**VAST user manual**

**James Thorson**

**Purpose** **of document**:

This document is intended to document the model structure and user-options available in package VAST. For guidance and examples of how to use the model, please see the Rmarkdown tutorials in the GitHub “/examples” directory. In the following, I try to use notation similar to the TMB code: I use parentheses to indicate a parameter or variable that is indexed by the specified indices, and I use subscripts for naming (e.g., to indicate different parameters for different model components). Feel free to change notation when describing the model to suite your purposes. For further details regarding terminology, motivation, and statistical properties, please read the papers listed on the GitHub main page.

**Model description**:

**Linear predictors**

The model potentially includes two linear predictors (because it is designed to support delta-models, which include two components). The first linear predictor represents encounter probability in a delta-model, or zero-inflation in a count-data model:

where is the predictor for observation , is an intercept for category and year , represents spatial variation at location for factor and is the loadings matrix that generates spatial covariation among categories for this linear predictor, is spatio-temporal variation and is the loadings matrix that generates spatio-temporal covariation for this predictor, is random variation in catchability among a grouping variable (tows or vessels) and is a loadings matrix that generates covariation in catchability among categories for this predictor, are measured density covariates that explain variation in density and is the estimated impact of density covariates, and are measured catchability covariates that explain variation in catchability and is the estimated impact of catchability covariates for this linear predictor. Similarly, the second linear predictor represents positive catch rates in a delta-model, or the count-data intensity function in a count-data model:

where all variables and parameters are defined similarly except using different subscripts (Thorson and Barnett In press, Thorson et al. In press). The loadings matrices are designed such that is the covariance among categories for a given spatial or spatio-temporal process (Thorson et al. 2015a), and when there is only one category is a 1x1 matrix (i.e. a scalar) such that its absolute value is the standard deviation for a given process. This model therefore reduces to a single-species spatio-temporal model (e.g., Thorson et al. 2015b) when only one category is available.

The user controls the number of spatial and spatio-temporal factors used for each component via input:

# Control number of factors

FieldConfig = c("Omega1"=1, "Epsilon1"=1, "Omega2"=1, "Epsilon2"=1)

where FieldConfig[1] controls , FieldConfig[2] controls , FieldConfig[3] controls , and FieldConfig[4] controls , and a value of zero “turns off” that component of spatial or spatio-temporal covariation. The user controls the number of catchability factors used for each component via input:

# Control number of spatial and spatio-temporal factors

OverdispersionConfig = c("Delta1"=0, "Delta2"=0)

where OverdispersionConfig[1] controls , and OverdispersionConfig[2] controls , and a value of zero again “turns off” that component of random covariation in catchability. For example, if the user inputs:

# Control number of spatial and spatio-temporal factors

OverdispersionConfig = c("Delta1"=1, "Delta2"=1)

then there will be one random effect estimated for each unique level of Data\_Geostat$Vessel for both the first and second linear predictors.

**Link functions**

There are different user-controlled options for link-functions that calculate expected encounter probability and positive catch rates given these two linear predictors.

# Control observation error

ObsModel = c("PosDist"=2, "Link"=0)

where the 2nd element of this vector controls the link functions.

1. ObsModel[2]=0 applies a logit-link for the first linear predictor:

where is the predictor encounter probability in a delta-model, or zero-inflation in a count-data model, and is the logistic function of , and:

where is the predicted biomass density for positive catch rates in a delta-model or mean-intensity function for a count-data model, is the exponential function of , and is the area-swept for observation , which enters as a linear offset for expected biomass given an encounter.

1. Alternatively, ObsModel[2]=1 corresponds to a “Poisson-link” function that approximates a Tweedie distribution:

where is the predictor encounter probability and is a complementary log-log link of , and:

where is the predicted biomass given that the species is encountered. In this “Poisson-process” link function, is interpreted as the density in number of individuals per area such that is the predicted number of individuals encountered, and is interpreted as the average weight per individual. Area-swept therefore enters as a linear offset for the expected number of individuals encountered (Thorson In review). This Poisson-link function should only be used for delta-models, and not for count-data models.

**Observation models**:

There are different user-controlled options for observation models for available sampling data, which are controlled by ObsModel[1].

# Control observation error

ObsModel = c("PosDist"=2, "Link"=0)

I distinguish between observation models for continuous-valued data (e.g., biomass, or numbers standardized to a fixed area), and observation models for count data (e.g., numbers treating area-swept as an offset). However, both are parameterized such that the expectation for sampling data .

*Continuous-valued data (e.g., biomass)*

If using an observation model with continuous support (e.g., a normal, lognormal, gamma, or Tweedie models), VAST calculates the probability of data as:

where ObsModel[1] controls the probability density function used for positive catch rates (see ?Data\_Fn for a list of options), where each options is defined to have with expectation and dispersion , where dispersion parameter varies among categories by default.

*Discrete-valued data (e.g., abundance)*

If using an observation model with discrete support (e.g., a Poisson, negative-binomial, Conway-Maxwell Poisson, or lognormal-Poisson models), VAST calculates the probability of data as:

where ObsModel[1] controls the probability mass function used (again, see ?Data\_Fn for a list of options), where I use … to signify that these probability mass functions generally can have one or more parameter governing dispersion, and the precise number and interpretation varies among observation models (i.e., the value of ObsModel[1]). For these count-data models, is the “zero-inflation probability” (i.e., the proportion of habitat in the immediate vicinity of location and time ) that is never occupied, while is the expected value for the probability mass function.

**Settings regarding spatial domain**

VAST approximates spatial and spatio-temporal variation as being piecewise-constant. To do so, the user specifies n\_x:

# Number of knots

n\_x = 1000

VAST then uses a k-means algorithm to identify the location of n\_x knots to minimize the total distance between the location of available data and the location of the nearest knot. This distributes knots as a function of the spatial intensity of sampling data.

VAST then uses a stochastic partial differential equation (SPDE) approximation to the probability density function for spatial and spatio-temporal variation (Lindgren et al. 2011). This SPDE approximation involves generating a triangulated mesh that has a vertex of a triangle at each knot, and VAST generates this triangulated mesh using package *R-INLA* (Lindgren 2012). Outputs from this triangulated mesh can then be used to calculate the precision (inverse-covariance) matrix for a multivariate normal probability density function for the value of a spatial variable at each mesh vertex. Specifically, the correlation between location and location for spatial and spatio-temporal terms included in the first linear predictor is approximated as following a Matern function:

where is a two-dimensional linear transformation representing geometric anisotropy (with a determinant of 1.0), is the Matern smoothness (fixed at 1.0), and governs the decorrelation distance for that first linear predictor ( is also separately estimated for the second linear predictor). By default, the two degrees of freedom in are estimated as fixed effects, but the user can specify isotropy (i.e., ) by specifying:

# Turn of geometric anisotropy

Data = Data\_Fn( …, Aniso=FALSE )

VAST then specifies that the spatial and spatio-temporal Gaussian random fields each have a variance of 1.0. By default VAST specifies these as follows:

where is the vector formed when subsetting for a given , and is the variance of , where other parameters are defined similarly. Specifying a variance of 1.0 ensures that the covariance among categories is defined by the loadings matrix for that term. However, VAST allows spatio-temporal variance to be specified differently as discussed in the section titled “Structure on parameters among years”.

**Structure on parameters among years**:

There are different user-controlled options for specifying structure for intercepts or spatio-temporal variation across time, using input:

# Control autoregressive structure for parameters over time

RhoConfig = c("Beta1"=0, "Beta2"=0, "Epsilon1"=0, "Epsilon2"=0)

By default (when RhoConfig[1]=0 and RhoConfig[2]=0) the model specifies that each intercept and is a fixed effect. However, other settings specify the following structure:

where RhoConfig[1] controls the specification of :

1. *Independent among years* – RhoConfig[1]=1 specifies
2. *Random walk*  – RhoConfig[1]=2 specifies
3. *Constant intercept* – RhoConfig[1]=3 specifies and (i.e., is constant for all )
4. *Autoregressive* – RhoConfig[1]=4 estimates as a fixed effect

and settings are defined identically for RhoConfig[2] specifying .

By default (when RhoConfig[3]=0 and RhoConfig[4]=0) the model specifies that each spatio-temporal random effect and is independent among years. However, other settings specify the following structure

where RhoConfig[3] controls the specification of :

1. *Random walk*  – RhoConfig[3]=2 specifies
2. *Autoregressive* – RhoConfig[3]=4 estimates as a fixed effect

and settings are defined identically for RhoConfig[4] specifying .

**Relationship to other named models**

VAST can be configured to be identical to (or closely mimic) many models that have previously been published in ecology and fisheries:

1. *Spatial Gompertz model*:If intercepts are constant across years, spatio-temporal variation follows an autoregressive process, and only one category is modelled, then VAST is identical to a spatio-temporal Gompertz model (Thorson et al. 2014).
2. *Spatial factor analysis*:If only one year is analysed and multiple category are modelled, VAST is similar to spatial factor analysis (Thorson et al. 2015a), although it permits the use of a delta-model (separate analysis of encounters and positive catch rates).
3. *Spatial dynamic factor analysis*: If intercepts are constant among years, spatio-temporal variation follows an autoregressive process, and multiple category are modelled, then VAST is similar to spatial dynamic factor analysis (Thorson et al. 2016a), although VAST allows separate estimates of spatial vs. spatio-temporal covariation and also the user of a delta-model.

**Settings regarding derived quantities**

After a nonlinear minimizer has identified the value of fixed effects that maximizes the Laplace approximation to the marginal likelihood, Template Model Builder predicts the value of random effects that maximizes the joint likelihood conditional on these fixed effects. Estimated values of fixed and random effects are then used to predict density for :

where and are identical to the values specified previously, except that catchability variables are excluded from their computation (i.e., and , etc.)

By default, density is used to predict total abundance for the entire domain (or a subset of the domain) for a given species:

where is the area associated with extrapolation-cell for index (Shelton et al. 2014, Thorson et al. 2015b). The user can also specify additional post-hoc calculations via input:

# Control observation error

RhoConfig = c("SD\_site\_density"=0, "SD\_site\_logdensity"=0, "Calculate\_Range"=0, "Calculate\_evenness"=0, "Calculate\_effective\_area"=0, "Calculate\_Cov\_SE"=0, 'Calculate\_Synchrony'=0, 'Calculate\_Coherence'=0)

1. *Distribution shift* – RhoConfig[3]=1 turns on calculation of the centroid of the population’s distribution:

where is a matrix representing location for each knot (by default is the location in Eastings and Northings of each knot), representing movement North-South and East-West). This model-based approach to estimating distribution shift can account for differences in the spatial distribution of sampling, unlike conventional sample-based estimators (Thorson et al. 2016b).

1. *Range expansion* – RhoConfig[5]=1 turns on calculation of effective area occupied. This involves calculating biomass-weighted average density:

Effective area occupied is then calculated as the area required to contain the population at this average density:

This effective-area occupied estimator can then be used to monitor range expansion or contraction or density-dependent range expansion (Thorson et al. 2016c).

**Works cited**

Lindgren, F. 2012. Continuous domain spatial models in R-INLA. ISBA Bull. **19**(4): 14–20.

Lindgren, F., Rue, H., and Lindström, J. 2011. An explicit link between Gaussian fields and Gaussian Markov random fields: the stochastic partial differential equation approach. J. R. Stat. Soc. Ser. B Stat. Methodol. **73**(4): 423–498. doi:10.1111/j.1467-9868.2011.00777.x.

Shelton, A.O., Thorson, J.T., Ward, E.J., and Feist, B.E. 2014. Spatial semiparametric models improve estimates of species abundance and distribution. Can. J. Fish. Aquat. Sci. **71**(11): 1655–1666. doi:10.1139/cjfas-2013-0508.

Thorson, J.T. In review. Three problems with the conventional delta-model for biomass sampling data, and a computationally efficient alternative.

Thorson, J.T., and Barnett, L.A.K. In press. Comparing estimates of abundance trends and distribution shifts using single- and multispecies models of fishes and biogenic habitat. ICES J. Mar. Sci. doi:10.1093/icesjms/fsw193.

Thorson, J.T., Ianelli, J.N., and Kotwicki, S. In press. The relative influence of temperature and size structure on fish distribution shifts: a case study on walleye pollock in the Bering Sea. Fish Fish.

Thorson, J.T., Ianelli, J.N., Larsen, E.A., Ries, L., Scheuerell, M.D., Szuwalski, C., and Zipkin, E.F. 2016a. Joint dynamic species distribution models: a tool for community ordination and spatio-temporal monitoring. Glob. Ecol. Biogeogr. **25**(9): 1144–1158. doi:10.1111/geb.12464.

Thorson, J.T., Pinsky, M.L., and Ward, E.J. 2016b. Model-based inference for estimating shifts in species distribution, area occupied and centre of gravity. Methods Ecol. Evol. **7**(8): 990–1002. doi:10.1111/2041-210X.12567.

Thorson, J.T., Rindorf, A., Gao, J., Hanselman, D.H., and Winker, H. 2016c. Density-dependent changes in effective area occupied for sea-bottom-associated marine fishes. Proc R Soc B **283**(1840): 20161853. doi:10.1098/rspb.2016.1853.

Thorson, J.T., Scheuerell, M.D., Shelton, A.O., See, K.E., Skaug, H.J., and Kristensen, K. 2015a. Spatial factor analysis: a new tool for estimating joint species distributions and correlations in species range. Methods Ecol. Evol. **6**(6): 627–637. doi:10.1111/2041-210X.12359.

Thorson, J.T., Shelton, A.O., Ward, E.J., and Skaug, H.J. 2015b. Geostatistical delta-generalized linear mixed models improve precision for estimated abundance indices for West Coast groundfishes. ICES J. Mar. Sci. J. Cons. **72**(5): 1297–1310. doi:10.1093/icesjms/fsu243.

Thorson, J.T., Skaug, H.J., Kristensen, K., Shelton, A.O., Ward, E.J., Harms, J.H., and Benante, J.A. 2014. The importance of spatial models for estimating the strength of density dependence. Ecology **96**(5): 1202–1212. doi:10.1890/14-0739.1.