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EFFECT OF LONG PERIOD OCEAN TIDES ON THE EARTH'S ROTATION

by

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- Spectra of polar motion excitation functions exhibit enhanced power in fortnightly tidal band
  - This enhanced power is attributed to ocean tidal excitation
- Upon subtracting atmospheric wind and pressure effects, fits for periodic terms at the *Mf* and *Mf'* tidal frequencies are obtained and compared to predictions of ocean tide models
  - Ocean tide models predict polar motion excitation effects that differ with each other, and with observations, by factors as large as 2–3
- Need improved models for effect of long-period ocean tides on Earth's rotation

APPROACH

- Polar motion excitation function
  - Use that derived from SPACE95 polar motion values
    - SPACE95 is a Kalman filter-based combination of space-geodetic Earth rotation measurements
  - Spans 1976.8–1995 at 1-day intervals
- Remove effects of atmospheric wind and pressure
  - Use the NCEP/NCAR reanalysis atmospheric angular momentum values
    - Spans 1979–1995 at 6-hour intervals
  - 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 SPACE95–AAM residual series
  - Fit for mean, trend, and periodic terms at the termensual (*M9* and *M9'*), fortnightly (*Mf* and *Mf'*), monthly (*Mm*), semiannual (*Ssa*), and annual (*Sa*) tidal frequencies
  - Fit to entire 17-year span of SPACE95–AAM residual series
    - 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)
  - Desai (1996)

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 $\mathbf{L} = \cdot\omega + \mathbf{h}$

- Assume rotation 's small perturbation from state of uniform rotation at rate Ω. Keeping terms to first order yields ong period Liouville eq.

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

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 $\mathbf{p}(t) \equiv x_p(t) - i\,y_p(t)$
  - 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 χ-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:

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

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

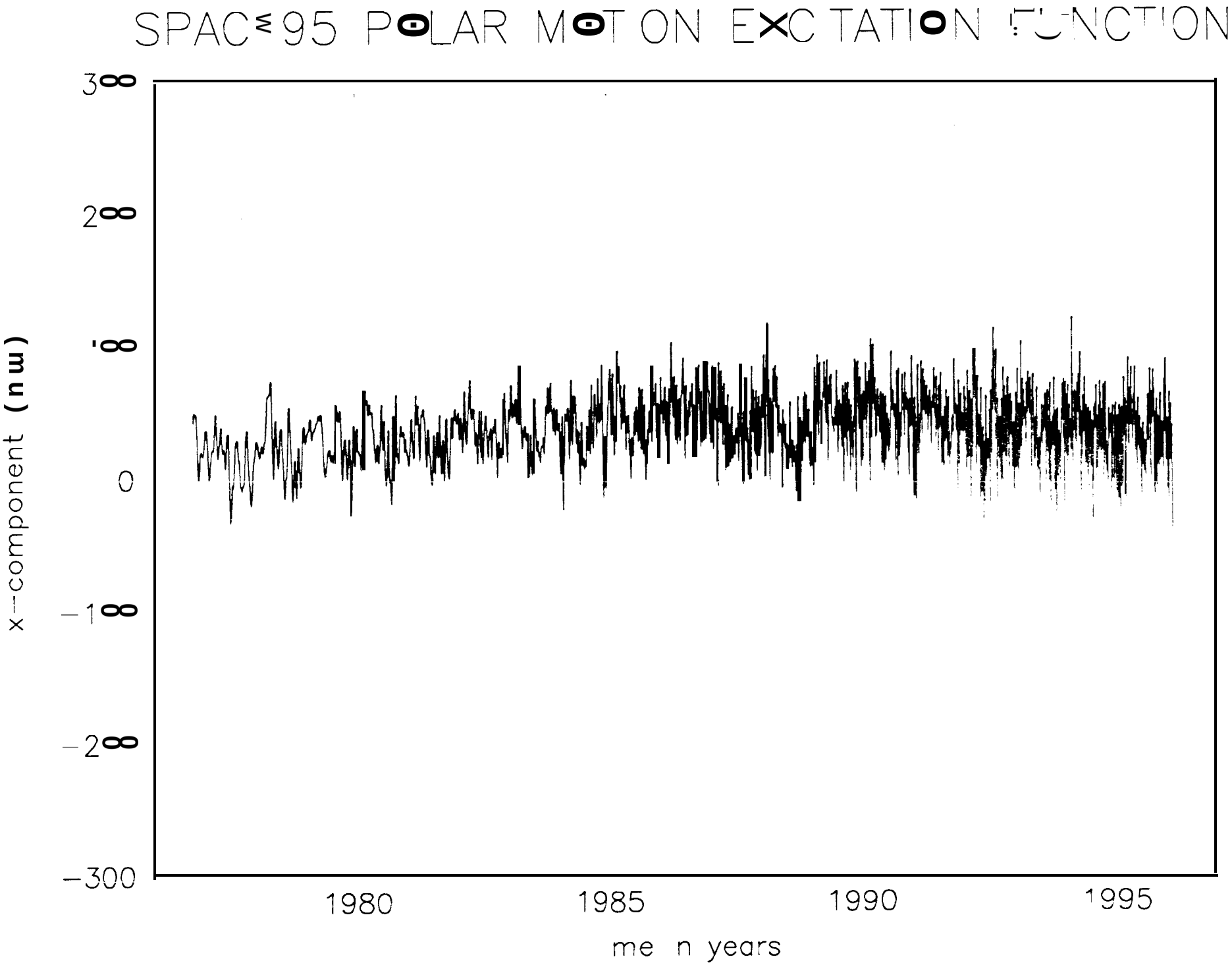
  - This is the equation for simple harmonic motion in the complex plane
  - The excitation pole is that pole about which the rotation pole instantaneously revolves
  - Changes in the excitation pole force changes in the polar motion
- Can be recovered from polar motion observations either by direct numerical differentiation or by deconvolution
- The SPACE95 polar motion excitation functions have been used here

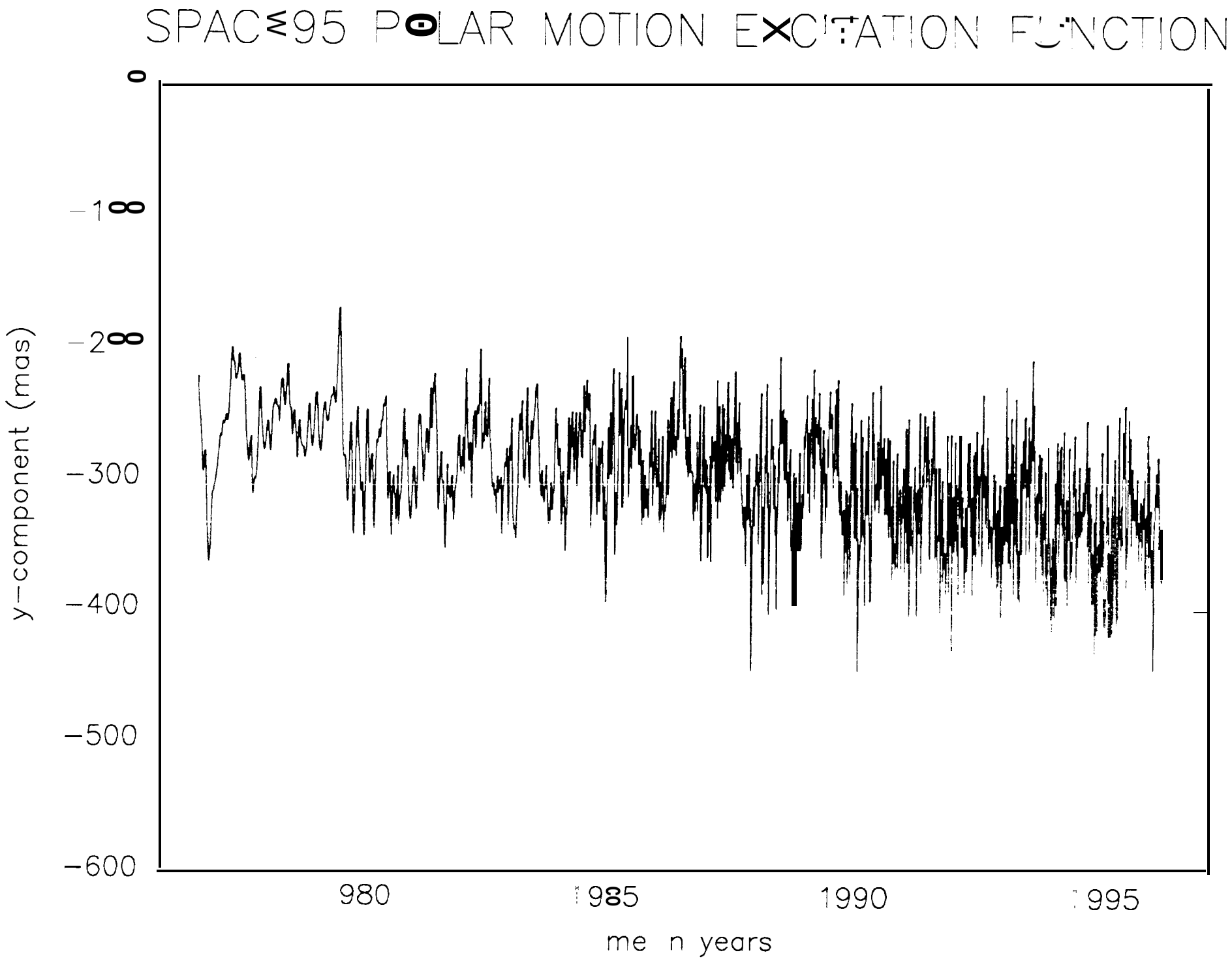
SPACE95 EARTH ORIENTATION SERIES

- 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 SIO 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 SPACE95
  - Consists of values for PMX, PMY, UT1–UTC, their formal uncertainties and correlations spanning October 6.0, 1976 to February 10.0, 1996 at daily intervals

SPACE95 POLAR MOTION EXCITATION FUNCTION

- SPACE95 consists of values for polar motion and UT1–UTC
- Kalman filter used to generate SPACE95
  - 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 SPACE95


SPACE95 POLAR MOTION EXCITATION FUNCTION
300
200
100
0
−100
−200
−300
x-component (mas)
1980
1985
1990
1995
time in years

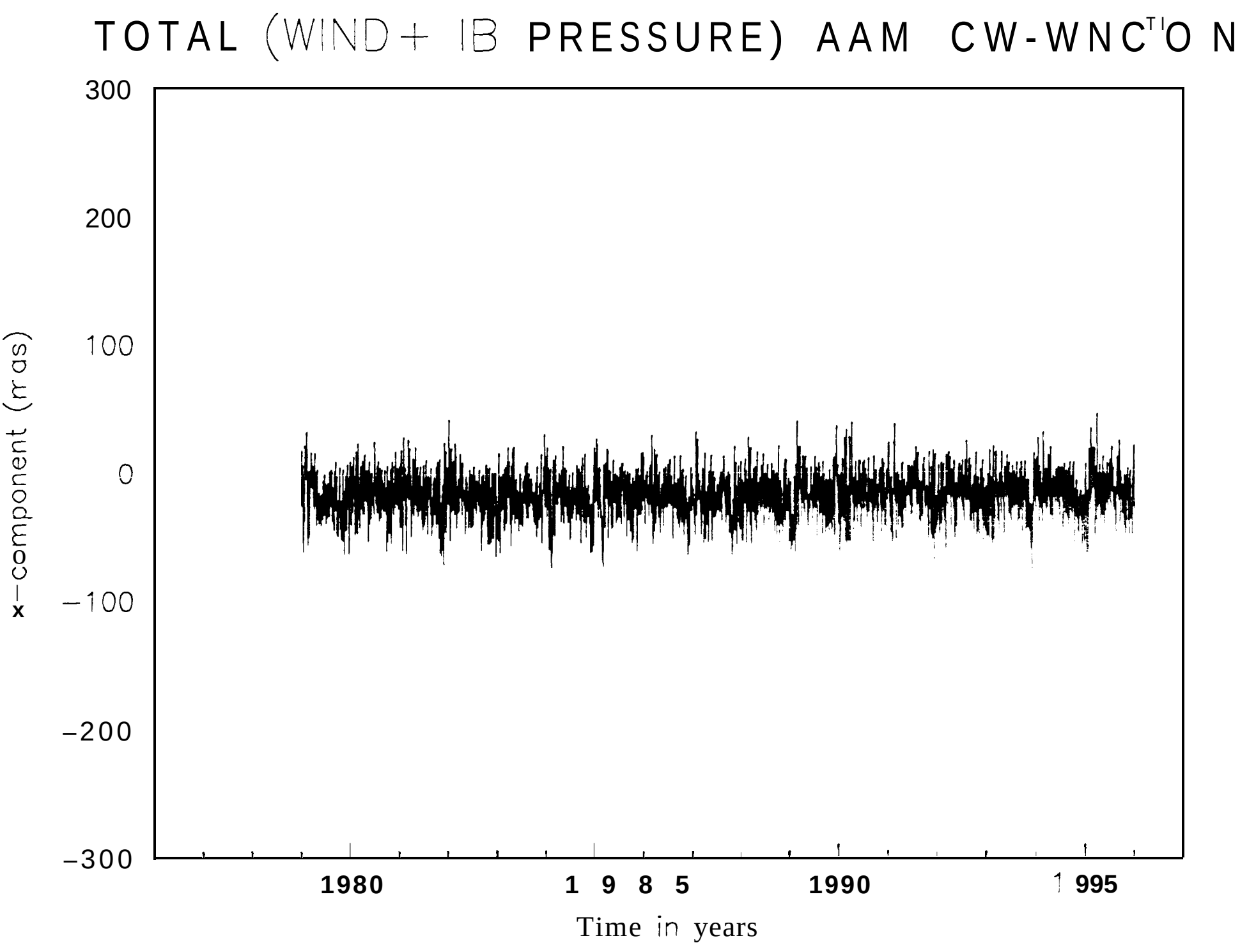

SPACE95 POLAR MOTION EXCITATION FUNCTION
0
-100
-200
-300
-400
-500
-600
y-component (mas)
1980
1985
1990
1995
time in years

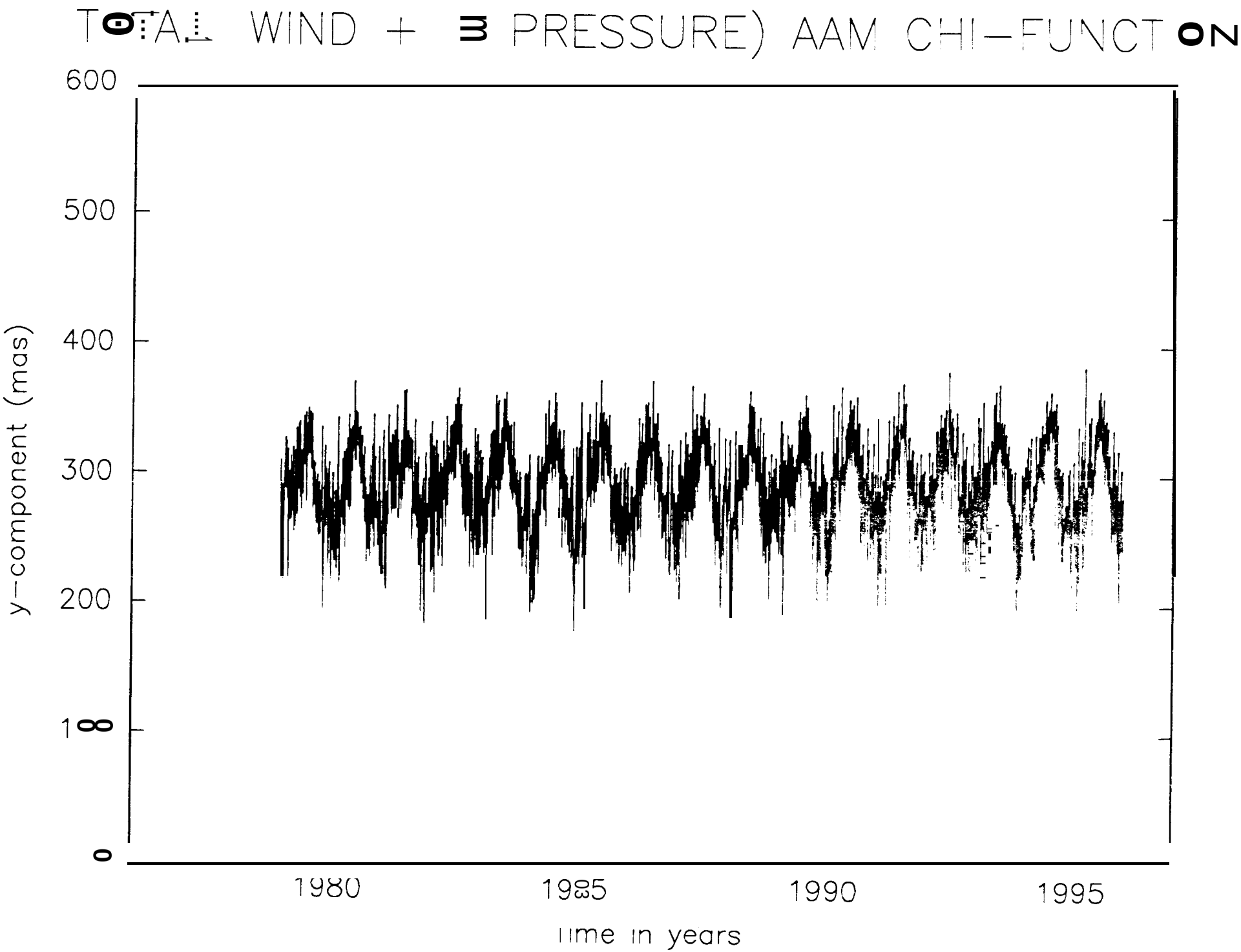
ATMOSPHERIC ANGULAR MOMENTUM (AAM)

- 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 χ-functions quantify the atmospheric excitation of Earth rotation
  - AAM pressure term (inertia tensor)
    - $$\chi_1^p + i\,\chi_2^p = \frac{-1.00\ a^4}{(C-A)\,g} \int p_s \sin\phi \cos^2\phi\,(\cos\lambda + i\,\sin\lambda)\,\mathrm{d}\lambda\,\mathrm{d}\phi$$
  - AAM wind term (relative angular momentum)
    - $$\chi_1^w + i\,\chi_2^w = \frac{-1.43\ a^3}{\Omega\,(C-A)\,g} \int (u \sin\phi \cos\phi + i\,v\,\cos\phi)\,(\cos\lambda + i\,\sin\lambda)\,\mathrm{d}p\,\mathrm{d}\lambda\,\mathrm{d}\phi$$
- AAM χ-functions are computed from the operational analyses of the:
  - 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 are computed from the reanalysis systems of the:
  - NASA / GSFC Data Assimilation Office (DAO)
  - NCEP / NCAR
  - ECMWF
- The NCEP / NCAR reana ysis AAM χ-functions were used here

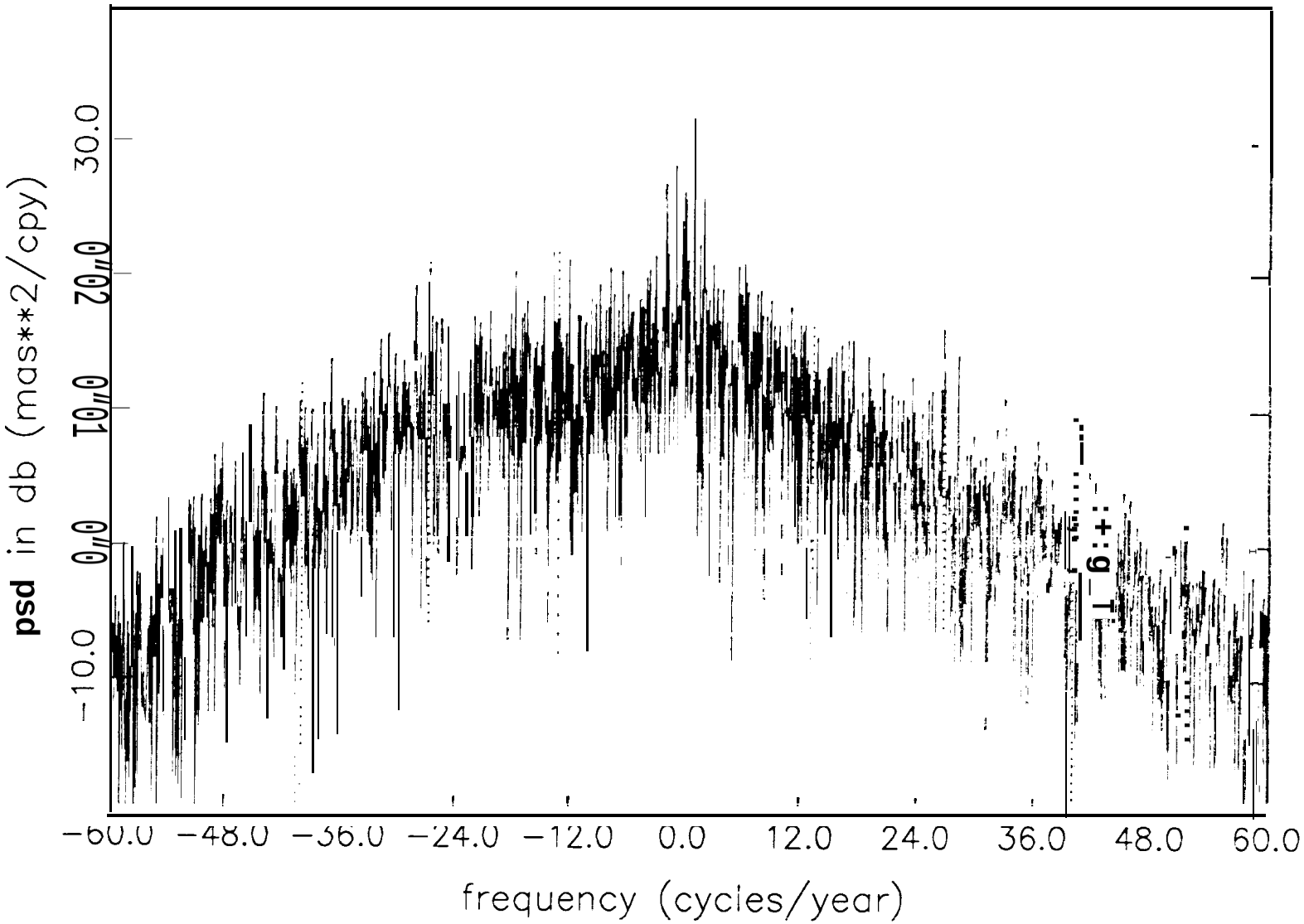
OCEANIC RESPONSE TO ATMOSPHERIC SURFACE PRESSURE FLUCTUATIONS

- 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

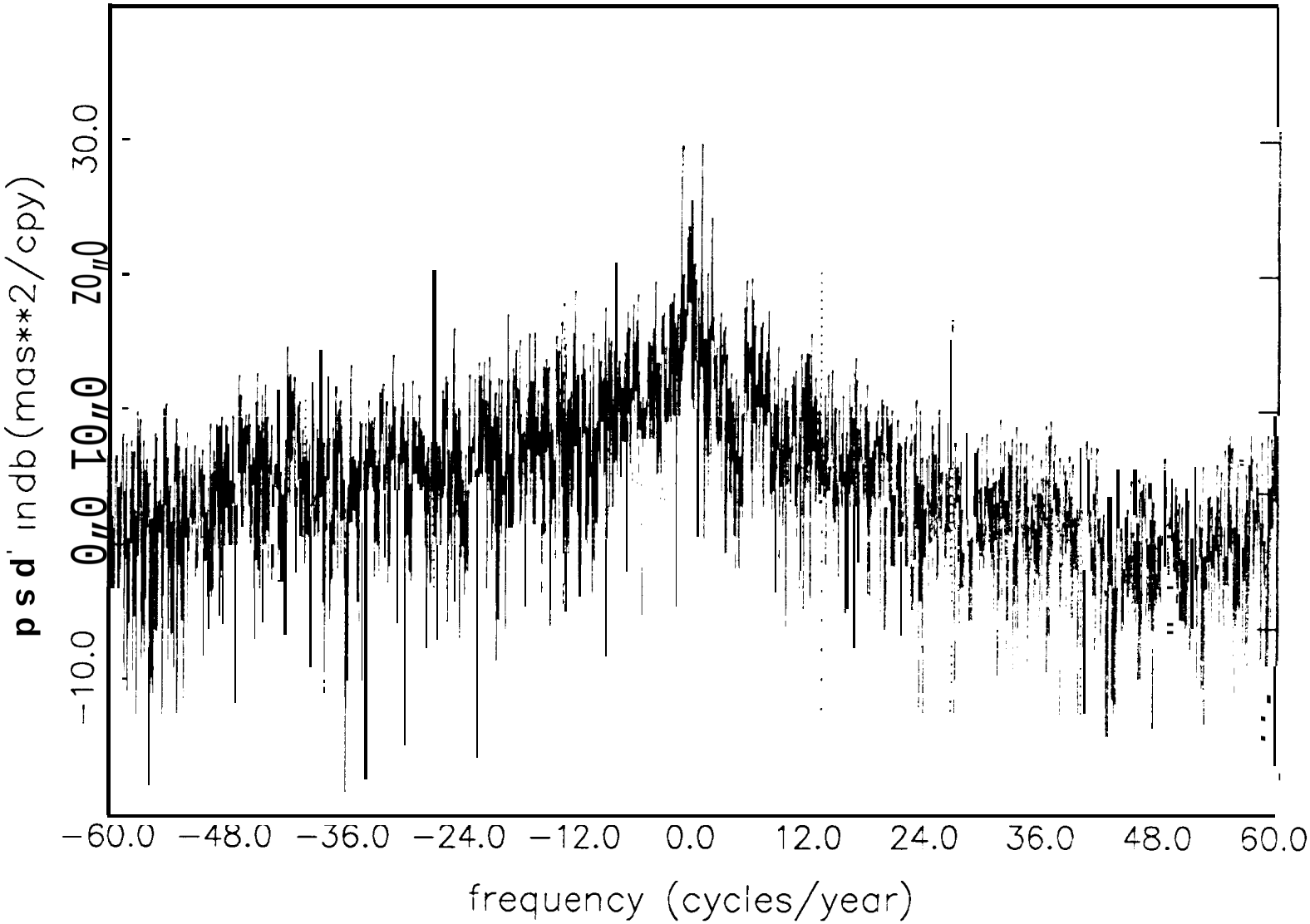

TOTAL (WIND+ IB PRESSURE) AAM CW-WNCTION
300
200
100
0
−100
−200
−300
x−component (mas)
1980
1985
1990
1995
Time in years

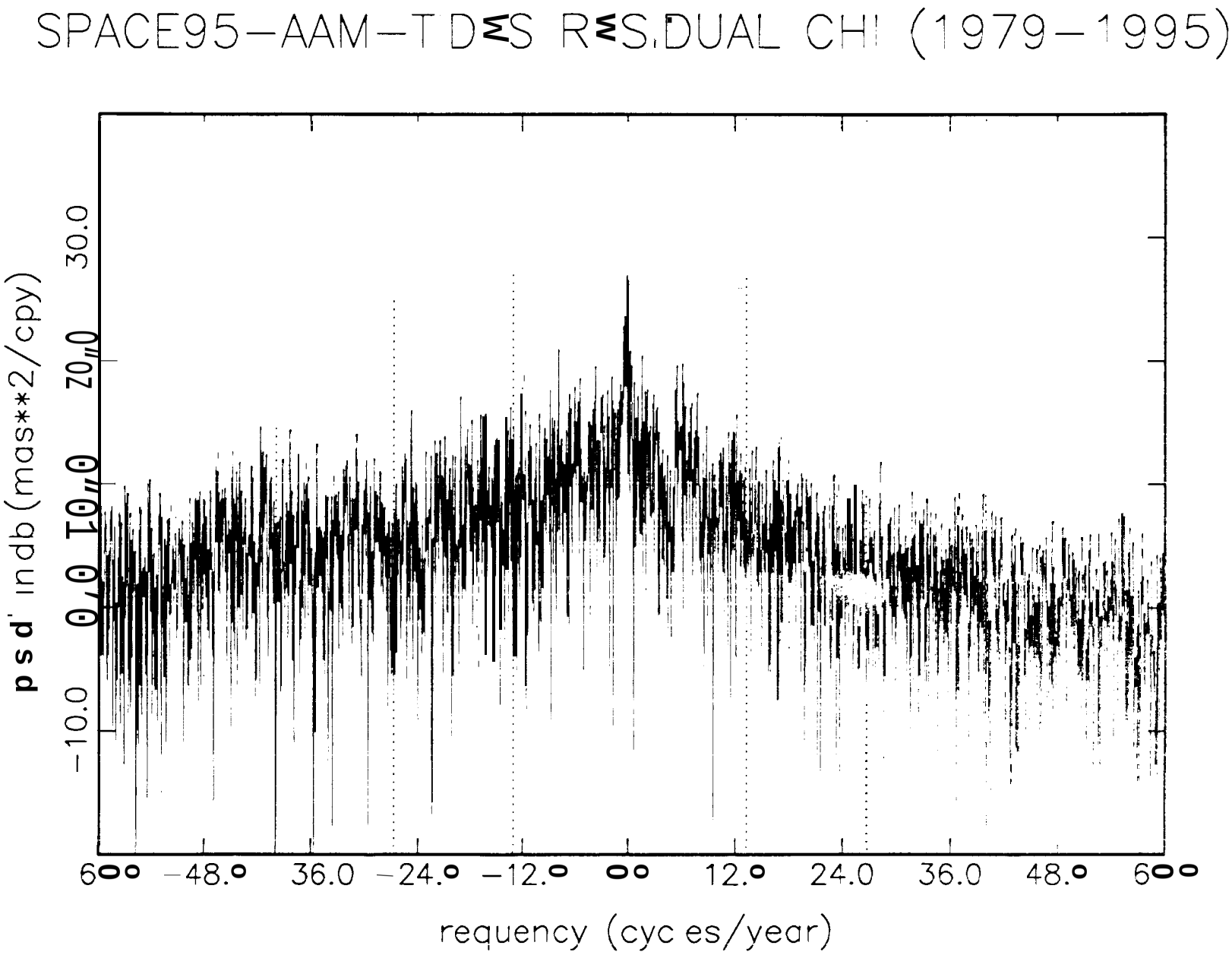

TOTAL WIND + PRESSURE) AAM CHI-FUNCTION
600
500
400
300
200
100
0
y-component (mas)
1980
1985
1990
1995
time in years

SPACE95 POLAR MOTION CH –FUNCT'ON 1979–1995)

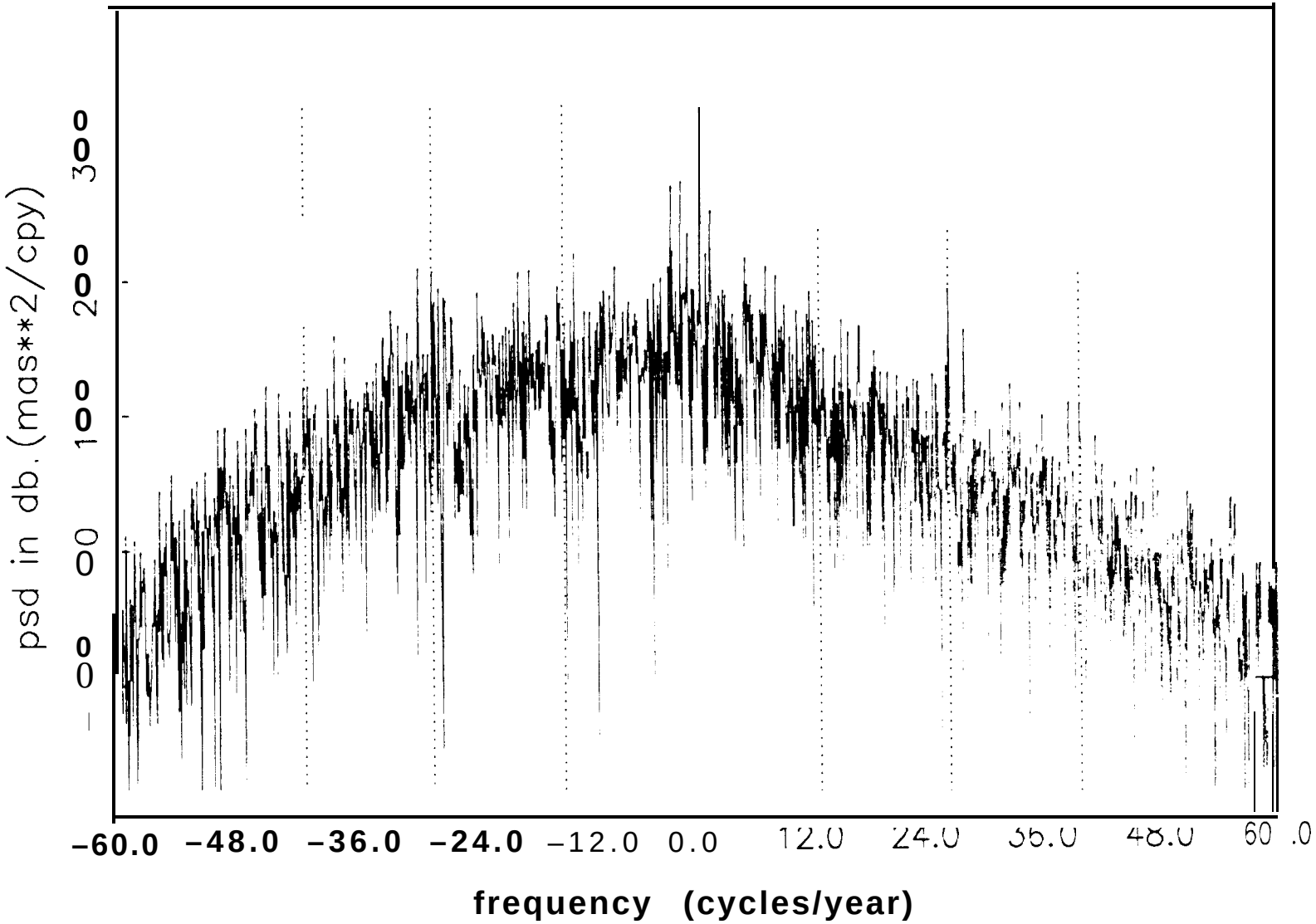


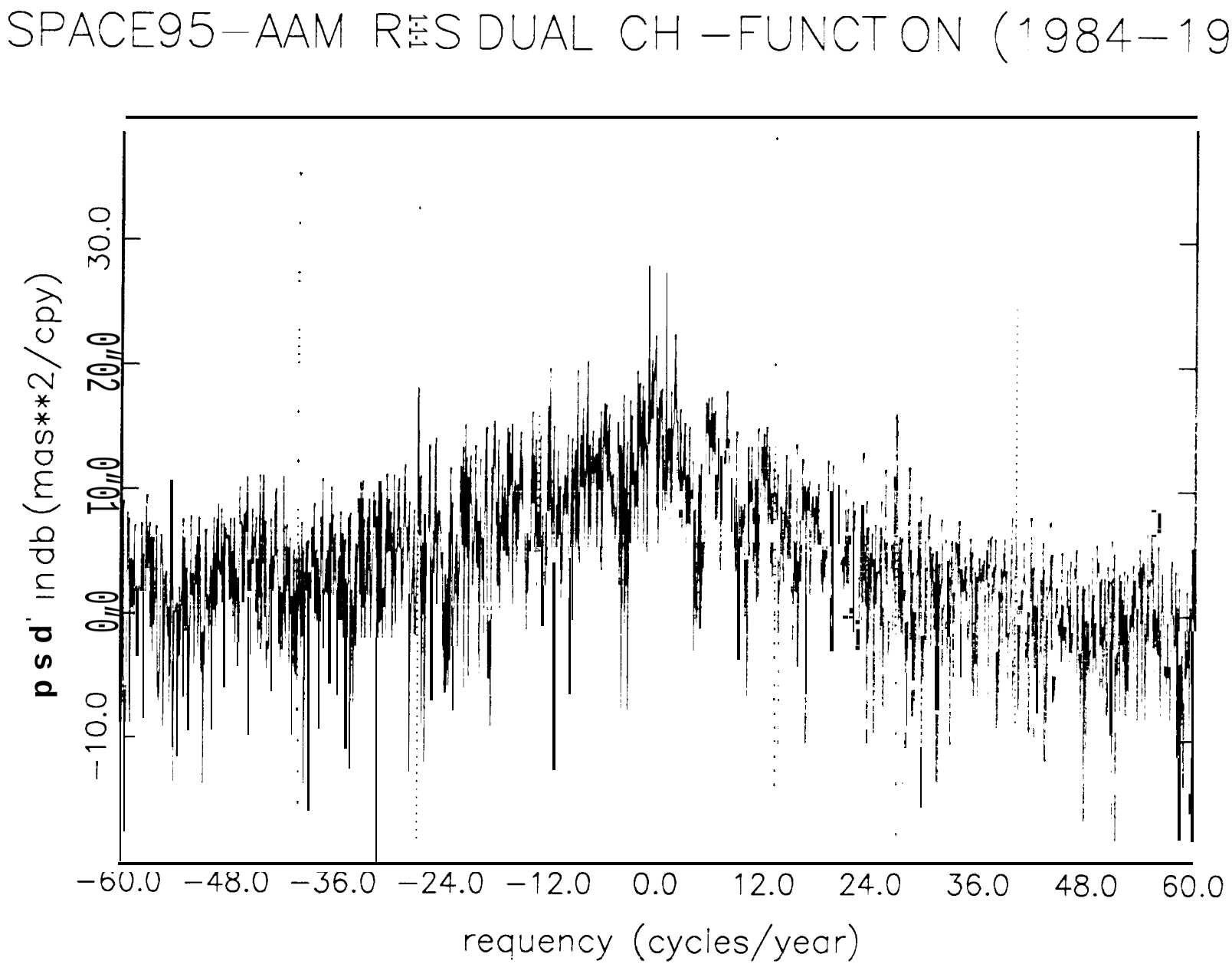
SPACE95 AAM RESIDUAL CHI FUNCTION 1979–1995

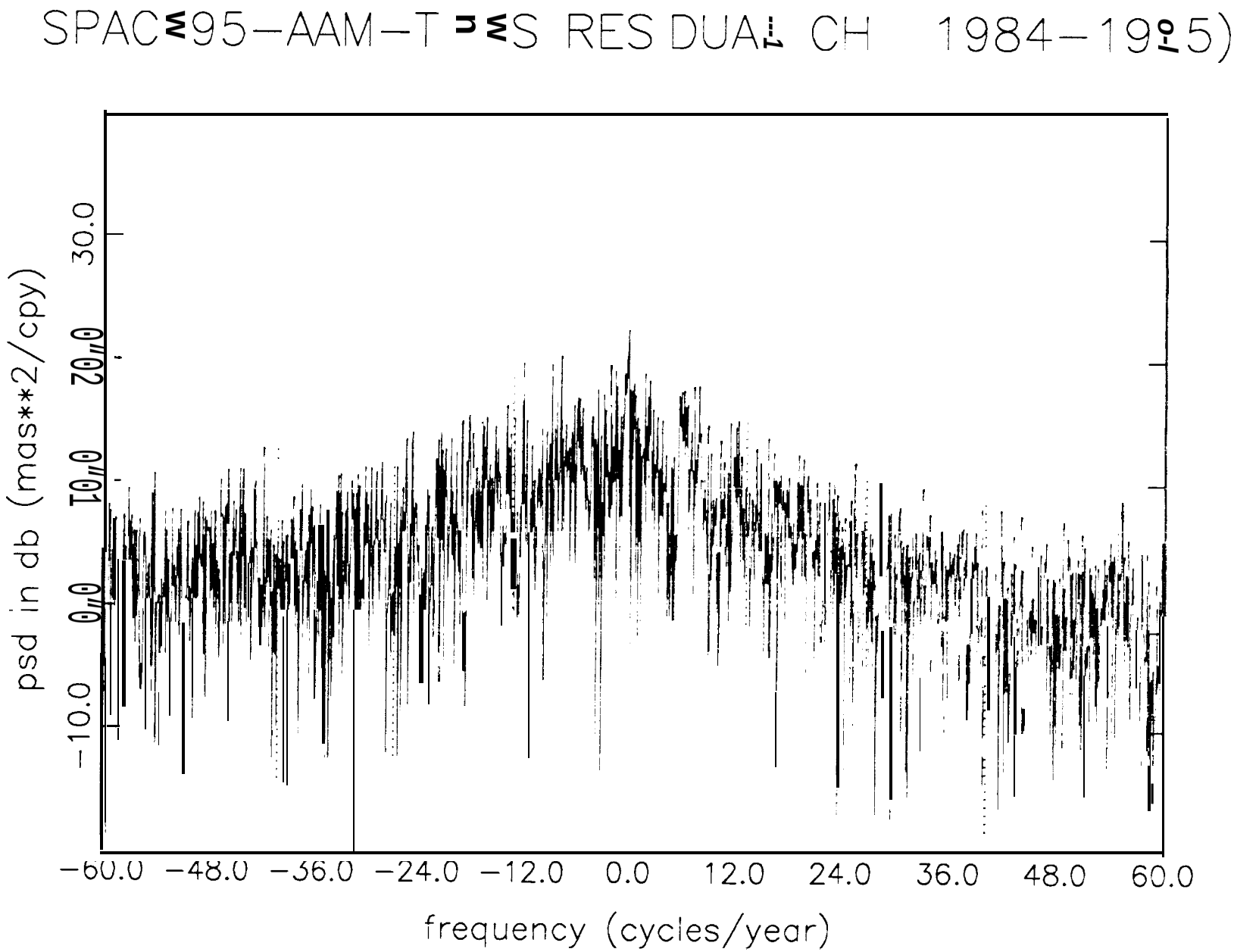



SPACE95–AAM–TIDES RESIDUAL CHI (1979–1995)
psd in db (mas**2/cpy)
30.0
20.0
10.0
0.0
-10.0
60.0
-48.0
36.0
-24.0
-12.0
0.0
12.0
24.0
36.0
48.0
60.0
requency (cycles/year)

SPACE95 POLAR MOTION CHI-FUNCTION (1984-1 995)




SPACE95–AAM RESIDUAL CH–FUNCTION (1984–1995)
psd' in db (mas**2/cpy)
30.0
20.0
10.0
0.0
−10.0
−60.0
−48.0
−36.0
−24.0
−12.0
0.0
12.0
24.0
36.0
48.0
60.0
requency (cycles/year)


SPACE95-AAM-TRUS RESIDUAL CH 1984-1995)
psd in db (mas**2/cpy)
30.0
20.0
10.0
0.0
-10.0
-60.0
-48.0
-36.0
-24.0
-12.0
0.0
12.0
24.0
36.0
48.0
60.0
frequency (cycles/year)

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

	Prograde Amplitude (mas)	Prograde Phase (degrees)	Retrograde Amplitude (mas)	Retrograde Phase (degrees)
***M9'* (9.12-day)**				
SPACE95–AAM	0.68 ± 0.30	−6 ± 25	0.60 ± 0.30	141 ± 28
Gross et al. (1996)	0.54 ± 0.45	38 ± 48	*0.21 ± 0.45*	79 ± 126
Dickman (1993)	0.13	73	0.21	15
***M9* (9.13-day)**				
SPACE95-AAM	*0.22 ± 0.30*	19 ± 78	0.33 ± 0.30	−37 ± 52
Gross et al. (1996)	0.47 ± 0.45	-"30 ± 55	0.41 ± 0.45	−95 ± 63
Dickman (1993)	0.32	73	0.52	15
***Mf'* (13.63-day)**				
SPACE95–AAM	1.37 ± 0.30	30 ± 13	1.36 ± 0.30	69 ± 13
Gross et al. (1996)	1.61 ± 0.45	56 ± 16	2.01 ± 0.45	87 ± 13
Dickman (1993)	0.52	100	0.71	8
Seiler/Gross (1993)	0.72	55	0.59	72
***Mf* (13.66-day)**				
SPACE95–AAM	1.69 ± 0.30	116 ± 10	*2.58 ± 0.30*	31 ± 7
Gross et al. (1996)	0.86 ± 0.45	93 ± 30	2.73 ± 0.45	14 ± 10
Dickman (1993)	1.26	100	1.72	8
Seiler/Gross (1993)	1.72	55	1.44	72
Desai (1996)	3.41	158	1.73	−4
***Mm* (27.55-day)**				
SPACE95–AAM	0.65 ± 0.30	95 ± 26	0.98 ± 0.30	−55 ± 17
Gross et al. (1996)	0.75 ± 0.45	49 ± 35	0.82 ± 0.45	−59 ± 32
Dickman (1993)	0.47	136	0.28	−7
Seiler/Gross (1993)	0.78	74	0.92	28
Desai (1996)	1.15	−50	0.90	153

Observed values are in blue. Model predictions are in green, red, black,

Quoted uncertainties in observed values are I-sigma formal errors.

Prograde (p) and retrograde (r) amplitudes A and phases a defined by:

$$\chi(t) = A_p e^{i\alpha_p} e^{i\phi(t)} + A_r e^{i\alpha_r} e^{-i\phi(t)}$$

where $\phi(t)$ is the tidal argument.

RESULTS

- At each tidal frequency, the different observed results, which are based upon different polar motion and AAM data sets spanning different time intervals, agree to within about 1σ of each other

- At the *Mm, M9*, and *M9'* tidal frequencies, the SPACE95–AAM residual spectrum shows no enhanced power, but the recovered amplitudes are somewhat larger than the formal error

  - Formal en or may be underestimated by factor of about 2-3

- Since no resonances in the ocean are expected between the nearby *Mf* and *Mf'* tidal frequencies, the observed prograde (or retrograde) phases at these frequencies should agree with each other

  - Retrograde phases differ by 38°, or "i .9o

  - Prograde phases differ by 86°, or 3.3o

  - 1 hus, prograde (retrograde) phases agree with each other to within about 3o (or to within about 1 inflated o)

- Model predictions differ with each other, and with observations, by factors as large as 2–3

- Discrepancies between 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 '

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