REVISION IN ARIMA SIGNAL EXTRACTION

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Resumen

El trabajo considera el problema de descomponer una serie observable, resultado de un proceso ARIMA, en señal y ruido. Es sabido que el estimador preliminar de la señal será objeto de revisiones, a medida que se disponga de nuevas observaciones. En el trabajo se deriva el modelo que sigue la revisión del estimador de la señal para el presente. Se trata de un proceso ARIMA estacionario, de obtención inmediata a partir del modelo general para la serie que se observa. El resultado se generaliza a continuación, para la revisión asociada con cualquier estimador preliminar de la señal. Se demuestra también que, excepto por un factor de escala o proporcionalidad, la revisión es la misma para cualquier descomposición admisible (con espectros no negativos para los componentes), y que la descomposición canónica, que maximiza la varianza del ruido, maximiza también la varianza de la revisión. Finalmente, se presenta un ejemplo, en el que los resultados anteriores se utilizan para determinar la precisión del estimador de la señal y para determinar la optimalidad de un proceso de revisiones.

Abstract

The problem of decomposing an observed series, assumed to follow an ARIMA process, into signal plus noise is considered. It is well-known that the preliminary estimates of the signal will be subject to revisions, as more data become available. For a general ARIMA process, the revision in the concurrent estimate of the signal is seen to follow a stationary ARMA process, easily computed from the overall series model. The results are extended to non-concurrent preliminary estimates. Finally, it is found that, except for a scale factor, the revisions are the same for all admissible decompositions, and that the canonical decomposition maximizes the variance of the revision.

Key words: ARIMA Models; Signal Extraction; Preliminary Estimates; Revisions; Unobserved Components; Canonical Decomposition.

1. INTRODUCTION

Consider the problem of decomposing an observed time series, which is assumed to follow an ARIMA process, into signal plus noise. It is well known (see Box-Hillmer-Tiao, 1978) that the signal (s_t) is estimated with a two-sided filter applied to the observed series. Hence, at least for periods not too distant from t, the estimate will depend on future values of the series. Replacing these unknown values with their forecasts, preliminary estimates of the signal can be obtained. This estimate will be subject to revisions since, as new observations become available, forecasts will be updated and eventually replaced with observations.

Revisions are of interest because, since the optimal estimate is the final one, they represent measurement error in the preliminary estimate, this estimate being the one of applied interest. Some results on the structure of revisions are provided in Pierce (1980), where it is seen that the revision between two estimates of the same signal, made T periods apart, follows a moving average process of order (T-1). In this paper, we further analyse the structure of the revision in preliminary estimates of the signal in an ARIMA model. In Section 2, the general background is developed. In Section 3, the model for the revision in the concurrent estimate of the signal for a general ARIMA model is derived. Section 4 extends the results to non-concurrent preliminary estimates. Section 5 presents some implications concerning revisions associated with different admissible decompositions of the same model and, finally, Section 6 contains an example.

2. REVISIONS IN THE CONCURRENT ESTIMATE OF THE SIGNAL

We wish to decompose an observed series z_t into:

$$z_t = s_t + u_t \ , \tag{2.1}$$

where s_t is the signal and u_t the noise. Let the models for z_t and s_t be given by the linear filters:

$$z_t = \psi_z(B)\ a_t \ ; \ s_t = \psi_s(B)\ c_t \ ,$$

where $\psi(B)$ denotes a rational function of the lag operator B, and u_t is white-noise, orthogonal to c_t. The minimum MSE linear estimate of s_t is (see, for example, Cleveland and Tiao, 1976).

$$\hat{s}_t = \nu(B)\ z_t \ , \tag{2.2}$$

where $\nu(B)$ is the two sided filter:

$$\nu(B) = \frac{\sigma_c^2}{\sigma_a^2} \ \frac{\psi_s(B)\ \ \psi_s(F)}{\psi_z(B)\ \ \psi_z(F)} \ ,$$

with $F = B^{-1}$. From:

$$\psi_z(B)\ a_t = \psi_s(B)\ c_t + u_t \ ,$$

equating the autocovariance generating functions (ACGF) of both sides of the equation, the following alternative expression for $\nu(B)$ is obtained:

$$\nu(B) = 1 - \frac{\sigma_u^2}{\sigma_a^2} \ \frac{1}{\psi_z(B)\ \ \psi_z(F)} \tag{2.3}$$

The filter $\nu(B)$ is centered and symmetric, hence $\hat{s}_t$ depends on observations posterior to t. Expression (2.2) provides thus the "final" estimate of s_t. With observations available up to time t, the concurrent estimate of s_t ($\hat{s}^o_t$) is obtained by replacing future values (z_{t+j}) with forecasts made at time t ($\hat{z}_t(j)$). Hence we can write:

$$\hat{s}_t = \nu_o\ z_t + \nu_1(z_{t-1}+z_{t+1}) + \nu_2(z_{t-2}+z_{t+2}) + \ldots$$

$$\hat{s}^o_t = \nu_o\ z_t + \nu_1(z_{t-1}+\hat{z}_t(1)) + \nu_2(z_{t-2}+\hat{z}_t(2)) + \ldots\ ,$$

and the total revision $d_t = \hat{s}_t - \hat{s}^o_t$ is therefore equal to:

$$d_t = \Sigma^{\infty}_{j=1}\ \nu_j\ e_t(j) \quad , \tag{2.4}$$

where $e_t(j) = z_{t+j} - \hat{z}_t(j)$ is the jth-period-ahead forecast error; the revision is, thus, a linear combination of the forecast function with origin t. Let H(B,F) denote the inverse ACGF of the observed series:

$$H(B,F) = 1/\psi_z(B)\ \psi_z(F) =$$

$$= h_o + \Sigma^{\infty}_{i=1}\ h_i\ (B^i + F^i). \tag{2.5}$$

Then, from (2.3)(2.4) and (2.5), it is obtained that

$$d_t = k\ \Sigma^{\infty}_{j=1}\ h_j\ e_t(j)\ , \tag{2.6}$$

where $k = -(\sigma^2_u/\sigma^2_a)$. Let $\psi_z(B) = 1 + \Sigma^{\infty}_{j=1}\ \psi_j\ B^j$; since

$$e_t(j) = a_{t+j} + \Sigma^{j-1}_{i=1}\ \psi_i\ a_{t+j-i}\ , \tag{2.7}$$

substituting in (2.6), d_t can be also expressed as

$$d_t = \Sigma_{j=1}^{\infty} n_j \, a_{t+j} \, , \tag{2.8}$$

where $n_j = k[h_j + \psi_1 h_{j+1} + \psi_2 h_{j+2} + \ldots]$, thus d_t is a moving average of future innovations. From (2.8) it is seen that, at t, the forecast of the revision d_t is zero and, since $\hat{s}_t^o$ can be expressed as a moving average of only past and present innovations, the concurrent estimate and its future revision are orthogonal.

3. A MODEL FOR THE REVISION

Consider first a general autoregressive model.

<u>Lemma 1</u>: Let z_t follow the AR(p) model:

$$(1-\phi_1 B-\ldots-\phi_p B^p)z_t = a_t \quad .$$

Then the revision in the concurrent estimate of the signal follows the MA(p-1) model:

$$d_t = -k(\phi_1\ a_{t+1} + \phi_2\ a_{t+2} + \ldots + \phi_p\ a_{t+p}). \qquad (3.1)$$

<u>Proof</u>: The coefficient h_j in (2.6) is equal to:

$$h_j = \begin{cases} -\phi_j + \Sigma_{i=1}^{p-j}\ \phi_i\ \phi_{i+j} & \text{for } j<p \\ -\phi_j & \text{for } j=p \\ 0 & \text{for } j>p \end{cases} \qquad (3.2)$$

Using (3.2) and (2.7) in (2.6), after simplifying, it is obtained that:

$$d_t = -k\ \Sigma_{j=1}^{p}\ (\Sigma_{i=0}^{p-j}\ \phi_{j+i}\ C_i)\ a_{t+j} \quad , \qquad (3.3)$$

where:

$$\begin{aligned} C_o &= 1 \\ C_1 &= \psi_1-\phi_1 \\ C_j &= \psi_j-\phi_j-\Sigma_{i=1}^{j-1}\ \psi_{j-i}\ \phi_i\ , \qquad j = 2,\ldots,p \end{aligned}$$

Therefore C_j is the coefficient of B^j in the generating function $C(B) = \phi(B)\psi(B)$. Since $\psi(B) = \phi(B)^{-1}$, it follows that $C_o=1$ and $C_j=0$ for $j>0$. Hence (3.3) simplifies into:

$$d_t = -k \sum_{j=1}^{p} \phi_j \, a_{t+j} \quad , \qquad \text{q.e.d.}$$

To illustrate the proof, for the AR(2) model:

$$(1-\phi_1 B-\phi_2 B^2) z_t = a_t \ ,$$

(2.3) becomes:

$$\nu(B) = 1+k(1-\phi_1 B-\phi_2 B^2)(1-\phi_1 F-\phi_2 F^2) \ ,$$

hence $h_1 = -\phi_1+\phi_1 \phi_2$, $h_2 = -\phi_2$, $h_j = 0$ $(j>2)$. Since $e_t(1) = a_{t+1}$ and $e_t(2) = a_{t+2} + \phi_1 a_{t+1}$, (2.6) yields:

$$d_t = -k(\phi_1 a_{t+1} + \phi_2 a_{t+2})$$

and the total revision is an MA(1).

Thus pure autoregressive models generate finite moving average revisions, and the final estimate of the signal will be available after a finite number of periods. From lemma 1, the result for a general ARIMA model is easily obtained:

<u>Theorem 1</u>: Let z_t follow the ARMA(p,q) model:

$$\phi(B) \, z_t = \theta(B) \, a_t \ ,$$

where $\phi(B)$ and $\theta(B)$ have no roots in common and unit roots may be present in the autoregressive polynomial. Then the revision in the concurrent estimate of the signal follows the ARMA (q, r-1) model:

$$\theta(F) \, d_t = k \, \lambda(F) \, a_t \ ,$$

where $\lambda(F) = \phi(F)-\theta(F)$, and $r = \max(p,q)$.

<u>Proof</u>: Let $\pi(B) = 1-\pi_1 B-\pi_2 B^2- \ldots = \phi(B)/\theta(B)$. Applying Lemma 1 to $\pi(B)\ z_t = a_t$, yields:

$$d_t = -k(\pi_1\ a_{t+1}+\pi_2\ a_{t+2}+\ldots) = -k(\pi_1\ F+\pi_2\ F^2+\ldots)\ a_t =$$

$$= k[\pi(F)-1]\ a_t = k\left[\frac{\phi(F)}{\theta(F)} -1\right] a_t\ , \qquad (3.4)$$

from which it is obtained that:

$$\theta(F)\ d_t = k\ [\phi(F)-\theta(F)]\ a_t = k\ \lambda(F)\ a_t\ , \quad \text{q.e.d.}$$

Notice that the polynomial $\lambda(F)$ can be expressed as:

$$\lambda(F) = (\theta_1-\phi_1)\ F\ +(\theta_2-\phi_2)\ F^2\ +\ \ldots\ ,$$

and does not include a constant. (Expression (3.4) can also be derived from theorem 1 in Pierce, 1980.)

The model for the revision associated with a finite MA model can be obtained as a particular case of the general result. Let z_t follow the MA(q) model $z_t = \theta(B)\ a_t$. Then, applying theorem 1, the revision in the concurrent estimate of the signal follows the ARMA (q,q-1) model:

$$\theta(F)\ d_t = k[\theta_1\ a_{t+1}+\ldots+\theta_q\ a_{t+q}]\ .$$

Finally, let z_t follow a (possibly nonstationary) ARIMA process, and consider a decomposition such as (2.1) with u_t white-noise, with positive variance. An important implication of theorem 1 is the following:

<u>Corollary 1</u>: The revision in the concurrent estimate of the signal is a stationary process.

<u>Proof</u>: Let $g_z(\omega)$ denote the spectrum of z_t. Since $\sigma_u^2>0$, it follows that min. $g_z(\omega)>0$. Thus z_t is an invertible process, hence the roots of $\theta(B)$ lie outside the unit circle. From theorem 1, $\theta(B)$ is the AR polynomial in the model for d_t, hence d_t is stationary. q.e.d.

As a consequence, even when the series and the signal are nonstationary, the revision will have finite variance. Still, although the series of revisions is stationary, theorem 1 implies that its autocorrelation function (ACF) will not be, in general, that of white noise. Since $E_t\ d_t = 0$, for this series, thus, the presence of autocorrelation does not imply forecastability.

4. REVISIONS IN NON-CONCURRENT ESTIMATES OF THE SIGNAL

The analysis in the previous section can be extended to revisions in a non-concurrent estimate. Let $\hat{s}_t^m$ denote the estimate of the signal s_t obtained at time t+m ($m \gtrless 0$), that is

$$\hat{s}_t^m = E_{t+m}\, s_t$$

Then, the associated revision $d_t^m = \hat{s}_t - \hat{s}_t^m$ is equal to

$$d_t^m = \Sigma_{j=1}^{\infty} \nu_{m+j}\, e_{t+m}(j) \ ,$$

a linear combination of the forecast function with origin (t+m). Moreover, using (2.7), the revision can also be expressed as a moving average of innovations posterior to period (t+m).

The model for the revision in purely autoregressive series can be derived in a manner similar to that of Section 3, although the structure of the ν-coefficients implied by (2.3) and (2.5), namely

$$\nu_o = 1 + k\, h_o$$
$$\nu_j = k\, h_j \qquad (j \neq 0)$$

induces an asymmetry between the cases $m \geq 0$ and $m < 0$. When $m \geq 0$, similarly to (3.1), the model for the revision is given by the expresion

$$d_t^m = -k(\phi_{m+1}\, a_{t+m+1} + \ldots + \phi_p\, a_{t+p}) \quad ,$$

or:

$$d_t^m = k[\phi(F) - (1 - \phi_1 F - \ldots \phi_m\, F^m)]a_t .$$

When m<0, the model for the revision becomes:

$$d_t^m = [k\ \phi(F)+1+\psi_1\ F^{-1}+\ldots+\psi_{-m-1}\ F^{m+1}]a_t\ ,$$

where the ψ-coefficients are given by $\psi(B) = \phi(B)^{-1}$.

Since the presence of noise ($\sigma_u^2>0$) implies invertibility of the process for z_t, from the results for autoregressive series, the model for the revision in any preliminary estimate of the signal in a general ARIMA model can be easily found. Thus, for example, the revision in the estimate of s_t obtained at (t+1), d_t^1, follows the model

$$\theta(F)\ d_t^1 = k[\phi(F)-(1-\pi_1\ B)\theta\ (F)]a_t\ .$$

Similarly, the model for the revision in the estimate of s_t obtained at (t-1) is given by

$$\theta(F)\ d_t^{-1} = [k\ \phi(F)+\theta(F)]a_t\ .$$

From the above expressions, updating formulas for the revision can be easily computed. For example, the change in the revision when the estimation period moves from (t-1) to t is equal to

$$d_t - d_t^{-1} = -(k+1)a_t\ ,$$

and, in general, the revision update when a new observation becomes available is a function of the last one-period-ahead forecast error.

5. REVISIONS AND CANONICAL DECOMPOSITION

Given the (invertible) model for z_t, the problem of decomposing z_t as in (2.1), with u_t white noise, has no unique solution. As shown in Box, Hillmer and Tiao (1978), the possible values of σ_u^2 are bounded, and every value of σ_u^2 between zero and this bound determines a unique acceptable model for the signal. The decomposition that results from setting σ_u^2 equal to its maximum value is termed "canonical". It provides the smoothest signal and, since the signal of any other acceptable decomposition is equal to the canonical signal plus added noise, its use has been advocated in the literature.

From the last equality in (3.4), it is seen that, for any acceptable decomposition, d_t can be expressed as:

$$d_t = \sigma_u^2 \, y_t \, , \tag{5.1}$$

where:

$$y_t = - \frac{1}{\sigma_a^2} \left[\frac{\phi(F)}{\theta(F)} - 1 \right] a_t$$

depends only on the parameters of the model for the observed series. Since y_t is, therefore, the same for all acceptable decompositions, the following result is obtained.

<u>Corollary 2</u>: Except for a scale factor, the revisions are the same in all acceptable decompositions. (In particular, the ACFs will all be identical.)

Finally, since (5.1) implies Var $(d_t) = \sigma_u^4$ Var (y_t), setting the variance of u_t equal to its maximum value maximizes the variance of d_t. This proves the result mentioned in Maravall (1984):

Corollary 3: Within all acceptable decompositions, the canonical one maximizes the variance of the revision.

As a consequence, the smoother the estimate of the signal, the larger the revision in the concurrent estimate will be. This can be interpreted as a price paid for cleaning the signal. It does not seem appropriate, however, to reduce revisions by labelling as signal what is purely white-noise variation.

6. EXAMPLE

The results of Sections 3 and 4 can be directly applied to situations in which there is interest in removing the noise (associated with transitory, self-cancelling, irregular variation) in order to obtain a better estimate of the underlying signal. This is often the case in economic policy making, where ignoring noise variation may avoid instability induced by over reacting; see Maravall and Pierce, 1985. In particular, since revisions reflect measurement error, the previous results can be used to assess the precision of a preliminary estimate. Consider, for example, the revision in the concurrent estimate of the signal in the basic trend-type structure in ARIMA models: the IMA (1,1) process. From theorem 1, the model for the revision is given by the AR(1) model:

$$(1-\theta F)\ d_t = k(\theta-1)\ a_{t+1}\ .$$

Hence $\mathrm{Var}\ (d_t) = \sigma_u^4(1-\theta)/(\sigma_a^2(1+\theta))$. For the canonical decomposition it is found that $\sigma_u^2 = (1+\theta)^2\ \sigma_a^2/4$, which yields:

$$\sigma_d^2 = \frac{(1+\theta)^2(1-\theta^2)}{16}\ \sigma_a^2 \qquad (6.1)$$

Figure 1 plots σ_d as a fraction of σ_a for different values of θ. The maximum occurs for θ=.5, in which case the standard deviation of the revision error is close to 1/3 that of the one-period ahead forecast error.

As a simple example, consider the series of the General Index of the Madrid Stock Exchange, used as an indicator of economic activity. There is interest in

estimating, for each new observation, which part should be considered signal and which part represents transitory noise. Figure 2 plotts the monthly series (in levels) for the period 1980-85, together with the concurrently estimated signal. Besides the point estimate, it is also of interest to determine the precision of the estimator. The series follows a random walk model, in which case, from (6.1), for the revision in the canonical signal, $\sigma_d = .25\ \sigma_a$. Since $\sigma_a = 6.6$ percent points, a confidence interval (at the 95% level) around the concurrent estimate of the signal, based on the size of the revision error, is approximately equal to $\hat{s}_t^o$ plus or minus 3.3 percent points. Additionally, the comparison of the theoretical ACF of the revisions, implied by the overall model for the series, and the empirical ACF of the obtained revisions provides, ultimately, a test for the adequacy of a given signal extraction and revision procedure. In our example, for the random walk, according to lemma 1, the revision in the concurrent estimate should be white noise. This is remarkably in agreement with the empirical ACF of the estimated revisions, displayed in Figure 3 (for the period 1975-84).

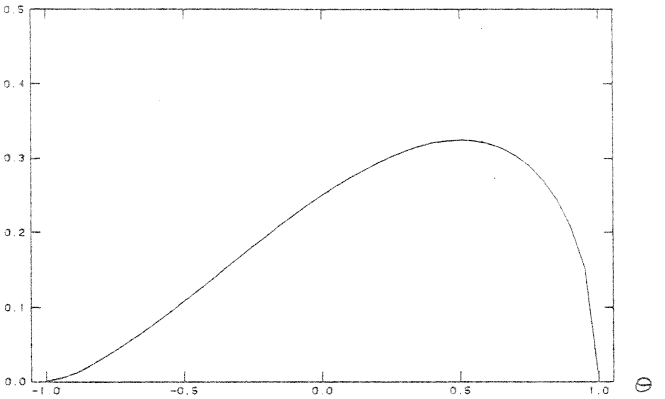

Figure 1

Standard Deviation of the Revision for an IMA(1,1)

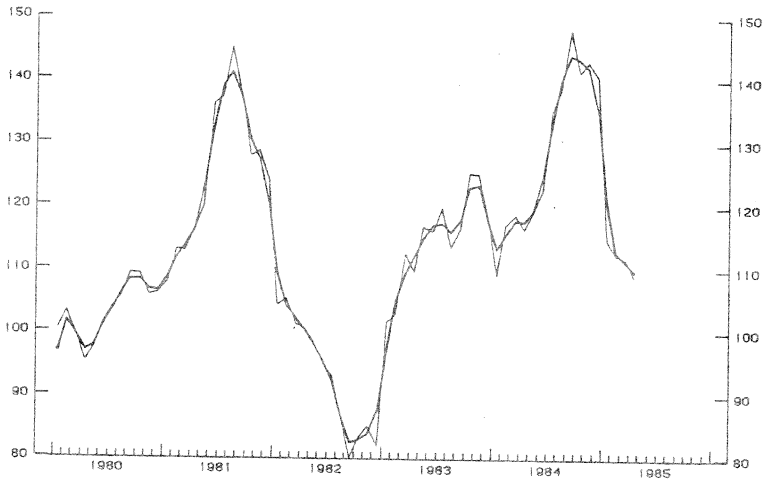

Figure 2

General Index of the Madrid Stock Exchange

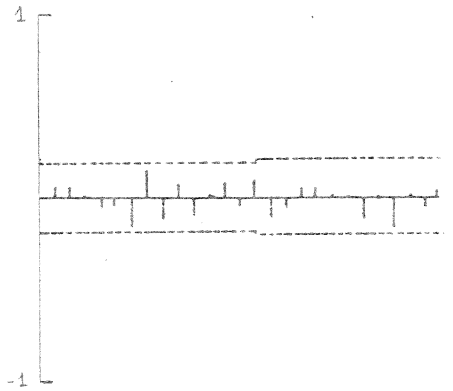

Figure 3

Autocorrelation Function of the Series of Revisions

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