

# State Space Models for Regional Epidemiological Indicators

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# Abstract

Short summary of the contents in English. . .

# Zusammenfassung

Kurze Zusammenfassung des Inhaltes in deutscher Sprache. . .



# Publications and Contributions

This thesis consists of mostly unpublished work. During my time as a PhD student I have, however, been fortunate to collaborate with many scientists on problems in mathematical epidemiology with a focus on COVID-19, which resulted in several publications. In this section I want to clarify what my contributions to these publications were and which contributions of the present thesis are new.

- [1] J. Bracher et al. “A Pre-Registered Short-Term Forecasting Study of COVID-19 in Germany and Poland during the Second Wave.” In: *Nature Communications* 12.1 (1 Aug. 27, 2021), p. 5173. ISSN: 2041-1723. DOI: [10.1038/s41467-021-25207-0](https://doi.org/10.1038/s41467-021-25207-0). URL: <https://www.nature.com/articles/s41467-021-25207-0> (visited on 09/30/2021).
- [2] Johannes Bracher et al. “National and Subnational Short-Term Forecasting of COVID-19 in Germany and Poland during Early 2021.” In: *Communications Medicine* 2.1 (1 Oct. 31, 2022), pp. 1–17. ISSN: 2730-664X. DOI: [10.1038/s43856-022-00191-8](https://doi.org/10.1038/s43856-022-00191-8). URL: <https://www.nature.com/articles/s43856-022-00191-8> (visited on 11/16/2022).
- [3] Jan Pablo Burgard, Stefan Heyder, Thomas Hotz, and Tyll Krueger. “Regional Estimates of Reproduction Numbers with Application to COVID-19.” Aug. 31, 2021. arXiv: [2108.13842](https://arxiv.org/abs/2108.13842) [stat]. URL: <http://arxiv.org/abs/2108.13842> (visited on 09/30/2021).
- [4] Sara M. Grundel, Stefan Heyder, Thomas Hotz, Tobias K. S. Ritschel, Philipp Sauerteig, and Karl Worthmann. “How to Coordinate Vaccination and Social Distancing to Mitigate SARS-CoV-2 Outbreaks.” In: *SIAM Journal on Applied Dynamical Systems* 20.2 (Jan. 1, 2021), pp. 1135–1157. DOI: [10.1137/20M1387687](https://doi.org/10.1137/20M1387687). URL: <https://epubs.siam.org/doi/abs/10.1137/20M1387687> (visited on 01/21/2022).
- [5] Sara Grundel, Stefan Heyder, Thomas Hotz, Tobias K. S. Ritschel, Philipp Sauerteig, and Karl Worthmann. “How Much Testing and Social Distancing Is Required to Control COVID-19? Some Insight Based on an Age-Differentiated Compartmental Model.” In: *SIAM Journal on Control and Optimization* 60.2 (Apr. 2022), S145–S169. ISSN: 0363-0129, 1095-7138. DOI: [10.1137/20M1377783](https://doi.org/10.1137/20M1377783). URL: <https://epubs.siam.org/doi/10.1137/20M1377783> (visited on 11/16/2022).

- [6] Thomas Hotz, Matthias Glock, Stefan Heyder, Sebastian Semper, Anne Böhle, and Alexander Krämer. “Monitoring the Spread of COVID-19 by Estimating Reproduction Numbers over Time.” Apr. 18, 2020. arXiv: [2004.08557](https://arxiv.org/abs/2004.08557) [q-bio, stat]. URL: <http://arxiv.org/abs/2004.08557> (visited on 07/20/2020).
- [7] K. Sherratt et al. *Predictive Performance of Multi-Model Ensemble Forecasts of COVID-19 across European Nations*. June 16, 2022. DOI: [10.1101/2022.06.16.22276024](https://doi.org/10.1101/2022.06.16.22276024). URL: <http://medrxiv.org/lookup/doi/10.1101/2022.06.16.22276024> (visited on 11/28/2022). preprint.



*Du musst bereit sein Dinge zu tun.*

— A meme on the internet, 2022.

## Acknowledgments

Put your acknowledgments here.

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## Chapter 1

### Introduction



## Chapter 2

# Epidemiological considerations

- COVID-19 induced unprecedented interest in epidemiological modelling from all disciplines, but also mathematics
- this chapter highlights challenges that epi modelling brings and what desirable outcomes would be from an applied perspective
- mathematical epidemiology concerns itself with modelling epidemiological systems, from small (local outbreaks) to large (epi/pandemics)
- conclusions from analysis only as good as the model and the data are
- depending on goal and circumstances different methods are applicable
- by its nature, data are observational so causal claims difficult
- in this thesis I focus on models for larger-scale epidemics, techniques would be flexible enough to deal with smaller scale as well, as long as latent states are gaussian

### 2.1 Objectives of epidemiological modelling

#### Monitoring

- monitoring is real-time scenario, interested in current developments, i.e. recent past and near future. complicated by potentially slow reporting, data revisions
- informs decision makers on whether measures should be taken
- ForecastHub(s) provide platform that creates ensemble forecast to obtain better predictions [3, 4, 20, 23]

#### Retrospective Analysis

- evaluation of measures taken, want interpretation as causal as possible
- informs decision makers on which measures were effective and how much

- difficult due to usual reasons: poor data quality, observational data, causal structure difficult, early/late adoption makes timing of measurements difficult
- cite some papers that did this [5, 12, 16]

### Scenario Modelling

- concerns itself with modelling the impact that variants, seasonality etc. have in specific scenarios
- find out whether there is already paper of ECDC to cite

## 2.2 Available data and its quality

- surprising amount of data available, but quality questionable,
- in Germany have data on reported cases and deaths by gender, age group, county, with reporting date of case and for some cases even date of symptom onset
- reporting of cases is regulated by Infektionsschutzgesetz
- parallel dataset for reports of hospitalisations
- have description section from Nowcasting draft here
- descriptive statistics of German COVID-19 data set
- even larger datasets that compile this for europe + EFTA (?) by ECDC or by world (JHU)
- quality of reported case data is potentially too low
  - reporting delays
  - weekday effects
  - testing regime changing (2G/3G)
  - ...
- data on commuting

## 2.3 Measures of epidemic spread

This section consists of the ideas published in [14], but has been rewritten to fit better into this thesis.

- not only epidemic spread but also speed of proliferation is of interest, enables forecasts
- measuring speed difficult: data problems ... (look at AK book article)
-

**Growth Factor**

**Reproduction number**

**Other indicators**

**Usefulness of indicators**

## **2.4 Dessiderata for epidemiological models**

- we want models to be able to include as much data as possible, while still being numerically tractable

**Regional dependencies and effects**

- German case data are reported on Landkreis level, performing analysis of each individual is not sensible
- inhabitants travel between regions, and measures were taken on regional level as well
- effects are not really spatial: euclidean distance is not so much of an issue but how closely connected regions are (give some examples)
- also want to account for other regional effects such as different socio-economic settings ...

**Temporal correlation**

**Interpretability**





## Chapter 3

# State space models

State space models are a versatile class of statistical models which allow to model non-stationary time series data and come along with straight-forward interpretation. The main idea of these models is to introduce unobserved **latent states** whose joint distribution is given by a Markov process and model the observed time series conditional on these states. By exploiting this structure, inference in state space models (SSMs) becomes computationally efficient, i.e. the complexity of algorithms is linear with respect to the number  $n$  of time points considered.

An additional advantage, that will become more explicit in Section 3.1, is that SSMs allow to interpret the modeled dynamics of latent states which makes

**Definition 3.1** (State Space Model). A **SSM** is a discrete time stochastic process  $(X_t, Y_t)_{t=0, \dots, n-1}$  taking values in a measurable space  $\mathcal{X} \times \mathcal{Y}$  such that

1. The marginal distribution of the **states**  $(X_0, \dots, X_{n-1})$  is a discrete time Markov process, i.e. for  $t = 1, \dots, n-1$

$$\mathbf{P}(X_t \in B | X_0, \dots, X_{t-1}) = \mathbf{P}(X_t \in B | X_{t-1}) \quad (3.1)$$

for all measurable  $B \subseteq \mathcal{X}$ .

2. Conditional on the state  $X_t$  and observation  $Y_{t-1}$ ,  $Y_t$  is independent of  $X_s$  and  $Y_{s-1}$ ,  $s < t$ , i.e.

$$\mathbf{P}(Y_t \in B | X_0, \dots, X_t, Y_0, \dots, Y_{t-1}) = \mathbf{P}(Y_t \in B | X_t, Y_{t-1})$$

for all measurable  $B \subseteq \mathcal{Y}$ .

For notational convenience we will write  $X_{s:t} = (X_s, \dots, X_t)$  for the vector that contains all states from  $s$  to  $t$ , dropping the first index if we consider the whole set of observations up to time  $t$ , so  $X_{:t} = X_{0:t}$ . Similarly we set  $Y_{s:t} = (Y_s, \dots, Y_t)$  and  $Y_t = Y_{0:t}$ .

picture of dependency structure

*Remark.* Contrary to the standard definition of a SSM, our Definition 3.1 allows  $Y_t$  to depend on  $Y_{t-1}$ . This is not a limitation of the standard definition: given a SSM of the form in Definition 3.1 we can transform it to the standard form by choosing states  $(X_t, Y_t) \in \mathcal{X} \times \mathcal{Y}$  and observations  $Y_t \in \mathcal{Y}$  such that the SSM becomes a stochastic process on  $(\mathcal{X} \times \mathcal{Y}) \times \mathcal{Y}$ .

Additionally, most computations and inferences in this thesis will be conditioned on a single set of observations  $Y$ . As such  $Y$  may be treated as fixed and  $Y_t$  only depends on  $X_t$ . The only exception to this is in simulation studies where we sample from the joint distribution of  $(X, Y)$ .

As the models considered in Chapter 4 will make extensive use of SSMs with this dependency structure we opt to use this non-standard definition here.

In most models we consider in this thesis we use  $\mathcal{X} = \mathbf{R}^m$ ,  $\mathcal{Y} = \mathbf{R}^p$  or  $\mathcal{Y} = \mathbf{Z}^p$  so that  $\mathcal{X}$  is  $m$  dimensional and  $\mathcal{Y}$  is  $p$  dimensional and equip these spaces with the usual Borel  $\sigma$ -Algebras.

Most models that I consider in this thesis will admit densities for the state transitions w.r.t. a common dominating measure  $\mu_{\mathcal{X}}$  and similar for the observations w.r.t. a (potentially different) domination measure  $\mu_{\mathcal{Y}}$ .

check whether there are models that violate this

*Notation* (Densities, conditional densities). I will use the standard abuse of notation for densities that makes the type of density „obvious“ from the arguments used. This means that  $p(x)$  is the density for all states  $X$ ,  $p(x_t|x_{t-1})$  the conditional density of  $X_t|X_{t-1}$  and similarly for observations:  $p(y|x)$  is the density of all observations  $Y$  conditional on all states  $X$ .

Note that this notation also implicitly includes the time  $t$  and allows for changes in, e.g., the state transition over time.

When densities stem from a parametric model parametrized by  $\theta \in \Theta \subseteq \mathbf{R}^k$  and the dependence of the model on  $\theta$  is of interest, i.e. because we try to estimate  $\theta$ , we indicate this by adding a subscript to the densities. If the dependence is not of interest, e.g. because  $\theta$  is fixed, I will usually omit  $\theta$  for better readability.

In this notation, the joint density of a parametric SSM factorizes as

$$\begin{aligned} p_{\theta}(x, y) &= p_{\theta}(x_0, \dots, x_{n-1}, y_0, \dots, y_{n-1}) \\ &= p_{\theta}(x_0) \prod_{t=1}^{n-1} p_{\theta}(x_t|x_{t-1}) \prod_{t=0}^{n-1} p_{\theta}(y_t|x_t, y_{t-1}), \end{aligned}$$

where  $p_{\theta}(y_0|x_0, y_{-1}) = p_{\theta}(y_0, x_0)$ .

As inferences we make in this thesis depend on the SSM only through the likelihood we identify almost sure versions of  $(X, Y)$  with itself, i.e. all equations involving  $X$  or  $Y$  are understood almost surely.

Given data  $(y_t)_{t=0, \dots, n-1}$  that may be modeled with a SSM the practitioner is confronted with several tasks, which provide the structure of this chapter:

1. Choosing a suitable, usually parametric, class of SSMs that include the effects of interest.
2. Fitting such a parametric model to the data at hand by either frequentist or Bayesian techniques.
3. Infer about the latent states  $X$  from the observations  $Y$  by determining, either analytically or through simulation, the smoothing distribution  $X|Y$ .

The first step, item 1, requires that the practitioner specifies a joint probability distribution for the states and observations (Section 3.1). Due to the

assumed dependency structure this boils down to specifying transition kernels for the states and observations. The setting Definition 3.1 is too abstract to perform inference in so further assumptions on the types of distributions for the latent states and observations are needed. In this chapter we will discuss Gaussian linear state space model (GLSSM) (Section 3.2), where both the posterior distribution and the likelihood are analytically available. For the epidemiological application we have in mind these are however insufficient due to the non-linear behaviour of incidences and the low count per region (Section 2.4). Such observations are better modeled with distributions on the natural numbers, i.e. with a Poisson or negative binomial distribution, leading to the class of logconcave Gaussian state space models (Section 3.3).

Regarding the second step, item 2, a frequentist practitioner will want to perform maximum likelihood inference on  $\theta$ . While asymptotic confidence intervals for  $\theta$  can be derived both theoretically and practically [10, Chapter 7], they are, in the context of this thesis, usually of little interest. We choose to view this fitting as an Empirical Bayes procedure and our main practical interest lies in analyzing the posterior distribution  $X|Y$ .

To obtain the maximum likelihood estimates  $\hat{\theta}$  one needs access to the likelihood

$$p(y) = \int_{\mathcal{X}^n} p(x, y) \, dx, \quad (3.2)$$

which is usually not analytically available. Direct numerical evaluation of Equation (3.2) is hopeless due to the high dimensionality of the state space  $\mathcal{X}^n$ . Instead we will resort to simulation based inference by importance sampling (see Section 3.4), an alternative would be particle filters [9].

The performance of these simulations depends crucially on constructing distributions that are close to the posterior  $p(x|y)$  but are easy to sample from. To this end, we construct suitable Gaussian state space models (Section 3.5) in which sampling from the posterior is analytically possible. This will be a good strategy if the target posterior  $p(x|y)$  can be well approximated by a Gaussian distribution — otherwise, we may want to account for multiple modes by considering mixtures of Gaussian state space models or account for heavy tails with t-distributed errors (Section 3.6).

### 3.1 Modelling epidemiological dessiderata with state space models

#### 3.2 Linear Gaussian state space models

- joint model is gaussian
- filtering distribution obtained by Kalman filter
- smoothing distribution obtained by Kalman smoother
- variants: sqrt filter / precision filter
- gaussian likelihood analytically available, MLE can be found by numerical methods (gradient descent or EM, depending on problem)

- computation is efficient: linear in time dimension  $n$
- $Y_{t+1}$  may also depend on  $Y_t$  as we will target the conditional distribution anyways

GLSSM are the working horses of most methods used in this thesis because they are analytically tractable and computationally efficient. Indeed for fixed dimension of states  $m$  and observations  $p$  the runtime of algorithms that we consider in this thesis is  $\mathcal{O}(n)$ .

**Definition 3.2** (GLSSM). A GLSSM is a state space model where states obey the transition equation

$$X_{t+1} = A_t X_t + u_t \varepsilon_{t+1} \quad t = 0, \dots, n-1, \quad (3.3)$$

and observations obey the observation equation

$$Y_t = B_t X_t + v_t + \eta_t \quad t = 0, \dots, n. \quad (3.4)$$

Here  $A_t \in \mathbf{R}^{m \times m}$  and  $B_t \in \mathbf{R}^{p \times m}$  are matrices that specify the systems dynamics. The **innovations**  $\varepsilon_{t+1}$  and **measurement noise**  $\eta_t$  are independent from one another and from the starting value  $X_0 \sim \mathcal{N}(\mathbf{E}X_0, \Sigma_0)$ .

Furthermore,  $\varepsilon_{t+1} \sim \mathcal{N}(0, \Sigma_t)$  and  $\eta_t \sim \mathcal{N}(0, \Omega)$  are centered Gaussian random variables and  $u_{t+1}, t = 1, \dots, n-1, v_t, t = 0, \dots, n$  are deterministic biases.

The defining feature of a GLSSM is that its joint distribution is Gaussian.

**Lemma 3.1.** A state space model can be written as a GLSSM if and only if its joint distribution is Gaussian.

technicailty: distinguish between a.s. version

*Proof.*

□

As the joint distribution of  $(X, Y)$  is Gaussian, so are conditional distributions of states given observations. Two such distributions are of interest: the **filtering distribution** is the conditional distribution of  $X_t$  given all observations until time  $t$ , that is  $Y_{0:t}$ . When  $t < n$  this is distinct from the **smoothing distribution**, i.e. the distribution of  $X_t$  given all observations  $Y$ .

Note that the filtering distributions does not specify a valid joint distribution for the states, but the smoothing does.

Both distributions may be obtained efficiently using the celebrated Kalman filter and smoother algorithms.

cite correctly

---

#### Algorithm 1: Kalman filter

---

**Input:** observations  $y = (y_0, \dots, y_n)$ , GLSSM

**Output:** filtered expectations  $\hat{X}_{t|t}$ , covariance matrices  $\Xi_{t|t}$ , likelihood  $p(y)$

*Initialization;*

$\hat{y}_{0|-1} = B_0 \hat{x}_{0|-1} + v_t$ ;

$\Psi_{0|-1} = B_0 \Sigma_0 B_0^T + \Omega_0$ ;

*Prediction;*

*Filter;*

---

---

**Algorithm 2:** Kalman smoother

---

**Input:** observations  $y = (y_0, \dots, y_n)$ , GLSSM**Output:** filtered expectations  $\hat{X}_{t|t}$  and covariance matrices  $\Xi_{t|t}$ *Initialization;* $\hat{y}_{0|-1} = B_0 \hat{x}_{0|-1} + v_t;$  $\Psi_{0|-1} = B_0 \Sigma_0 B_0^T + \Omega_0;$ *Prediction;**Filter;*

---

Notice that the Kalman filter calculates the likelihood  $p(y)$  while filtering — this is possible because of the dependency structure of the state space model — this makes inference via maximum likelihood possible in GLSSMs.

To ensure numerical stability in these algorithms, the square root filter and smoother [19] may be used, see also [Schneider1986Kalmanfilter] for an accessible introduction to it and other variants.

The Kalman smoother computes the marginal distributions  $X_t|Y$  for  $t = 0, \dots, n-1$  and, owing to the Markov structure of the states, these are enough to specify the joint distribution  $X|Y$ , allowing to simulate from it.

---

**Algorithm 3:** Forwards filter, backwards smoother [13, Proposition 1]

---

**Input:** TODO**Output:** TODO*Something;*

---

The modeling capacity of GLSSM is, however, limited: most interesting phenomena follow neither linear dynamics nor are well modeled by a Gaussian distribution. Nevertheless, linearization of non-linear dynamics suggests that GLSSMs may have some use as approximations to these more complicated phenomena, provided they are sufficiently close to Gaussian models, e.g. uni-modal and without heavy tails. We start to move away from linear Gaussian models by allowing observations that are non-Gaussian.

### 3.3 Logconcave Gaussian state space models

- replace gaussian observations with log concave observations
- motivation for logconcave distributions: posterior has unique mode, because up to constants  $\log p(x|y) = -\frac{1}{2}(x - \mu)^T \Sigma^{-1}(x - \mu) + \log p(y|x)$  so  $\log p(x|y)$  is concave
- not restricted to same type of distribution per time step (though in ISSSM it will be)
- Laplace approximation sensible for these types of models: single mode
- special case: exponential family distributions

The distribution of observations is never Gaussian - all statisticians may hope for is that the data-generating mechanism is close enough to a Gaussian distribution that inferences made carry over. For epidemiological models, Gaussian distributions are appropriate if incidences are high, e.g. during large outbreaks in a whole country. When case numbers are small, the discrete nature of incidences is better captured by a distribution on  $\mathbf{N}_0$ , and standard distributions used are the Poisson and negative binomial distributions, see . Both the Poisson and negative binomial belong to the class of exponential family distributions. As such, their densities have a simple structure, allowing only for a linear interaction between the natural parameter and the densities argument. We refer to [6] for a comprehensive treatment of exponential families and use their definitions throughout this chapter.

auto/cref?

**Definition 3.3** (exponential family). Let  $\mu$  be a  $\sigma$ -finite measure on  $\mathbf{R}^p$  and denote by

$$\Theta = \left\{ \theta \in \mathbf{R}^p : \int \exp(\theta^T x) \, d\mu(y) < \infty \right\}$$

the set of parameters  $\theta$  such that the moment-generating function of  $\mu$  is finite. For every  $\theta \in \Theta$

$$p_\theta(y) = Z(\theta)^{-1} \exp(\theta^T y)$$

defines a probability density with respect to the measure  $\mu$ , where

$$Z(\theta) = \int \exp(\theta^T x) \, d\mu(y)$$

is the normalizing constant. We call both the densities  $p_\theta$  and induced probability measures

$$\mathbf{P}_\theta(A) = \int_A p_\theta(y) \, d\mu(y),$$

for measurable  $A \subset \mathbf{R}^p$  **standard exponential families**.

Conversely, let  $\mathbf{P}_\theta, \theta \in \Theta$  be a given parametric family of probability measures on some space  $\mathcal{Y}$  that is absolutely continuous with respect to a common dominating measure  $\mu$ . Suppose there exists a reparametrization  $\eta : \Theta \rightarrow \mathbf{R}^p$ , a statistic  $T : \mathcal{Y} \rightarrow \mathbf{R}^p$  and functions  $Z : \Theta \rightarrow \mathbf{R}$ ,  $h : \mathcal{Y} \rightarrow \mathbf{R}$  exist, such that

$$p_\theta(y) = \frac{dP_\theta}{d\mu} = Z(\theta) h(y) \exp(\eta(\theta)^T T(y)),$$

then we call  $\mathbf{P}_\theta, \theta \in \Theta$  and  $p_\theta, \theta \in \Theta$  a  **$p$ -dimensional exponential family**.

necessary?

**Definition 3.4** (curved exponential family).

Exponential families have the attractive property that they are log-concave in their parameters. As such the Fisher-information is always positive semidefinite, which will be crucial in defining surrogate Gaussian models in .

later section

**Lemma 3.2** (log-concavity of exponential family distributions). *Let  $p_\theta, \theta \in \Theta$  be a natural dimensional exponential family and  $\Theta$  open in  $\mathbf{R}^p$ . In this case  $\theta \rightarrow \log p_\theta(y)$  is concave for every  $y \in \mathbf{R}^p$ .*

*Proof.* As  $\log p_\theta(y) = -\log Z(\theta) + \theta^T y$  it suffices to show that  $\log Z(\theta)$  is convex. However,  $\log Z(\theta)$  is the cumulant generating function of the base measure  $\mu$  which is known to be convex.  $\square$

more reasoning? differentiate under integral, check if dominated convergence applies, or look for a ref

We now generalize definition 3.2 to allow for non-gaussian observations by replacing the observation equation eq. (3.4) by more general exponential families.

**Definition 3.5** (Logconcave state space model (LCSSM)). A **LCSSM** is a state space model where states obey the transition equation

$$X_{t+1} = A_t X_t + u_t \varepsilon_{t+1}$$

and the conditional distribution of  $Y_t$  given  $X_t$  comes from an exponential family with respect to a base measure  $\mu_t$ , i.e.

$$p(y_t|x_t) = h_t(y_t)Z_t(x_t) \exp(\eta_t(x_t)^T T_t(y_t))$$

for suitable functions  $h_t, Z_t, \eta_t, T_t$ .

LCSSM only logconcave observations would suffice, then EF is just an instance of this

*Remark.* To simplify notation we will drop in our notation the dependence of  $h$ ,  $Z$ , and  $T$  on  $t$  and assume that the base measure  $\mu_t$  is the same for all relevant  $t$ .

As in the previous chapter, after having observed  $Y$ , one is interested in the conditional distribution of states  $X$ , given  $Y$ . If the observations are not Gaussian, this is a difficult task as the distribution is not analytically tractable. Instead approximations, e.g. the Laplace approximation (LA) (see ??, or simulation based inference, e.g. importance sampling or MCMC-methods, are used. Similarly, fitting hyperparameters  $\theta$  by maximum likelihood inference becomes more difficult as evaluating  $\ell(\theta) = p(y) = \int p(x, y) dx$  is not analytically available, thus requiring numerical or simulation methods for evaluation and gradient descent or EM-techniques for optimization (.

really EM?

In this thesis we will use importance sampling methods, which are the focus of the next section.

move this to the LA section

Under appropriate assumptions on the observation distributions, the LA is given by a (possibly degenerate) GLSSM [11, 22], though the derivations and computations are more involved in the nonlinear case or if the observation densities are not log-concave.

**Theorem 3.1** (LA of LCSSM).

this paragraph to modelling chapter

The Poisson distribution arises from the law of small numbers: if there is a large population where every individual has, independently, a small probability of becoming infected in a small window of time then the total number of infections in that window of time is well approximated by the Poisson distribution. Indeed, the law of small numbers remains valid for small dependencies [2, 21]. However, incidences observed from the SARS-CoV-2 epidemic tend to follow a negative binomial distribution [7].

### 3.4 Importance Sampling

some intro

Importance sampling is a simulation technique that allows to approximate expectations by sampling from a tractable approximation, the proposal, to the measure of interest, the target, and weighting samples according to their importance. As the user has freedom in the choice of approximation (except for some technical conditions), importance sampling also acts as a variance reduction technique with better approximations resulting in smaller Monte-Carlo variance. Thus the role that importance sampling plays is twofold: first it allows to perform Monte-Carlo integration even if sampling from the target is not possible, and second it allows to do so in an efficient way by choosing, to be defined precicely below, the approximation in an optimal way.

insert

Alternative approaches to importance sampling for performing inference in SSMs include Markov chain Monte Carlo (MCMC) and sequential Monte Carlo (SMC). Recall from Chapter that this inference concerns three objectives: maximum likelihood estimation, i.e. evaluation and optimization of the likelihood, the posterior distribution  $X_{:n}|Y_{:n}$  and prediction of future states and observations. Let us give a concise comparison of these alternative approaches, weighing their advantages and disadvantages over importance sampling, in particular for the SSMs that this thesis deals with.

cite brook handbook

MCMC is a simulation technique that allows to generate correlated samples from a distribution by constructing a Markov chain that has as its invariant distribution the desired distribution. In the most general method, Metropolis Hastings MCMC, one needs access to the density of the sought distribution up to a constant to simulate a step in the Markov chain. While this method is very general, it fails in high dimensions and a lot of current research in MCMC methods deals with this curse of dimensionality .

quotes

cite something

dis-advantages MCMC over IS

SMC [9], sometimes called a particle filter, uses sequential importance sampling to provide a particle approximation to the filtering distributions  $X_t|Y_{:t}$ , essentially decomposing the problem into a  $n$  importance sampling steps. To avoid particle collapse, SMC is usually equipped with a resampling step once the effective sample size of the current set of particles drops below a specified level. Once the final filtering distribution  $X_n|Y_{:n}$  is approximated, the smoothing distribution may be obtained in several ways ... .

look up Chopin

Conveniently, SMC allows us to approximate the likelihood  $\ell(\theta)$  for a single parameter by a single pass of the particle filter. However, the discrete nature of resampling makes the approximated likelihood non-continuous, complicating maximum likelihood inference. [9, Chapter 14.3] discusses several strategies: the first amounts to importance sampling of the order as discussed in this thesis, where one fixes a reference parameter  $\theta_0$  to perform importance sampling with  $p_{\theta_0}(x|y)$  against  $p_{\theta}(x|y)$ . The second strategy only works in the univariate case and consists of approximating the non-continuous inverse CDFs appearing in the resampling step by continuous ones. Under j stochastic gradient ascent

more

This chapter proceeds with a general treatment of importance sampling. Subsequently, we will focus our attention on LCSSMs and how we can exploit their structure to perform importance sampling efficiently.

Suppose we have a function  $h : \mathcal{X} \rightarrow \mathbf{R}$  whose integral

$$\zeta = \int_{\mathcal{X}} h(x) \, dx$$



we want to compute. Furthermore, suppose that we can write

$$\int_{\mathcal{X}} h(x) dx = \int_{\mathcal{X}} f(x) d\mathbf{P}(x) = \mathbf{P}(f)$$

for a probability measure  $\mathbf{P}$  and function  $f : \mathcal{X} \rightarrow \mathbf{R}$ . Let  $\mathbf{G}$  be another measure on  $\mathcal{X}$  such that  $f\mathbf{P}$  is absolutely continuous with respect to  $\mathbf{G}$ ,  $f\mathbf{P} \ll \mathbf{G}$ , and let  $v = \frac{d f\mathbf{P}}{d \mathbf{G}}$  be the corresponding Radon-Nikodym derivative. Then

$$\zeta = \int_{\mathcal{X}} h(x) dx = \int_{\mathcal{X}} f(x) d\mathbf{P}(x) = \int_{\mathcal{X}} v(x) d\mathbf{G}(x)$$

which suggests to estimate  $\zeta$  by Monte-Carlo integration:

$$\hat{\zeta} = \frac{1}{N} \sum_{i=1}^N v(X_i)$$

for  $X_i \stackrel{\text{i.i.d}}{\sim} \mathbf{G}$ ,  $i = 1, \dots, N$ . Here we call  $\hat{\zeta}$  the importance sampling estimate of  $\zeta$ .

A classical result is that the minimum MSE proposal  $\mathbf{G}^*$  has a closed form.

**Proposition 3.1** ([9, Proposition 8.2]). *[minimum MSE proposal] The proposal  $\mathbf{G}^*$  that minimizes the MSE of importance sampling is given by*

$$\mathbf{G}^* = \frac{|f|}{\mathbf{P}(|f|)} \mathbf{P}$$

If one is not interested in a particular  $h$  but rather in an approximation of  $\mathbf{P}$ , and  $\mathbf{P}$  is absolutely continuous with respect to  $\mathbf{G}$ , then one may view

$$\hat{\mathbf{P}}_N = \frac{1}{N} \sum_{i=1}^N v(X_i) \delta_{X_i}$$

as a particle approximation of  $\mathbf{P}$ , in the sense that for sufficiently well behaved test functions  $f$ ,  $\mathbf{P}(f) \approx \hat{\mathbf{P}}_N(f)$ . In this setting [1] shows that the random measure  $\hat{\mathbf{P}}_N$  converges to  $\mathbf{P}$  at rate  $\mathcal{O}(\frac{1}{N})$  in an appropriate metric.

check

To perform importance sampling one must be able to evaluate the weights  $v$ . In a Bayesian setting this is usually infeasible: if  $\mathbf{P}$  is a posterior distribution then the integration constant of its density is intractable. In this case one can usually evaluate the weights up to a constant, i.e.  $w(x) \propto_x \frac{d\mathbf{P}}{d\mathbf{G}}(x)$  is available. The missing constant is then  $\int w(x) d\mathbf{G}$  which is itself amenable to importance sampling. This leads to the self-normalized importance sampling weights  $W_i = \frac{w(X_i)}{\sum_{i=1}^N w(X_i)}$  and Monte Carlo estimates  $\hat{\zeta} = \sum_{i=1}^N W_i f(X_i)$  and particle approximation  $\hat{\mathbf{P}}_N = \sum_{i=1}^N W_i \delta_{X_i}$ .

In both cases one can show that once second moments of  $w$  with respect to  $\mathbf{G}$  exist the Monte-Carlo estimates are consistent and asymptotically normal at the usual rates, see [9, Chapter 8]. However, the finite sample variance of  $\hat{\zeta}$ , and thus the practical performance of the procedure, depends on the variance of  $w \cdot f$  under  $\mathbf{G}$ , and thus on the proposal  $\mathbf{G}$ . [1] show that the expected mean squared TV distance between  $\hat{\mathbf{P}}_N$  and  $\mathbf{P}$  may be bounded, up to a constant,

check if true

by the second moments of  $w$ . In addition they provide bounds that involve the KL-divergence

$$\mathcal{D}_{\text{KL}}(\mathbf{P}, \mathbf{G}) = \int \log \frac{d\mathbf{P}}{d\mathbf{G}} d\mathbf{P},$$

fostering the intuition that  $\mathbf{G}$  should be close to  $\mathbf{P}$  for the particle approximation  $\hat{\mathbf{P}}_N$  to be close to  $\mathbf{P}$ .

more referenceable defs in this chapter

To judge the convergence of importance sampling several criteria are discussed in the literature. The classic effective sample size (ESS)[17]

$$\text{ESS} = \frac{1}{\sum_{i=1}^N W_i^2}$$

arises from the asymptotic efficiency of importance sampling estimates and is easy to interpret, though care has to be taken in particular settings. Assessing convergence through the variance of  $\mathbf{P}_n$  is, while natural, flawed [8] and should be avoided. As a remedy [8] suggest the heuristic  $q_N = \mathbf{E}Q_N$  where

find literature

$$Q_N = \max_{1 \leq i \leq N} W_i.$$

This judges whether importance sampling has collapsed to just a few particles and is amenable to Monte-Carlo integration.

discuss problems/remedies of high dimensional importance sampling

In the context of this thesis, importance sampling serves as the main tool to facilitate inference in SSMS, both for maximum likelihood estimation and access to the smoothing distribution. As the dimension of the state space is  $n \cdot m^2$ , which will usually be large, we have to perform importance sampling efficiently, exploiting the dependence structure.

decide where to put this

As the likelihood of a general state space model is neither analytically nor numerically tractable one has to resort to Monte-Carlo techniques. Recall that the likelihood is a high-dimensional integral of the form

$$\ell(\theta) = p_\theta(y) = \int p_\theta(y, x) dx = \int p_\theta(y|x)p_\theta(x) dx = \mathbf{E}p_\theta(y|X).$$

By the standard law of large numbers we can approximate  $\ell(\theta)$  by

$$\hat{\ell}(\theta) = \frac{1}{N} \sum_{i=1}^N p_\theta(y|X^i)$$

for  $N \in \mathbf{N}$  samples  $X^i \stackrel{\text{i.i.d}}{\sim} p(x)$ . However, the variance of  $\hat{\ell}(\theta)$  is likely to be very high if samples  $X^i$  are drawn from the prior distribution  $p(x)$  as they are not informed by the observations  $y$ . As  $p_\theta(x|y) \propto p_\theta(x, y)$  a more promising approach would be to use samples  $X^i \sim p_\theta(x|y)$ , but this distribution is usually not available.

cite

While bayesian computational approaches such as MCMC are able to generate (approximate) samples from this posterior distribution, importance sampling tries to find a distribution close to the target and re-weights samples to ensure unbiased estimates of  $\ell(\theta)$ .

- importance sampling as a variance reduction technique
- importance sampling as a technique to make intractable distributions tractable

- importance sampling vs. other methods:
  - vs. ABC
  - vs. MCMC
  - vs. INLA (isn't this MCMC?)
- measuring how good IS performs: ESS and other measures
- related results regarding performance of IS (Chatterje, Agapiou)

## LA

LA goes back to Laplace [18] who invented the technique to approximate moments of otherwise intractable distributions. Since [24, 25] rediscovered its use to approximate posterior means and variances, it has been a staple method for statisticians .

cite something

The method is based on a second-order Taylor series expansion of the log target density  $\log p(x)$  around its mode  $\hat{x}$ , i.e. matching mode and curvature. Assuming the density is sufficiently smooth, the mode exists and is unique we have

$$\log p(x) \approx \log p(\hat{x}) + \underbrace{\nabla_x \log p(\hat{x})}_{=0} (x - \hat{x}) + \frac{1}{2} (x - \hat{x})^T H (x - \hat{x})$$

where  $H$  is the Hessian of  $\log p$  evaluated at the mode. As  $\log p(\hat{x})$  does not depend on  $x$ , the right-hand side can be seen (up to additive constants) as the density of a Gaussian distribution with mean  $\hat{x}$  and covariance matrix  $\Sigma = -H^{-1}$ .

If  $p$  is log-concave in  $x$ ,  $H$  is guaranteed to be negative semidefinite and the LA yields an actual Gaussian distribution.

what to do if we cannot guarantee this

The main advantage of the LA is that fast to obtain and, for sufficiently well-behaved distributions on a moderate dimensional space, provides reasonably high ESS. Additionally, the Newton-Raphson iterations to find the mode and Hessian are robust and require no simulation, unlike the other methods discussed further below. For the SSMs we consider in this thesis, the numerical methods can be implemented using the Kalman filter and smoother [11, 22], even in the degenerate case where  $H$  is indefinite [15].

incorporate some of the citations from How good is your LA

However, as the LA is a local approximation, it may be an inappropriate description of the global behavior of the target, see example 3.1 for a breakdown of LA. Additionally, even if LA works in principle, its ESS will usually degenerate quickly once the dimension increases whereas the cross-entropy method (CE-method) and efficient importance sampling (EIS) do so at a slower pace.

- approximate at mode, problematic if posterior is not unimodal (but then gaussian approximation probably not worth it)
- can be solved by KF, even if non log-concave ()

think about whether to generalize to non LC, problem might be that sqrt filter does not work

## CE-method

To provide a global approximation to the target, the CE-method selects from a parametric family  $(G_\psi)_{\psi \in \Psi}$  of proposals the one that minimizes the Kullback Leibler divergence (KL-divergence) to the target.

## Efficient importance sampling

### Comparison

**Example 3.1** (Failure of LA). Consider the Gaussian scale mixture  $\mathbf{P} = \frac{1}{2} (\mathcal{N}(0, 1) + \mathcal{N}(0, \varepsilon^{-2}))$  with mode  $x^* = 0$ . The LA is  $\mathbf{G}_{\text{LA}} = \mathcal{N}\left(0, \frac{1}{\varepsilon^2 - \varepsilon + 1}\right)$ , whose variance goes to 1 as  $\varepsilon$  goes to 0, so the LA will miss close to  $\frac{1}{2}$  of the total mass. For  $\varepsilon$  small enough, the variance of the LA will be smaller than  $\frac{1}{2\varepsilon^2}$ , whence the second moment of the weights is infinite and importance sampling fails.

The CE-method minimizes the KL-divergence between  $\mathbf{P}$  and  $\mathbf{G}_\psi$ , is given by  $\mathbf{G}_{\text{CE}} = \mathcal{N}(0, \sigma^2)$ , where  $\sigma^2 = \frac{1}{2} (1 + \varepsilon^{-2})$  is the variance of  $\mathbf{P}$ . As  $\sigma^2 > \frac{1}{2}\varepsilon^{-2}$ , the weights have finite second moment, and importance sampling is consistent.

add proof for  $\frac{1}{2}$  to appendix

## 3.5 Gaussian importance sampling for state space models

Most models in this thesis can be viewed as an inverse problem of the form

$$\begin{aligned} \mathbf{R}^{n \cdot m} \ni X &\sim \mathcal{N}(\mu, \Sigma) \\ Y|X &\sim Y|BX \sim p(y|s) \end{aligned}$$

and the state space formulation allows for efficient computation of, e.g.,  $p(y|x)$ . To perform importance sampling for the smoothing distribution  $p(x|y)$  we want to have close tractable approximations, that also depend on few parameters, ideally only  $\mathcal{O}(n)$  many.

paragraph about laplace approximation for the posterior

In total we want to perform importance sampling with proposal distributions  $g(x|z)$  given by Gaussian linear models of the form

$$\begin{aligned} X &\sim \mathcal{N}(\mu, \Sigma) \\ Z &= BX + \eta \\ \eta &\sim \mathcal{N}(0, \Omega). \end{aligned}$$

The dependency structure of the state space model implies that  $\Omega$  should be a blockdiagonal matrix with at most  $n \cdot m^2$  many non-zero entries. If, additionally, the observations  $y_t$  are conditionally independent given  $x_t$ , i.e. if  $p(y_t|s_t) = \prod_{i=1}^p p(y_t^i|s_t^i)$ , then  $\Omega$  is a diagonal matrix with only  $\mathcal{O}(n \cdot m)$  many non-zero entries.

The proposal distribution  $g(x|z)$  is then parameterized by the synthetic observations  $z$  and the entries of  $\Omega$  and we denote this set of parameters by  $\psi = (z, \Omega)$ . The following results on this distribution will be useful when analysing Gaussian importance sampling.

move to other subsection

The Laplace approximation chooses  $\psi_{\text{LA}}$  such that the mode of  $g(x|z)$  and the curvature at the mode match that of the true posterior, while the CE-method and EIS choose  $\psi_{\text{CE}}$  and  $\psi_{\text{EIS}}$  the solutions to associated optimization problems.

This means that we can treat all three methods in the same framework, facilitating comparison between the resulting three importance sampling proposals.

### Gaussian smoothing proposals

In this section, we analyze the properties of Gaussian proposals for importance sampling in SSMs that exploit the available Markov property of states. As mentioned in the introduction to this section, these proposals are conditional distributions  $\mathbf{P}^{X|Z=z}$  where  $\mathbf{R}^m \ni X \sim \mathcal{N}(\mu, \Sigma)$  and  $Z = BX + \eta \in \mathbf{R}^p$  where  $\eta \sim \mathcal{N}(0, \Omega)$  is independent of  $X$ . Standard results from linear regression theory imply that the conditional distribution in question is again a Gaussian distribution,  $X|Z = z \sim \mathcal{N}(\bar{\mu}, \bar{\Sigma})$  with mean

$$\bar{\mu} = \mu + \Sigma B^T (B \Sigma B^T + \Omega)^{-1} (z - B\mu), \quad (3.5)$$

$$= \bar{\Sigma} (\Sigma^{-1} \mu + B^T \Omega^{-1} z) \quad (3.6)$$

and covariance matrix

$$\bar{\Sigma} = \Sigma - \Sigma B^T (B \Sigma B^T + \Omega)^{-1} B \Sigma \quad (3.7)$$

$$= (\Sigma^{-1} + B^T \Omega^{-1} B)^{-1}. \quad (3.8)$$

Note that Equations (3.5) and (3.7) are more general, requiring only  $B \Sigma B + \Omega$  be invertible, while the others require both  $\Sigma$  and  $\Omega$  to be invertible, see [9, Lemma 7.1] for further discussion.

**Proposition 3.2** (Exponential family of smoothing distribution). *Suppose  $\Omega$  is invertible. In this case the family of conditional distributions  $X|Z = z$  parameterized by  $z$  and  $\Omega$  form an exponential family*

$$p(x|z) = h(x) \exp(\langle \eta, T(x) \rangle - A(\eta))$$

where the parameters are

$$\eta = (\eta_1, \eta_2) = \left( \bar{\Sigma}^{-1} \bar{\mu}, -\frac{1}{2} \Omega^{-1} \right)$$

and

$$\begin{aligned} h(x) &= \frac{1}{\sqrt{(2\pi)^m \det \Sigma}} \exp \left( -\frac{1}{2} x^T \Sigma^{-1} x \right) \\ A(\eta) &= \frac{1}{2} (\log \det (I - \Sigma \operatorname{diag} (2\eta_2)) + \bar{\mu}^T \bar{\Sigma}^{-1} \bar{\mu}) \\ &= \frac{1}{2} \log \det (I - \Sigma \operatorname{diag} (2\eta_2)) + \frac{1}{2} \eta_1^T (\Sigma^{-1} - \operatorname{diag}(2\eta_2)) \eta_1 \\ T(x) &= (x, x x^T). \end{aligned}$$

Note that  $\eta_1 = \Sigma^{-1} \mu + B^T \Omega^{-1} z \in \Sigma^{-1} \mu + \operatorname{im} B^T$  making the exponential family curved if  $\operatorname{rank} B < m$ .

fix  $\Omega$  and  $\operatorname{diag} \omega$  here

probably cite something about curved exponential families, e.g. Brown1986Fundamentals

### Analysis of optimal parameters

**Theorem 3.2** (Optimal EIS proposal). *Let  $p(x)$  be some density and consider importance sampling by exponential family proposals with densities*

$$q_\psi(x) = h(x) \exp(\langle \psi, S(x) \rangle - A(\psi))$$

*with natural parameter  $\psi \in \mathbf{R}^k$ , base measure  $h$ , sufficient statistic  $S$  and log-partition function  $A$ . The parameter  $\hat{\psi}$  that minimizes the variance of log importance sampling weights  $\log w_\psi(x) = \log p(x) - \log q_\psi(x)$  is given by*

$$\begin{aligned} \hat{\psi} &= \operatorname{argmin}_\psi \operatorname{Var}(\log w_\psi(X)) \\ &= \operatorname{Cov}(S(X))^{-1} \operatorname{Cov}\left(S(X), \log \frac{p(X)}{h(X)}\right) \end{aligned}$$

where  $X \sim p$ .

formultae this, consider exact assumptions

*Proof.*

□

*Remark* (Optimal Gaussian proposal). As the family of Gaussian distributions  $\mathcal{N}(\mu, \Sigma)$  form an exponential family with natural parameter  $\psi = (\Sigma^{-1}\mu, -\frac{1}{2}\Sigma^{-1})$  and sufficient statistic  $S(x) = (x, xx^T)$ , Theorem 3.2 implies that the optimal EIS Gaussian proposal involves up to fourth order moments of  $p$ .

As a consequence we expect EIS to produce proposals that are more robust to skewness and heavier than Gaussian tails than the Laplace approximation .

which is validated by simulations in section ...

### Analysis of convergence (?)

Additionally, each iteration of the CE and EIS method may be seen as performing M-estimation and as such the one step estimates  $\psi_{CE}$  and  $\psi_{EIS}$  are, in the limit as the number of samples  $M$  goes to  $\infty$ , asymptotically normally distributed.

Analyzing the multi-step behavior of these iterative estimates is more complex, as we want to keep a fixed seed, i.e. common random numbers, to ensure numerical convergence. Thus the distribution of the second iterate conditional on the first iterate depends only the conditional distribution of the common random numbers given the first iterate, which is intractable.

check

apply van der vaart

**Theorem 3.3** (Consistency of importance sampling estimates).

calculate asymptotic covariances

**Theorem 3.4** (Asymptotic normality of importance sampling estimates).

all iterative procedures are M-estimators, so a single step is (in the limit of samples  $N \rightarrow \infty$ ), under some regularity conditions, asymptotically normal, compare asymptotic variances

*Proof.*

□

### 3.6 Accounting for multimodality and heavy tails

interpret this in a sensible way, probably EIS more numerically stable

Performing importance sampling with the Gaussian models discussed so far will work well only if the smoothing distribution  $p(x|y)$  is well approximated by a Gaussian distribution. However, a Gaussian distribution is a very specific kind of distribution, in particular, it is an unimodal distribution and has light tails .

check for correct wording

If the smoothing distribution violates any of these assumptions, importance sampling with the models presented so far is likely to fail, i.e. requiring large sample sizes for both finding the optimal importance sampling parameter  $\hat{\psi}$  as well as the final importance sampling evaluation.

There are however techniques to keep most of the computational efficiency discussed in the above sections to address both multimodality as well as heavy tails.

We start with heavier than gaussian tails: the textbook example of a heavy tailed distribution is the multivariate  $t$ -distribution with density

....

for degrees of freedom  $\nu > 1$ , location  $\mu$  and scale matrix  $\Sigma$ . When  $\nu > 2$  then this distribution has mean  $\mu$  and if  $\nu > 3$  it has covariance matrix ? .

?

check

The main properties necessary to facilitate Gaussian importance sampling strategies above are that the distribution  $p(x|y)$  is analytically tractable and simulation from it is possible. These properties still hold for the multivariate  $t$ -distribution and, in fact, for the even larger class of elliptical distributions:

**Theorem 3.5** (Conditional distribution of elliptical distributions).

cite the correct book

As one can readily see from Theorem 3.5 the parameters of the smoothing distribution  $p(x|y)$  if  $p(x, y)$  follows an elliptical distribution is again elliptical and its parameters only depend on quantities that are computed by the Kalman smoother.

elaborate

present some models with heavy tails

### 3.7 Maximum likelihood estimation





## Chapter 4

# Analysis of selected models

### 4.1 Spatial reproduction number model

1. essentially the Regional model presented in ECMI

### 4.2 Regional growth factor model

### 4.3 Nowcasting hospitalizations



## Chapter 5

## Discussion



Chapter 6

Conclusion (?)



## Appendix A

# Implementation in Python





## Appendix B

### Proofs (?)



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# Declaration

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*Ilmenau, October 2023*

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Stefan Heyder