojave Desert; near Madrid, Spain; and near Canberra, Australia. This strategic placement permits constant observation of spacecrafts as the Earth rotates, and helps to make the DSN the largest and most sensitive scientific telecommunications system in the world.
It has been shown that the prediction accuracy of the nutation corrections is of the order of their determination error (Brzeziński and Kosek, 2004; Kalarus et al., 2006). The prediction errors of the x, y pole coordinates and UT1-UTC data even for a few days in the future are ten or hundred times greater than their determination errors due to irregularities in the motion of the pole and the spin of the Earth. Thus, there is a need to improve the accuracy of Earth rotation prediction.

There were many attempts to improve the EOP prediction accuracy and the results were presented by many authors (Freedman et al., 1994; Kalarus and Kosek, 2004; Kosek et al., 1998; McCarthy and Luzum, 1991; Niedzielski and Kosek, 2007; Schuh et al., 2002).
In October 2005 due to initiative of Prof. Harald Schuh of the Technical University of Vienna the EOP Prediction Comparison Campaign (EOP PCC) started (Kalarus et al., 2008). The main idea of this campaign was to compare the various methods, models, techniques and strategies that can be applied to the EOP prediction. During the EOP PCC organized by the IERS about ten participating groups/methods were submitting prediction results of x, y pole coordinates, UT1- UTC, LOD, and celestial pole offsets dX, dY (or $d\psi, d\varepsilon$) data until march 2008. The mean prediction errors for each prediction group/method were calculated by the same statistical methods in Space Research Centre, Polish Academy of Sciences, by dr. M. Kalarus and the results were presented at many international conferences. The main achievement of the EOP PCC was that the combined predictions of the EOP data have better accuracy than the individual predictions and that incorporating atmospheric excitation functions and their forecasts improve prediction accuracy of UT1-UTC data (Kalarus et al., 2008). At the European Geosciences Union (EGU) 2006 General Assembly the IERS has established a Working Group on Prediction (WGP) to investigate the optimum input data sets for the EOP predictions and the strengths and weaknesses of the various prediction algorithms (Wooden et al., 2006; Wooden, 2008a,b). The goal of this Working Group is to follow up on the results of the EOP PCC, by answering fundamental questions concerning the prediction of polar motion and UT1-UTC. This Working Group was formed to investigate the fundamental properties of different prediction algorithms, the inherent qualities in the input data series, and the interactions between data and algorithms. The aim of this paper is investigation of the influence of fluid excitation functions as well as of wide band oscillations in pole coordinates data on prediction errors of these data. To attain this objective the pole coordinates model data were computed from fluid excitation functions and using Discrete Wavelet Transform (DWT). Such approach enables estimation of the influence of different frequency bands of pole coordinates data on their prediction errors.

2. DATA

The following data sets were used in the analysis:

- x, y pole coordinates data from the IERS EOPC04_05 combined solution with the sampling interval of 1 day (IERS, 2008).
- Equatorial components $\chi_1^{AAM}, \chi_2^{AAM}$ of atmospheric angular momentum from aam.ncep.reanalysis.* data in 1948-2008.6 which are the sum of mass and motion terms with the sampling interval of 6 hours (AER, 2008). These data were averaged using boxcar time window with 1 day length and interpolated with 1 day sampling interval.
- Equatorial components $\chi_1^{OAM}, \chi_2^{OAM}$ of ocean angular momentum which are the sum of mass and motion terms, created after connection of two separate files with the sampling interval of 1 day: 1) c20010701.oam (or gross03.oam) from Jan. 1980 to Mar. 2002, 2) ECCO_kf049f.oam from Mar. 2002 to Mar. 2006 (JPL, 2008).
- Equatorial components $\chi_1^{HAM}, \chi_2^{HAM}$ of hydrology angular momentum obtained by numerical integration of water storage data: water_ncep_1979.dat, water_ncep_1980.dat,

…, water_ncep_2004.dat in 1979 - 2004 from National Centers for Environmental Prediction (NCEP) with the sampling interval of 1 day (NCEP, 2008).

The most important criterion of choosing fluid excitation functions in this paper is the longest possible data time span. However, all these functions have internal errors and there are differences between their estimates especially in the case of HAM excitation function. There are more accurate estimates of HAM excitation functions based on the GRACE observations (Nastula et al., 2007) however they cannot be applied in this paper due to their too short data time span.

3. COMPUTATION OF THE POLE COORDINATES MODEL DATA FROM THE FLUID EXCITATION FUNCTIONS

To examine the influence of fluid excitation functions on prediction errors of x, y pole coordinates data first the pole coordinates model data were computed from the equatorial components of these excitation functions. The differential equation of polar motion is given by the following formula (Brzeziński, 1992):

$$\frac{i}{\sigma_{ch}}\dot{m}(t) + m(t) = \chi(t)\,, \tag{1}$$

where $m(t) = x(t) - iy(t)$ are the polar motion data to be determined, $\chi(t) = \chi_1(t) + i\chi_2(t)$ are equatorial components corresponding to atmospheric, ocean and hydrology excitation functions, $\sigma_{ch} = \frac{2\pi}{T_{ch}}\left(1 + \frac{i}{2Q}\right)$ is the complex-valued Chandler frequency, $T_{ch} = 433$ *days* is the Chandler period and $Q = 170$ is the quality factor.

Solution of this equation in discrete time moments can be obtained using the trapezoidal rule of numerical integration:

$$m(t + \Delta t) = m(t)\cdot\exp\left(i\sigma_{ch}\Delta t\right) - i\frac{\sigma_{ch}\Delta t}{2}\left[\chi(t + \Delta t) + \chi(t)\cdot\exp\left(i\sigma_{ch}\Delta t\right)\right] \tag{2}$$

where Δt is the sampling interval of data.

3.1 Coherence between pole coordinates data and the pole coordinates model data

To investigate the time-frequency relations between pole coordinates data and the pole coordinates model data calculated from fluid excitation functions the spectro temporal Morlet wavelet coherence was computed. The wavelet transform coefficients of a complex-valued function are defined by the frequency domain formula (Chui, 1992):

$$X(b,a) = \frac{1}{2\pi}|a|^{1/2}\int_{-\infty}^{\infty}\breve{x}(\omega)\overline{\breve{\varphi}}(a\omega)\exp(ib\omega)d\omega\,, \tag{3}$$

where $a \neq 0$ and b are the dilation (period) and the translation (time) parameters, respectively, $\breve{x}(\omega)$ is the continuous Fourier transform of a complex-valued function $x(t)$, $\breve{\varphi}(\omega) \approx \exp(-(\omega - 2\pi)^2/2)$ is the continuous Fourier transform of the complex-valued Morlet wavelet function which is given by the following time domain formula (Schmitz-Hübsch and Schuh, 1999):

$$\varphi(t) \approx \exp(-t^2/2)\exp(i2\pi \cdot t)/\sqrt{2\pi} \; . \qquad (4)$$

The spectro-temporal coherence between two complex-valued time series $x(t)$ and $y(t)$ $t = 0,1,...,n-1$, is defined as the running correlation coefficient between the wavelet transform coefficient estimates $\hat{X}(b,a),\ \hat{Y}(b,a)$ computed from these two time series (Popiński et al., 2002):

$$\hat{\kappa}_{xy}(t,a) = \frac{\left| \sum_{b=-M}^{M} \hat{X}(t+b,a)\overline{\hat{Y}(t+b,a)} \right|}{\sqrt{\sum_{b=-M}^{M} \left| \hat{X}(t+b,a) \right|^2 \sum_{b=-M}^{M} \left| \hat{Y}(t+b,a) \right|^2}}, \qquad (5)$$

where $M = 500$ is a positive integer.
To estimate the coherence statistical error the formula of Van Milligen (1999) was applied:

$$err\left[\hat{\kappa}_{xy}(t,a)\right] = \sqrt{\frac{|a|}{\Delta t(2M+1)}} \; . \qquad (6)$$

Figure 1 shows the maps of the Morlet Wavelet Transform (MWT) spectro-temporal coherence between the IERS x, y pole coordinates data and the x, y pole coordinates model data computed from equatorial components of atmospheric angular momentum excitation functions, and the sum of atmospheric and ocean as well as the sum of atmospheric, ocean and hydrology excitation functions. When x, y pole coordinates model data are computed from the sum of atmospheric and ocean excitation functions, then the coherence is higher than in the case when the x, y pole coordinates model data are computed from atmospheric excitation functions only. When x, y pole coordinates model data are computed from the sum of atmospheric, ocean and hydrology excitation functions, then the coherence does not change significantly in relation to the previous case.

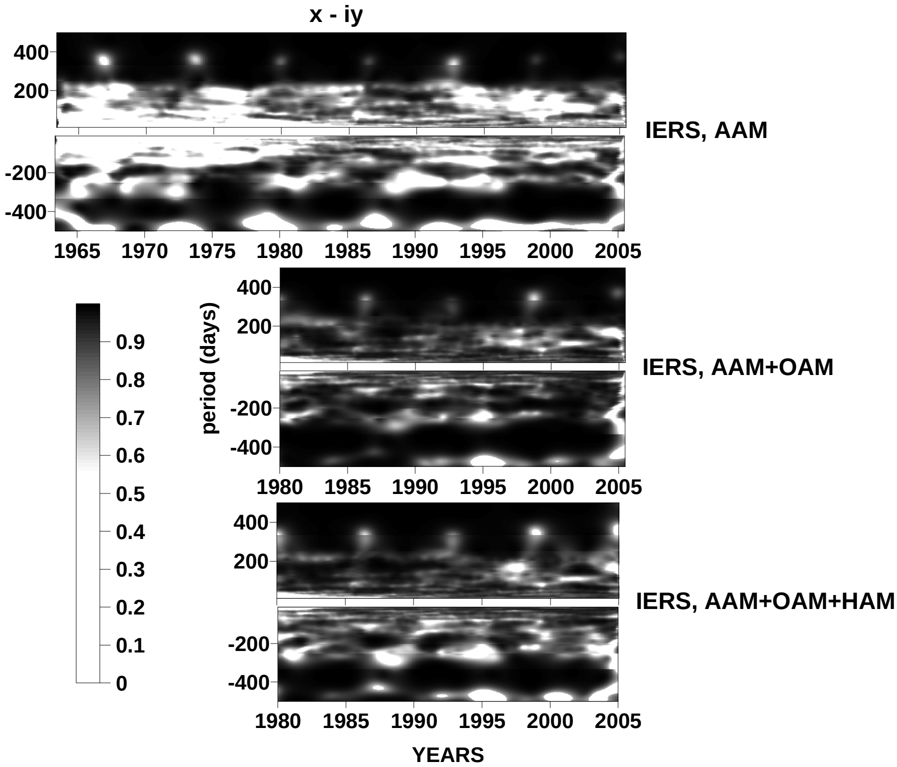

Fig. 1. The MWT spectro-temporal coherence between the IERS x, y pole coordinates data and the x, y pole coordinates model data computed from AAM, AAM+OAM and AAM+OAM+HAM excitation functions. All coherence values less than coherence statistical error (eq. (6)) were set to zero.

4. POLE COORDINATES MODEL DATA BASED ON DISCRETE WAVELET TRANSFORM

To show the influence of wide-band oscillations in x, y pole coordinates data on the prediction errors of these data, the discrete wavelet transform band pass filter (DWTBPF) was applied to filter these oscillations.
The DWT j-th frequency component of a complex-valued signal $x(t)$ is given by the formula:

$$x_j(t) = \sum_{k=-2^{j-1}}^{2^{j-1}-1} S_{j,k}\varphi_{j,k}(t) \qquad for \qquad t = 0,1,...,n-1, \quad j = j_0, j_0+1,..., p-1, \tag{7}$$

where

$$S_{j,k} = \sum_{t=0}^{n-1} x(t)\varphi_{j,k}(t) \tag{8}$$

are the DWT coefficients, and $n = 2^p$ is the number of data, p is a positive integer,

$$\varphi_{j,k}(t) = \sqrt{n}\,2^{-j/2}\varphi_j(t - n/2 - 2^{-j}kn) \tag{9}$$

are the discrete Shannon wavelet functions (Benedetto and Frazier, 1994).
For fixed lowest frequency index $0 \le j_0 \le p-2$ and time index $k = -2^{j_0}, -2^{j_0}+1, ..., 2^{j_0}-1$,

$$\varphi_{j_0}(t) = \frac{1}{n}\exp[-i\pi(t-n/2)/n]\frac{\sin[2^{j_0+1}\pi(t-n/2)/n]}{\sin[\pi(t-n/2)/n]}, \qquad \varphi_{j_0}(n/2) = 2^{j_0+1}/n .$$

For higher frequency index $j = j_0+1, j_0+2, ..., p-1$ and $k = -2^{j-1}, -2^{j-1}+1, ..., 2^{j-1}-1$,

$$\varphi_j(t) = \frac{1}{n}\exp[-i\pi(t-n/2)/n]\frac{\sin[2^j\pi(t-n/2)/n](2\cos[2^j\pi(t-n/2)/n]-1)}{\sin[\pi(t-n/2)/n]}, \ \varphi_j(n/2) = 2^j/n .$$

The DWTBPF enables computation of such frequency components of complex-valued time series that their sum is equal to the input time series:

$$\sum_{j=j_0}^{p-1} x_j(t) = x(t) . \qquad (10)$$

Similar approach to decomposition of real-valued times series using discrete Meyer wavelet functions was presented by Popiński and Kosek (1995).

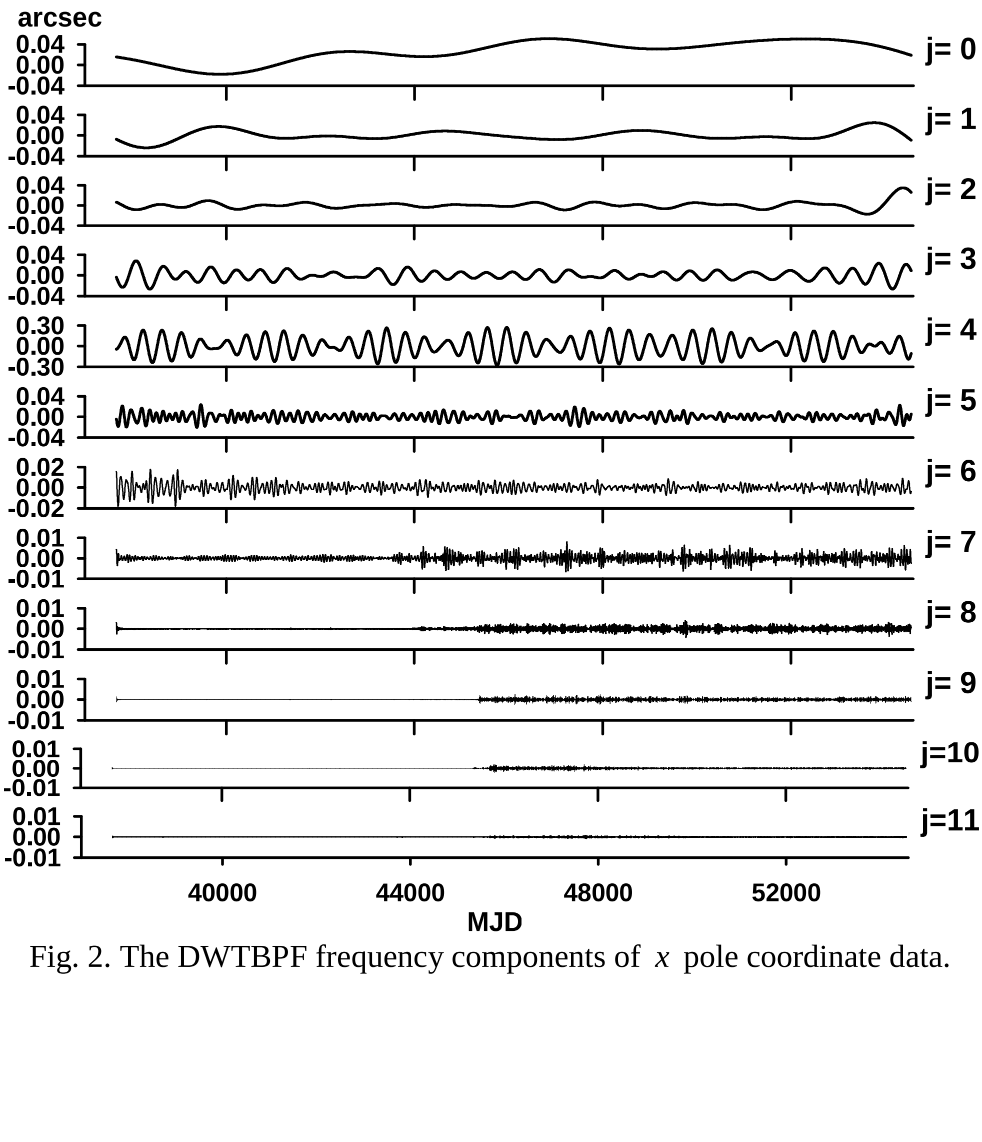

Fig. 2. The DWTBPF frequency components of x pole coordinate data.

Figure 2 shows an example of the decomposition of x pole coordinate data into 12 frequency components. One of the frequency components with the frequency index $j = 4$ corresponds to the sum of the Chandler and annual oscillations and one component with the frequency index $j = 5$ corresponds to the semiannual oscillation. Components with the frequency index $j < 4$ correspond to longer period oscillations and components with the frequency index $j > 4$ correspond to shorter period oscillations.

5. PREDICTION OF POLE COORDINATES DATA

To predict x, y pole coordinates data or the x, y pole coordinates model data the combination of the LS model extrapolation and AR prediction algorithm was applied (LS+AR) (Kosek et al., 2004, 2008). In this prediction algorithm first the LS model which consists of the Chandler circle, annual and semi-annual ellipses and linear trend is fit to x, y pole coordinates data. The difference between x, y pole coordinates data and its LS model gives the LS model residuals. Prediction of x, y pole coordinates data is the sum of the LS model extrapolation and the AR prediction of the LS model residuals.

5.1 Prediction of x, y pole coordinates model data computed from fluid excitation functions.

The maps in Figure 3 show the absolute values of the differences between the IERS x, y pole coordinates data and their predictions computed by the LS+AR prediction method, at starting prediction epoch from 1980 till 2008 and reaching from one day to one year in the future, as well as the absolute values of the differences between the x, y pole coordinates model data computed from atmospheric, ocean and hydrology excitation functions and their predictions. It can be noticed that fluid excitation functions alone do not explain all the prediction errors of pole coordinates data, however some irregular and unpredictable oscillations in x, y pole coordinates data after 2006 are possibly caused by atmospheric excitation. Some irregular and unpredictable oscillations from 1980 to 1982 and at the end of 2002 and beginning of 2003 in x, y pole coordinates data are probably caused by irregular ocean excitation. The prediction errors of the x, y pole coordinates model data computed from hydrology excitation and their predictions are very small so the influence of hydrology excitation function on prediction errors of the IERS x, y pole coordinates data is negligible.

5.2 Prediction of the x, y pole coordinates model data computed as the sum of frequency components determined by the DWTBPF.

The pole coordinates model data were constructed as the sum of different frequency components computed by the DWTBPF but including the frequency component with the frequency index $j = 4$ corresponding to the sum of the Chandler and annual oscillations. The LS+AR prediction errors of the x, y pole coordinates model data computed by summing the chosen DWTBPF components are shown in Figure 4. The prediction errors of pole coordinates data (Fig. 3) are similar to the prediction errors of the pole coordinates model data being the sum of Chandler, annual and shorter period oscillations. The prediction errors for prediction lengths reaching from 1 day to about 100 days in the future of the pole coordinates model data constructed as the sum of the Chandler, annual and longer period oscillations are very small.

Figure 5 shows a comparison of the mean prediction errors of the IERS x, y pole coordinates data and of the x, y pole coordinates model data computed using the sum of atmospheric and ocean excitation functions, as well as by summing the DWTBPF frequency components corresponding to Chandler, annual and shorter period oscillations. The mean prediction errors of the x, y pole coordinates model data computed from the combined ocean and atmospheric excitation are of the same order as the mean prediction errors of the x, y pole coordinates model data computed by summing the frequency components corresponding to Chandler and annual oscillations and shorter period frequency components.

6. CONCLUSIONS

The contribution of the joint atmosphere and ocean angular momentum excitation to the mean prediction errors of x, y pole coordinates data is almost equal to the contribution of the sum of Chandler + annual and shorter period frequency components. Both contributions explain about 80÷90% of the total prediction error.

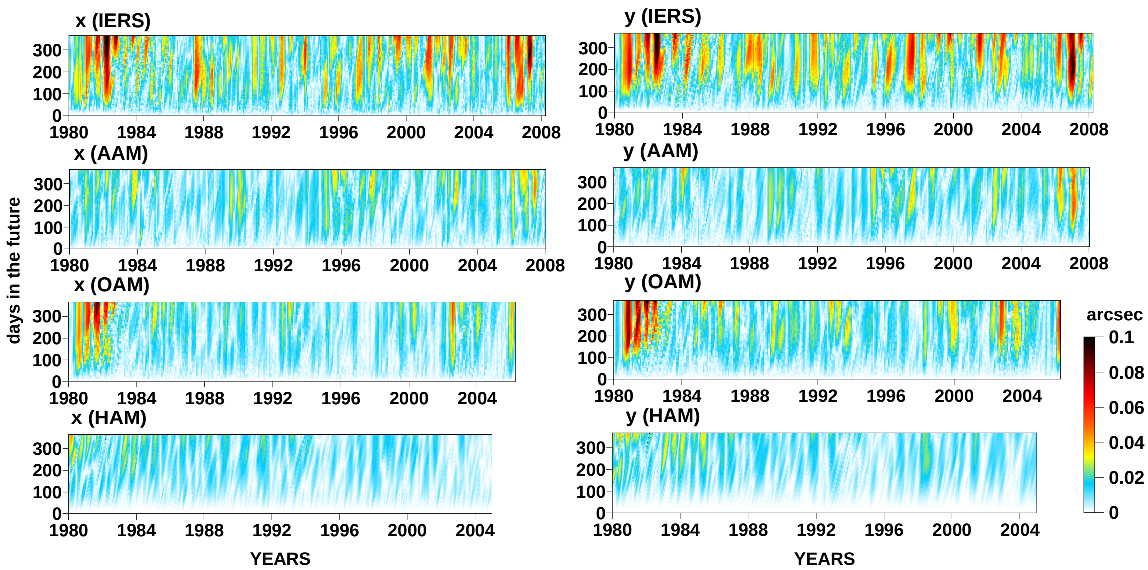

Fig. 3. The LS+AR prediction errors of the IERS x, y pole coordinates data and of the x, y pole coordinates model data computed from AAM, OAM and HAM excitation functions.

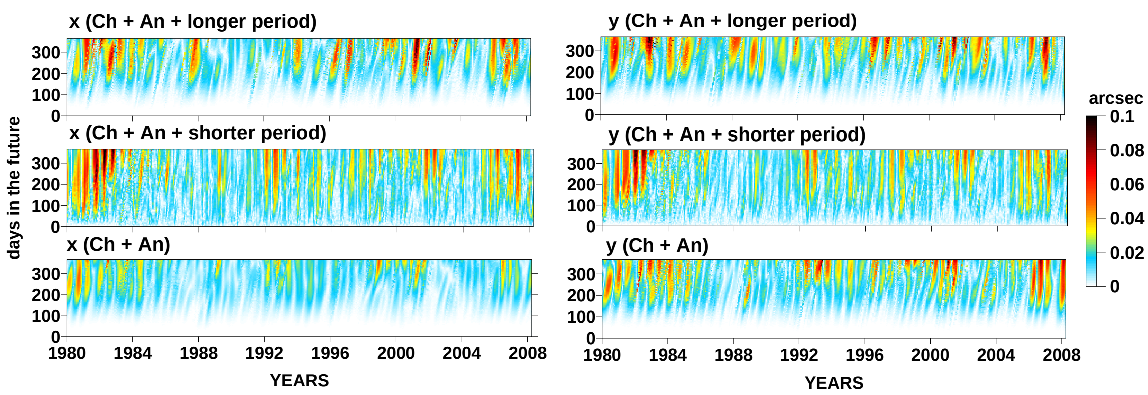

Fig. 4. The LS+AR prediction errors of the x, y pole coordinates model data computed by summing the chosen DWTBPF components.

Big prediction errors of the IERS x, y pole coordinates data in 1981-1982 and in 2006-2007 are mostly caused by wide-band ocean and atmospheric excitation, respectively. The contribution of the hydrology angular momentum excitation to the prediction errors of the x, y pole coordinates data is negligible.

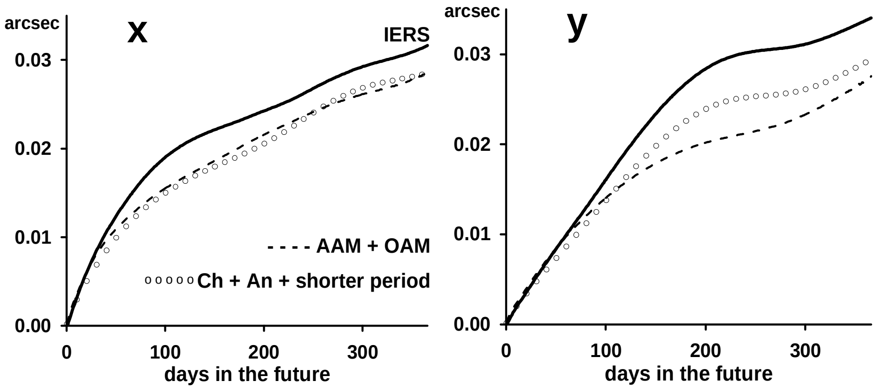

Fig. 5. The mean LS+AR prediction errors of the IERS x, y pole coordinates data (thin line), and of the x, y pole coordinates model data computed from AAM+OAM excitation functions (dashed line), as well as by summing the DWTBPF components corresponding to Chandler, annual and shorter period oscillations (circle line).

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