JPL

Atmospheric and Oceanic Excitation of Polar Motion During 1992–1 994

by

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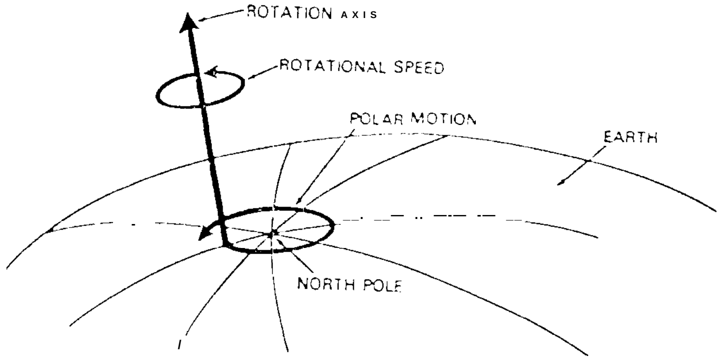
- **Use products of Ocean General Circulation Models (OGCMs) to evaluate effects of ocean current and bottom pressure changes on length-of-day and polar motion during 1992–1994**
  - Princeton Modular Ocean Model (MOM)
  - Miami Isopycnal-Coordinate Ocean Model (MICOM)
- **Compare model-predicted effects with observations of length-of-day and polar motion excitation**
  - After removing atmospheric effects

VARIATIONS IN EARTH's ROTATION

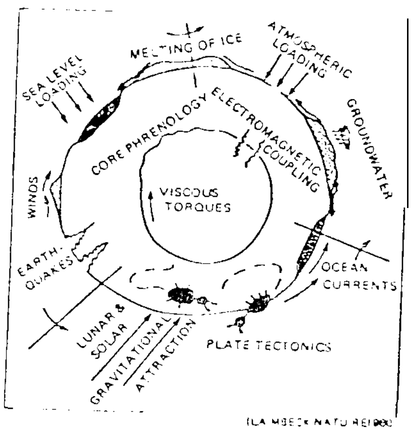


- POLAR MOTION: THE QUASI-PERIODIC, PROGRADE MOTION OF THE ROTATION AXIS AROUND THE NORTH POLE (scale ~ 10 meters)
- LENGTH-oF-DAY VARIATION: VARIATION IN THE ROTATIONAL SPEED. (~ 1 msec/day)

MI LESION:

- DYNAMICS BY EULER, 1752
- CHANDLER'S DISCOVERY OF POLAR MOTION, 1891.
- ASTROMETRIC C) BSERVATION BY ILS (International Latitude Service) SINCE 1900
- ADVENT OF ATOMIC CLOCK IN 1950's
- NEW OBSERVATION TECHNIQUES SATELLITE DOPPLER, SATELLITE LASER FLANGING, VERY-LONG-BASELINE INTERFEROMET RY SINCE 1970's.

POSSIBLE CAUSES:



- ATMOSPHERIC/OCEANIC CIRCULATION?
- SEISMIC ACTIVITIES?
- IMANTLE CONVECTION?
- CORE -MANTLE COUPLING?
- S OLAR ACTIVITIES?

SCIENTIFIC SIGNIFICANCE:

- TO IMPROVE UNDERSTANDING OF EARTH's GLOBAL DYANAMICS
- INFERENCE FOR EARTH's INTERIOR STRUCTURES

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 results in long period Liouville equation

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

$$= \chi(t) - \frac{i}{\Omega} \frac{\partial \chi}{\partial t}$$

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

In time domain:

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

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

[illegible]

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

OCEAN ANGULAR MOMENTUM (OAM)

- Angular momentum of oceans changes due to:
  - changes in strength and direction of oceanic currents
  - changes in mass distribution of oceans (changes in ocean-bottom pressure)
- Under principle of conservation of angular momentum, the rotation of the solid Earth changes as OAM is exchanged with the solid Earth
- OAM can be computed from products of OGCMs by:

[illegible] pressure changes (inertia tensor)

$$\mathbf{M}^p(t) = M_1^p [illegible] + i\, M_2^p\, t) = -\int_{V_o} r^2\, \Omega\, \rho(\mathbf{r},t)\, \sin\phi\, \cos\phi\, (\cos\lambda + i\, \sin\lambda)\, d\,V$$

$$M_3^p(t) = \int_{V_o} r^2\, \Omega\, \rho(\mathbf{r},t)\, \cos^2 [illegible]$$

[illegible] current changes (relative angular momentum)

$$\mathbf{M}^c(t) = M_1^c(t) + i\, M_2^c(t) = \int_{V_o} \rho(\mathbf{r},t)\, r\, \sin\phi\, u(\mathbf{r},t) + i\, v(\mathbf{r},t)]\, (\cos\lambda + i\, \sin\lambda)\, d\,V$$

$$M_3^c(t) = \int_{V_o} \rho(\mathbf{r},t)\, r\, \cos\phi\, u(\mathbf{r},t)\, d\,V$$

- OAM is related to Earth rotation excitation functions by:

$$\chi(t = \chi_1(t + i\, \chi_2(t = \frac{1.6}{\Omega\,(C-A)} \left[\mathbf{M}^c [illegible] + \frac{\mathbf{M}^p(t)}{1.44} \right]$$

$$\Delta\Lambda(t) = \frac{\Lambda_o}{C_m\, \Omega}\; M_3^c(t) + 0.756\, M_3^p\, t)$$

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 (matter term)

$$\chi_1^p + i\,\chi_2^p = \frac{-1.00\,a^4}{(C-A)\,g}\int p_s \sin\phi\cos^2\phi\,(\cos\lambda + i\sin\lambda)\,d\lambda\,d\phi$$

$$\chi_3^p(t) = \frac{0.70\,a^4}{C\,g}\int p_s\,\cos^3\phi\,d\lambda\,d\phi$$

  - AAM wind term (relative angular momentum)

$$\chi_1^w + i\,\chi_2^w = \frac{-1.43\,a^3}{\Omega\,(C-A)\,g}\int(u\sin\phi\cos\phi + \quad v\cos\phi)\,(\cos\lambda + \quad \sin\lambda)\,dp\,d\lambda\,d\phi$$

$$\chi_3^w(t) = \frac{a^3}{C\,\Omega\,g}\int u\cos^2\phi\,dp\,d\lambda\,d\phi$$

- AAM χ-functions are computed from the operational analyses of the:
  - ECMWF • JMA • NCEP • UKMO
- AAM χ-functions are computed from the reanalysis systems of the:
  - NASA / GSFC Data Assimilation Office (DAO) • NCEP / NCAR • ECMWF

OCEANIC RESPONSE TO ATMOSPHERIC SURFACE PRESSURE FLUCTUATIONS

- How do oceans transmit atmospheric surface pressure fluctuations to ocean bottom?
  - [illegible]
- Inverted barometer assumption
  - [illegible]
  - [illegible]
- Rigid ocean (no inverted barometer) assumption
  - [illegible]
- 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

SPACE96 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 and IGS combined series)
- **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
- **Adj uted series combined using Kalman filter to form SPACE96**
  - Consists of values for PMX, PMY, UT1−UTC, their formal uncertainties and correlations spanning September 28.0, 1976 to February 8.0, 1997 at daily intervals

SPACE96 EXCITATION FUNCTIONS

- SPACE96 consists of values for polar motion and UT1−UTC
- Kalman filter used to generate SPACE96
  - ... for the polar motion and Earth rotation process
  - ... excitation functions as well as polar motion and UT1
- Excitation functions used here are those estimated by Kalman filter when generating SPACE96
  - ... functions
  - ...

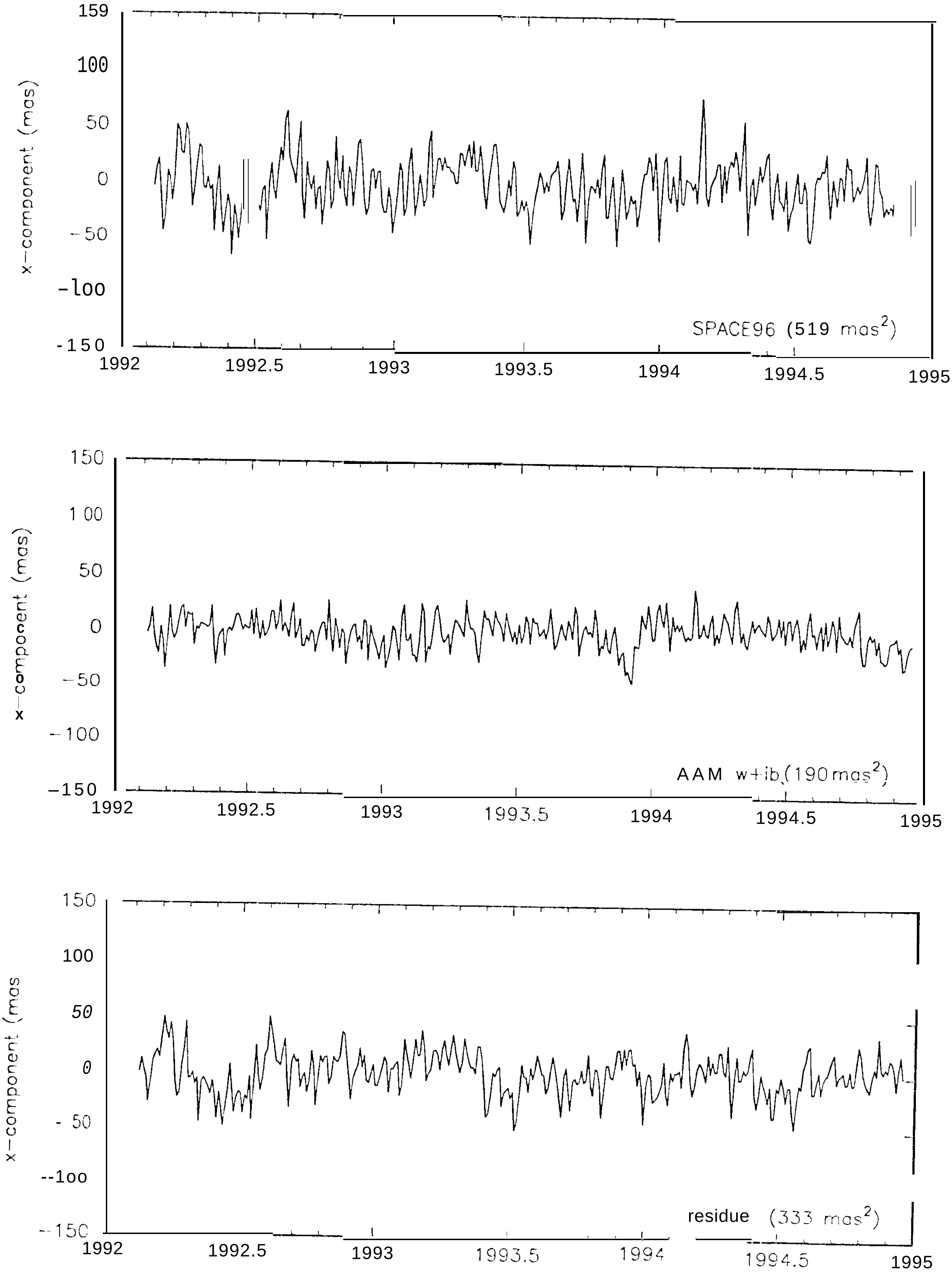
APPROACH

- Earth rotation observations
  - Use SPACE96 Earth rotation excitation functions
    - SPACE96 is a Kalman filter-based combination of space-geodetic Earth rotation measurements
    - Solid Earth and ocean tidal effects have been removed from lod values
    - Daily values at noon spanning 1976.8–1997.1
  - Form 3-day averages of daily noon values; demean and detrend

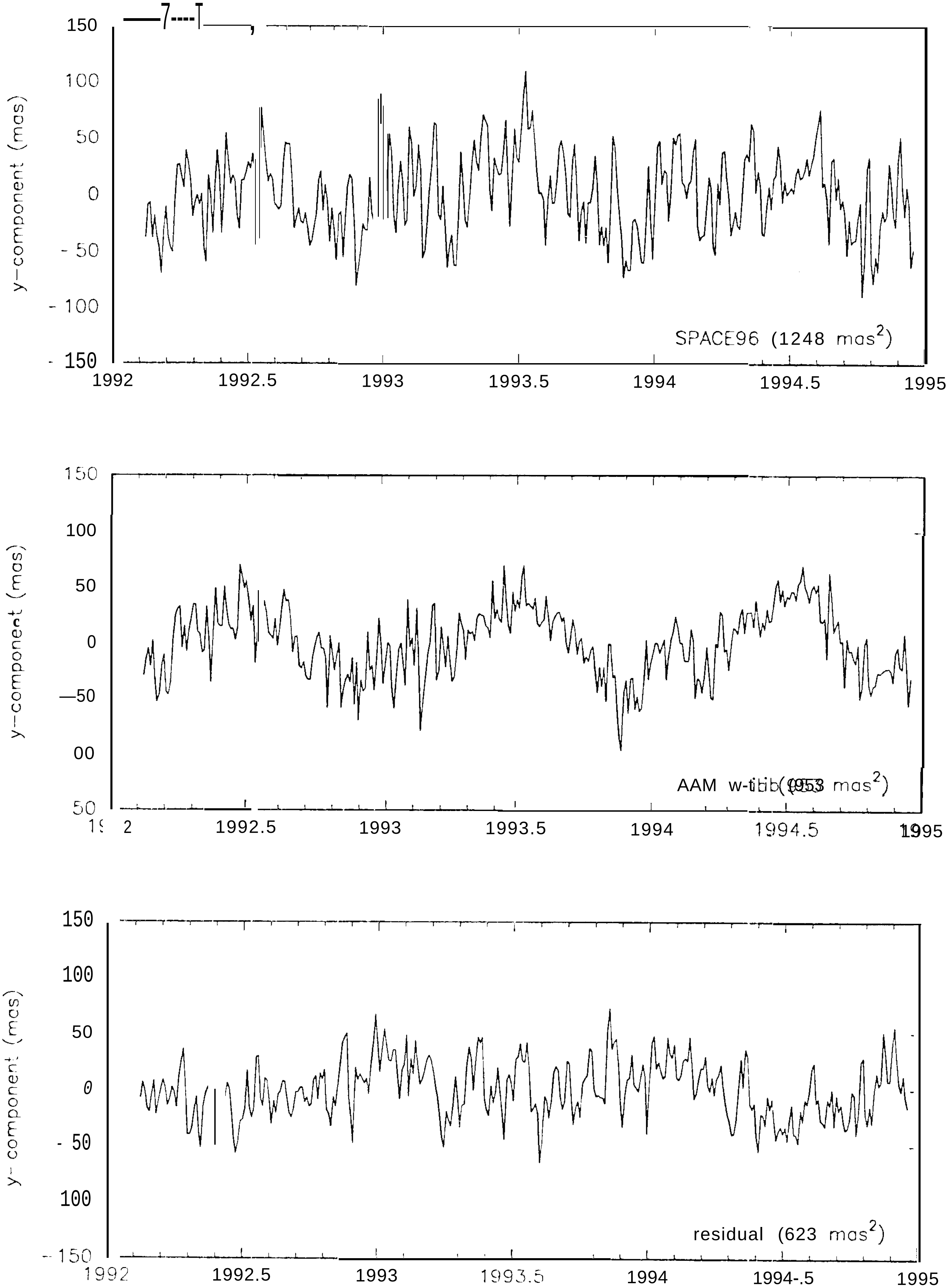
- Remove effects of atmospheric wind and pressure
  - Use the NCEP/NCAR reanalysis atmospheric angular momentum values
    - 6-hour values spanning 1979–present
    - Pressure term used is that computed assuming oceans respond as inverted barometer to imposed atmospheric pressure changes
  - Average over diurnal cycle by forming centered average of 5 successive values with weights 1/8, 1/4, 1/4, 1/4, 1/8
  - Form 3-day average of daily noon values; demean and detrend

- Compare residua to predictions of OGCM
  - Use OAM values computed from POM and MICOM models run at JPL by Yi Chao
    - 3-day averaged values at noon spanning 1992–1994
  - Convert to Earth rotation excitation functions
  - Correct mass term for effects of n[illegible]
  - Detrend to account [illegible]
    climatological forci[illegible]

POLAR MOTION EXCITATION SERIES



POLAR MOTION EXCITATION SERIES



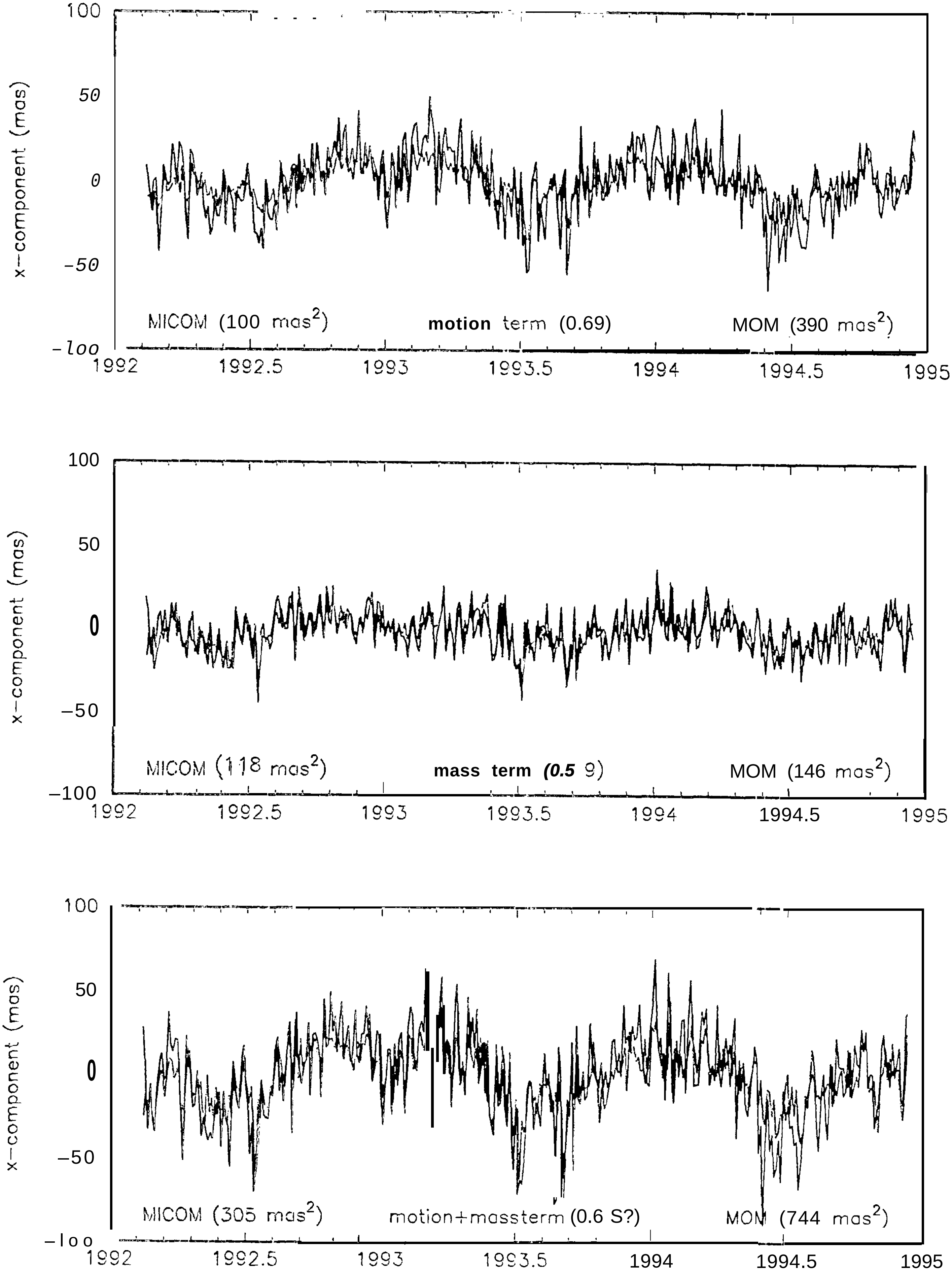
BOUSSINESQ MODELS

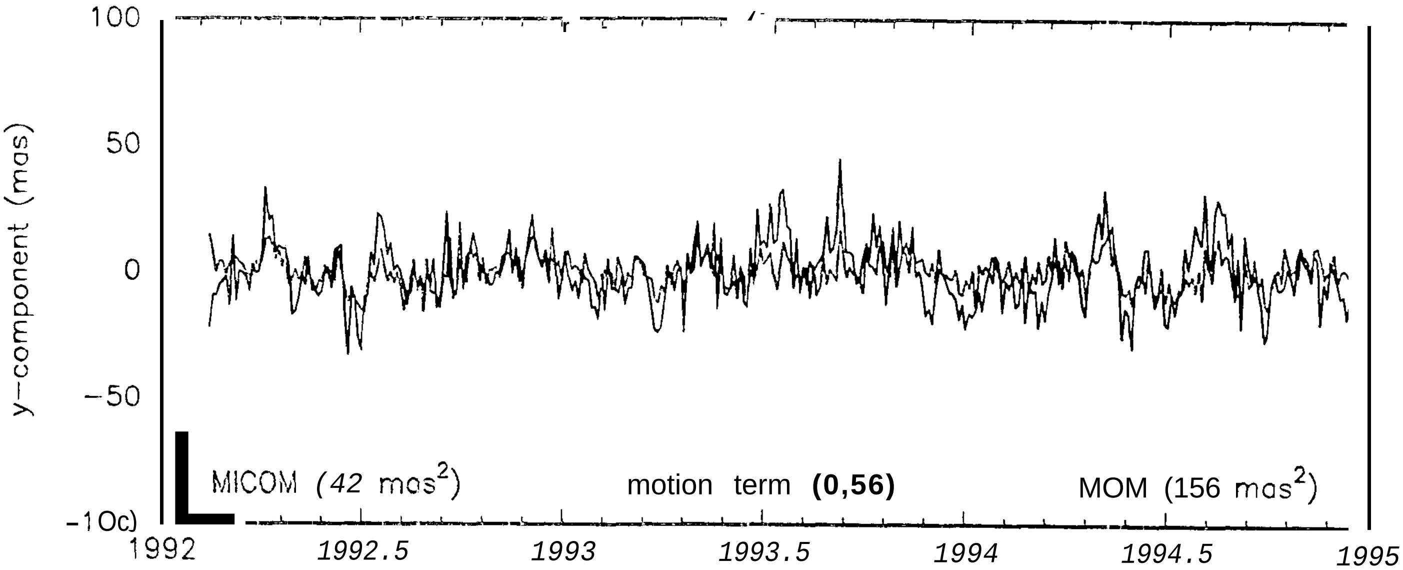
- The Boussinesq approximation is commonly used in ocean general circulation models (OGCMs)
  - Density variations in oceans are small
    - Usually less than ± 2.5% of average density
  - Under Boussinesq approximation, density variations are ignored except in the gravitational buoyancy force
    - Density is not constant but changes as temperature, pressure, and salinity changes
- Boussinesq models conserve volume, not mass
  - Under Boussinesq approximation, conservation of mass equation $\nabla \cdot (\rho \mathbf{u}) = 0$ reduces to $\nabla \cdot \mathbf{u} = 0$ (conservation of volume)
- In Boussinesq ocean models, imposed heat flux can lead to model mass changes
  - Imposed heat flux => temperature changes => density changes via equation of state
  - Since model volume is constant, model mass must change to accommodate density change
    - Boussinesq models do not properly represent steric sea level, but can be corrected to do so (Greatbatch, 1994; Mellor & Ezer, 1995)
- Must account for mass non-conservation
  - Here, we apply a factor designed to ensure mass conservation:

$$p^c(t) = p^u(t) + \Delta p(t) = p^u(t) + p^u(t)\frac{\Delta m(t)}{m(t)} = \frac{p^u(t)}{m(t)} \langle m \rangle$$

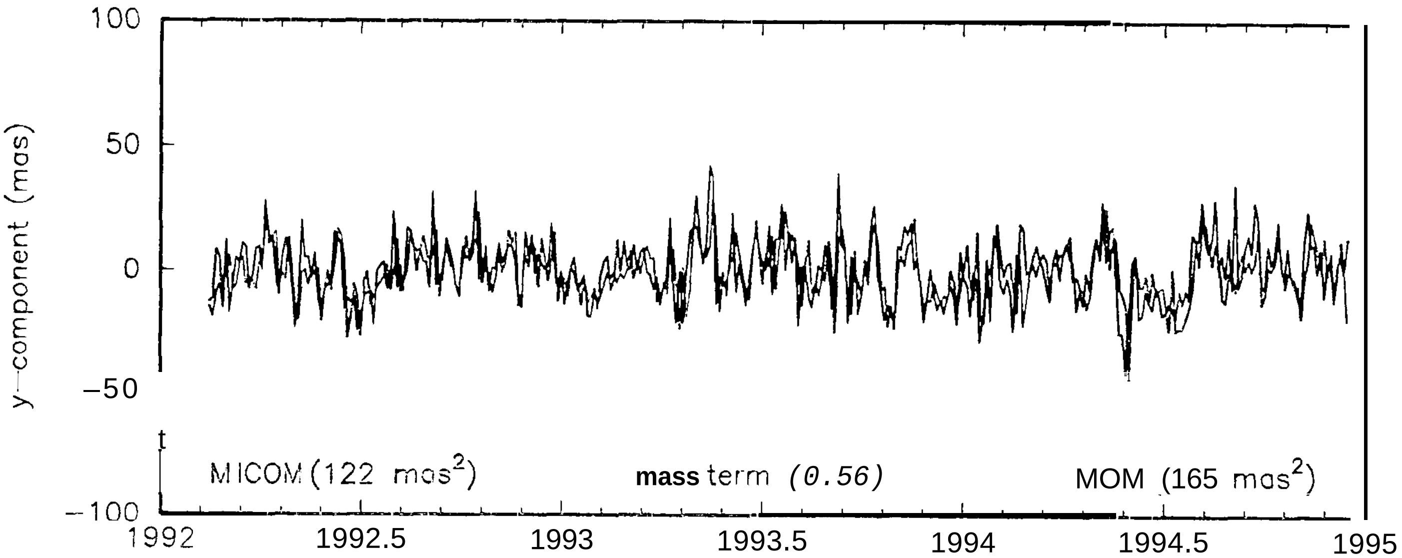
where: superscript c (u) denotes corrected (uncorrected) parameter $p(t)$, $\Delta p(t)$ is the correction applied, $m(t)$ is model mass at time t, $\langle m \rangle$ is time-averaged model mass = $m(t) + \Delta m(t)$

OCEANIC EXCITATION OF POLAR MOTION

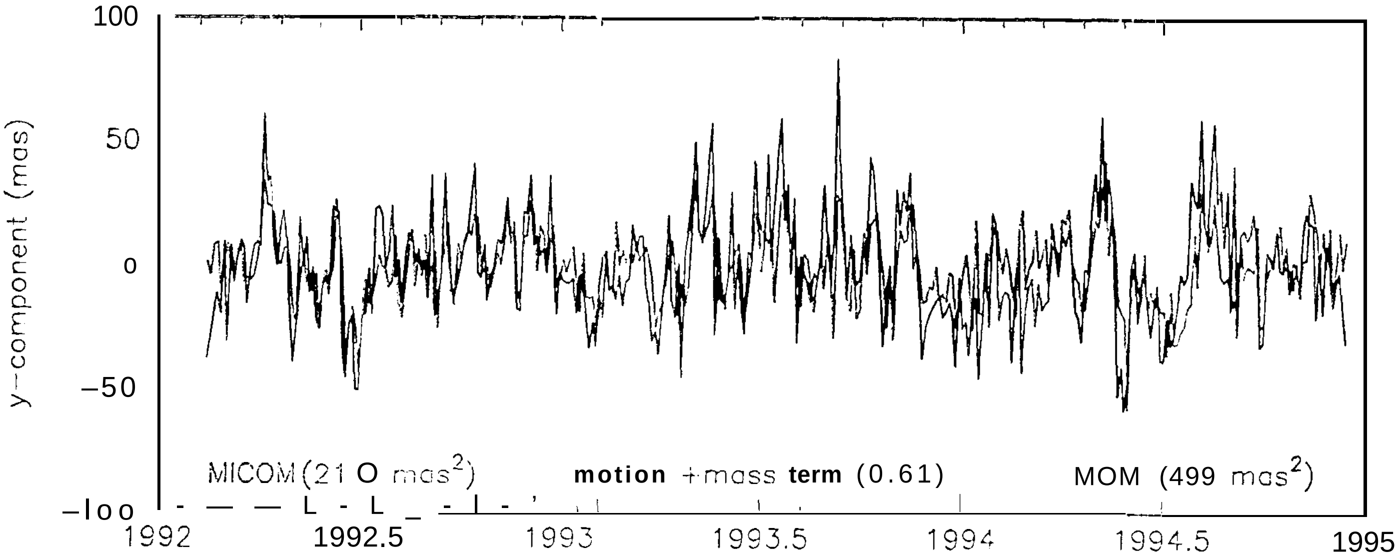




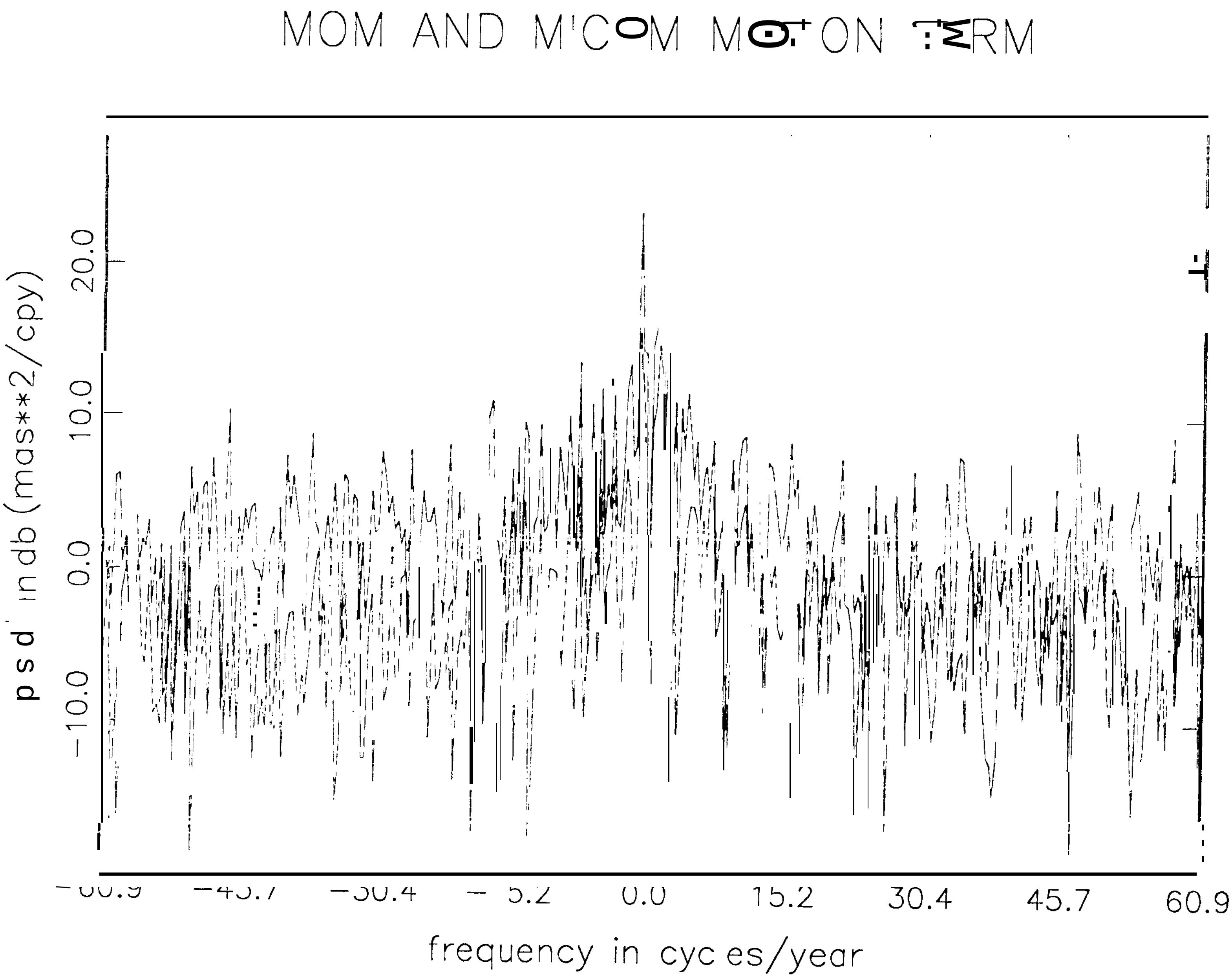
100
50
0
−50
−100
y−component (mas)
MICOM (42 mas²)
motion term (0,56)
MOM (156 mas²)
1992
1992.5
1993
1993.5
1994
1994.5
1995



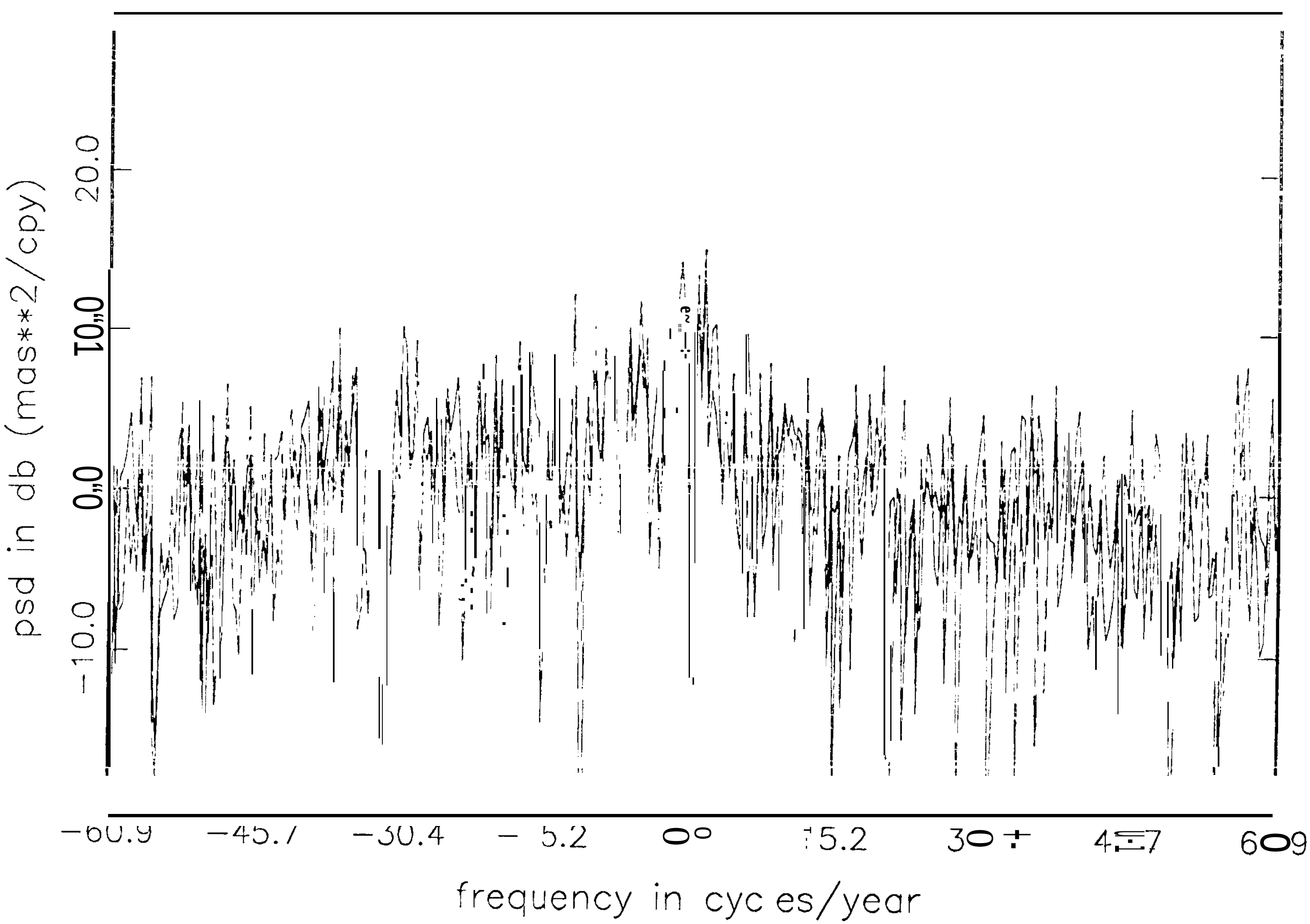
100
50
0
−50
−100
y−component (mas)
MICOM (122 mas²)
mass term (0.56)
MOM (165 mas²)
1992
1992.5
1993
1993.5
1994
1994.5
1995



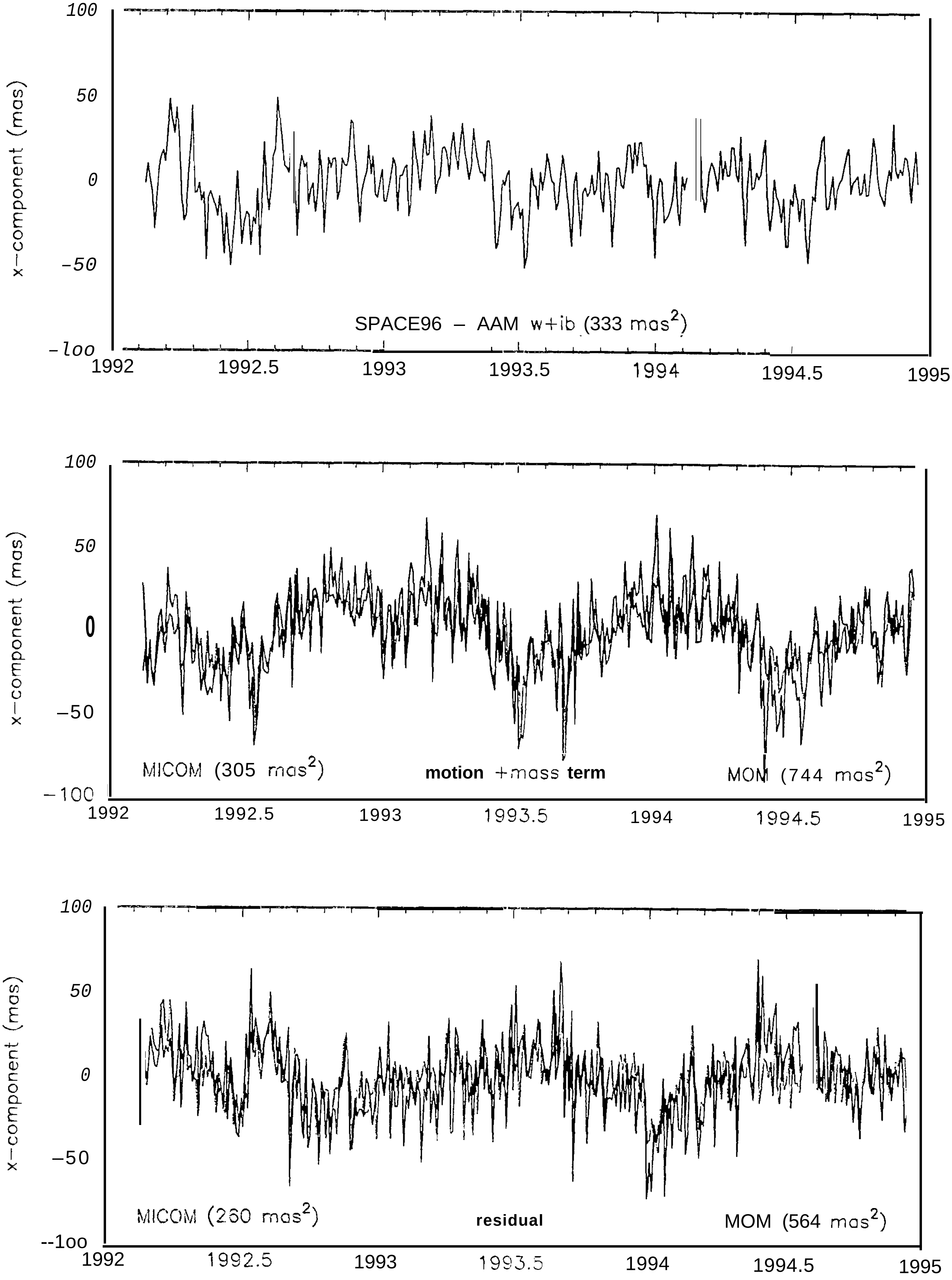
100
50
0
−50
−100
y−component (mas)
MICOM (210 mas²)
motion +mass term (0.61)
MOM (499 mas²)
1992
1992.5
1993
1993.5
1994
1994.5
1995


MOM AND M'COM MOTION TERM
psd in db (mas**2/cpy)
20.0
10.0
0.0
-10.0
-45.7
-30.4
0.0
15.2
30.4
45.7
60.9
frequency in cyc es/year

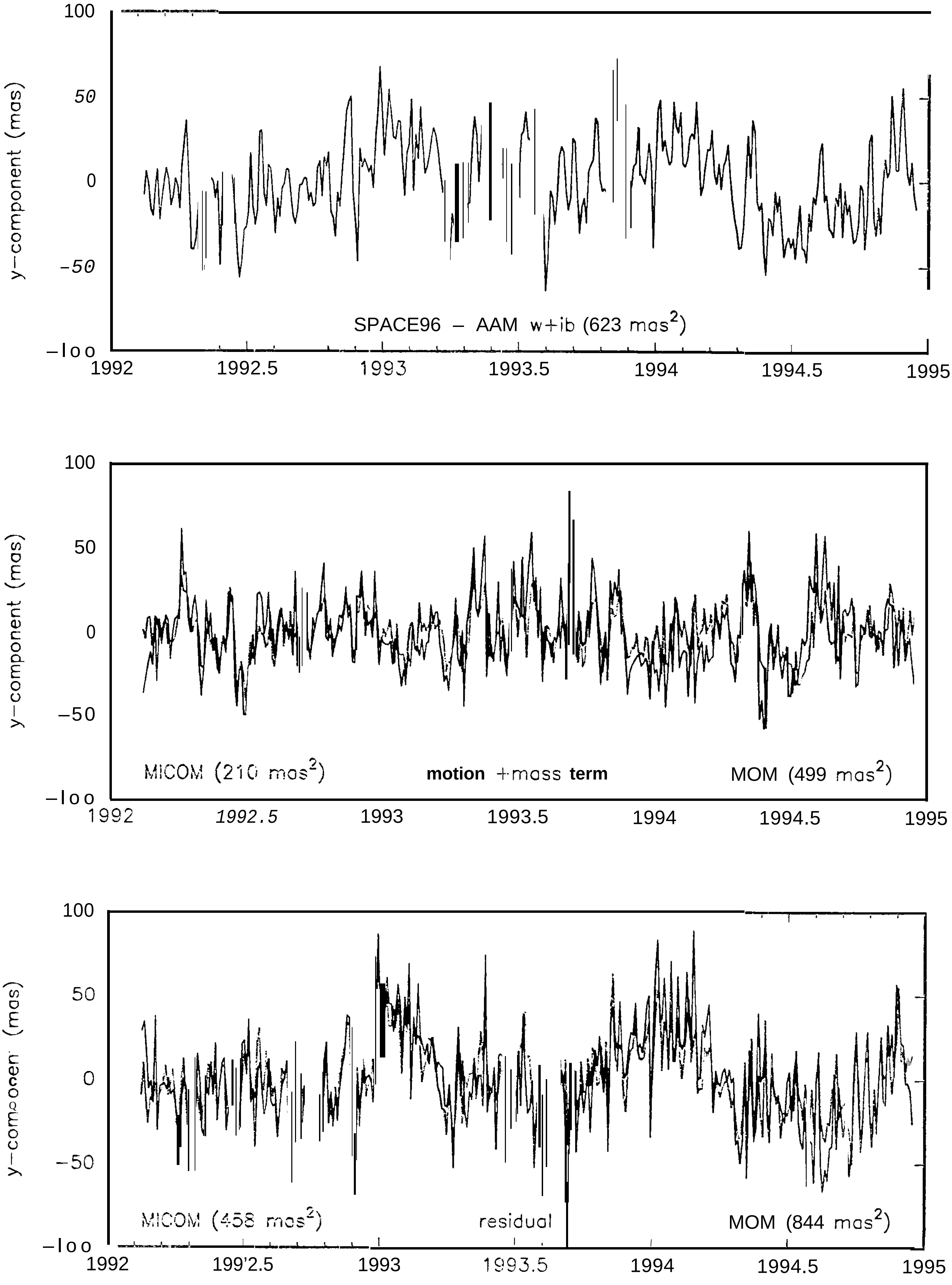
MOM AND MICOM MASS TERM



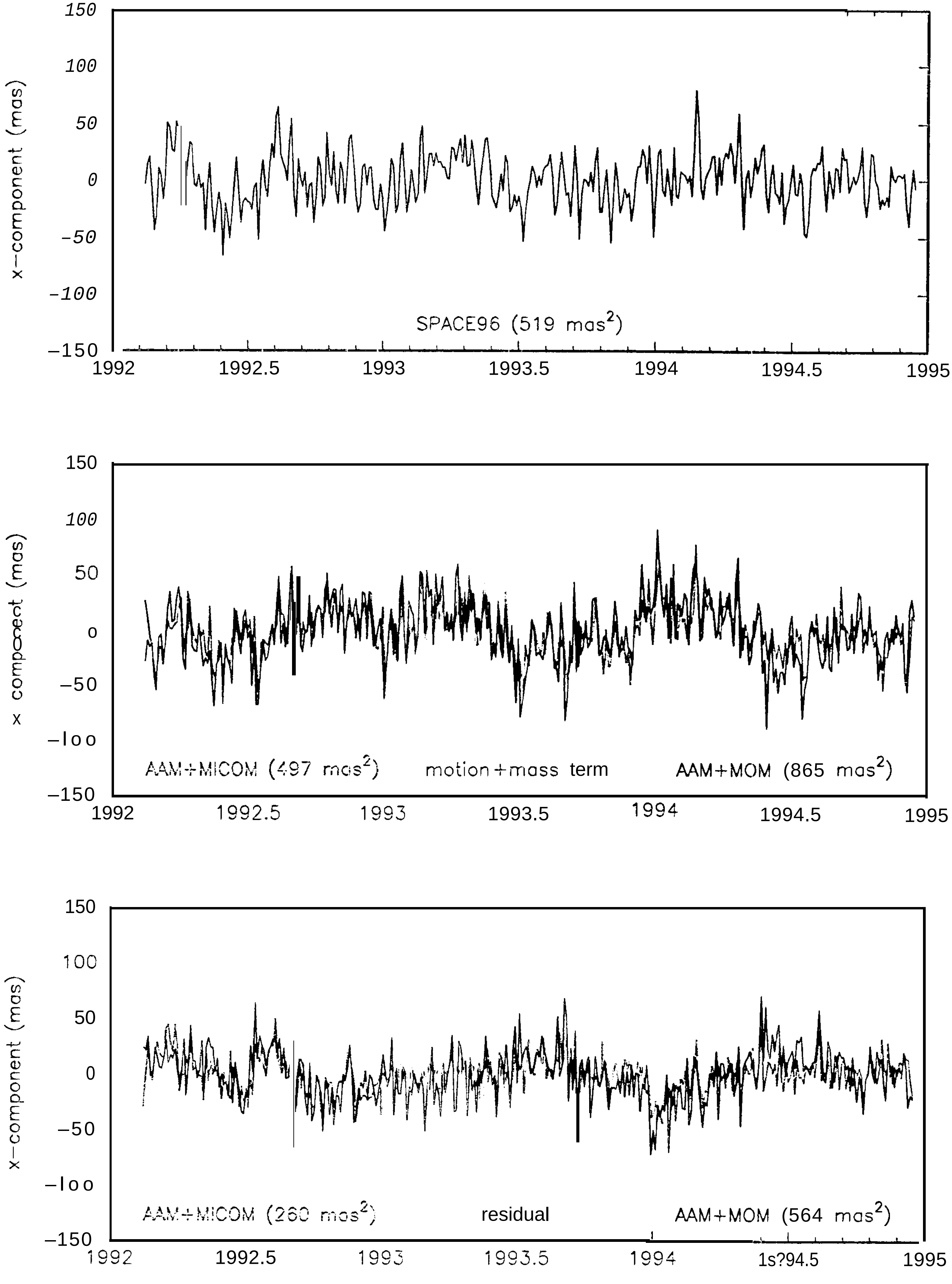
PO LAR MOT ION E_. XCITATION SERIES



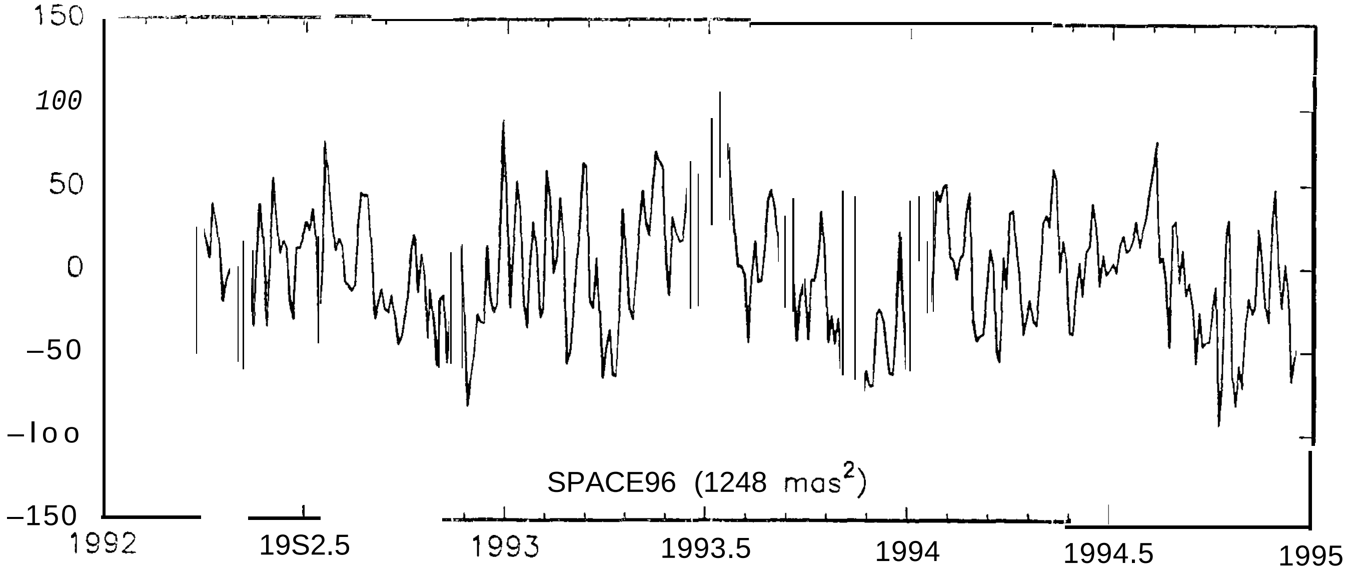
POLAR MOTION EXCITATION SERIES

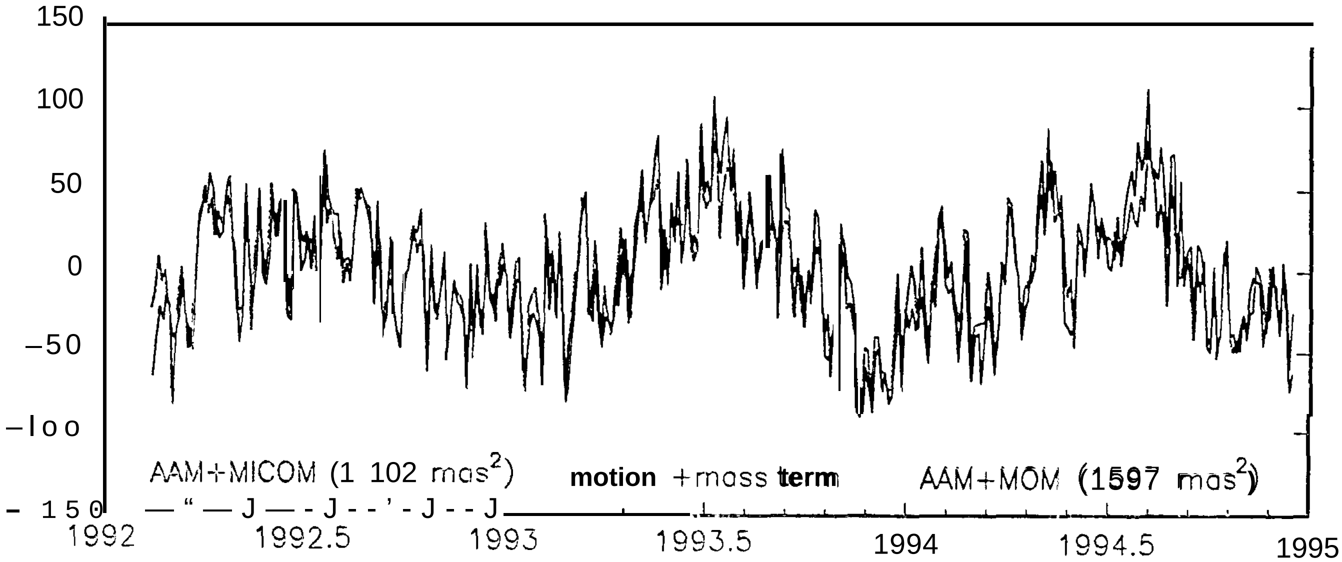


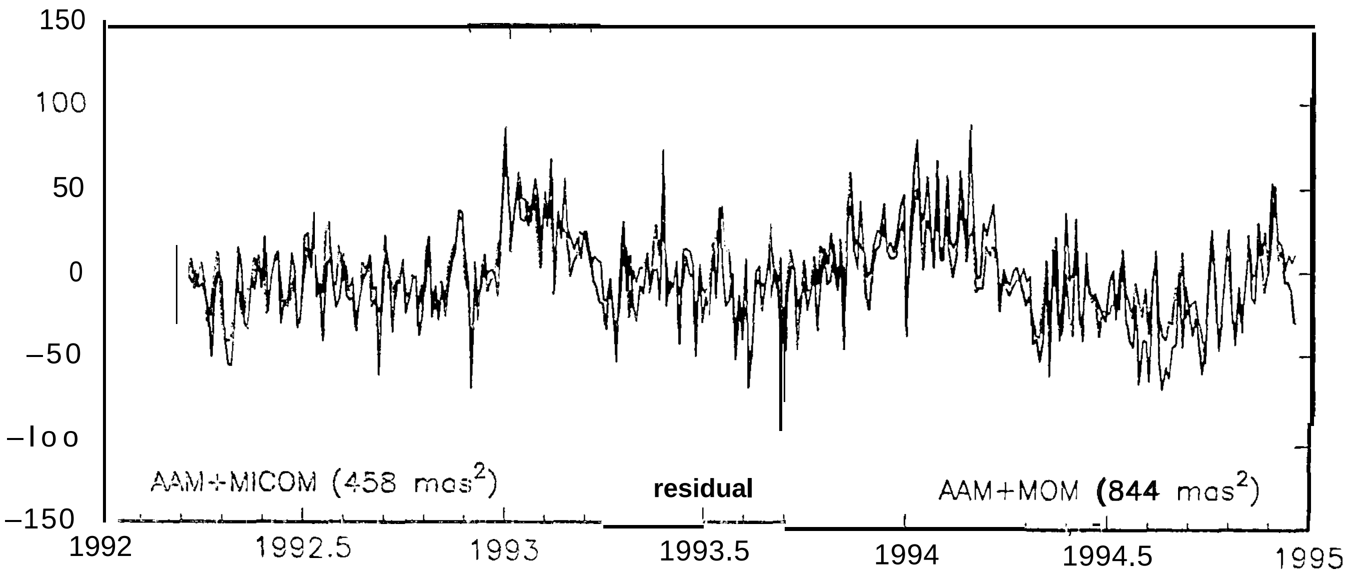
PO LAR MOT ION E XC ITAT ON SER ES



POLAR MOTION EXCITATION SERIES







CORRELATION

BETWEEN SPACE96 & AAM / OAM SERIES

AAM / OAM series	PMX	PMY	CMPLX
AAM wind	0.46	0.55	0.50
AAM ib	0.36	0.65	0.59
MICOM current	0.26	0.13	0.23
MICOM height	CL%?	0.31	0.39
AAM w+ib	0.59	0.71	0.69
MICOM c+h	0.48	0.30	0.37
AAM+MICOM	0.74	0.80	0.78

BETWEEN SPACE96-AAM RESIDUAL & OAM SERIES

OAM series	PMX	PMY	CMPLX
MICOM current	0.45	0.41	0.42
MICOM height	0.53	0.44	0.47
MICOM c+h	0.59	0.52	0.54

BETWEEN SPACE96-OAM RESIDUAL & AAM SERIES

AAM series	PMX	PMY	CMPLX
AAM wind	0.19	0.49	0.37
AAM ib	0.59	0.74	0.70
AAM w+ib	0.65	0.78	0.74

% VARIANCE EXPLAINED

OF SPACE96 BY AAM / OAM SERIES

AAM / OAM series	PMX	PMY	CMPLX
AAM wind	20.0	20.1	20.1
AAM ib	9.0	40.9	31.9
MICOM current	3.7	1.3	2.0
MICOM height	27.0	9.9	14.8
AAM w+ib	34.7	48.7	44.8
MICOM c+h	14.3	7.7	9.5
AAM+MICOM	50.0	62.4	58.8

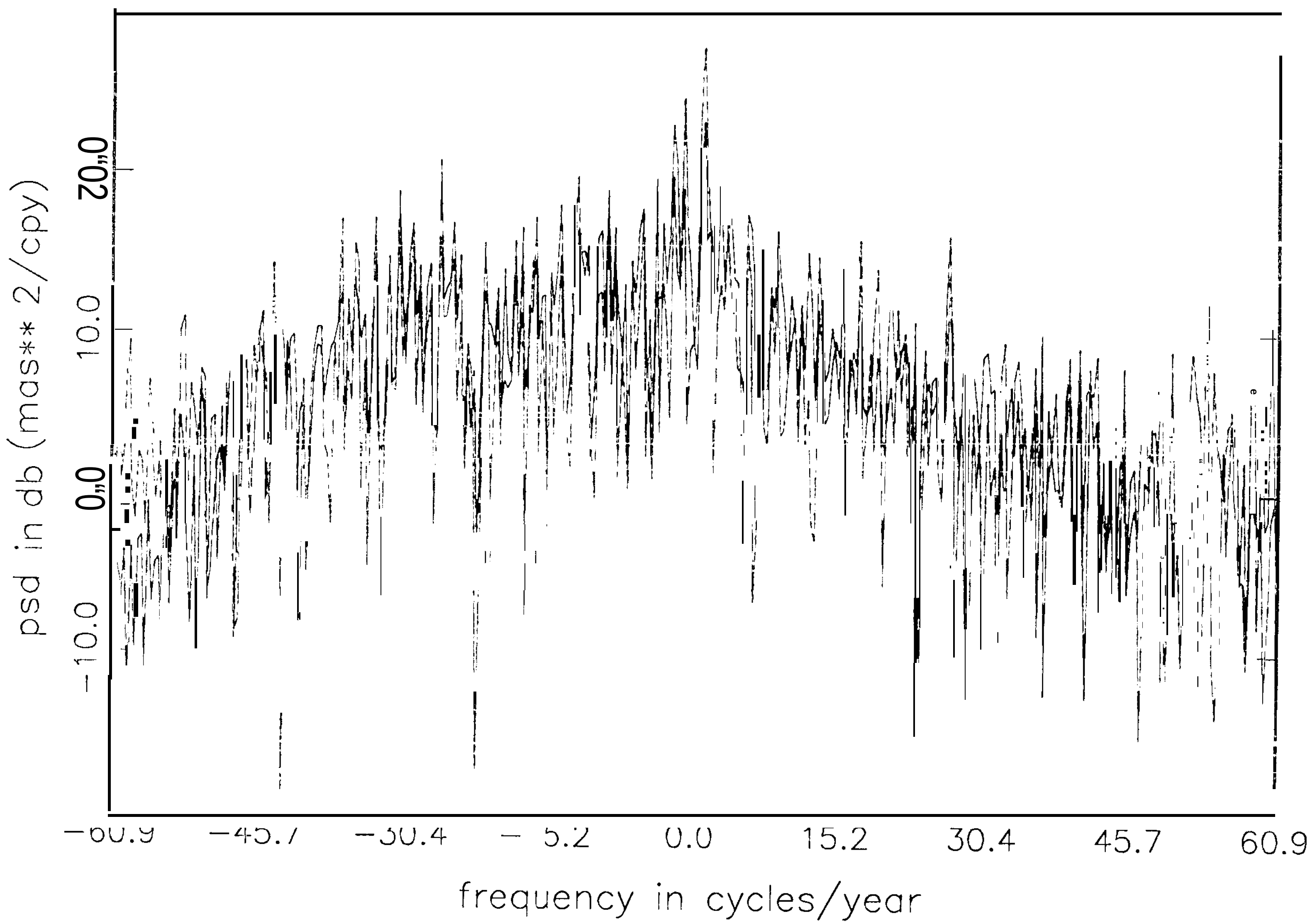
OF SPACE96-AAM RESIDUAL BY OAM SERIES

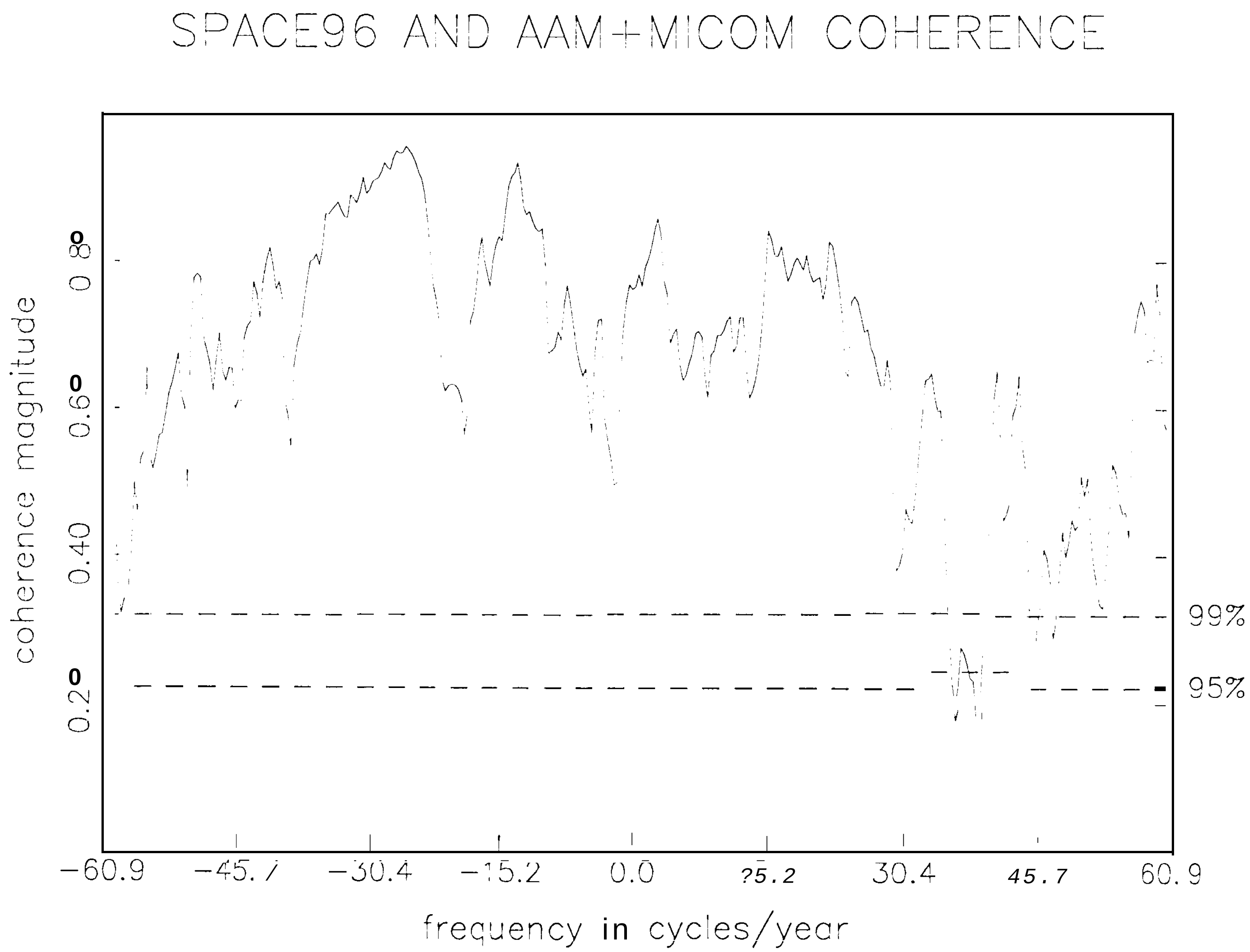
OAM series	PMX	PMY	CMPLX
MICOM current	19.8	14.8	16.5
MICOM height	27.9	19.1	22.2
MICOM c+h	21.9	26.5	24.9

OF SPACE96-OAM RESIDUAL BY AAM SERIES

AAM series	PMX	PMY	CMPLX
AAM wind	0.1	17.6	12.9
AAM ib	[illegible]	54.7	49.3
AAM w+ib	41.5	58.2	54.6

SPACE96 AND AAM+M COM SPECTRA




SPACE96 AND AAM+MICOM COHERENCE
coherence magnitude
0.8
0.6
0.40
0.2
99%
95%
−60.9
−45.7
−30.4
−15.2
0.0
?5.2
30.4
45.7
60.9
frequency in cycles/year

Conclusions

By making proper allowance for climate and mass drifts, angular momentum variations produced by 2 substantially different OGCMs were shown to be very similar

- Both current and mass terms agree

Comparisons with geodetic and atmospheric data show that the model-simulated OAM series can significant] y improve closure of the Earth's axial angular momentum budget

- Results enhance confidence in robustness of model simulations

High-quality geodetic measurements have the potential to serve as benchmarks for validating and improving complex geophysical models

- Benefits to both geodetic studies and ocean/atmosphere modeling

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