

Package ‘bayesianETAS’

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Title Bayesian Estimation of the Temporal and Spatio-Temporal ETAS
Models for Earthquake Occurrences

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Imports MASS

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Description The Epidemic Type Aftershock Sequence (ETAS) model is widely used for modelling and forecasting earthquake occurrences. This package implements Bayesian estimation routines for both the temporal and spatial ETAS model, allowing samples to be drawn from the full posterior distribution of the model parameters given an earthquake catalogue. The methods are described in Ross (2021) ``Bayesian Estimation of the ETAS Model for Earthquake Occurrences" <[doi:10.1785/0120200198](https://doi.org/10.1785/0120200198)>.

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estimateETAS

Draws samples from the posterior distribution of the ETAS model

Description

This function implements the latent variable MCMC scheme from (Ross 2019) which draws samples from the Bayesian posterior distribution of the Epidemic Type Aftershock Sequence (ETAS) model. Either the temporal ETAS or the spatio-temporal (with a bivariate Gaussian trigger kernel) can be sampled.

The ETAS model is widely used to quantify the degree of seismic activity in a geographical region, and to forecast the occurrence of future mainshocks and aftershocks (Ross 2019). The temporal ETAS model is a point process where the probability of an earthquake occurring at time t depends on the previous seismicity H_t , and is defined by the conditional intensity function:

$$\lambda(t|H_t) = \mu + \sum_{t[i]<t} \kappa(m[i]|K, \alpha)h(t - t[i]|c, p)$$

where

$$\kappa(m_i|K, \alpha) = Ke^{\alpha(m_i - M_0)}$$

and

$$h(t_i|c, p) = \frac{(p-1)c^{p-1}}{(t-t_i+c)^p}$$

and $s()$ is a spatial triggering kernel. The public spatio-temporal fitting routines currently use a Gaussian spatial triggering kernel with a homogeneous spatial background over the supplied area and no spatial edge correction. $s()$ can also be omitted to fit the temporal ETAS model without a spatial component. The summation is over all previous earthquakes that occurred in the region, with the i 'th such earthquake occurring at time t_i at spatial location (x_i, y_i) and having magnitude m_i . The quantity M_0 denotes the magnitude of completeness of the catalog, so that $m_i \geq M_0$ for all i . The temporal ETAS model has 5 parameters: μ controls the background rate of seismicity, K and α determine the productivity (average number of aftershocks) of an earthquake with magnitude m , and c and p are the parameters of the Modified Omori Law (which has here been normalized to integrate to 1) and represent the speed at which the aftershock rate decays over time. Each earthquake is assumed to have a magnitude which is an independent draw from the Gutenberg-Richter law $p(m_i) = \beta e^{\beta(m_i - M_0)}$.

Usage

```
estimateETAS(
  ts,
  ms,
  M0,
  maxTime = NULL,
  xs = NULL,
  ys = NULL,
  area = NULL,
```

```

sims = 5000,
burnin = 1000,
initval = NA,
sigma2_prior_shape = 3,
sigma2x_prior_rate = NULL,
sigma2y_prior_rate = NULL,
handle_ties = c("error", "jitter"),
c_lower = NULL
)

```

Arguments

ts	Vector containing the earthquake times
ms	Vector containing the earthquake magnitudes
M0	Magnitude of completeness.
maxTime	Length of the time window [0,maxTime] the catalog was observed over. If not specified, will be taken as the time of the last earthquake.
xs	(For the spatio-temporal ETAS model only), a vector containing the x coordinates of the earthquakes
ys	(For the spatio-temporal ETAS model only), a vector containing the y coordinates of the earthquakes
area	(For the spatio-temporal ETAS model only), a single number containing the area of the rectangular spatial region containing the earthquakes. For example if the earthquakes are defined on [28,35]x[-119,-128] then the area would be 7x9 = 63. If this is not specified then it will be calculated based on the distance between the furthest apart earthquakes in the catalog.
sims	Number of posterior samples to draw
burnin	Number of burnin samples. If (eg) sims=5000 and burnin=2000 then 7000 samples will be drawn with the first 2000 discarded
initval	Initial value at which to start the estimation. If specified, should be a vector, with elements (mu, K, alpha, c, p) for the temporal model and (mu, K, alpha, c, p, sigma2x,sigma2y) for the spatio-temporal model. If unspecified, the sampler will be initialized at the maximum likelihood estimate of the model parameters
sigma2_prior_shape	Shape parameter for the inverse-gamma prior on Gaussian spatial variances, using a shape/rate convention. Must be greater than 2.
sigma2x_prior_rate	Rate parameter for the inverse-gamma prior on σ_x^2 . If NULL, a scale-aware default equal to $2 * (0.1 * diff(range(xs)))^2$ is used.
sigma2y_prior_rate	Rate parameter for the inverse-gamma prior on σ_y^2 . If NULL, a scale-aware default equal to $2 * (0.1 * diff(range(ys)))^2$ is used.
handle_ties	How to handle duplicate event times. The default "error" stops because continuous-time ETAS requires strictly increasing event times. "jitter" applies a deterministic, order-preserving jitter before fitting. This is a preprocessing convention, not part of the ETAS model.

`c_lower` Lower bound for the Omori c parameter. If NULL, a data-scale default equal to one tenth of the smallest positive event-time gap after tie handling is used.

Details

In the spatio-temporal version of the model, $s()$ is the multivariate Gaussian with diagonal covariance parameters σ_x^2 and σ_y^2 . The spatial background is homogeneous over the supplied area and no spatial edge correction is implemented.

The inverse-gamma priors for σ_x^2 and σ_y^2 use a shape/rate convention. If the spatial prior rates are not supplied, the defaults are scale-aware: $2 * (0.1 * diff(range(xs)))^2$ for σ_x^2 and $2 * (0.1 * diff(range(ys)))^2$ for σ_y^2 . Degenerate coordinate ranges require explicit prior rates.

The likelihood assumes strictly increasing event times. By default duplicate times are rejected. With `handle_ties = "jitter"`, tied event times are separated deterministically by a small amount before fitting. The Omori c parameter is constrained to be greater than `c_lower`; this prevents finite-resolution catalogues with exact or near ties from driving c to zero.

Value

A data frame containing the posterior samples. Each row is a single sample, and the columns correspond to (μ, K, α, c, p) for the temporal model and $(\mu, K, \alpha, c, p, \sigma_x, \sigma_y)$ for the spatio-temporal model

Author(s)

Gordon J Ross

References

Gordon J. Ross - Bayesian Estimation of the ETAS Model for Earthquake Occurrences (2019)

Examples

```
#temporal model
ts <- c(1, 2, 3, 5, 8)
ms <- c(3.0, 3.1, 3.3, 3.2, 3.0)
samples <- estimateETAS(ts, ms, M0=3, maxTime=10, sims=20, burnin=5,
  initval=c(0.1, 0.1, 0.5, 0.2, 1.5))
apply(samples, 2, median) #point estimate

#spatio-temporal model
xs <- c(1, 2, 3, 4, 5)
ys <- c(1, 1.5, 2, 1.5, 1)
samples <- estimateETAS(ts, ms, M0=3, maxTime=10, xs=xs, ys=ys,
  area=25, sims=20, burnin=5,
  initval=c(0.1, 0.1, 0.5, 0.2, 1.5, 1, 1))
apply(samples, 2, median) #point estimate
```

maxLikelihoodETAS	<i>Estimate the parameters of the ETAS model using maximum likelihood.</i>
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Description

The ETAS model is widely used to quantify the degree of seismic activity in a geographical region, and to forecast the occurrence of future mainshocks and aftershocks (Ross 2019). The temporal ETAS model is a point process where the probability of an earthquake occurring at time t depends on the previous seismicity H_t , and is defined by the conditional intensity function:

$$\lambda(t|H_t) = \mu + \sum_{t[i]<t} \kappa(m[i]|K, \alpha)h(t - t[i]|c, p)$$

where

$$\kappa(m_i|K, \alpha) = Ke^{\alpha(m_i - M_0)}$$

and

$$h(t_i|c, p) = \frac{(p - 1)c^{p-1}}{(t - t_i + c)^p}$$

and $s()$ is a spatial triggering kernel. The public spatio-temporal fitting routines currently use a Gaussian spatial triggering kernel with a homogeneous spatial background over the supplied area and no spatial edge correction. $s()$ can also be omitted to fit the temporal ETAS model without a spatial component. The summation is over all previous earthquakes that occurred in the region, with the i 'th such earthquake occurring at time t_i at spatial location (x_i, y_i) and having magnitude m_i . The quantity M_0 denotes the magnitude of completeness of the catalog, so that $m_i \geq M_0$ for all i . The temporal ETAS model has 5 parameters: μ controls the background rate of seismicity, K and α determine the productivity (average number of aftershocks) of an earthquake with magnitude m , and c and p are the parameters of the Modified Omori Law (which has here been normalized to integrate to 1) and represent the speed at which the aftershock rate decays over time. Each earthquake is assumed to have a magnitude which is an independent draw from the Gutenberg-Richter law $p(m_i) = \beta e^{\beta(m_i - M_0)}$.

Usage

```
maxLikelihoodETAS(
  ts,
  ms,
  M0,
  maxTime = NULL,
  xs = NULL,
  ys = NULL,
  area = NULL,
  initval = NA,
  displayOutput = FALSE,
  zeromu = FALSE,
  handle_ties = c("error", "jitter"),
  c_lower = NULL
)
```

Arguments

ts	Vector containing the earthquake times
ms	Vector containing the earthquake magnitudes
M0	Magnitude of completeness.
maxTime	Length of the time window [0,maxTime] the catalog was observed over. If not specified, will be taken as the time of the last earthquake.
xs	(For the spatio-temporal ETAS model only), a vector containing the x coordinates of the earthquakes
ys	(For the spatio-temporal ETAS model only), a vector containing the y coordinates of the earthquakes
area	(For the spatio-temporal ETAS model only), a single number containing the area of the rectangular spatial region containing the earthquakes. For example if the earthquakes are defined on [28,35]x[-119,-128] then the area would be 7x9 = 63. If this is not specified then it will be calculated based on the distance between the furthest apart earthquakes in the catalog.
initval	Initial value at which to start the estimation. A vector, with elements (mu, K, alpha, c, p) for temporal fitting or (mu, K, alpha, c, p, sigma2x, sigma2y) for spatio-temporal fitting.
displayOutput	If TRUE, display likelihood values during model fitting.
zeromu	If the ETAS model is fit to a single aftershock sequence, we may want to force mu=0 in the model to have no background rate. Set zeromu=TRUE and the ETAS model will be fit under the assumption that mu=0
handle_ties	How to handle duplicate event times. The default "error" stops because continuous-time ETAS requires strictly increasing event times. "jitter" applies a deterministic, order-preserving jitter before fitting. This is a preprocessing convention, not part of the ETAS model.
c_lower	Lower bound for the Omori c parameter. If NULL, a data-scale default equal to one tenth of the smallest positive event-time gap after tie handling is used.

Details

In the spatio-temporal version of the model, $s(\cdot)$ is the multivariate Gaussian with diagonal covariance parameters σ_x^2 and σ_y^2 . The spatial background is homogeneous over the supplied area and no spatial edge correction is implemented. This function estimates the parameters of the ETAS model (both temporal and spatio-temporal) using maximum likelihood. Parameters are optimized on constrained transformed scales from multiple starting values, but the result is still a numerical maximum of a non-convex likelihood.

The likelihood assumes strictly increasing event times. By default duplicate times are rejected. With `handle_ties = "jitter"`, tied event times are separated deterministically by a small amount before fitting. The Omori c parameter is constrained to be greater than `c_lower`; this prevents finite-resolution catalogues with exact or near ties from driving c to zero.

Value

A list consisting of

params	A vector containing the estimated parameters, in the order (mu,K,alpha,c,p) for the temporal model or (mu,K,alpha,c,p,sigma2x,sigma2y) for the spatio-temporal model
loglik	The corresponding loglikelihood

Author(s)

Gordon J Ross

References

Gordon J. Ross - Bayesian Estimation of the ETAS Model for Earthquake Occurrences (2019)

Examples

```
#temporal model
ts <- c(1, 2, 3, 5, 8)
ms <- c(3.0, 3.1, 3.3, 3.2, 3.0)
maxLikelihoodETAS(ts, ms, M0=3, maxTime=10)

#spatio-temporal model
xs <- c(1, 2, 3, 4, 5)
ys <- c(1, 1.5, 2, 1.5, 1)
maxLikelihoodETAS(ts, ms, M0=3, maxTime=10, xs=xs, ys=ys, area=25)
```

simulateETAS

Simulates synthetic data from the ETAS model

Description

The ETAS model is widely used to quantify the degree of seismic activity in a geographical region, and to forecast the occurrence of future mainshocks and aftershocks (Ross 2019). The temporal ETAS model is a point process where the probability of an earthquake occurring at time t depends on the previous seismicity H_t , and is defined by the conditional intensity function:

$$\lambda(t|H_t) = \mu + \sum_{t[i]<t} \kappa(m[i]|K, \alpha)h(t - t[i]|c, p)$$

where

$$\kappa(m_i|K, \alpha) = Ke^{\alpha(m_i - M_0)}$$

and

$$h(t_i|c, p) = \frac{(p-1)c^{p-1}}{(t - t_i + c)^p}$$

and $s()$ is a spatial triggering kernel. The public spatio-temporal routines currently use a Gaussian spatial triggering kernel with a homogeneous spatial background over the supplied area and no spatial edge correction. $s()$ can also be omitted to fit the temporal ETAS model without a spatial component. The summation is over all previous earthquakes that occurred in the region, with the i 'th such earthquake occurring at time t_i at spatial location (x_i, y_i) and having magnitude m_i . The quantity M_0 denotes the magnitude of completeness of the catalog, so that $m_i \geq M_0$ for all i . The temporal ETAS model has 5 parameters: μ controls the background rate of seismicity, K and α determine the productivity (average number of aftershocks) of an earthquake with magnitude m , and c and p are the parameters of the Modified Omori Law (which has here been normalized to integrate to 1) and represent the speed at which the aftershock rate decays over time. Each earthquake is assumed to have a magnitude which is an independent draw from the Gutenberg-Richter law $p(m_i) = \beta e^{\beta(m_i - M_0)}$.

Usage

```
simulateETAS(
  mu,
  K,
  alpha,
  c,
  p,
  beta,
  M0,
  maxTime,
  sigma2x = NULL,
  sigma2y = NULL,
  xmin = NULL,
  xmax = NULL,
  ymin = NULL,
  ymax = NULL
)
```

Arguments

mu	Parameter of the ETAS model as described above.
K	Parameter of the ETAS model as described above.
alpha	Parameter of the ETAS model as described above.
c	Parameter of the ETAS model as described above.
p	Parameter of the ETAS model as described above.
beta	Parameter of the Gutenberg-Richter law used to generate earthquake magnitudes.
M0	Magnitude of completeness.
maxTime	Length of the time window $[0, \text{maxTime}]$ the catalog was observed over. If not specified, will be taken as the time of the last earthquake.
sigma2x	(For the spatio-temporal ETAS model only) Parameter of the spatio-temporal model as described above.

sigma2y	(For the spatio-temporal ETAS model only) Parameter of the spatio-temporal model as described above.
xmin	(For the spatio-temporal ETAS model only) Minimum x value of the spatial region
xmax	(For the spatio-temporal ETAS model only) Maximum x value of the spatial region
ymin	(For the spatio-temporal ETAS model only) Minimum y value of the spatial region
ymax	(For the spatio-temporal ETAS model only) Maximum y value of the spatial region

Details

In the spatio-temporal version of the model, $s()$ is the multivariate Gaussian with diagonal covariance parameters σ_x^2 and σ_y^2 . Spatial simulation uses a bounded-window discard convention: proposed spatial offspring outside the requested window are discarded and discarded offspring do not generate descendants. This is not an edge-corrected simulation of an infinite-plane ETAS process observed through a bounded window.

This function simulates sample data from the ETAS model (either temporal or spatio-temporal) over a particular time interval $[0, T]$, For the spatio-temporal model we also specify the range of the x axis region $[xmin, xmax]$ and the y axis region $[ymin, ymax]$.

Value

A list consisting of

ts	The simulated earthquake times
ms	The simulated earthquake magnitudes
locs	(For the spatio-temporal ETAS model only) A two column matrix wher the i'th row is the (x,y) location of earthquake i

Author(s)

Gordon J Ross

References

Gordon J. Ross - Bayesian Estimation of the ETAS Model for Earthquake Occurrences (2019)

Examples

```
set.seed(1)

#temporal model
beta <- 2.4; M0 <- 3; maxTime <- 20
catalog <- simulateETAS(0.1, 0.05, 1.0, 0.5, 2, beta, M0, maxTime)

#spatio-temporal model
```

```
sigma2x <- 0.2; sigma2y <- 0.2
xmin <- 0; xmax <- 10; ymin <- 0; ymax <- 10
catalog <- simulateETAS(0.1, 0.05, 1.0, 0.5, 2, beta, M0, maxTime,
  sigma2x, sigma2y, xmin, xmax, ymin, ymax)
```

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