

# Package ‘FKF.SP’

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**Title** Fast Kalman Filtering Through Sequential Processing

**Version** 0.3.4

**Description** Fast and flexible Kalman filtering and smoothing implementation utilizing sequential processing, designed for efficient parameter estimation through maximum likelihood estimation. Sequential processing is a univariate treatment of a multivariate series of observations and can benefit from computational efficiency over traditional Kalman filtering when independence is assumed in the variance of the disturbances of the measurement equation. Sequential processing is described in the textbook of Durbin and Koopman (2001, ISBN:978-0-19-964117-8). ‘FKF.SP’ was built upon the existing ‘FKF’ package and is, in general, a faster Kalman filter/smoothen.

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fkf.SP	<i>Fast Kalman Filtering using Sequential Processing.</i>
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## Description

The `fkf.SP` function performs fast and flexible Kalman filtering using sequential processing. It is designed for efficient parameter estimation through maximum likelihood estimation. Sequential processing (SP) is a univariate treatment of a multivariate series of observations that increases computational efficiency over traditional Kalman filtering in the general case. SP takes the additional assumption that the variance of disturbances in the measurement equation are independent. `fkf.SP` is based from the `fkf` function of the FKF package but is, in general, a faster Kalman filtering method. `fkf` and `fkf.SP` share identical arguments (except for the `GGt` argument, see **Arguments**). `fkf.SP` is compatible with missing observations (i.e. NA's in argument `yt`).

## Usage

```
fkf.SP(
  a0,
  P0,
  dt,
  ct,
  Tt,
  Zt,
  HHt,
  GGt,
  yt,
  verbose = FALSE,
  smoothing = FALSE
)
```

## Arguments

<code>a0</code>	A vector giving the initial value/estimation of the state variable
<code>P0</code>	A matrix giving the variance of <code>a0</code>
<code>dt</code>	A matrix giving the intercept of the transition equation

ct	A matrix giving the intercept of the measurement equation
Tt	An array giving factor of the transition equation
Zt	An array giving the factor of the measurement equation
HHt	An array giving the variance of the innovations of the transition equation
GGt	A vector giving the diagonal elements of the matrix for the variance of disturbances of the measurement equation. Covariance between disturbances is not supported under the sequential processing method.
yt	A matrix containing the observations. "NA"- values are allowed
verbose	A logical. When verbose = TRUE, A list object is output, which provides filtered values of the Kalman filter (see <b>Value</b> ).
smoothing	A logical. When smoothing = TRUE, Kalman smoothing is additionally performed and smoothed values returned (see <b>Value</b> ).

## Details

### Parameters:

The `fkf.SP` function builds upon the `fkf` function of the FKF package by adjusting the Kalman filtering algorithm to utilize sequential processing. Sequential processing can result in significant decreases in processing time over the traditional Kalman filter algorithm. Sequential processing has been empirically shown to grow linearly with respect to the dimensions of  $y_t$ , rather than exponentially as is the case with the traditional Kalman filter algorithm (Aspinall et al., 2022, P104).

The `fkf.SP` and `fkf` functions feature highly similar arguments for compatibility purposes; only argument `GGt` has changed from an array type object to a vector or matrix type object. The `fkf.SP` function takes the additional assumption over the `fkf` function that the variance of the disturbances of the measurement equation are independent; a requirement of SP (see below).

Parameters can either be constant or deterministic time-varying. Assume the number of discrete time observations is  $n$  i.e.  $y = y_t$  where  $t = 1, \dots, n$ . Let  $m$  be the dimension of the state variable and  $d$  the dimension of the observations. Then, the parameters admit the following classes and dimensions:

dt	either a $m \times n$ (time-varying) or a $m \times 1$ (constant) matrix.
Tt	either a $m \times m \times n$ or a $m \times m \times 1$ array.
HHt	either a $m \times m \times n$ or a $m \times m \times 1$ array.
ct	either a $d \times n$ or a $d \times 1$ matrix.
Zt	either a $d \times m \times n$ or a $d \times m \times 1$ array.
GGt	either a $d \times n$ (time-varying) or a $d \times 1$ matrix.
yt	a $d \times n$ matrix.

### State Space Form

The following notation follows that of Koopman *et al.* (1999). The Kalman filter is characterized by the transition and measurement equations:

$$\alpha_{t+1} = d_t + T_t \cdot \alpha_t + H_t \cdot \eta_t$$

$$y_t = c_t + Z_t \cdot \alpha_t + G_t \cdot \epsilon_t$$

where  $\eta_t$  and  $\epsilon_t$  are i.i.d.  $N(0, I_m)$  and i.i.d.  $N(0, I_d)$ , respectively, and  $\alpha_t$  denotes the state vector. The parameters admit the following dimensions:

$$\begin{array}{lll} a_t \in R^m & d_t \in R^m & \eta_t \in R^m \\ T_t \in R^{m \times m} & H_t \in R^{m \times m} & \\ y_t \in R^d & c_t \in R^d & \epsilon_t \in R^d \\ Z_t \in R^{d \times m} & G_t \in R^{d \times d} & \end{array}$$

Note that fkf.SP takes as input HHT and GGt which corresponds to  $H_t H_t'$  and  $diag(G_t)^2$  respectively.

### Sequential Processing Iteration:

Traditional Kalman filtering takes the entire observational vector  $y_t$  as the items for analysis. SP is an alternate approach that filters the elements of  $y_t$  one at a time. Sequential processing is described in the textbook of Durbin and Koopman (2001) and is described below.

Let  $p$  equal the number of observations at time  $t$  (i.e. when considering possible missing observations  $p \leq d$ ). The SP iteration involves treating the vector series:  $y_1, \dots, y_n$  instead as the scalar series  $y_{1,1}, \dots, y_{(1,p)}, y_{2,1}, \dots, y_{(n,p_n)}$ . This univariate treatment of the multivariate series has the advantage that the function of the covariance matrix,  $F_t$ , becomes  $1 \times 1$ , avoiding the calculation of both the inverse and determinant of a  $p \times p$  matrix. This can increase computational efficiency (especially under the case of many observations, i.e.  $p$  is large)

For any time point, the observation vector is given by:

$$y_t' = (y_{(t,1)}, \dots, y_{(t,p)})$$

The filtering equations are written as:

$$\begin{aligned} a_{t,i+1} &= a_{t,i} + K_{t,i} v_{t,i} \\ P_{t,i+1} &= P_{t,i} - K_{t,i} F_{t,i} K_{t,i}' \end{aligned}$$

Where:

$$\begin{aligned} \hat{y}_{t,i} &= c_t + Z_t \cdot a_{t,i} \\ v_{t,i} &= y_{t,i} - \hat{y}_{t,i} \\ F_{t,i} &= Z_{t,i} P_{t,i} Z_{t,i}' + GG_{t,i} \\ K_{t,i} &= P_{t,i} Z_{t,i}' F_{t,i}^{-1} \\ i &= 1, \dots, p \end{aligned}$$

Transition from time  $t$  to  $t + 1$  occurs through the standard transition equations.

$$\alpha_{t+1,1} = d_t + T_t \cdot \alpha_{t,p}$$

$$P_{t+1,1} = T_t \cdot P_{t,p} \cdot T_t' + H H t$$

The log-likelihood at time  $t$  is given by:

$$\log L_t = -\frac{p}{2} \log(2\pi) - \frac{1}{2} \sum_{i=1}^p \left( \log F_i + \frac{v_i^2}{F_i} \right)$$

Where the log-likelihood of observations is:

$$\log L = \sum_t^n \log L_t$$

### Compiled Code:

fkf.SP wraps the C-functions fkf\_SP, fkf\_SP\_verbose and fkfs\_SP, which each rely upon the linear algebra subroutines of BLAS (Basic Linear Algebra Subprograms). These C-functions are called when verbose = FALSE, verbose = TRUE and smoothing = TRUE, respectively.

The difference in these compiled functions are in the values returned from them. The fkfs\_SP also performs Kalman filtering and subsequently smoothing within the singular compiled C-code function.

### Value

A numeric value corresponding to the log-likelihood calculated by the Kalman filter. Ideal for maximum likelihood estimation through optimization routines such as optim.

When verbose = TRUE, an S3 class of type 'fkf.SP' with the following elements is also returned, corresponding to the filtered state variables and covariances of the Kalman filter algorithm:

att	A $m \times n$ -matrix containing the filtered state variables, i.e. $\text{att}[, t] = a_{t t}$ .
at	A $m \times (n + 1)$ -matrix containing the predicted state variables, i.e. $\text{at}[, t] = a_t$ .
Ptt	A $m \times m \times n$ -array containing the variance of att, i.e. $\text{Ptt}[, , t] = P_{t t}$ .
Pt	A $m \times m \times (n + 1)$ -array containing the variance of at, i.e. $\text{Pt}[, , t] = P_t$ .
yt	A $d \times n$ -matrix containing the input observations.
Tt	either a $m \times m \times n$ or a $m \times m \times 1$ -array, depending on the argument provided.
Zt	either a $d \times m \times n$ or a $d \times m \times 1$ -array, depending on the argument provided.
Ftin	A $d \times n$ -matrix containing the scalar inverse of the prediction error variances.
vt	A $d \times n$ -matrix containing the observation error.
Kt	A $m \times d \times n$ -array containing the Kalman gain of state variables at each observation.
logLik	The log-likelihood.

In addition to the elements above, the following elements corresponding to the smoothed values output from Kalman smoothing are also returned when smoothing = TRUE. The fks.SP provides more detail regarding Kalman smoothing.

ahatt	A $m \times n$ -matrix containing the smoothed state variables, i.e. $\text{ahatt}[, t] = a_{t n}$
Vt	A $m \times m \times n$ -array containing the variances of ahatt, i.e. $\text{Vt}[, , t] = P_{t n}$

### Log-Likelihood Values:

When there are no missing observations (i.e. "NA" values) in argument yt, the return of function fkf.SP and the logLik object returned within the list of function fkf are identical. When NA's are present, however, log-likelihood values returned by fkf.SP are always higher. This is due to low bias in the log-likelihood values output by fkf, but does not influence parameter estimation. Further details are available within this package's vignette.

## References

- Aspinall, T. W., Harris, G., Gepp, A., Kelly, S., Southam, C., and Vanstone, B. (2022). *The Estimation of Commodity Pricing Models with Applications in Capital Investments*. [Available Online](#).
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- Koopman, S. J., Shephard, N., Doornik, J. A. (1999). Statistical algorithms for models in state space using SsfPack 2.2. *Econometrics Journal*, Royal Economic Society, vol. 2(1), pages 107-160.
- Durbin, James, and Siem Jan Koopman (2001). *Time series analysis by state space methods*. Oxford university press.
- David Luethi, Philipp Erb and Simon Oztzger (2018). FKF: Fast Kalman Filter. R package version 0.2.3. <https://CRAN.R-project.org/package=FKF>

## Examples

```
## <-----
##Example 1 - Filter a state space model - Nile data
## <-----

# Observations must be a matrix:
yt <- rbind(datasets::Nile)

## Set constant parameters:
dt <- ct <- matrix(0)
Zt <- Tt <- matrix(1)
a0 <- yt[1] # Estimation of the first year flow
P0 <- matrix(100) # Variance of 'a0'
## These can be estimated through MLE:
GGt <- matrix(15000)
HHT <- matrix(1300)

# 'verbose' returns the filtered values:
output <- fkf.SP(a0 = a0, P0 = P0, dt = dt, ct = ct,
                Tt = Tt, Zt = Zt, HHT = HHT, GGt = GGt,
                yt = yt, verbose = TRUE)

## <-----
##Example 2 - ARMA(2,1) model estimation.
## <-----

#Length of series
n <- 1000

#AR parameters
AR <- c(ar1 = 0.6, ar2 = 0.2, ma1 = -0.2, sigma = sqrt(0.2))

## Sample from an ARMA(2, 1) process
a <- stats::arima.sim(model = list(ar = AR[c("ar1", "ar2")], ma = AR["ma1"]), n = n,
```

```

innov = rnorm(n) * AR["sigma"])

##State space representation of the four ARMA parameters
arma21ss <- function(ar1, ar2, ma1, sigma) {
  Tt <- matrix(c(ar1, ar2, 1, 0), ncol = 2)
  Zt <- matrix(c(1, 0), ncol = 2)
  ct <- matrix(0)
  dt <- matrix(0, nrow = 2)
  GGt <- matrix(0)
  H <- matrix(c(1, ma1), nrow = 2) * sigma
  HHt <- H %*% t(H)
  a0 <- c(0, 0)
  P0 <- matrix(1e6, nrow = 2, ncol = 2)
  return(list(a0 = a0, P0 = P0, ct = ct, dt = dt, Zt = Zt, Tt = Tt, GGt = GGt,
             HHt = HHt))
}

## The objective function passed to 'optim'
objective <- function(theta, yt) {
  sp <- arma21ss(theta["ar1"], theta["ar2"], theta["ma1"], theta["sigma"])
  ans <- fkf.SP(a0 = sp$a0, P0 = sp$P0, dt = sp$dt, ct = sp$ct, Tt = sp$Tt,
               Zt = sp$Zt, HHt = sp$HHt, GGt = sp$GGt, yt = yt)
  return(-ans)
}

## Parameter estimation - maximum likelihood estimation:
theta <- c(ar = c(0, 0), ma1 = 0, sigma = 1)
ARMA_MLE <- optim(theta, objective, yt = rbind(a), hessian = TRUE)

## -----
## Example 3 - Nile Model Estimation:
## -----

#Nile's annual flow:
yt <- rbind(Nile)

##Incomplete Nile Data - two NA's are present:
yt[c(3, 10)] <- NA

## Set constant parameters:
dt <- ct <- matrix(0)
Zt <- Tt <- matrix(1)
a0 <- yt[1] # Estimation of the first year flow
P0 <- matrix(100) # Variance of 'a0'

## Parameter estimation - maximum likelihood estimation:
##Unknown parameters initial estimates:
GGt <- HHt <- var(c(yt), na.rm = TRUE) * .5
#Perform maximum likelihood estimation
Nile_MLE <- optim(c(HHt = HHt, GGt = GGt),
                 fn = function(par, ...)
                 -fkf.SP(HHt = matrix(par[1]), GGt = matrix(par[2]), ...),

```

```

        yt = yt, a0 = a0, P0 = P0, dt = dt, ct = ct,
        Zt = Zt, Tt = Tt)
## -----
## Example 4 - Dimensionless Treering Example:
## -----

## tree-ring widths in dimensionless units
y <- treering

## Set constant parameters:
dt <- ct <- matrix(0)
Zt <- Tt <- matrix(1)
a0 <- y[1]           # Estimation of the first width
P0 <- matrix(100)    # Variance of 'a0'

## Parameter estimation - maximum likelihood estimation:
Treering_MLE <- optim(c(HHt = var(y, na.rm = TRUE) * .5,
                      GGt = var(y, na.rm = TRUE) * .5),
                    fn = function(par, ...)
                      -fkf.SP(HHt = array(par[1],c(1,1,1)), GGt = matrix(par[2]), ...),
                    yt = rbind(y), a0 = a0, P0 = P0, dt = dt, ct = ct,
                    Zt = Zt, Tt = Tt)

```

fks.SP

*Fast Kalman Smoother through Sequential Processing*

## Description

The Kalman smoother is a backwards algorithm that is run after the Kalman filter that allows the user to refine estimates of previous states to produce "smoothed" estimates of state variables. This function performs the "Kalman smoother" algorithm using sequential processing, an approach that can substantially improve processing time over the traditional Kalman filtering/smoothing algorithms. The primary application of Kalman smoothing is in conjunction with expectation-maximization to estimate the parameters of a state space model. This function is called after running `fkf.SP`. `fks.SP` wraps the C-function `fks_SP` which relies upon the linear algebra subroutines of BLAS (Basic Linear Algebra Subprograms).

## Usage

```
fks.SP(FKF.SP_obj)
```

## Arguments

`FKF.SP_obj` An S3-object of class "fkf.SP", returned by `fkf.SP` when using the argument `verbose = TRUE`.

## Details

fks.SP is typically called after the `fkf.SP` function to calculate "smoothed" estimates of state variables and their corresponding variances. Smoothed estimates are used when utilizing expectation-maximization (EM) to efficiently estimate the parameters of a state space model.

### Sequential Processing Kalman smoother solution:

The fks.SP function uses the solution to the Kalman smoother through sequential processing provided in the textbook of Durbin and Koopman (2001).

Given a state space model has been filtered through the sequential processing Kalman filter algorithm described in `fkf.SP`, the smoother can be reformulated for the univariate series:

$$y'_t = (y_{(1,1)}, y_{(1,2)}, \dots, y_{(1,p_1)}, y_{(2,1)}, \dots, y_{(t,p_t)})$$

The sequential processing Kalman smoother approach iterates backwards through both observations and time, i.e.:  $i = p_t, \dots, 1$  and  $t = n, \dots, 1$ , where  $p_t$  is the number of observations at time  $t$  and  $n$  is the total number of observations.

The initialisations are:

$$r_{(n,p_n)} = 0$$

$$N_{(n,p_n)} = 0$$

Then,  $r$  and  $N$  are recursively calculated through:

$$L_{t,i} = I_m - K_{t,i}Z_{t,i}$$

$$r_{(t,i-1)} = Z'_{t,i}F_{t,i}^{-1}v_{t,i} + L'_{t,i}r_{t,i}$$

$$N_{t,i-1} = Z'_{t,i}F_{t,i}^{-1}Z_{t,i} + L'_{t,i}N_{t,i}L_{t,i}$$

$$r_{t-1,p_t} = T'_{t-1}r_{t,0}$$

$$N_{t-1,p_t} = T'_{t-1}N_{t,0}T_{t-1}$$

for  $i = p_t, \dots, 1$  and  $t = n, \dots, 1$

The equations for  $r_{t-1,p_t}$  and  $N_{t-1,p_t}$  do not apply for  $t = 1$

Under this formulation, the values for  $r_{t,0}$  and  $N_{t,0}$  are the same as the values for the smoothing quantities of  $r_{t-1}$  and  $N_{t-1}$  of the standard smoothing equations, respectively.

The standard smoothing equations for  $\hat{a}_t$  and  $V_t$  are used:

$$\hat{a}_t = a_t + P_t r_{t-1}$$

$$V_t = P_t - P_t N_{t-1} P_t$$

Where:

$$a_t = a_{t,1}$$

$$P_t = P_{t,1}$$

In the equations above,  $r_{t,i}$  is an  $m \times 1$  vector,  $I_m$  is an  $m \times m$  identity matrix,  $K_{t,i}$  is an  $m \times 1$  column vector,  $Z_{t,i}$  is a  $1 \times m$  row vector, and both  $F_{t,i}^{-1}$  and  $v_{t,i}$  are scalars. The reduced dimensionality of many of the variables in this formulation compared to traditional Kalman smoothing can result in increased computational efficiency.

Finally, in the formulation described above,  $a_t$  and  $P_t$  correspond to the values of `att` and `ptt` returned from the `fkf.SP` function, respectively.

## Value

An S3-object of class `fks.SP`, which is a list with the following elements:

`ahatt` A  $m \times n$ -matrix containing the smoothed state variables, i.e. `ahatt[, t] = a_{t|n}`  
`Vt` A  $m \times m \times n$ -array containing the variances of `ahatt`, i.e. `Vt[, , t] = P_{t|n}`

## References

Aspinall, T. W., Harris, G., Gepp, A., Kelly, S., Southam, C., and Vanstone, B. (2022). *The Estimation of Commodity Pricing Models with Applications in Capital Investments*. [Available Online](#).

Durbin, James, and Siem Jan Koopman (2001). *Time series analysis by state space methods*. Oxford university press.

## Examples

```
### Perform Kalman Filtering and Smoothing through sequential processing:
#Nile's annual flow:
yt <- Nile

# Incomplete Nile Data - two NA's are present:
yt[c(3, 10)] <- NA

dt <- ct <- matrix(0)
Zt <- Tt <- matrix(1)
a0 <- yt[1] # Estimation of the first year flow
P0 <- matrix(100) # Variance of 'a0'

# Parameter estimation - maximum likelihood estimation:
# Unknown parameters initial estimates:
GGt <- HHt <- var(yt, na.rm = TRUE) * .5
HHt = matrix(HHt)
GGt = matrix(GGt)
yt = rbind(yt)
# Filter through the Kalman filter - sequential processing:
Nile_filtered <- fkf.SP(HHt = matrix(HHt), GGt = matrix(GGt), a0 = a0, P0 = P0, dt = dt, ct = ct,
```

```
Zt = Zt, Tt = Tt, yt = rbind(yt), verbose = TRUE)  
# Smooth filtered values through the Kalman smoother - sequential processing:  
Smoothed_Estimates <- fks.SP(Nile_filtered)
```

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