JPL

DETECTION OF POLAR MOTION EXCITATION BY THE FORTNIGHTLY OCEAN TIDES

by

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- **Spectra of polar motion excitation functions exhibit enhanced power in fortnightly tidal band**
- **Upon subtracting atmospheric wind and pressure effects, fits for periodic terms at the /Wand *Mf'* tidal frequencies can fully account for the observed enhanced power in the fortnightly tidal band**
- **Ocean tide models predict polar motion excitation effects that are generally two to three times smaller than those observed at fortnightly periods**
  - **Need improved models for effect of long-period ocean tides on Earth's rotation**

APPROACH

- **Polar motion excitation function**
  - Use that derived from SPACE94 polar motion values
    - SPACE94 is a Kalman filter-based combination of space-geodetic Earth rotation measurements
  - Spans 1976.8–1994 at l-day intervals
- **Remove effects of atmospheric wind and pressure**
  - Use atmospheric angular momentum values computed from operational analyses of National Centers for Environmental Prediction (formerly the National Meteorological Center)
  - Pressure term used is that computed assuming oceans respond as inverted barometer to imposed atmospheric pressure changes
- **Least-squares fit for periodic terms at tidal frequencies to SPACE94–AAM residual series**
  - Fit for mean, trend, and periodic terms at the weekly (*M9* and *M9'*), fortnightly (*Mf* and *Mf'*), monthly (*Mm*), semiannual (*Ssa*), and annual (*Sa*) tidal frequencies
  - Fit to entire 18.2-year span of data set
    - Data set spanning about 18.6 years must be used in order to resolve periodic terms at the *M9* and *M9'* tidal frequencies, or at the *Mf* and *Mf'* tidal frequencies, since that is their beat period
- **Compare recovered empirical tidal effects with those predicted by ocean tide models**
  - Seiler (1991) as analyzed for polar motion effects by Gross (1993) and Brosche & Wünsch (1994)
  - Dickman (1993)

LONG PERIOD LIOUVILLE EQUATION

- **Conservation of angular momentum expressed within rotating, body-fixed reference frame**

$$\frac{\partial \mathbf{L}}{\partial t} + \omega \times \mathbf{L} = \tau$$

where the angular momentum vector $\mathbf{L} = \mathbf{I} \cdot \omega + \mathbf{h}$

- **Assume rotation is small perturbation from state of uniform rotation at rate Ω. Keeping terms to first order yields long period Liouville eq.**

$$\mathbf{m}(t) + \frac{i}{\sigma_{cw}} \frac{\partial \mathbf{m}}{\partial t} = \psi(t) = \chi(t) - \frac{i}{\Omega} \frac{\partial \chi}{\partial t}$$

where: $\mathbf{m} \equiv (\omega_1 + i\,\omega_2)/\Omega$ (terrestrial location of rotation pole)

$\psi(t)$, $\chi(t)$ are the polar motion excitation functions

σ_{cw} is complex-valued frequency of Chandler wobble

- **Written in terms of reported polar motion parameters ~(~)= $x_p(t) - i\, y_p(t)$**
  - **In time domain:**

$$\mathbf{p}(t) + \frac{i}{\sigma_{cw}} \frac{\partial \mathbf{p}}{\partial t} = \chi(t) = \frac{1.61}{\Omega\,(C-A)} \left[\mathbf{h}(t) + \frac{\Omega\, \mathbf{c}(t)}{1.44} \right]$$

  - **In frequency domain:**

$$\mathbf{p}(\sigma) = \frac{\sigma_{cw}}{\sigma_{cw} - \sigma} \chi(\sigma)$$

POLAR MOTION EXCITATION FUNCTIONS

- **In Earth rotation theory, the excitation functions, or z-functions, are the forcing functions that cause changes in the Earth's rotation (length-of-day) and orientation (polar motion)**

- **In general, they are functions of changes in**
  - **the Earth's inertia tensor**
  - **relative angular momentum**

- **At frequencies far from the Free Core Nutation resonance (that is, at periods long compared to a day), the polar motion excitation functions $\chi(t)$ are related to the polar motion parameters $x_p(t)$ and $y_p(t)$ by:**

$$\mathrm{p}(t) + \frac{i}{\sigma_{cw}} \frac{\partial \mathrm{p}}{\partial t} = \chi(t)$$

where: $\mathrm{p}(t) \equiv x_p(t) - i\, y_p(t)$ $\chi(t) \equiv \chi_1(t) + i\,\chi_2(t)$

  - **This is the equation for simple harmonic motion in the complex plane**
  - **The excitation pole is that pole about which the rotation pole instantaneously revolves**
  - **Changes in the excitation pole force changes in the polar motion**

- **Can be recovered from polar motion observations either by direct numerical differentiation or by deconvolution**

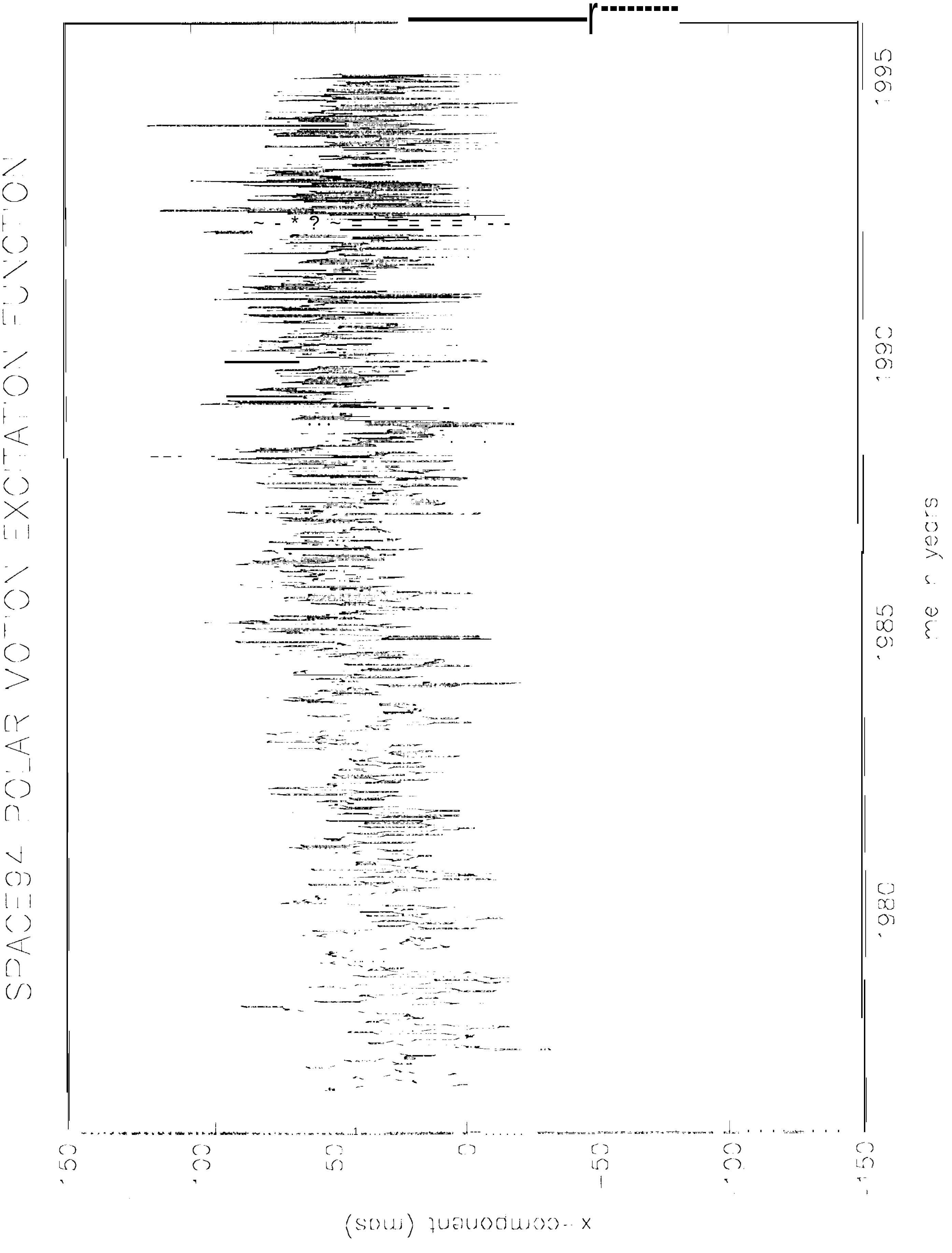
- **The SPACE94 polar motion excitation functions have been used here**

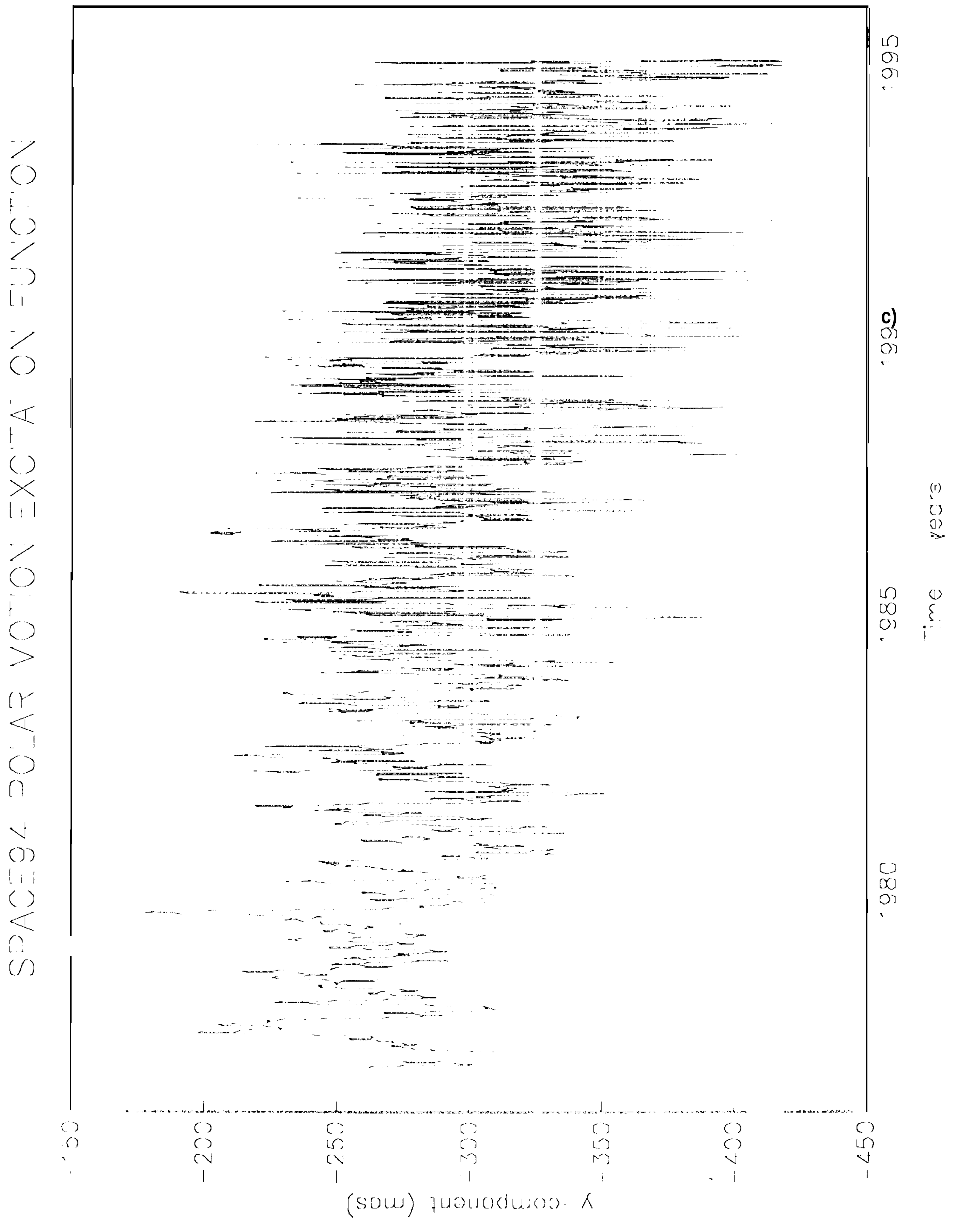
SPACE94 EARTH ORIENTATION SERIES

- A combination of space-geodetic Earth rotation measurements
  - LLR (from JPL analysis center)
  - SLR (from University of Texas Center for Space Research analysis center)
  - VLBI [from IRIS "Intensive" (both NOAA & USNO analyses), NASA's Deep Space Network at JPL, and NASA's Space Geodesy Program at GSFC]
  - GPS (from S10 and JPL analysis centers)
- Individual series adjusted prior to their combination
  - Leap seconds and tidal terms removed (when necessary) from UT1 values
    - Yoder *et al.* [1981] model used to remove effect of all long period solid Earth tides
    - Dickman [1993] model used to remove ocean tidal corrections to the Yoder *et al.* [1981] model values at the *Mf*, *Mf'*, *Mm,* and *Ssa* tidal frequencies
    - Herring [1993] empirical model used to remove effect of semidiurnal and diurnal ocean tides on NOAA's IRIS "Intensive" UT1 values
  - Bias and rate of each series adjusted to be in agreement with each other
  - Stated uncertainties of each series adjusted so its residual with respect to a combination of all other series has a reduced chi-square of one
  - Outlying data points deleted
- Adjusted series combined using Kalman filter to form SPACE94
  - Consists of values for PMX, PMY, UT1–UTC, their formal uncertainties and correlations spanning October 6.0, 1976 to January 27.0, 1995 at daily intervals

SPACE94 POLAR MOTION EXCITATION FUNCTION

- SPACE94 consists of values for polar motion and UT1-UTC
- Kalman filter used to generate SPACE94
  - Contains a model for the polar motion process
  - Produces estimates of excitation functions as well as polar motion and UT1-UTC
- Polar motion excitation functions used here are those estimated by Kalman filter when generating SPACE94


SPACE94 POLAR MOTION EXCITATION FUNCTION
1980
1985
1990
1995
time in years
150
100
50
0
-50
-100
-150
x-component (mas)


SPACE94 POLAR MOTION EXCITATION FUNCTION
-150
-200
-250
-300
-350
-400
-450
y-component (mas)
1980
1985
1990
1995
time years

c)

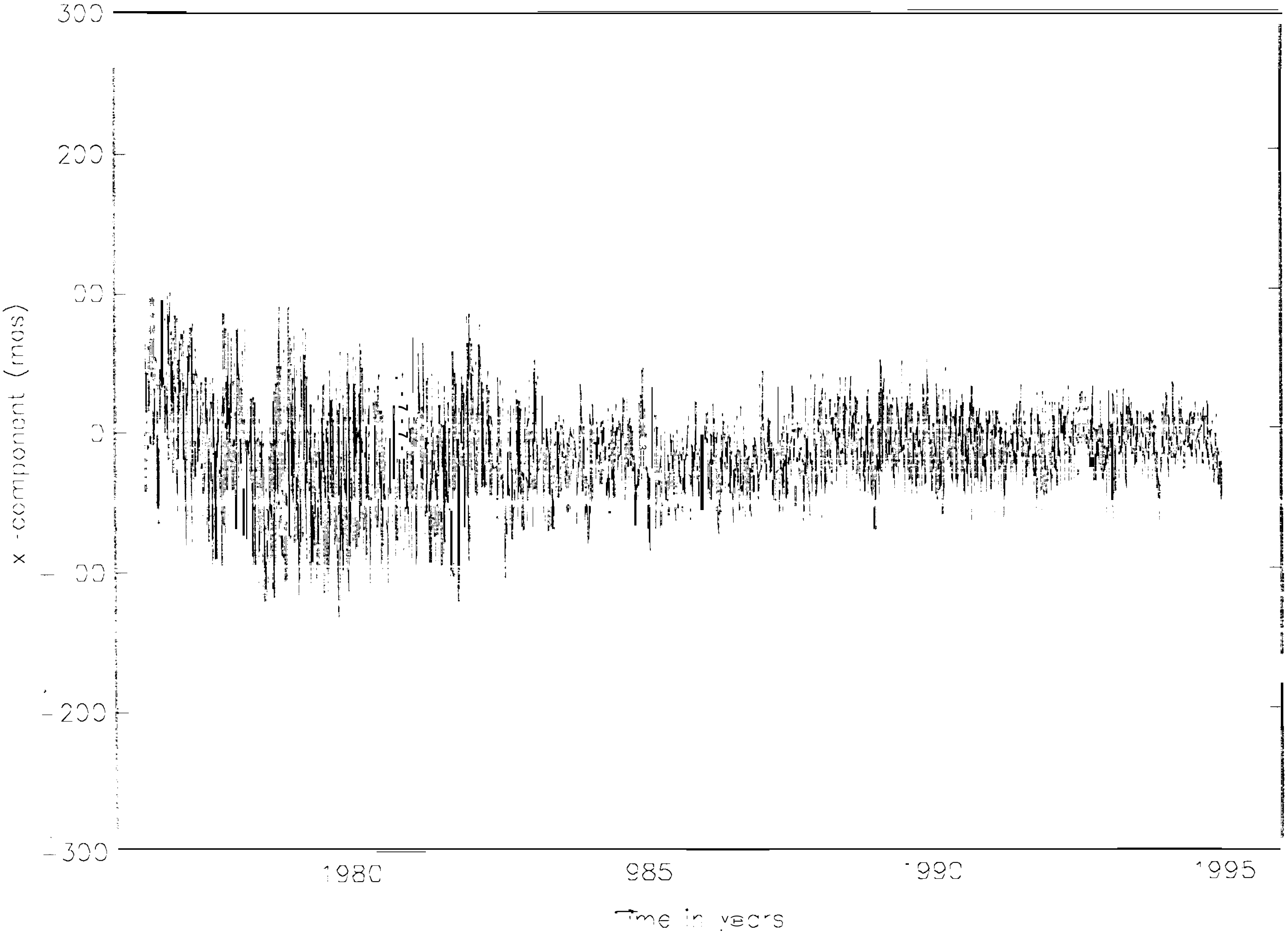
ATMOSPHERIC ANGULAR MOMENTUM (AAM)

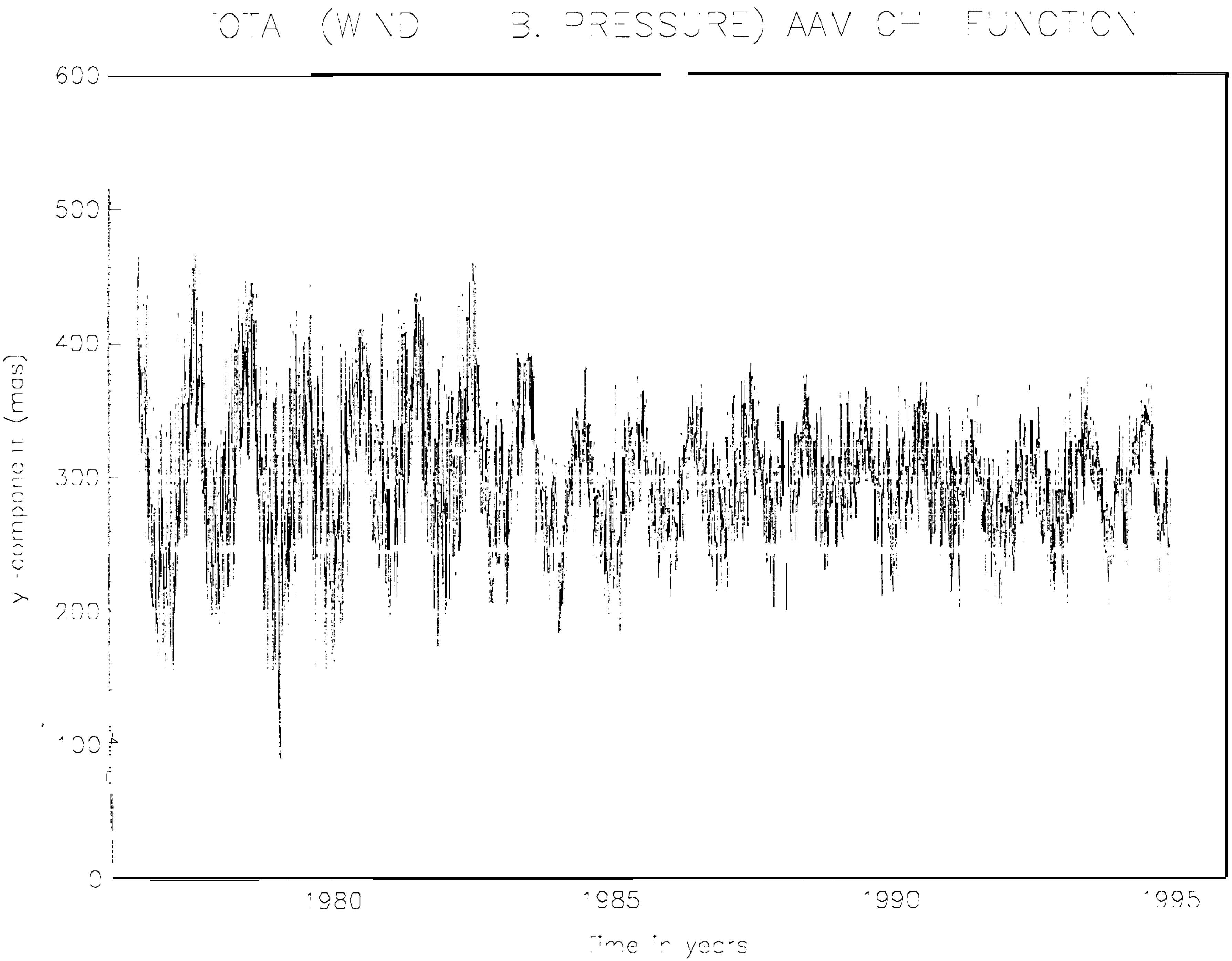
- **Angular momentum of atmosphere changes due to:**
  - **Changes in strength and direction of atmospheric winds**
  - **Changes in mass distribution of atmosphere (changes in atmospheric pressure)**
- **Under principle of conservation of angular momentum, the rotation of the solid Earth changes as AAM is exchanged with the solid Earth**
- **AAM %-functions quantify the atmospheric excitation of Earth rotation**
  - **AAM pressure term (inertia tensor)**
    - $\chi_1^P + i\,\chi_2^P = \dfrac{-1.00\ a^4}{(C-A)\,g} \int p_s \sin\phi \cos^2\phi\,(\cos\lambda + i \sin\lambda)\,\mathrm{d}\lambda\,\mathrm{d}\phi$
  - **AAM wind term (relative angular momentum)**
    - $\chi_1^w + i\,\chi_2^w = \dfrac{-1.43\ a^3}{\Omega\,(C-A)\,g} \int (u \sin\phi \cos\phi + i\ v\ \cos\phi)\,(\cos\lambda + i \sin\lambda)\,\mathrm{d}p\,\mathrm{d}\lambda\,\mathrm{d}\phi$
- **AAM χ-functions are computed from operational analyses of:**
  - **Japan Meteorological Agency (JMA)**
  - **United Kingdom Met. Office (UKMO)**
  - **National Centers for Environmental Prediction (NCEP)**
  - **European Centre for Medium-Range Weather Forecasts (ECMWF)**
- **AAM χ-functions from the NCEP were chosen for use here**
  - **It is the only series currently available that fully overlaps in time with SPACE94**

OCEANIC RESPONSE TO ATMOSPHERIC SURFACE PRESSURE FLUCTUATIONS

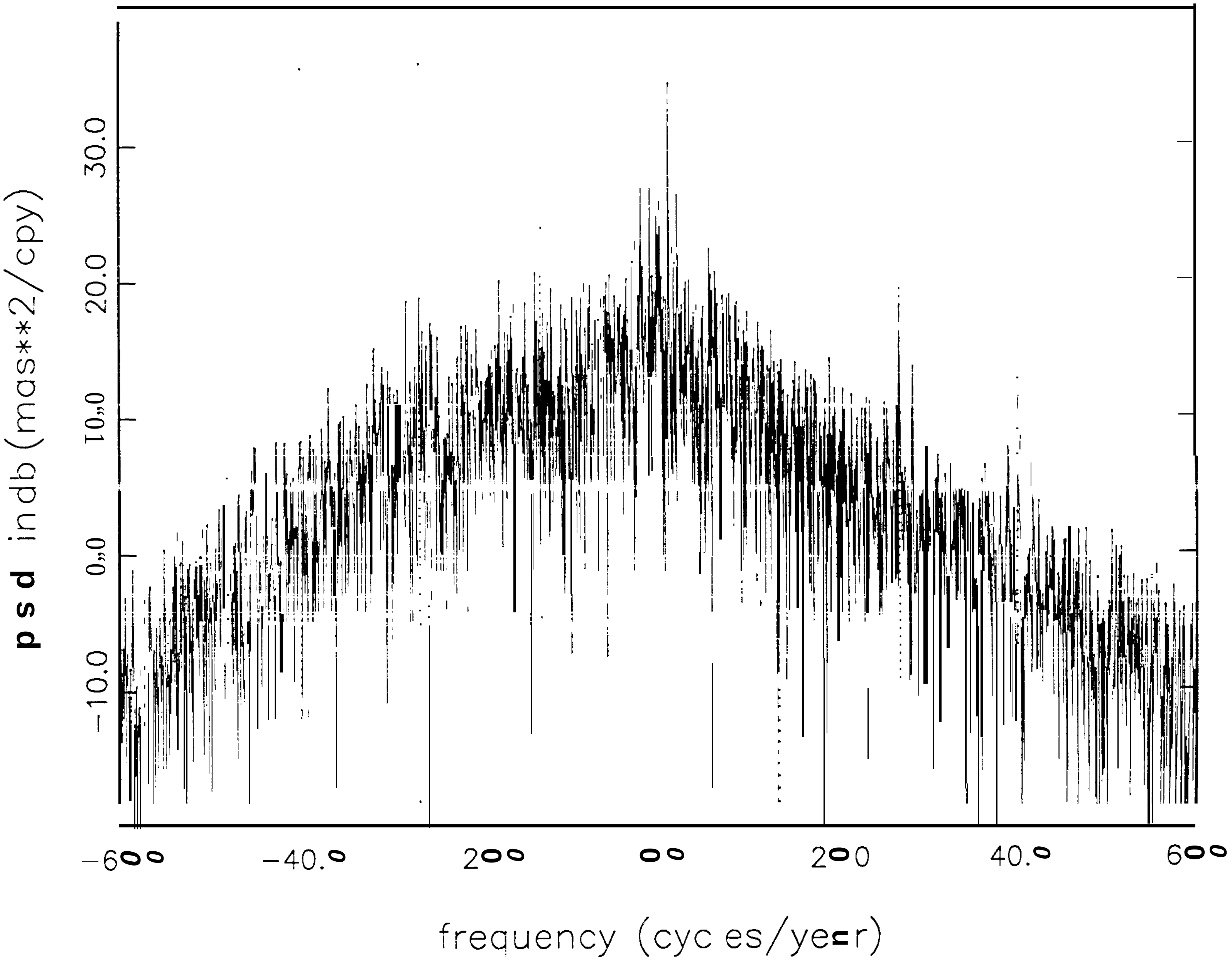
- **How do oceans transmit atmospheric surface pressure fluctuations to ocean bottom?**
  - **For AAM pressure term, need pressure evaluated at crustal surface**
- **Inverted barometer assumption**
  - **Ocean response to imposed atmospheric surface pressure fluctuations is such that pressure at ocean bottom does not change**
  - **Generally held to be valid at long periods (> a few days)**
- **Rigid ocean (no inverted barometer) assumption**
  - **Atmospheric surface pressure fluctuations fully transmitted (without attenuation) to the ocean bottom**
- **AAM pressure terms are available that have been computed under each of these assumptions**
- **AAM pressure term computed under inverted barometer assumption chosen for use here**

TOTAL (WIND + I.B. PRESSURE) AAM CHI-FUNCTION

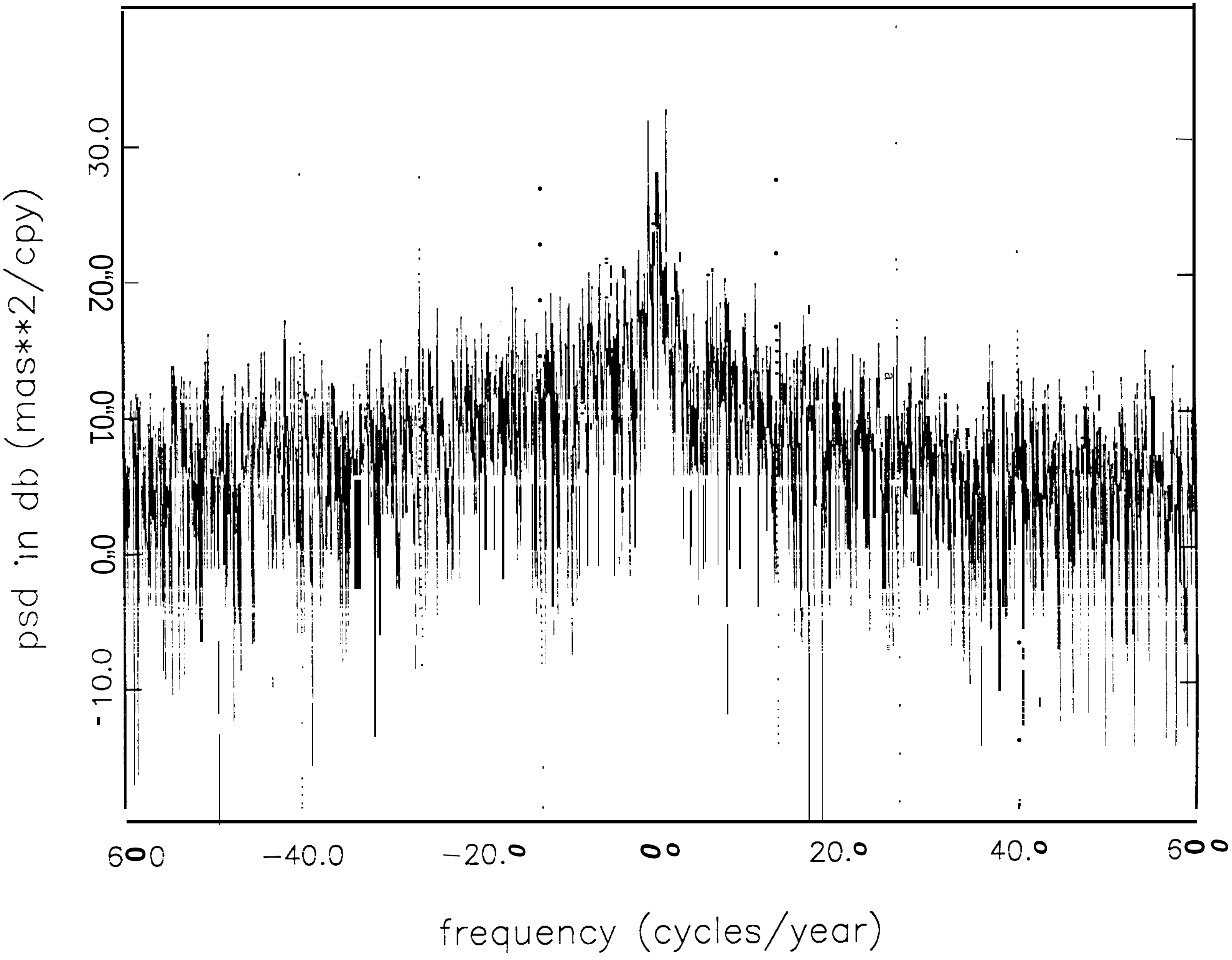


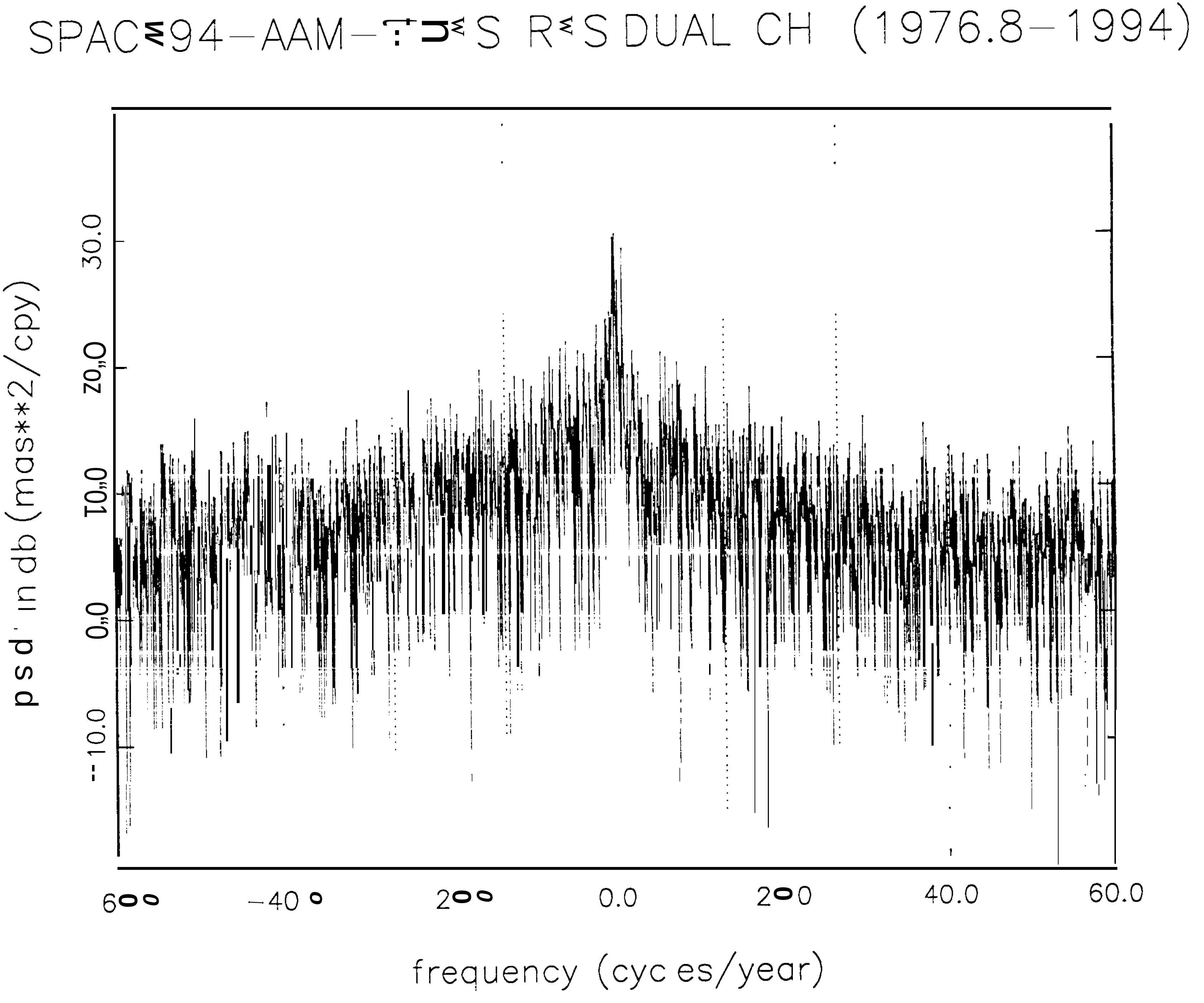

TOTA (WIND B. PRESSURE) AAV CH FUNCTION
600
500
400
300
200
100
0
y -component (mas)
1980
1985
1990
1995
Time in years

SPACE94 POLAR MOTION CHI-FUNCTION 1976.8–1994)

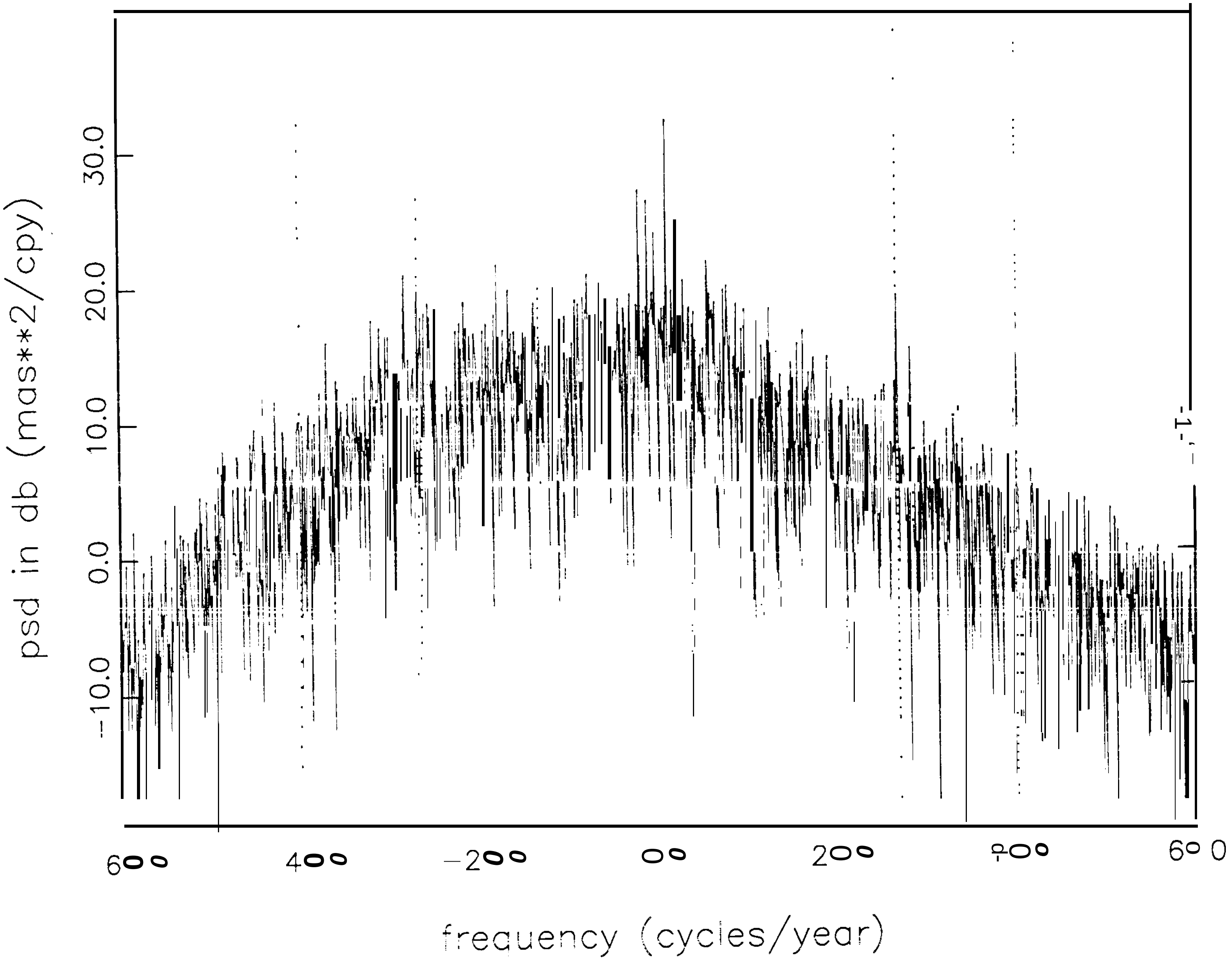


SPACE94-AAM RESIDUAL CHI FUNCTION (1976.8-1994)

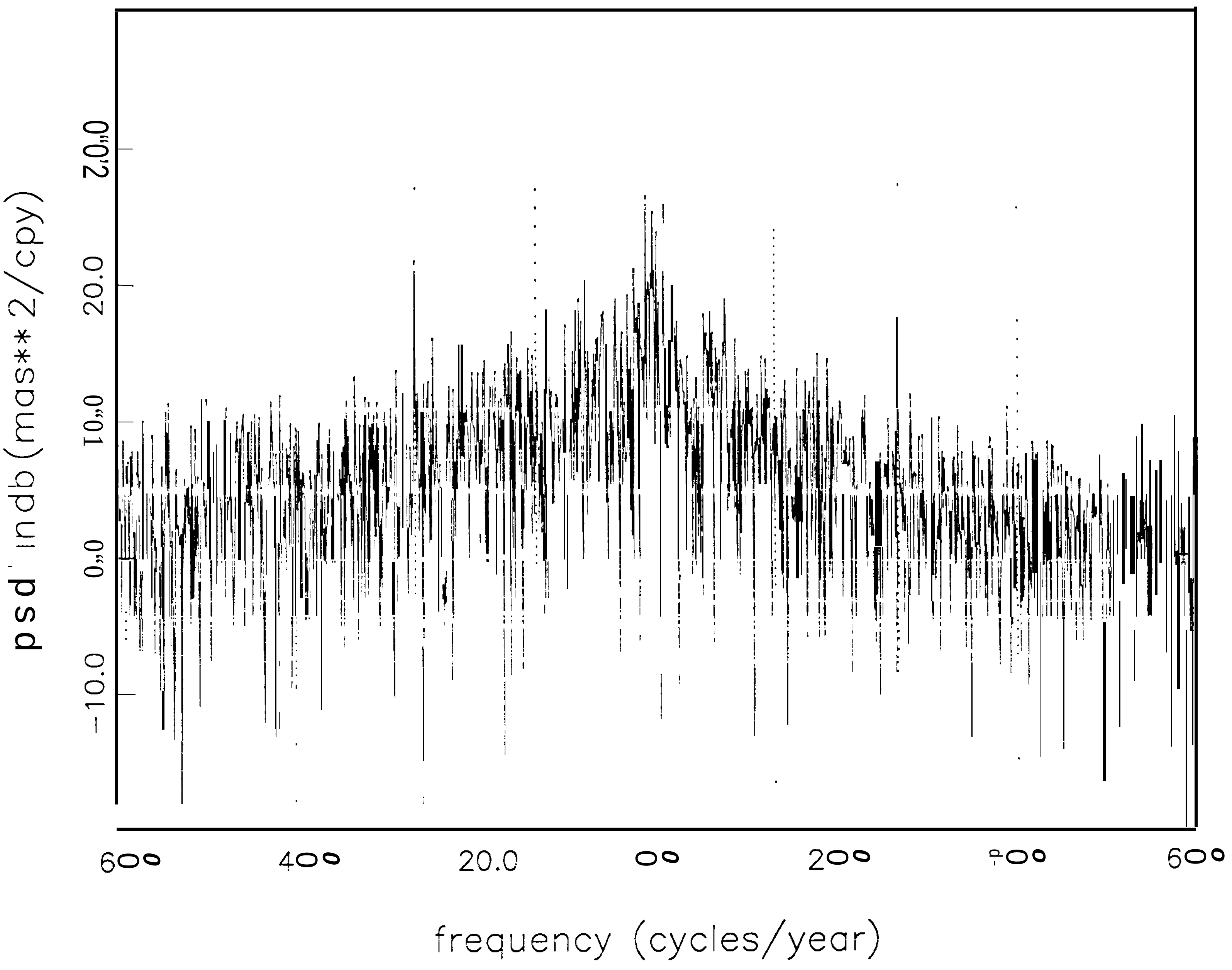



SPACE94-AAM-TUS RES DUAL CH (1976.8-1994)
psd in db (mas**2/cpy)
30.0
20.0
10.0
0.0
-10.0
-60.0
-40.0
-20.0
0.0
20.0
40.0
60.0
frequency (cycles/year)

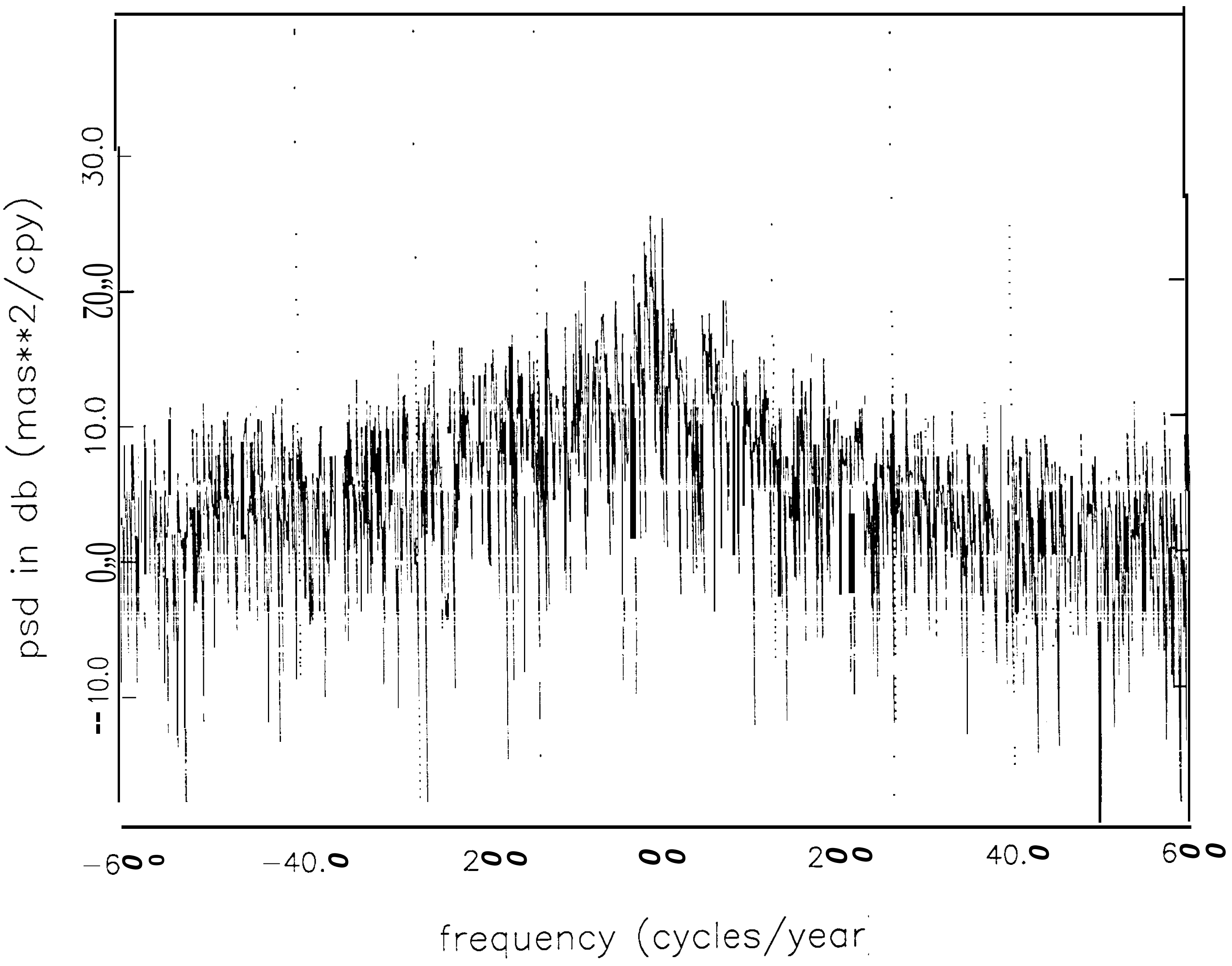
SPACE94 POLAR MOTION CHI FUNCTION (1984–1994)



SPACE94-AAM RESIDUAL CHI-FUNCTION (1984-1994)



SPACW94-AAM-TDWS RESDUAL CH (1984-1994)



Observed & Predicted Effects of Long-Period Ocean Tides on the Polar Motion Excitation Function $\chi(t)$

	Prograde		Retrograde	
	Amplitude (mas)	Phase (degrees)	Amplitude (mas)	Phase (degrees)
M9' (9.12-day)				
SPACE94–AAM	0.54 ± 0.45	38 ± 48	0.21 ± 0.45	79 ± 126
Dickman	0.13	73	0.21	15
M9 (9.13-day)				
SPACE94–AAM	0.47 ± 0.45	-30 ± 55	0.41 ± 0.45	–95 ± 63
Dickman	0.32	73	0.52	15
Mf' (13.63-day)				
SPACE94-AAM	1.61 ± 0.45	56 ± 16	2.01 ± 0.45	87 ± 13
Dickman	0.52	100	0.71	8
Seiler/Gross	0.72	55	0.59	72
Mf (13.66-day)				
SPACE94–AAM	0.86 ± 0.45	93 ± 30	2.73 ± 0.45	14 ± 10
Dickman	1.26	100	1.72	8
Seiler/Gross	1.72	55	1.44	72
Mm (27.55-day)				
SPACE94–AAM	0.75 ± 0.45	49 ± 35	0.82 ± 0.45	-59 ± 32
Dickman	0.47	136	0.28	–7
Seiler/Gross	0.78	74	0.92	28

Quoted uncertainties are l-sigma formal errors

Prograde and retrograde amplitudes *A* and phases ϕ defined by:

$$\chi(t) = A_p \, e^{i\alpha_p} \, e^{i\,\phi(t)} + \mathrm{A,} \; e^{i\alpha_r} \, e^{-i\,\phi(t)}$$

where the subscript *p* denotes prograde and *r* denotes retrograde

RESULTS

- **At *Mf* tidal frequency, observations agree best with Dickman model predictions**
  - Prograde phases differ by 7’)
  - Retrograde phases differ by 6°
  - Dickman predicted prograde amplitude 47% too large
  - Dickman predicted retrograde amplitude 37% too small
- **At *Mf'* tidal frequency, observations agree best with Seiler model predictions**
  - Prograde phases differ by 1”
  - Retrograde phases differ by 15’)
  - Seiler predicted prograde amplitude < 1/2 that observed
  - Seiler predicted retrograde amplitude < 1/3 that observed
- **At the *M9* and *M9'* tidal frequencies, spectrum shows no enhanced power, and the recovered amplitudes are at level of formal error**
  - Observations provide upper limit for effect at these frequencies
- **At the *Mm* tidal frequency, spectrum shows no enhanced power, but the recovered amplitudes are somewhat larger than the formal error**
  - Formal error may be underestimated by about factor of 2
  - Observations provide upper limit for effect at this frequency
- **Discrepancies between the 2 model predictions, and between predictions and observations, illustrate the need for improved models for effect of long-period ocean tides on the Earth’s rotation**