Tensors for signal and frequency estimation in subspace-based methods: when they are useful?

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Introduction to Singular Spectrum Analysis (SSA)

Problems that can be solved by SSA-related methods:

- Signal extraction
- Frequency estimation
- Smoothing and Noise reduction
- Signal decomposition (Trend and Periodicity extraction)
- Forecasting
- Missing data imputation
- Change in structure detection
- Many others...

SSA Materials

Books:

- J.Elsner and A.Tsonis. Singular Spectrum Analysis: A New Tool in Time Series Analysis, Plenum, 1996.
- N.Golyandina, V.Nekrutrin and A.Zhigljavsky. Analysis of Time Series Structure: SSA and Related Techniques, CRC Press, 2001.
- S.Sanei and H.Hassani. Singular Spectrum Analysis for Biomedical Signals, CRC Press, 2016.
- N.Golyandina, A.Korobeynikov and A.Zhigljavsky. Singular spectrum analysis with R, Springer, 2018.
- N.Golyandina and A.Zhigljavsky. Singular Spectrum Analysis for Time Series, Springer, 2013, 2020 (2nd Edition).

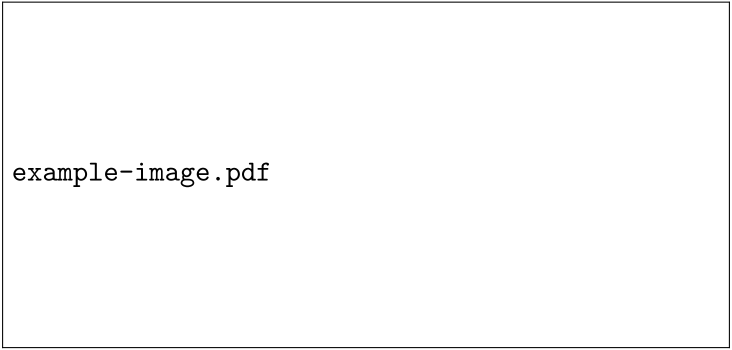
Implementations:

- R Package: Rssa
  https://CRAN.R-project.org/package=Rssa
- Python Package: py-ssa-lib (less features)
  https://pypi.org/project/py-ssa-lib

SSA Decomposition example

Decomposition of time series:

- Low-frequency component + high-frequency component
- Signal + noise
- Trend + Seasonality + Noise



Some data: demonstration of series decomposition with SSA

ESPRIT Frequency estimation example

ESPRIT — SSA-related method for parameters estimation

`example-image.pdf`

Pole motion data probably

1. Estimate — interpretation
2. Estimate — interpretation

Complex Time Series

Common origins of complex-valued time series:

- Can be constructed from two related features
- Arise as a result of applying the Fourier transform to real data

SSA Algorithm: Embedding

Input: time series $\mathsf{X} = (x_1, x_2, \dots, x_N)$, window length L, signal rank r.

1. **Embedding**. Constructing the L-*Trajectory* Hankel matrix $\mathbf{X} \in \mathbb{C}^{L \times K}$ from the series X, where $K = N - L + 1$:

$$\mathbf{X} = \mathcal{T}^{(L)}(\mathsf{X}) = \begin{pmatrix} x_1 & x_2 & x_3 & \dots & x_K \\ x_2 & x_3 & x_4 & \dots & x_{K+1} \\ x_3 & x_4 & x_5 & \dots & x_{K+2} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ x_L & x_{L+1} & x_{L+2} & \dots & x_N \end{pmatrix}$$

SSA Algorithm: Decomposition, Grouping, Reconstruction

2. **Decomposition**. Constructing the singular value decomposition (SVD) of matrix $\mathbf{X}$: $\mathbf{X} = \sum_{j=1}^{\operatorname{rank}\mathbf{X}} \sqrt{\lambda_j} U_j V_j^{\mathrm{H}} = \sum_{j=1}^{\operatorname{rank}\mathbf{X}} \widehat{\mathbf{X}}_j$ where H denotes Hermitian conjugation, U_j and V_j are left and right singular vectors of $\mathbf{X}$, $\sqrt{\lambda_j}$ — its singular values in descending order.

3. **Grouping**. Grouping the terms $\widehat{\mathbf{X}}_j$ from the decomposition related to the signal: $\mathbf{S} = \sum_{j=1}^{r} \widehat{\mathbf{X}}_j = \Pi_r \mathbf{X}$, where Π_r is the projector onto the space of matrices with rank not greater than r.

4. **Reconstruction**. Applying projection onto the space of Hankel matrices: $\widetilde{\mathbf{S}} = \Pi_{\mathcal{H}} \widehat{\mathbf{S}}$, and return to the series form: $\widetilde{\mathsf{S}} = \left(\mathcal{T}^{(L)}\right)^{-1} (\widetilde{\mathbf{S}})$

Series rank

Definition

Series X has rank $d < N/2$, if the rank of its L-trajectory matrix equals d for any L such that $d \leqslant \min(L, N - L + 1)$.
If such d exists, then X is called a series of finite rank.

If the signal S is a series of finite rank, then it is generally recommended to use $\mathrm{rank}(\mathsf{S})$ as parameter r in the SSA method

Series rank examples

- rank of S with $s_n = A\sin(2\pi\omega n + \varphi)$, $0 < \omega < 1/2$, equals 2
- rank of S with $s_n = A\exp(\alpha n)$, $\alpha \in \mathbb{C}$, equals 1

Signal Model

What we consider a signal $\mathsf{S} = (s_1, s_2, \ldots, s_N)$:

- The trajectory matrix $\mathbf{S} = \mathcal{T}^{(L)}(\mathsf{S})$ is rank-deficient
  ($\implies$ the time series is of some finite rank: $\mathrm{rank}(\mathsf{S}) = r$)
- Any signal S can be represented in the form of a finite sum:

$$s_n = \sum_j p_j(n) \exp(\alpha_j n + \mathrm{i}(2\pi\omega_j n + \varphi_j)),$$

  where $p_j(n)$ is a polynomial in n

- Real case:

$$s_n = \sum_j p_j(n) \exp(\alpha_j n) \sin(2\pi\omega_j n + \varphi_j),$$

ESPRIT method estimates damping factors α_j and frequencies ω_j

ESPRIT Algorithm: General Idea

$$s_n = \sum_{j=1}^{2} \exp(\alpha_j n + \mathrm{i}(2\pi\omega_j n + \varphi_j)) = A_1 z_1^n + A_2 z_2^n$$

where $A_j = \exp(\mathrm{i}\varphi_j)$, $z_j = \exp(\alpha_j + \mathrm{i}2\pi\omega_j)$

Signal subspace basis is given by

$$\mathbf{M} = \begin{pmatrix} z_1 & z_2 \\ z_1^2 & z_2^2 \\ \vdots & \vdots \\ z_1^L & z_2^L \end{pmatrix} \Rightarrow \overline{\mathbf{M}} = \underline{\mathbf{M}} \begin{pmatrix} z_1 & \\ & z_2 \end{pmatrix} \Rightarrow \underline{\mathbf{M}}^{-} \overline{\mathbf{M}} = \begin{pmatrix} z_1 & \\ & z_2 \end{pmatrix}$$

where $\overline{\mathbf{M}}$ denotes $\mathbf{M}$ without the first row, $\underline{\mathbf{M}}$ — without the last
$\underline{\mathbf{M}}^{-}$ denotes the pseudoinverse of $\underline{\mathbf{M}}$

ESPRIT Algorithm

Input: same as in SSA: X, L, r

1. **Embedding**. $\mathbf{X} = \mathcal{T}^{(L)}(\mathsf{X})$
2. **Decomposition**. $\mathbf{X} = \sum_{j=1}^{\operatorname{rank}\mathbf{X}} \sqrt{\lambda_j} U_j V_j^{\mathrm{H}}$, $\mathbf{U}_r = [U_1 : U_2 : \ldots : U_r]$
3. **Estimation**. Finding eigenvalues z_j of matrix $\underline{\mathbf{U}}_r^{-} \overline{\mathbf{U}}_r$

   Using $z_j = \exp(\alpha_j + \mathrm{i}2\pi\omega_j)$ parameters α_j and ω_j can be found

Multi-Channel Time Series, MSSA

$\mathsf{X} = \left(\mathsf{X}^{(1)}, \mathsf{X}^{(2)}, \ldots, \mathsf{X}^{(P)}\right), \qquad \mathsf{X}^{(p)} = \left(x_1^{(p)}, x_2^{(p)}, \ldots, x_N^{(p)}\right)$ – channels

The only change in the algorithms — Embedding step:

$$\mathbf{X} = \mathcal{T}_{\mathrm{MSSA}}^{(L)}(\mathsf{X}) = \left[\mathbf{X}^{(1)} : \mathbf{X}^{(2)} : \ldots : \mathbf{X}^{(P)}\right],$$

$$\mathbf{X}^{(p)} = \mathcal{T}^{(L)}(\mathsf{X}^{(p)})$$

When to chose MSSA over SSA for each channel:

- All channels have "similar" structure
- "Supporting" channels with lower noise level

Intoduction of Tensors

$$\begin{array}{rlcccl} \text{Basic SSA:} & \text{Time series X} & \mapsto & \text{Matrix } \mathbf{X} & \mapsto & \mathrm{SVD}(\mathbf{X}) \\ \text{Tensor SSA:} & \text{Time series X} & \mapsto & \text{Tensor } \mathcal{X} & \mapsto & \underbrace{\mathrm{TD}}_{\text{Some Tensor Decomposition}}(\mathcal{X}) \end{array}$$

Tensor SVD Extensions:

- Higher-Order SVD (HOSVD)
- Canonical Polyadic Decomposition (CPD)
- T-SVD
- $(L_r, L_r, 1)$-Decomposition

Mapping Time Series to Tensor

$$\mathsf{X} = (x_1, x_2, \ldots, x_N)$$

$$\mathsf{X} = \left(\mathsf{X}^{(1)}, \mathsf{X}^{(2)}, \ldots, \mathsf{X}^{(P)}\right)$$