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A TRESHOLD MODEL FOR PREVACCINATION MEASLES DATA : SOME EMPIRICAL RESULTS FOR ENGLAND AND ITALY

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Abstract. This paper considers the application of threshold autoregressive models to pre-vaccination measles time series in an attempt to explain differences in the epidemic dynamics as a function of the level reached by the series in a recent past. Data for the English cities of, London, Manchester and Cambridge, and for the provinces of Milano, Roma and Pisa in Italy are used in the illustration. The parametric, or autoregressive, spectrum, calculated for each piece-wise model clearly evidences such differences.

Key words: threshold autoregressive models, autoregressive (gain) spectrum.

1. INTRODUCTION

The dynamics of the spread of measles, in the absence of vaccination, is generally thought to follow a non-linear pattern in time and has been largely modelled in the past by the use of causal compartmental mathematical models (see Anderson and May (1991), Finkenstadt and Grenfell (2000), Bjornstad et al. (2002), Grenfell et al. (2002)). These models have incorporated the interactions between the number of reported cases and variables such as births, age structures, residential population and population densities. Pure time series analysis has generally been discarded as being inadequate for describing the phenomena; the time series of reported cases was itself plagued by under-reporting which is thought to have been approximately 50 percent in the UK (see Manfredi et al. (2002) for an evaluation of the Italian data). However, if the under-reporting varied little over time, time series methods could still be applied in shedding light on interesting aspects of the dynamics of the phenomena and such information might ultimately be useful to the model builder himself.

This paper was initially motivated by an interest in Italian data for the pre-vaccination period 1949-76 collected on a regional basis in which a well defined minimum, in august, is rapidly reached, but the maximum is often spread over two or three months during the period January – March. Cleur (2004) investigated the presence of specific types of non-linearities in this data and estimated time series models with autoregressive conditional heteroschedastic (ARCH) errors or bilinear models when these were identified as possible generators of the data. The present paper advances the idea that there does not exist one model for the whole series, but that it could change with the level (numer of reported cases) reached. This idea, which is sustained by results obtained from the estimation of Self Exciting Threshold Autoregressive (SETAR) models for the Italian data, is further confirmed when applied to similar data for the UK. The empirical results for many series, when put together, become repetitive and therefore it was decided to present the analysis carried out on bi-weekly data covering the period 1944 - 1965 for the cities of, London, Manchester and Cambridge and for monthly data covering the period 1949 - 1976 for the Provinces of Milano, Roma and Pisa; data for the single towns and cities in Italy were not available, but a comparison with the UK data can, in any case, be made on the basis of the populations of the territorial units considered.

2. METHODS

The time series for London, Manchester and Cambridge were obtained from the web site *www.zoo.cam.ac.uk/zoostaff/grenfell/measles.htm* and are part of the data set reporting pre-vaccination measles time series for 60 towns and cities in England and Wales for the period 1944 – 1965. London and Manchester were chosen for their population size as well as geographical location. Cambridge instead is a town with approximately 100.000 inhabitants and a low number of reported cases.

The data for the provinces of Milano, Roma and Pisa are part of the data published by the Istituto Nazionale di Statistica (ISTAT), Italy's Central Statistical Office, on measles time series for all the provinces in Italy. Roma and Milano were selected for the same reasons as London and Manchester. Pisa is a province with approximately 100.000 inhabitants and comparable to Cambridge for the number of reported cases.

Each series was log transformed to stabilise the variance (a value of 1 was added to all the data before the transformation in order to avoid the problem of log(zero) for those months without reported cases), and then centred for the mean. This means that negative values of a series correspond to low values of reported cases, whereas high values, and in particular very high positive values, correspond to epidemic outbursts. One should be particularly interested in adequately modelling the positive values.

After experimenting various forms of the SETAR model it was decided to estimate the following for each log transformed mean-centered time series (see Priestley (1988) and Tong et al. (1980) for an introduction to SETAR models):

$$X_t = c_1 + \sum_{j=1}^{6} \alpha_j X_{t-j} + \varepsilon_{1t} \qquad \text{if } 0 \le X_{t-d} < T \qquad (1a)$$

$$X_t = c_2 + \sum_{j=1}^{6} \beta_j X_{t-j} + \varepsilon_{2t} \qquad \text{if } X_{t-d} \ge T \qquad (1b)$$

$$X_t = c_3 + \sum_{j=1}^{6} \gamma_j X_{t-j} + \varepsilon_{3t} \qquad \text{if } X_{t-d} < 0 \qquad (1c)$$

In other words, whereas two "regimes" (or subsets or states) are defined for the positive data, only one model is fitted to the negative values. The fitted model for each "regime" is a "best subset" autoregressive model with maximum lag 6, i. e. only significant lags up to lag 6 are retained. The optimum values of the threshold coefficient T and the lag d are obtained using AIC statistics as in Tong and Lim (1980); the only difference with their method is that we estimate the "best subset" and not the full model of order 6 and the values of T and d are found simultaneously by minimising the AIC statistic, using a grid search method, over a two dimensional grid of values; d varied in the interval from

1 to 4 bi-weeks for the UK data and from 1 to 2 months for the Italian data. These values of *d* were forced on the grounds of their practical importance. The results are reported in Tables (1a) – (1f).

Differences in the SETAR model coefficients are useful for shedding light on the different characteristics of each series when it varies at different levels. However, in order to make such differences more evident and interesting, the autoregressive (or parametric or gain) spectrum (see Hamilton (1994) and Priestley (1981)) for each estimated autoregressive model is calculated. The results are reported in Figure 2 .

In Figure 1 fitted values from each estimated model are compared with the observed counterpart and will be fundamental in evaluating the opportunity of applying SETAR models.

3. RESULTS

Figure 1 is useful in our bid to find a model which adapts well to the data. As can be seen, the threshold models identified provide an excellant fit for London and Manchester; these two cities are characterised by a large number of reported cases. Overall, for the remaining four series, the threshold model gives a very good representation of the positive values of the mean centred data, but the local minimums are always over estimated. This is particularly true of Cambridge and the province of Pisa where the local minimums correspond to a large number of fade outs, i.e. zero reported cases; obviously, (1c) in the threshold model in unable to adequately represent this phenomena. In fact the presence of many fade outs in these two series reduces R^2 quite sensibly. However, since it is the outburst of an epidemic which is of prime concern and not that of having few reported cases, the use of a SETAR model to predict epidemics can be considered satisfactory. These results may also be interpreted as suggesting a phenomena which could be amplitude dependent.

There are some differences between the threshold values, *T*, but the lag value *d* found by the selection procedure for each SETAR model defines a 2 months span.

A much more interesting result that emerges from the estimated SETAR models are the differences in their frequency domain properties. The autoregressive spectrum was calculated for each of the three autoregressive models defined in equations (1a) – (1c). In Figure 2 the spectrum is reproduced in the band (0-0.8) since it tails off and rapidly converges to zero beyond frequency $\lambda = 0.8$; (the spectrum is generally estimated in the frequency interval $(0, \pi)$).

The three spectra for any one series are different, at times in form (some are peaked whilst others are not), but more often in terms of the peak frequency thereby confirming the conjecture that the dynamic properties vary with the level reached. Sharp peaks are present in the spectra generated by models (1a) and (1b) for London, Manchester, and the provinces of Milano and Roma. Given the nature of these peaks as well as the very high values of R^2, they might indicate true cyclical behaviour; thus, for London, for example, the peaks at frequencies 0.27 and 0.19 correspond, respectively, to cycles with periodicity of approximately 12 and 16 months. For Cambridge and the province of Pisa, the peaks present are not as marked as in the other cases, but nonetheless indicate differences in the dynamics of the series at different levels.

4. DISCUSSION

The results presented above have been obtained from data where negative values correspond to a small number of reported cases during a two week, for bi-weekly data, or monthly interval. Positive values, and particularly large positive values, are a result of outbursts of epidemics and it is for this reason that we concentrate our attention mainly on models (1a) and (1b). The peak in the spectrum from model (1b) for London, for instance, means that the response 2 months after a positive value crosses the threshold level of 1.1 (converted to the original frequency of reported cases by taking the exponential of the sum of 1.1 and the mean value of 6.1144 for London means nearly 500 reported cases in a bi-week) is cyclical with periodicity of approximately 16 months; similar interpretations may be given to a peak in the spectrum for the other two models.

The threshold model is seen to give very good results for territorial units with a large number of reported cases. The presence of fade-outs and a relatively low level of reported cases is not always adequately represented by the autoregressive structure imbedded in the threshold model.

The results reported correspond to the models selected automatically using the AIC statistic in the procedure described above. Different spectral properties are obtained from other manually selected models which further confirms the belief that the phenomena of measles is amplitude dependent

It emerges from the published literature that the dynamics of the spread of measles are best understood when considered along with demographic variables such as birth rates, age structures and community size in causal models such as the SEIR and TSIR models (see Finkenstadt et al. (2000) and Grenfell et al.(2002)). However, classical time series methods could also be useful for understanding the phenomena. This paper has shown that non-linearities in measles time series in a pre-vaccination period are amplitude dependent and can be profitably explained in piece-wise linear models like the threshold autoregressive model. This approach, when transformed to the frequency domain, has enabled us to identify different dynamics at different levels reached by a series which further confirms the amplitude dependent hypothesis. The estimated threshold model, like most time series models, given the excellent fit to the empirical data, should be useful for purposes of forecasting within a pre-vaccination era. On the other hand, the results from the frequency domain analysis should be useful for identifying the information that has to be incorporated into a causal mathematical model.

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TABLE 1. Estimates of SETAR model (1a)-(1c)
(1a) $0 < X_{t-d} < T$ (1b) $X_{t-d} > T$ (1c) $X_{t-d} < 0$.
N = number of data points used in estimation of model in column 1

1a. London : $T = 1.1,\ d = 4$

	N	μ	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6	R^2
(1a)	158	0.05	1.47	-0.37	-0.13	-	-	-0.13	0.95
(1b)	147	0.03	1.23	-0.27	-	0.24	-0.22	-0.09	0.92
(1c)	289	0.09	1.13	-	-0.11	-	-	-0.03	0.92

1b. Manchester : $T = 1.1,\ d = 4$

	N	μ	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6	R^2
(1a)	164	0.06	1.20	-	-0.20	-	-0.14	-	0.89
(1b)	139	0.15	1.08	-	-0.11	-	-	-0.14	0.89
(1c)	291	0.04	0.90	0.12	-	-0.08	-	-	0.82

1c. Cambridge : $T = 1.1,\ d = 4$

	N	μ	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6	R^2
(1a)	96	0.04	0.89	0.05	-	-	-	-0.12	0.72
(1b)	164	0.41	1.03	-	-0.14	-0.17	-	-	0.78
(1c)	334	-0.12	0.83	-	-	-	-0.07	-	0.57

1d. Milano : $T = 0.8,\ d = 2$

	N	μ	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6	R^2
(1a)	92	-0.09	1.14	-0.30	-	-0.15	-	-0.23	0.82
(1b)	85	-0.26	1.27	-	-0.28	-0.06	-	-0.17	0.81
(1c)	133	0.06	1.00	-0.33	-	-	0.22	-0.15	0.60

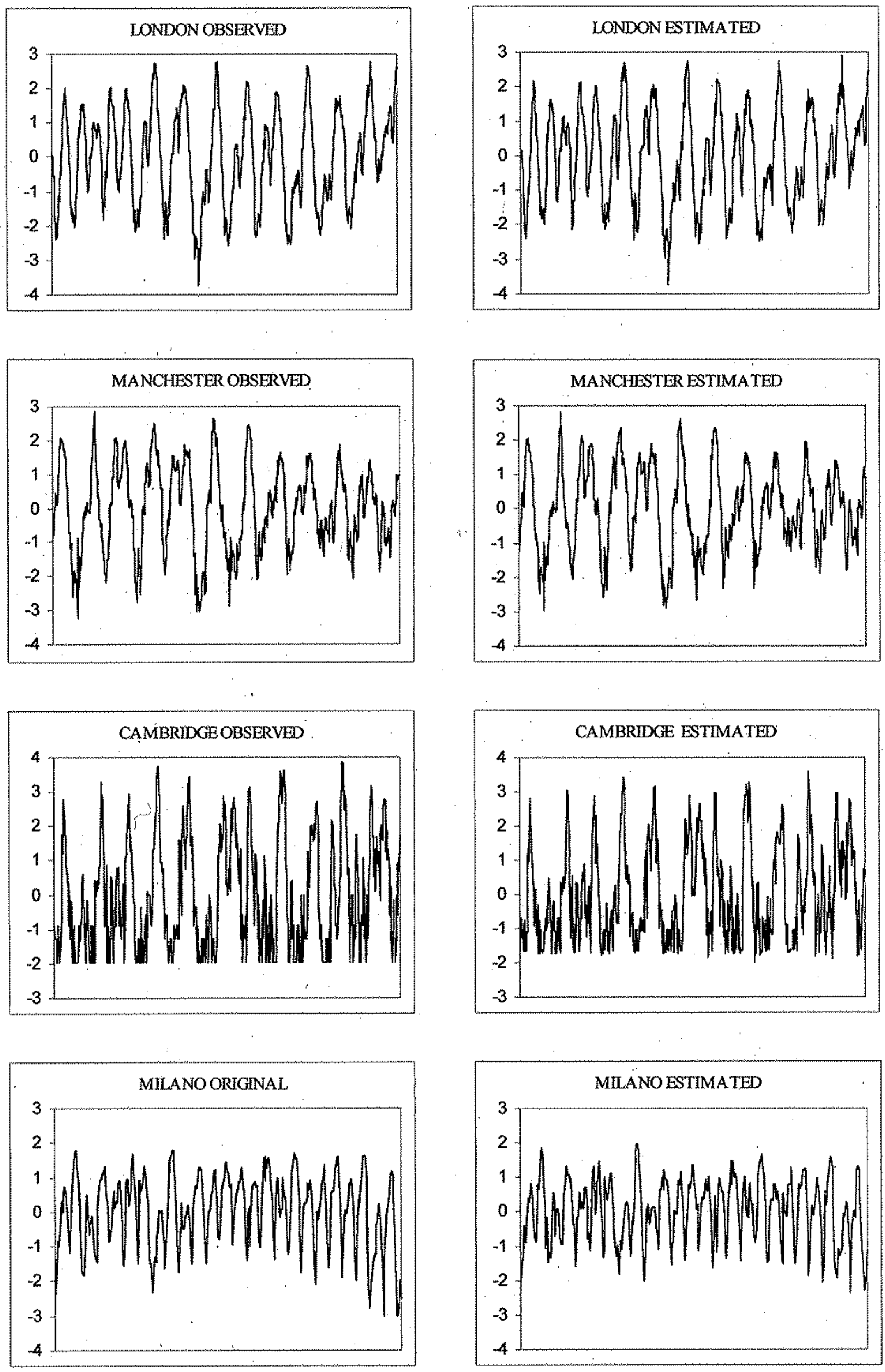
1e. Roma : $T = 1.3,\ d = 3$

	N	μ	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6	R^2
(1a)	86	-0.07	1.22	-0.43	-	-	-0.33	0.12	0.88
(1b)	85	-0.24	1.56	-0.67	-	-	-	-0.13	0.92
(1c)	141	-0.02	0.95	-	-	-0.40	-	0.26	0.74

1f. Pisa : $T = 1.3,\ d = 23$

	N	μ	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6	R^2
(1a)	90	-0.10	0.96	-	-0.09	-0.15	-	-	0.63
(1b)	72	-0.11	1.07	-	-	-0.34	-	-	0.81
(1c)	148	-0.01	0.76	0.21	-0.28	-	-	-	0.58

FIGURE 1. Observed data and estimated values using threshold model (1a) – (1c)



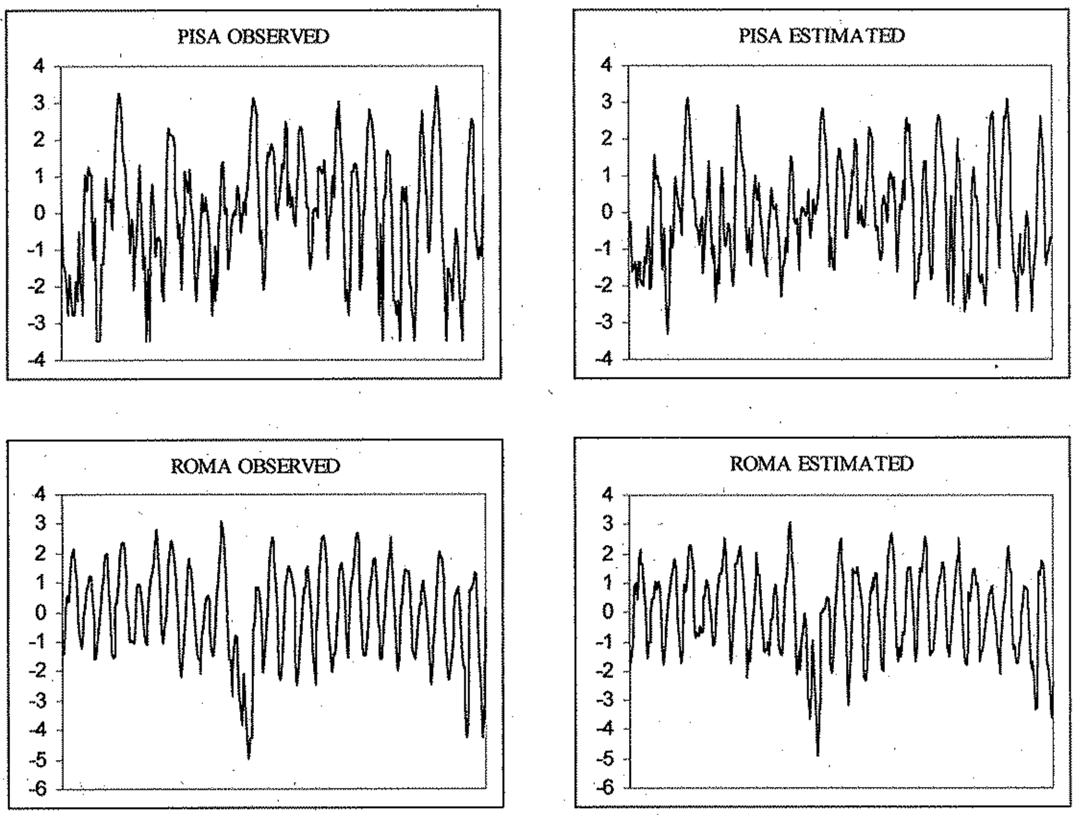
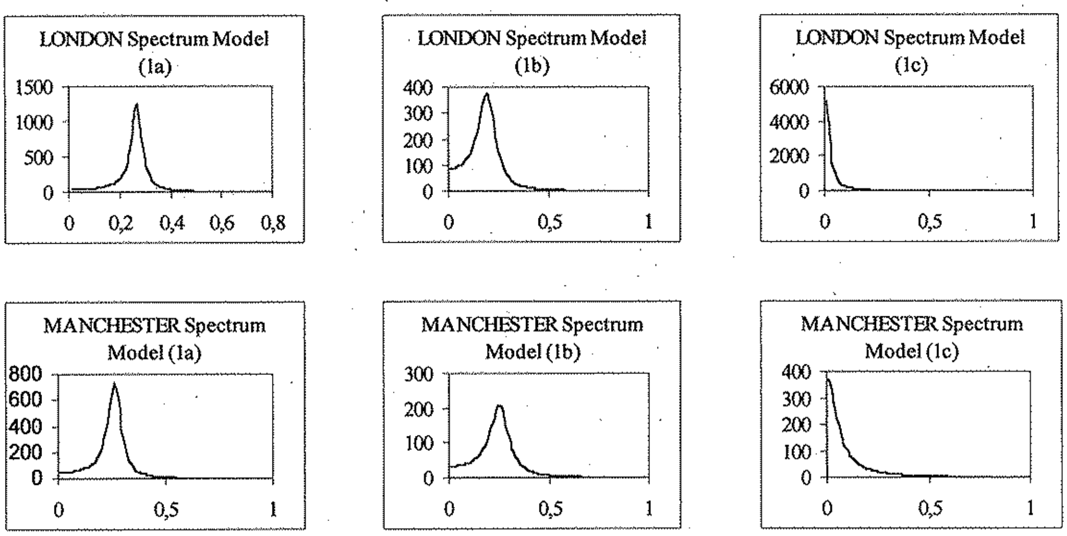
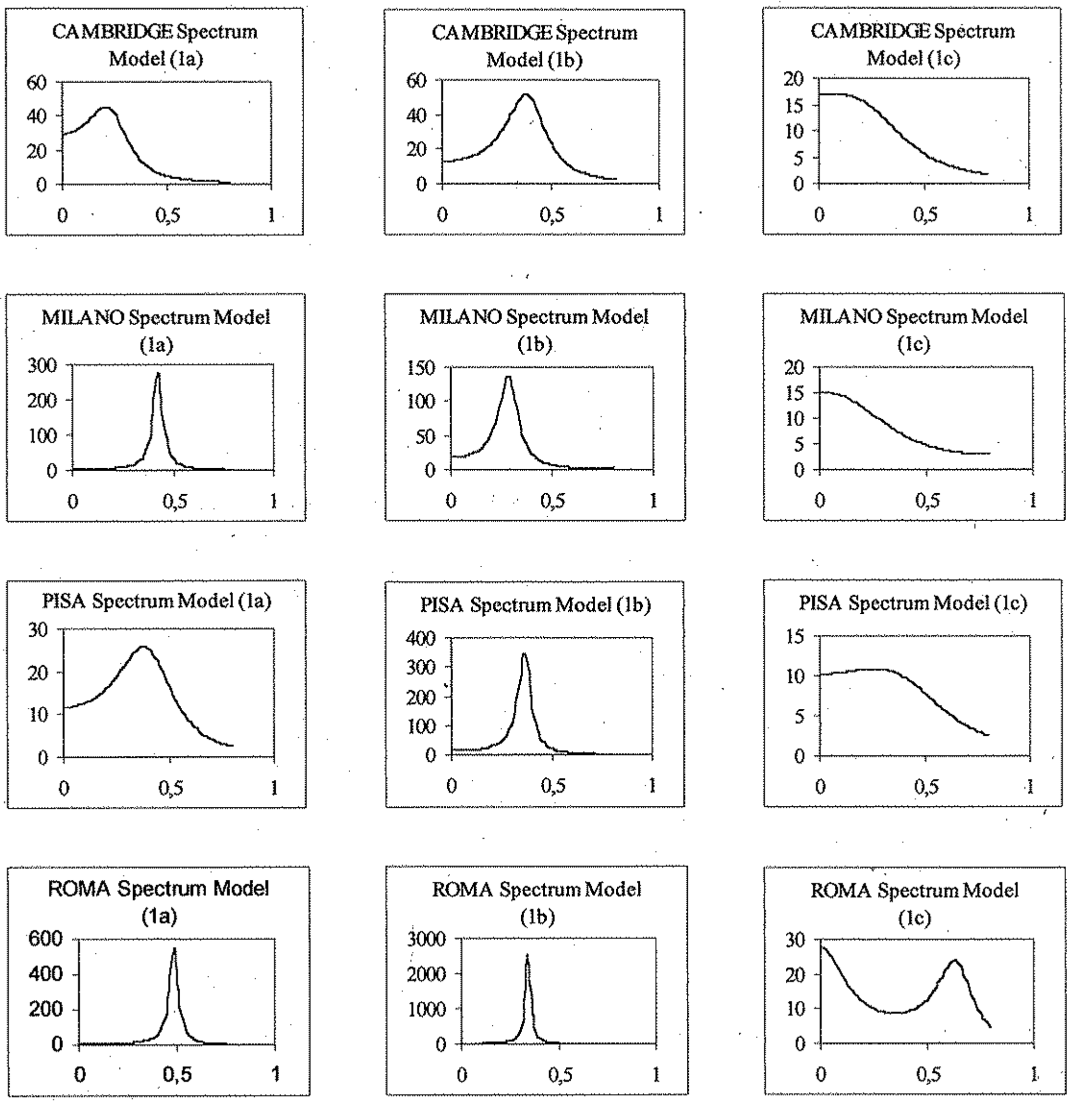


FIGURE 2. Autoregressive (gain) spectra from SETAR Model (1a) – (1c)




CAMBRIDGE Spectrum Model (1a)
60
40
20
0
0
0,5
1
CAMBRIDGE Spectrum Model (1b)
60
40
20
0
0
0,5
1
CAMBRIDGE Spectrum Model (1c)
20
15
10
5
0
0
0,5
1
MILANO Spectrum Model (1a)
300
200
100
0
0
0,5
1
MILANO Spectrum Model (1b)
150
100
50
0
0
0,5
1
MILANO Spectrum Model (1c)
20
15
10
5
0
0
0,5
1
PISA Spectrum Model (1a)
30
20
10
0
0
0,5
1
PISA Spectrum Model (1b)
400
300
200
100
0
0
0,5
1
PISA Spectrum Model (1c)
15
10
5
0
0
0,5
1
ROMA Spectrum Model (1a)
600
400
200
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ROMA Spectrum Model (1b)
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Anno: 1995

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Anno: 1996

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Anno: 1997

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Anno: 1998

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Anno: 1999

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Elenco dei report pubblicati

Anno: 2000

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Anno: 2001

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Anno: **2002**

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Anno: **2003**

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Anno: **2004**

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