

# NAG Fortran Library Chapter Introduction

## G13 – Time Series Analysis

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## 1 Scope of the Chapter

This chapter provides facilities for investigating and modelling the statistical structure of series of observations collected at equally spaced points in time. The models may then be used to forecast the series.

The chapter covers the following models and approaches.

1. Univariate time series analysis, including autocorrelation functions and autoregressive moving average (ARMA) models.
2. Univariate spectral analysis.
3. Transfer function (multi-input) modelling, in which one time series is dependent on other time series.
4. Bivariate spectral methods including coherency, gain and input response functions.
5. Vector ARMA models for multivariate time series.
6. Kalman filter models.
7. GARCH models for volatility.

## 2 Background to the Problems

### 2.1 Univariate Analysis

Let the given time series be  $x_1, x_2, \dots, x_n$ , where  $n$  is its length. The structure which is intended to be investigated, and which may be most evident to the eye in a graph of the series, can be broadly described as

- (a) trends – linear or possibly higher-order polynomial;
- (b) seasonal patterns, associated with fixed integer seasonal periods. The presence of such seasonality and the period will normally be known *a priori*. The pattern may be fixed, or slowly varying from one season to another;
- (c) cycles, or waves of stable amplitude and period  $p$  (from peak to peak). The period is not necessarily integer, the corresponding absolute frequency (cycles/time unit) being  $f = 1/p$  and angular frequency  $\omega = 2\pi f$ . The cycle may be of pure sinusoidal form like  $\sin(\omega t)$ , or the presence of higher harmonic terms may be indicated, e.g., by asymmetry in the wave form;
- (d) quasi-cycles, i.e., waves of fluctuating period and amplitude; and
- (e) irregular statistical fluctuations and swings about the overall mean or trend.

Trends, seasonal patterns, and cycles might be regarded as **deterministic** components following fixed mathematical equations, and the quasi-cycles and other statistical fluctuations as **stochastic** and describable by short-term correlation structure. For a finite data set it is not always easy to discriminate between these two types, and a common description using the class of autoregressive integrated moving-average (ARIMA) models is now widely used. The form of these models is that of difference equations (or recurrence relations) relating present and past values of the series. The user is referred to Box and Jenkins (1976) for a thorough account of these models and how to use them. We follow their notation and outline the recommended steps in ARIMA model building for which routines are available.

#### 2.1.1 Transformations

If the variance of the observations in the series is not constant across the range of observations it may be useful to apply a variance-stabilizing transformation to the series. A common situation is for the variance to increase with the magnitude of the observations and in this case typical transformations used are the log or square root transformation. A range–mean or standard deviation–mean plot provides a quick and easy way of detecting non-constant variance and of choosing, if required, a suitable transformation. This is a plot of the range or standard deviation of successive groups of observations against their means.

#### 2.1.2 Differencing operations

These may be used to simplify the structure of a time series.

First-order differencing, i.e., forming the new series

$$\nabla x_t = x_t - x_{t-1}$$

will remove a linear trend. First-order seasonal differencing

$$\nabla_s x_t = x_t - x_{t-s}$$

eliminates a fixed seasonal pattern.

These operations reflect the fact that it is often appropriate to model a time series in terms of changes from one value to another. Differencing is also therefore appropriate when the series has something of the nature of a random walk, which is by definition the accumulation of independent changes.

Differencing may be applied repeatedly to a series, giving

$$w_t = \nabla^d \nabla_s^D x_t$$

where  $d$  and  $D$  are the orders of differencing. The derived series  $w_t$  will be shorter, of length  $N = n - d - s \times D$ , and extend for  $t = 1 + d + s \times D, \dots, n$ .

### 2.1.3 Sample autocorrelations

Given that a series has (possibly as a result of simplifying by differencing operations) a homogeneous appearance throughout its length, fluctuating with approximately constant variance about an overall mean level, it is appropriate to assume that its statistical properties are **stationary**. For most purposes the correlations  $\rho_k$  between terms  $x_t, x_{t+k}$  or  $w_t, w_{t+k}$  separated by lag  $k$  give an adequate description of the statistical structure and are estimated by the sample autocorrelation function (acf)  $r_k$ , for  $k = 1, 2, \dots$

As described by Box and Jenkins (1976), these may be used to indicate which particular ARIMA model may be appropriate.

### 2.1.4 Partial autocorrelations

The information in the autocorrelations  $\rho_k$  may be presented in a different light by deriving from them the coefficients of the partial autocorrelation function (pacf)  $\phi_{k,k}$ , for  $k = 1, 2, \dots$ .  $\phi_{k,k}$  measures the correlation between  $x_t$  and  $x_{t+k}$  conditional upon the intermediate values  $x_{t+1}, x_{t+2}, \dots, x_{t+k-1}$ . The corresponding sample values  $\hat{\phi}_{k,k}$  give further assistance in the selection of ARIMA models.

Both acf and pacf may be rapidly computed, particularly in comparison with the time taken to estimate ARIMA models.

### 2.1.5 Finite lag predictor coefficients and error variances

The partial autocorrelation coefficient  $\phi_{k,k}$  is determined as the final parameter in the minimum variance predictor of  $x_t$  in terms of  $x_{t-1}, x_{t-2}, \dots, x_{t-k}$ ,

$$x_t = \phi_{k,1}x_{t-1} + \phi_{k,2}x_{t-2} + \dots + \phi_{k,k}x_{t-k} + e_{k,t}$$

where  $e_{k,t}$  is the prediction error, and the first subscript  $k$  of  $\phi_{k,i}$  and  $e_{k,t}$  emphasizes the fact that the parameters will alter as  $k$  increases. Moderately good estimates  $\hat{\phi}_{k,i}$  of  $\phi_{k,i}$  are obtained from the sample acf, and after calculating the pacf up to lag  $L$ , the successive values  $v_1, v_2, \dots, v_L$  of the prediction error variance estimates,  $v_k = \text{var}(e_{k,t})$ , are available, together with the final values of the coefficients  $\hat{\phi}_{k,1}, \hat{\phi}_{k,2}, \dots, \hat{\phi}_{k,L}$ . If  $x_t$  has non-zero mean,  $\bar{x}$ , it is adequate to use  $x_t - \bar{x}$  in place of  $x_t$  in the prediction equation.

Although Box and Jenkins (1976) do not place great emphasis on these prediction coefficients, their use is advocated for example by Akaike (1971), who recommends selecting an optimal order of the predictor as the lag for which the final prediction error (FPE) criterion  $(1 + k/n)(1 - k/n)^{-1}v_k$  is a minimum.

### 2.1.6 ARIMA models

The correlation structure in stationary time series may often be represented by a model with a small number of parameters belonging to the autoregressive moving-average (ARMA) class. If the stationary series  $w_t$  has been derived by differencing from the original series  $x_t$ , then  $x_t$  is said to follow an ARIMA

model. Taking  $w_t = \nabla^d x_t$ , the (non-seasonal) ARIMA  $(p, d, q)$  model with  $p$  autoregressive parameters  $\phi_1, \phi_2, \dots, \phi_p$  and  $q$  moving-average parameters  $\theta_1, \theta_2, \dots, \theta_q$ , represents the structure of  $w_t$  by the equation

$$w_t = \phi_1 w_{t-1} + \dots + \phi_p w_{t-p} + a_t - \theta_1 a_{t-1} - \dots - \theta_q a_{t-q}, \quad (1)$$

where  $a_t$  is an uncorrelated series (white noise) with mean 0 and constant variance  $\sigma_a^2$ . If  $w_t$  has a non-zero mean  $c$ , then this is allowed for by replacing  $w_t, w_{t-1}, \dots$  by  $w_t - c, w_{t-1} - c, \dots$  in the model. Although  $c$  is often estimated by the sample mean of  $w_t$  this is not always optimal.

A series generated by this model will only be stationary provided restrictions are placed on  $\phi_1, \phi_2, \dots, \phi_p$  to avoid unstable growth of  $w_t$ . These are called **stationarity** constraints. The series  $a_t$  may also be usefully interpreted as the linear **innovations** in  $x_t$  (and in  $w_t$ ), i.e., the error if  $x_t$  were to be predicted using the information in all past values  $x_{t-1}, x_{t-2}, \dots$ , provided also that  $\theta_1, \theta_2, \dots, \theta_q$  satisfy **invertibility** constraints. This allows the series  $a_t$  to be regenerated by rewriting the model equation as

$$a_t = w_t - \phi_1 w_{t-1} - \dots - \phi_p w_{t-p} + \theta_1 a_{t-1} + \dots + \theta_q a_{t-q}. \quad (2)$$

For a series with short-term correlation only, i.e.,  $r_k$  is not significant beyond some low lag  $q$  (see Box and Jenkins (1976) for the statistical test), then the pure moving-average model MA( $q$ ) is appropriate, with no autoregressive parameters, i.e.,  $p = 0$ .

Autoregressive parameters are appropriate when the acf pattern decays geometrically, or with a damped sinusoidal pattern which is associated with quasi-periodic behaviour in the series. If the sample pacf  $\hat{\phi}_{k,k}$  is significant only up to some low lag  $p$ , then a pure autoregressive model AR( $p$ ) is appropriate, with  $q = 0$ . Otherwise moving-average terms will need to be introduced, as well as autoregressive terms.

The seasonal ARIMA  $(p, d, q, P, D, Q, s)$  model allows for correlation at lags which are multiples of the seasonal period  $s$ . Taking  $w_t = \nabla^d \nabla_s^D x_t$ , the series is represented in a two-stage manner via an intermediate series  $e_t$ :

$$w_t = \Phi_1 w_{t-s} + \dots + \Phi_P w_{t-s \times P} + e_t - \Theta_1 e_{t-s} - \dots - \Theta_Q e_{t-s \times Q} \quad (3)$$

$$e_t = \phi_1 e_{t-1} + \dots + \phi_p e_{t-p} + a_t - \theta_1 a_{t-1} - \dots - \theta_q a_{t-q} \quad (4)$$

where  $\Phi_i, \Theta_i$  are the seasonal parameters and  $P, Q$  are the corresponding orders. Again,  $w_t$  may be replaced by  $w_t - c$ .

### 2.1.7 ARIMA model estimation

In theory, the parameters of an ARIMA model are determined by a sufficient number of autocorrelations  $\rho_1, \rho_2, \dots$ . Using the sample values  $r_1, r_2, \dots$  in their place it is usually (but not always) possible to solve for the corresponding ARIMA parameters.

These are rapidly computed but are not fully efficient estimates, particularly if moving-average parameters are present. They do provide useful **preliminary** values for an efficient but relatively slow iterative method of estimation. This is based on the least-squares principle by which parameters are chosen to minimize the sum of squares of the innovations  $a_t$ , which are regenerated from the data using ;(2) of , or the reverse of ;(3) of and ;(4) of in the case of seasonal models.

Lack of knowledge of terms on the right-hand side of ;(2) of , when  $t = 1, 2, \dots, \max(p, q)$ , is overcome by introducing  $q$  unknown series values  $w_0, w_1, \dots, w_{1-q}$  which are estimated as nuisance parameters, and using correction for transient errors due to the autoregressive terms. If the data  $w_1, w_2, \dots, w_N = w$  is viewed as a single sample from a multivariate Normal density whose covariance matrix  $V$  is a function of the ARIMA model parameters, then the exact likelihood of the parameters is

$$-\frac{1}{2} \log |V| - \frac{1}{2} w^T V^{-1} w.$$

The least-squares criterion as outlined above is equivalent to using the quadratic form

$$QF = w^T V^{-1} w$$

as an objective function to be minimized. Neglecting the term  $-\frac{1}{2} \log |V|$  yields estimates which differ very little from the exact likelihood except in small samples, or in seasonal models with a small number of

whole seasons contained in the data. In these cases bias in moving-average parameters may cause them to stick at the boundary of their constraint region, resulting in failure of the estimation method.

Approximate standard errors of the parameter estimates and the correlations between them are available after estimation.

The model residuals,  $\hat{a}_t$ , are the innovations resulting from the estimation and are usually examined for the presence of autocorrelation as a check on the adequacy of the model.

### 2.1.8 ARIMA model forecasting

An ARIMA model is particularly suited to extrapolation of a time series. The model equations are simply used for  $t = n + 1, n + 2, \dots$  replacing the unknown future values of  $a_t$  by zero. This produces future values of  $w_t$ , and if differencing has been used this process is reversed (the so-called integration part of ARIMA models) to construct future values of  $x_t$ .

Forecast error limits are easily deduced.

This process requires knowledge only of the model orders and parameters together with a limited set of the terms  $a_{t-i}, e_{t-i}, w_{t-i}, x_{t-i}$  which appear on the right-hand side of the models ;(3) of and ;(4) of (and the differencing equations) when  $t = n$ . It does not require knowledge of the whole series.

We call this the state set. It is conveniently constituted after model estimation. Moreover, if new observations  $x_{n+1}, x_{n+2}, \dots$  come to hand, then the model equations can easily be used to update the state set before constructing forecasts from the end of the new observations. This is particularly useful when forecasts are constructed on a regular basis. The new innovations  $a_{n+1}, a_{n+2}, \dots$  may be compared with the residual standard deviation,  $\sigma_a$ , of the model used for forecasting, as a check that the model is continuing to forecast adequately.

## 2.2 Univariate Spectral Analysis

In describing a time series using spectral analysis the fundamental components are taken to be sinusoidal waves of the form  $R \cos(\omega t + \phi)$ , which for a given angular frequency  $\omega$ ,  $0 \leq \omega \leq \pi$ , is specified by its amplitude  $R > 0$  and phase  $\phi$ ,  $0 \leq \phi < 2\pi$ . Thus in a time series of  $n$  observations it is not possible to distinguish more than  $n/2$  independent sinusoidal components. The frequency range  $0 \leq \omega \leq \pi$  is limited to a shortest wavelength of two sampling units because any wave of higher frequency is indistinguishable upon sampling (or is aliased with) a wave within this range. Spectral analysis follows the idea that for a series made up of a **finite** number of sine waves the amplitude of any component at frequency  $\omega$  is given to order  $1/n$  by

$$R^2 = \left( \frac{1}{n^2} \right) \left| \sum_{t=1}^n x_t e^{i\omega t} \right|^2.$$

### 2.2.1 The sample spectrum

For a series  $x_1, x_2, \dots, x_n$  this is defined as

$$f^*(\omega) = \left( \frac{1}{2n\pi} \right) \left| \sum_{t=1}^n x_t e^{i\omega t} \right|^2,$$

the scaling factor now being chosen in order that

$$2 \int_0^\pi f^*(\omega) d\omega = \sigma_x^2,$$

i.e., the spectrum indicates how the sample variance ( $\sigma_x^2$ ) of the series is distributed over components in the frequency range  $0 \leq \omega \leq \pi$ .

It may be demonstrated that  $f^*(\omega)$  is equivalently defined in terms of the sample autocorrelation function (acf)  $r_k$  of the series as

$$f^*(\omega) = \left(\frac{1}{2\pi}\right) \left(c_0 + 2 \sum_{k=1}^{n-1} c_k \cos k\omega\right),$$

where  $c_k = \sigma_x^2 r_k$  are the sample autocovariance coefficients.

If the series  $x_t$  does contain a **deterministic** sinusoidal component of amplitude  $R$ , this will be revealed in the sample spectrum as a sharp peak of approximate width  $\pi/n$  and height  $(n/2\pi)R^2$ . This is called the discrete part of the spectrum, the variance  $R^2$  associated with this component being in effect concentrated at a single frequency.

If the series  $x_t$  has no deterministic components, i.e., is purely **stochastic** being stationary with acf  $r_k$ , then with increasing sample size the expected value of  $f^*(\omega)$  converges to the theoretical spectrum – the **continuous** part

$$f(\omega) = \left(\frac{1}{2\pi}\right) \left(\gamma_0 + 2 \sum_{k=1}^{\infty} \gamma_k \cos(\omega k)\right),$$

where  $\gamma_k$  are the theoretical autocovariances.

The sample spectrum does **not** however converge to this value but at each frequency point fluctuates about the theoretical spectrum with an exponential distribution, being independent at frequencies separated by an interval of  $2\pi/n$  or more. Various devices are therefore employed to smooth the sample spectrum and reduce its variability. Much of the strength of spectral analysis derives from the fact that the error limits are multiplicative so that features may still show up as significant in a part of the spectrum which has a generally low level, whereas they are completely masked by other components in the original series. The spectrum can help to distinguish deterministic cyclical components from the stochastic quasi-cycle components which produce a broader peak in the spectrum. (The deterministic components can be removed by regression and the remaining part represented by an ARIMA model.)

A large discrete component in a spectrum can distort the continuous part over a large frequency range surrounding the corresponding peak. This may be alleviated at the cost of slightly broadening the peak by tapering a portion of the data at each end of the series with weights which decay smoothly to zero. It is usual to correct for the mean of the series and for any linear trend by simple regression, since they would similarly distort the spectrum.

### 2.2.2 Spectral smoothing by lag window

The estimate is calculated directly from the sample covariances  $c_k$  as

$$f(\omega) = \left(\frac{1}{2\pi}\right) \left(c_0 + 2 \sum_{k=1}^{M-1} w_k c_k \cos k\omega\right),$$

the smoothing being induced by the lag window weights  $w_k$  which extend up to a **truncation lag**  $M$  which is generally much less than  $n$ . The smaller the value of  $M$ , the greater the degree of smoothing, the spectrum estimates being independent only at a wider frequency separation indicated by the **bandwidth**  $b$  which is proportional to  $1/M$ . It is wise, however, to calculate the spectrum at intervals appreciably less than this. Although greater smoothing narrows the error limits, it can also distort the spectrum, particularly by flattening peaks and filling in troughs.

### 2.2.3 Direct spectral smoothing

The unsmoothed sample spectrum is calculated for a fine division of frequencies, then averaged over intervals centred on each frequency point for which the smoothed spectrum is required. This is usually at a coarser frequency division. The bandwidth corresponds to the width of the averaging interval.

## 2.3 Linear Lagged Relationships Between Time Series

We now consider the context in which one time series, called the dependent or output series  $y_1, y_2, \dots, y_n$ , is believed to depend on one or more explanatory or input series, e.g.,  $x_1, x_2, \dots, x_n$ . This dependency may follow a simple linear regression, e.g.,

$$y_t = vx_t + n_t$$

or more generally may involve lagged values of the input

$$y_t = v_0x_t + v_1x_{t-1} + v_2x_{t-2} + \cdots + n_t.$$

The sequence  $v_0, v_1, v_2, \dots$  is called the **impulse response function (IRF)** of the relationship. The term  $n_t$  represents that part of  $y_t$  which cannot be explained by the input, and it is assumed to follow a univariate ARIMA model. We call  $n_t$  the (output) noise component of  $y_t$ , and it includes any constant term in the relationship. It is assumed that the input series,  $x_t$ , and the noise component,  $n_t$ , are independent.

The part of  $y_t$  which is explained by the input is called the input component  $z_t$ :

$$z_t = v_0x_t + v_1x_{t-1} + v_2x_{t-2} + \cdots$$

so  $y_t = z_t + n_t$ .

The eventual aim is to model both these components of  $y_t$  on the basis of observations of  $y_1, y_2, \dots, y_n$  and  $x_1, x_2, \dots, x_n$ . In applications to forecasting or control both components are important. In general there may be more than one input series, e.g.,  $x_{1,t}$  and  $x_{2,t}$ , which are assumed to be independent and corresponding components  $z_{1,t}$  and  $z_{2,t}$ , so

$$y_t = z_{1,t} + z_{2,t} + n_t.$$

### 2.3.1 Transfer function models

In a similar manner to that in which the structure of a univariate series may be represented by a finite-parameter ARIMA model, the structure of an input component may be represented by a **transfer function (TF)** model with delay time  $b$ ,  $p$  autoregressive-like parameters  $\delta_1, \delta_2, \dots, \delta_p$  and  $q + 1$  moving-average-like parameters  $\omega_0, \omega_1, \dots, \omega_q$ :

$$z_t = \delta_1 z_{t-1} + \delta_2 z_{t-2} + \cdots + \delta_p z_{t-p} + \omega_0 x_{t-b} - \omega_1 x_{t-b-1} - \cdots - \omega_q x_{t-b-q}.$$

If  $p > 0$  this represents an IRF which is infinite in extent and decays with geometric and/or sinusoidal behaviour. The parameters  $\delta_1, \delta_2, \dots, \delta_p$  are constrained to satisfy a stability condition identical to the stationarity condition of autoregressive models. There is no constraint on  $\omega_0, \omega_1, \dots, \omega_q$ .

### 2.3.2 Cross-correlations

An important tool for investigating how an input series  $x_t$  affects an output series  $y_t$  is the sample **cross-correlation function (CCF)**  $r_{xy}(k)$ , for  $k = 0, 1, 2, \dots$  between the series. If  $x_t$  and  $y_t$  are (jointly) stationary time series this is an estimator of the theoretical quantity

$$\rho_{xy}(k) = \text{corr}(x_t, y_{t+k}).$$

The sequence  $r_{yx}(k)$ , for  $k = 0, 1, 2, \dots$ , is distinct from  $r_{xy}(k)$ , though it is possible to interpret

$$r_{yx}(k) = r_{xy}(-k).$$

When the series  $y_t$  and  $x_t$  are believed to be related by a transfer function model, the CCF is determined by the IRF  $v_0, v_1, v_2, \dots$  and the autocorrelation function of the input  $x_t$ .

In the **particular** case when  $x_t$  is an uncorrelated series or **white noise** (and is uncorrelated with any other inputs):

$$\rho_{xy}(k) \propto v_k$$

and the sample CCF can provide an estimate of  $v_k$ :

$$\tilde{v}_k = (s_y/s_x)r_{xy}(k)$$

where  $s_y$  and  $s_x$  are the sample standard deviations of  $y_t$  and  $x_t$ , respectively.

In theory the IRF coefficients  $v_b, \dots, v_{b+p+q}$  determine the parameters in the TF model, and using  $\tilde{v}_k$  to estimate  $\tilde{v}_k$  it is possible to solve for **preliminary** estimates of  $\delta_1, \delta_2, \dots, \delta_p, \omega_0, \omega_1, \dots, \omega_q$ .

### 2.3.3 Prewhitening or filtering by an ARIMA model

In general an input series  $x_t$  is not white noise, but may be represented by an ARIMA model with innovations or residuals  $a_t$  which are white noise. If precisely the same operations by which  $a_t$  is generated from  $x_t$  are applied to the output  $y_t$  to produce a series  $b_t$ , then the transfer function relationship between  $y_t$  and  $x_t$  is preserved between  $b_t$  and  $a_t$ . It is then possible to estimate

$$\tilde{v}_k = (s_b/s_a)r_{ab}(k).$$

The procedure of generating  $a_t$  from  $x_t$  (and  $b_t$  from  $y_t$ ) is called prewhitening or filtering by an ARIMA model. Although  $a_t$  is necessarily white noise, this is not generally true of  $b_t$ .

### 2.3.4 Multi-input model estimation

The term multi-input model is used for the situation when one output series  $y_t$  is related to one or more input series  $x_{j,t}$ , as described in Section 2.3. If for a given input the relationship is a simple linear regression, it is called a simple input; otherwise it is a transfer function input. The error or noise term follows an ARIMA model.

Given that the orders of all the transfer function models and the ARIMA model of a multi-input model have been specified, the various parameters in those models may be (simultaneously) estimated.

The procedure used is closely related to the least-squares principle applied to the innovations in the ARIMA noise model.

The innovations are derived for any proposed set of parameter values by calculating the response of each input to the transfer functions and then evaluating the noise  $n_t$  as the difference between this response (combined for all the inputs) and the output. The innovations are derived from the noise using the ARIMA model in the same manner as for a univariate series, and as described in Section 2.1.5.

In estimating the parameters, consideration has to be given to the lagged terms in the various model equations which are associated with times prior to the observation period, and are therefore unknown. The subroutine descriptions provide the necessary detail as to how this problem is treated.

Also, as described in Section 2.1.6 the sum of squares criterion

$$S = \sum a_t^2$$

is related to the quadratic form in the exact log-likelihood of the parameters:

$$-\frac{1}{2} \log |V| - \frac{1}{2} w^T V^{-1} w.$$

Here  $w$  is the vector of appropriately differenced noise terms, and

$$w^T V^{-1} w = S/\sigma_a^2,$$

where  $\sigma_a^2$  is the innovation variance parameter.

The least-squares criterion is therefore identical to minimization of the quadratic form, but is not identical to exact likelihood. Because  $V$  may be expressed as  $M\sigma_a^2$ , where  $M$  is a function of the ARIMA model parameters, substitution of  $\sigma_a^2$  by its maximum likelihood estimator yields a concentrated (or profile) likelihood which is a function of

$$|M|^{1/N} S.$$

$N$  is the length of the differenced noise series  $w$ , and  $|M| = \det M$ .

Use of the above quantity, called the deviance,  $D$ , as an objective function is preferable to the use of  $S$  alone, on the grounds that it is equivalent to exact likelihood, and yields estimates with better properties. However, there is an appreciable computational penalty in calculating  $D$ , and in large samples it differs very little from  $S$ , except in the important case of seasonal ARIMA models where the number of whole seasons within the data length must also be large.

The user is given the option of taking the objective function to be either  $S$  or  $D$ , or a third possibility, the marginal likelihood. This is similar to exact likelihood but can counteract bias in the ARIMA model due to the fitting of a large number of simple inputs.

Approximate standard errors of the parameter estimates and the correlations between them are available after estimation.

The model residuals  $\hat{a}_t$  are the innovations resulting from the estimation, and they are usually examined for the presence of either autocorrelation or cross-correlation with the inputs. Absence of such correlation provides some confirmation of the adequacy of the model.

### 2.3.5 Multi-input model forecasting

A multi-input model may be used to forecast the output series provided future values (possibly forecasts) of the input series are supplied.

Construction of the forecasts requires knowledge only of the model orders and parameters, together with a limited set of the most recent variables which appear in the model equations. This is called the state set. It is conveniently constituted after model estimation. Moreover, if new observations  $y_{n+1}, y_{n+2}, \dots$  of the output series and  $x_{n+1}, x_{n+2}, \dots$  of (all) the independent input series become available, then the model equations can easily be used to update the state set before constructing forecasts from the end of the new observations. The new innovations  $a_{n+1}, a_{n+2}, \dots$  generated in this updating may be used to monitor the continuing adequacy of the model.

### 2.3.6 Transfer function model filtering

In many time series applications it is desired to calculate the response (or output) of a transfer function model for a given input series.

Smoothing, detrending, and seasonal adjustment are typical applications. The user must specify the orders and parameters of a transfer function model for the purpose being considered. This may then be applied to the input series.

Again, problems may arise due to ignorance of the input series values prior to the observation period. The transient errors which can arise from this cause may be substantially reduced by using ‘backforecasts’ of these unknown observations.

## 2.4 Multivariate Time Series

Multi-input modelling represents one output time series in terms of one or more input series. Although there are circumstances in which it may be more appropriate to analyse a set of time series by modelling each one in turn as the output series with the remainder as inputs, there is a more symmetric approach in such a context. These models are known as vector autoregressive moving-average (VARMA) models.

### 2.4.1 Differencing and transforming a multivariate time series

As in the case of a univariate time series, it may be useful to simplify the series by differencing operations which may be used to remove linear or seasonal trend, thus ensuring that the resulting series to be used in the model estimation is stationary. It may also be necessary to apply transformations to the individual components of the multivariate series in order to stabilize the variance. Commonly used transformations are the log and square root transformations.

### 2.4.2 Model identification for a multivariate time series

Multivariate analogues of the autocorrelation and partial autocorrelation functions are available for analysing a set of  $k$  time series,  $x_{i,1}, x_{i,2}, \dots, x_{i,n}$ , for  $i = 1, 2, \dots, k$ , thereby making it possible to obtain some understanding of a suitable VARMA model for the observed series.

It is assumed that the time series have been differenced if necessary, and that they are jointly stationary. The lagged correlations between all possible pairs of series, i.e.,

$$\rho_{ijl} = \text{corr}(x_{i,t}, x_{j,t+l})$$

are then taken to provide an adequate description of the statistical relationships between the series. These quantities are estimated by sample auto- and cross-correlations  $r_{ijl}$ . For each  $l$  these may be viewed as elements of a (lagged) autocorrelation matrix.

Thus consider the **vector process**  $x_t$  (with elements  $x_{it}$ ) and lagged autocovariance matrices  $\Gamma_l$  with elements of  $\sigma_i\sigma_j\rho_{ijl}$  where  $\sigma_i^2 = \text{var}(x_{i,t})$ . Correspondingly,  $\Gamma_l$  is estimated by the matrix  $C_l$  with elements  $s_i s_j r_{ijl}$  where  $s_i^2$  is the sample variance of  $x_{it}$ .

For a series with short-term cross-correlation only, i.e.,  $r_{ijl}$  is not significant beyond some low lag  $q$ , then the pure vector MA( $q$ ) model, with no autoregressive parameters, i.e.,  $p = 0$ , is appropriate.

The correlation matrices provide a description of the joint statistical properties of the series. It is also possible to calculate matrix quantities which are closely analogous to the partial autocorrelations of univariate series (see Section 2.1.3). Wei (1990) discusses both the partial autoregression matrices proposed by Tiao and Box (1981) and partial lag correlation matrices.

In the univariate case the partial autocorrelation function (pacf) between  $x_t$  and  $x_{t+l}$  is the correlation coefficient between the two after removing the linear dependence on each of the intervening variables  $x_{t+1}, x_{t+2}, \dots, x_{t+l-1}$ . This partial autocorrelation may also be obtained as the last regression coefficient associated with  $x_t$  when regressing  $x_{t+l}$  on its  $l$  lagged variables  $x_{t+l-1}, x_{t+l-2}, \dots, x_t$ . Tiao and Box (1981) extended this method to the multivariate case to define the partial autoregression matrix. Heyse and Wei (1985) also extended the univariate definition of the pacf to derive the correlation matrix between the vectors  $x_t$  and  $x_{t+l}$  after removing the linear dependence on each of the intervening vectors  $x_{t+1}, x_{t+2}, \dots, x_{t+l-1}$ , the partial lag correlation matrix.

Note that the partial lag correlation matrix is a correlation coefficient matrix since each of its elements is a properly normalised correlation coefficient. This is not true of the partial autoregression matrices (except in the univariate case for which the two types of matrix are the same). The partial lag correlation matrix at lag 1 also reduces to the regular correlation matrix at lag 1; this is not true of the partial autoregression matrices (again except in the univariate case).

Both the above share the same cut-off property for autoregressive processes; that is for an autoregressive process of order  $p$ , the terms of the matrix at lags  $p + 1$  and greater are zero. Thus if the sample partial cross-correlations are significant only up to some low lag  $p$  then a pure vector AR( $p$ ) model is appropriate with  $q = 0$ . Otherwise moving-average terms will need to be introduced as well as autoregressive terms.

Under the hypothesis that  $x_t$  is an autoregressive process of order  $l - 1$ ,  $n$  times the sum of the squared elements of the partial lag correlation matrix at lag  $l$  is asymptotically distributed as a  $\chi^2$  variable with  $k^2$  degrees of freedom where  $k$  is the dimension of the multivariate time series. This provides a diagnostic aid for determining the order of an autoregressive model.

The partial autoregression matrices may be found by solving a multivariate version of the Yule–Walker equations to find the autoregression matrices, using the final regression matrix coefficient as the partial autoregression matrix at that particular lag.

The basis of these calculations is a multivariate autoregressive model:

$$x_t = \phi_{l,1}x_{t-1} + \dots + \phi_{l,l}x_{t-l} + e_{l,t}$$

where  $\phi_{l,1}, \phi_{l,2}, \dots, \phi_{l,l}$  are **matrix coefficients**, and  $e_{l,t}$  is the vector of errors in the prediction. These coefficients may be rapidly computed using a recursive technique which requires, and simultaneously furnishes, a backward prediction equation:

$$x_{t-l-1} = \psi_{l,1}x_{t-l} + \psi_{l,2}x_{t-l+1} + \dots + \psi_{l,l}x_{t-1} + f_{l,t}$$

(in the univariate case  $\psi_{l,i} = \phi_{l,i}$ ).

The forward prediction equation coefficients,  $\phi_{l,i}$ , are of direct interest, together with the covariance matrix  $D_l$  of the prediction errors  $e_{l,t}$ . The calculation of these quantities for a particular maximum equation lag  $l = L$  involves calculation of the same quantities for increasing values of  $l = 1, 2, \dots, L$ .

The quantities  $v_l = \det D_l / \det \Gamma_0$  may be viewed as generalized variance ratios, and provide a measure of the efficiency of prediction (the smaller the better). The reduction from  $v_{l-1}$  to  $v_l$  which occurs on extending the order of the predictor to  $l$  may be represented as

$$v_l = v_{l-1}(1 - \rho_l^2)$$

where  $\rho_l^2$  is a multiple squared partial autocorrelation coefficient associated with  $k^2$  degrees of freedom.

Sample estimates of all the above quantities may be derived by using the series covariance matrices  $C_l$ , for  $l = 1, 2, \dots, L$ , in place of  $\Gamma_l$ . The best lag for prediction purposes may be chosen as that which yields the minimum final prediction error (FPE) criterion:

$$\text{FPE}(l) = v_l \times \frac{(1 + lk^2/n)}{(1 - lk^2/n)}.$$

An alternative method of estimating the sample partial autoregression matrices is by using multivariate least-squares to fit a series of multivariate autoregressive models of increasing order.

### 2.4.3 VARMA model estimation

The cross-correlation structure of a stationary multivariate time series may often be represented by a model with a small number of parameters belonging to the vector autoregressive moving-average (VARMA) class. If the stationary series  $w_t$  has been derived by transforming and/or differencing the original series  $x_t$ , then  $w_t$  is said to follow the VARMA model:

$$w_t = \phi_1 w_{t-1} + \dots + \phi_p w_{t-p} + \epsilon_t - \theta_1 \epsilon_{t-1} - \dots - \theta_q \epsilon_{t-q},$$

where  $\epsilon_t$  is a vector of uncorrelated residual series (white noise) with zero mean and constant covariance matrix  $\Sigma$ ,  $\phi_1, \phi_2, \dots, \phi_p$  are the  $p$  autoregressive (AR) **parameter matrices** and  $\theta_1, \theta_2, \dots, \theta_q$  are the  $q$  moving-average (MA) **parameter matrices**. If  $w_t$  has a non-zero mean  $\mu$ , then this can be allowed for by replacing  $w_t, w_{t-1}, \dots$  by  $w_t - \mu, w_{t-1} - \mu, \dots$  in the model.

A series generated by this model will only be stationary provided restrictions are placed on  $\phi_1, \phi_2, \dots, \phi_p$  to avoid unstable growth of  $w_t$ . These are **stationarity** constraints. The series  $\epsilon_t$  may also be usefully interpreted as the linear **innovations** in  $w_t$ , i.e., the error if  $w_t$  were to be predicted using the information in all past values  $w_{t-1}, w_{t-2}, \dots$ , provided also that  $\theta_1, \theta_2, \dots, \theta_q$  satisfy what are known as **invertibility** constraints. This allows the series  $\epsilon_t$  to be generated by rewriting the model equation as

$$\epsilon_t = w_t - \phi_1 w_{t-1} - \dots - \phi_p w_{t-p} + \theta_1 \epsilon_{t-1} + \dots + \theta_q \epsilon_{t-q}.$$

The method of maximum likelihood may be used to estimate the parameters of a specified VARMA model from the observed multivariate time series together with their standard errors and correlations.

The residuals from the model may be examined for the presence of autocorrelations as a check on the adequacy of the fitted model.

### 2.4.4 VARMA model forecasting

Forecasts of the series may be constructed using a multivariate version of the univariate method. Efficient methods are available for updating the forecasts each time new observations become available.

## 2.5 Cross-spectral Analysis

The relationship between two time series may be investigated in terms of their sinusoidal components at different frequencies. At frequency  $\omega$  a component of  $y_t$  of the form

$$R_y(\omega) \cos(\omega t - \phi_y(\omega))$$

has its amplitude  $R_y(\omega)$  and phase lag  $\phi_y(\omega)$  estimated by

$$R_y(\omega) e^{i\phi_y(\omega)} = \frac{1}{n} \sum_{t=1}^n y_t e^{i\omega t}$$

and similarly for  $x_t$ . In the univariate analysis only the amplitude was important – in the cross analysis the phase is important.

### 2.5.1 The sample cross-spectrum

This is defined by

$$f_{xy}^*(\omega) = \frac{1}{2\pi n} \left( \sum_{t=1}^n y_t e^{i\omega t} \right) \left( \sum_{t=1}^n x_t e^{-i\omega t} \right).$$

It may be demonstrated that this is equivalently defined in terms of the sample CCF,  $r_{xy}(k)$ , of the series as

$$f_{xy}^*(\omega) = \frac{1}{2\pi} \sum_{-(n-1)}^{(n-1)} c_{xy}(k) e^{i\omega k}$$

where  $c_{xy}(k) = s_x s_y r_{xy}(k)$  is the cross-covariance function.

### 2.5.2 The amplitude and phase spectrum

The cross-spectrum is specified by its real part or cospectrum  $cf^*(\omega)$  and imaginary part or quadrature spectrum  $qf^*(\omega)$ , but for the purpose of interpretation the cross-amplitude spectrum and phase spectrum are useful:

$$A^*(\omega) = |f_{xy}^*(\omega)|, \quad \phi^*(\omega) = \arg(f_{xy}^*(\omega)).$$

If the series  $x_t$  and  $y_t$  contain deterministic sinusoidal components of amplitudes  $R_y, R_x$  and phases  $\phi_y, \phi_x$  at frequency  $\omega$ , then  $A^*(\omega)$  will have a peak of approximate width  $\pi/n$  and height  $(n/2\pi)R_y R_x$  at that frequency, with corresponding phase  $\phi^*(\omega) = \phi_y - \phi_x$ . This supplies no information that cannot be obtained from the two series separately. The statistical relationship between the series is better revealed when the series are purely stochastic and jointly stationary, in which case the expected value of  $f_{xy}^*(\omega)$  converges with increasing sample size to the theoretical cross-spectrum

$$f_{xy}(\omega) = \frac{1}{2\pi} \sum_{-\infty}^{\infty} \gamma_{xy}(k) e^{i\omega k}$$

where  $\gamma_{xy}(k) = \text{cov}(x_t, y_{t+k})$ . The sample spectrum, as in the univariate case, does not, however, converge to the theoretical spectrum without some form of smoothing which either implicitly (using a lag window) or explicitly (using a frequency window) averages the sample spectrum  $\hat{f}_{xy}^*(\omega)$  over wider bands of frequency to obtain a smoothed estimate  $\hat{f}_{xy}(\omega)$ .

### 2.5.3 The coherency spectrum

If there is no statistical relationship between the series at a given frequency, then  $f_{xy}(\omega) = 0$ , and the smoothed estimate  $\hat{f}_{xy}(\omega)$ , will be close to 0. This is assessed by the squared coherency between the series:

$$\hat{W}(\omega) = \frac{|\hat{f}_{xy}(\omega)|^2}{\hat{f}_{xx}(\omega)\hat{f}_{yy}(\omega)}$$

where  $\hat{f}_{xx}(\omega)$  is the corresponding smoothed univariate spectrum estimate for  $x_t$ , and similarly for  $y_t$ . The coherency can be treated as a squared multiple correlation. It is similarly invariant in theory not only to simple scaling of  $x_t$  and  $y_t$ , but also to filtering of the two series, and provides a useful test statistic for the relationship between autocorrelated series. Note that without smoothing,

$$|f_{xy}^*(\omega)|^2 = f_{xx}^*(\omega) f_{yy}^*(\omega),$$

so the coherency is 1 at all frequencies, just as a correlation is 1 for a sample of size 1. Thus smoothing is essential for cross-spectrum analysis.

### 2.5.4 The gain and noise spectrum

If  $y_t$  is believed to be related to  $x_t$  by a linear lagged relationship as in Section 2.3, i.e.,

$$y_t = v_0 x_t + v_1 x_{t-1} + v_2 x_{t-2} + \cdots + n_t,$$

then the theoretical cross-spectrum is

$$f_{xy}(\omega) = V(\omega) f_{xx}(\omega)$$

where

$$V(\omega) = G(\omega)e^{i\phi(\omega)} = \sum_{k=0}^{\infty} v_k e^{ik\omega}$$

is called the frequency response of the relationship.

Thus if  $x_t$  were a sinusoidal wave at frequency  $\omega$  (and  $n_t$  were absent),  $y_t$  would be similar but multiplied in amplitude by  $G(\omega)$  and shifted in phase by  $\phi(\omega)$ . Furthermore, the theoretical univariate spectrum

$$f_{yy}(\omega) = G(\omega)^2 f_{xx}(\omega) + f_n(\omega)$$

where  $n_t$ , with spectrum  $f_n(\omega)$ , is assumed independent of the input  $x_t$ .

Cross-spectral analysis thus furnishes estimates of the gain

$$\hat{G}(\omega) = |\hat{f}_{xy}(\omega)| / \hat{f}_{xx}(\omega)$$

and the phase

$$\hat{\phi}(\omega) = \arg\left(\hat{f}_{xy}(\omega)\right).$$

From these representations of the estimated frequency response  $\hat{V}(\omega)$ , parametric TF models may be recognised and selected. The noise spectrum may also be estimated as

$$\hat{f}_{y|x}(\omega) = \hat{f}_{yy}(\omega)(1 - \hat{W}(\omega))$$

– a formula which reflects the fact that in essence a regression is being performed of the sinusoidal components of  $y_t$  on those of  $x_t$  over each frequency band.

Interpretation of the frequency response may be aided by extracting from  $\hat{V}(\omega)$  estimates of the IRF  $\hat{v}_k$ . It is assumed that there is no anticipatory response between  $y_t$  and  $x_t$ , i.e., no coefficients  $v_k$  with  $k = -1, -2$  are needed (their presence might indicate feedback between the series).

### 2.5.5 Cross-spectrum smoothing by lag window

The estimate of the cross-spectrum is calculated from the sample cross-variances as

$$\hat{f}_{xy}(\omega) = \frac{1}{2\pi} \sum_{-M+S}^{M+S} w_{k-S} c_{xy}(k) e^{i\omega k}.$$

The lag window  $w_k$  extends up to a truncation lag  $M$  as in the univariate case, but its centre is shifted by an alignment lag  $S$  usually chosen to coincide with the peak cross-correlation. This is equivalent to an alignment of the series for peak cross-correlation at lag 0, and reduces bias in the phase estimation.

The selection of the truncation lag  $M$ , which fixes the bandwidth of the estimate, is based on the same criteria as for univariate series, and the same choice of  $M$  and window shape should be used as in univariate spectrum estimation to obtain valid estimates of the coherency, gain etc., and test statistics.

### 2.5.6 Direct smoothing of the cross-spectrum

The computations are exactly as for smoothing of the univariate spectrum except that allowance is made for an implicit alignment shift  $S$  between the series.

## 2.6 Kalman Filters

Kalman filtering provides a method for the analysis of multi-dimensional time series. The underlying model is:

$$X_{t+1} = A_t X_t + B_t W_t$$

$$Y_t = C_t X_t + V_t$$

where  $X_t$  is the unobserved state vector,  $Y_t$  is the observed measurement vector,  $W_t$  is the state noise,  $V_t$  is the measurement noise,  $A_t$  is the state transition matrix,  $B_t$  is the noise coefficient matrix and  $C_t$  is the

measurement coefficient matrix at time  $t$ . The state noise and the measurement noise are assumed to be uncorrelated with zero mean and covariance matrices:

$$E\{W_t W_t^T\} = Q_t \text{ and } E\{V_t V_t^T\} = R_t.$$

If the system matrices  $A_t$ ,  $B_t$ ,  $C_t$  and the covariance matrices  $Q_t$ ,  $R_t$  are known then Kalman filtering can be used to compute the minimum variance estimate of the stochastic variable  $X_t$ .

The estimate of  $X_t$  given observations  $Y_1$  to  $Y_{t-1}$  is denoted by  $\hat{X}_{t|t-1}$  with state covariance matrix  $E\{\hat{X}_{t|t-1} \hat{X}_{t|t-1}^T\} = P_{t|t-1}$  while the estimate of  $X_t$  given observations  $Y_1$  to  $Y_t$  is denoted by  $\hat{X}_{t|t}$  with covariance matrix  $E\{\hat{X}_{t|t} \hat{X}_{t|t}^T\} = P_{t|t}$ .

The update of the estimate,  $\hat{X}_{t+1|t}$ , from time  $t$  to time  $t+1$ , is computed in two stages.

First, the update equations are

$$\hat{X}_{t|t} = \hat{X}_{t|t-1} + K_t r_t, \quad P_{t|t} = (I - K_t C_t) P_{t|t-1}$$

where the residual  $r_t = Y_t - C_t X_{t|t-1}$  has an associated covariance matrix  $H_t = C_t P_{t|t-1} C_t^T + R_t$ , and  $K_t$  is the Kalman gain matrix with

$$K_t = P_{t|t-1} C_t^T H_t^{-1}.$$

The second stage is the one-step-ahead prediction equations given by

$$\hat{X}_{t+1|t} = A_t \hat{X}_{t|t}, \quad P_{t+1|t} = A_t P_{t|t} A_t^T + B_t Q_t B_t^T.$$

These two stages can be combined to give the one-step-ahead update-prediction equations

$$\hat{X}_{t+1|t} = A_t \hat{X}_{t|t-1} + A_t K_t r_t.$$

The above equations thus provide a method for recursively calculating the estimates of the state vectors  $\hat{X}_{t|t}$  and  $\hat{X}_{t+1|t}$  and their covariance matrices  $P_{t|t}$  and  $P_{t+1|t}$  from their previous values. This recursive procedure can be viewed in a Bayesian framework as being the updating of the prior by the data  $Y_t$ .

The initial values  $\hat{X}_{1|0}$  and  $P_{1|0}$  are required to start the recursion. For stationary systems,  $P_{1|0}$  can be computed from the following equation:

$$P_{1|0} = A_1 P_{1|0} A_1^T + B_1 Q_1 B_1^T,$$

which can be solved by iterating on the equation. For  $\hat{X}_{1|0}$  the value  $E\{X\}$  can be used if it is available.

### 2.6.1 Computational methods

To improve the stability of the computations the square root algorithm is used. One recursion of the square root covariance filter algorithm which can be summarized as follows:

$$\begin{pmatrix} R_t^{1/2} & C_t S_t & 0 \\ 0 & A_t S_t & B_t Q_t^{1/2} \end{pmatrix} U = \begin{pmatrix} H_t^{1/2} & 0 & 0 \\ G_t & S_{t+1} & 0 \end{pmatrix}$$

where  $U$  is an orthogonal transformation triangularizing the left-hand pre-array to produce the right-hand post-array,  $S_t$  is the lower triangular Cholesky factor of the state covariance matrix  $P_{t+1|t}$ ,  $Q_t^{1/2}$  and  $R_t^{1/2}$  are the lower triangular Cholesky factor of the covariance matrices  $Q$  and  $R$  and  $H_t^{1/2}$  is the lower triangular Cholesky factor of the covariance matrix of the residuals. The relationship between the Kalman gain matrix,  $K_t$ , and  $G_t$  is given by

$$A_t K_t = G_t \left( H_t^{1/2} \right)^{-1}.$$

To improve the efficiency of the computations when the matrices  $A_t$ ,  $B_t$  and  $C_t$  do not vary with time the system can be transformed to give a simpler structure. The transformed state vector is  $U^* X$  where  $U^*$  is the transformation that reduces the matrix pair  $(A, C)$  to lower observer Hessenberg form. That is, the matrix  $U^*$  is computed such that the compound matrix

$$\begin{pmatrix} CU^{*T} \\ U^*AU^{*T} \end{pmatrix}$$

is a lower trapezoidal matrix. The transformations need only be computed once at the start of a series, and the covariance matrices  $Q_t$  and  $R_t$  can still be time-varying.

## 2.6.2 Model fitting and forecasting

If the state space model contains unknown parameters,  $\theta$ , these can be estimated using maximum likelihood. Assuming that  $W_t$  and  $V_t$  are normal variates the log-likelihood for observations  $Y_t, t = 1, 2, \dots, n$  is given by

$$\text{constant} - \frac{1}{2} \sum_{t=1}^n \ln(\det(H_t)) - \frac{1}{2} \sum_{t=1}^n r_t^T H_t^{-1} r_t.$$

Optimal estimates for the unknown model parameters  $\theta$  can then be obtained by using a suitable optimizer routine to maximize the likelihood function.

Once the model has been fitted forecasting can be performed by using the one-step-ahead prediction equations. The one-step-ahead prediction equations can also be used to ‘jump over’ any missing values in the series.

## 2.6.3 Kalman filter and time series models

Many commonly used time series models can be written as state space models. A univariate ARMA( $p, q$ ) model can be cast into the following state space form:

$$\begin{aligned} x_t &= Ax_{t-1} + B\epsilon_t \\ w_t &= Cx_t \end{aligned}$$

where  $r = \max(p, q + 1)$ , the first element of the state vector  $x_t$  is  $w_t$ ,

$$A = \begin{pmatrix} \phi_1 & 1 & & & \\ \phi_2 & & 1 & & \\ \cdot & & & \cdot & \\ \cdot & & & & \cdot \\ \phi_{r-1} & & & & 1 \\ \phi_r & 0 & 0 & \cdot & \cdot & 0 \end{pmatrix}, B = \begin{pmatrix} 1 \\ -\theta_1 \\ -\theta_2 \\ \cdot \\ \cdot \\ -\theta_{r-1} \end{pmatrix} \text{ and } C^T = \begin{pmatrix} 1 \\ 0 \\ 0 \\ \cdot \\ \cdot \\ 0 \end{pmatrix}.$$

The representation for a  $k$ -variate ARMA( $p, q$ ) series (VARMA) is very similar to that given above, except now the state vector is of length  $kr$  and the  $\phi$  and  $\theta$  are now  $k \times k$  matrices and the 1s in  $A$ ,  $B$  and  $C$  are now the identity matrix of order  $k$ . If  $p < r$  or  $q + 1 < r$  then the appropriate  $\phi$  or  $\theta$  matrices are set to zero, respectively.

Since the compound matrix

$$\begin{pmatrix} C \\ A \end{pmatrix}$$

is already in lower observer Hessenberg form (i.e., it is lower trapezoidal with zeros in the top right-hand triangle) the invariant Kalman filter algorithm can be used directly without the need to generate a transformation matrix  $U^*$ .

## 2.7 GARCH Models

### 2.7.1 ARCH models and their generalisations

Rather than modelling the mean (for example using regression models) or the autocorrelation (by using ARMA models) there are circumstances in which the variance of a time series needs to be modelled. This is common in financial data modelling where the variance (or standard deviation) is known as volatility. The ability to forecast volatility is a vital part in deciding the risk attached to financial decisions like portfolio selection. The basic model for relating the variance at time  $t$  to the variance at previous times is

the autoregressive conditional heteroskedastic (ARCH) model. The standard ARCH model is defined as

$$y_t | \psi_{t-1} \sim N(0, h_t),$$

$$h_t = \alpha_0 + \sum_{i=1}^q \alpha_i \epsilon_{t-1}^2,$$

where  $\psi_t$  is the information up to time  $t$  and  $h_t$  is the conditional variance.

In a similar way to that in which autoregressive models were generalised to ARMA models the ARCH models have been generalised to a GARCH model; see Engle (1982), Bollerslev (1986) and Hamilton (1994).

$$h_t = \alpha_0 + \sum_{i=1}^q \alpha_i \epsilon_{t-1}^2 + \sum_{j=1}^p \beta_j h_{t-j}.$$

This can be combined with a regression model:

$$y_t = b_0 + \sum_{i=1}^k b_i x_{it} + \epsilon_t,$$

where  $\epsilon_t | \psi_{t-1} \sim N(0, h_t)$  and where  $x_{it}$ , for  $i = 1, \dots, k$  are the exogenous variables.

The above models assume that the change in variance,  $h_t$ , is symmetric with respect to the shocks, that is, that a large negative value of  $\epsilon_{t-1}$  has the same effect as a large positive value of  $\epsilon_{t-1}$ . A frequently observed effect is that a large negative value  $\epsilon_{t-1}$  often leads to a greater variance than a large positive value. The following three asymmetric models represent this effect in different ways using the parameter  $\lambda$  as a measure of the asymmetry.

Type I AGARCH( $p, q$ )

$$h_t = \alpha_0 + \sum_{i=1}^q \alpha_i (\epsilon_{t-i} + \gamma)^2 + \sum_{j=1}^p \beta_j h_{t-j}.$$

Type II AGARCH( $p, q$ )

$$h_t = \alpha_0 + \sum_{i=1}^q \alpha_i (|\epsilon_{t-i}| + \gamma \epsilon_{t-i})^2 + \sum_{j=1}^p \beta_j h_{t-j}.$$

GJR-GARCH( $p, q$ ), or Glosten, Jagannathan and Runkle GARCH (Glosten *et al.* (1993))

$$h_t = \alpha_0 + \sum_{i=1}^q (\alpha_i + \gamma S_{t-1}) \epsilon_{t-1}^2 + \sum_{j=1}^p \beta_j h_{t-j},$$

where  $S_t = 1$  if  $\epsilon_t < 0$  and  $S_t = 0$  if  $\epsilon_t \geq 0$ .

The first assumes that the effects of the shocks are symmetric about  $\gamma$  rather than zero, so that for  $\gamma < 0$  the effect of negative shocks is increased and the effect of positive shocks is decreased. Both the Type II AGARCH and the GJR GARCH (Glosten *et al.* (1993)) models introduce asymmetry by increasing the value of the coefficient of  $\epsilon_{t-1}^2$  for negative values of  $\epsilon_{t-1}$ . In the case of the Type II AGARCH the effect is multiplicative while for the GJR GARCH the effect is additive.

Coefficient	$\epsilon_{t-1} < 0$	$\epsilon_{t-1} > 0$
Type II AGARCH	$\alpha_i(1 - \gamma)^2$	$\alpha_i(1 + \gamma)^2$
GJR GARCH	$\alpha_i + \gamma$	$\alpha_i$

(Note that in the case of GJR GARCH,  $\gamma$  needs to be positive to inflate variance after negative shocks while for Type I and Type II AGARCH,  $\gamma$  needs to be negative.)

A third type of GARCH model is the exponential GARCH (EGARCH). In this model the variance relationship is on the log scale and hence asymmetric.

$$\ln(h_t) = \alpha_0 + \sum_{i=1}^q \alpha_i z_{t-i} + \sum_{i=1}^q \phi_i (|z_{t-i}| - E[|z_{t-i}|]) + \sum_{j=1}^p \beta_j \ln(h_{t-j}),$$

where  $z_t = \frac{\epsilon_t}{\sqrt{h_t}}$  and  $E[|z_{t-i}|]$  denotes the expected value of  $|z_{t-i}|$ .

Note that the  $\phi_i$  terms represent a symmetric contribution to the variance while the  $\alpha_i$  terms give an asymmetric contribution.

Another common characteristic of financial data is that it is heavier in the tails (leptokurtic) than the Normal distribution. To model this the Normal distribution is replaced by a scaled Student's  $t$ -distribution (that is a Student's  $t$ -distribution standardised to have variance  $h_t$ ). The Student's  $t$ -distribution is such that the smaller the degrees of freedom the higher the kurtosis for degrees of freedom  $> 4$ .

### 2.7.2 Fitting GARCH models

The models are fitted by maximising the conditional log-likelihood. For the Normal distribution the conditional log-likelihood is

$$\frac{1}{2} \sum_{i=1}^T \left( \log(h_i) + \frac{\epsilon_i^2}{h_i} \right).$$

For the Student's  $t$ -distribution the function is more complex. An approximation to the standard errors of the parameter estimates is computed from the Fisher information matrix.

## 3 Recommendations on Choice and Use of Available Routines

**Note:** refer to the Users' Note for your implementation to check that a routine is available.

### 3.1 ARMA-type Models

ARMA-type modelling usually follows the methodology made popular by Box and Jenkins. It consists of four steps: identification, model fitting, model checking and forecasting. The availability of routines for each of these four steps is given below for the three types of modelling situation considered: univariate, input-output and multivariate.

#### 3.1.1 Univariate series

##### (a) Model identification

The routine G13AUF may be used in obtaining either a range–mean or standard deviation–mean plot for a series of observations, which may be useful in detecting the need for a variance-stabilising transformation. G13AUF computes the range or standard deviation and the mean for successive groups of observations and G01AGF may then be used to produce a scatter plot of range against mean or of standard deviation against mean.

The routine G13AAF may be used to difference a time series. The  $N = n - d - s \times D$  values of the differenced time series which extends for  $t = 1 + d + s \times D, \dots, n$  are stored in the first  $N$  elements of the output array.

The routine G13ABF may be used for direct computation of the autocorrelations. It requires the time series as input, after optional differencing by G13AAF.

An alternative is to use G13CAF, which uses the FFT to carry out the convolution for computing the autocovariances. Circumstances in which this is recommended are

- (i) if the main aim is to calculate the smoothed sample spectrum,
- (ii) if the series length and maximum lag for the autocorrelations are both very large, in which case appreciable computing time may be saved.

For more precise recommendations, see Gentleman and Sande (1966). In this case the autocorrelations  $r_k$  need to be obtained from the autocovariances  $c_k$  by  $r_k = c_k/c_0$ .

The routine G13ACF computes the partial autocorrelation function and prediction error variance estimates from an input autocorrelation function. Note that G13DNF, which is designed for multivariate time series, may also be used to compute the partial autocorrelation function together with  $\chi^2$  statistics and their significance levels.

Finite lag predictor coefficients are also computed by the routine G13ACF. It may have to be used twice, firstly with a large value for the maximum lag  $L$  in order to locate the optimum FPE lag, then again with  $L$  reset to this lag.

The routine G13DXF may be used to check that the autoregressive part of the model is stationary and that the moving-average part is invertible.

(b) Model estimation

The routine G13ADF is used to compute preliminary estimates of the ARIMA model parameters, the sample autocorrelations of the appropriately differenced series being input. The model orders are required.

The main routine for parameter estimation for ARIMA models is G13AEF, and an easy-to-use version is G13AFF. Both these routines use the least-squares criterion of estimation.

In some circumstances the use of G13BEF or G13DCF, which use maximum likelihood, is recommended.

The routines require the time series values to be input, together with the ARIMA orders. Any differencing implied by the model is carried out internally. They also require the maximum number of iterations to be specified, and return the state set for use in forecasting.

G13AEF should be preferred to G13AFF for:

- (i) more information about the differenced series, its backforecasts and the intermediate series;
- (ii) greater control over the output at successive iterations;
- (iii) more detailed control over the search policy of the non-linear least-squares algorithm;
- (iv) more information about the first and second derivatives of the objective function during and upon completion of the iterations.

G13BEF is primarily designed for estimating relationships between time series. It is, however, easily used in a univariate mode for ARIMA model estimation. The advantage is that it allows (optional) use of the exact likelihood estimation criterion, which is not available in G13AEF or G13AFF. This is particularly recommended for models which have seasonal parameters, because it reduces the tendency of parameter estimates to become stuck at points on the parameter space boundary. The model parameters estimated in this routine should be passed over to G13AJF for use in univariate forecasting.

The routine G13DCF is primarily designed for fitting vector ARMA models to multivariate time series but may also be used in a univariate mode. It allows the use of either the exact or conditional likelihood estimation criterion, and allows the user to fit non-multiplicative seasonal models which are not available in G13AEF, G13AFF or G13BEF.

(c) Model checking

G13ASF calculates the correlations in the residuals from a model fitted by either G13AEF or G13AFF. In addition the standard errors and correlations of the residual autocorrelations are computed along with a portmanteau test for model adequacy. G13ASF can be used after a univariate model has been fitted by G13BEF, but care must be taken in selecting the correct inputs to G13ASF. Note that if G13DCF has been used to fit a non-multiplicative seasonal model to a univariate series then G13DSF may be used to check the adequacy of the model.

(d) Forecasting using an ARIMA model

Given that the state set produced on estimation of the ARIMA model by either G13AEF or G13AFF has been retained, G13AHF can be used directly to construct forecasts for  $x_{n+1}, x_{n+2}, \dots$ , together with probability limits. If some further observations  $x_{n+1}, x_{n+2}, \dots$  have come to hand since model estimation (and there is no desire to re-estimate the model using the extended series), then G13AGF

can be used to update the state set using the new observations, prior to forecasting from the end of the extended series. The original series is not required.

The routine G13AJF is provided for forecasting when the ARIMA model is known but the state set is unknown. For example, the model may have been estimated by a procedure other than the use of G13AEF or G13AFF, such as G13BEF. G13AJF constructs the state set and optionally constructs forecasts with probability limits. It is equivalent to a call to G13AEF with zero iterations requested, followed by an optional call to G13AHF, but it is much more efficient.

### 3.1.2 Input-output/transfer function modelling

#### (a) Model identification

Normally use G13BCF for direct computation of cross-correlations, from which cross-covariances may be obtained by multiplying by  $s_y s_x$ , and impulse response estimates (after prewhitening) by multiplying by  $s_y/s_x$ , where  $s_y, s_x$  are the sample standard deviations of the series.

An alternative is to use G13CCF, which exploits the FFT to carry out the convolution for computing cross-covariances. The criteria for this are the same as given in Section 3.1.1 for calculation of autocorrelations. The impulse response function may also be computed by spectral methods without prewhitening using G13CGF.

G13BAF may be used to prewhiten or filter a series by an ARIMA model.

G13BBF may be used to filter a time series using a transfer function model.

#### (b) Estimation of input-output model parameters

The routine G13BDF is used to obtain preliminary estimates of transfer function model parameters. The model orders and an estimate of the impulse response function (see Section 3.2.1) are required.

The simultaneous estimation of the transfer function model parameters for the inputs, and ARIMA model parameters for the output, is carried out by G13BEF.

This routine requires values of the output and input series, and the orders of all the models. Any differencing implied by the model is carried out internally.

The routine also requires the maximum number of iterations to be specified, and returns the state set for use in forecasting.

#### (c) Input-output model checking

The routine G13ASF, primarily designed for univariate time series, can be used to test the residuals from an input-output model.

#### (d) Forecasting using an input-output model

Given that the state set produced on estimation of the model by G13BEF has been retained, the routine G13BHF can be used directly to construct forecasts of the output series. Future values of the input series (possibly forecasts previously obtained using G13AHF) are required.

If further observations of the output and input series have become available since model estimation (and there is no desire to re-estimate the model using the extended series) then G13BGF can be used to update the state set using the new observations prior to forecasting from the end of the extended series. The original series are not required.

The routine G13BJF is provided for forecasting when the multi-input model is known, but the state set is unknown. The set of output and input series must be supplied to the routine which then constructs the state set (for future use with G13BGF and/or G13BHF) and also optionally constructs forecasts of the output series in a similar manner to G13BHF.

In constructing probability limits for the forecasts, it is possible to allow for the fact that future input series values may themselves have been calculated as forecasts using ARIMA models. Use of this option requires that these ARIMA models be supplied to the routine.

- (e) Filtering a time series using a transfer function model

The routine for this purpose is G13BBF.

### 3.1.3 Multivariate series

- (a) Model identification

The routine G13DLF may be used to difference the series. The user must supply the differencing parameters for each component of the multivariate series. The order of differencing for each individual component does not have to be the same. The routine may also be used to apply a log or square root transformation to the components of the series.

The routine G13DMF may be used to calculate the sample cross-correlation or cross-covariance matrices. It requires a set of time series as input. The user may request either the cross-covariances or cross-correlations.

The routine G13DNF computes the partial lag correlation matrices from the sample cross-correlation matrices computed by G13DMF, and the routine G13DPF computes the least-squares estimates of the partial autoregression matrices and their standard errors. Both routines compute a series of  $\chi^2$  statistic that aid the determination of the order of a suitable autoregressive model. G13DBF may also be used in the identification of the order of an autoregressive model. The routine computes multiple squared partial autocorrelations and predictive error variance ratios from the sample cross-correlations or cross-covariances computed by G13DMF.

The routine G13DXF may be used to check that the autoregressive part of the model is stationary and that the moving-average part is invertible.

- (b) Estimation of VARMA model parameters

The routine for this purpose is G13DCF. This routine requires a set of time series to be input, together with values for  $p$  and  $q$ . The user must also specify the maximum number of likelihood evaluations to be permitted and which parameters (if any) are to be held at their initial (user-supplied) values. The fitting criterion is either **exact** maximum likelihood or **conditional** maximum likelihood.

G13DCF is primarily designed for estimating relationships between time series. It may, however, easily be used in univariate mode for non-seasonal and non-multiplicative seasonal ARIMA model estimation. The advantage is that it allows (optional) use of the exact maximum likelihood estimation criterion, which is not available in either G13AEF or G13AFF. The conditional likelihood option is recommended for those models in which the parameter estimates display a tendency to become stuck at points on the boundary of the parameter space. When one of the series is known to be influenced by all the others, but the others in turn are mutually independent and do not influence the output series, then G13BEF (the transfer function model fitting routine) may be more appropriate to use.

- (c) VARMA model checking

G13DSF calculates the cross-correlation matrices of residuals for a model fitted by G13DCF. In addition the standard errors and correlations of the residual correlation matrices are computed along with a portmanteau test for model adequacy.

- (d) Forecasting using a VARMA model

The routine G13DJF may be used to construct a chosen number of forecasts using the model estimated by G13DCF. The standard errors of the forecasts are also computed. A reference vector is set up by G13DJF so that should any further observations become available the existing forecasts can be efficiently updated using G13DKF. On a call to G13DKF the reference vector itself is also updated so that G13DKF may be called again each time new observations are available.

## 3.2 Spectral Methods

### 3.2.1 Univariate spectral estimation

Two routines are available, G13CAF carrying out smoothing using a lag window and G13CBF carrying out direct frequency domain smoothing. Both can take as input the original series, but G13CAF alone can

use the sample autocovariances as alternative input. This has some computational advantage if a variety of spectral estimates needs to be examined for the same series using different amounts of smoothing.

However, the real choice in most cases will be which of the four shapes of lag window in G13CAF to use, or whether to use the trapezium frequency window of G13CBF. The references may be consulted for advice on this, but the two most recommended lag windows are the Tukey and Parzen. The Tukey window has a very small risk of supplying negative spectrum estimates; otherwise, for the same bandwidth, both give very similar results, though the Parzen window requires a higher truncation lag (more acf values).

The frequency window smoothing procedure of G13CBF with a trapezium shape parameter  $p \simeq \frac{1}{2}$  generally gives similar results for the same bandwidth as lag window methods with a slight advantage of somewhat less distortion around sharp peaks, but suffering a rather less smooth appearance in fine detail.

### 3.2.2 Cross-spectrum estimation

Two routines are available for the main step in cross-spectral analysis. To compute the cospectrum and quadrature spectrum estimates using smoothing by a lag window, G13CCF should be used. It takes as input either the original series or cross-covariances which may be computed in a previous call of the same routine or possibly using results from G13BCF. As in the univariate case, this gives some advantage if estimates for the same series are to be computed with different amounts of smoothing.

The choice of window shape will be determined as the same as that which has already been used in univariate spectrum estimation for the series.

For direct frequency domain smoothing, G13CDF should be used, with similar consideration for the univariate estimation in choice of degree of smoothing.

The cross-amplitude and squared coherency spectrum estimates are calculated, together with upper and lower confidence bounds, using G13CEF. For input the cross-spectral estimates from either G13CCF or G13CDF and corresponding univariate spectra from either G13CAF or G13CBF are required.

The gain and phase spectrum estimates are calculated together with upper and lower confidence bounds using G13CFF. The required input is as for G13CEF above.

The noise spectrum estimates and impulse response function estimates are calculated together with multiplying factors for confidence limits on the former, and the standard error for the latter, using G13CGF. The required input is again the same as for G13CEF above.

### 3.3 Kalman Filtering

Two routines are available for Kalman filtering: G13EAF for time varying systems and G13ABF for time invariant systems. The latter will optionally compute the required transformation to lower observer Hessenberg form. Both these routines return the Cholesky factor of the residual covariance matrix,  $H_t$ , with the Cholesky factor of the state covariance matrix  $S_{t+1}$  and the Kalman gain matrix,  $K_t$  pre-multiplied by  $A_t$ ; in the case of G13EBF these may be for the transformed system. To compute the updated state vector and the residual vector the required matrix-vector multiplications can be performed by F06PAF (SGEMV/DGEMV).

### 3.4 GARCH Models

The main choice in selecting a type of GARCH model is whether the data is symmetric or asymmetric and if asymmetric what form of asymmetry should be included in the model.

A symmetric ARCH or GARCH model can be fitted by G13FAF and the volatility forecast by G13FBF. For asymmetric data the choice is between the type of asymmetry as described in Section 2.7.

GARCH Type	Fit	Forecast
Type I	G13FAF	G13FBF
Type II	G13FCF	G13FDF
GJR	G13FEF	G13FFF
EGARCH	G13FGF	G13FHF

All routines allow the option of including regressor variables in the model and the choice between Normal and Student's  $t$ -distribution for the errors.

### 3.5 Time Series Simulation

There are routines available in Chapter G05 for generating a realisation of a time series from a specified model: G05EGF and G05EWF for univariate time series and G05HDF for multivariate time series. There is also a suite of routines for simulating GARCH models: G05HKF, G05HLF, G05HMF and G05HNF.

### 3.6 Summary of Recommendations

#### ARMA Modelling

Differencing .....	G13AAF
ACF .....	G13ABF
PACF .....	G13ACF
Fitting .....	G13BEF
Forecasting .....	G13AJF
Diagnostic checking .....	G13ASF

#### Univariate spectral analysis

Bartlett, Tukey, Parzen windows .....	G13CAF
Direct smoothing .....	G13CBF

#### Transfer function modelling

Pre-whitening .....	G13BAF
Cross-correlations .....	G13BCF
Fitting .....	G13BEF
Forecasting .....	G13BJF

#### Bivariate spectral analysis

Bartlett, Tukey, Parzen windows .....	G13CCF
Direct smoothing .....	G13CDF
Other representations .....	G13CEF
	G13CFF
	G13CGF

#### Vector ARMA

Differencing .....	G13DLF
Cross-correlations .....	G13DMF
Partial-correlations/autoregressions .....	G13DBF
	G13DNF
	G13DPF
Fitting .....	G13DCF
Forecasting .....	G13DJF
Diagnostic checks .....	G13DSF

#### Kalman filter

Time invariant .....	G13EBF
Time varying .....	G13EAF

#### GARCH

##### Symmetric ARCH/GARCH

Fitting .....	G13FAF
Forecasting .....	G13FBF

Asymmetric ARCH/GARCH	
Fitting .....	G13FAF G13FCF G13FEF
Forecasting .....	G13FBF G13FDF G13FFF
EGARCH	
Fitting .....	G13FGF
Forecasting .....	G13FHF

#### 4 Routines Withdrawn or Scheduled for Withdrawal

The following routines have been withdrawn. Advice on replacing calls to those withdrawn since Mark 13 is given in the document ‘Advice on Replacement Calls for Withdrawn/Superseded Routines’.

Withdrawn Routine	Mark of Withdrawal	Replacement Routine(s)
G13DAF	17	G13DMF

#### 5 References

- Akaike H (1971) Autoregressive model fitting for control *Ann. Inst. Statist. Math.* **23** 163–180
- Bollerslev T (1986) Generalised autoregressive conditional heteroskedasticity *Journal of Econometrics* **31** 307–327
- Box G E P and Jenkins G M (1976) *Time Series Analysis: Forecasting and Control* (Revised Edition) Holden-Day
- Engle R (1982) Autoregressive conditional heteroskedasticity with estimates of the variance of United Kingdom inflation *Econometrica* **50** 987–1008
- Gentleman W S and Sande G (1966) Fast Fourier transforms for fun and profit *Proc. Joint Computer Conference, AFIPS* **29** 563–578
- Glosten L, Jagannathan R and Runkle D (1993) Relationship between the expected value and the volatility of nominal excess return on stocks *Journal of Finance* **48** 1779–1801
- Hamilton J (1994) *Time Series Analysis* Princeton University Press
- Heyse J F and Wei W W S (1985) The partial lag autocorrelation function *Technical Report No. 32* Department of Statistics, Temple University, Philadelphia
- Tiao G C and Box G E P (1981) Modelling multiple time series with applications *J. Am. Stat. Assoc.* **76** 802–816
- Wei W W S (1990) *Time Series Analysis: Univariate and Multivariate Methods* Addison-Wesley