An SVD in Spherical Surface Wave Tomography

Michael Quellmalz
(joint work with Ralf Hielscher and Daniel Potts)

Chemnitz University of Technology
Faculty of Mathematics

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Content

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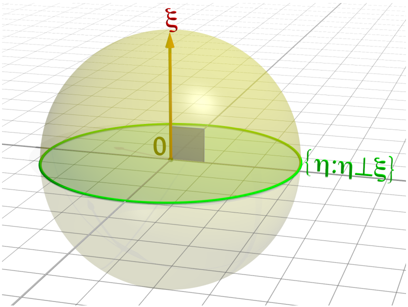
Funk–Radon transform

- Sphere $\mathbb{S}^2 = \{\boldsymbol{\xi} \in \mathbb{R}^3 : \|\boldsymbol{\xi}\| = 1\}$
- Function $f\colon \mathbb{S}^2 \to \mathbb{C}$
- **Funk–Radon transform** (a.k.a. Funk transform or spherical Radon transform)

$$\mathcal{F}\colon C(\mathbb{S}^2) \to C(\mathbb{S}^2),$$

$$\mathcal{F}f(\boldsymbol{\xi}) = \int_{\langle \boldsymbol{\xi}, \boldsymbol{\eta} \rangle = 0} f(\boldsymbol{\eta}) \,\mathrm{d}\lambda(\boldsymbol{\eta})$$



Theorem [Funk 1911]

Any even function f can be reconstructed from $\mathcal{F}f$.

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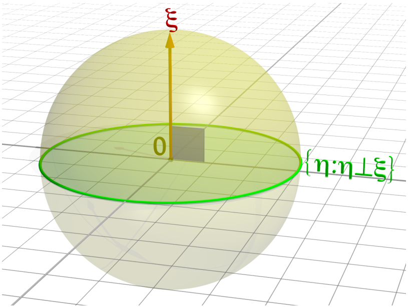

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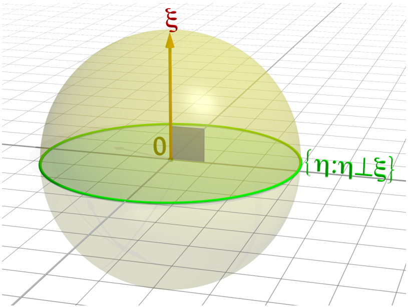

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Spherical surface wave tomography

- Seismic waves propagate along the surface of the earth
- Speed of propagation depends on the position on $\mathbb{S}^2$

Method

- Measure the traveltimes of surface waves between many pairs of epicenter and detector
- Reconstruct the local speed of propagation

Assumption

A wave propagates along the arc of a great circle.

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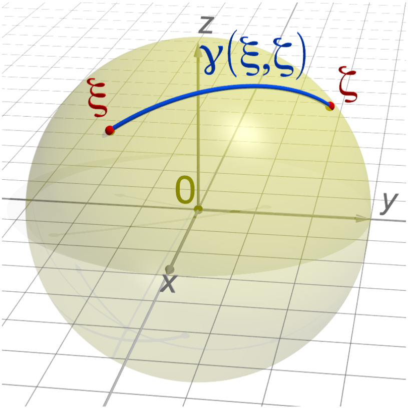
The arc transform: first parameterization

- Function $f\colon \mathbb{S}^2 \to \mathbb{R}$
  - Surface waves: $f = \frac{1}{c}$ (c ... speed of sound)
- $\xi,\ \zeta \in \mathbb{S}^2$ not antipodal
- $\gamma(\xi,\ \zeta)$ great circle arc

Definition

$$\mathcal{B}f(\xi,\zeta) = \int_{\gamma(\xi,\zeta)} f \,\mathrm{d}\gamma$$



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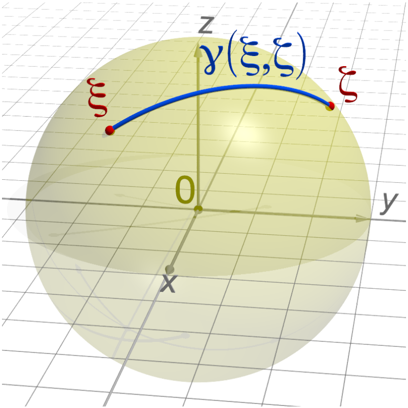

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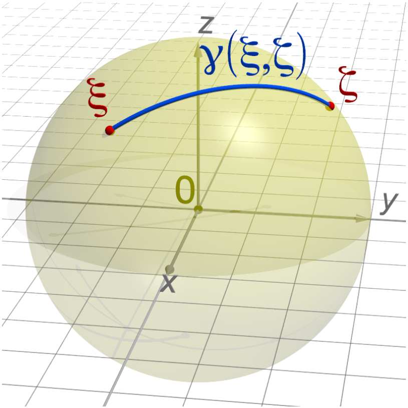

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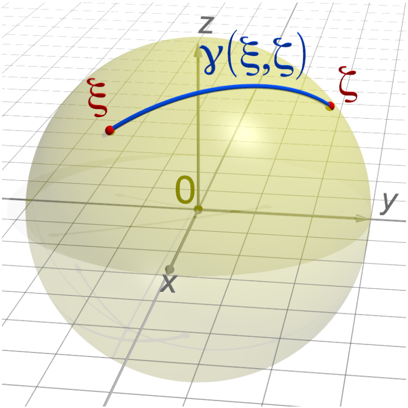

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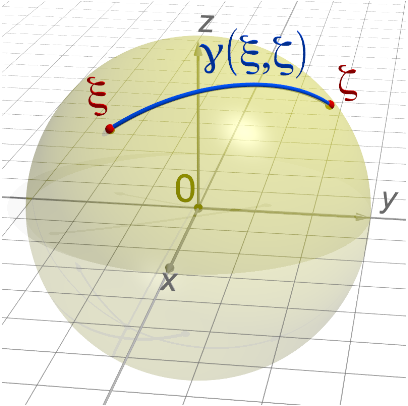

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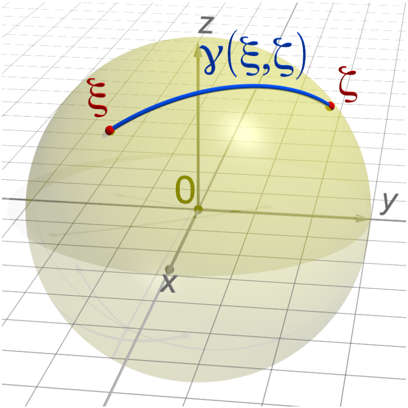

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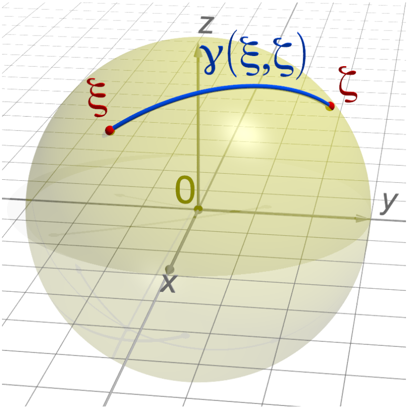

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We choose a different parameterization

The arc transform: alternative parameterization

- $\psi = \arccos(\boldsymbol{\xi}^\top \boldsymbol{\zeta})$ ... length of γ
- $Q \in \mathrm{SO}(3)$ such that
  - $Q\boldsymbol{\xi} = \boldsymbol{e}_{-\psi/2}$
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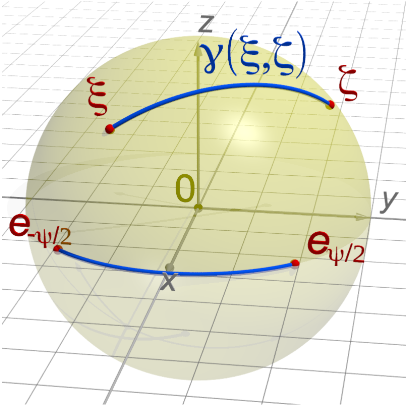
  where $\boldsymbol{e}_\psi = (\sin\psi, \cos\psi, 0)$



Definition

$$\mathcal{A}\colon C(\mathbb{S}^2) \to C(\mathrm{SO}(3) \times [0, 2\pi]),$$

$$\mathcal{A}f(Q, \psi) = \int_{-\psi/2}^{\psi/2} f(Q^{-1}\boldsymbol{e}_\varphi)\,\mathrm{d}\varphi$$

Theorem

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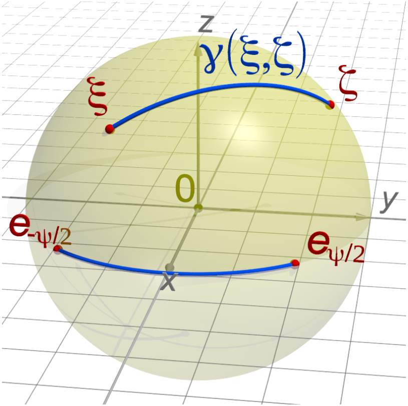

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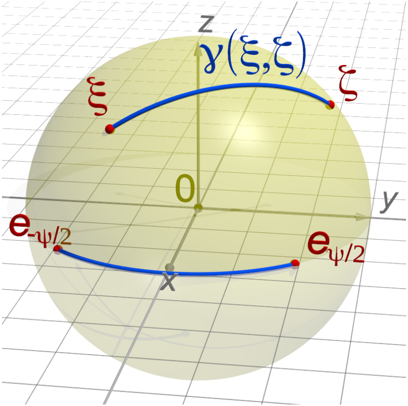

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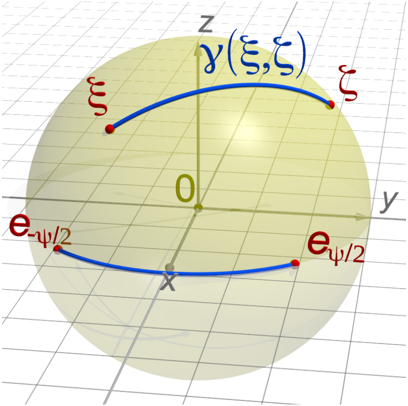

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Notation: On the sphere $\mathbb{S}^2$

- Spherical coordinates

$$\boldsymbol{\xi}(\varphi, \vartheta) = \sin(\vartheta)\boldsymbol{e}_\varphi + \cos\vartheta \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

- Orthonormal basis on $L^2(\mathbb{S}^2)$: **spherical harmonics** of degree $n \in \mathbb{N}$

$$Y_n^k(\varphi, \vartheta) = \sqrt{\frac{2n+1}{4\pi} \frac{(n-k)!}{(n+k)!}} P_n^k(\cos\vartheta)\, \mathrm{e}^{\mathrm{i}k\varphi}, \qquad k = -n, \dots, n$$

- P_n^k ... associated Legendre function

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Notation: On the rotation group $\mathrm{SO}(3)$

- Rotation group

$$\mathrm{SO}(3) = \{Q \in \mathbb{R}^{3\times 3} : Q^{-1} = Q^\top, \det(Q) = 1\}$$

- Orthogonal basis on $L^2(\mathrm{SO}(3))$: **rotational harmonics** (Wigner D-functions)

$$D_n^{j,k}(Q) = \int_{\mathbb{S}^2} Y_n^k(Q^{-1}\xi)\,\overline{Y_n^j(\xi)}\,\mathrm{d}\xi$$

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Theorem

[Dahlen & Tromp 1998]

Let $n \in \mathbb{N}$ and $k \in \{-n, \dots, n\}$. Then

$$\mathcal{A}Y_n^k(Q, \psi) = \sum_{j=-n}^{n} \widetilde{P}_n^j(0)\, D_n^{j,k}(Q)\, s_j(\psi),$$

where

$$s_j(\psi) = \begin{cases} \psi, & j = 0 \\ \frac{2\sin(j\psi/2)}{j}, & j \neq 0 \end{cases}$$

and

$$\widetilde{P}_n^j(0) = \begin{cases} (-1)^{\frac{n+j}{2}} \sqrt{\frac{2n+1}{4\pi} \frac{(n-j-1)!!(n+j-1)!!}{(n-j)!!(n+j)!!}}, & n+j \text{ even} \\ 0, & n+j \text{ odd.} \end{cases}$$

Singular value decomposition for full data [Hielscher, Potts, Q. 2017]

The operator $\mathcal{A}\colon L^2(\mathbb{S}^2) \to L^2(\mathrm{SO}(3) \times [0, 2\pi])$ is compact with the singular value decomposition

$$\mathcal{A} Y_n^k = \sigma_n \, E_n^k, \quad n \in \mathbb{N},\ k \in \{-n, \ldots, n\},$$

with singular values

$$\sigma_n = \sqrt{\frac{32\pi^3}{2n+1}} \sqrt{\frac{\pi^2}{3} \left| \widetilde{P}_n^0(0) \right|^2 + \sum_{j=1}^{n} \frac{1}{j^2} \left| \widetilde{P}_n^j(0) \right|^2} \in \mathcal{O}\left(\frac{1}{\sqrt{n}} \right)$$

and the orthonormal functions in $L^2(\mathrm{SO}(3) \times [0, 2\pi])$

$$E_k^n = \sigma_n^{-1} \sum_{j=-n}^{n} \widetilde{P}_n^j(0) \, D_n^{j,k}(Q) \, s_j(\psi).$$

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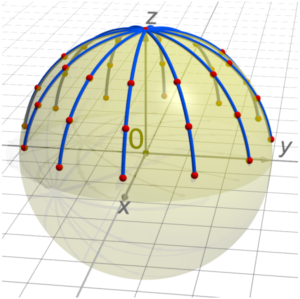
Arcs from the north pole

- Fix one endpoint of the arcs as the north pole e^3:

$$\mathcal{B}f(\boldsymbol{\xi}(\varphi,\vartheta)) = \int_{\gamma(\boldsymbol{e}^3,\,\boldsymbol{\xi}(\varphi,\vartheta))} f \,\mathrm{d}\gamma$$

- Then f can be recovered from $\mathcal{B}f$ by

$$f(\boldsymbol{\xi}(\varphi,\vartheta)) = \frac{\mathrm{d}}{\mathrm{d}\vartheta}\mathcal{B}f(\boldsymbol{\xi}(\varphi,\vartheta)).$$



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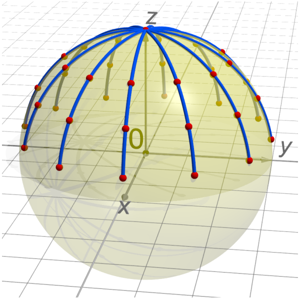
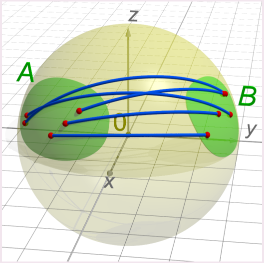


Arcs between two sets [Amirbekyan 2007]

Let Ω be an open subset of $\mathbb{S}^2$ and $A, B \subset \Omega$ nonempty sets with $\overline{A \cup B} = \overline{\Omega}$. If $f \in C(\mathbb{S}^2)$ and

$$\int_{\gamma(\boldsymbol{\xi},\boldsymbol{\zeta})} f \,\mathrm{d}\gamma = 0 \qquad \forall \boldsymbol{\xi} \in A, \boldsymbol{\zeta} \in B,$$

then $f \equiv 0$ on $\overline{A \cup B}$.



Arcs from the boundary of a set [Hielscher, Potts, Q. 2017]

Let $\Omega \subset \mathbb{S}^2$ be convex and strictly contained in a hemisphere. If $f \in C(\mathbb{S}^2)$ and

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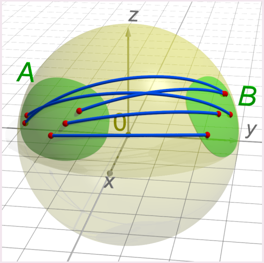

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Arcs with fixed length

We fix the arclength $\psi \in [0, 2\pi]$ and define

$$\mathcal{A}_\psi = \mathcal{A}(\cdot, \psi) \colon L^2(\mathbb{S}^2) \to L^2(\mathrm{SO}(3)).$$

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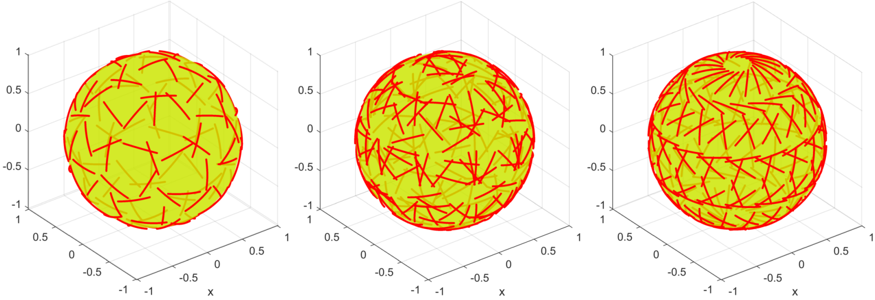


Singular Value Decomposition

[Hielscher, Potts, Q. 2017]

Let $\psi \in (0, 2\pi)$ be fixed. The operator $\mathcal{A}_\psi \colon L^2(\mathbb{S}^2) \to L^2(\mathrm{SO}(3))$ has the SVD

$$\mathcal{A}_\psi Y_n^k = \mu_n(\psi)\, Z_{n,\psi}^k, \quad n \in \mathbb{N},\, k \in \{-n, \dots, n\},$$

with singular values

$$\mu_n(\psi) = \sqrt{\sum_{j=-n}^{n} \frac{8\pi^2}{2n+1} \left|\widetilde{P}_n^j(0)\right|^2 s_j(\psi)^2}$$

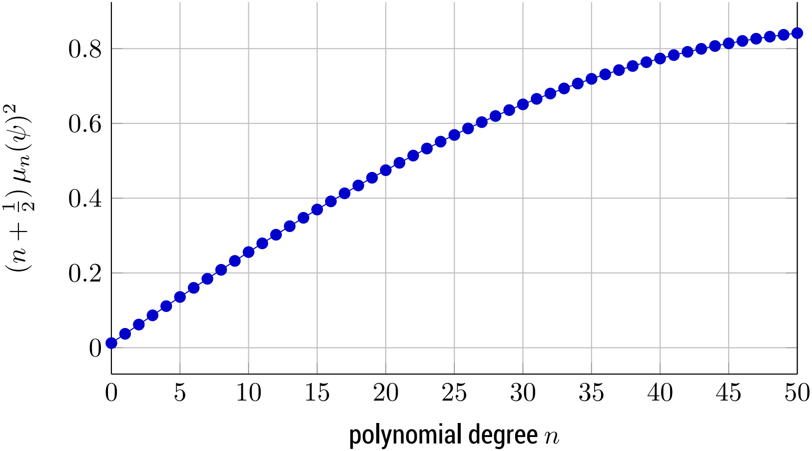
and singular functions

$$Z_{n,\psi}^k = \frac{1}{\mu_n(\psi)} \sum_{j=-n}^{n} \widetilde{P}_n^j(0)\, s_j(\psi)\, D_n^{j,k} \in L^2(\mathrm{SO}(3)).$$

Hence $\mathcal{A}_\psi$ is injective.

Singular values $\mu_n(\psi)$: dependency on n

$\psi = 0.02\,\pi$



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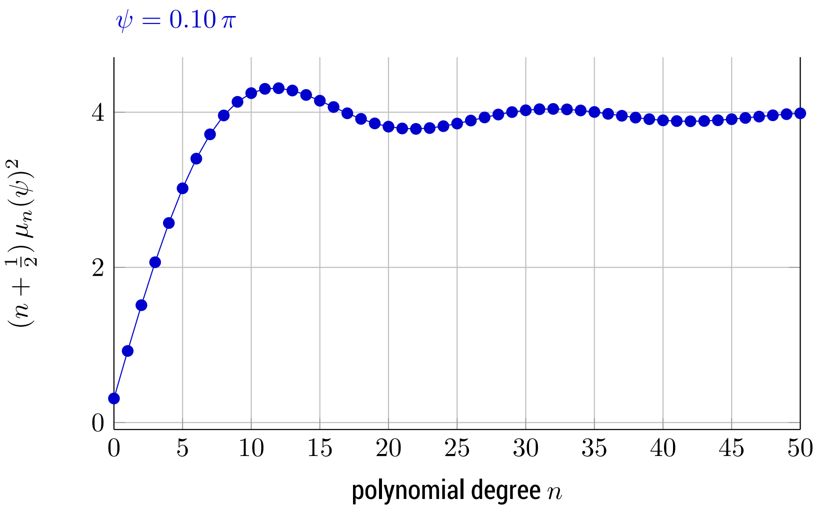

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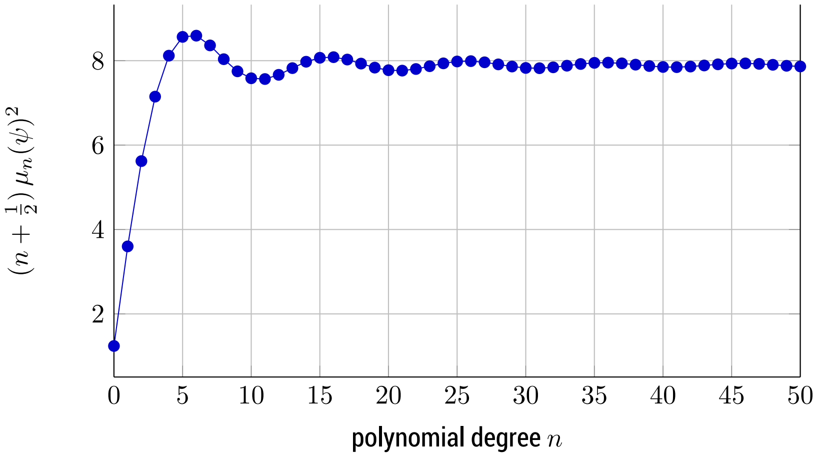
$\psi = 0.20\,\pi$



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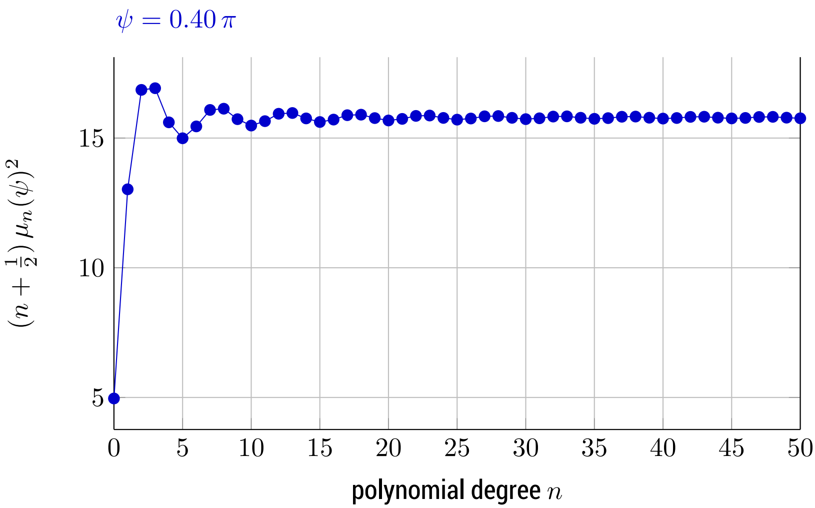
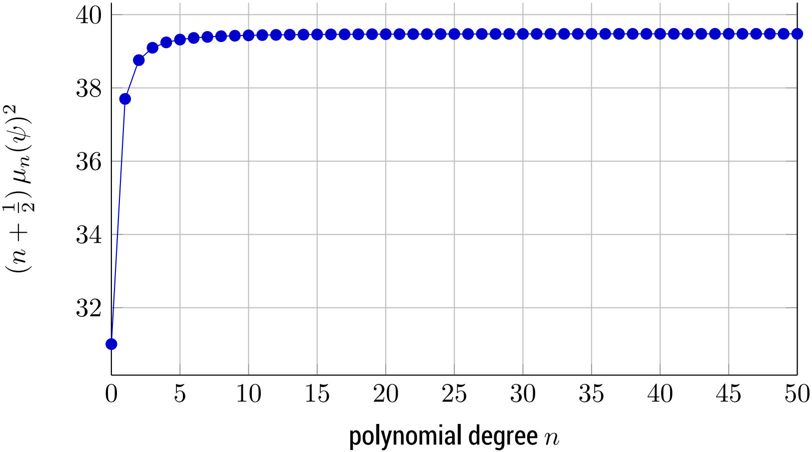


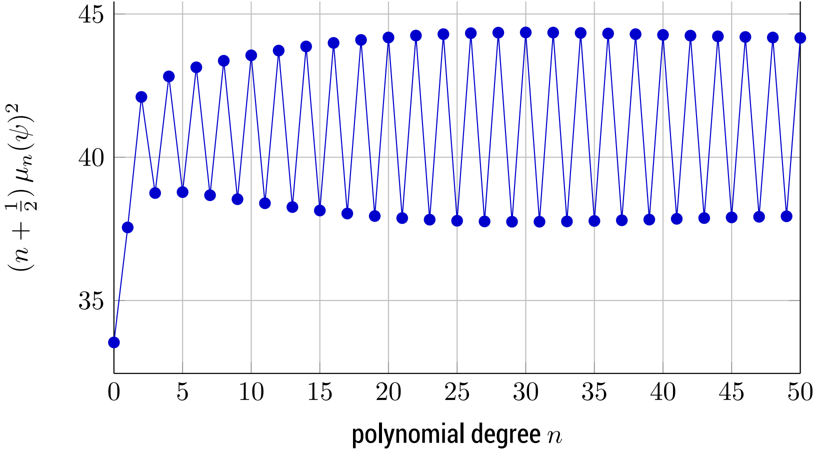
Singular values $\mu_n(\psi)$: dependency on n

$\psi = 1.00\,\pi$ **(half circle)**



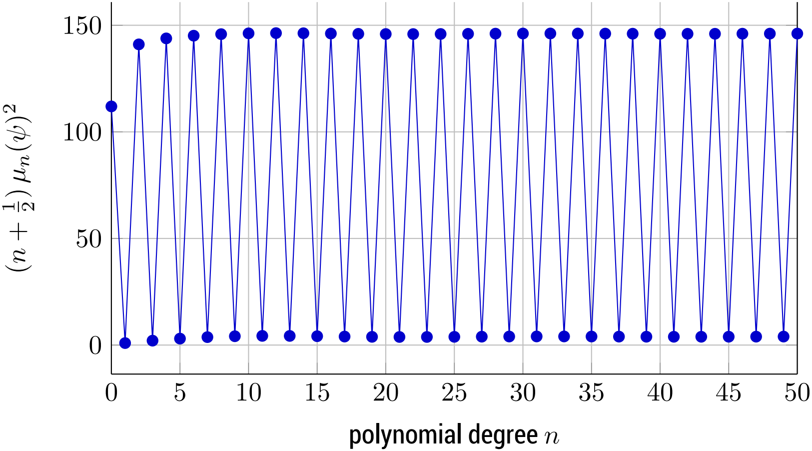
Singular values $\mu_n(\psi)$: dependency on n

$\psi = 1.04\,\pi$



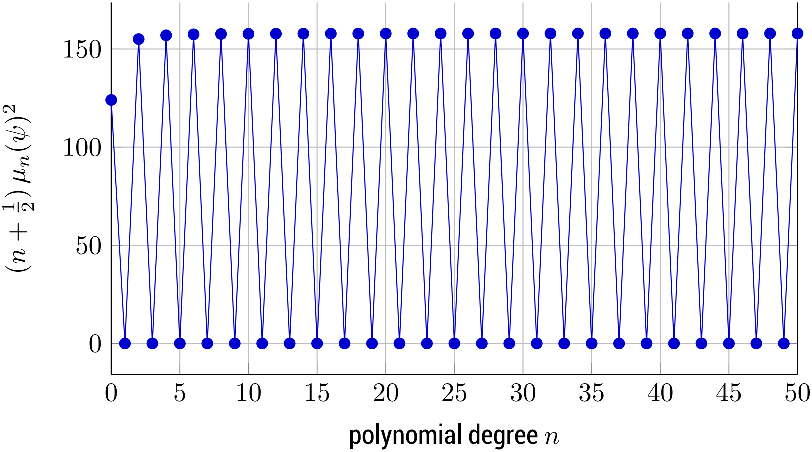
Singular values $\mu_n(\psi)$: dependency on n

$\psi = 1.90\,\pi$

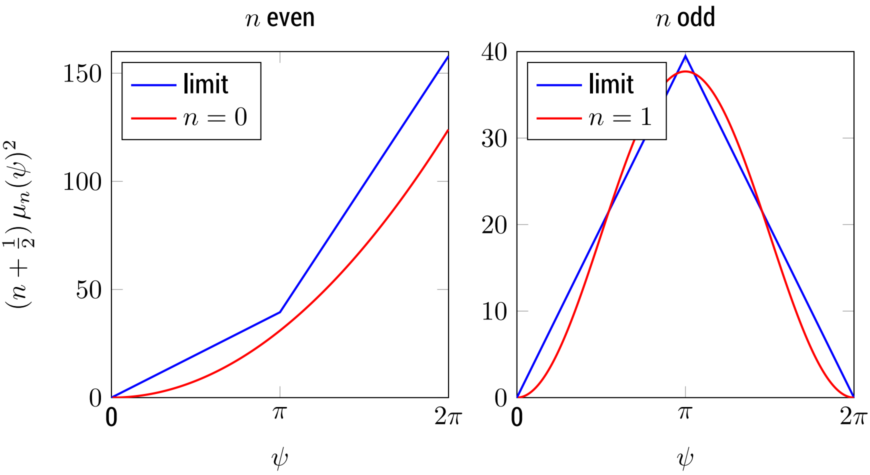


Singular values $\mu_n(\psi)$: dependency on n

$\psi = 2.00\,\pi$ **(Funk–Radon transform)**



Singular values $\mu_n(\psi)$: dependency on arc-length ψ



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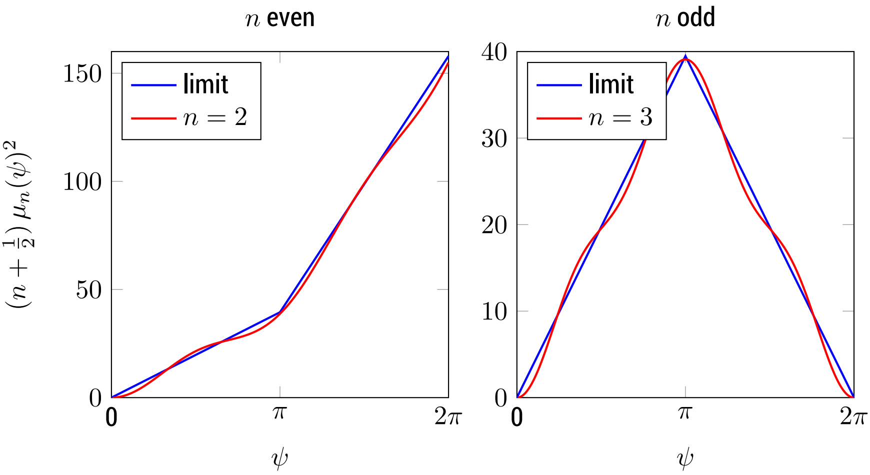

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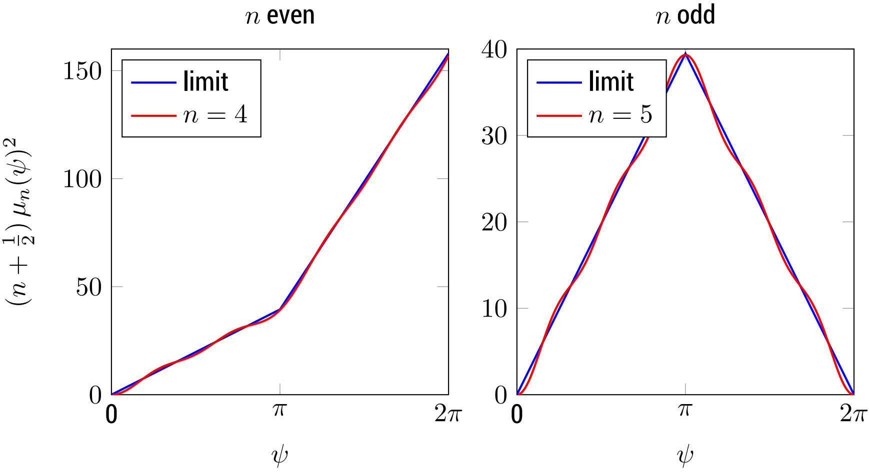

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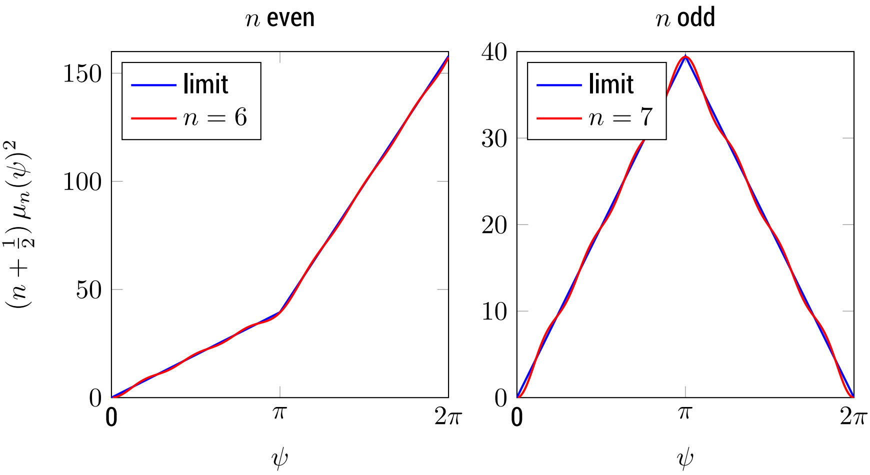

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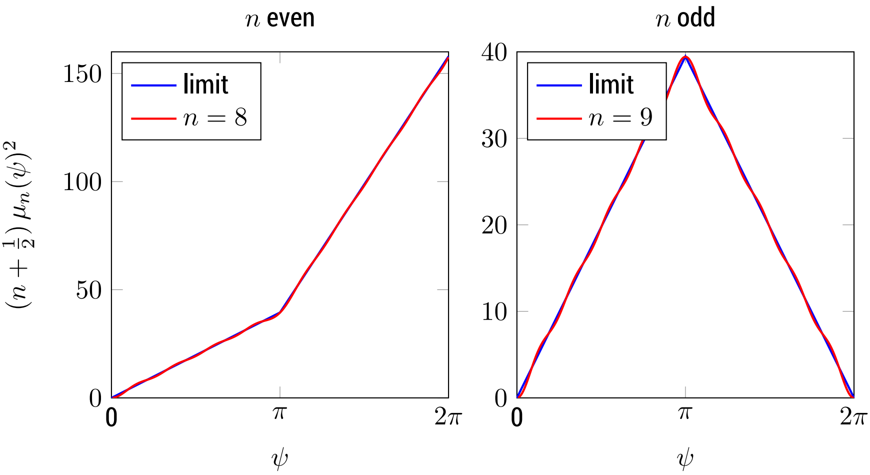
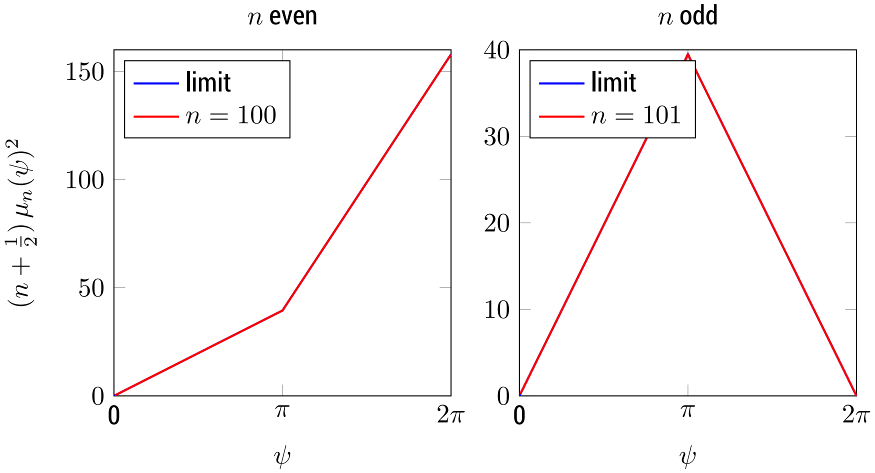


Singular values $\mu_n(\psi)$: dependency on arc-length ψ



Singular values: asymptotic behavior

Theorem

[Hielscher, Potts, Q. 2017]

The singular values $\mu_n(\psi)$ of $\mathcal{A}_\psi$ satisfy

$$\lim_{\substack{n\to\infty \\ n \text{ even}}} \left(n+\tfrac{1}{2}\right)\mu_n(\psi)^2 = \begin{cases} 4\pi\psi, & \psi \in [0,\pi] \\ 12\pi\psi - 8\pi^2, & \psi \in [\pi, 2\pi], \end{cases}$$

$$\lim_{\substack{n\to\infty \\ n \text{ odd}}} \left(n+\tfrac{1}{2}\right)\mu_n(\psi)^2 = \begin{cases} 4\pi\psi, & \psi \in [0,\pi] \\ 8\pi^2 - 4\pi\psi, & \psi \in [\pi, 2\pi]. \end{cases}$$

Special cases

- $\psi = 2\pi$: **Funk–Radon transform**: Injective only for even functions
- $\psi = \pi$: **Half-circle transform**: Injective for all functions [Groemer 1998]
  half circles in one hemisphere [Rubin 2019]

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Conclusion

- Mathematical framework for the circle arcs transform via parametrization by length and direction
- SVD for full data
- SVD for arcs having fixed length
- Circle arc transform is injective for fixed arclength

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