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INVESTIGATION OF THE IONOSPHERIC SHORT-TERM VARIABILITY

Final Technical Report

by

ZWI HOUMINER

January 1995 - December 1996

United States Army
EUROPEAN RESEARCH OFFICE OF THE US ARMY
London, England
Contract number: N68171-95-c-9028
R&D 7483-EE 01

Principal Investigator: Prof. G. Shaviv
ASHER SPACE RESEARCH INSTITUTE
Technion, Haifa 32000, Israel

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ABSTRACT

Both the total electron content of the ionosphere (TEC) and the critical frequency of the F2 layer (foF2) exhibit large day-to-day variations during quiet and active geomagnetic periods. It is of great interest to ascertain whether good correlation exists between TEC daily variability about the monthly mean and foF2 variations. With the availability of the global GPS constellation to provide instantaneous time-delay values such a correlation may enable the improvement of HF short-term predictions using passive monitoring of TEC.

To determine the correlation one year of TEC and foF2 data were collected from June 1995 until May 1996. The TEC data was determined from GPS time-delay measurements at Matera, Italy, obtained from the data base of the International GPS Services for Geodynamics. The foF2 measurements came from Rome, Italy.

The analysis showed, that for large percentages of the time very good correlation exists between TEC and foF2 short-term variations. The correlation coefficient varies from 0.7 - 0.8 during the summer months to about 0.5 - 0.6 during the winter. A study of the diurnal dependence of the correlation indicates that better correlation exists during day-time than night-time.

The high correlation between TEC and foF2 indicates that real-time ionospheric HF prediction improvements are feasible when using transionospheric time-delay measurements.

KEY WORDS

Ionospheric variability; HF propagation; HF short-term predictions; Total electron content (TEC); foF2; Transionospheric time-delay; GPS.

TABLE OF CONTENT

1. INTRODUCTION

HF radio communication depends on the ability of the ionosphere to return the radio signal incident on it back to Earth. Predictions of ionization levels in the various ionospheric regions are derived from models and are used as a basis for planning and frequency management of HF radio systems worldwide. Uncertainties or inaccuracies in the models of the ionosphere have long been known to be one of the major causes if not the major cause, for inaccuracies in the calculated propagation characteristics. This is particularly true for those applications of ionospheric predictions involving timescales that are less than the monthly average or monthly median.

To reduce average monthly RMS errors in predictions, adaptive techniques that use real-time observations to correct model biases have been devised. Examples of such are (1) sounding the desired communication path prior to information transmittal or (2) sounding the vertical ionosphere to determine a real-time model reference point and then to adjust the model for the future, until the next reference sounding. While the first is appropriate for fixed point communication paths, it is cumbersome and causes EM interference over wide geographic areas, whereas the second technique, while not causing interference, may not yield values representative of ionospheric conditions at the reflection point of an oblique path.

A method that is potentially global in nature involves the monitoring of satellite-emitted signals which yield information on the ionospheric parameters along the propagation path such as time-delay or TEC and converting such information into the HF propagation parameters of interest (foF2). The advantage of monitoring satellite-emitted signals is the fact that it is passive for the potential user, and the existence of a global network of satellites (e.g., the Global Positioning System, or GPS) affords the possibility of global coverage.

To assess the possible immprovement of HF short-term predictions from transionospheric measurements, a correlation study between TEC daily variability about the monthly mean and foF2 variability was conducted. Several months of TEC data taken in Haifa, Israel during 1980, as well as GPS time-delay measurements taken during the summer of 1992 in Jerusalem, Israel were correlated with foF2 measurements from Cape Zevgari, Cyprus. The results of this study were reported and published in various scientific conferences [1],[2],[3],[4],[5], scientific journals [6] and the Final Technical Report of contract DAJA-93-C-0035 [7].

The above results showed that very good correlation exists between TEC and foF2, indicating that real-time HF prediction improvements by passive means are feasible. However the previous studies were based on a limited amount of data and thus it was decided to increase the data base by collecting new foF2 and TEC measurements for at least one more year. In this report we present the results of the new study, which was conducted during the minimum phase of the last sunspot cycle.

2. EXPERIMENTAL DATA

The experimental data is divided into two periods: 1994-1995 and 1995-1996. The first were collected from June 1994 until May 1995. The TEC data were obtained from GPS observations taken at the National Physical Laboratory in Jerusalem, while the foF2 measurements were from Nicosia, Cyprus and were received from World Data Center A in Boulder, Colorado. Unfortunately most of the data received both from Jerusalem (for the period July-November 1994) as well as from Boulder (from September 1994 until May 1995) were either unreliable, missing or incomplete and could not be used for the correlation analysis.

When it was realized that we would not be able to use the Cyprus data, it was decided to use other sources. GPS time-delay measurements can be obtained from the data base of the international GPS services for Geodynamics (IGS). The IGS data base contains measurements from some 50 locations around the world and can be accessed via the internet. The nearest location to Israel is in Italy and thus from June 1995 until June 1996 we obtained GPS time-delay data from Matera, Italy (40.65°N 16.7°E) while the foF2 measurements came from Rome, Italy (41.9°N 12.5°E)

The TEC were determined from the raw IGS data with a software package developed by the Philips Laboratory, Hanscom Field, Mass and adapted for use on the Technion computer [8].

3. CORRELATION RESULTS

For each month of observations, the hourly values of the variability of both the TEC and foF2 were determined. The variability is calculated by substracting the monthly average value from each hourly value and dividing by the monthly average value. Another parameter of interest is the slab thickness, which is proportional to the ratio $TEC/(foF2)^2$. The slab thickness can be calculated for each hour of observations and its variability determined in the same way as for TEC or foF2.

Both the variation in foF2 and TEC are noisy on an hour-to-hour basis, which is caused by measurements and data reduction errors rather than by physical phenomena. To reduce the noise, the variations in TEC and foF2 were smoothed by a 3 hour running mean. Crosscorrelation analysis was performed on the foF2 and TEC variabilities both for the unsmoothed and smoothed data. Autocorrelation analysis was also performed on the unsmoothed TEC and foF2 data.

A complete set of results for the period June 1995-May 1996 are given in Appendix A. The following figures are shown for every month:

a. Hourly values of the variability of foF2 and TEC.
b. Smoothed hourly values of the variability of foF2 and TEC

c. Cross-correlation function between hourly values of foF2 and TEC for the unsmoothed data.
d. Auto-correlation functions for the unsmoothed foF2 and TEC.
e. Hourly values of the variability of the slab-thickness τ.

The cross-correlation coefficients for both the smoothed and unsmoothed data for the period June 1995-May 1996 are given in Table 1. It can be seen that the correlation coefficients for the unsmoothed data vary between 0.78 for June 1995 to 0.53 for February 1996. The correlation coefficient for the smoothed data vary between 0.84 and 0.58 for the same months.

The diurnal variations of the correlation coefficients for the various seasons are shown in Figure 1. Each point in the figure represents correlation results for a 4 hour block. It can be seen that the diurnal variations are similar for all the seasons besides the winter of 1996. Minimum correlation coefficients accur at night near sun rise and a broad maximum is observed during the day-time. There is no apparent diurnal variation for the winter months. The reason for this is unclear. The highest correlation coefficients for both day-time and night-time are observed in the summer of 1995.

4. CONCLUSIONS

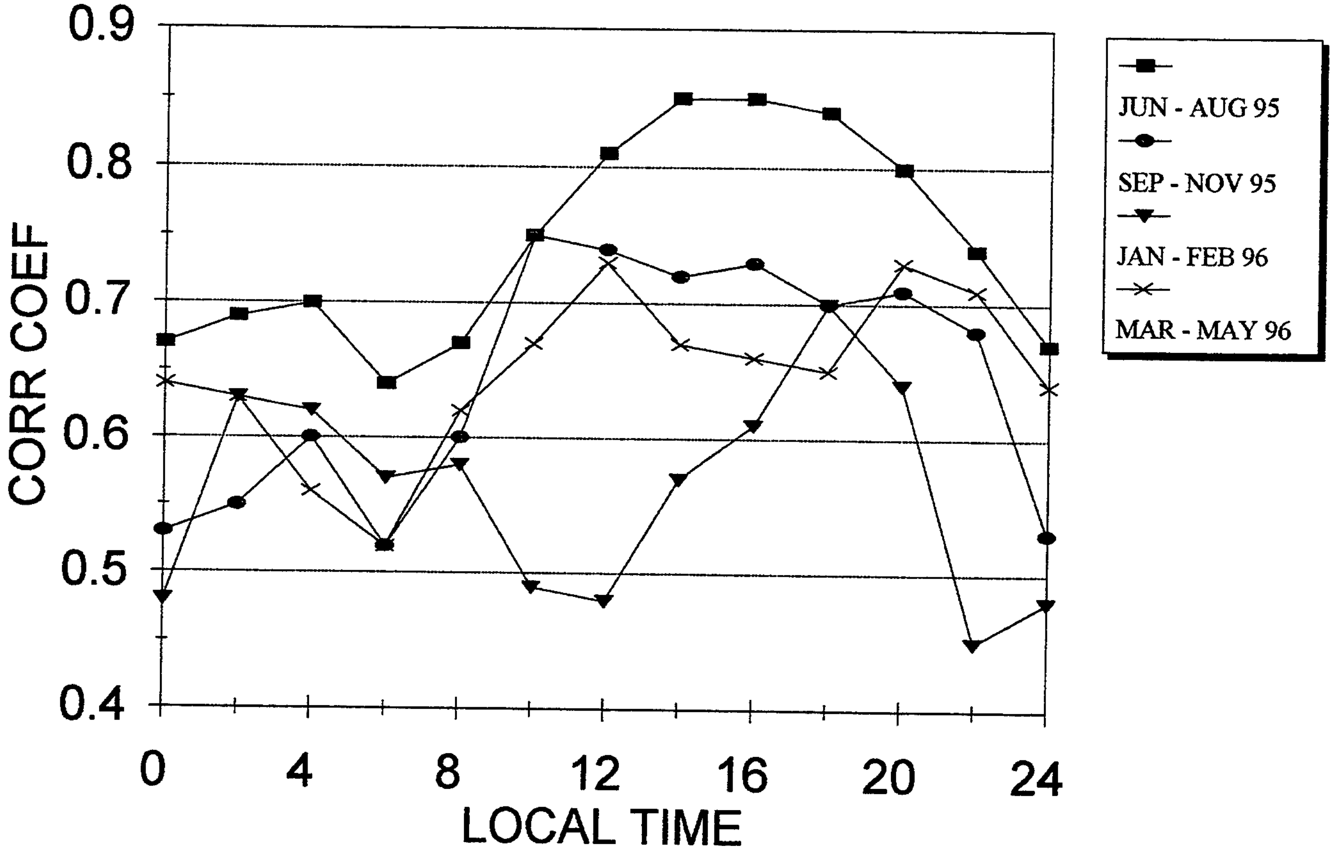
The high cross-correlation coefficient for foF2 and TEC raises the possibility that real-time TEC measurements may be used to update foF2 value determinations. The cross-correlation may even be higher if the geographic subionospheric point of the TEC measurements is closer to the geographic point of the foF2 measurement, which introduces an error, in addition to the possible inherent measurements un-certainties. TEC measurements utilizing satellite emitted signals are passive in nature and do not burden the electromagnetic spectrum. In addition, the availability of the global GPS constellation to provide instantaneous time-delay, or equivalently TEC, values could provide an instan-

Table 1

ITALY 1995/6

MONTH	CORR COEF NO SMOOTHING	CORR COEF 3-POINT SMOOTHING
JUN 1995	0.78	0.84
JUL	0.75	0.82
AUG	0.70	0.76
SEP	0.74	0.80
OCT	0.59	0.67
NOV	0.64	0.75
DEC	0.66	0.76
JAN 1996	0.63	0.74
FEB	0.53	0.58
MAR	0.66	0.72
APR	0.63	0.68
MAY	0.60	0.64

Figure 1


0.9
0.8
0.7
0.6
0.5
0.4
CORR COEF
0
4
8
12
16
20
24
LOCAL TIME
JUN - AUG 95
SEP - NOV 95
JAN - FEB 96
MAR - MAY 96

taneous updating of foF2 models on a global basis as well as on a regional basis. Such capability is important for HF communication along short, medium and long range paths.

5. LIST OF PUBLICATIONS

[1] Z. Houminer & H. Soicher, "Improvement of foF2 short-term predictions from transionospheric time-delay measurements." National Radio Science Meeting, University of Colorado, Boulder, 5-8 January 1994.

[2] H. Soicher & Z. Houminer, "Real-time ionoshperic HF prediction improvements by passive means." 19th Army Science Conference, Orlando, Florida, 20-23 June 1994.

[3] Z. Houminer & H. Soicher, "Assessment of foF2 short-term variations from GPS time-delay measurements." International Beacon Satellite Symposium, Aberystwyth, Wales, 11-15 July 1994.

[4] H. Soicher & Z. Houminer,"Passive HF propagation evaluation technique". AGARD Conference Proceedings 574, April 1996.

[5] Z. Houminer & H. Soicher, "Improved short-term predictions of foF2 using GPS time-delay measurements." Ionospheric Effects Symposium, Alexandria, VA, USA, 7-9 May 1996.

[6] Z. Houminer & H. Soicher, "Improved short-term predictions of foF2 using GPS time-delay measurements." Radio Science, 31, 1099-1108, 1996.

[7] Z. Houminer, "Investigation of the ionospheric short-term variability", Final Technical Report, October 1994.

[8] P. Doherty, Private Communication, 1995.

APPENDIX A

Experimental results for the period June 1995-May 1996.
The following figures are shown for every month:

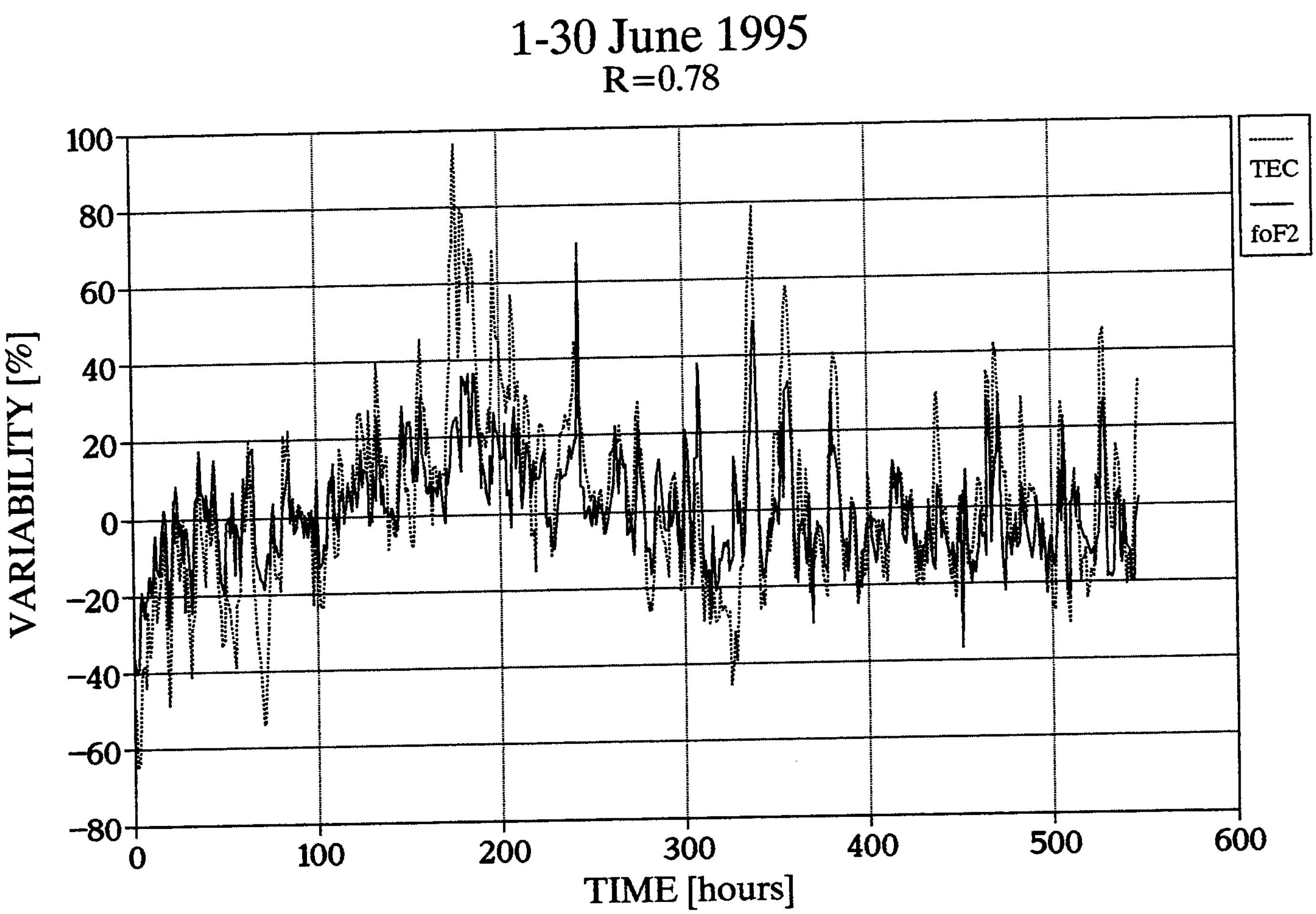
a. Hourly values of the variability of foF2 and TEC

b. Smoothed hourly values of the variability of foF2 and TEC.

c. Cross-correlation function between hourly values of foF2 and TEC for the unsmoothed data.

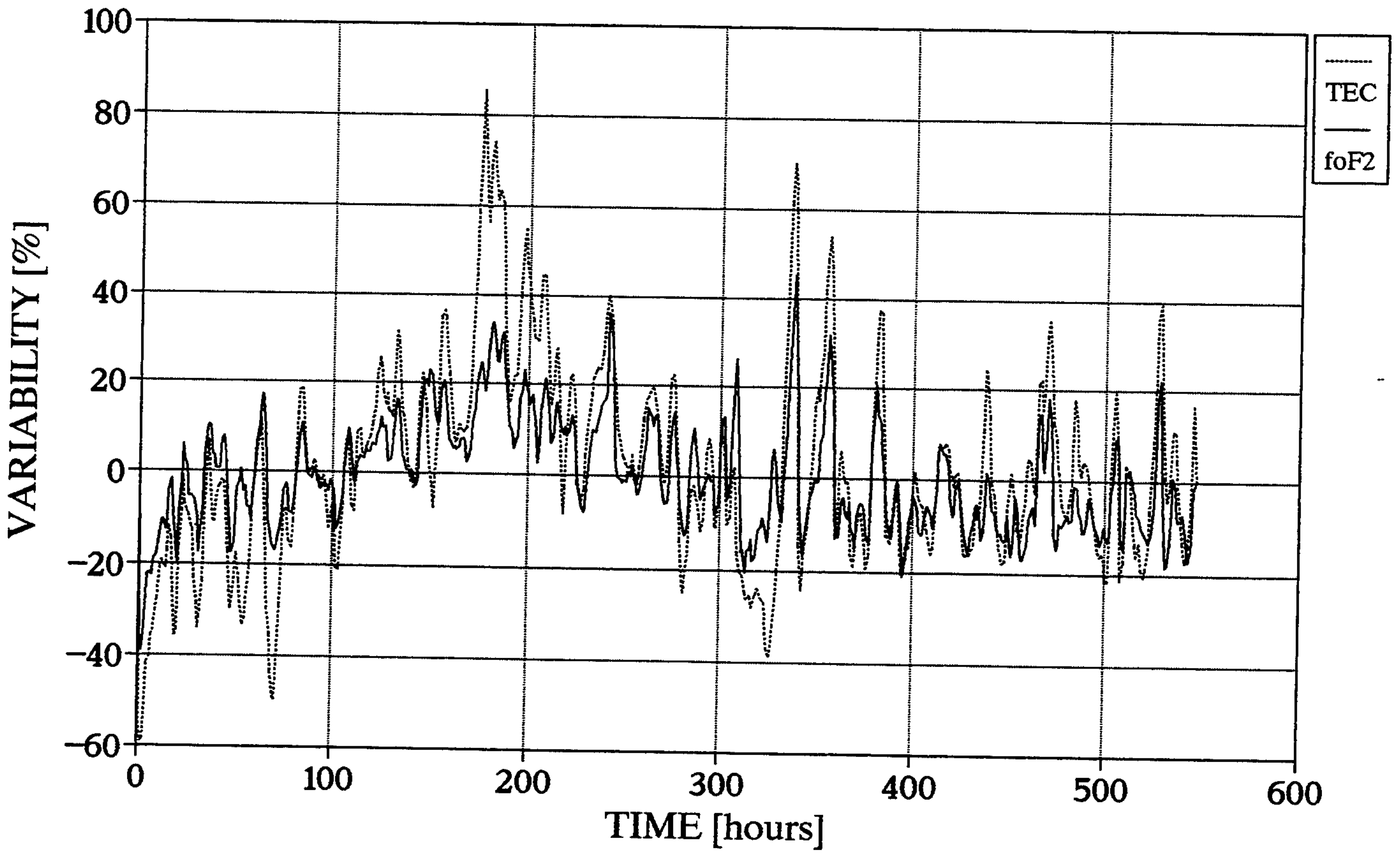
d. Auto-correlation functions for the unsmoothed foF2 and TEC variations.

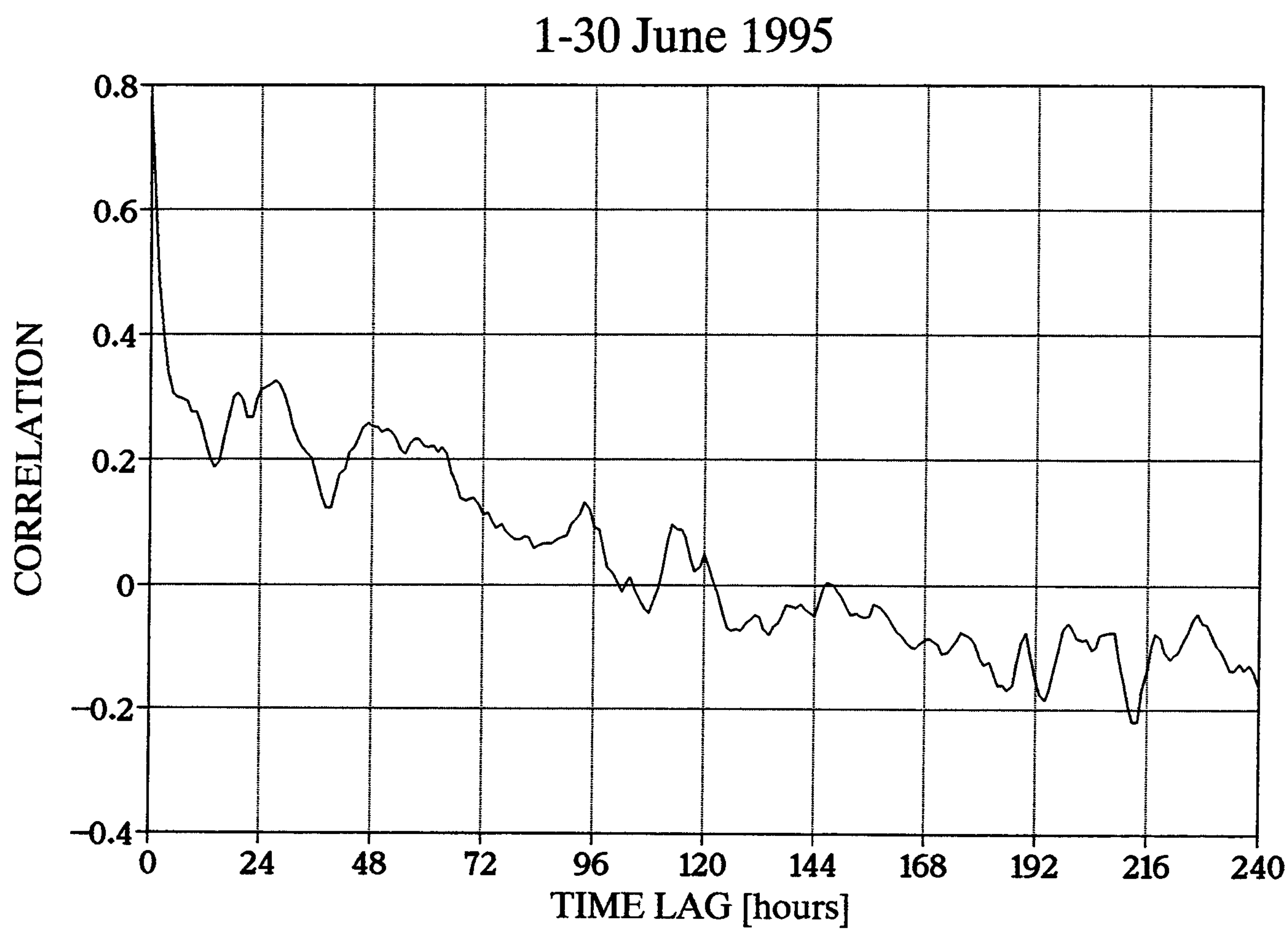
e. Hourly values of the variability of the slabthickness.

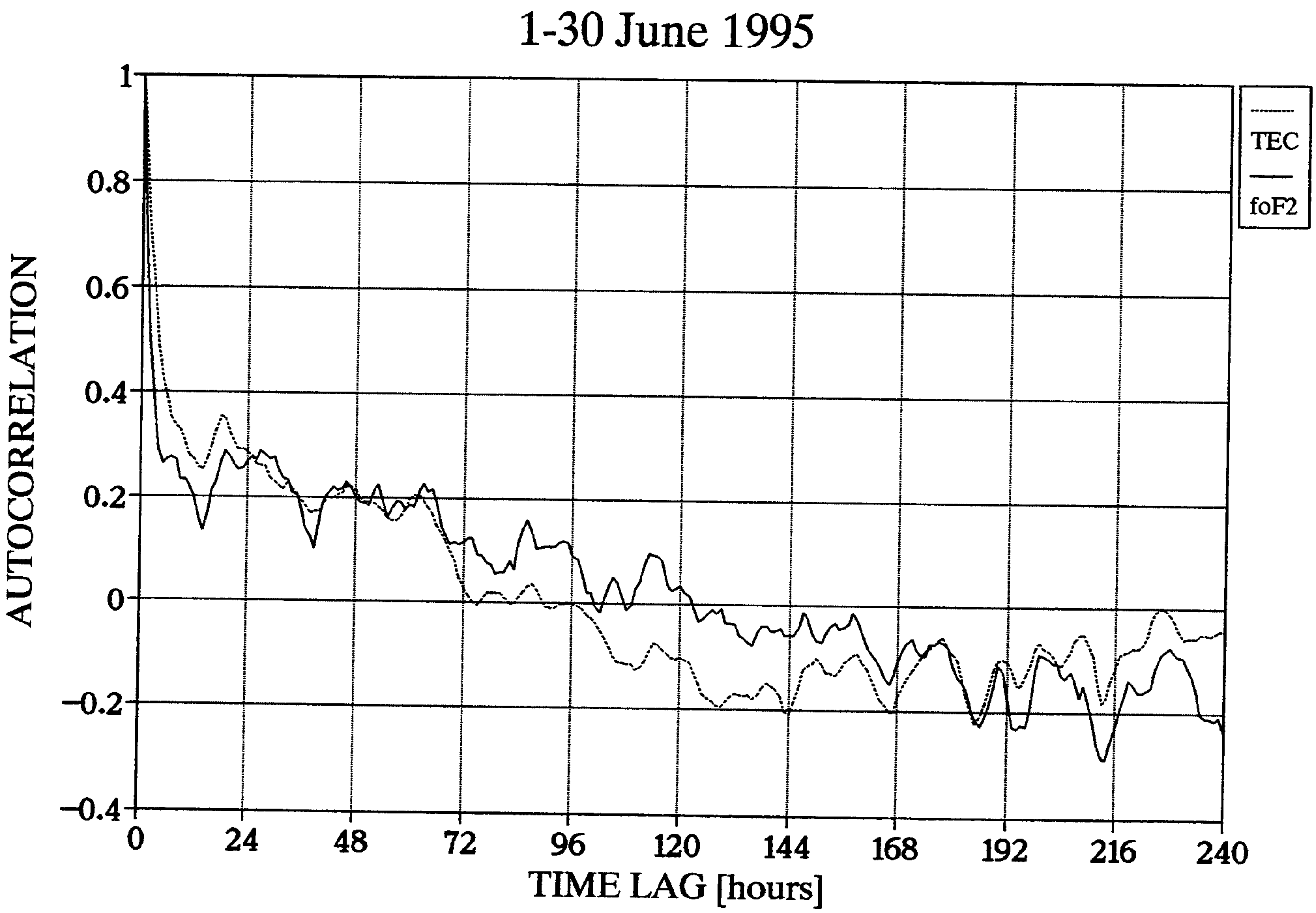


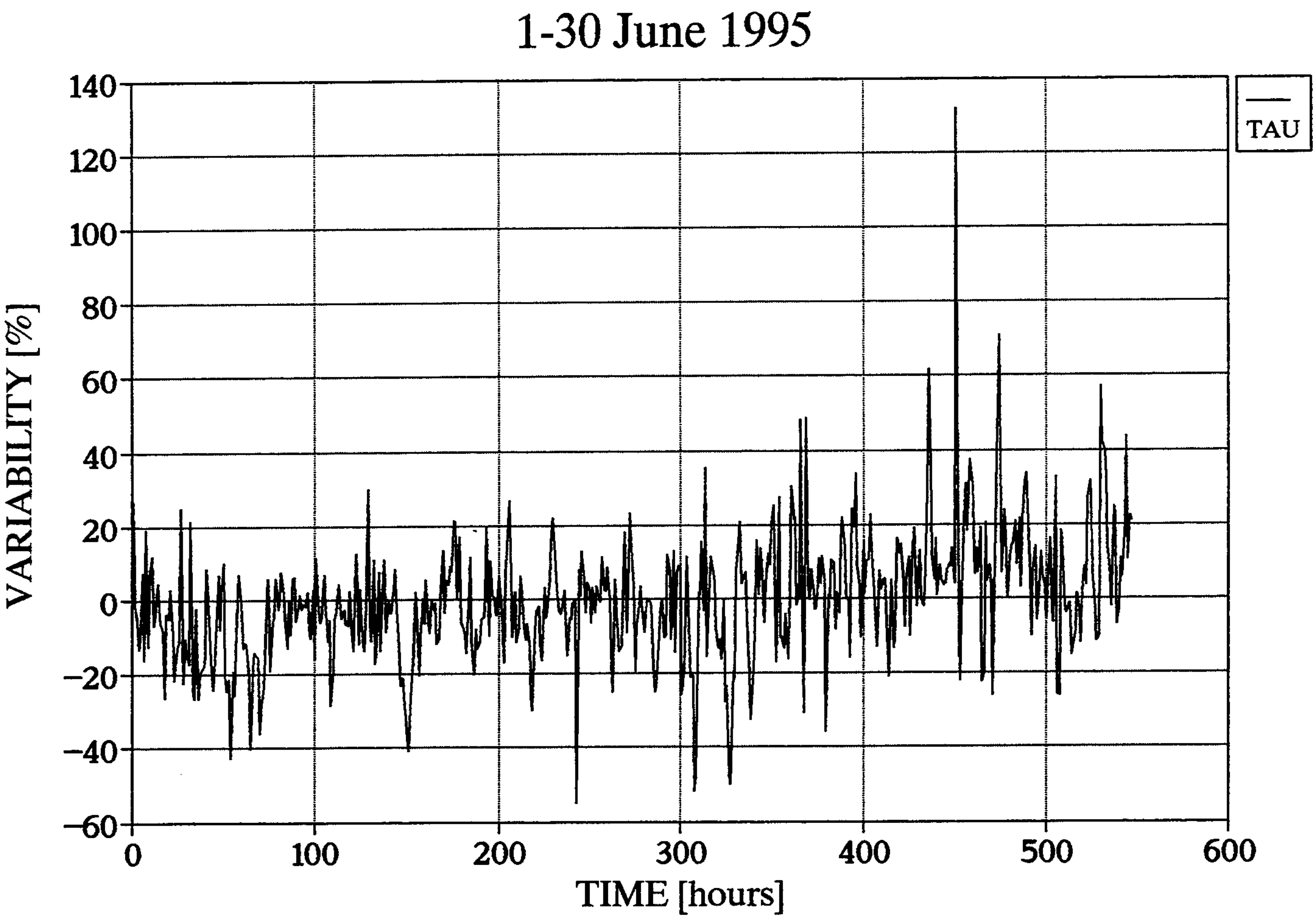
1-30 June 1995
R=0.78
TEC
foF2
VARIABILITY [%]
TIME [hours]
100
80
60
40
20
0
−20
−40
−60
−80
0
100
200
300
400
500
600

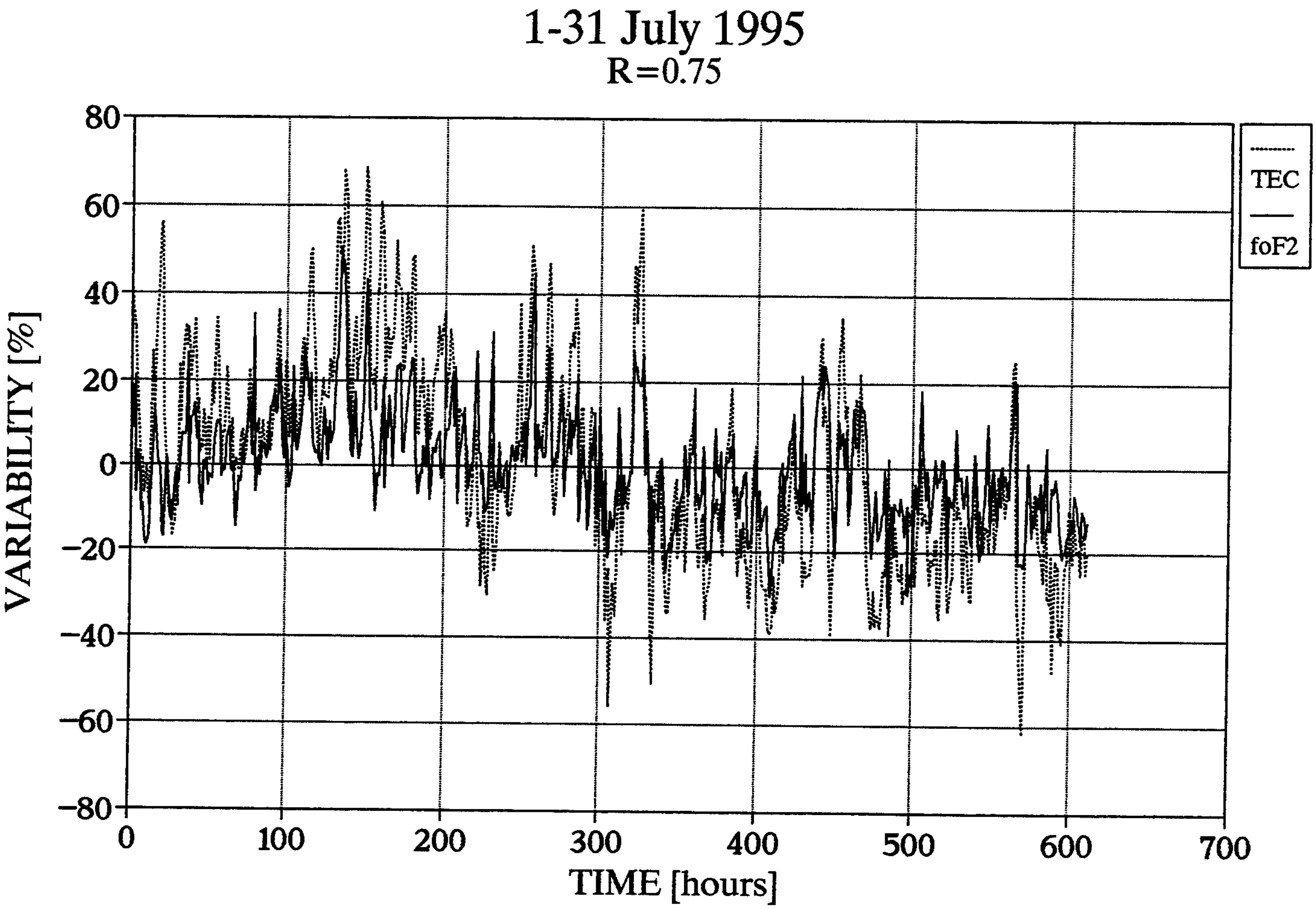
1-30 June 1995
3 point smoothing R=0.84

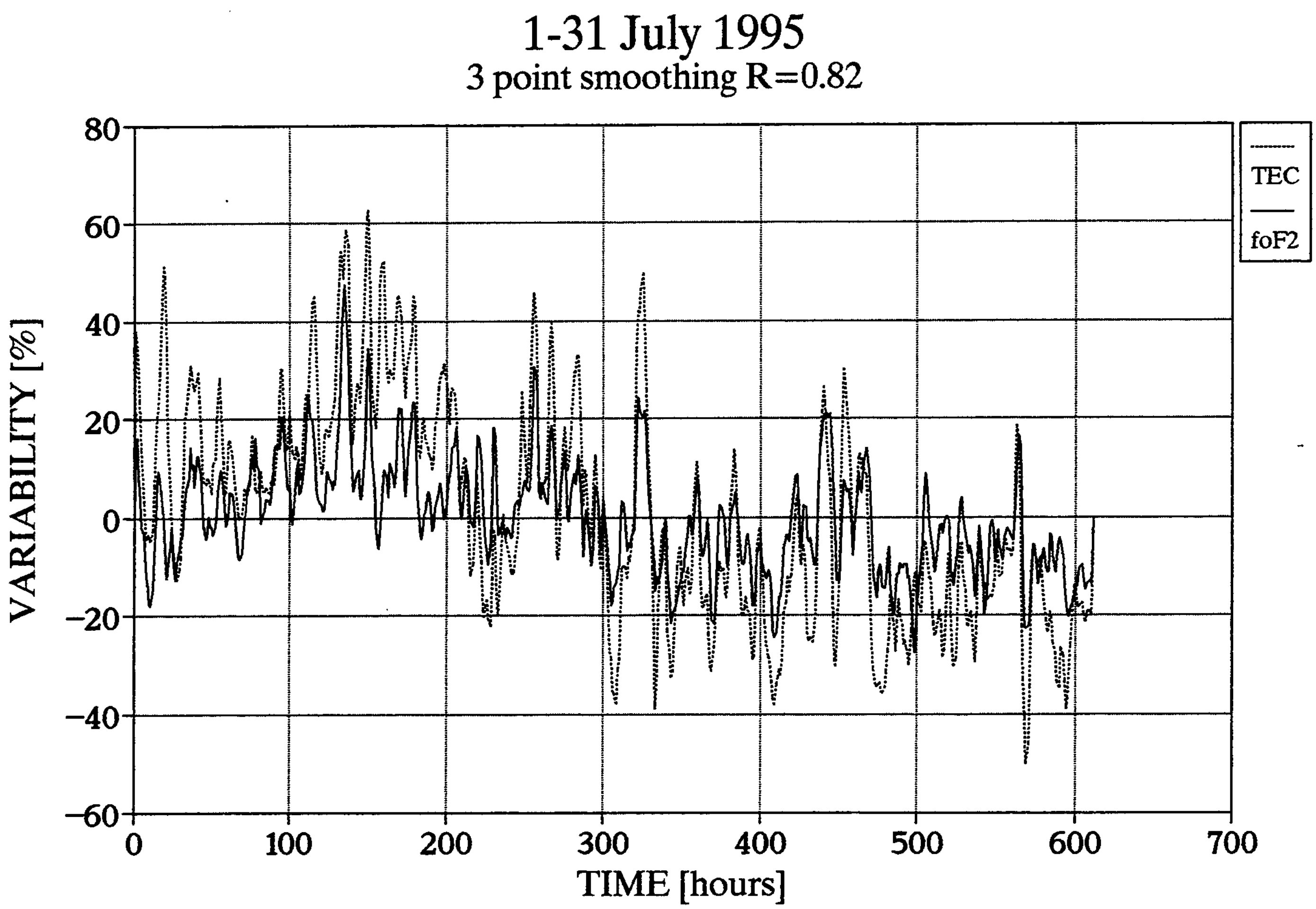


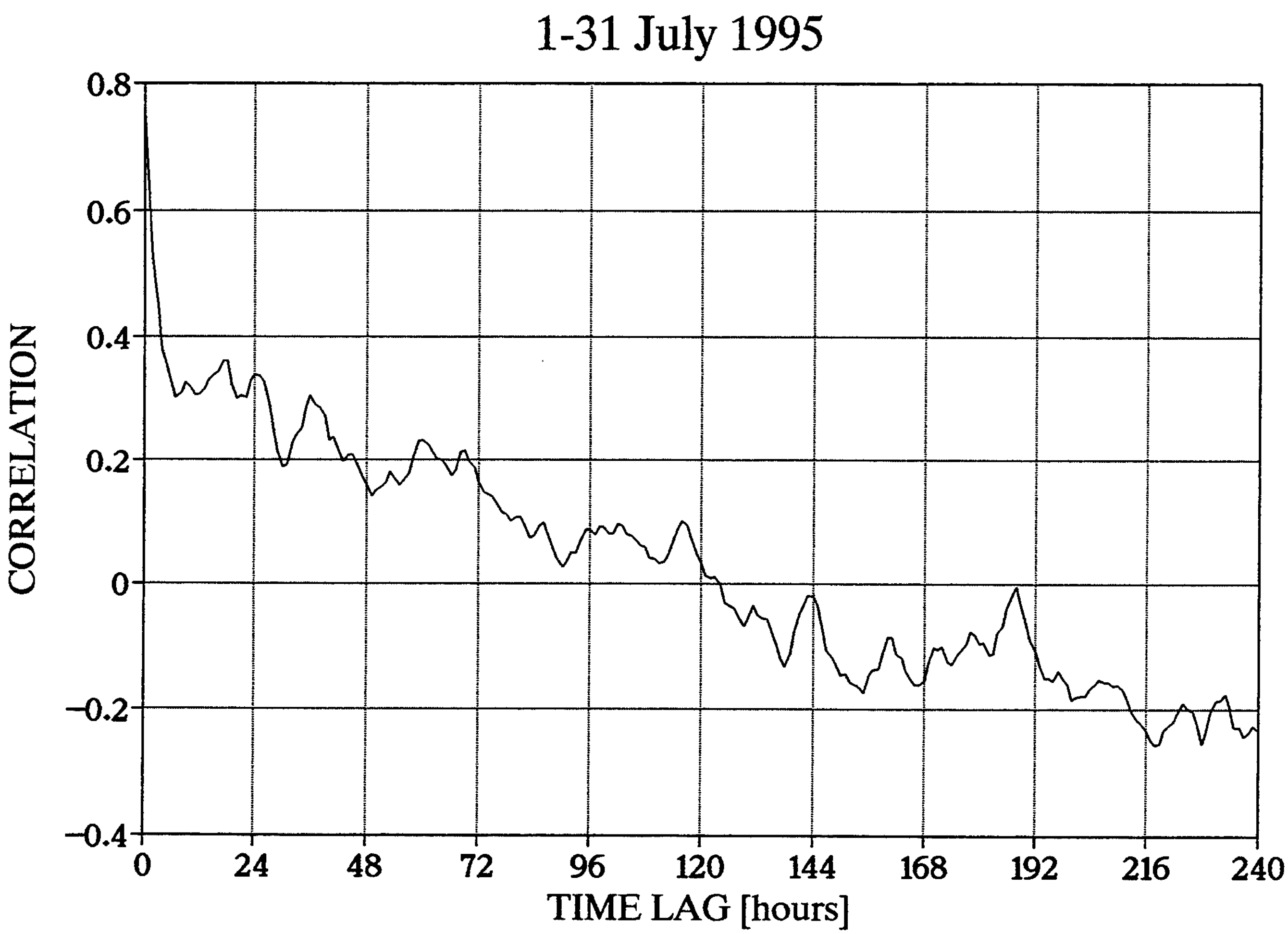

1-30 June 1995
0.8
0.6
0.4
0.2
0
−0.2
−0.4
CORRELATION
0
24
48
72
96
120
144
168
192
216
240
TIME LAG [hours]

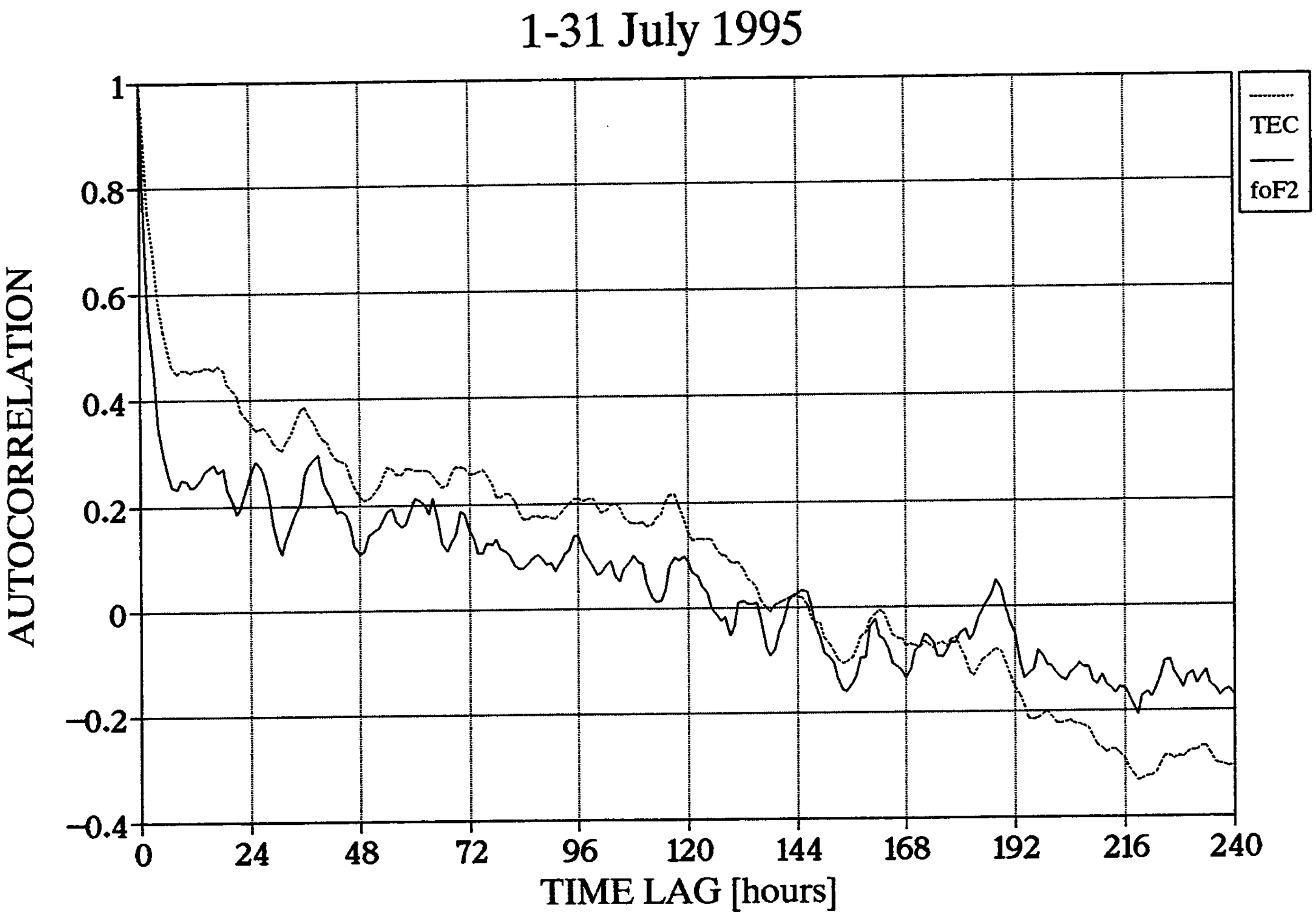

1-30 June 1995
AUTOCORRELATION
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
0
24
48
72
96
120
144
168
192
216
240
TIME LAG [hours]
TEC
foF2


1-30 June 1995
140
120
100
80
60
40
20
0
−20
−40
−60
VARIABILITY [%]
0
100
200
300
400
500
600
TIME [hours]
TAU

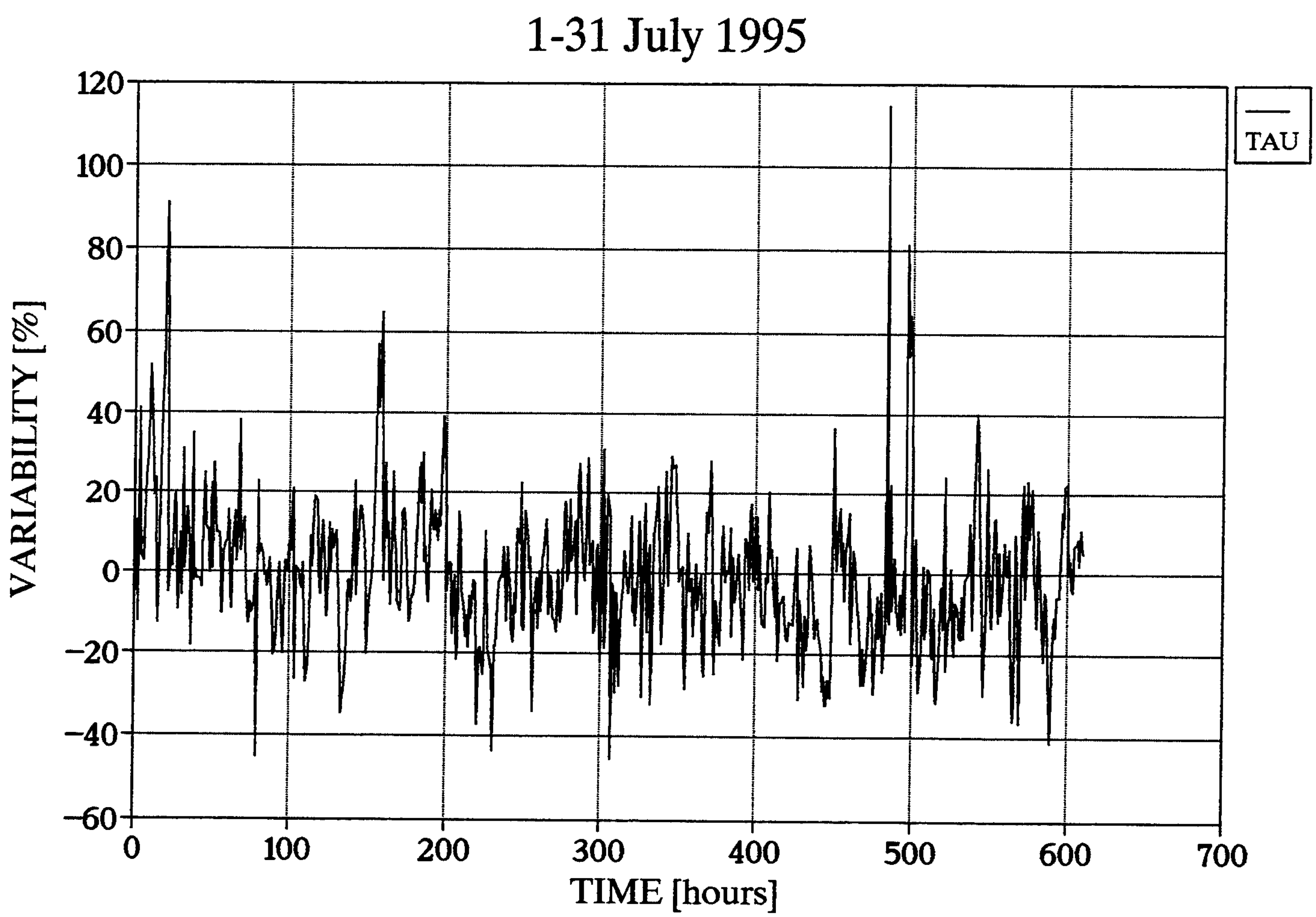

1-31 July 1995
R=0.75
80
60
40
20
0
−20
−40
−60
−80
VARIABILITY [%]
0
100
200
300
400
500
600
700
TIME [hours]
TEC
foF2


1-31 July 1995
3 point smoothing R=0.82
80
60
40
20
0
−20
−40
−60
VARIABILITY [%]
0
100
200
300
400
500
600
700
TIME [hours]
TEC
foF2

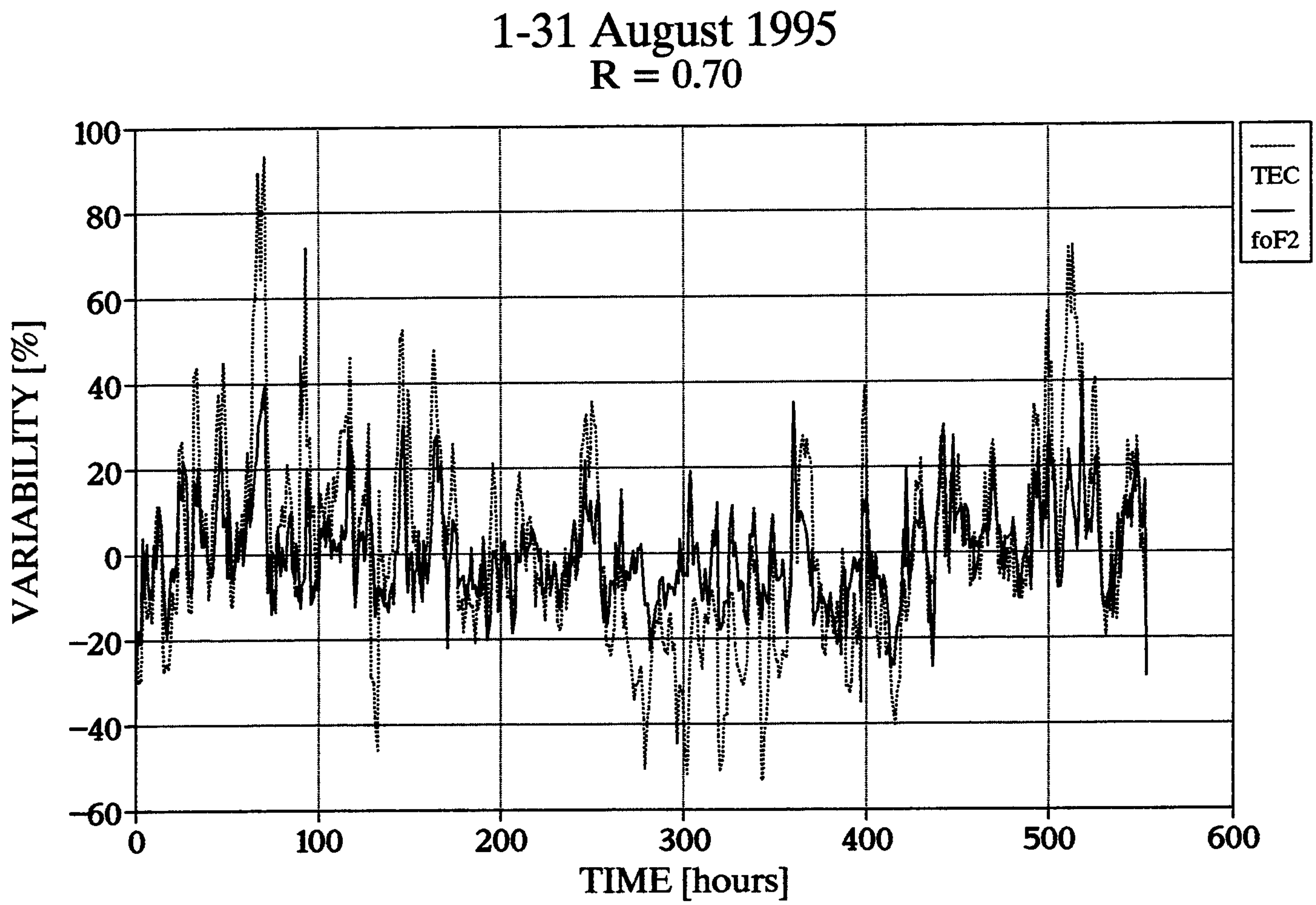

1-31 July 1995
0.8
0.6
0.4
0.2
0
−0.2
−0.4
CORRELATION
0
24
48
72
96
120
144
168
192
216
240
TIME LAG [hours]

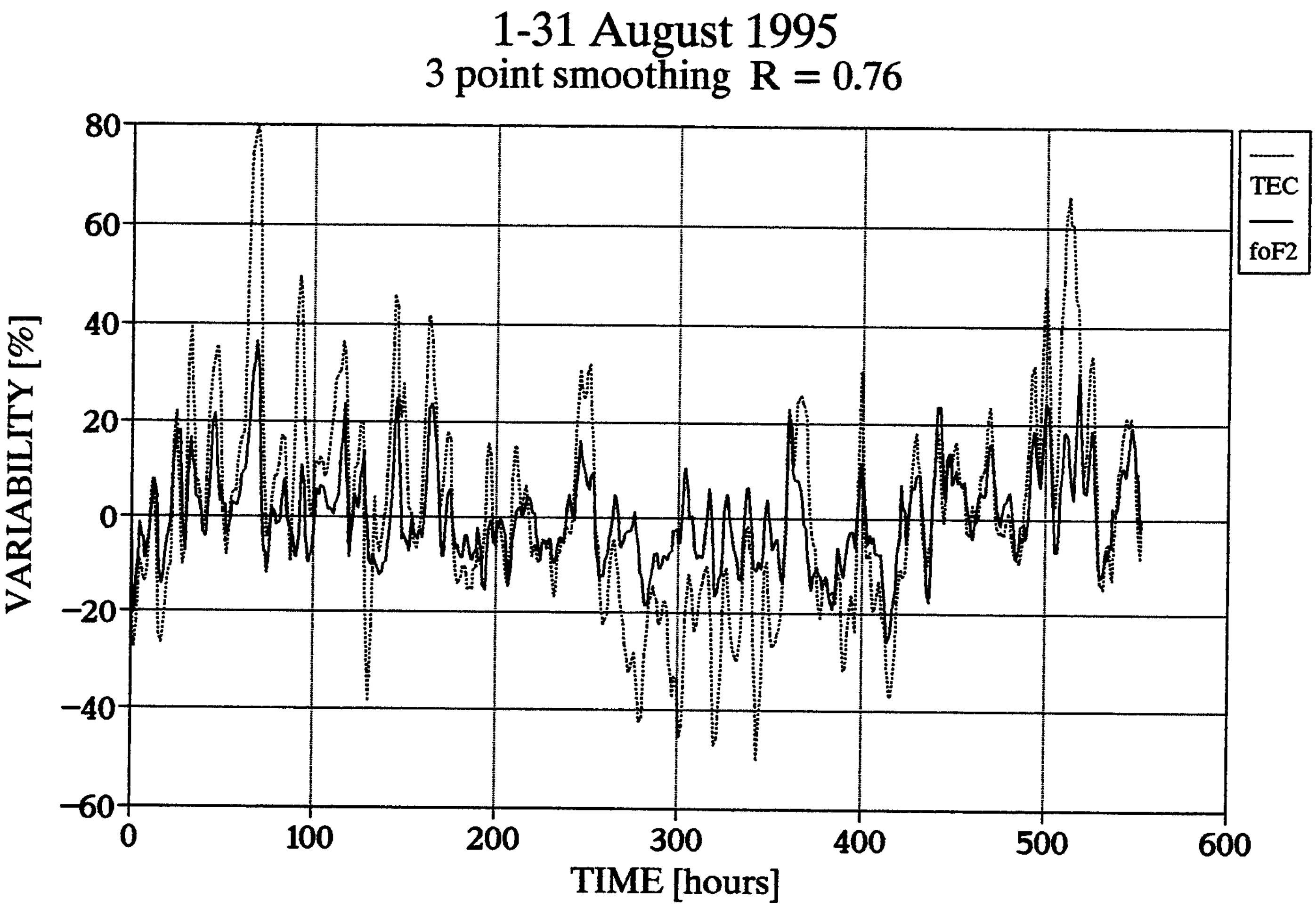


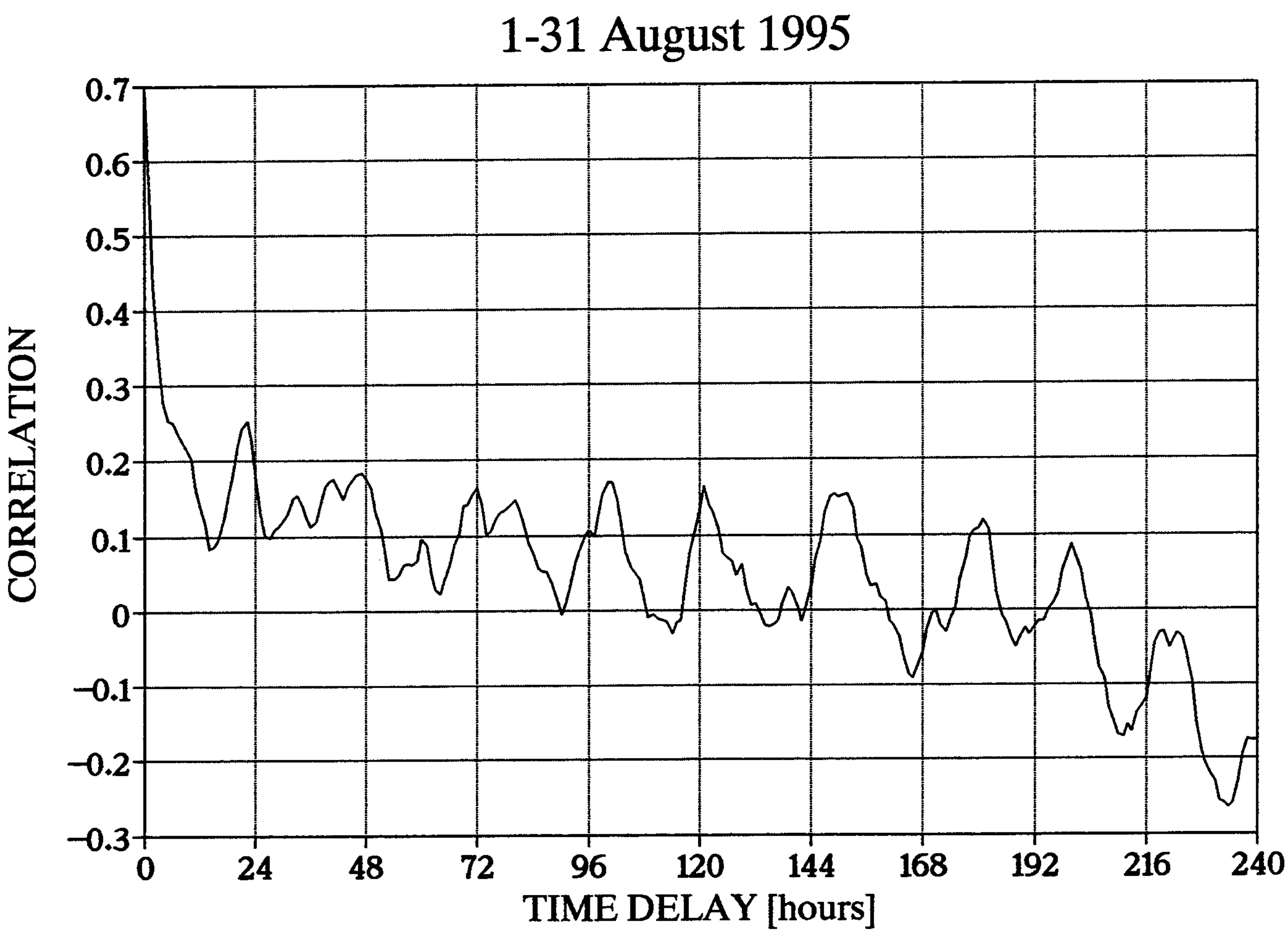
1-31 July 1995
AUTOCORRELATION
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
0
24
48
72
96
120
144
168
192
216
240
TIME LAG [hours]
TEC
foF2

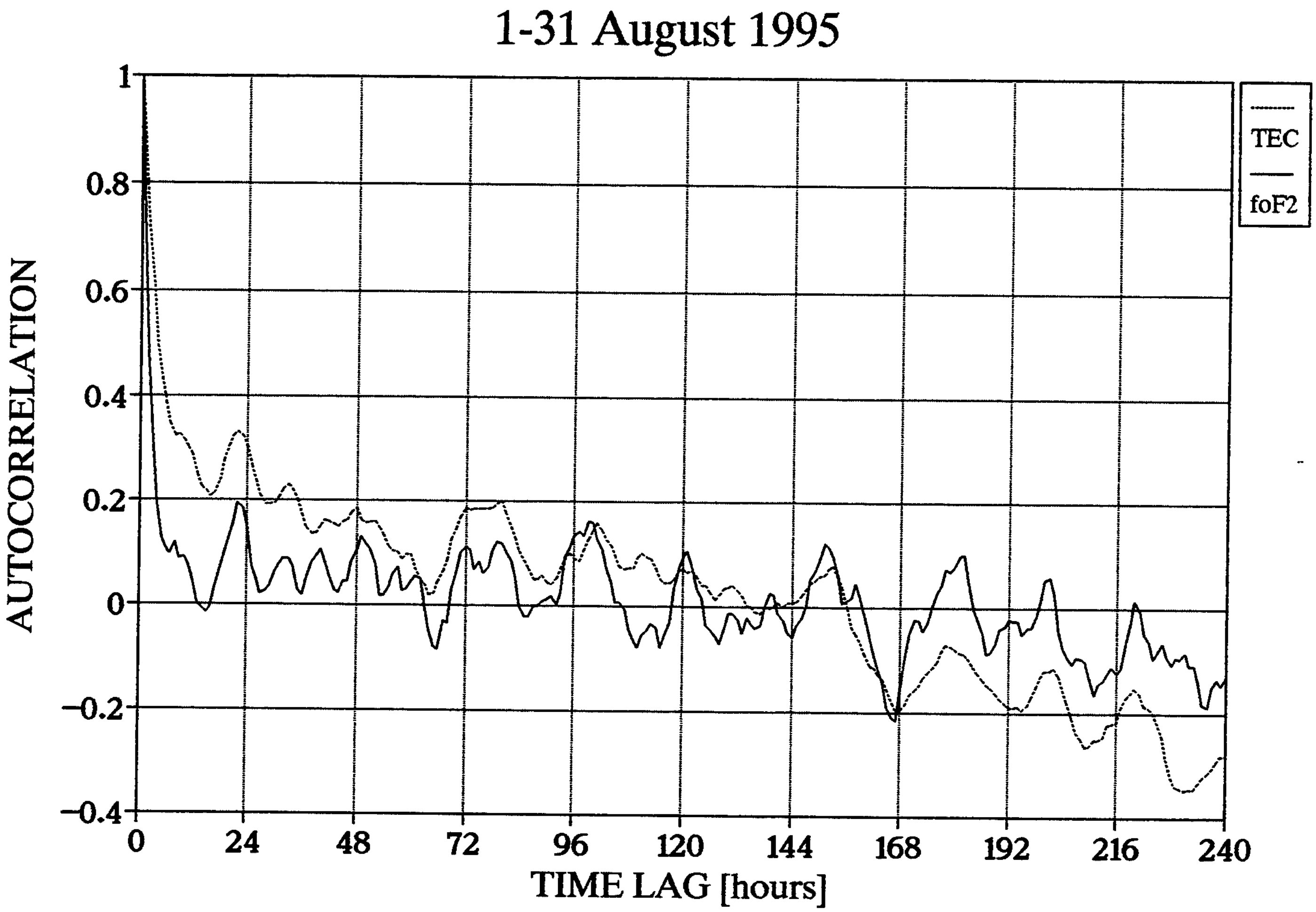


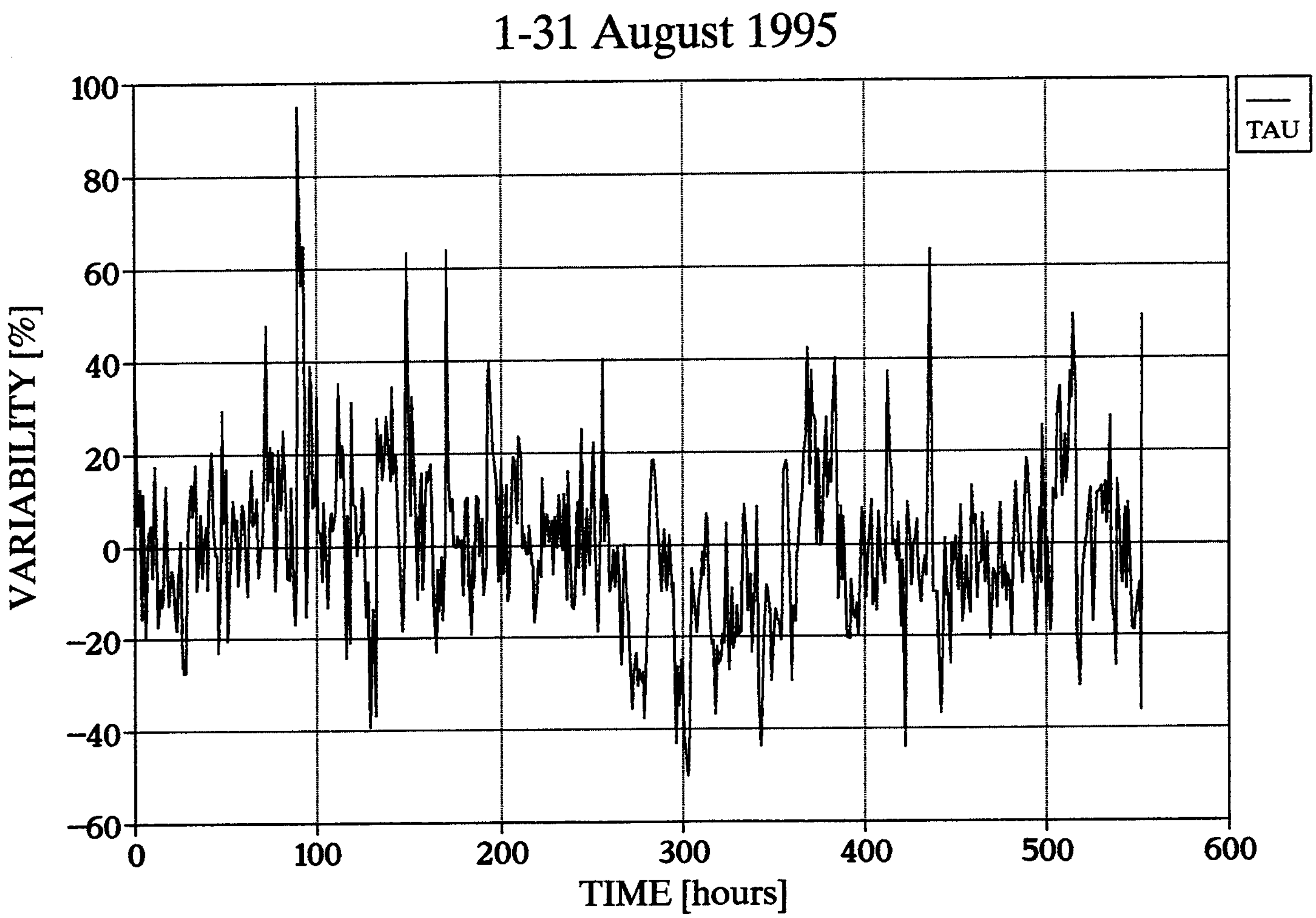
1-31 July 1995
TAU
VARIABILITY [%]
TIME [hours]
120
100
80
60
40
20
0
−20
−40
−60
0
100
200
300
400
500
600
700

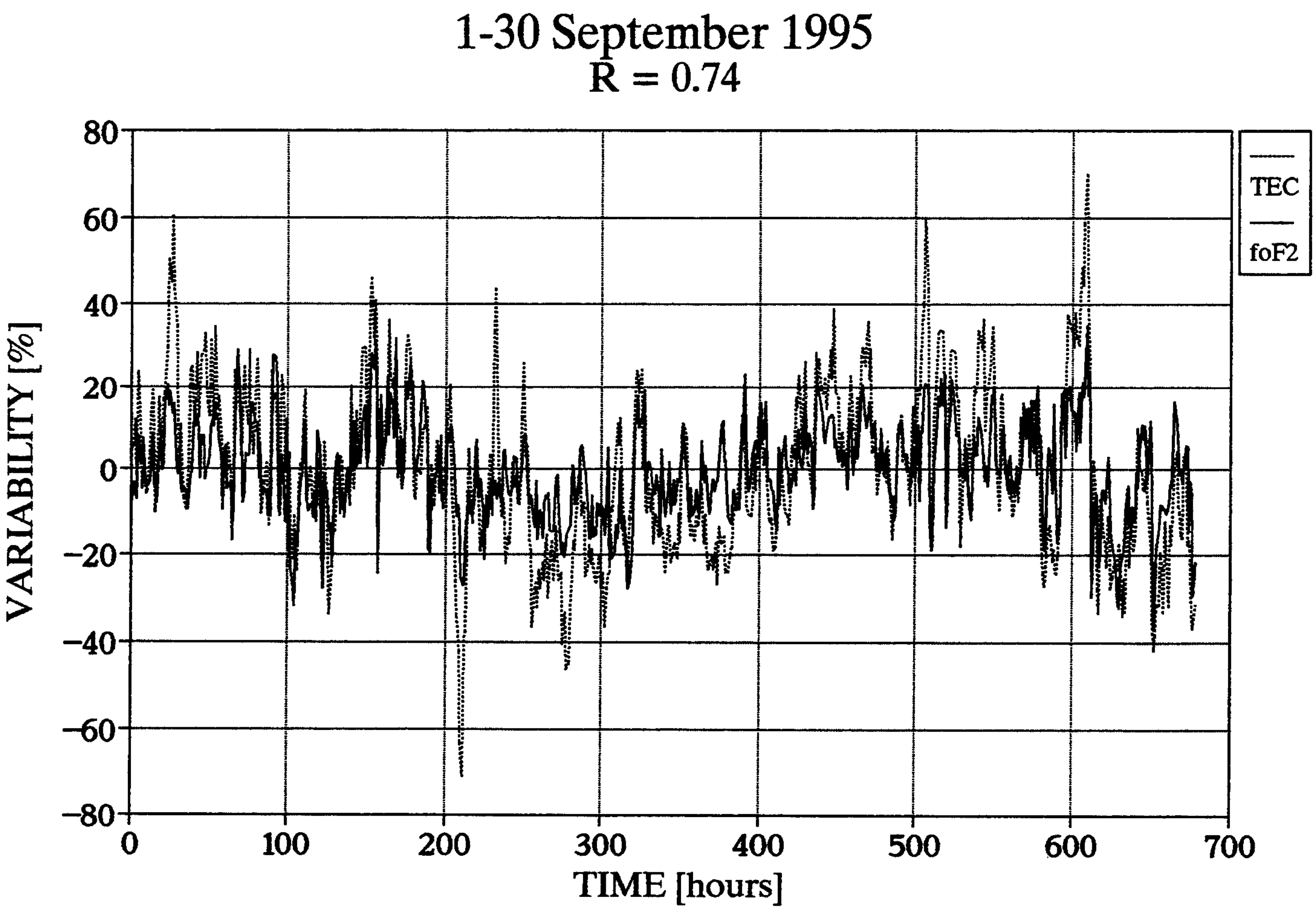

1-31 August 1995
R = 0.70
100
80
60
40
20
0
−20
−40
−60
VARIABILITY [%]
0
100
200
300
400
500
600
TIME [hours]
TEC
foF2


1-31 August 1995
3 point smoothing R = 0.76
80
60
40
20
0
−20
−40
−60
VARIABILITY [%]
0
100
200
300
400
500
600
TIME [hours]
TEC
foF2


1-31 August 1995
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
CORRELATION
0
24
48
72
96
120
144
168
192
216
240
TIME DELAY [hours]


1-31 August 1995
AUTOCORRELATION
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
0
24
48
72
96
120
144
168
192
216
240
TIME LAG [hours]
TEC
foF2


1-31 August 1995
100
80
60
40
20
0
−20
−40
−60
0
100
200
300
400
500
600
VARIABILITY [%]
TIME [hours]
TAU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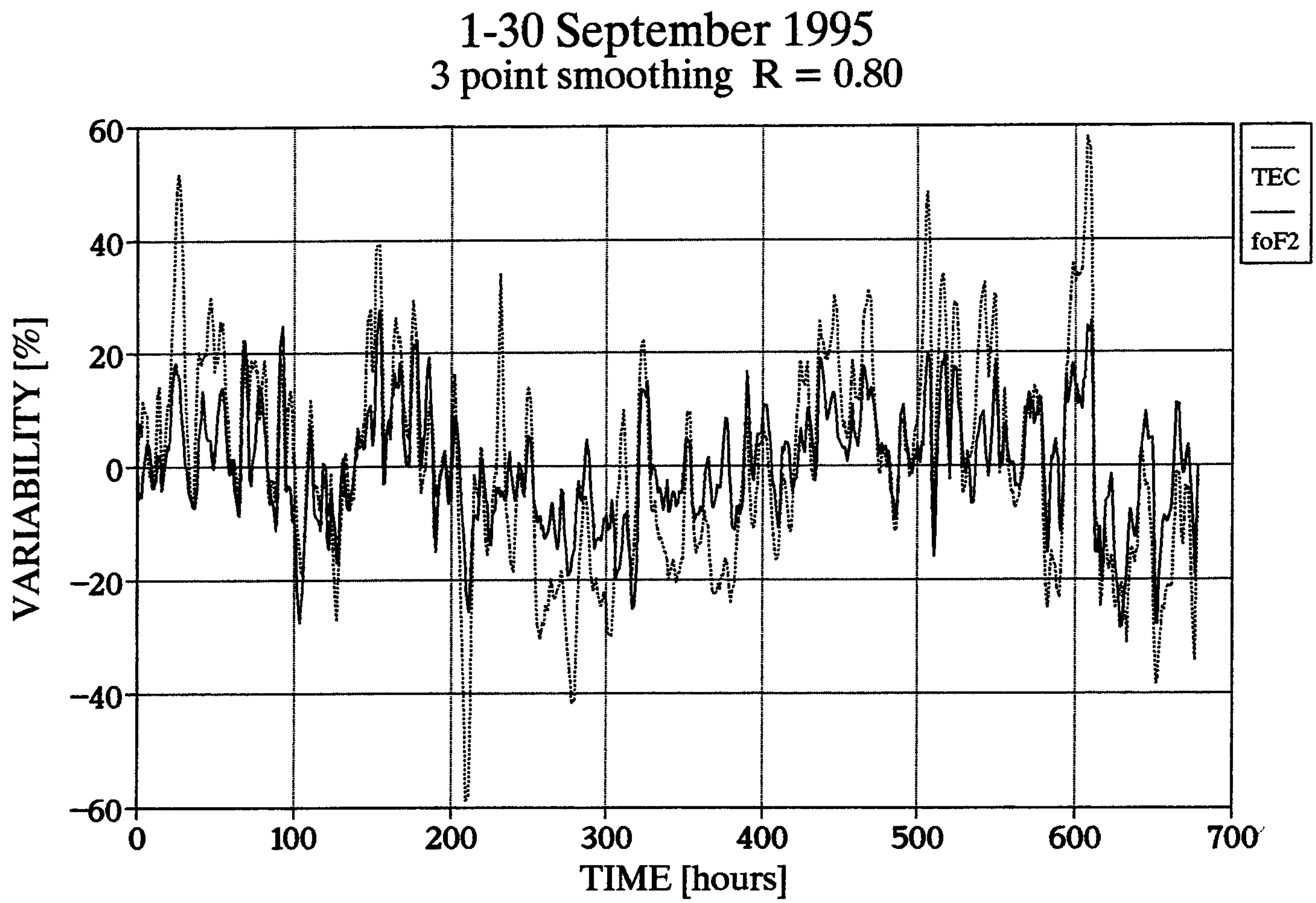
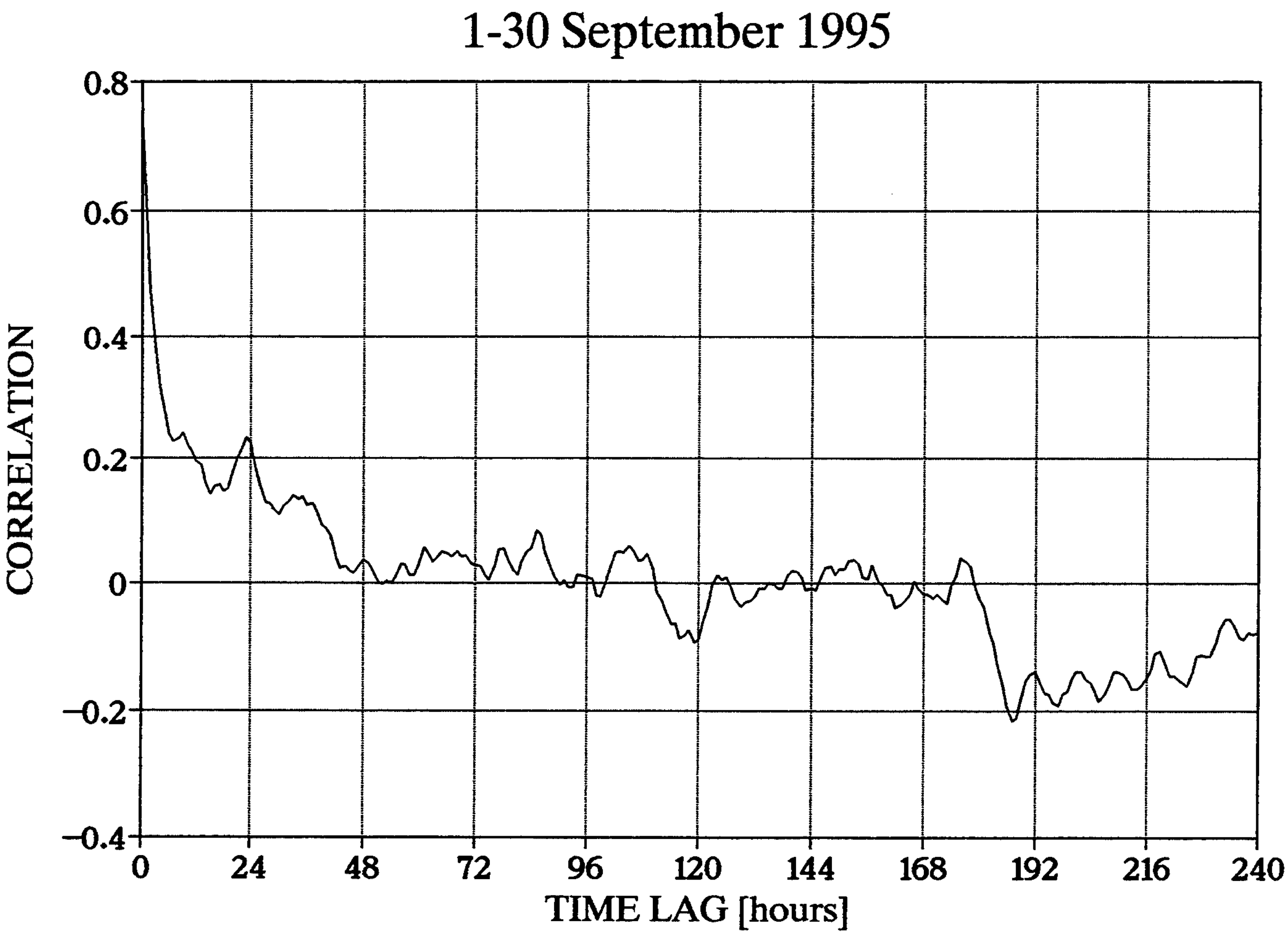
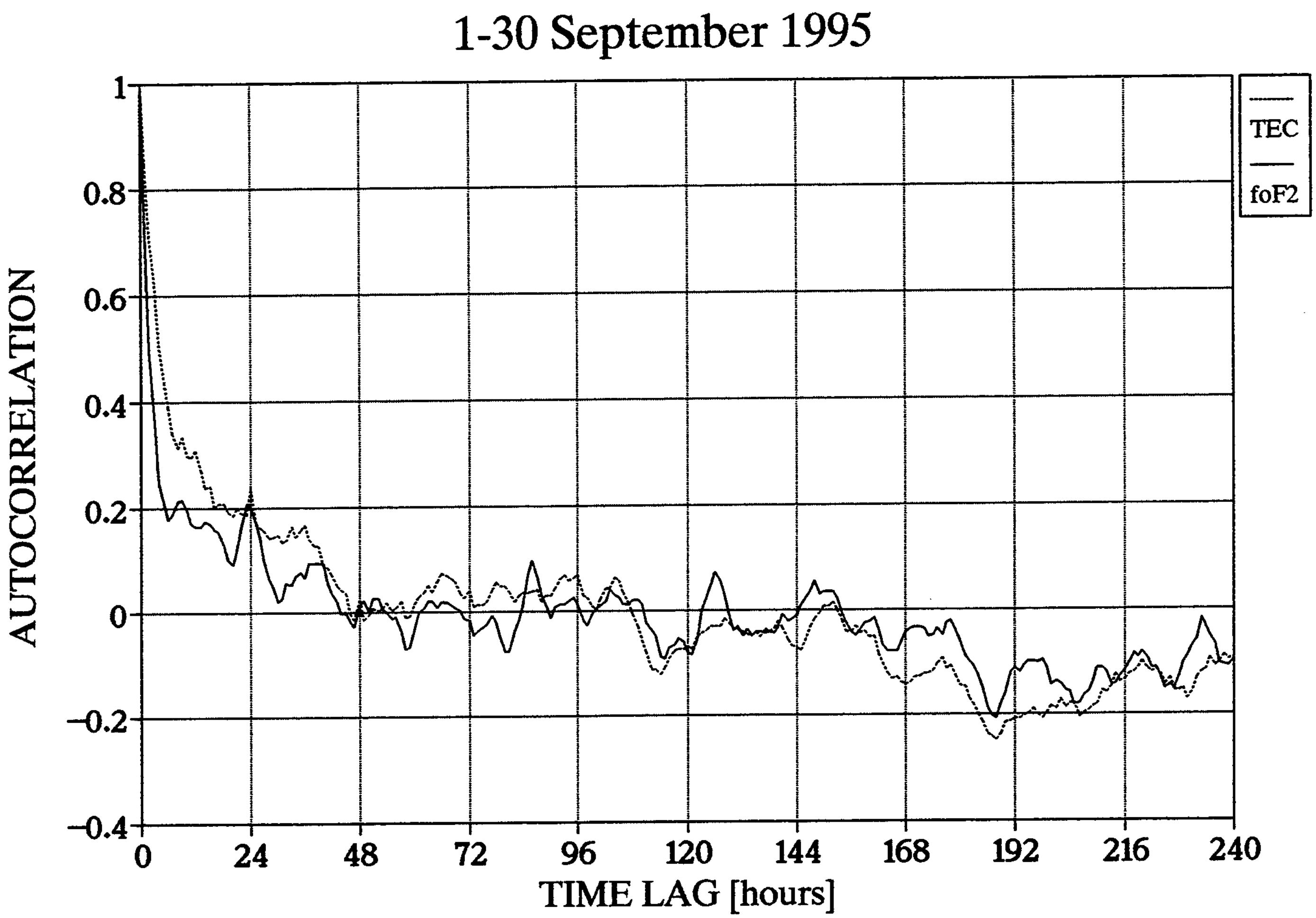
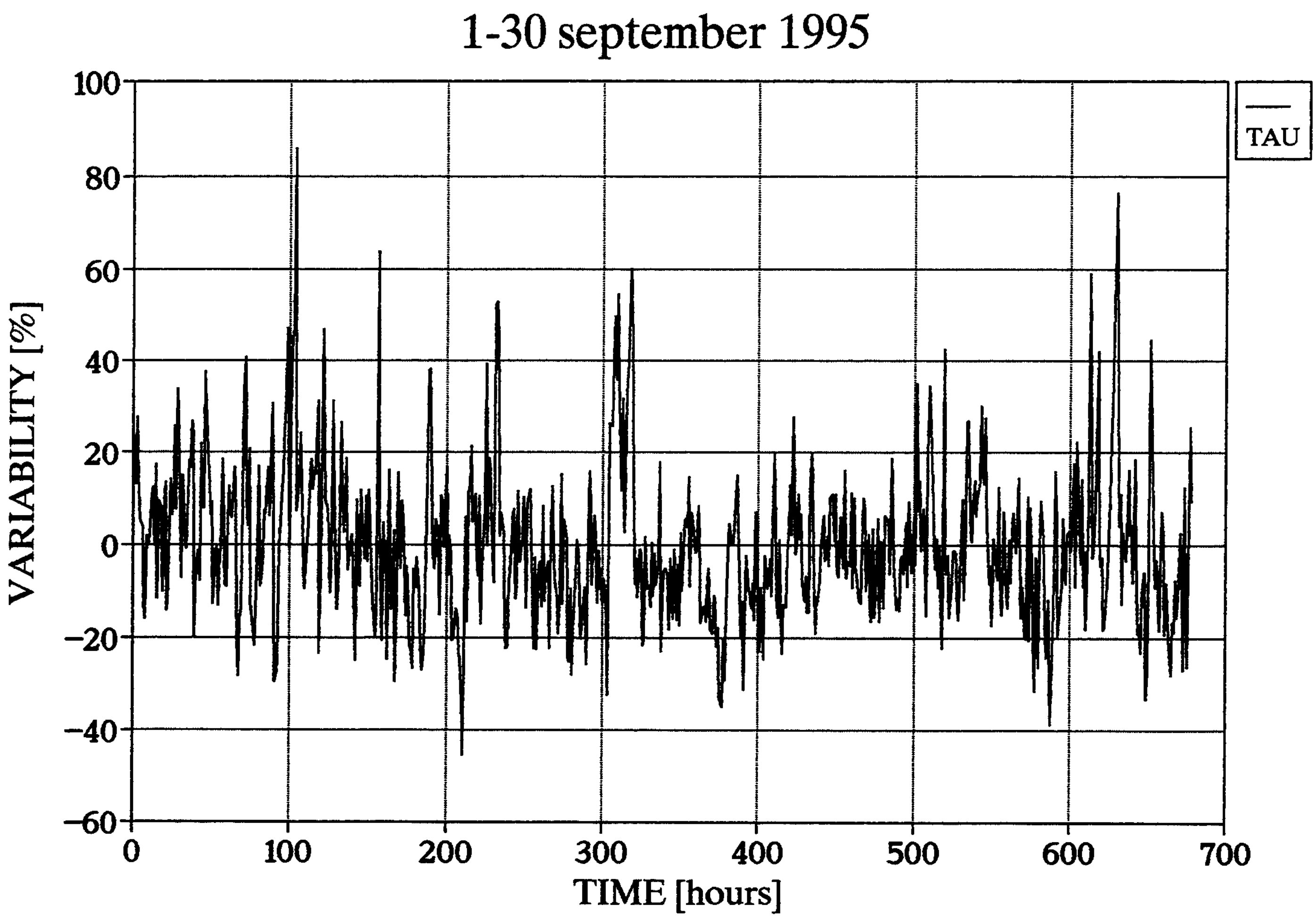
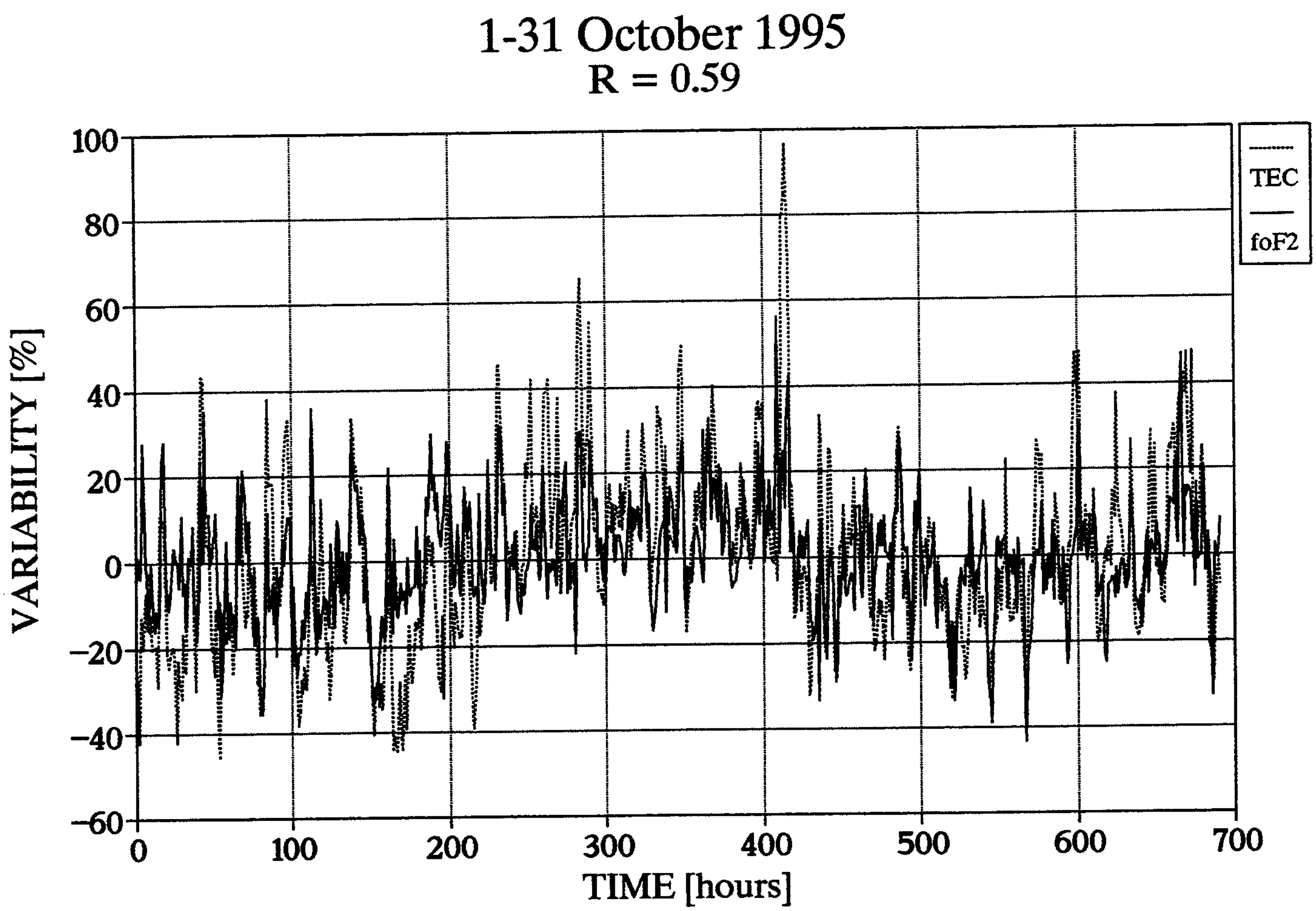
R = 0.74
80
60
40
20
0
−20
−40
−60
−80
0
100
200
300
400
500
600
700
TIME [hours]
VARIABILITY [%]
TEC
foF2


1-30 September 1995
3 point smoothing R = 0.80
VARIABILITY [%]
TIME [hours]
TEC
foF2
60
40
20
0
−20
−40
−60
0
100
200
300
400
500
600
700

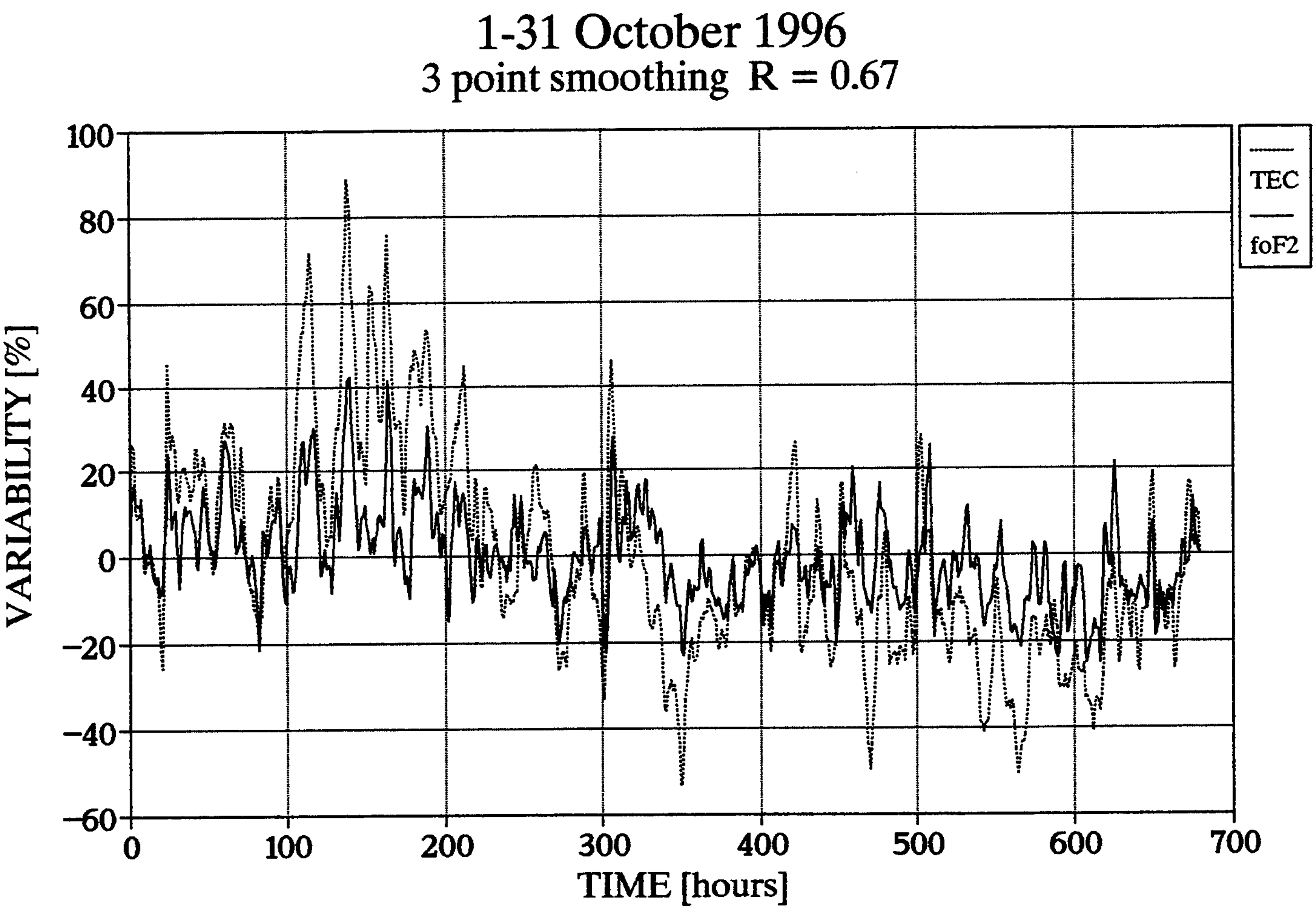

1-30 September 1995
0.8
0.6
0.4
0.2
0
−0.2
−0.4
CORRELATION
0
24
48
72
96
120
144
168
192
216
240
TIME LAG [hours]

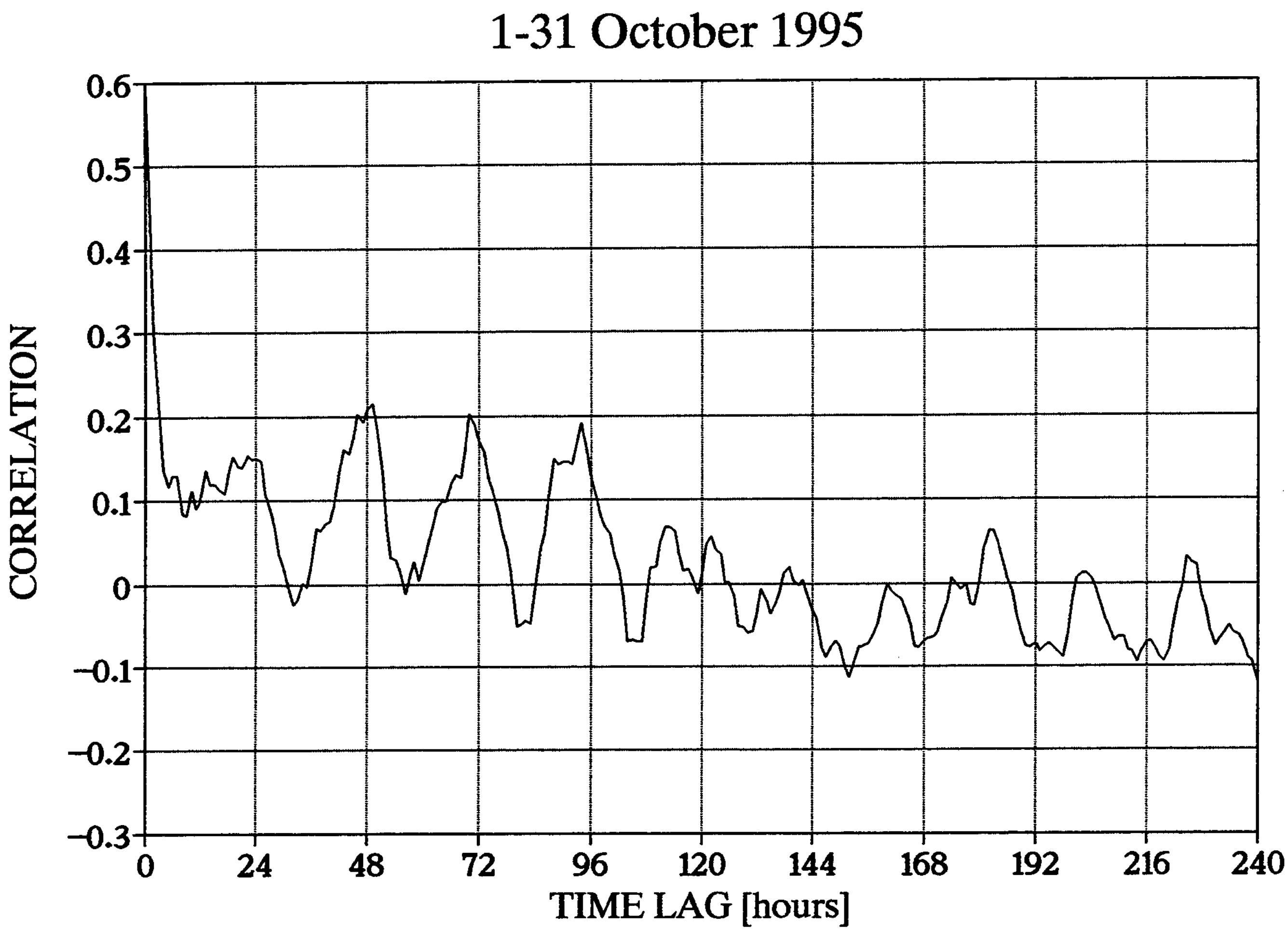

1-30 September 1995
AUTOCORRELATION
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
0
24
48
72
96
120
144
168
192
216
240
TIME LAG [hours]
TEC
foF2

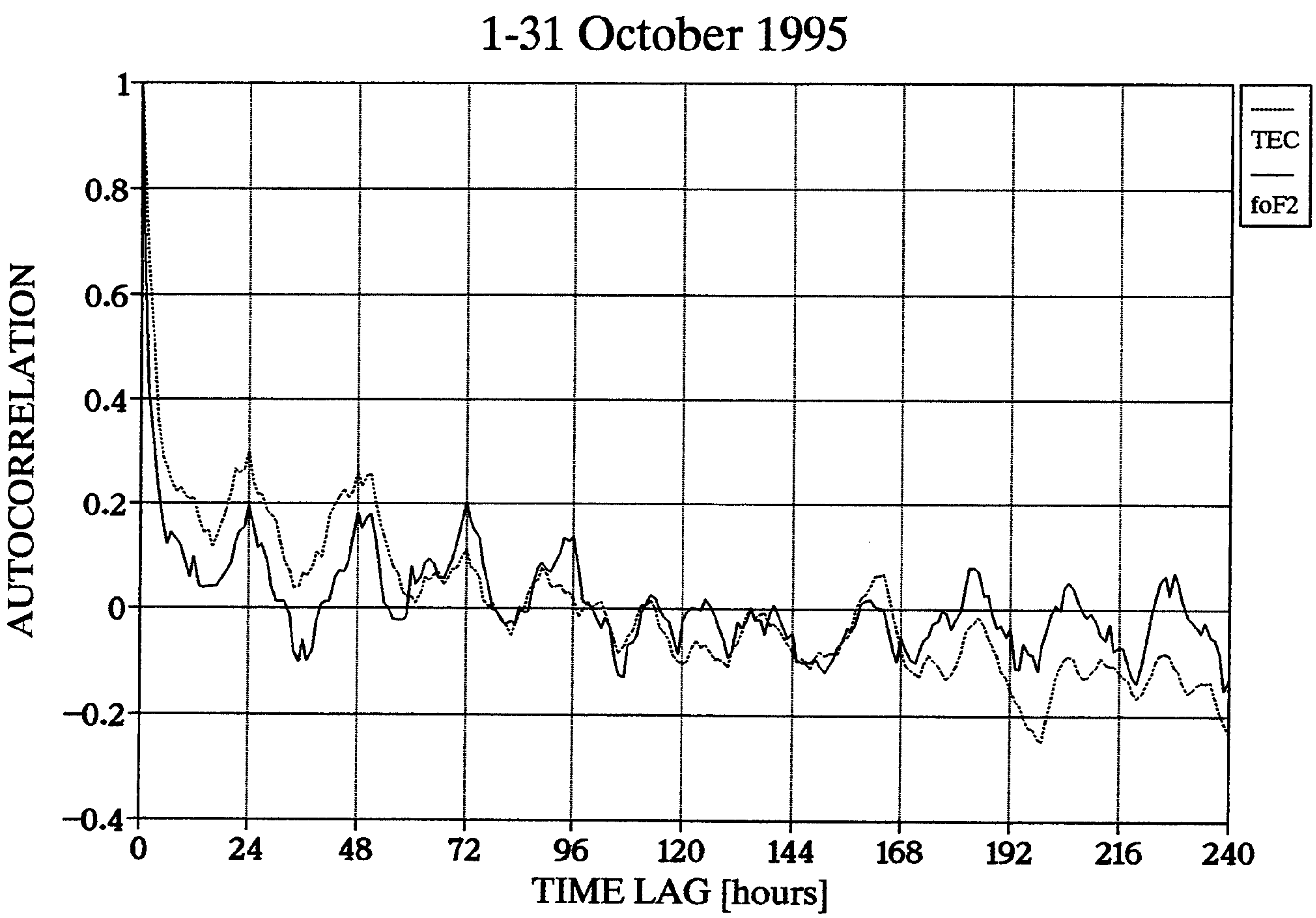

1-30 september 1995
TAU
100
80
60
40
20
0
−20
−40
−60
VARIABILITY [%]
0
100
200
300
400
500
600
700
TIME [hours]



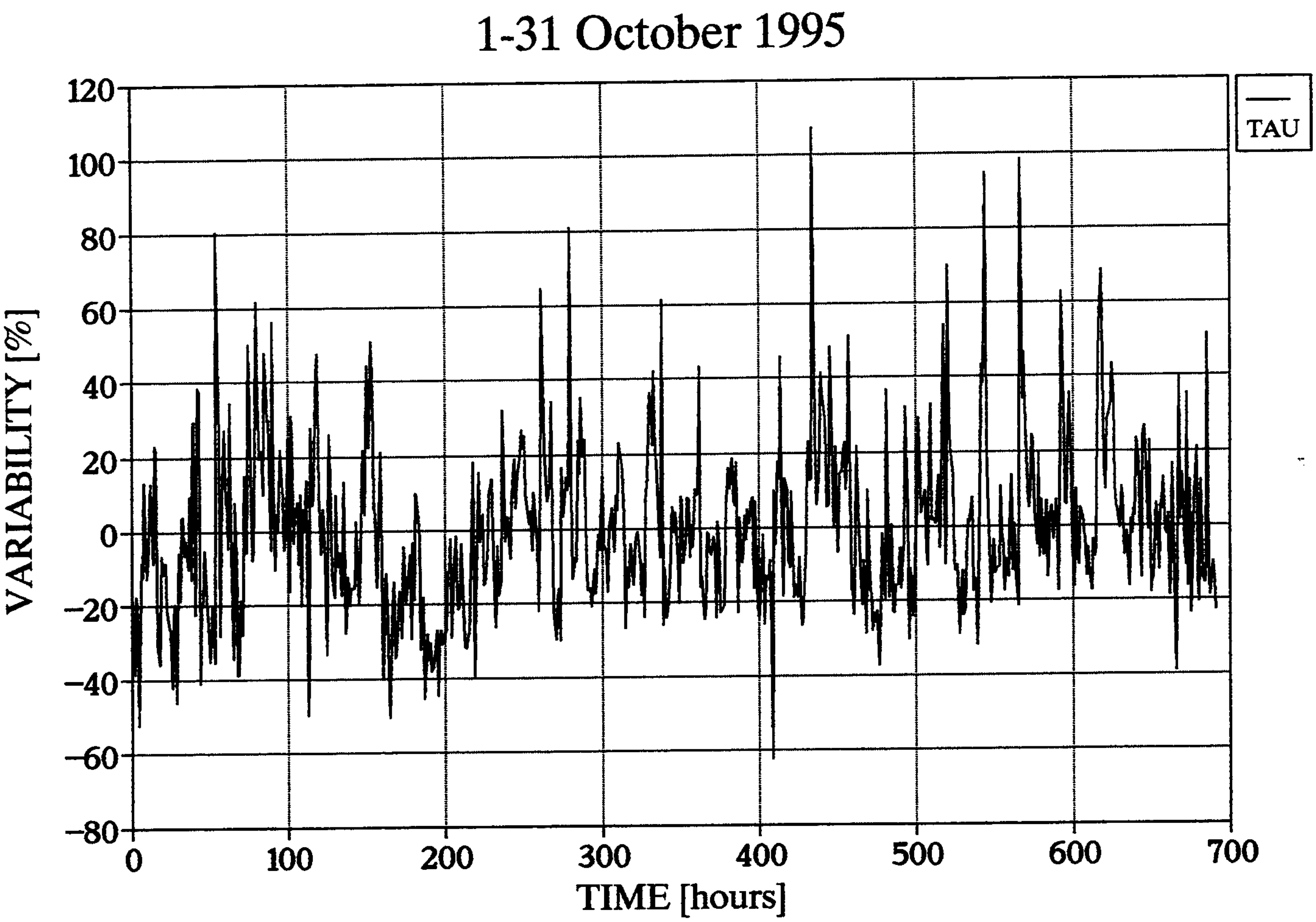
1-31 October 1995
R = 0.59
TEC
foF2
VARIABILITY [%]
TIME [hours]
100
80
60
40
20
0
−20
−40
−60
0
100
200
300
400
500
600
700

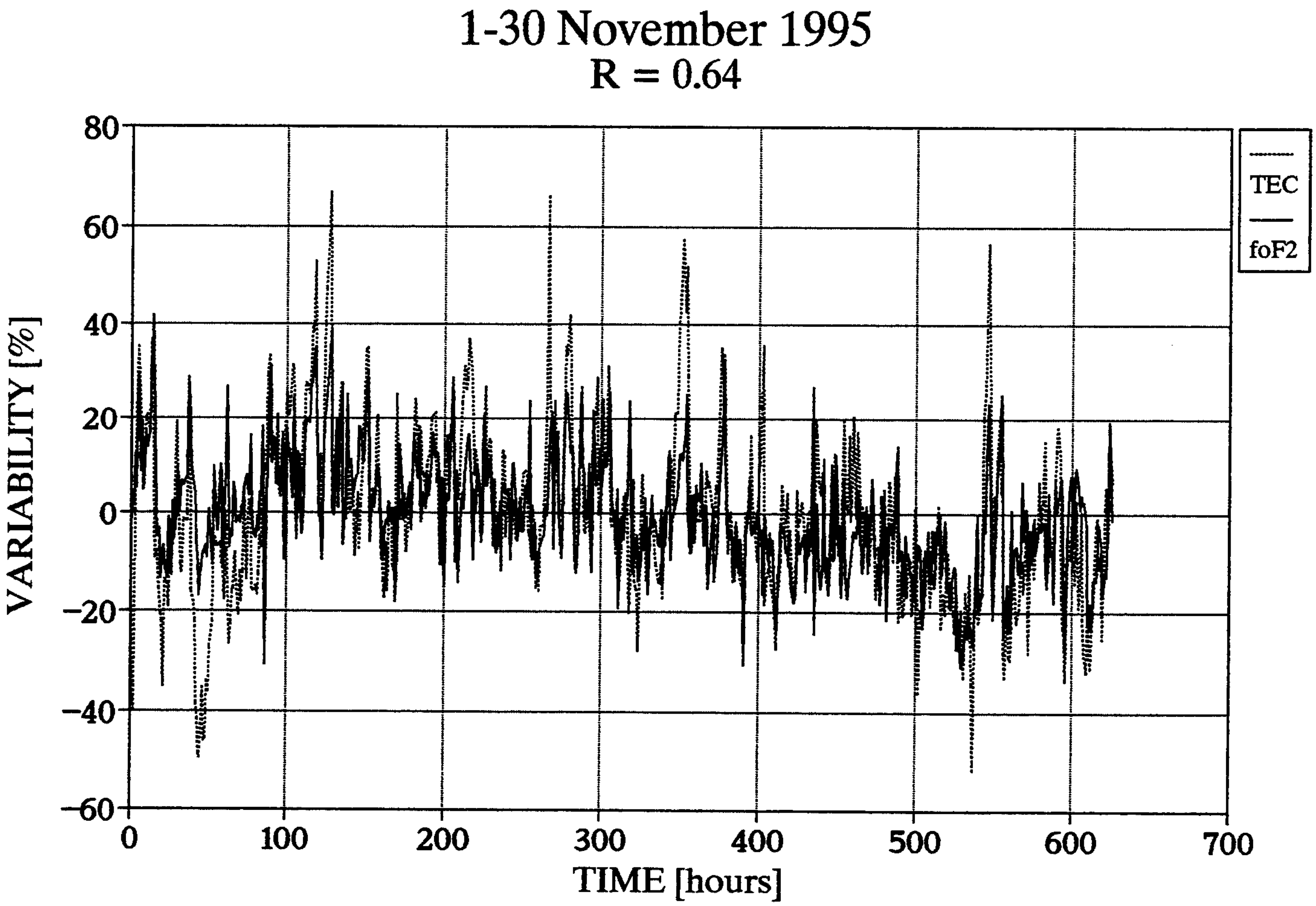

1-31 October 1996
3 point smoothing R = 0.67
TEC
foF2
VARIABILITY [%]
100
80
60
40
20
0
−20
−40
−60
0
100
200
300
400
500
600
700
TIME [hours]

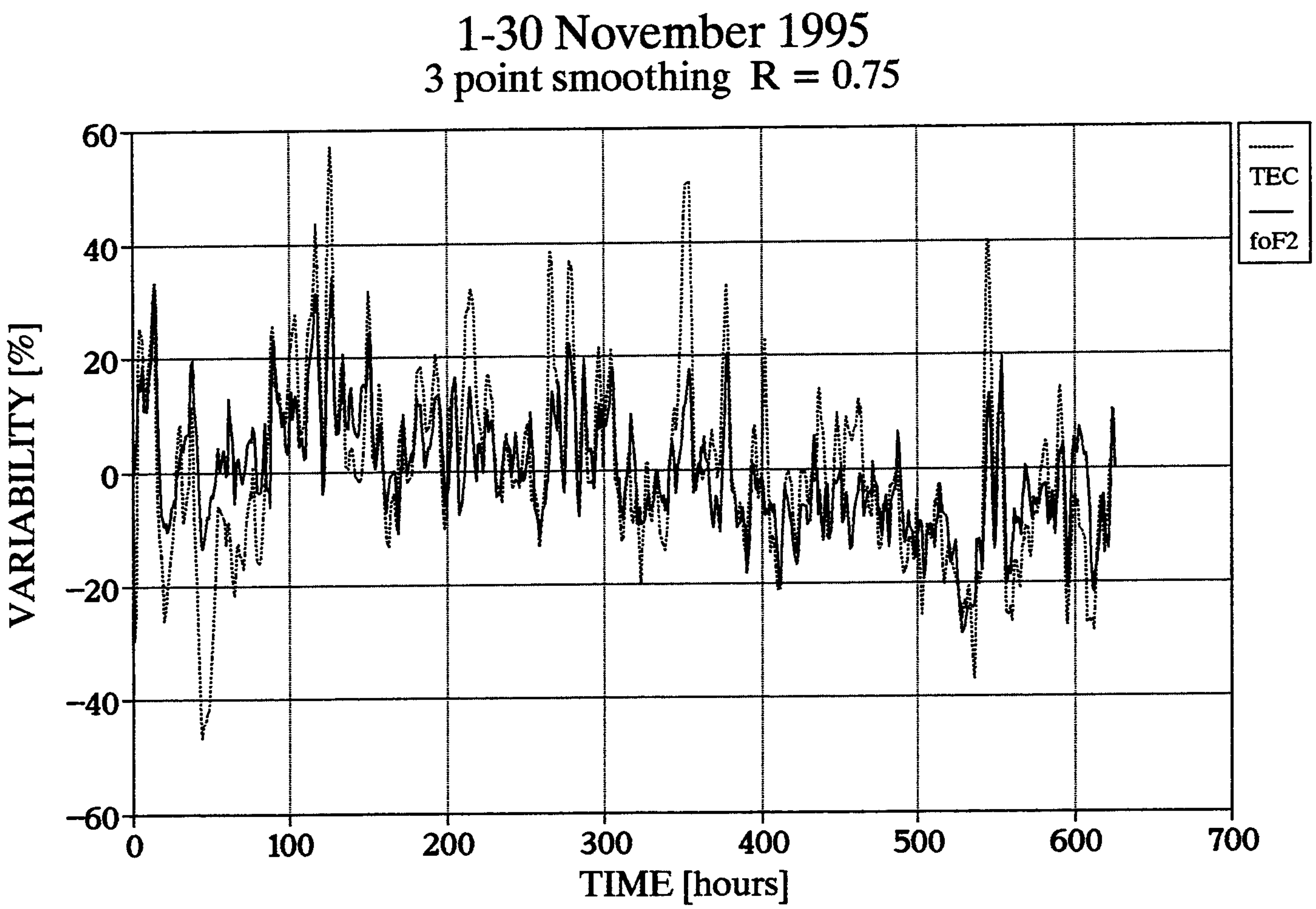

1-31 October 1995
CORRELATION
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
0
24
48
72
96
120
144
168
192
216
240
TIME LAG [hours]



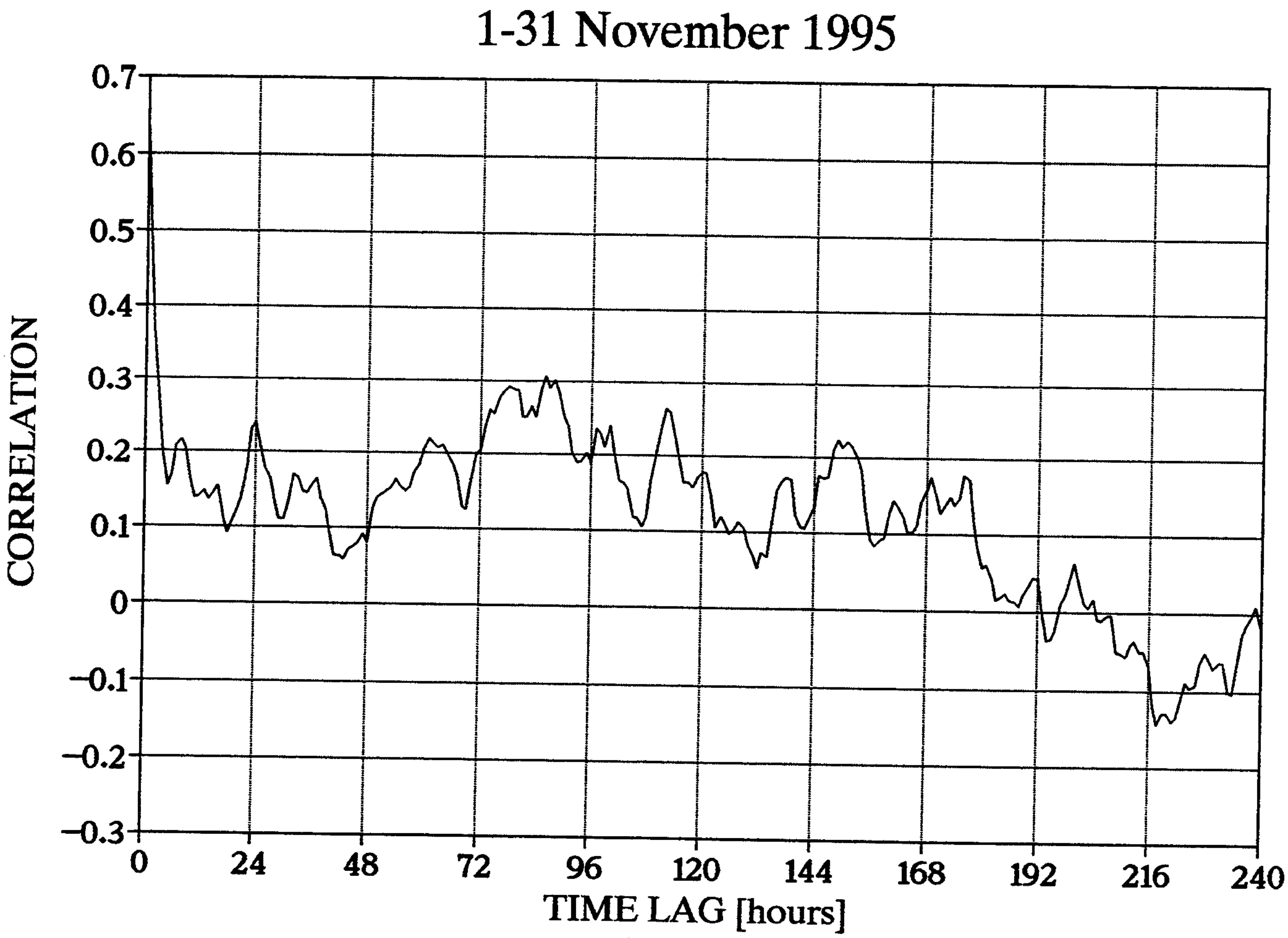
1-31 October 1995
AUTOCORRELATION
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
0
24
48
72
96
120
144
168
192
216
240
TIME LAG [hours]
TEC
foF2

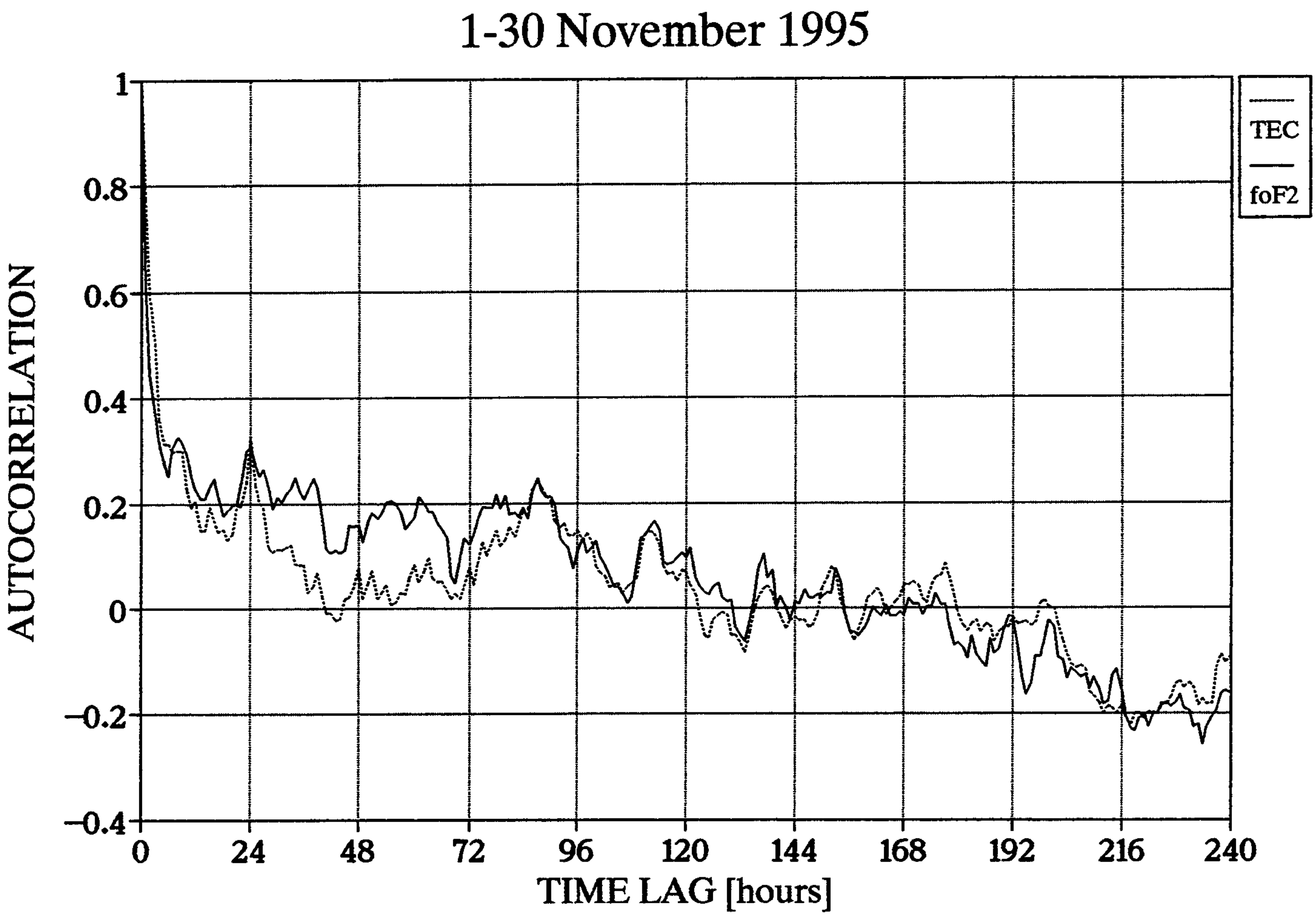

1-31 October 1995
VARIABILITY [%]
TIME [hours]
TAU
120
100
80
60
40
20
0
−20
−40
−60
−80
0
100
200
300
400
500
600
700

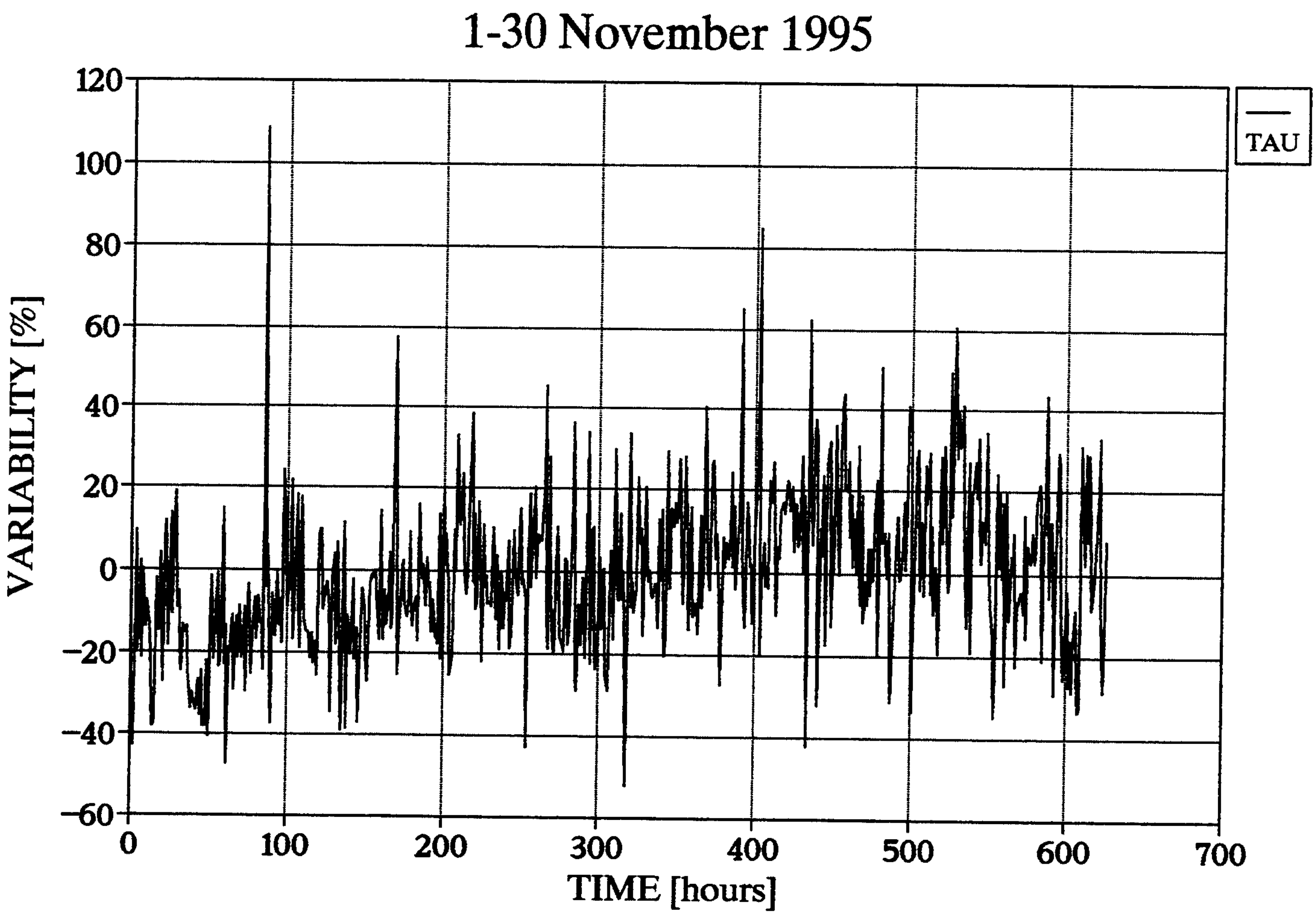

1-30 November 1995
R = 0.64
80
60
40
20
0
−20
−40
−60
VARIABILITY [%]
0
100
200
300
400
500
600
700
TIME [hours]
TEC
foF2

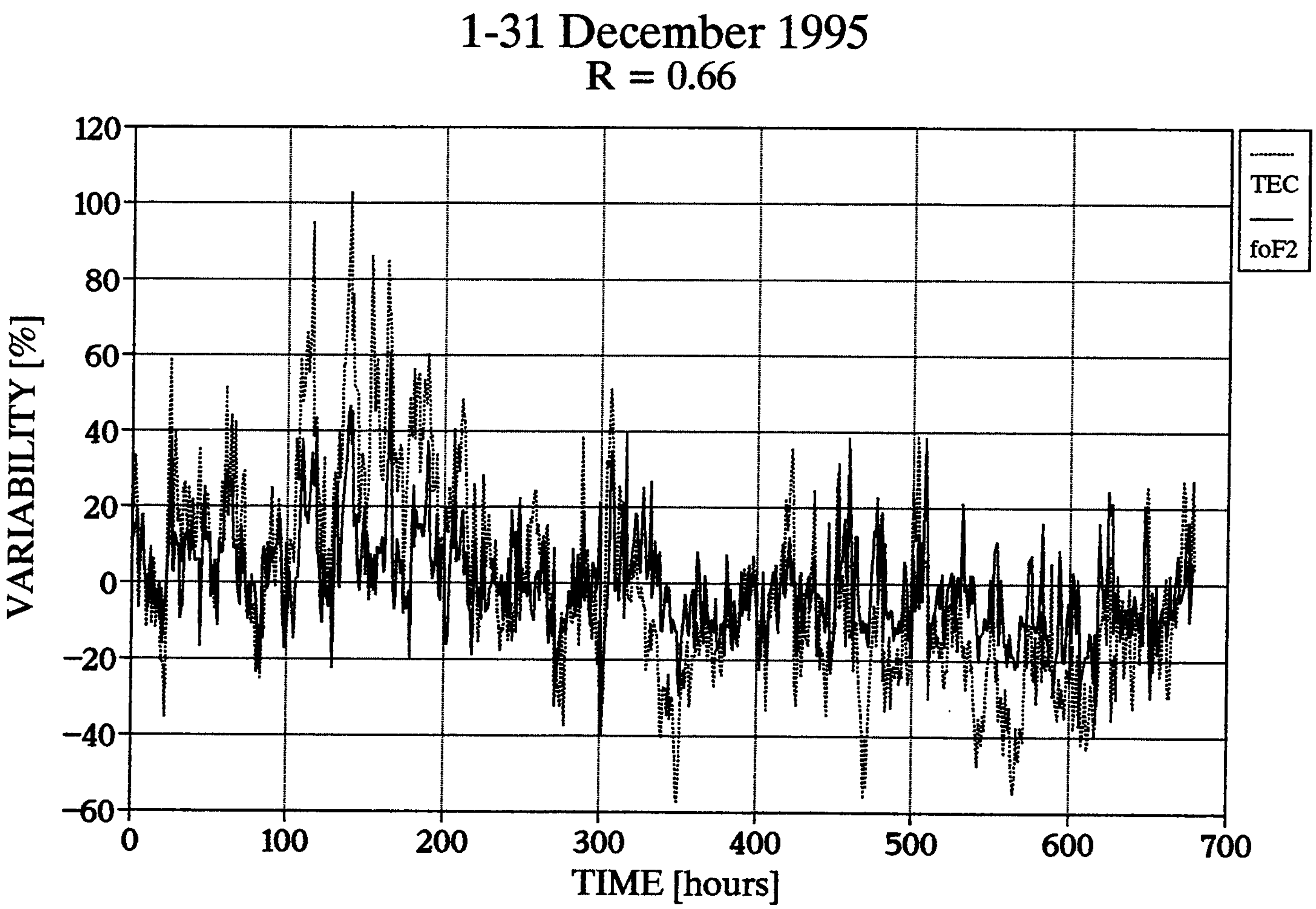


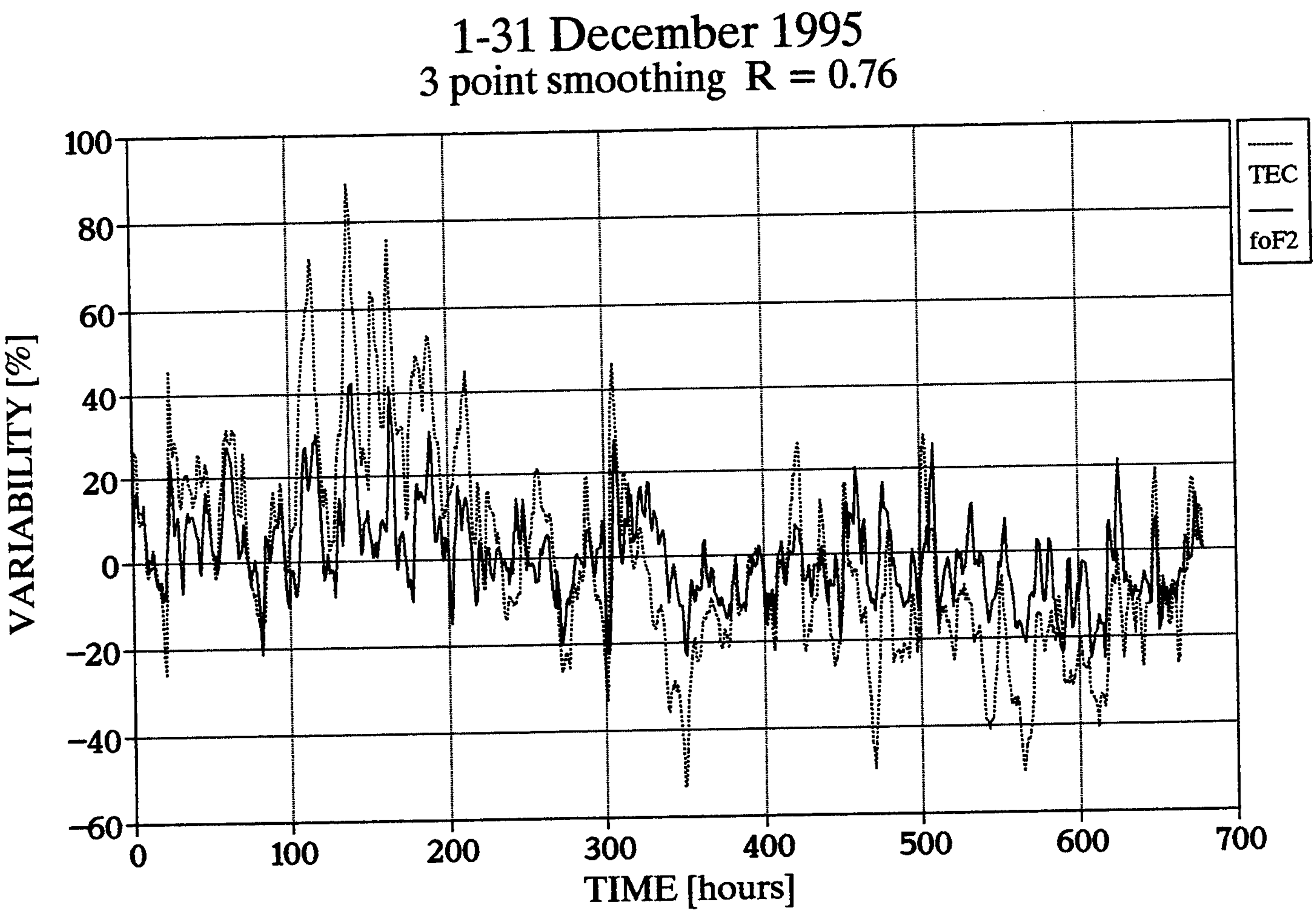
1-30 November 1995
3 point smoothing R = 0.75
60
40
20
0
−20
−40
−60
VARIABILITY [%]
0
100
200
300
400
500
600
700
TIME [hours]
TEC
foF2


1-31 November 1995
CORRELATION
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
0
24
48
72
96
120
144
168
192
216
240
TIME LAG [hours]

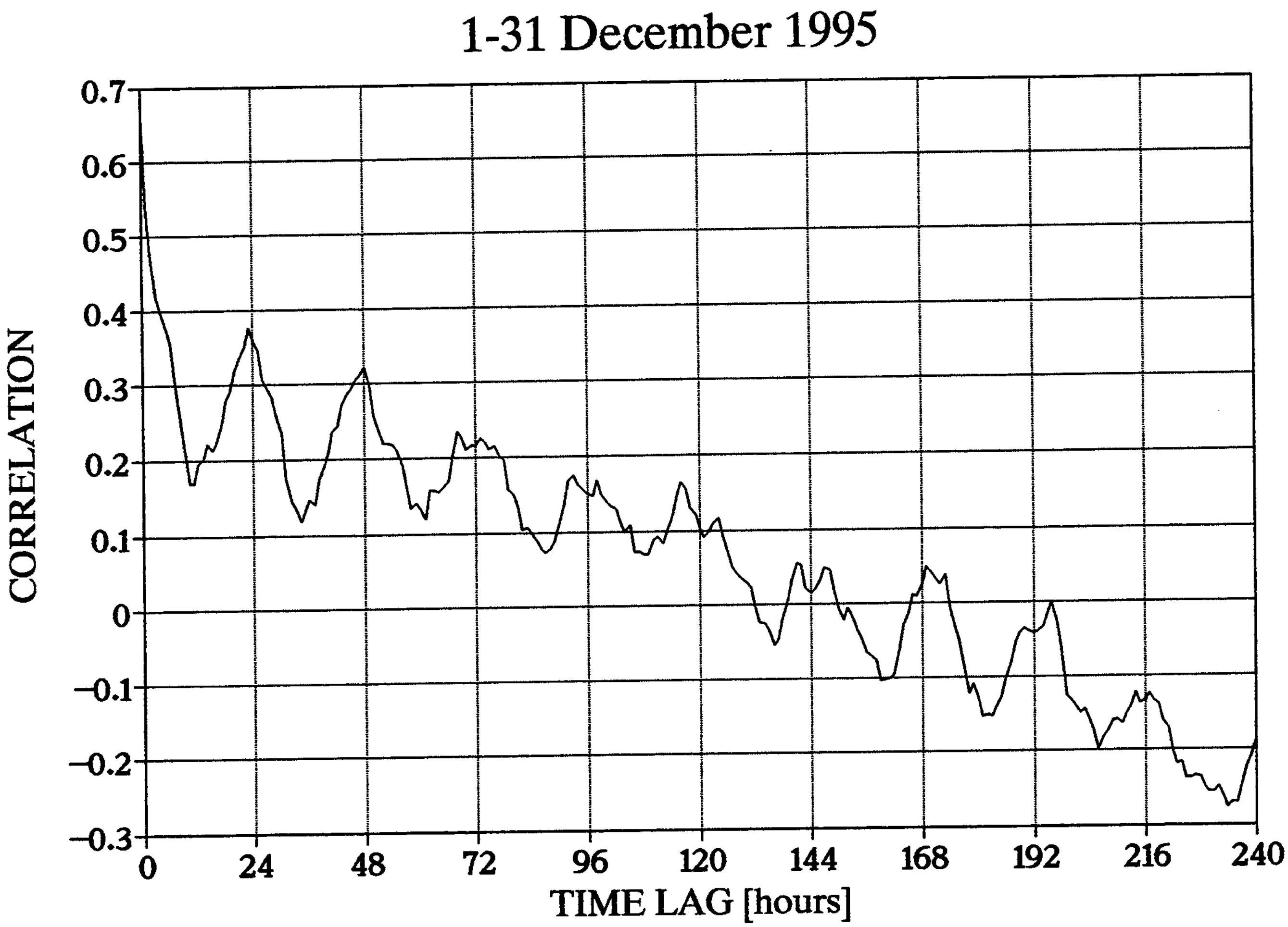

1-30 November 1995
AUTOCORRELATION
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
0
24
48
72
96
120
144
168
192
216
240
TIME LAG [hours]
TEC
foF2

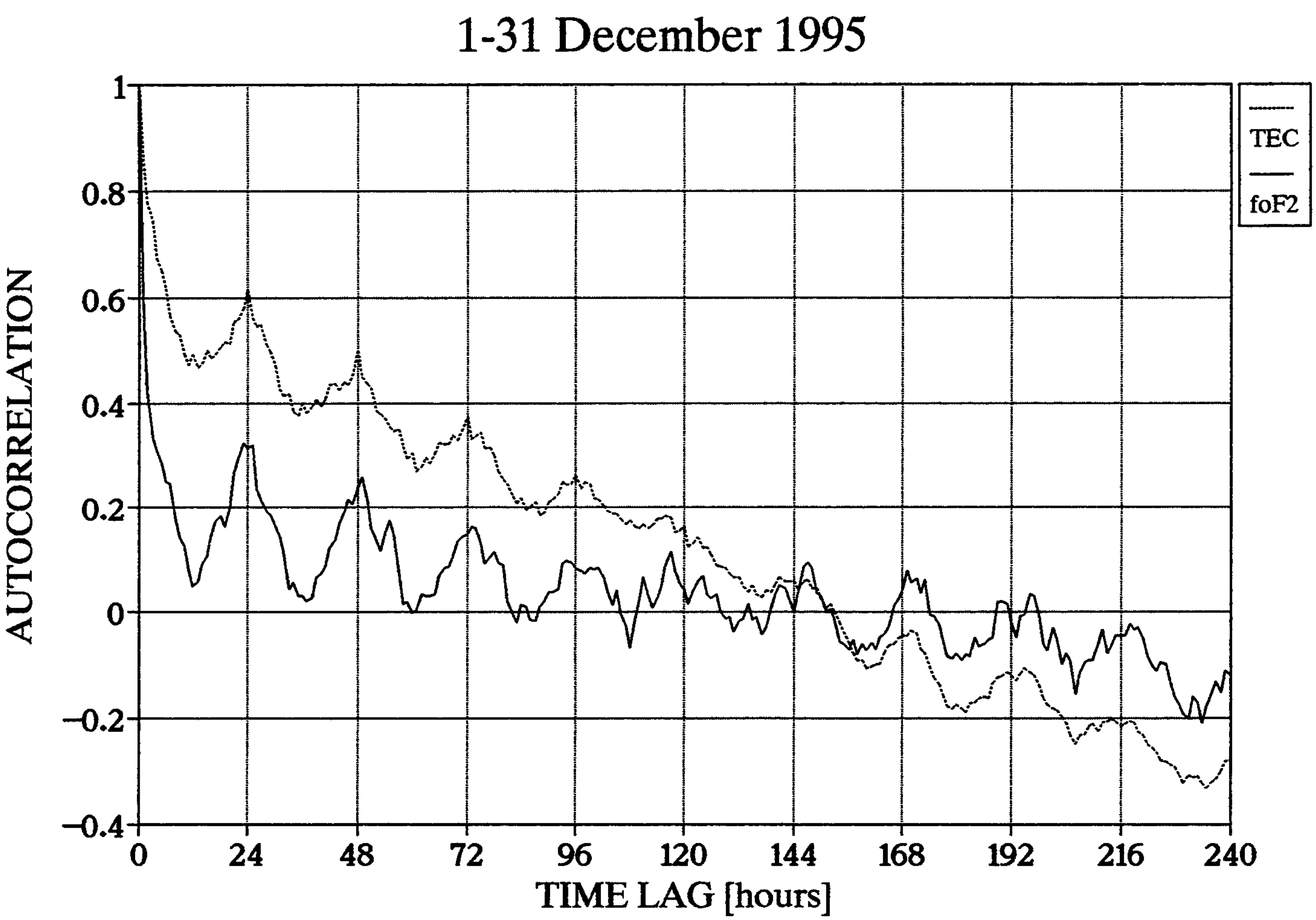

1-30 November 1995
120
100
80
60
40
20
0
−20
−40
−60
VARIABILITY [%]
0
100
200
300
400
500
600
700
TIME [hours]
TAU


1-31 December 1995
R = 0.66
VARIABILITY [%]
TIME [hours]
TEC
foF2
120
100
80
60
40
20
0
−20
−40
−60
0
100
200
300
400
500
600
700

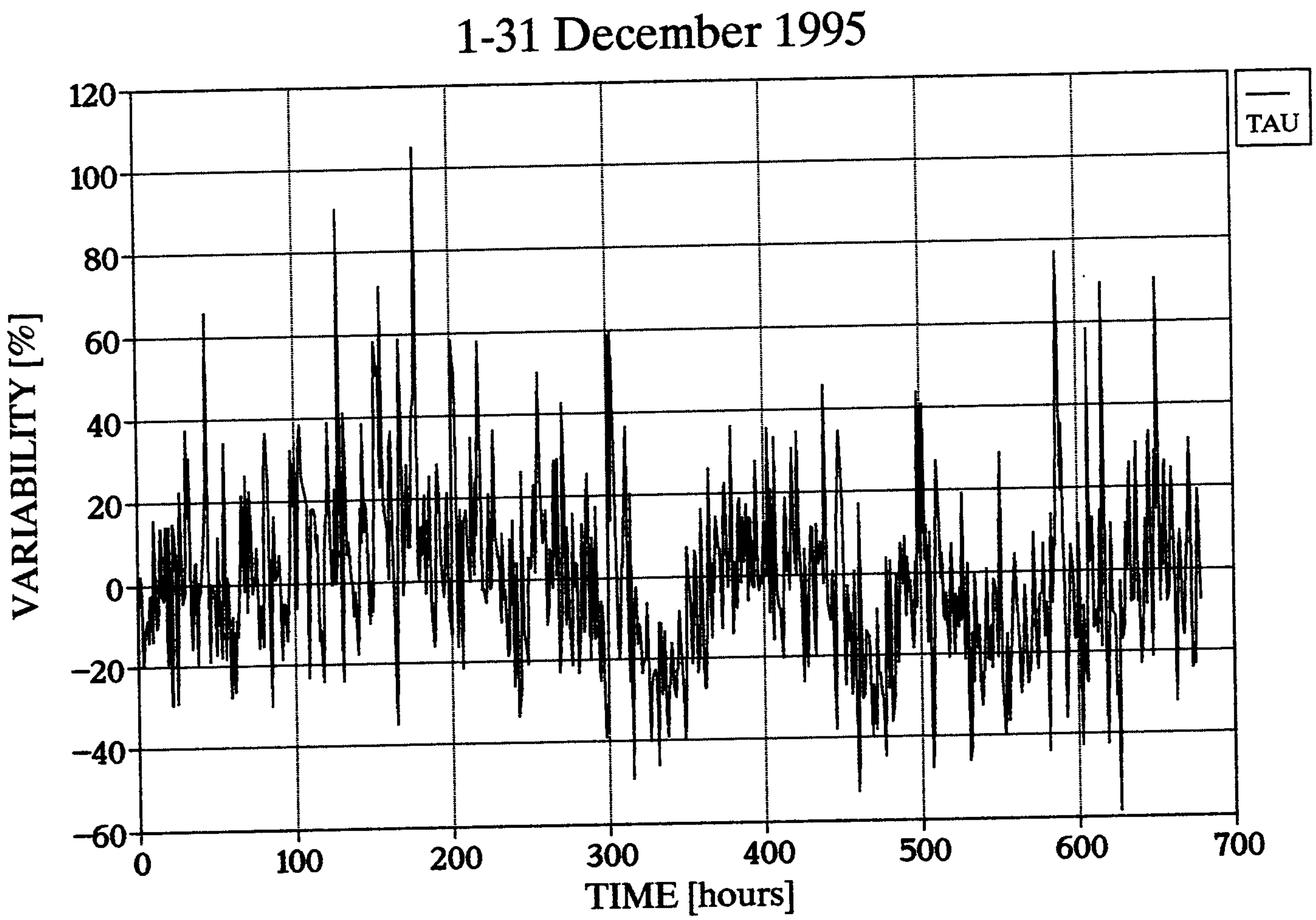


1-31 December 1995
3 point smoothing R = 0.76
TEC
foF2
VARIABILITY [%]
100
80
60
40
20
0
−20
−40
−60
0
100
200
300
400
500
600
700
TIME [hours]

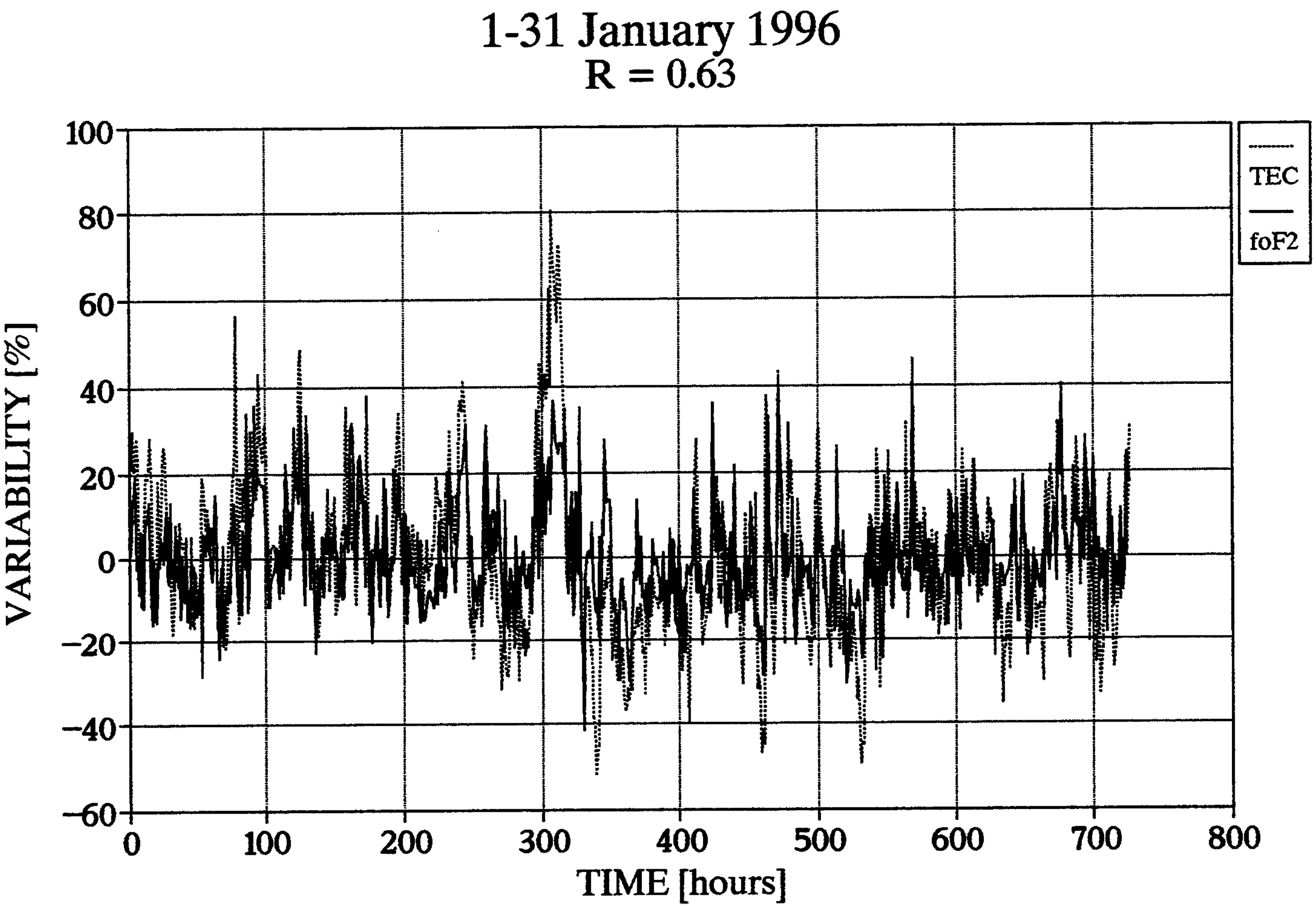

1-31 December 1995
CORRELATION
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
0
24
48
72
96
120
144
168
192
216
240
TIME LAG [hours]

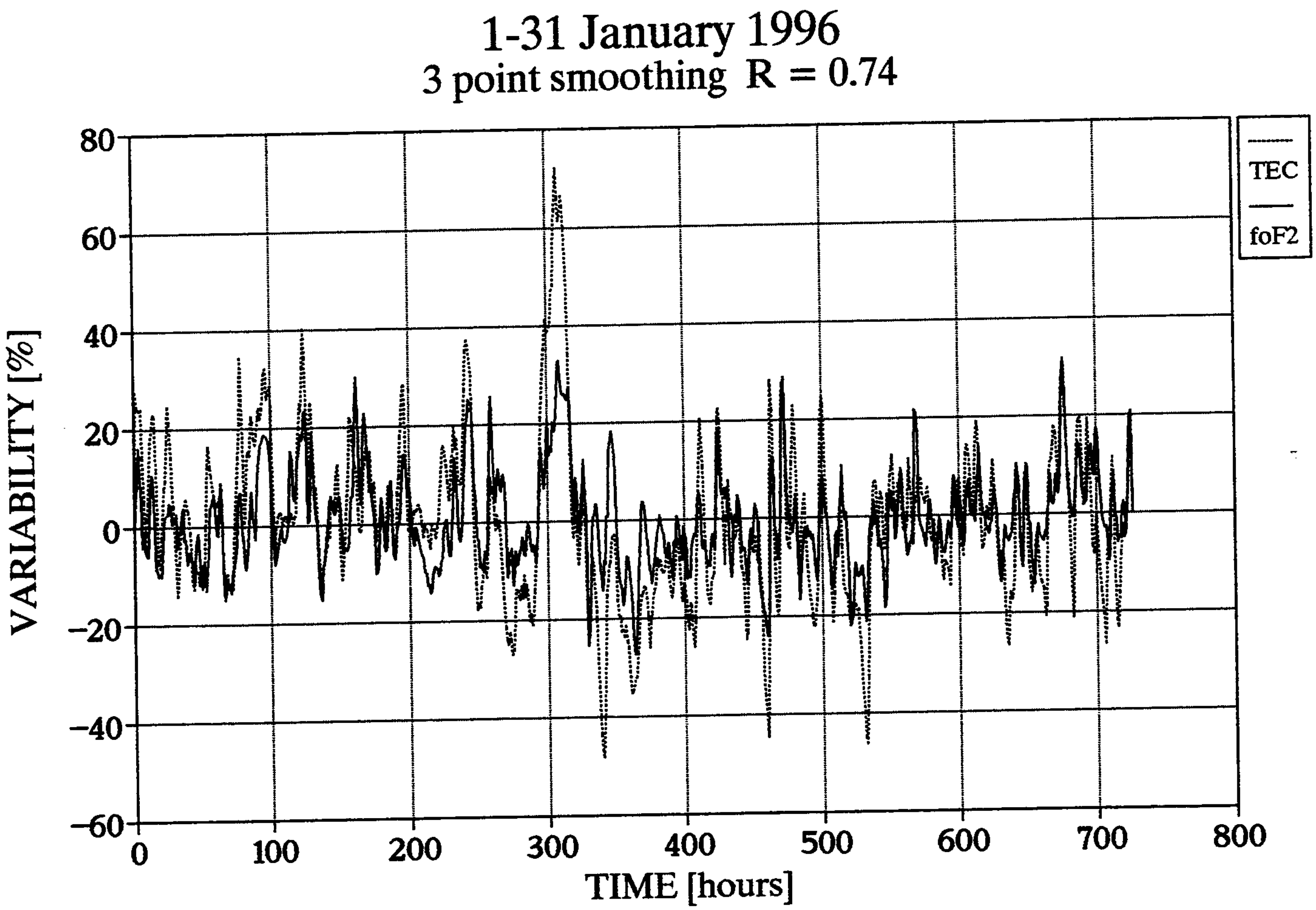


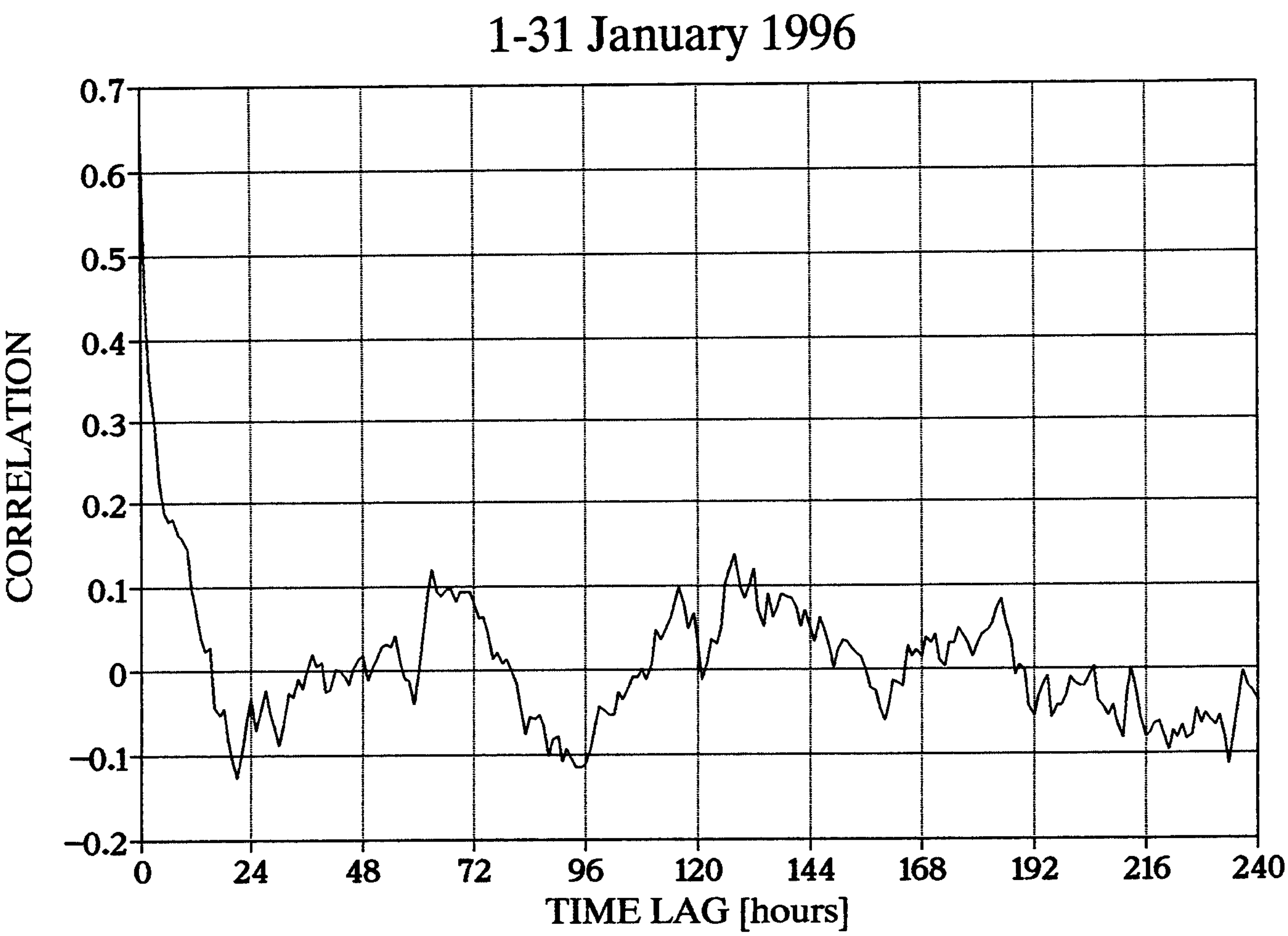
1-31 December 1995
AUTOCORRELATION
TIME LAG [hours]
TEC
foF2
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
0
24
48
72
96
120
144
168
192
216
240

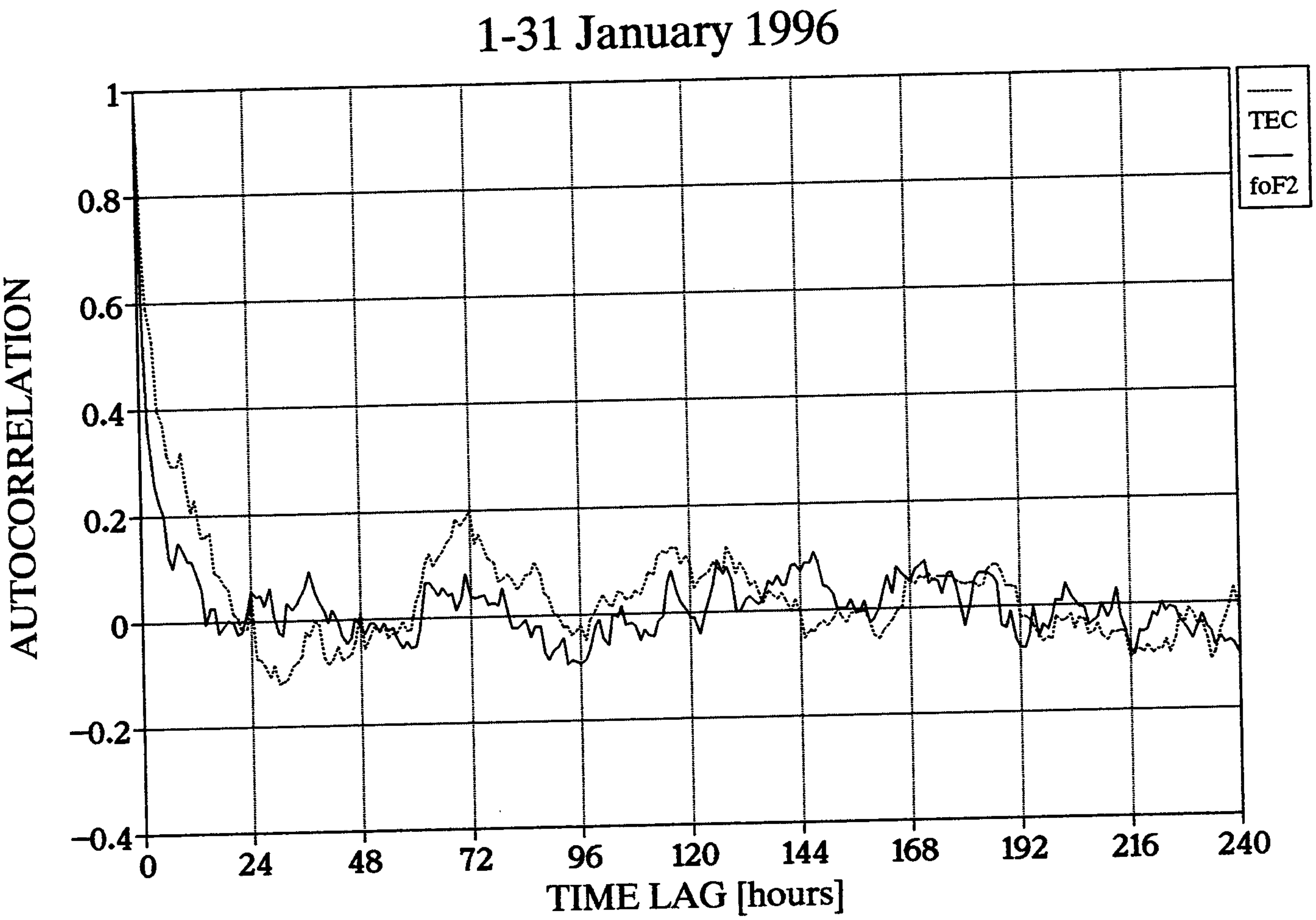


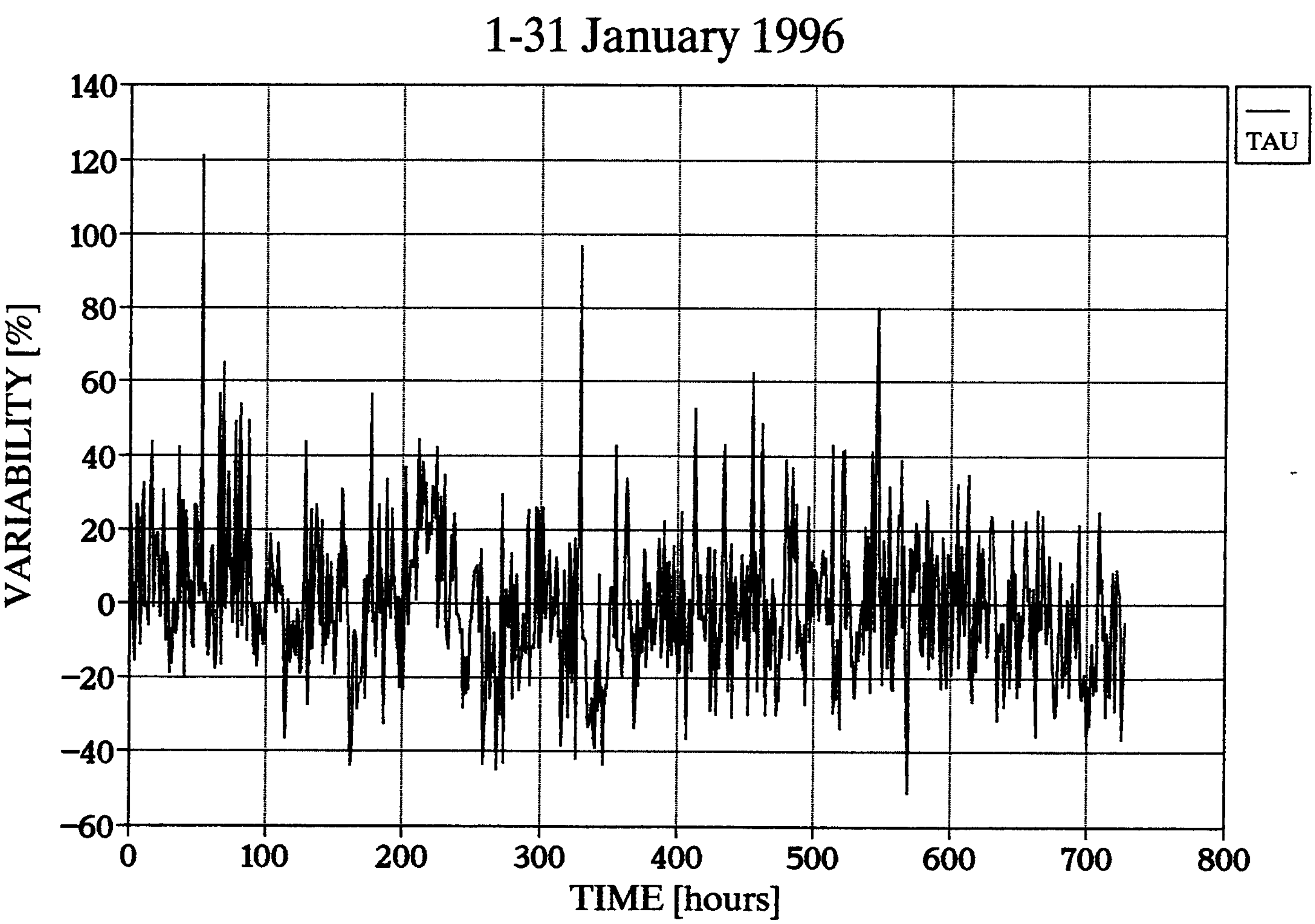
1-31 December 1995
VARIABILITY [%]
TIME [hours]
TAU
120
100
80
60
40
20
0
−20
−40
−60
0
100
200
300
400
500
600
700

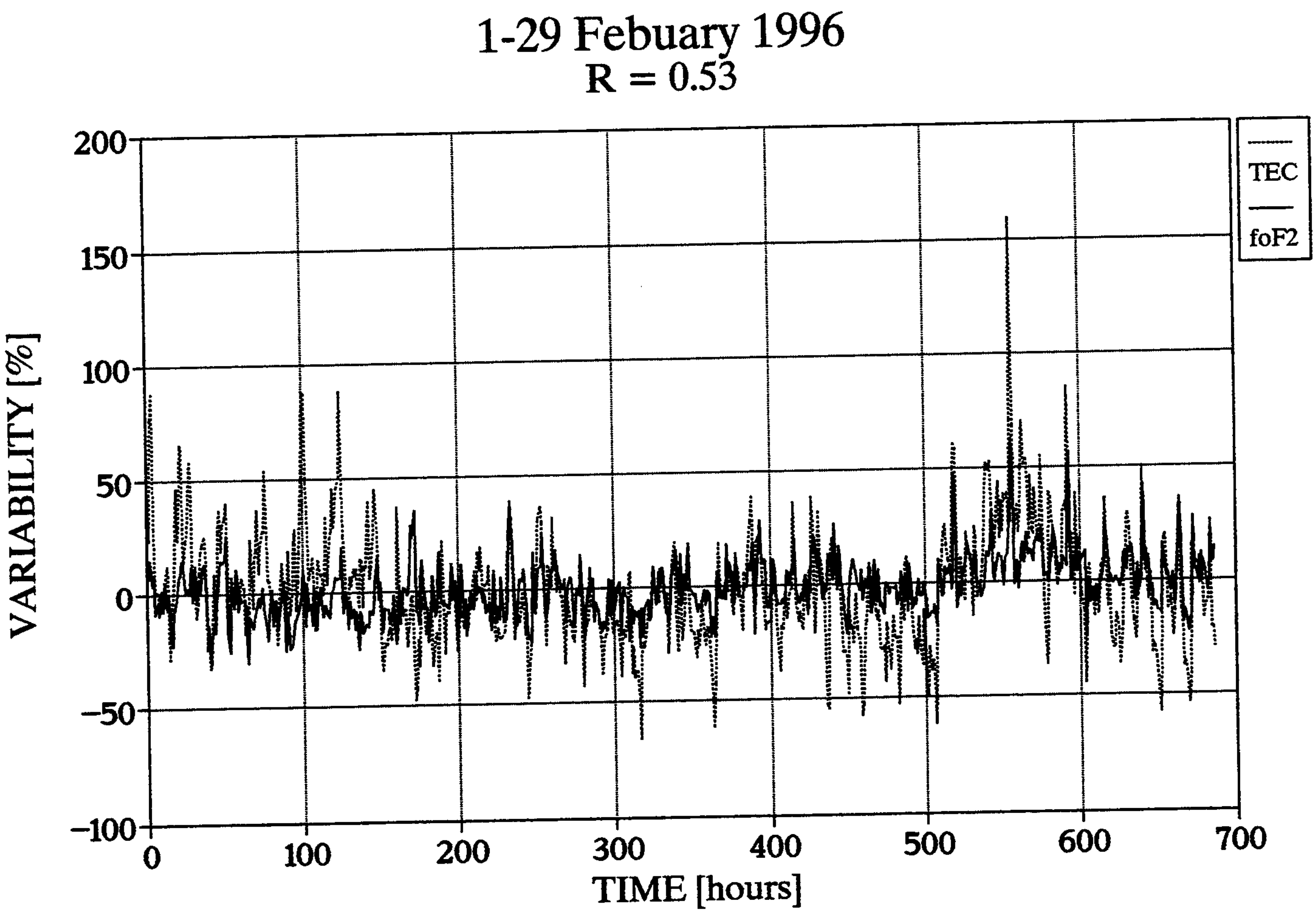

1-31 January 1996
R = 0.63
VARIABILITY [%]
TIME [hours]
TEC
foF2
100
80
60
40
20
0
−20
−40
−60
0
100
200
300
400
500
600
700
800

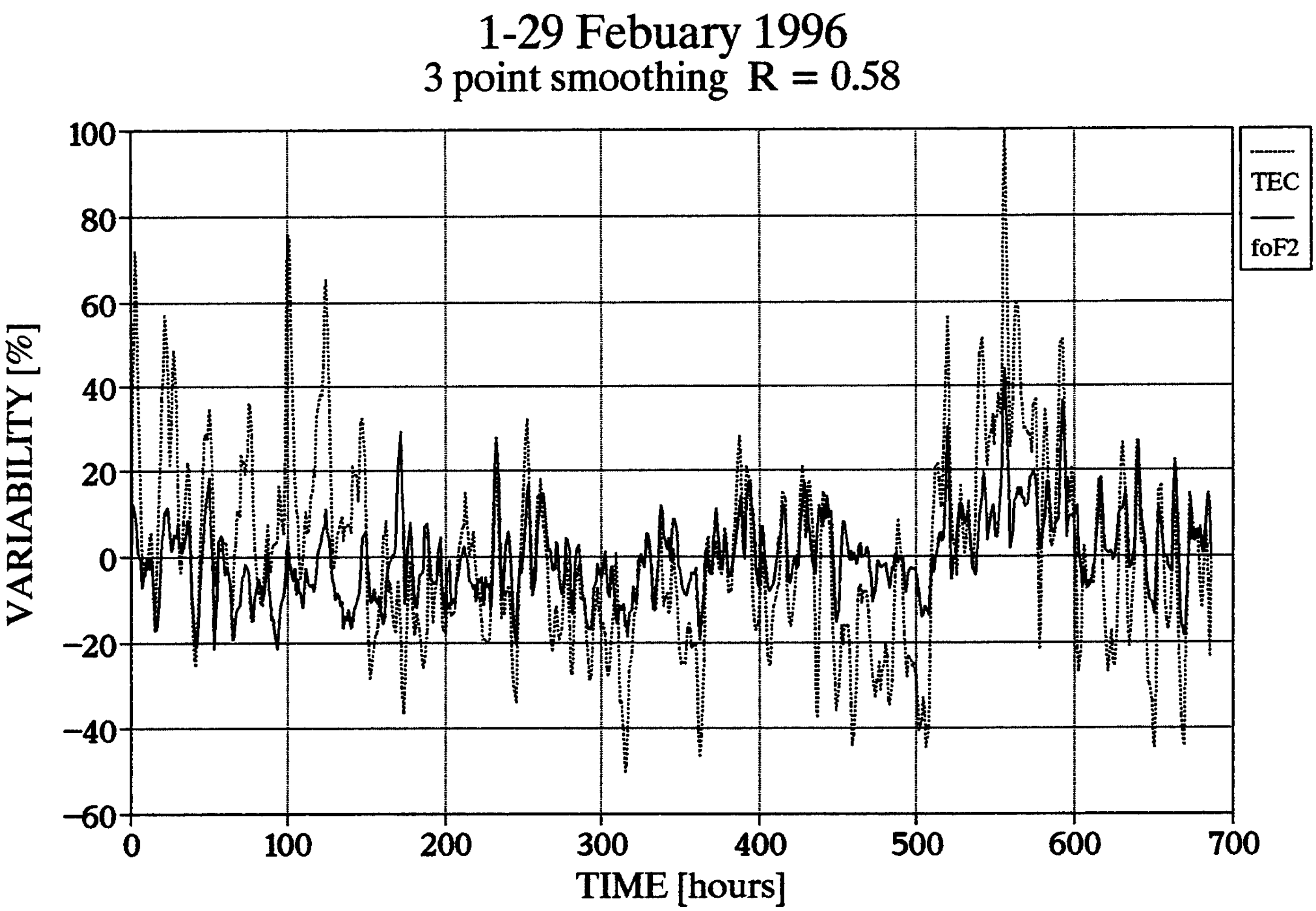

1-31 January 1996
3 point smoothing R = 0.74
TEC
foF2
80
60
40
20
0
−20
−40
−60
VARIABILITY [%]
0
100
200
300
400
500
600
700
800
TIME [hours]


1-31 January 1996
CORRELATION
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
0
24
48
72
96
120
144
168
192
216
240
TIME LAG [hours]

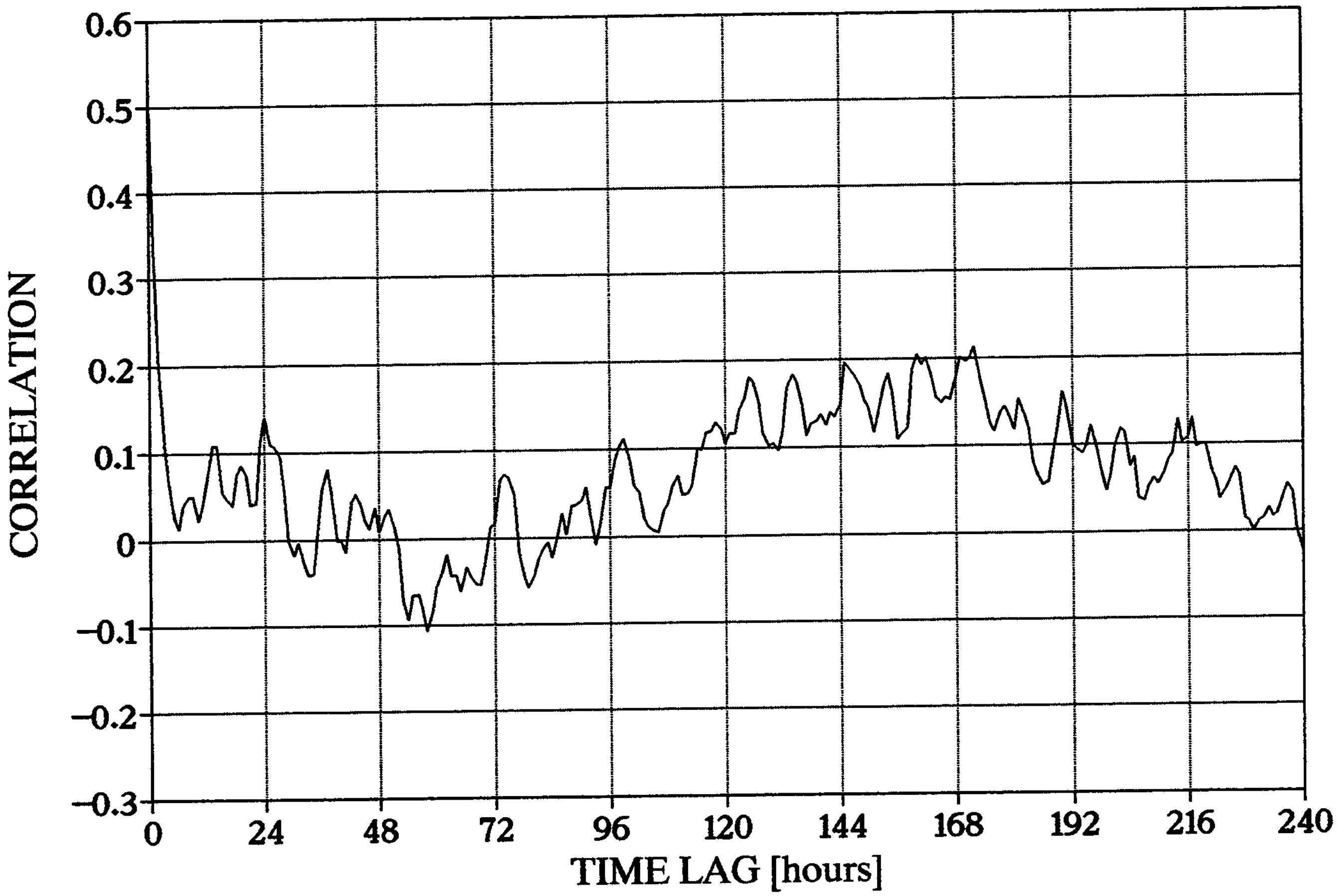

1-31 January 1996
TEC
foF2
AUTOCORRELATION
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
0
24
48
72
96
120
144
168
192
216
240
TIME LAG [hours]

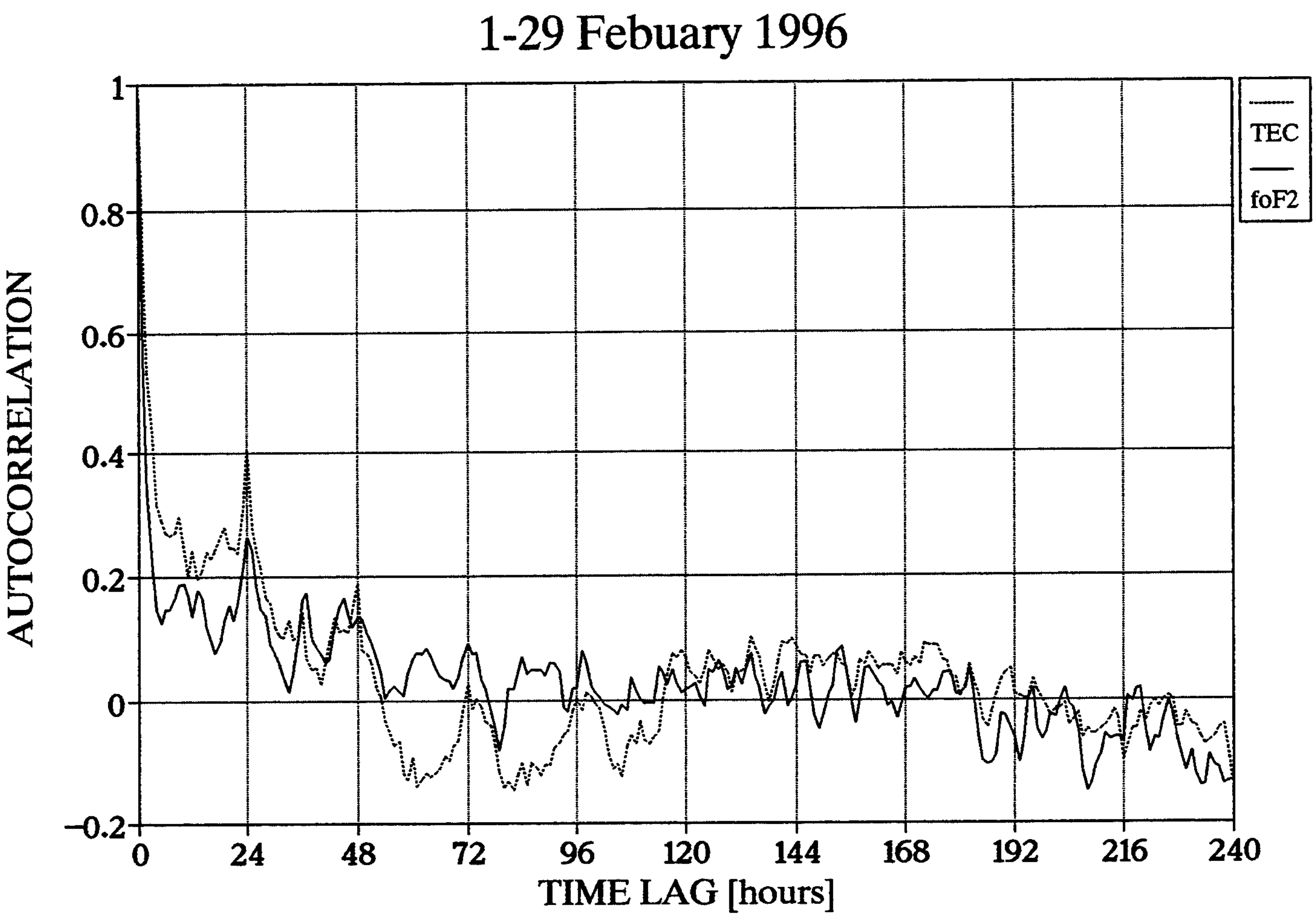

1-31 January 1996
VARIABILITY [%]
140
120
100
80
60
40
20
0
−20
−40
−60
0
100
200
300
400
500
600
700
800
TIME [hours]
TAU

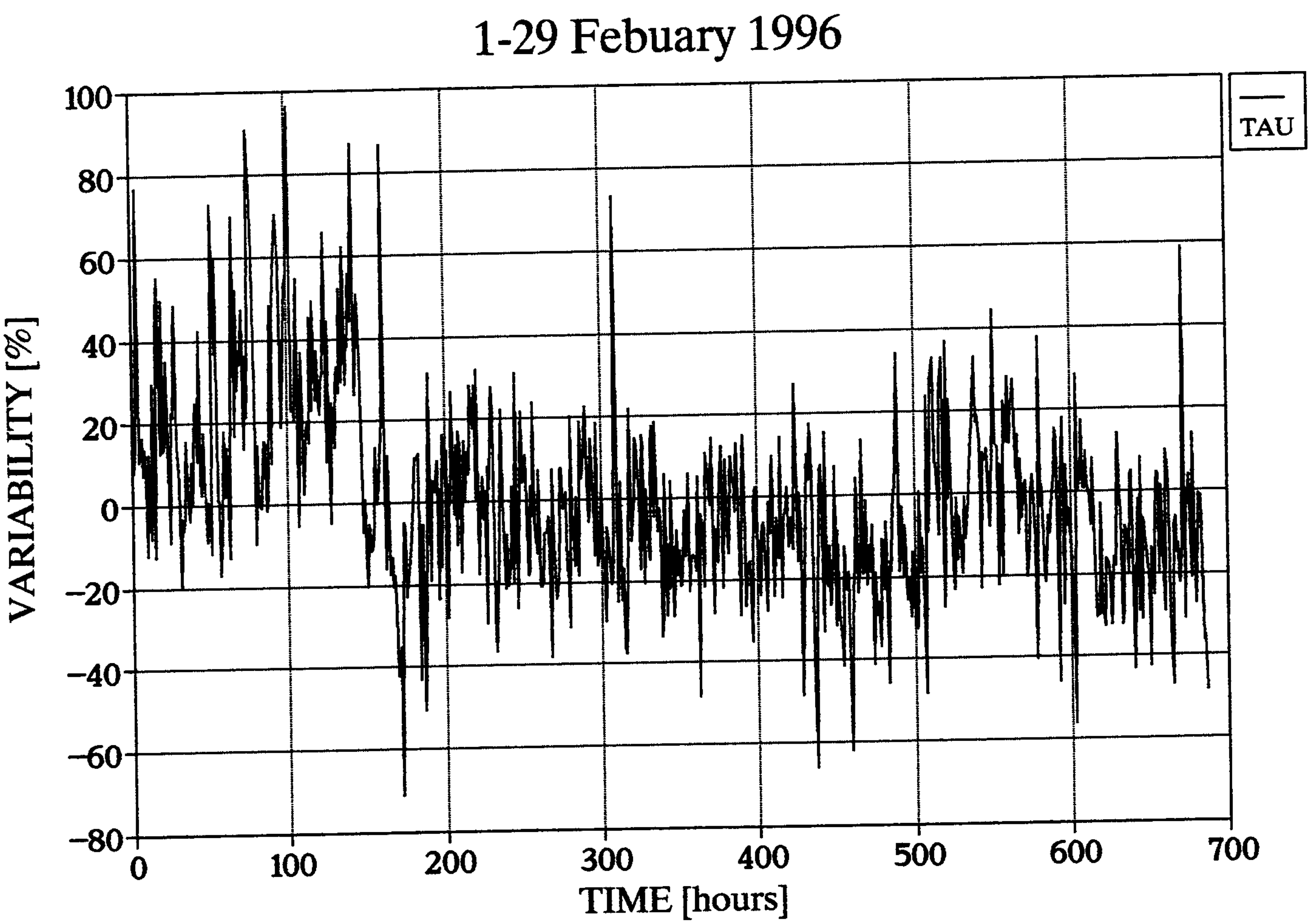

1-29 Febuary 1996
R = 0.53
TEC
foF2
VARIABILITY [%]
200
150
100
50
0
−50
−100
0
100
200
300
400
500
600
700
TIME [hours]

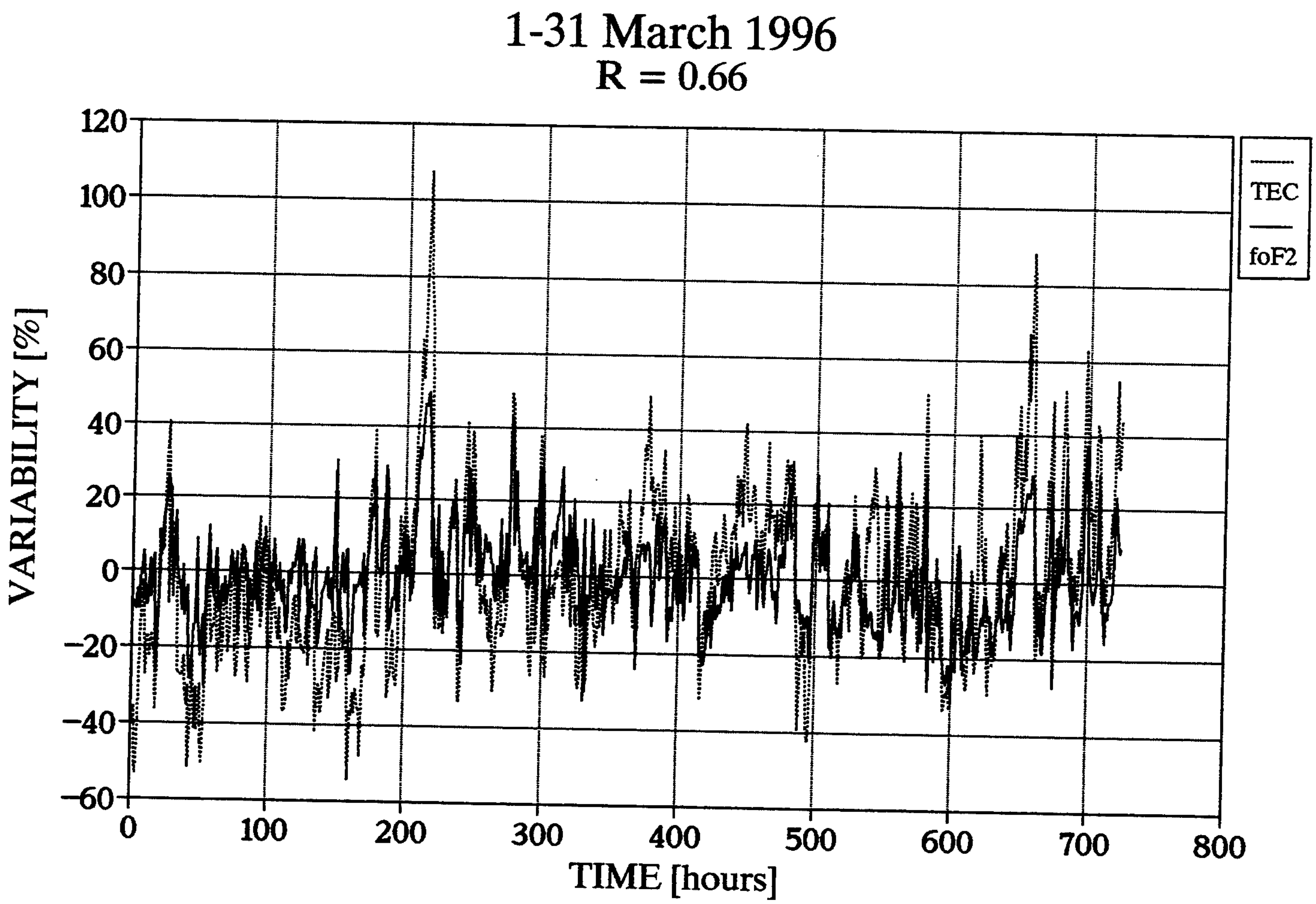

1-29 Febuary 1996
3 point smoothing R = 0.58
VARIABILITY [%]
TIME [hours]
TEC
foF2
100
80
60
40
20
0
−20
−40
−60
0
100
200
300
400
500
600
700

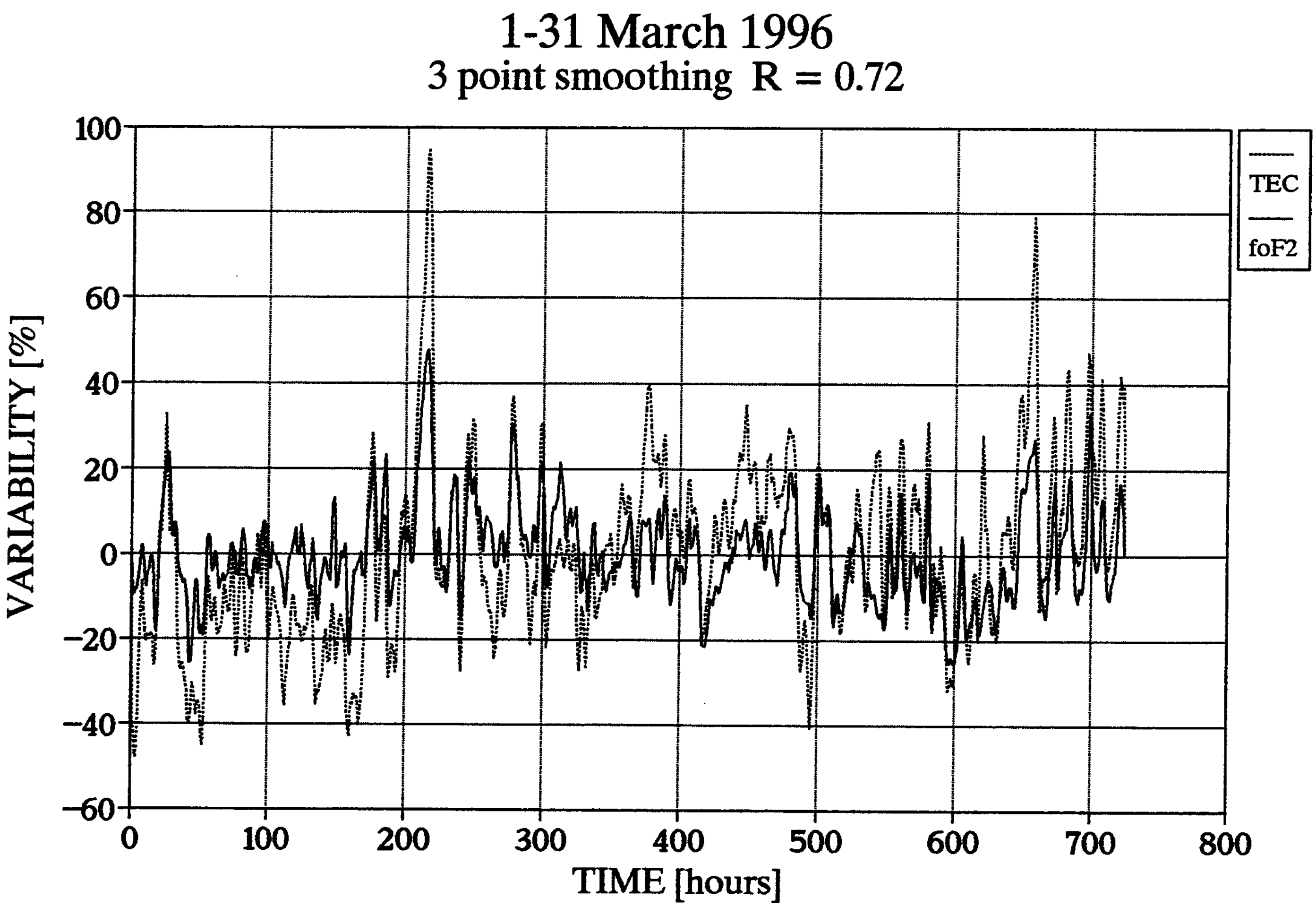
1-29 Febuary 1996

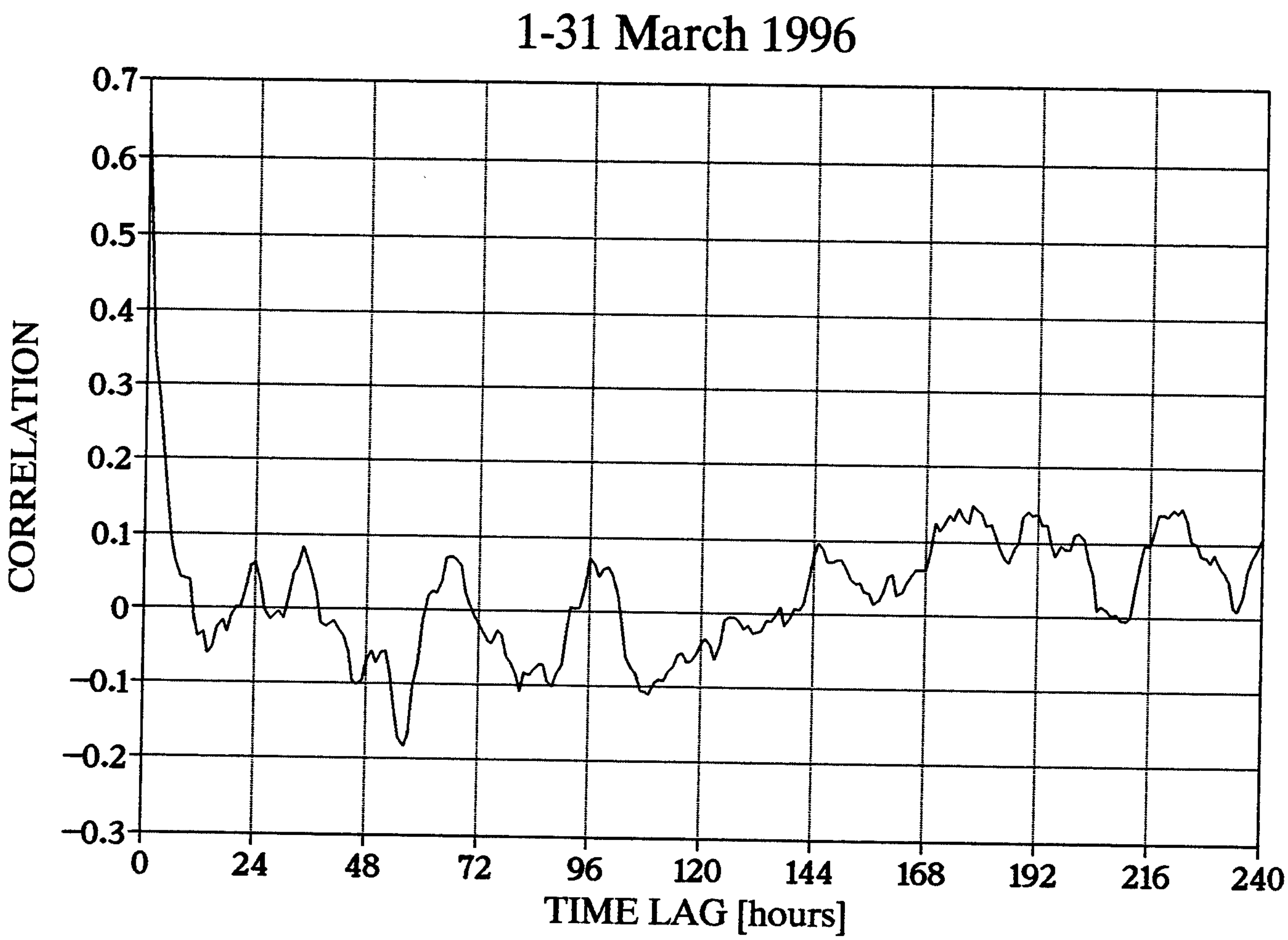


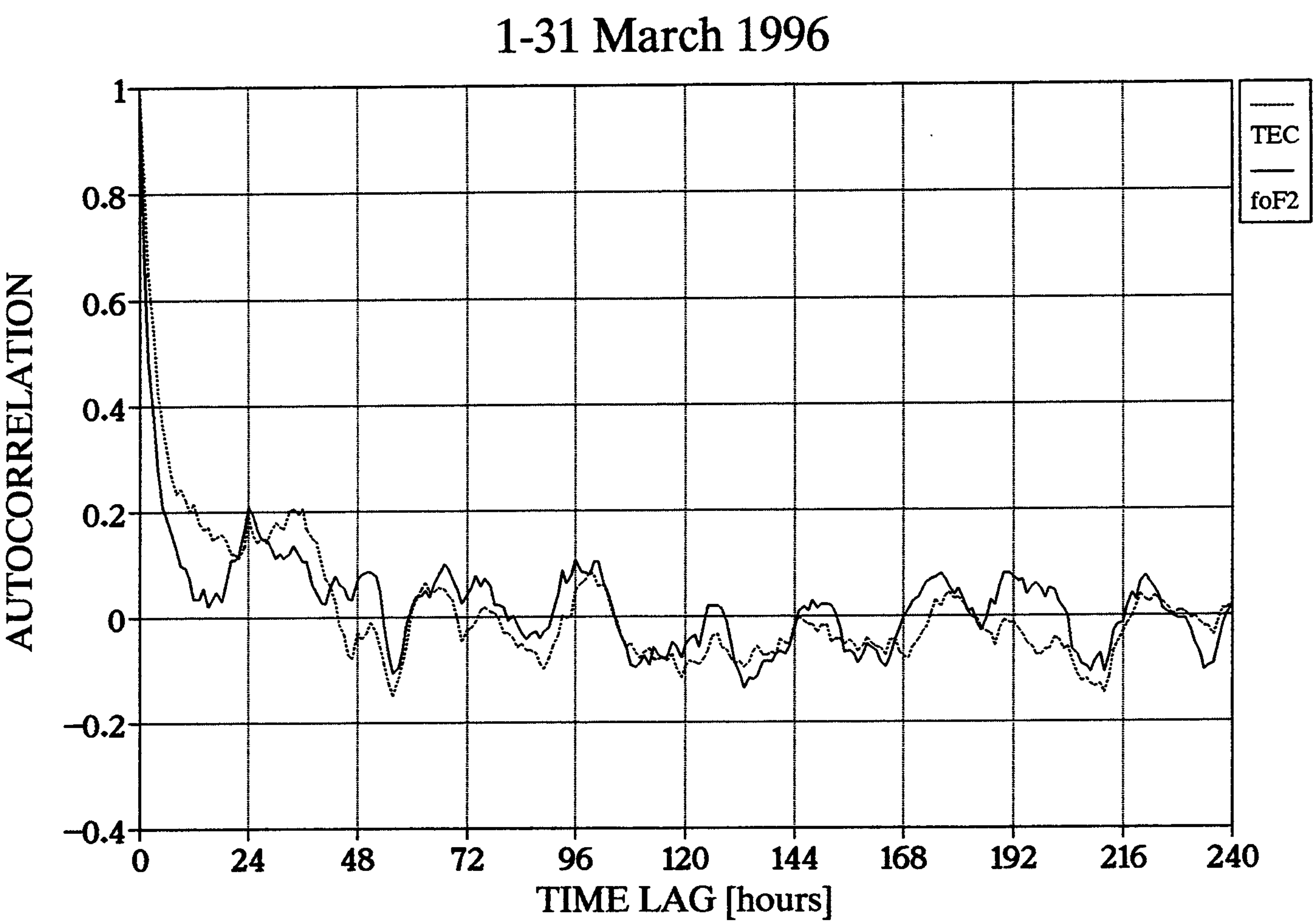

1-29 Febuary 1996
1
0.8
0.6
0.4
0.2
0
−0.2
AUTOCORRELATION
0
24
48
72
96
120
144
168
192
216
240
TIME LAG [hours]
TEC
foF2

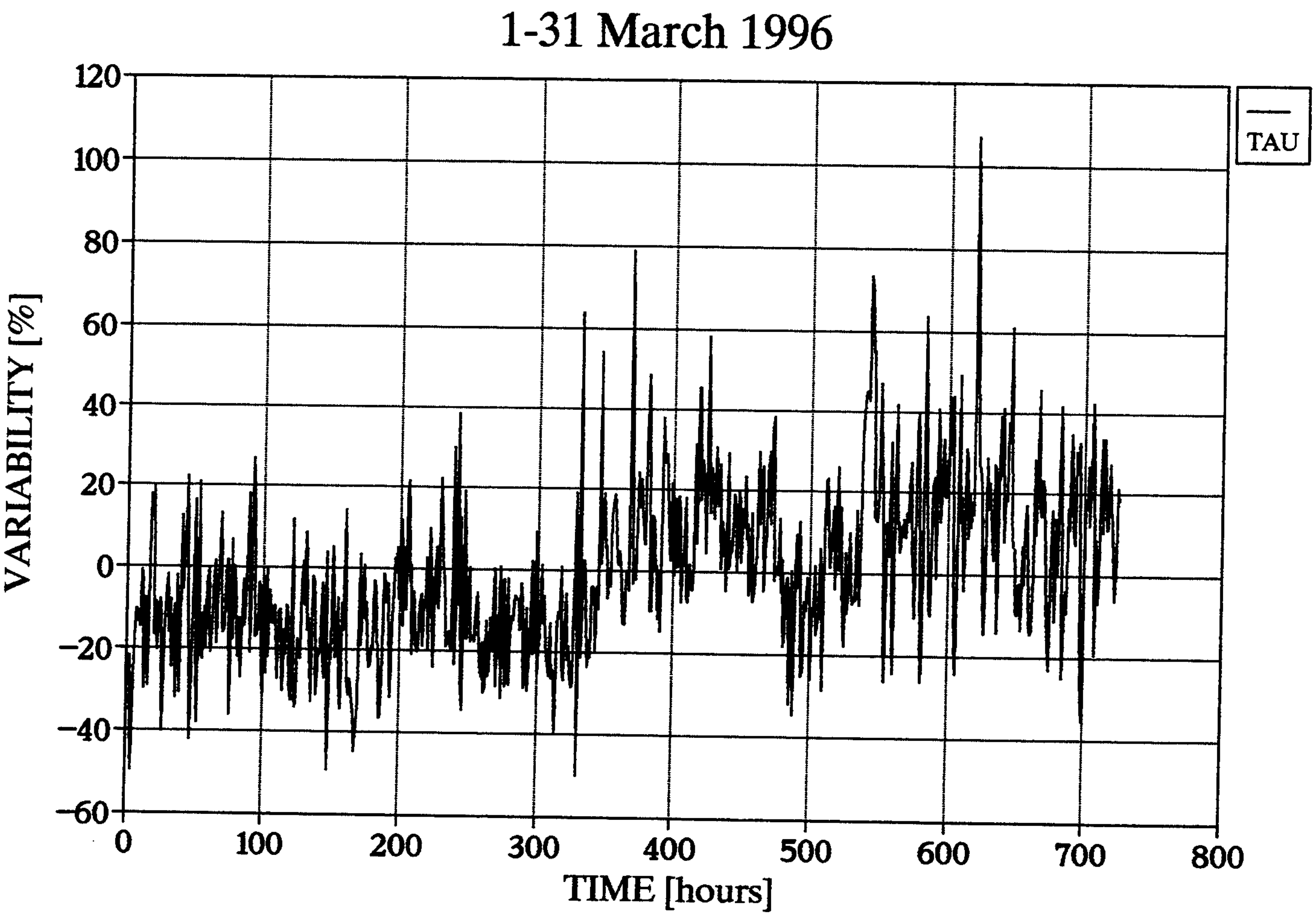

1-29 Febuary 1996
TAU
VARIABILITY [%]
100
80
60
40
20
0
−20
−40
−60
−80
0
100
200
300
400
500
600
700
TIME [hours]

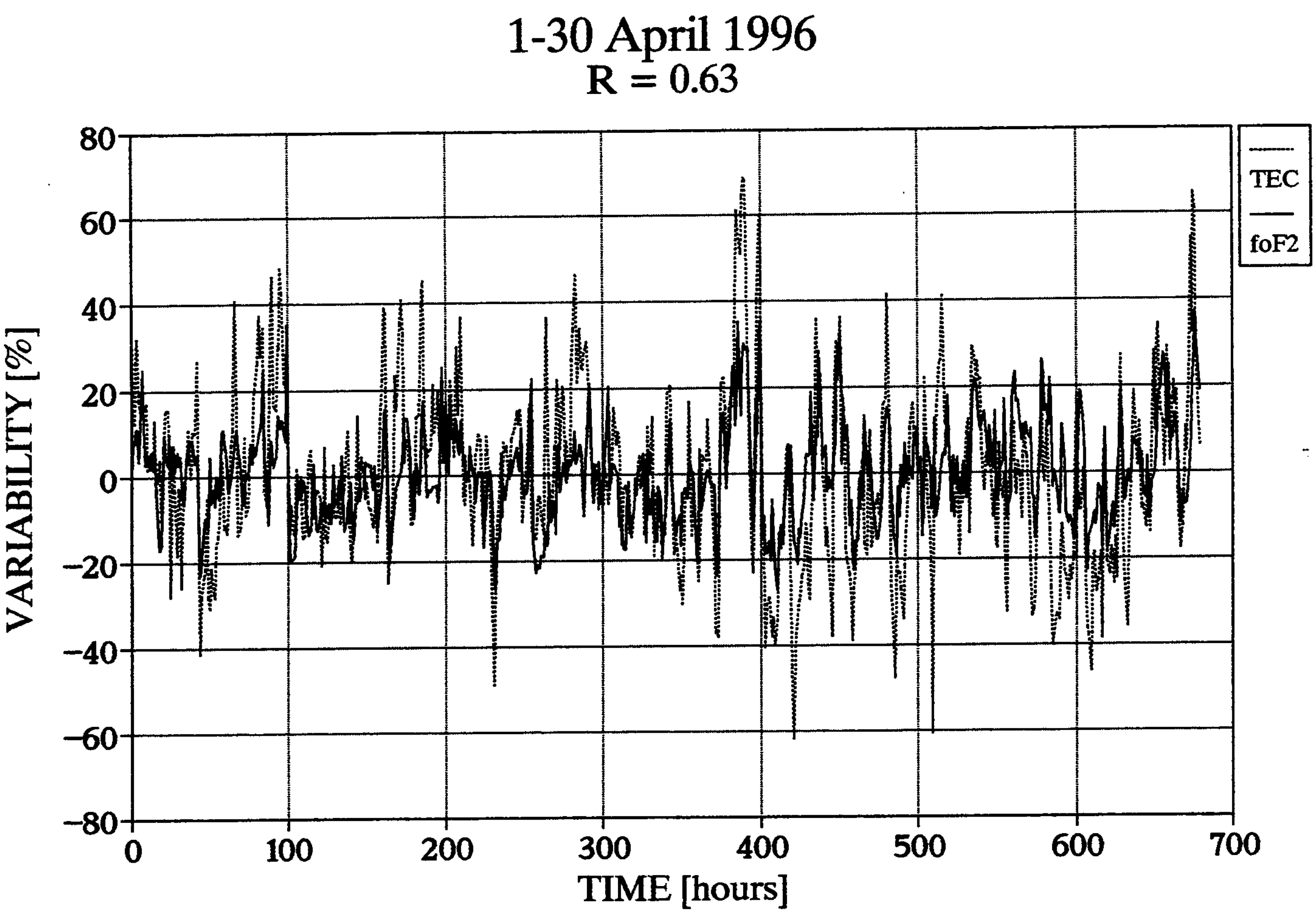

1-31 March 1996
R = 0.66
VARIABILITY [%]
TIME [hours]
TEC
foF2
120
100
80
60
40
20
0
−20
−40
−60
0
100
200
300
400
500
600
700
800

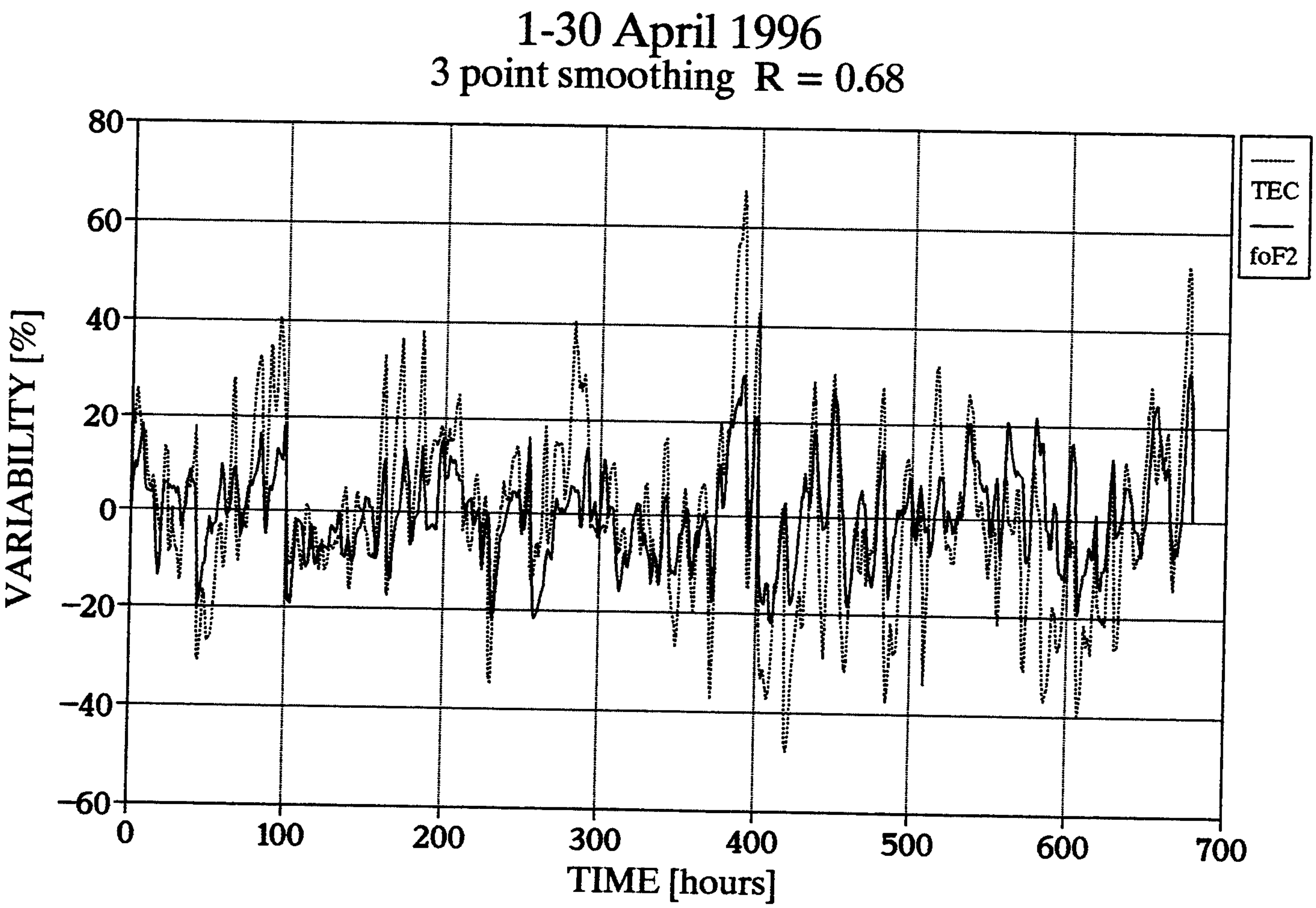

1-31 March 1996
3 point smoothing R = 0.72
VARIABILITY [%]
100
80
60
40
20
0
−20
−40
−60
0
100
200
300
400
500
600
700
800
TIME [hours]
TEC
foF2

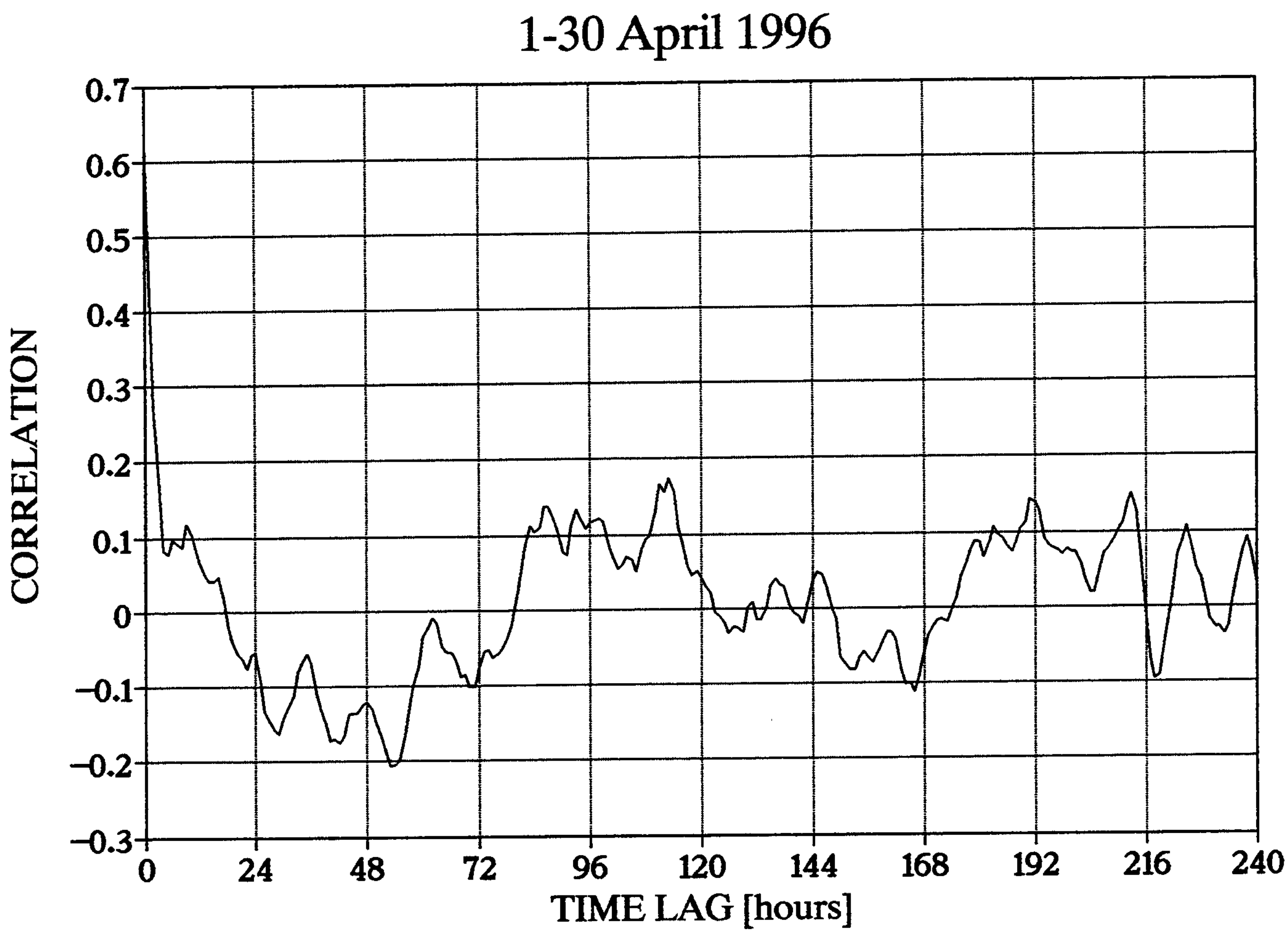

1-31 March 1996
CORRELATION
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
0
24
48
72
96
120
144
168
192
216
240
TIME LAG [hours]

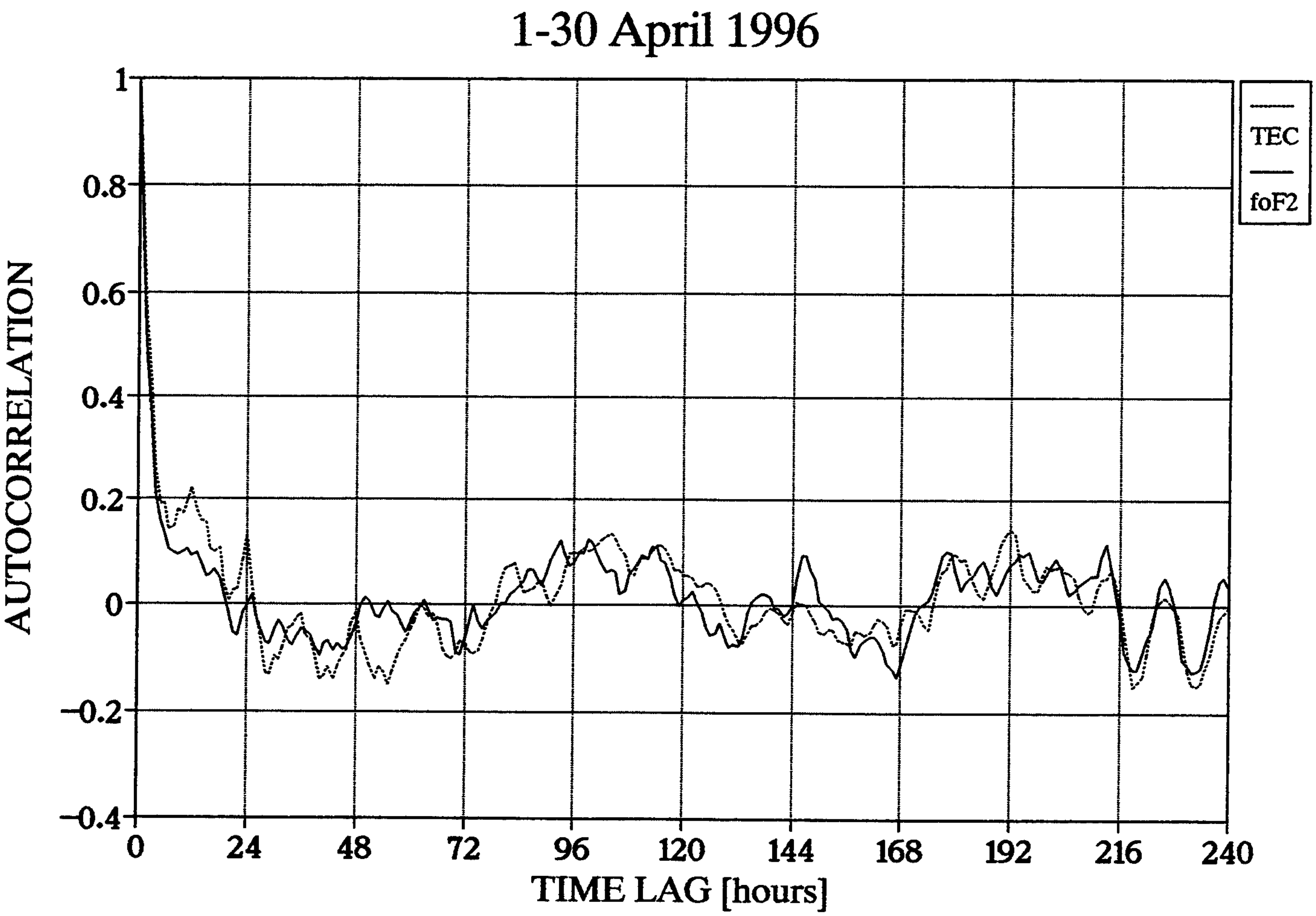

1-31 March 1996
AUTOCORRELATION
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
0
24
48
72
96
120
144
168
192
216
240
TIME LAG [hours]
TEC
foF2


1-31 March 1996
120
100
80
60
40
20
0
−20
−40
−60
0
100
200
300
400
500
600
700
800
VARIABILITY [%]
TIME [hours]
TAU

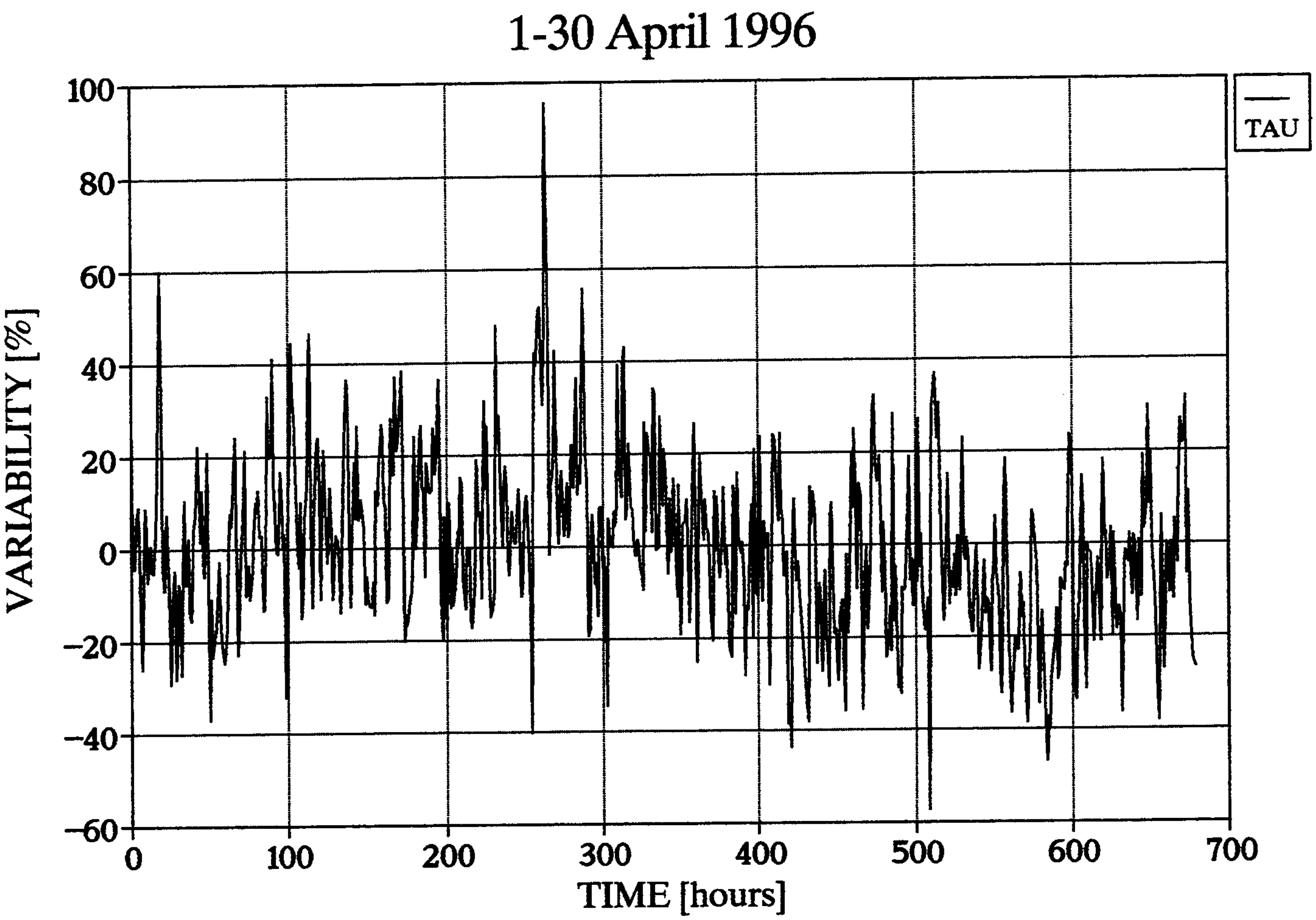

1-30 April 1996
R = 0.63
80
60
40
20
0
−20
−40
−60
−80
VARIABILITY [%]
0
100
200
300
400
500
600
700
TIME [hours]
TEC
foF2

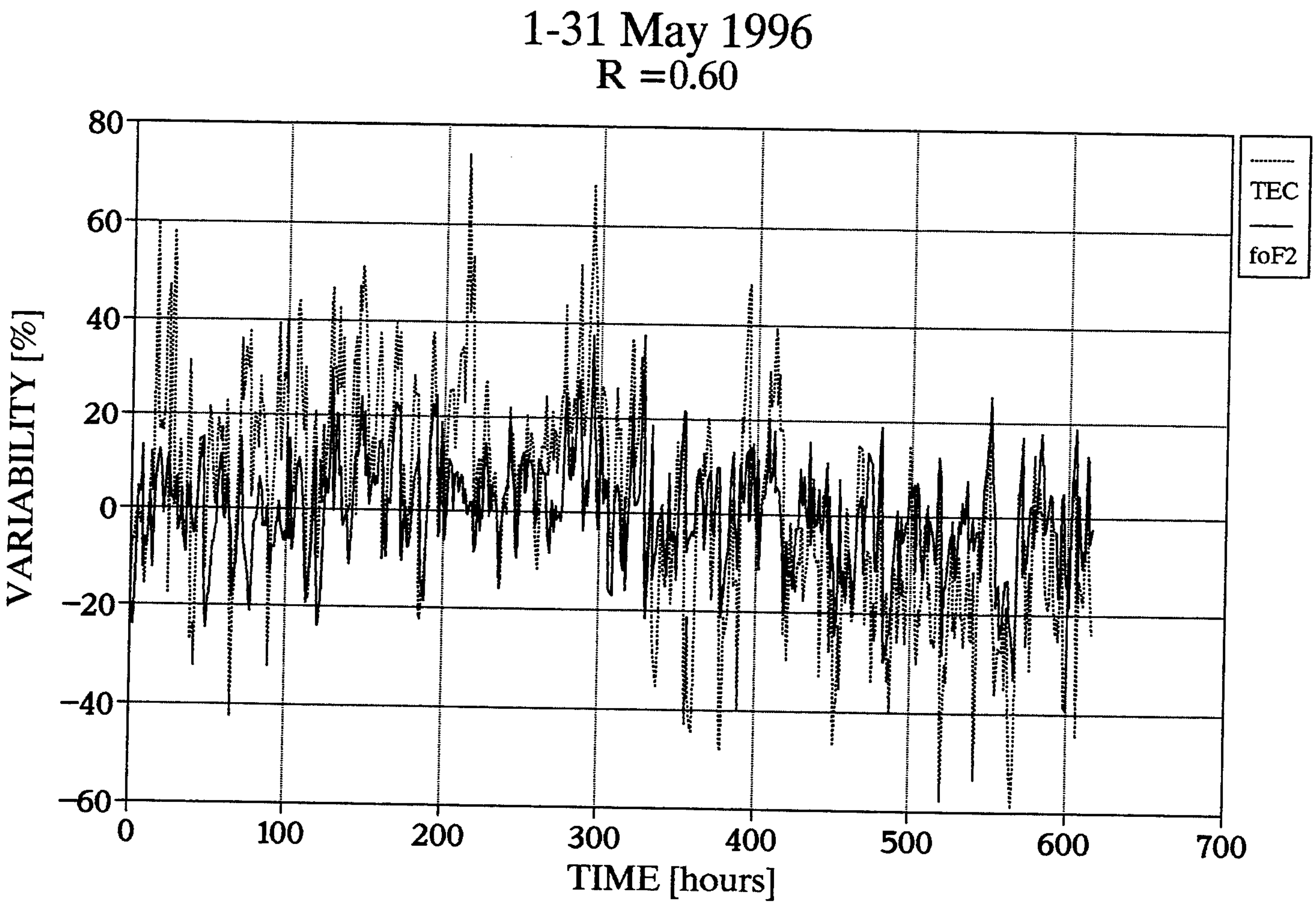

1-30 April 1996
3 point smoothing R = 0.68
80
60
40
20
0
−20
−40
−60
VARIABILITY [%]
0
100
200
300
400
500
600
700
TIME [hours]
TEC
foF2


1-30 April 1996
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
CORRELATION
0
24
48
72
96
120
144
168
192
216
240
TIME LAG [hours]

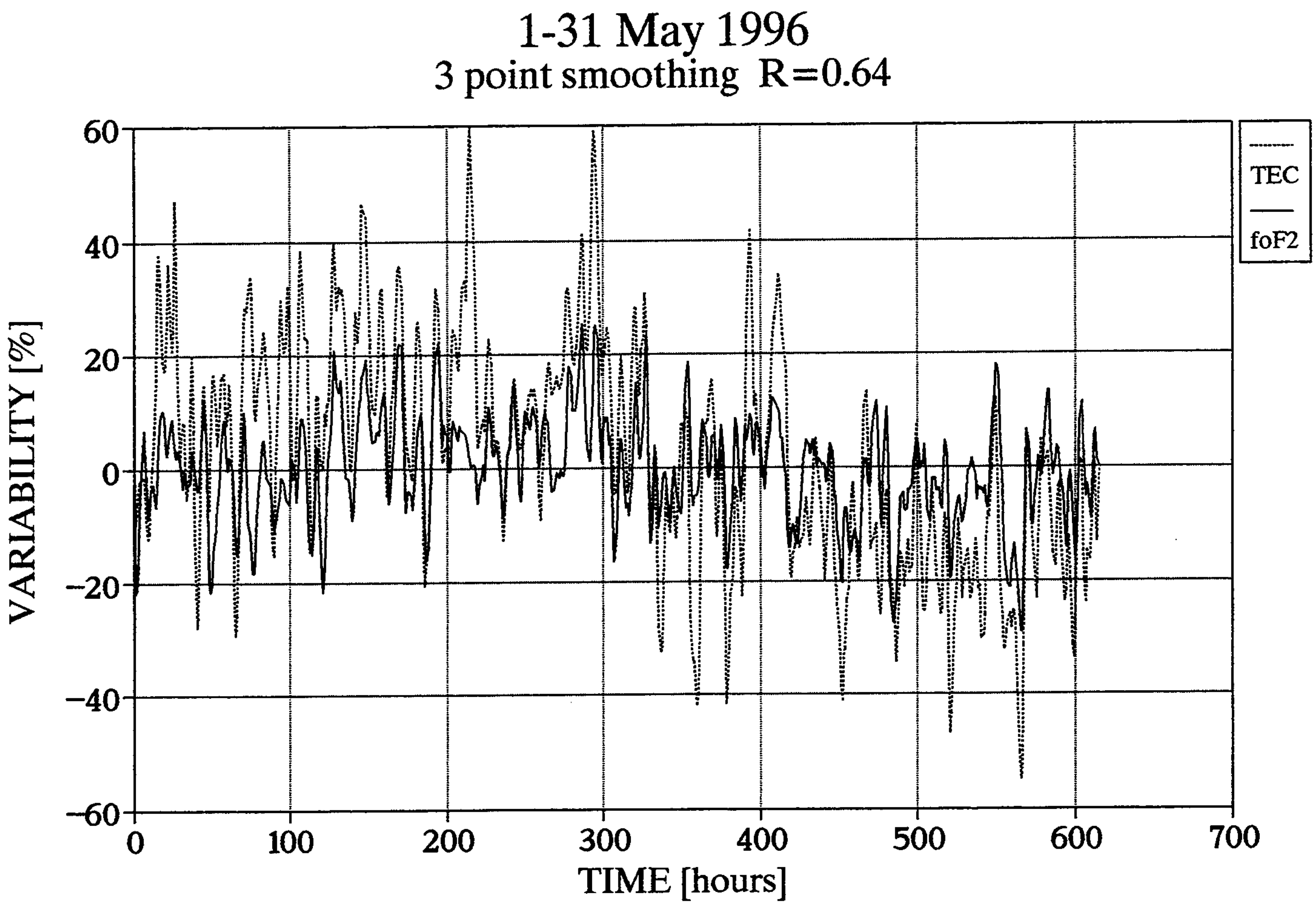


1-30 April 1996
AUTOCORRELATION
TIME LAG [hours]
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
0
24
48
72
96
120
144
168
192
216
240
TEC
foF2

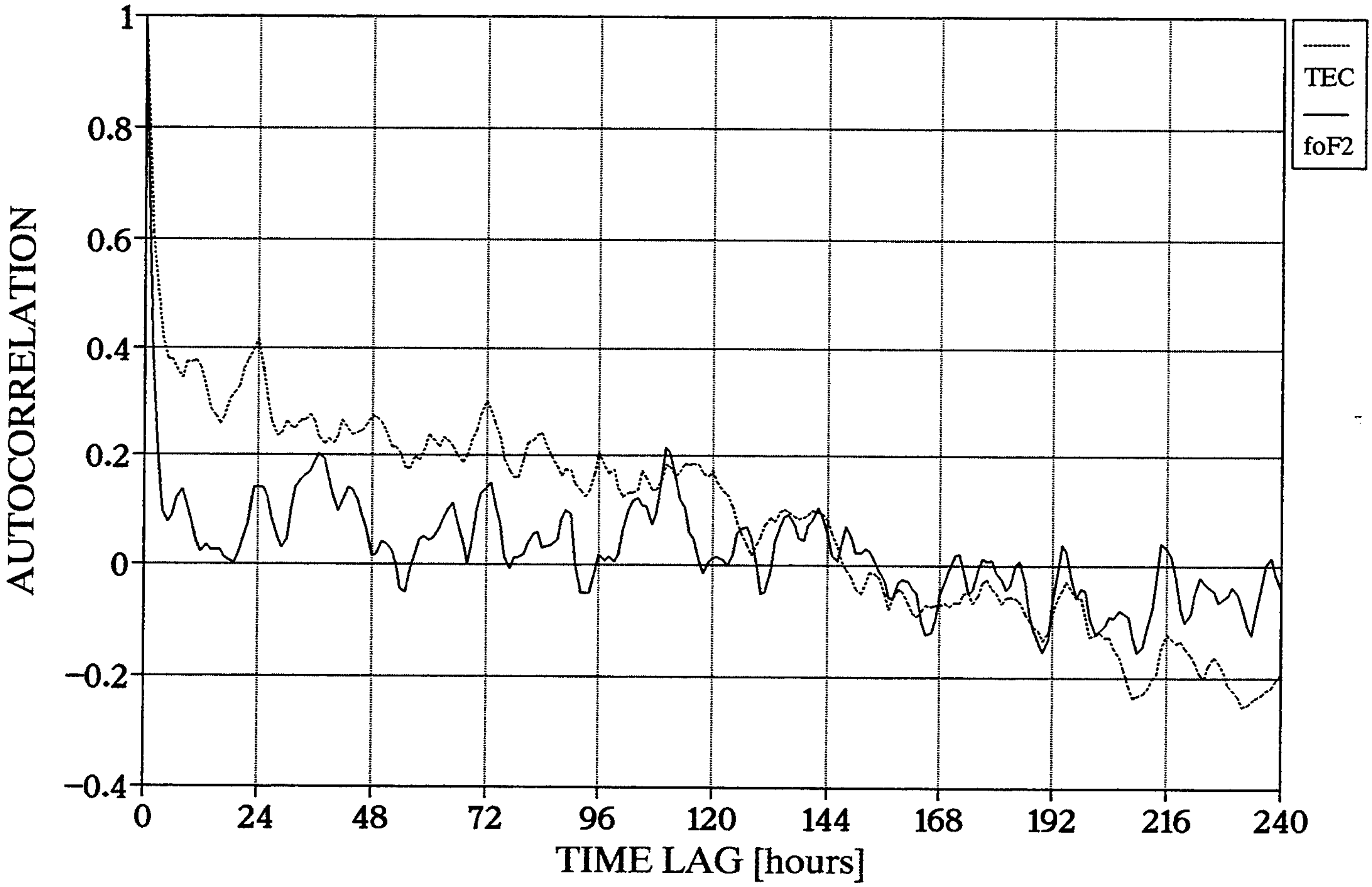

1-30 April 1996
TAU
VARIABILITY [%]
TIME [hours]
100
80
60
40
20
0
−20
−40
−60
0
100
200
300
400
500
600
700

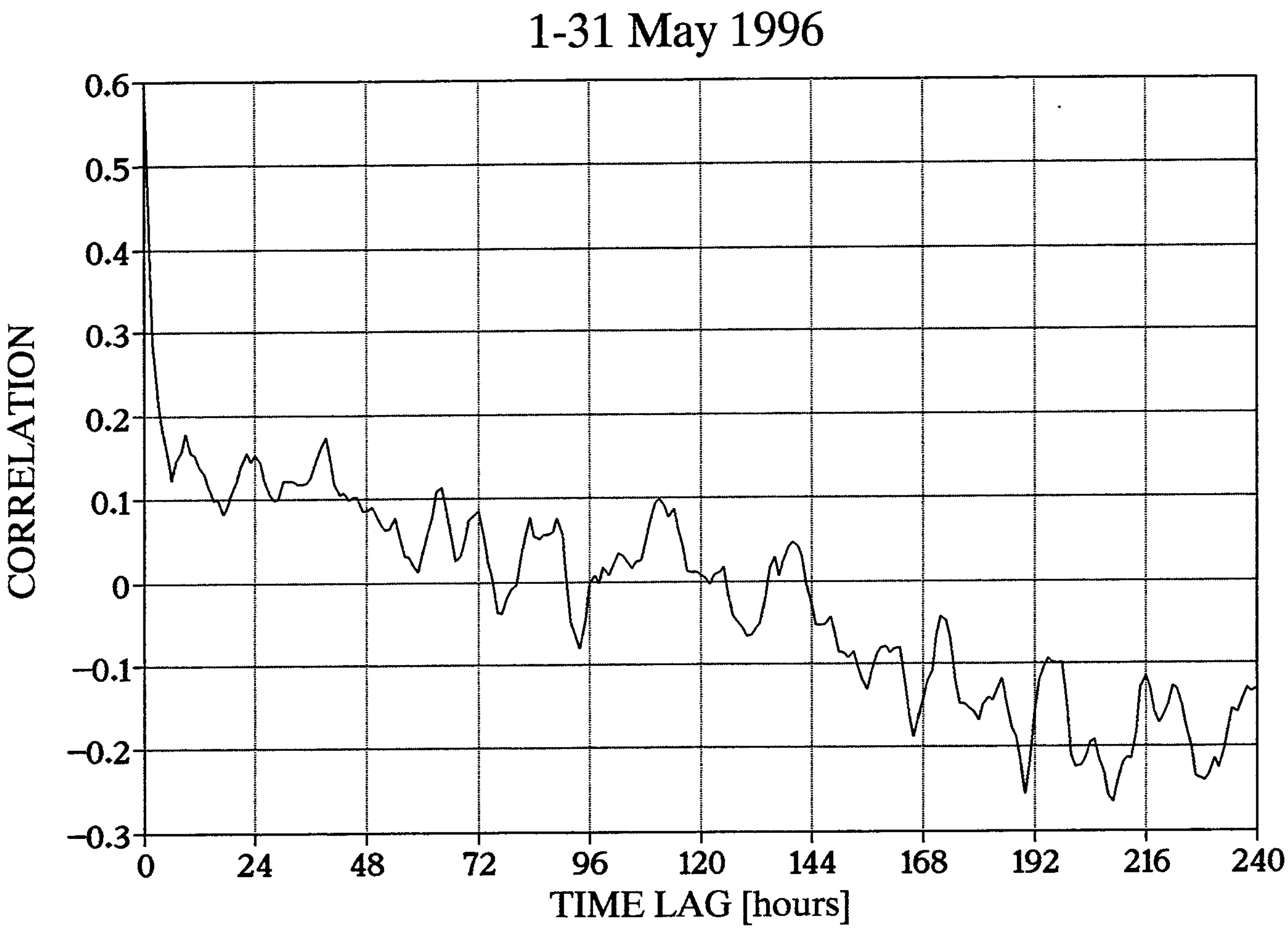


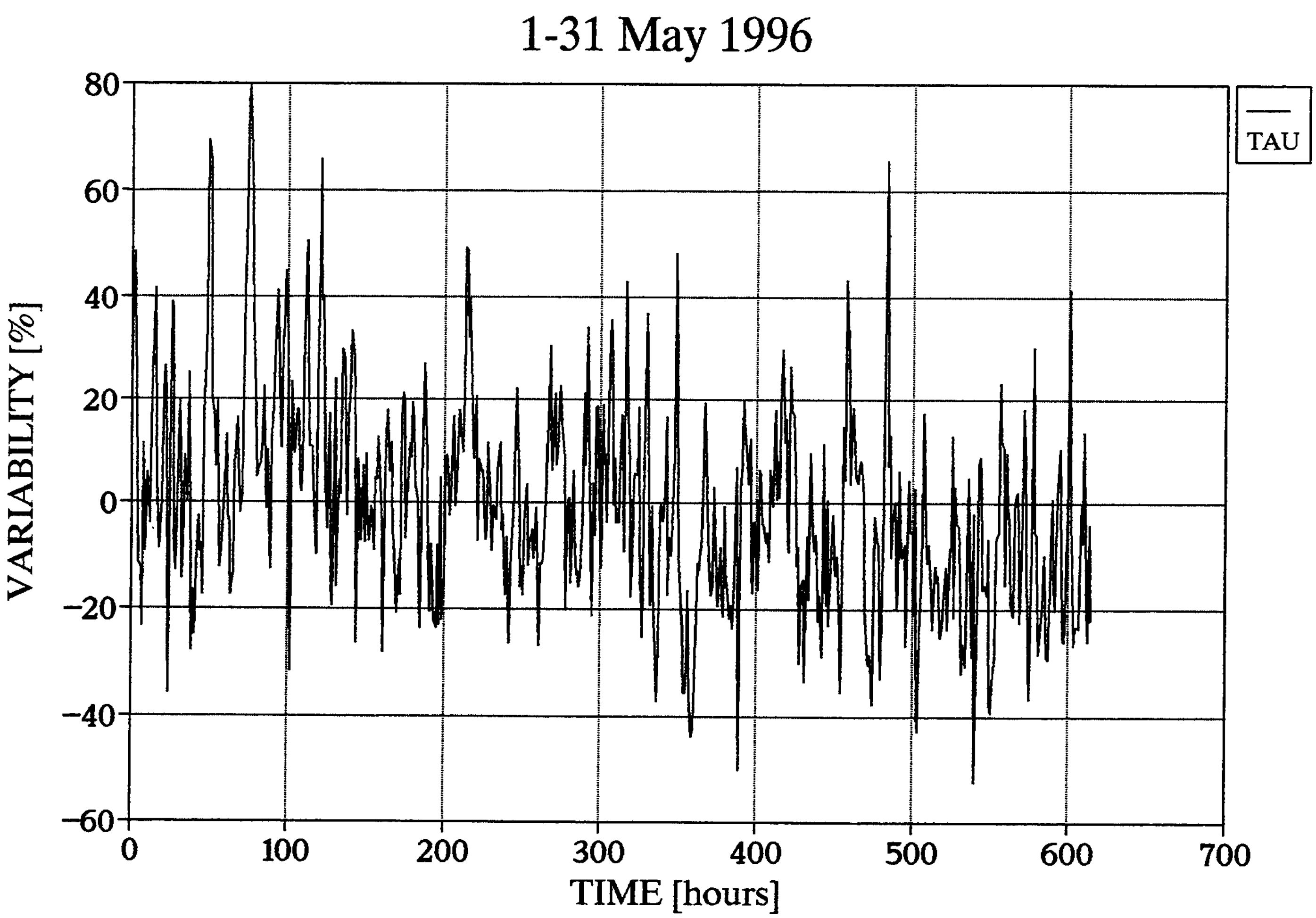
1-31 May 1996
R =0.60
80
60
40
20
0
−20
−40
−60
VARIABILITY [%]
0
100
200
300
400
500
600
700
TIME [hours]
TEC
foF2


1-31 May 1996
3 point smoothing R=0.64
60
40
20
0
−20
−40
−60
0
100
200
300
400
500
600
700
VARIABILITY [%]
TIME [hours]
TEC
foF2

1-31 May 1996


1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
AUTOCORRELATION
0
24
48
72
96
120
144
168
192
216
240
TIME LAG [hours]
TEC
foF2


1-31 May 1996
CORRELATION
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
0
24
48
72
96
120
144
168
192
216
240
TIME LAG [hours]


1-31 May 1996
80
60
40
20
0
−20
−40
−60
VARIABILITY [%]
0
100
200
300
400
500
600
700
TIME [hours]
TAU