Laser-Doppler-Korrelationsmessungen in turbulenten Strömungen

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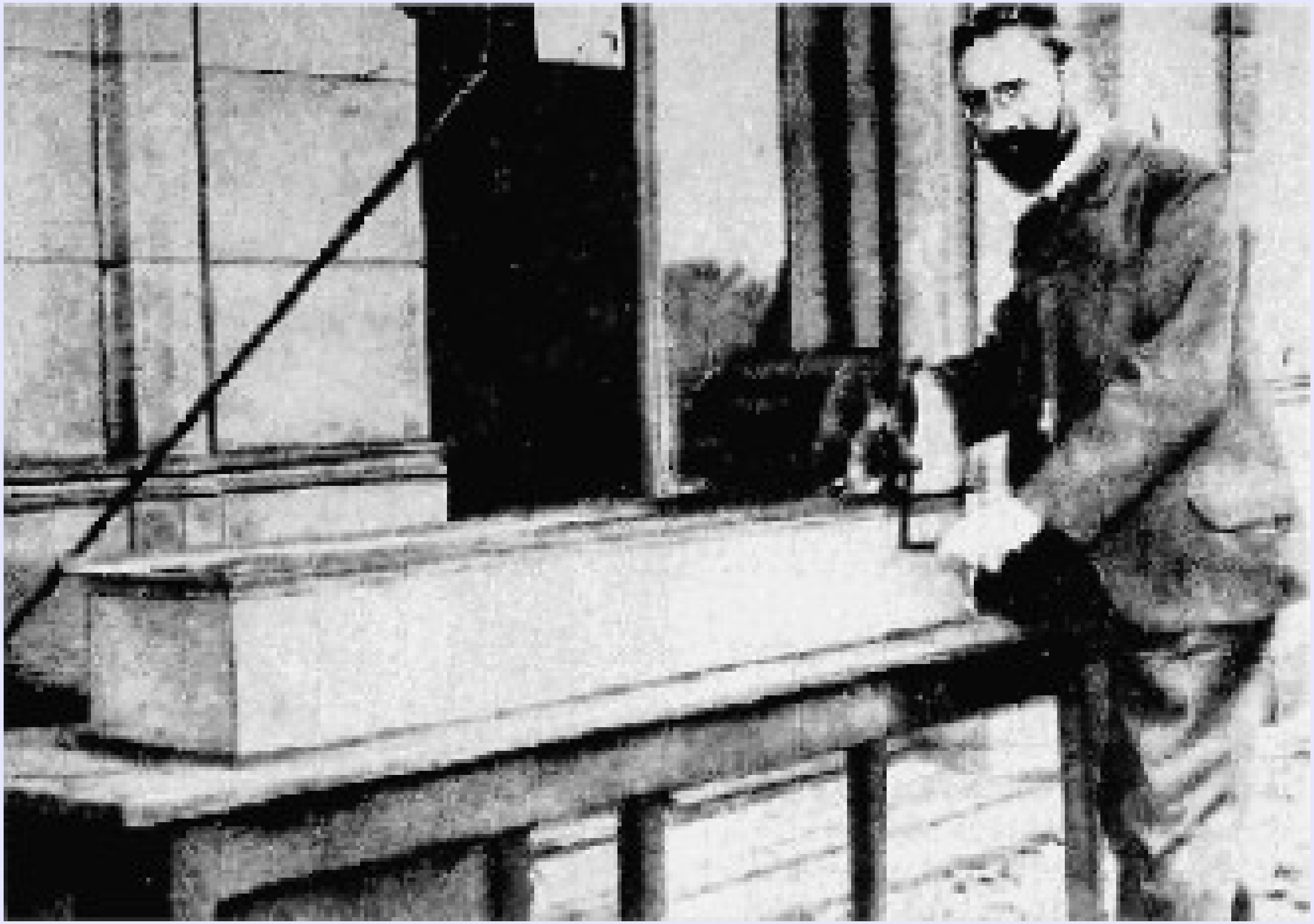
Göttingen

TU Dresden, 17.11.2006

Max-Planck-Institut für Dynamik und Selbstorganisation



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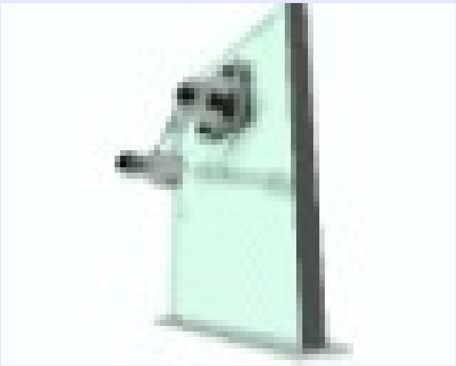
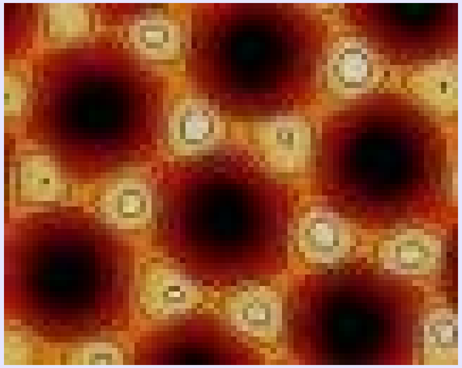
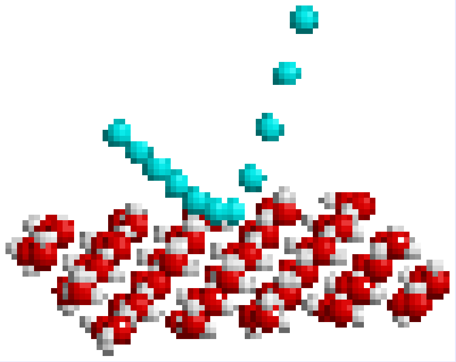
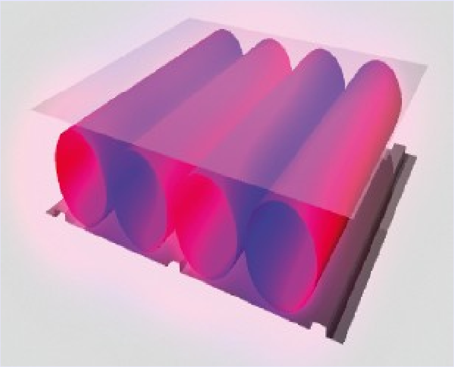
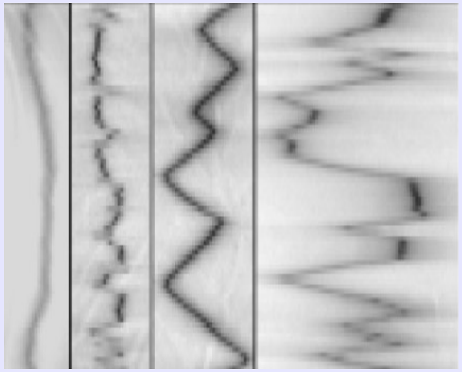
Nichtlineare Dynamik	Dynamik komplexer Fluide	Hydrodynamik, Strukturbildung und Nanobiokomplexität	Molekulare Wechselwirkungen
			

Abteilung Hydrodynamik, Strukturbildung und Nanobiokomplexität

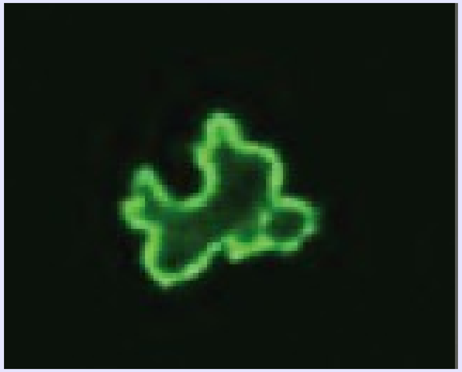
Thermische Konvektion



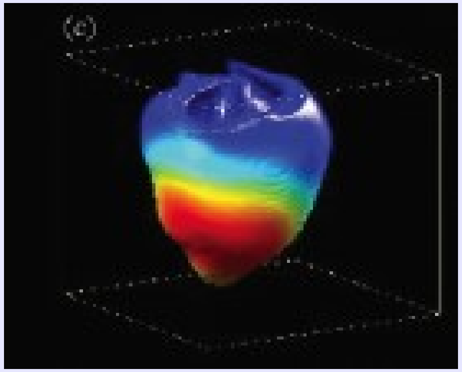
Tektonik



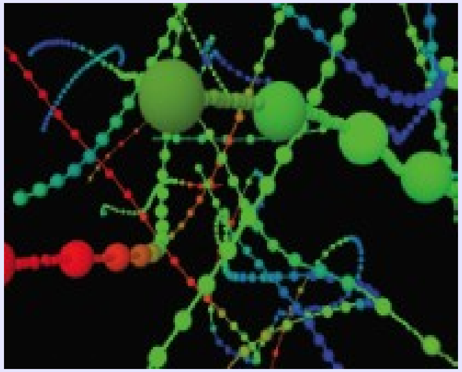
Chemotaxis



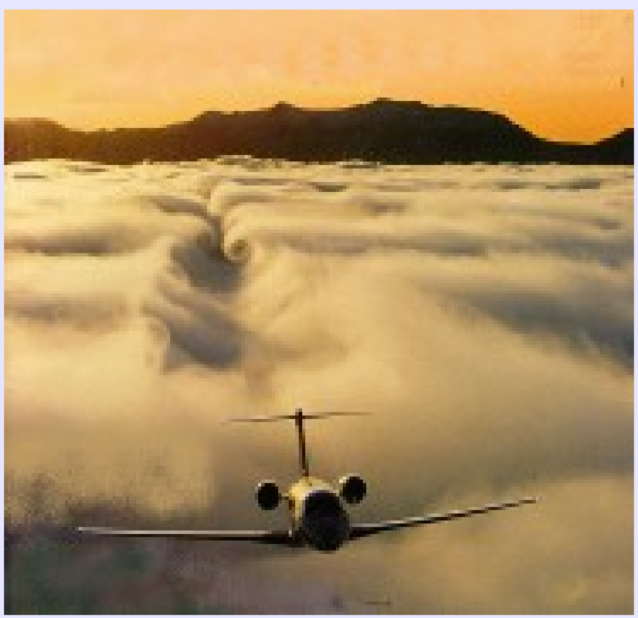
Herzdynamik



Turbulenz



Turbulenz



Navier-Stokes-Gleichung

$$\rho \frac{\partial u}{\partial t} + \rho (u \cdot \nabla) u = -\nabla p + \eta \Delta u + (\lambda + \eta) \nabla (\nabla \cdot u) + f$$

Randbedingungen ⇨ Direkte Numerische Simulation (DNS)

+ alle Strömungsparameter zugänglich

Navier-Stokes-Gleichung

$$\rho\frac{\partial u}{\partial t}+\rho(u\cdot\nabla)u=-\nabla p+\eta\Delta u+(\lambda+\eta)\nabla(\nabla\cdot u)+f$$

Randbedingungen ⇨ Direkte Numerische Simulation (DNS)

+ alle Strömungsparameter zugänglich
− numerisch aufwendig
− einfache (periodische) Randbedingungen
− keine realen (komplexen) Strömungen

Navier-Stokes-Gleichung

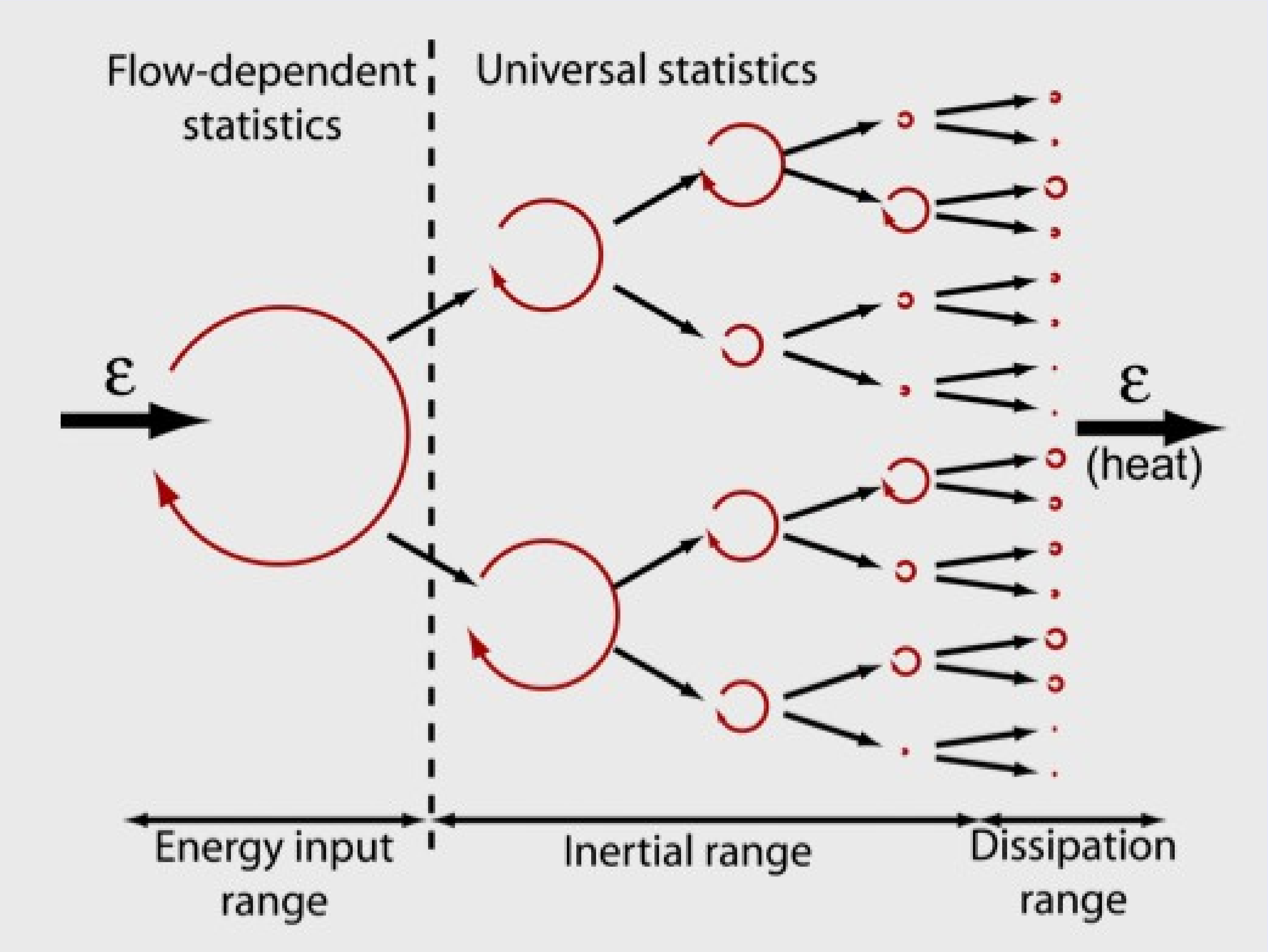
$$\rho\frac{\partial u}{\partial t}+\rho(u\cdot\nabla)u=-\nabla p+\eta\Delta u+(\lambda+\eta)\nabla(\nabla\cdot u)+f$$

Randbedingungen ⇨ Direkte Numerische Simulation (DNS)

+ alle Strömungsparameter zugänglich
− numerisch aufwendig
− einfache (periodische) Randbedingungen
− keine realen (komplexen) Strömungen

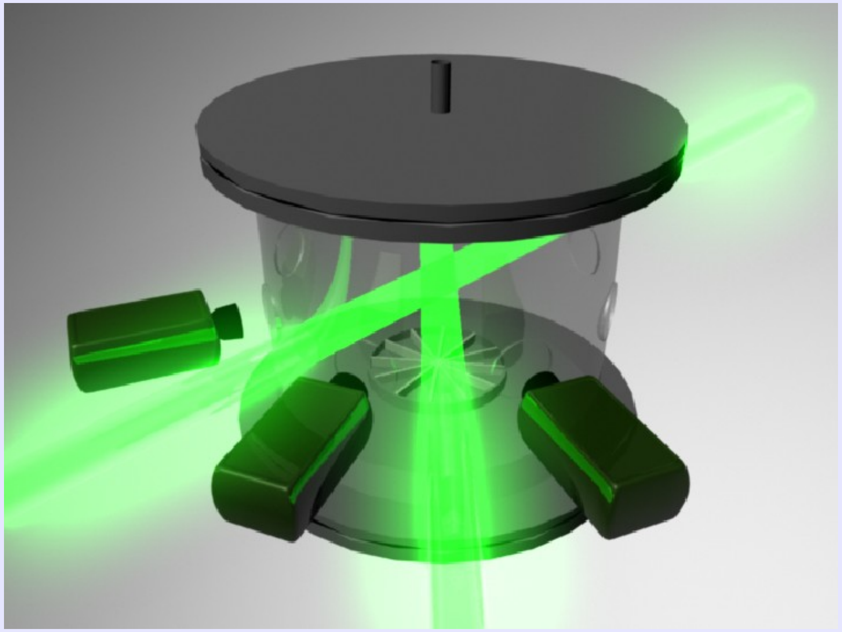
⇨ Turbulenzmodelle

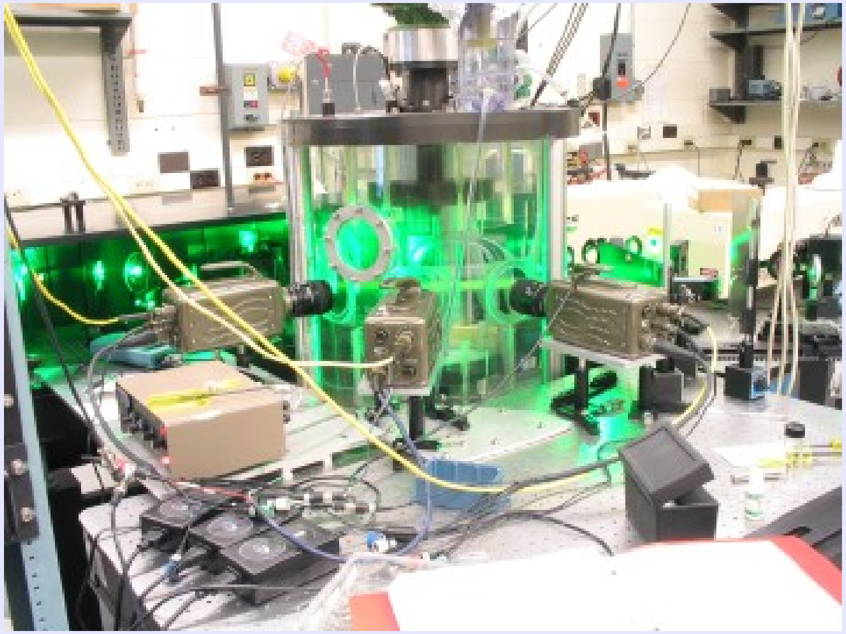
Kolmogorov

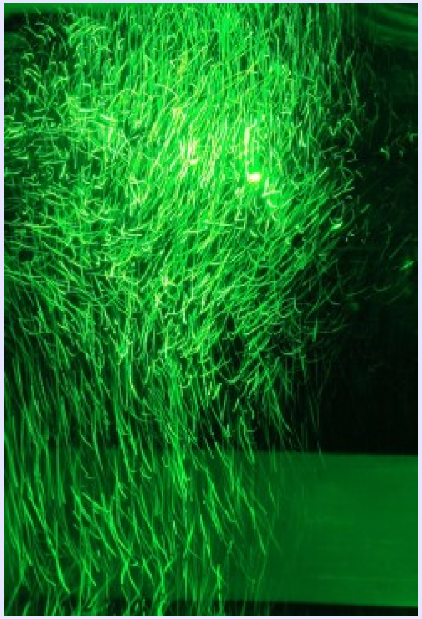


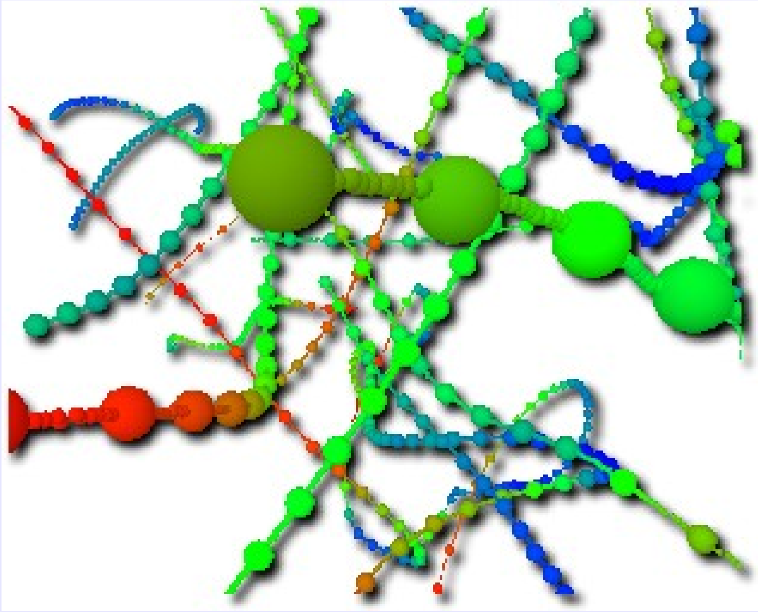
Flow-dependent statistics
Universal statistics
ε
ε
(heat)
Energy input range
Inertial range
Dissipation range

French Washing Machine

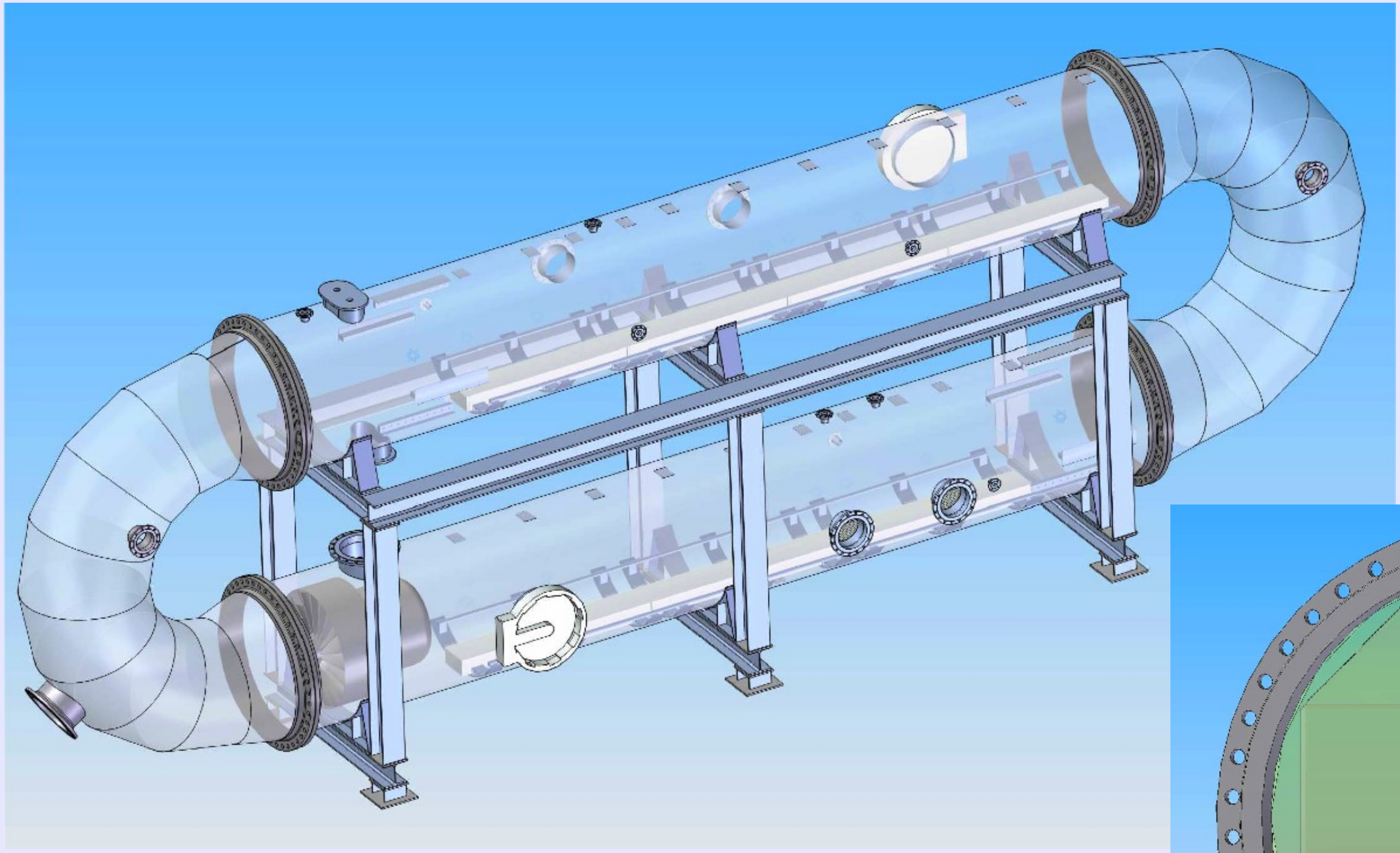


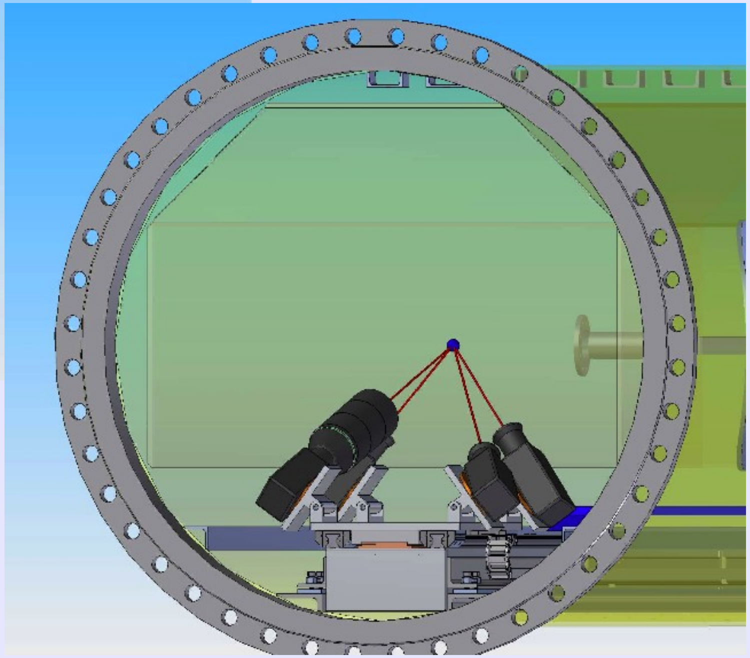




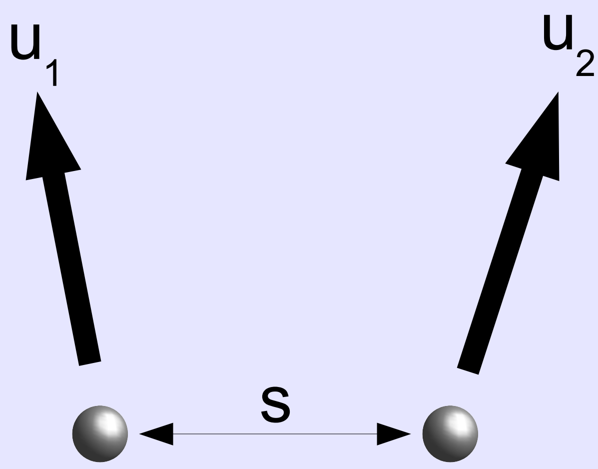


SF_6-Druckwindkanal

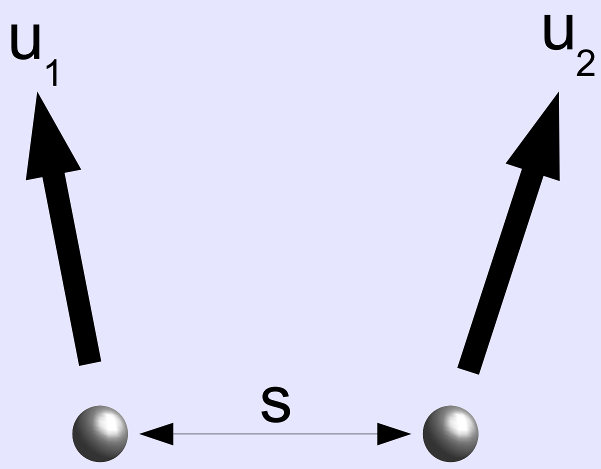


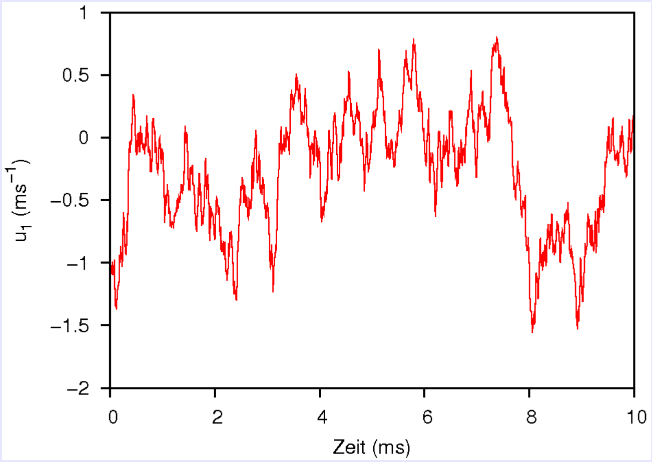


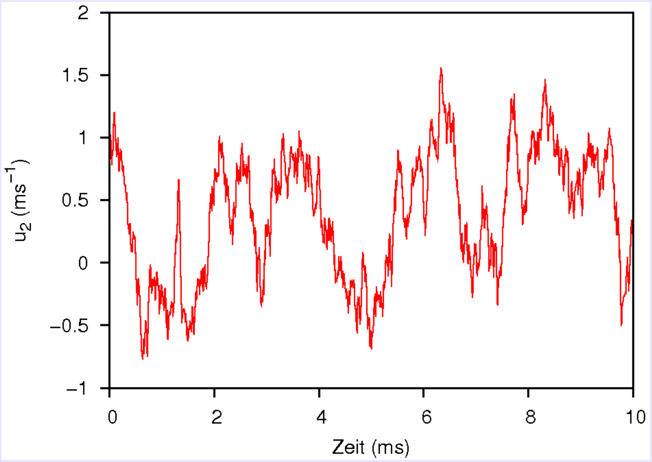
Korrelationsfunktion



Korrelationsfunktion







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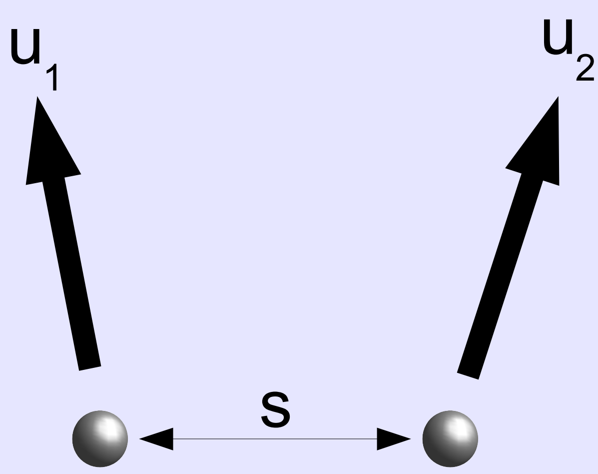
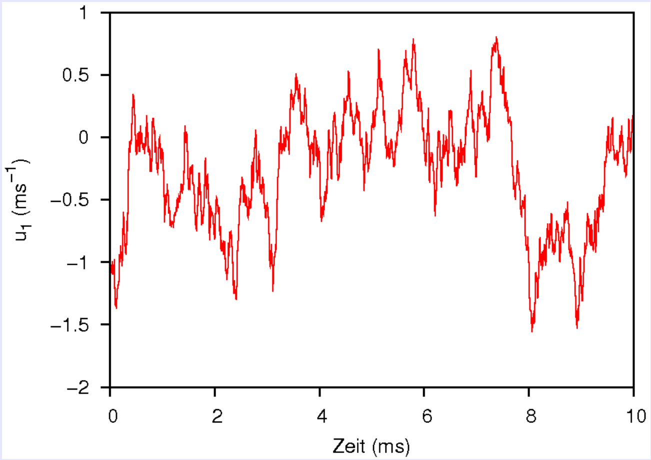
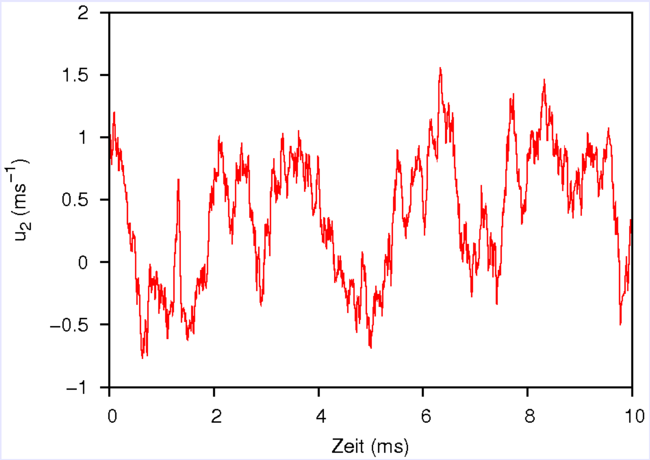


u_1	u_2	$u_1 \cdot u_2$
+	+	+
−	−	+
		+





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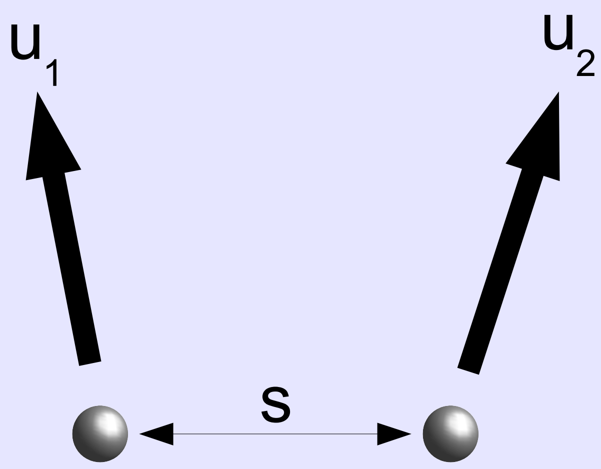
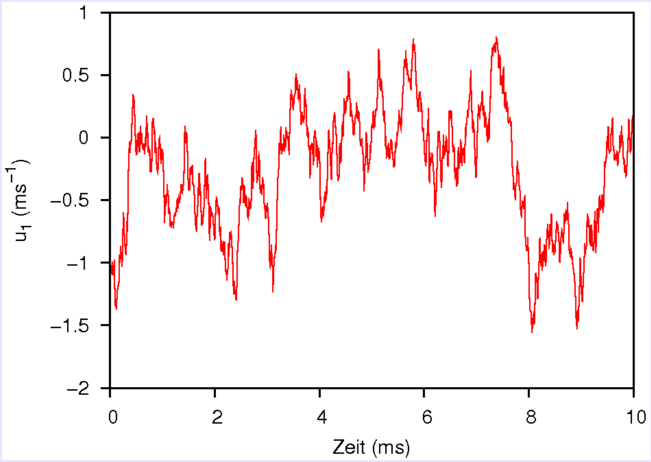
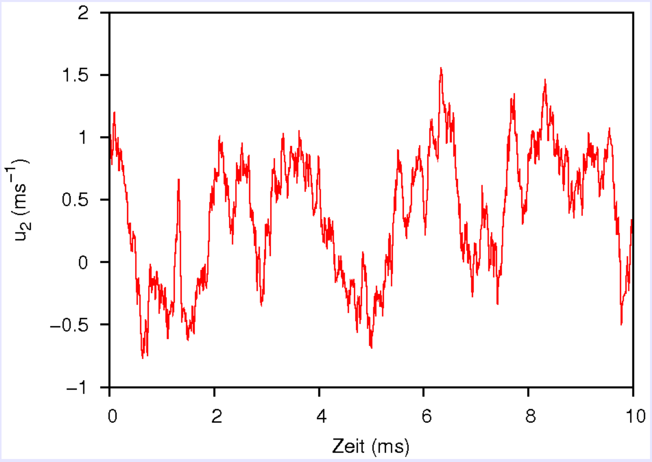


u_1	u_2	$u_1 \cdot u_2$
+	−	−
−	+	−
		−





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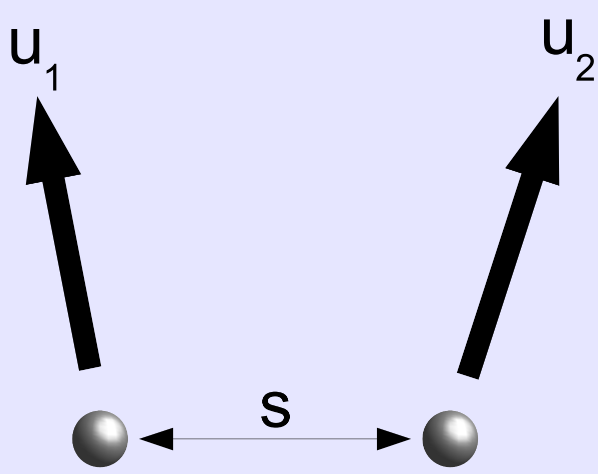
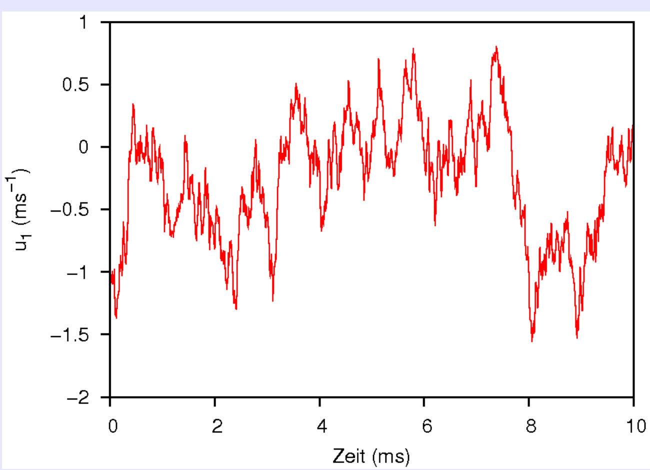
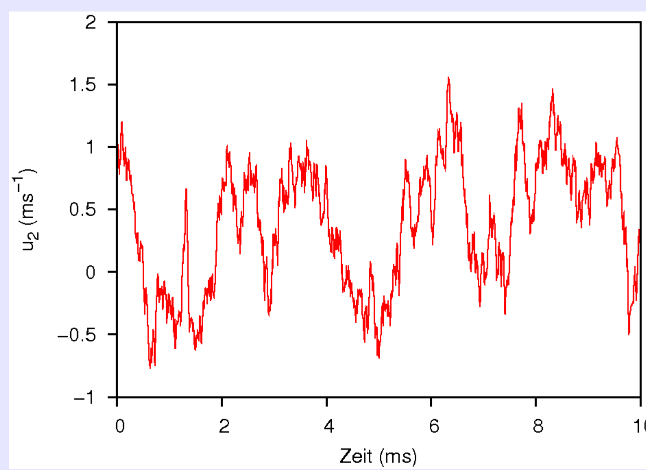


u_1	u_2	$u_1 \cdot u_2$
+	+	+
+	−	−
−	+	−
−	−	+
		0





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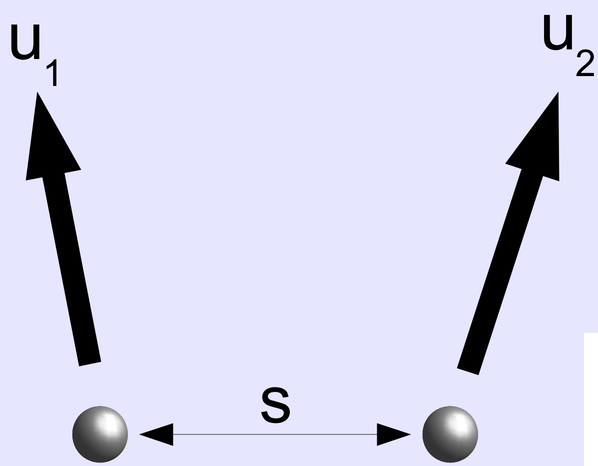
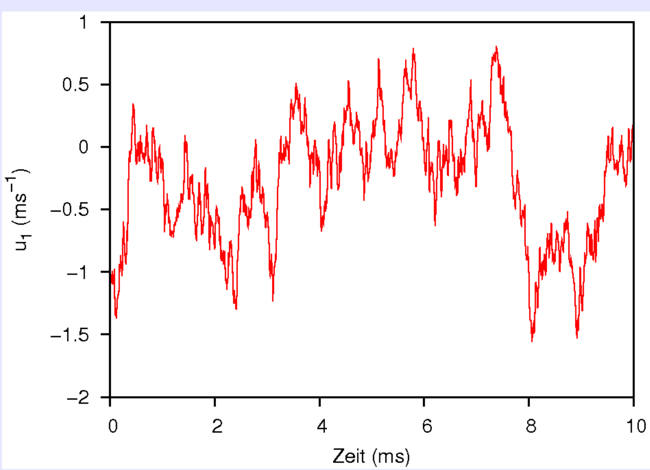
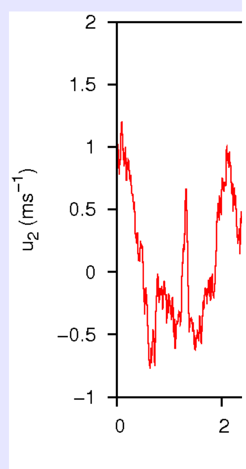
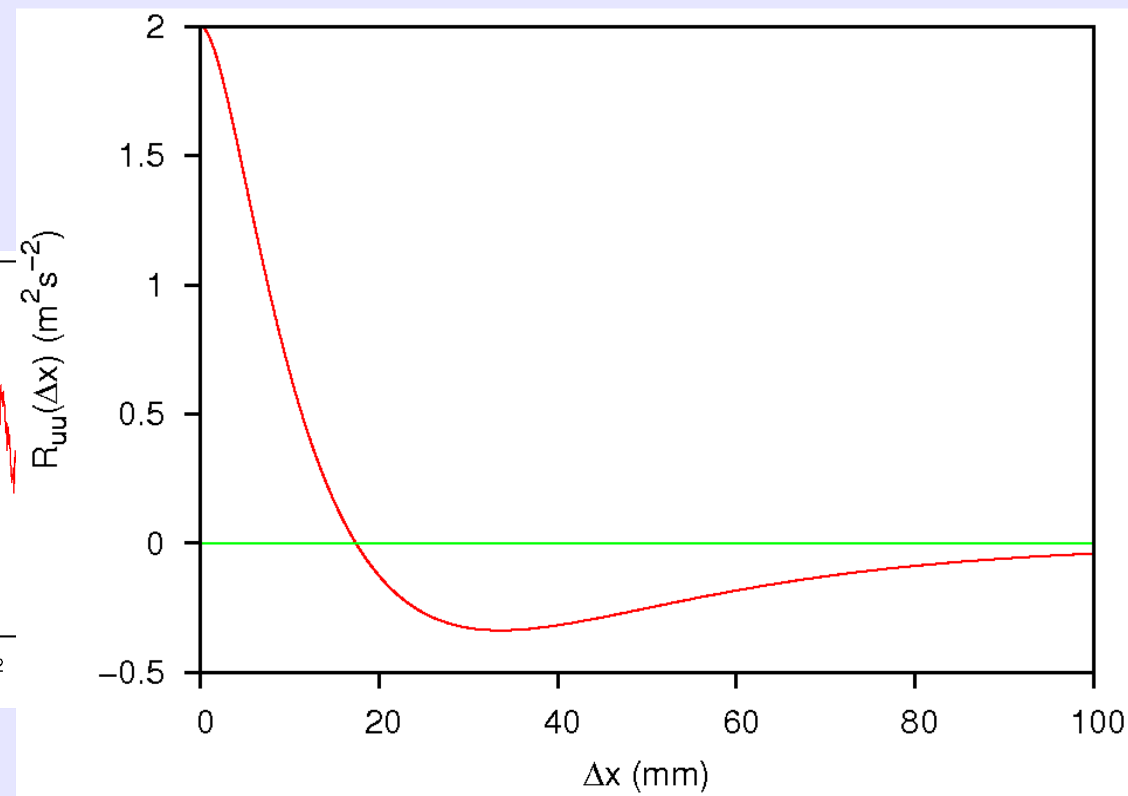


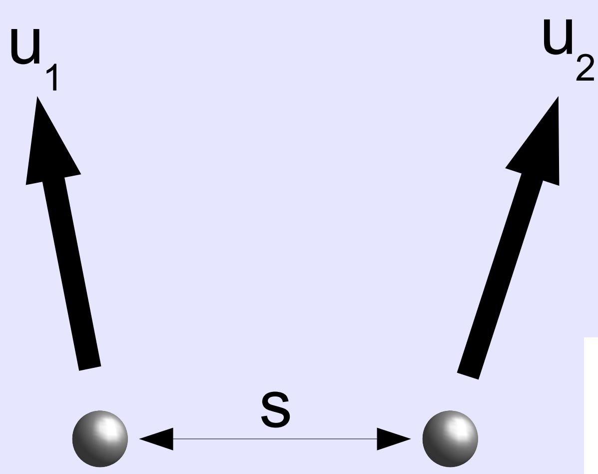
$$R_{u_1 u_2}(\Delta x) = \mathrm{E}\{u_1(x)\, u_2(x+\Delta x)\}$$



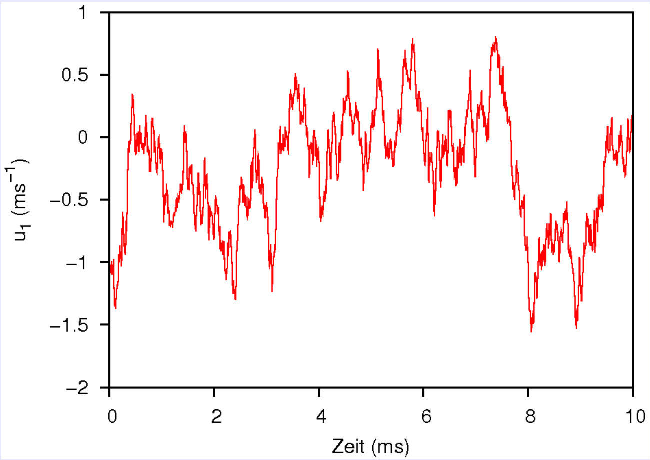


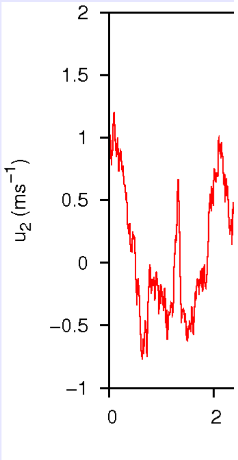


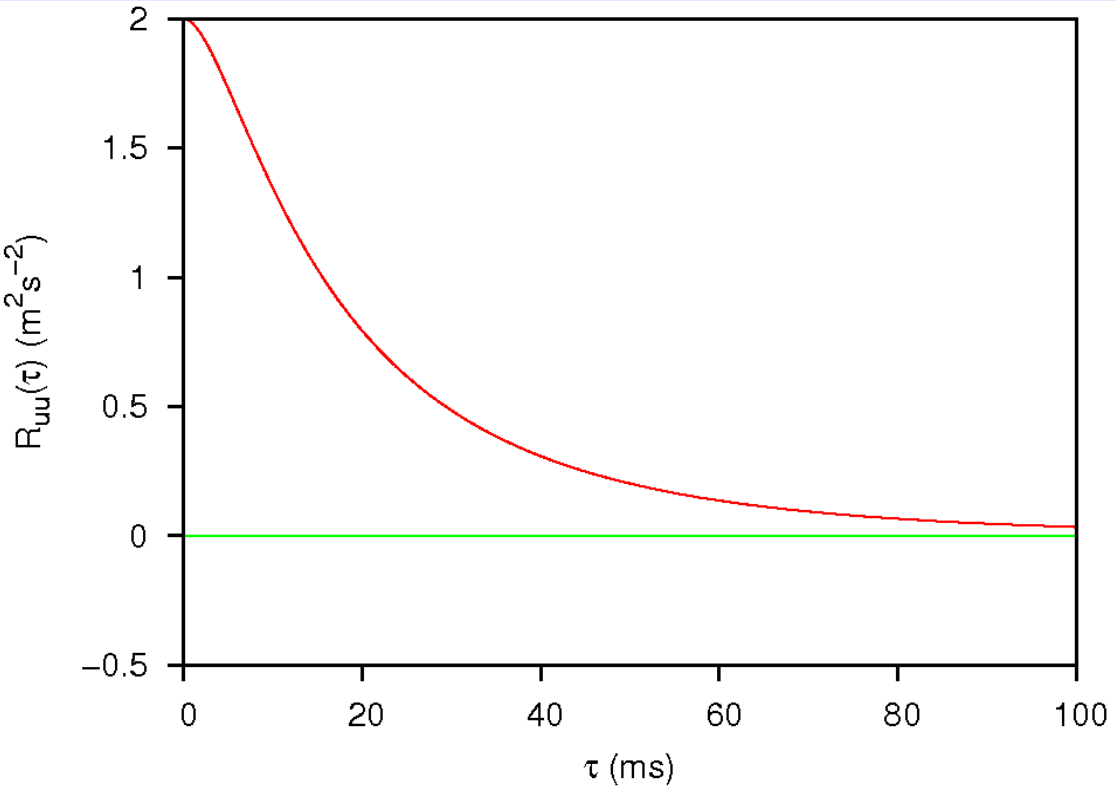
Korrelationsfunktion



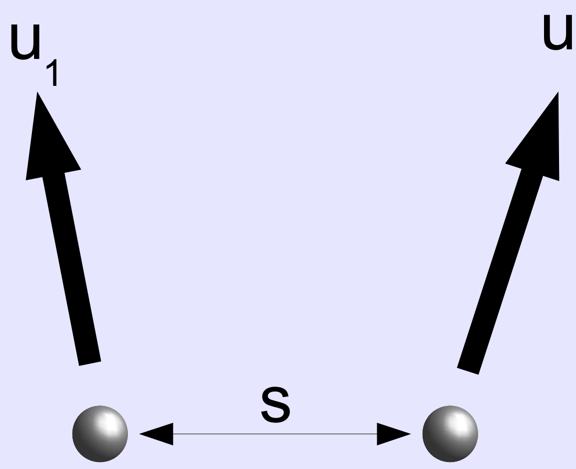
$$R_{u_1 u_2}(\tau) = \mathrm{E}\{u_1(t)\, u_2(t+\tau)\}$$



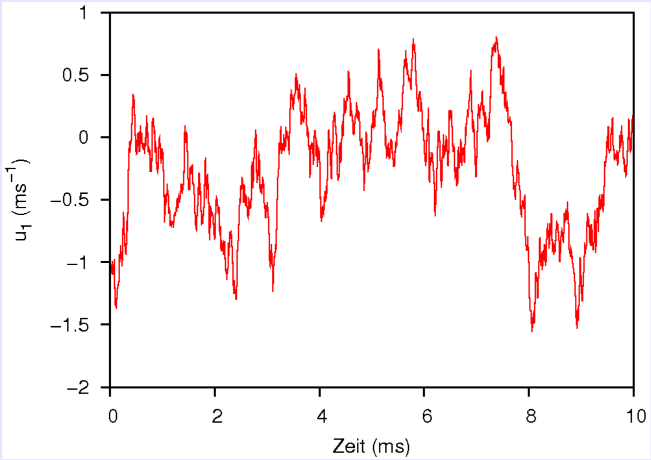


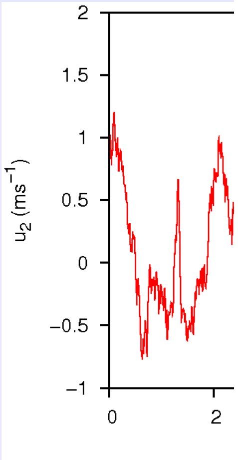


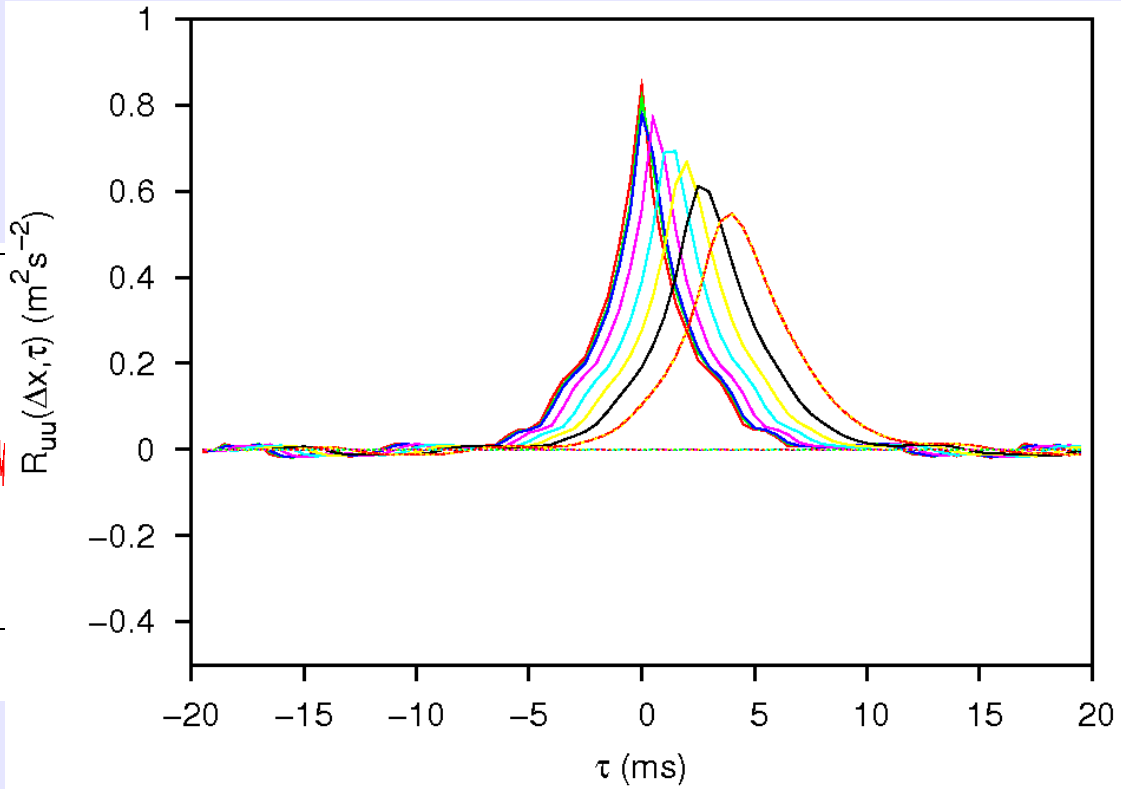
Korrelationsfunktion



$$R_{u_1 u_2}(\Delta x, \tau) = \mathrm{E}\{u_1(x,t)\, u_2(x+\Delta x, t+\tau)\}$$

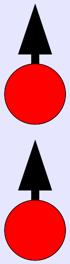


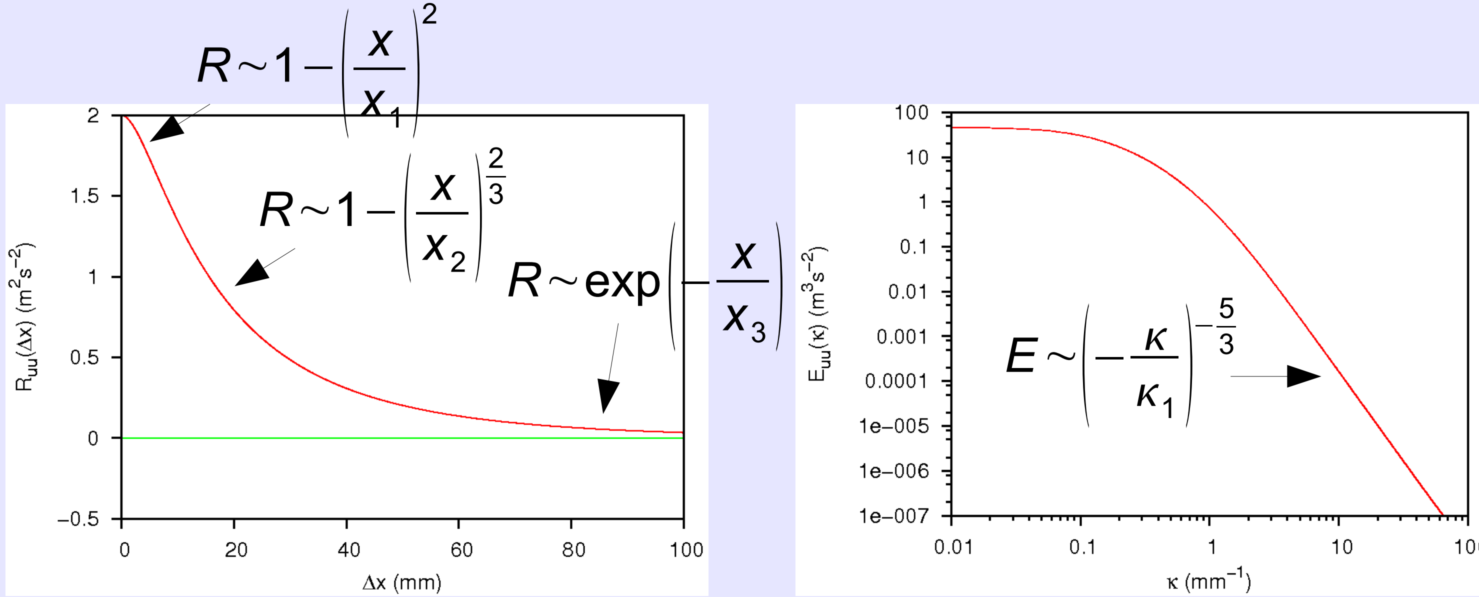




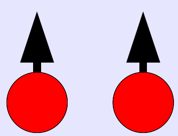
Turbulenzspektrum

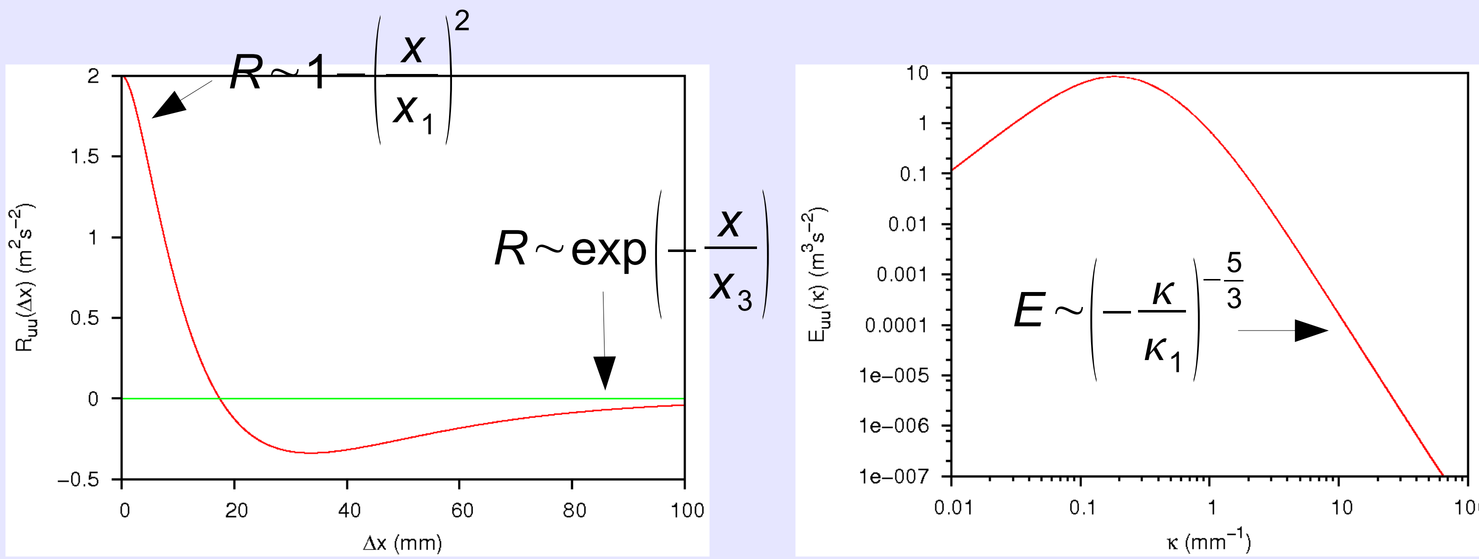
f-Korrelation



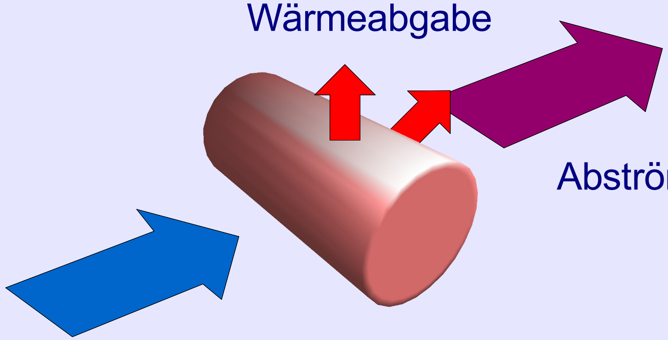


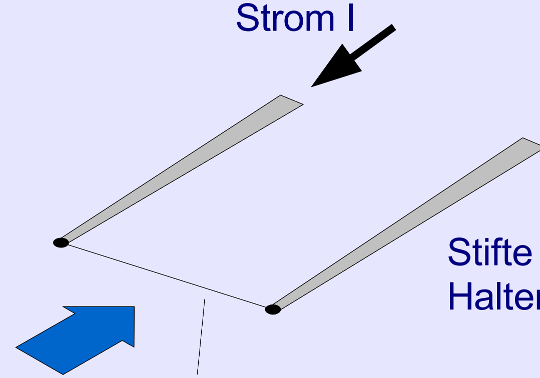
g-Korrelation

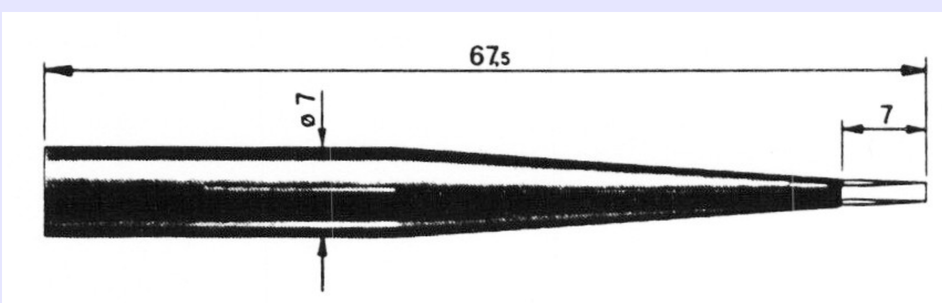


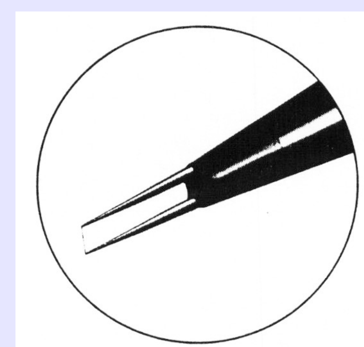


Hitzdrahtanemometer

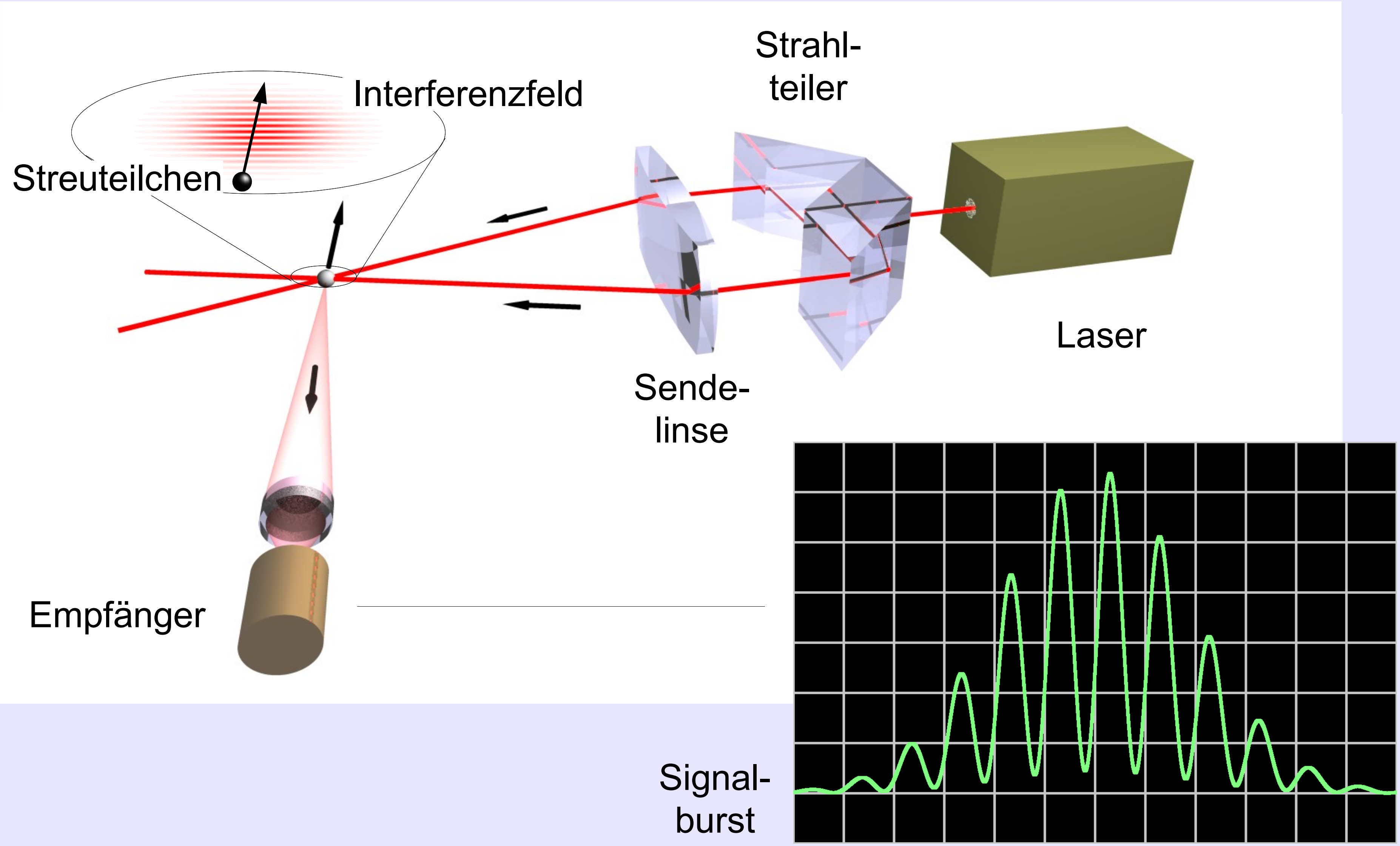






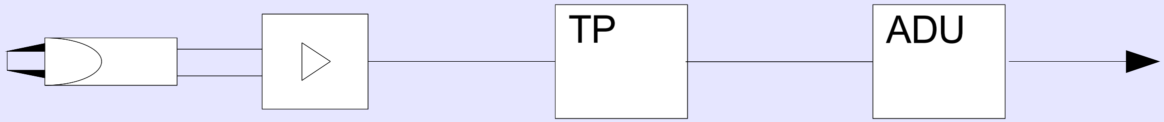


Laser-Doppler-Anemometer



Datensatzaufnahme und -verarbeitung in der Strömungsmesstechnik

Hitzdrahtanemometer



Diskreter Datensatz $u_i(t_i)$

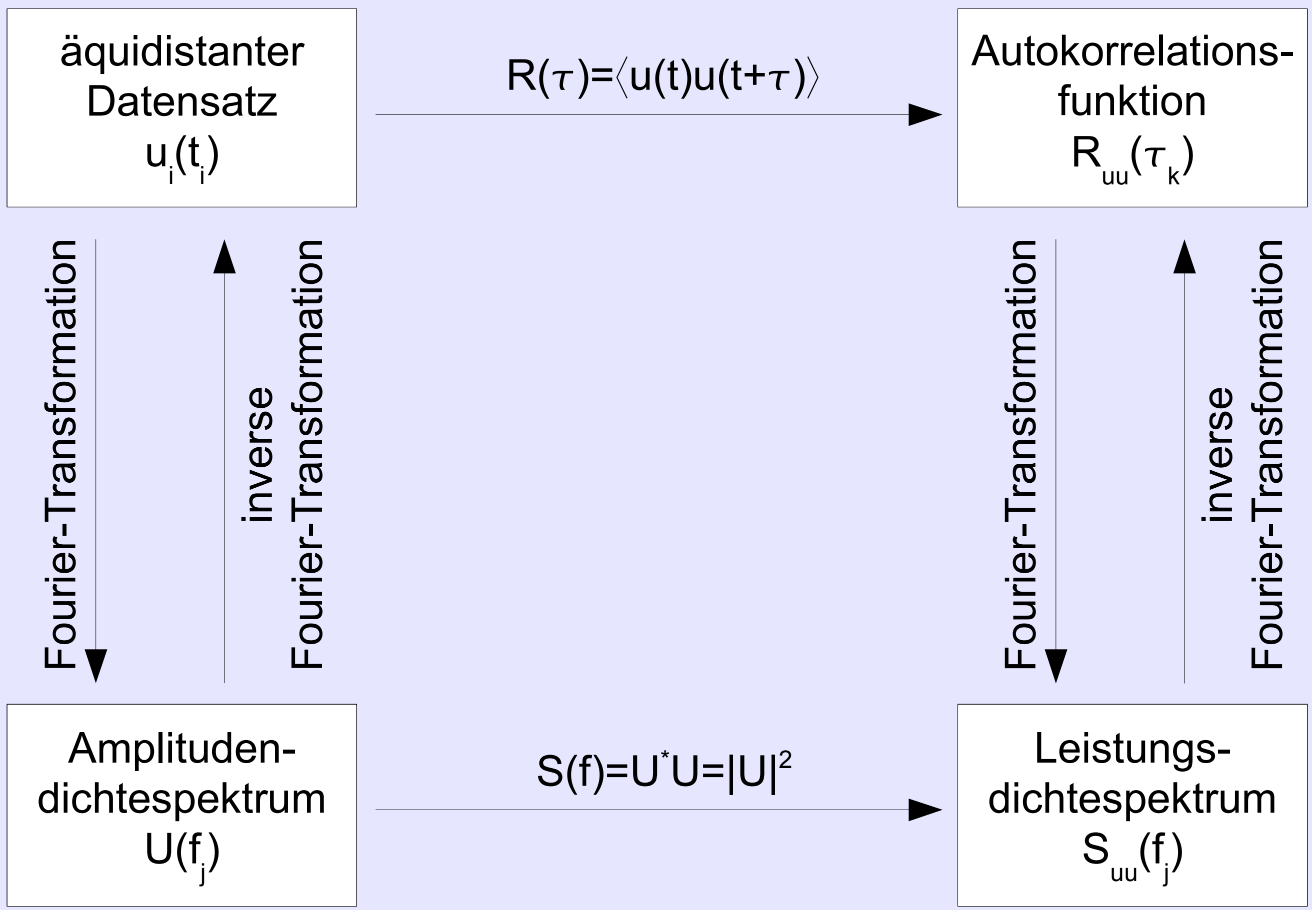
- äquidistant abgetastet
- schmalbandiges Rauschen

Sensor

Vorverstärker
Anpassung

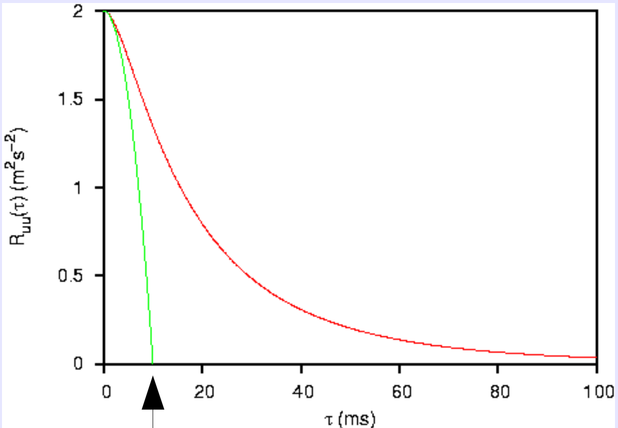
Analoges Filter:
- Anti-Aliasing
- Rauschunterdrückung

AD-Umsetzer:
- Diskretisierung



Zeitliche Kennfunktionen

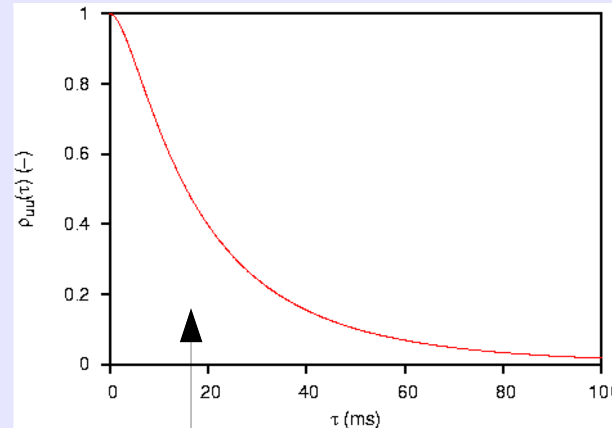
zeitliche Autokorrelationsfunktion



Taylor-Zeitmaß T_λ

Normierung

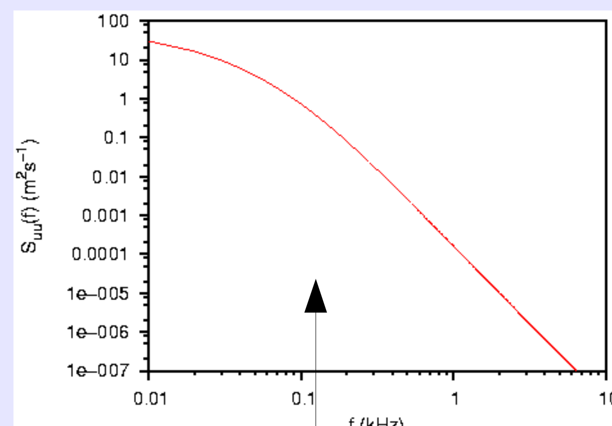
Korrelationskoeffizient



integrales Zeitmaß T_L

spektrale Leistungsdichte

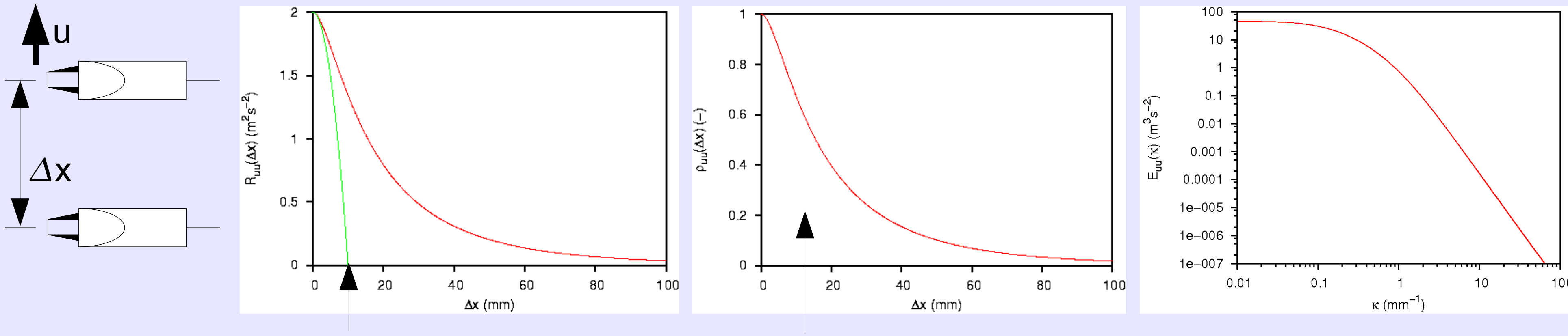
Fourier-Transformation



Varianz

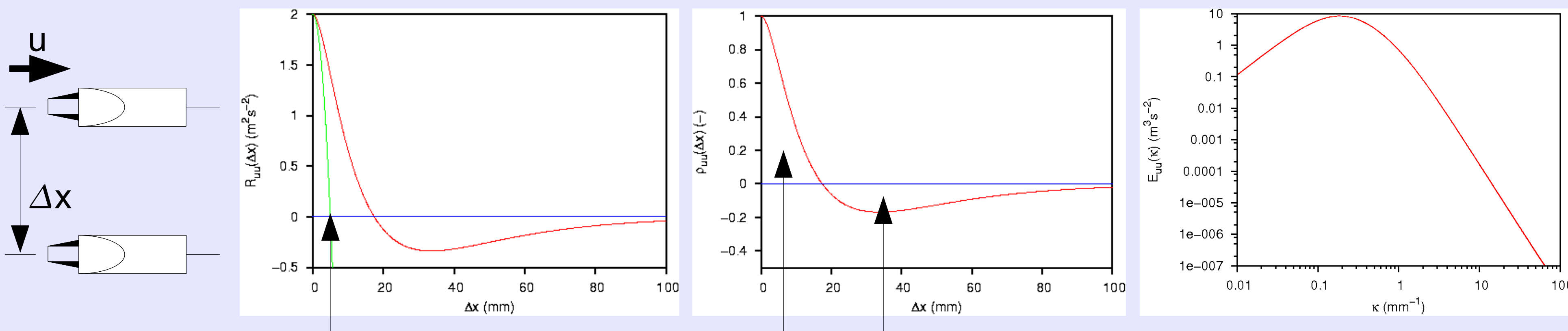
Räumliche Kennfunktionen

räumliche Korrelationsfunktion | räumlicher Korrelationskoeffizient | Wellenzahlspektrum



Taylor-Mikromaß λ_f

integrales Längenmaß L_f

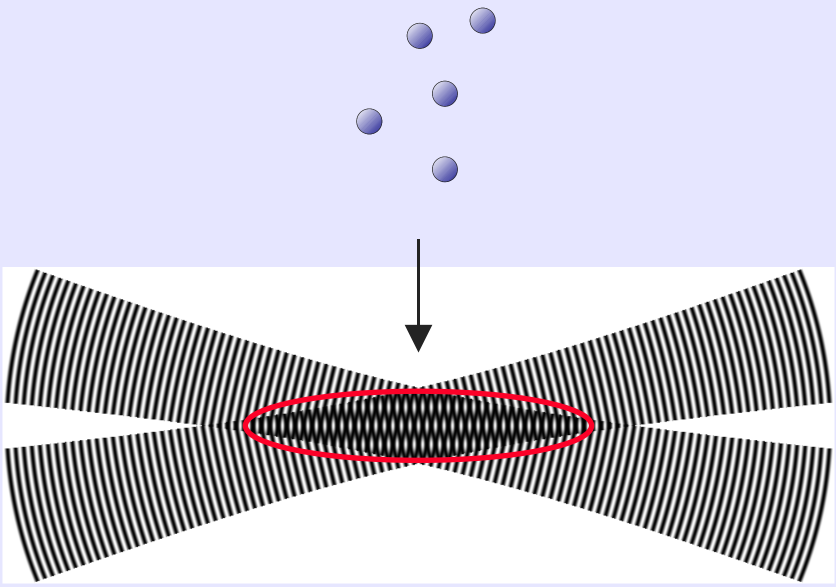


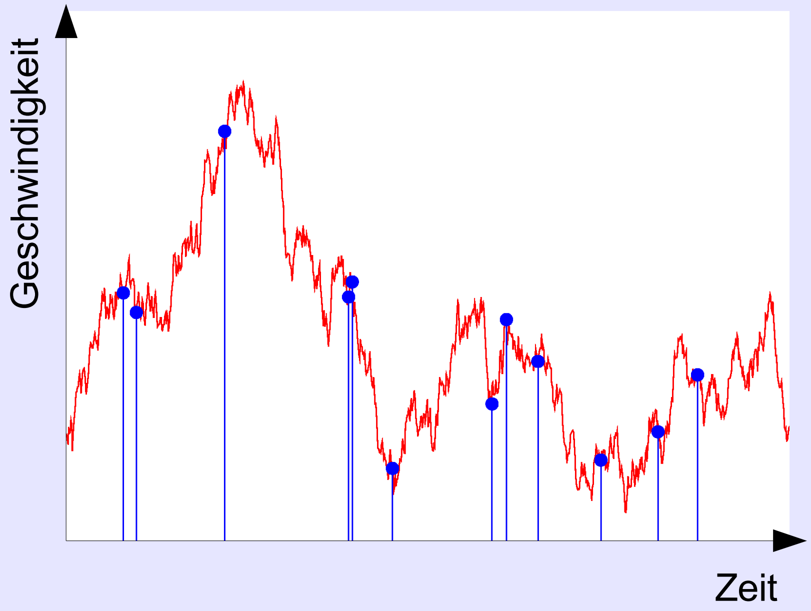
Taylor-Mikromaß λ_g

integrales Längenmaß L_g

Abschätzung der Dissipationsrate ε

LDA-Datensatz



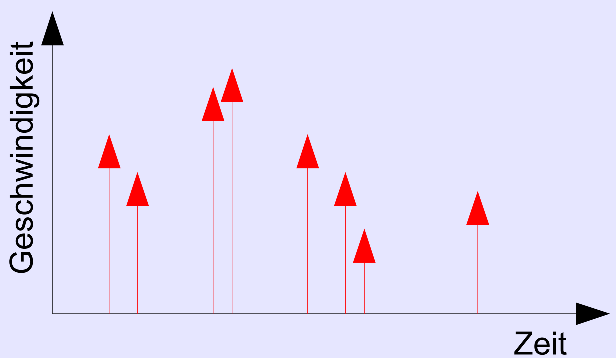


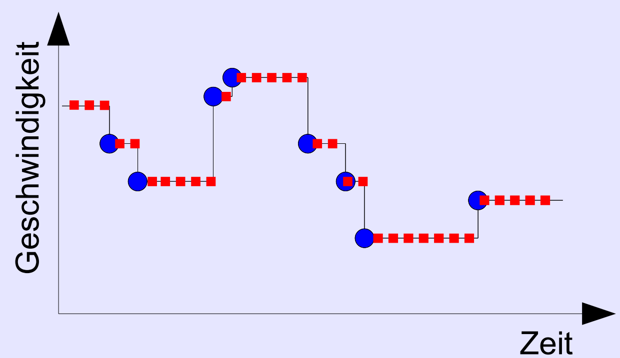
Einzelteilchenmessung	⇨	zufällig abgetastete Zeitreihe
Unsicherheit der Frequenzschätzung	⇨	breitbandiges Rauschen
Korrelation zw. Teilchenrate und Geschwindigkeit	⇨	Korrelation zw. Datenrate und Geschwindigkeit
Interferenz des Streulichtes verschiedener Teilchen	⇨	Prozessortotzeit

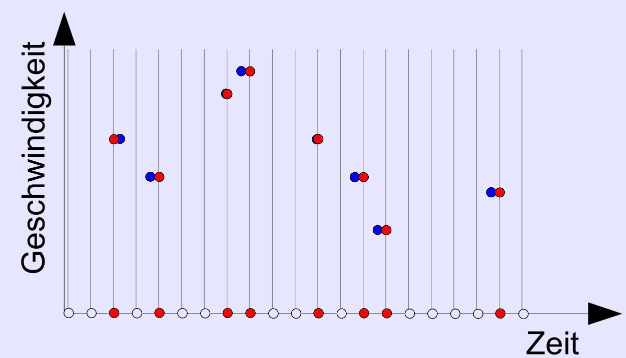
Strategien für die Auswertung von unregelmäßig abgetasteten Datensätzen

unregelmäßig abgetasteter Datensatz

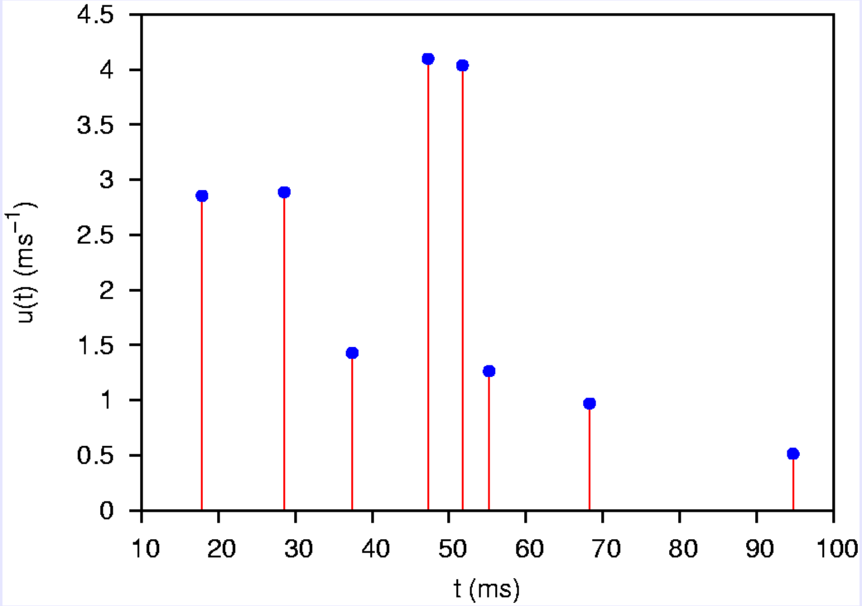
Direkte Verarbeitung	Signalrekonstruktion und regelmäßige Wiederabtastung	Transformation in einen dünn besetzten Datensatz
◆ Mathematische Beschreibung des Signals (z.B. Folge von Dirac-Impulsen) ◆ Berücksichtigung der unregelmäßigen Abtastung ◆ Entwicklung geeigneter Schätzer	◆ Wahl einer geeigneten Rekonstruktions- bzw. Interpolationsvorschrift ◆ Klassische Datenverarbeitung	◆ Quantisierung der Abtastzeitpunkte oder -intervalle ◆ Berücksichtigung von Signallücken ◆ Schätzer aus der Prozessidentifikation





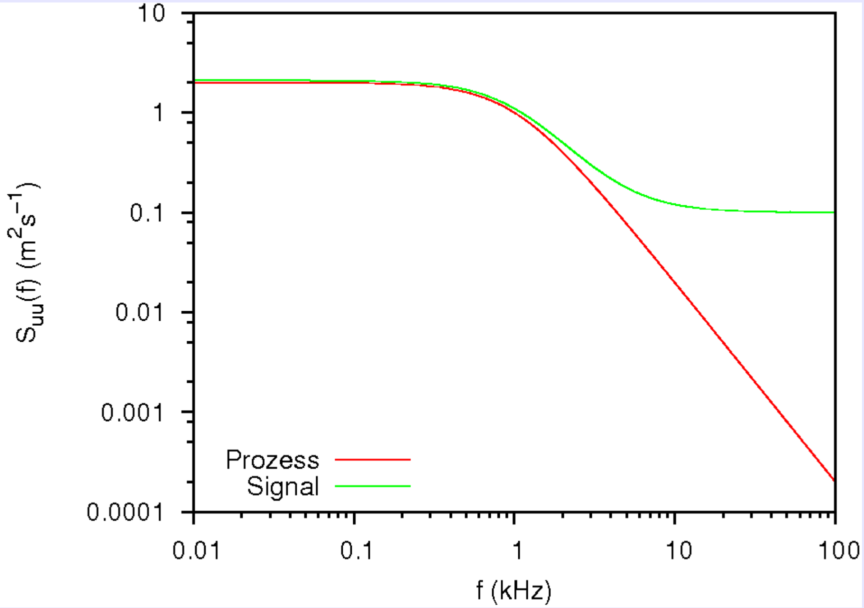


- Prinzip der direkten Spektralanalyse



$$S_S(f) \stackrel{\text{def}}{=} \frac{1}{T}\left|\int_0^T u(t)\, e^{-2\pi j f t_i}\right|^2 = \frac{T}{N^2}\left|\sum_{i=1}^{N} u_i e^{-2\pi j f t_i}\right|^2$$

- Systematischer Fehler aufgrund der unregelmäßigen Abtastung

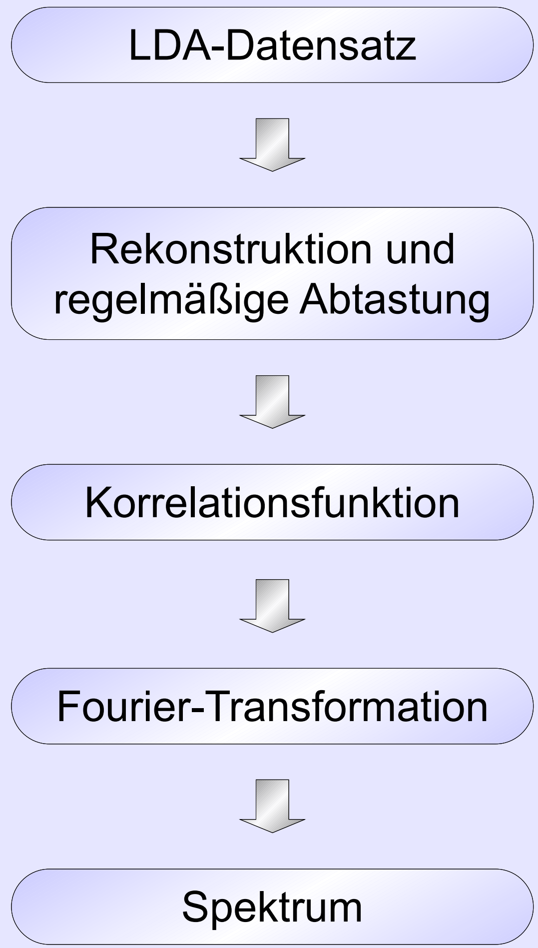


Fehlerabschätzung: $E\{S_S\} = S_P + \frac{T}{N}\sigma_u^2$

Korrektur: $\hat{S}_P(f) = \frac{T}{N^2}\left\{\left|\sum_{i=1}^{N} u_i e^{-2\pi j f t_i}\right|^2 - \sum_{i=1}^{N} u_i^2\right\}$

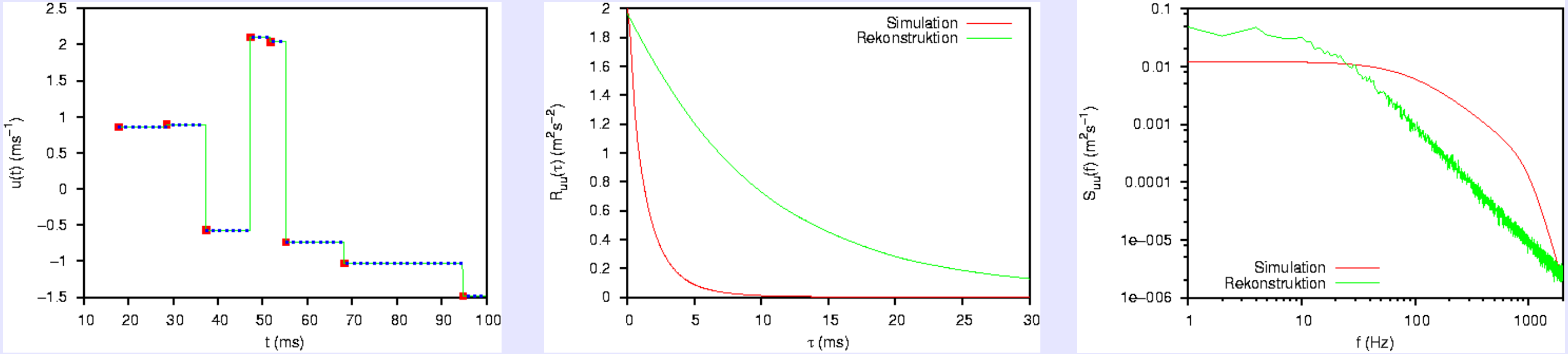
[GAS77]

- Ablauf

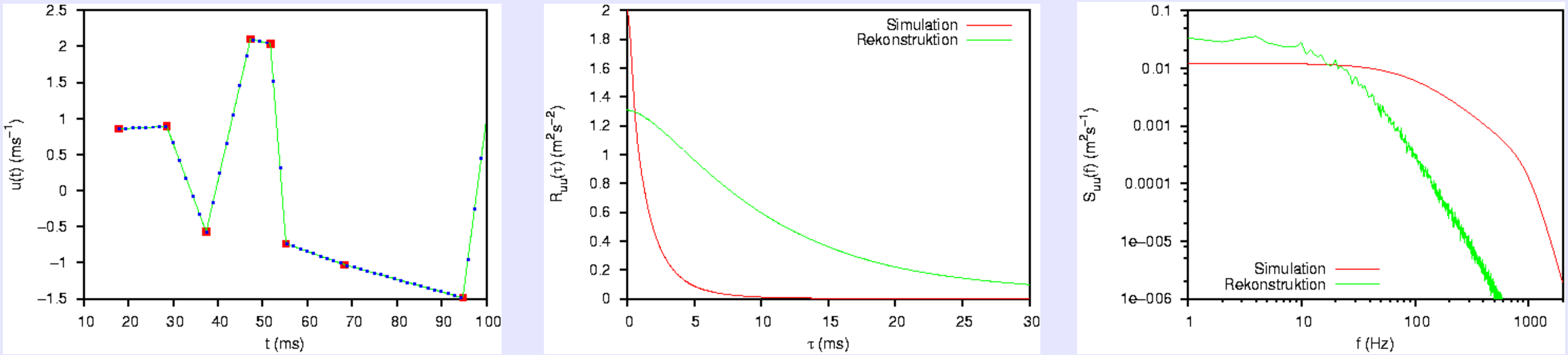

LDA-Datensatz
Rekonstruktion und regelmäßige Abtastung
Korrelationsfunktion
Fourier-Transformation
Spektrum

Auswirkung der Rekonstruktion

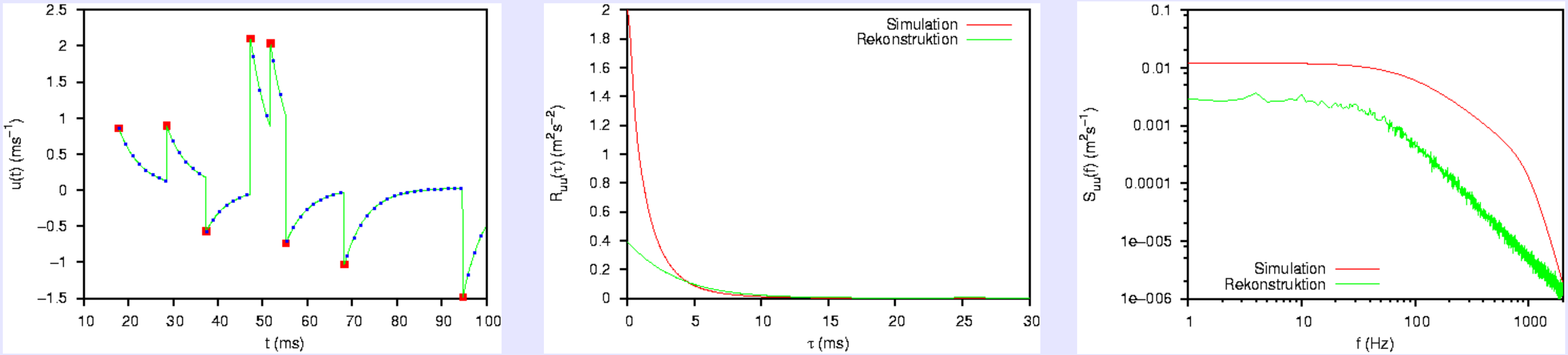
- Sample-and-Hold-Rekonstruktion



- lineare Interpolation

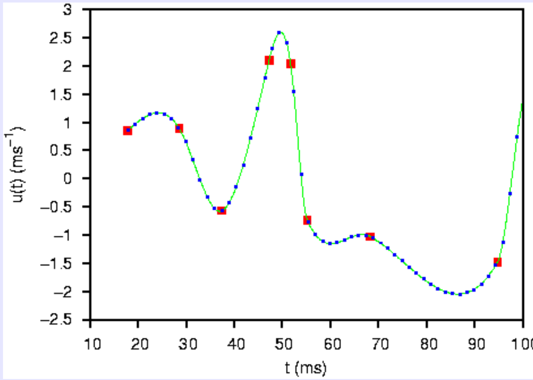


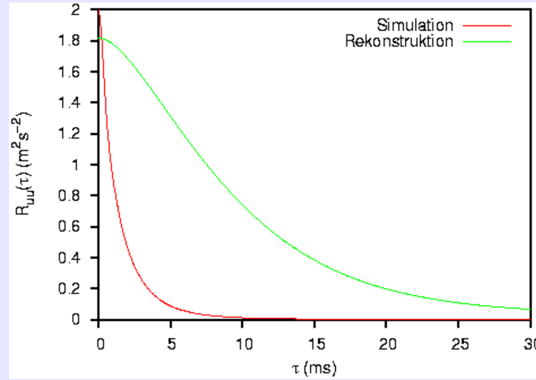
- exponentielle Rekonstruktion [HOS94]

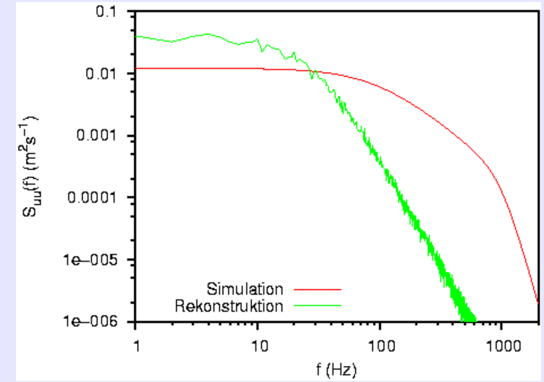


Auswirkung der Rekonstruktion

- Spline-Interpolation







- Kalman-Rekonstruktion [BEN95,MAA94]
- Shannon-Rekonstruktion [CLA85,VEY88]
- Anpassung einer bandbegrenzten Funktion (POCS) [LEE92,KUO92,SAU87,YEH90]
- fraktale Rekonstruktion [STR88,STR91,CHA92]

Allen Rekonstruktionen (unabhängig von der Rekonstruktionsvorschrift) ist gemeinsam:

- Bei hoher Datenrate sind alle Verfahren geeignet, aus dem unregelmäßig abgetasteten LDA-Datensatz einen regelmäßig abgetasteten Datensatz zu erzeugen, der die spektralen Eigenschaften des Strömungsprozesses widerspiegelt.
- Bei geringer Datenrate verändern sich die spektralen Eigenschaften. Der spektrale Charakter des Rekonstruktionsergebnisses wird direkt und unabhängig vom zugrundeliegenden Strömungsprozess von der verwendeten Rekonstruktionsvorschrift und der Datenrate bestimmt.

Korrektur des Rekonstruktionseinflusses [NOB96,98a]

1. Analyse des rekonstruierten Datensatzes

LDA-Datensatz

↓

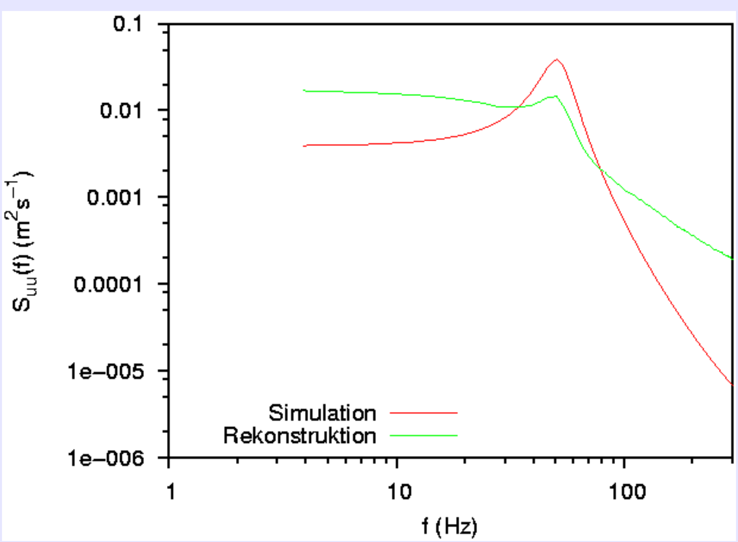
Rekonstruktion

↓

Resampling

↓

Korrelations- und Spektralanalyse



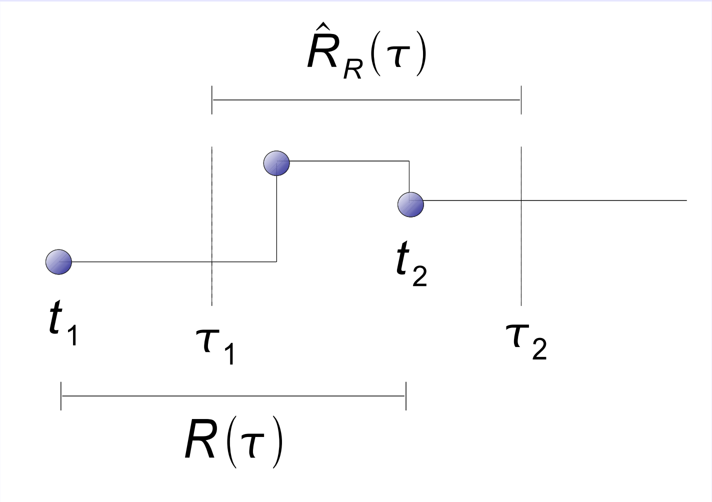
2. Abschätzung des Filters

LDA-Datensatz → Rekonstruktion → Resampling → Korrelations- und Spektralanalyse

Wahre ACF

$$E\{\hat{R}_R(\tau)\} = MR(\tau)$$

Nach Rekonstruktion erwartete ACF



3. Korrektur

LDA-Datensatz

↓

Rekonstruktion

↓

Resampling

↓

Korrelations- und Spektralanalyse

Wahre ACF

↓

$$E\{\hat{R}_R(\tau)\} = MR(\tau)$$

↓

Nach Rekonstruktion erwartete ACF

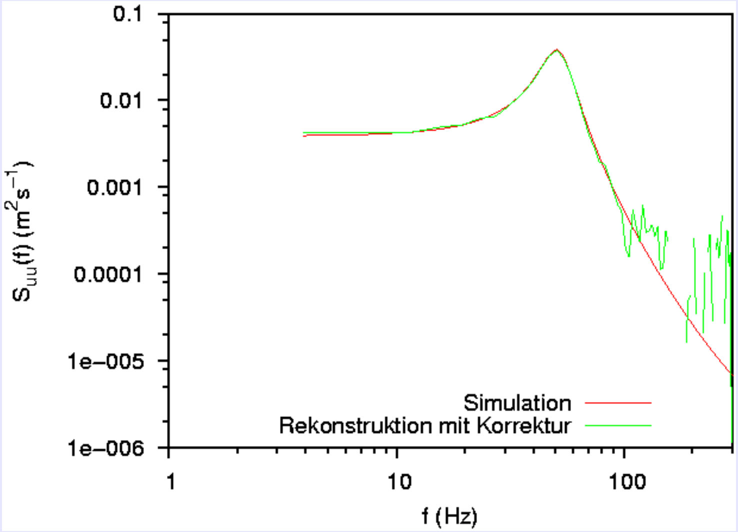
Korrigierte ACF

↑

$$\hat{R}(\tau) = M^{-1}\hat{R}_R(\tau)$$

↑

Nach Rekonstruktion bestimmte ACF



- Sample-and-Hold-Rekonstruktion
  - Rekonstruktionsvorschrift
  - Interpolationsfilter

$$u_R(t)=u_i \qquad t_i \leqslant t < t_{i+1}$$

$$E\left\{\hat{R}_R(\tau_k)\right\}=e^{-\dot{n}\tau_k}\left\{R(0)+\frac{(e^{\dot{n}\Delta\tau}-1)^2}{1-e^{2\dot{n}\Delta\tau}}\sum_{\xi=1}^{\infty} e^{-\dot{n}\tau_\xi}(1-e^{2\dot{n}\min(k,\xi)\Delta\tau})R(\tau_\xi)\right\}$$

  - Korrektur

$$\hat{R}(\tau_k)=\begin{cases}\hat{R}_R(0) & \text{für } k=0\\ (2c+1)\hat{R}_R(\tau_k)-c\left[\hat{R}_R(\tau_{k-1})+\hat{R}_R(\tau_{k+1})\right] & \text{sonst}\end{cases} \qquad c=\frac{e^{-\dot{n}\Delta\tau}}{(1-e^{-\dot{n}\Delta\tau})^2}$$

- Proportional-Ein-Punkt-Rekonstruktion (exp., Korrelationskoeffizient, S&H)
  - Rekonstruktionsvorschrift
  - Interpolationsfilter

$$u_R(t)=u_i f_R(t-t_i) \qquad t_i \leqslant t < t_{i+1}$$

$$E\left\{\hat{R}_R(\tau_k)\right\}=R(0)\sum_{i=-\infty}^{0} f_R(-\tau_i) f_R(\tau_k-\tau_i)\left(1-e^{-\dot{n}\Delta\tau}\right)e^{-\dot{n}(\tau_k-\tau_i)}$$
$$+\sum_{\xi=1}^{\infty} R(\tau_\xi)\sum_{i=1}^{\min(k,\xi)} f_R(\tau_\xi-\tau_i) f_R(\tau_k-\tau_\xi)\left(1-e^{-\dot{n}\Delta\tau}\right)^2 e^{-\dot{n}(\tau_k-2\tau_i+\tau_\xi)}$$

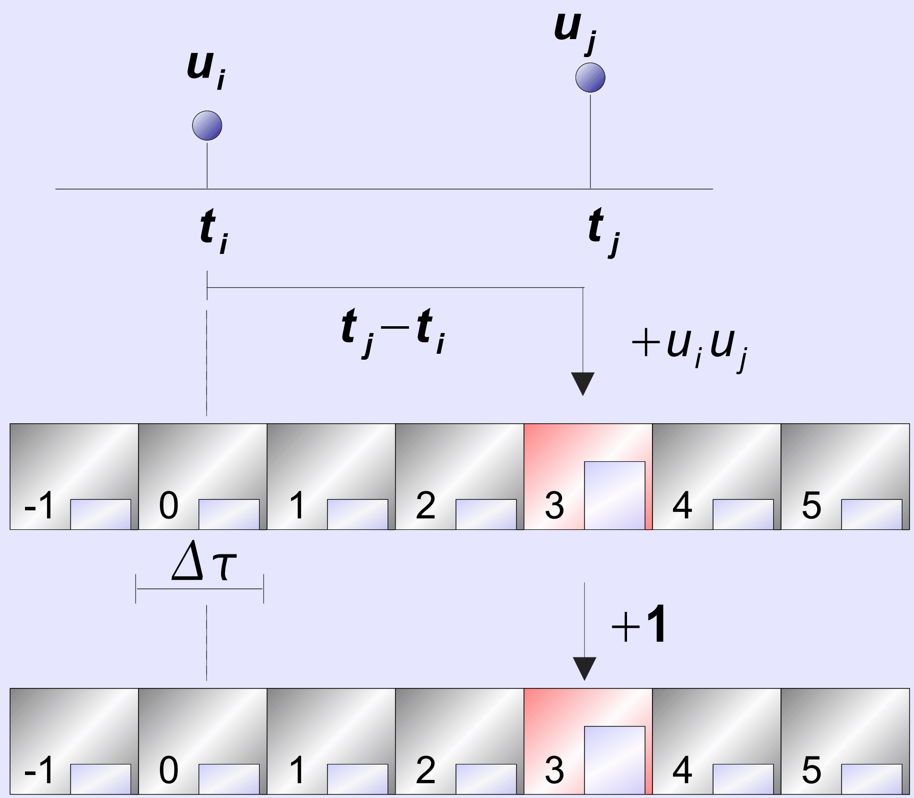
  - Korrektur erfolgt numerisch durch Lösung des linearen Gleichungssystems

- andere Interpolationen
  - prinzipiell auch für andere Interpolationen geeignet
  - numerischer Aufwand steigt mit der Anzahl der verwendeten Stützstellen stark an
  - geringer Gewinn gegenüber Sample-and-Hold-Interpolation

- Ablauf mit Filterkorrektur

- Grundprinzip [GAS75, MAY74, 78, SCO74]

$$i=1\ldots N$$
$$j=1\ldots N \qquad j\neq i$$



$$z_k=\sum_{i=1}^{N}\sum_{\substack{j=1\\ j\neq i}}^{N} u_i u_j b_k(t_j-t_i)$$

$$n_k=\sum_{i=1}^{N}\sum_{\substack{j=1\\ j\neq i}}^{N} b_k(t_j-t_i)$$

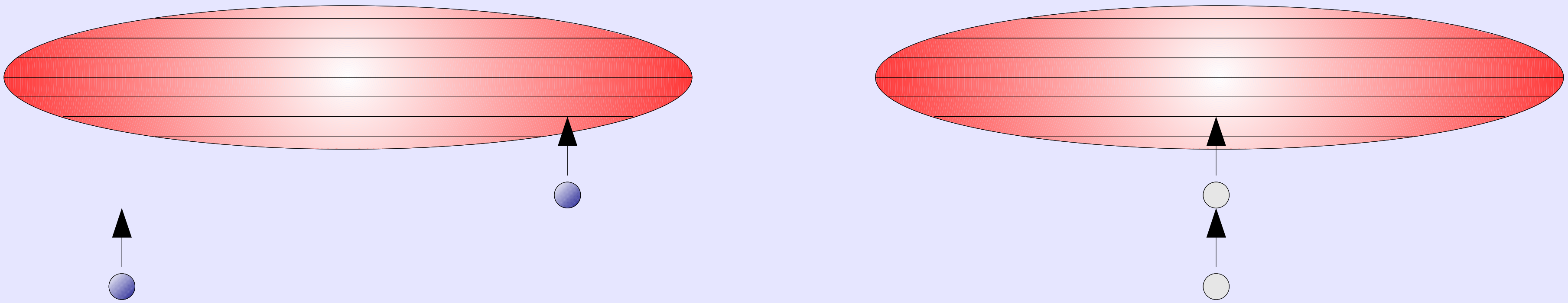
$$b_k(\Delta t)=\begin{cases}1 & \text{für}\,(k-1/2)\Delta\tau\leq\Delta t<(k+1/2)\Delta\tau\\ 0 & \text{sonst}\end{cases}$$

AKF
$$\hat{R}_k=z_k/n_k$$

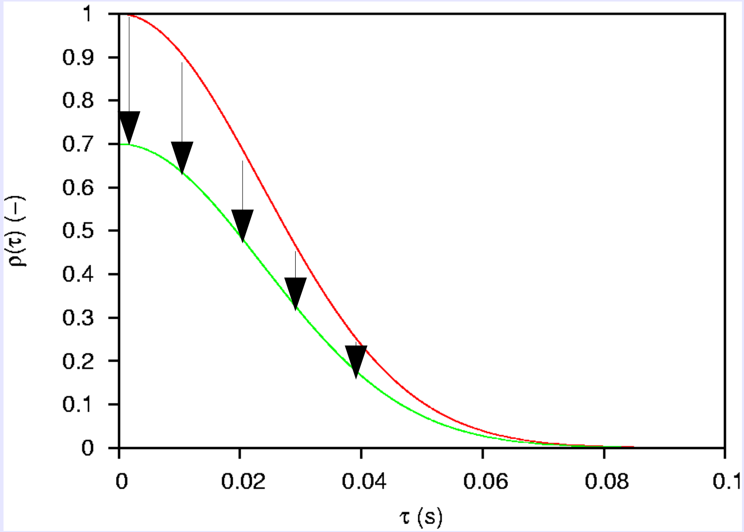
- Fehler
  - Geschwindigkeitsbias
  - Mittelung über Slotbreite
  - Normierungsfehler
  - Totzeit
  - Datenrauschen

  - Räumliche Ausdehnung des Messvolumens
- Korrektur
  - Wichtung
  - Fuzzy Slotting
  - Local Normalization
  - Local Time Estimation
  - Re-Normierung + Modellanpassung

- Bias durch räumliche Ausdehnung des Messvolumens
  - Zwei kurz aufeinanderfolgende Teilchen mit großem Abstand quer zur Strömung
  - Wertung wie zwei aufeinanderfolgende Teilchen ohne Abstand quer zur Strömung

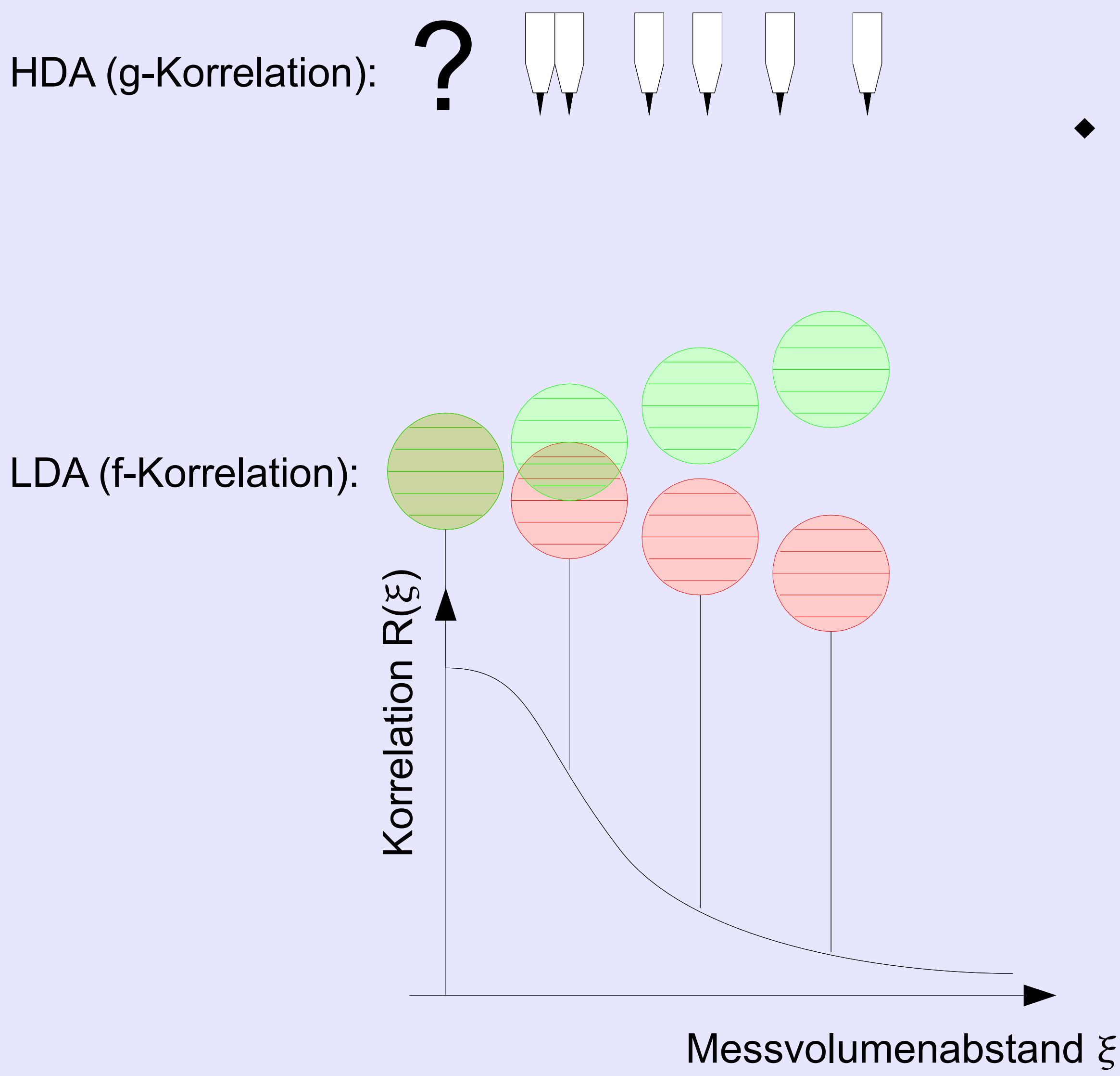


  - Verringerung der f-Korrelation



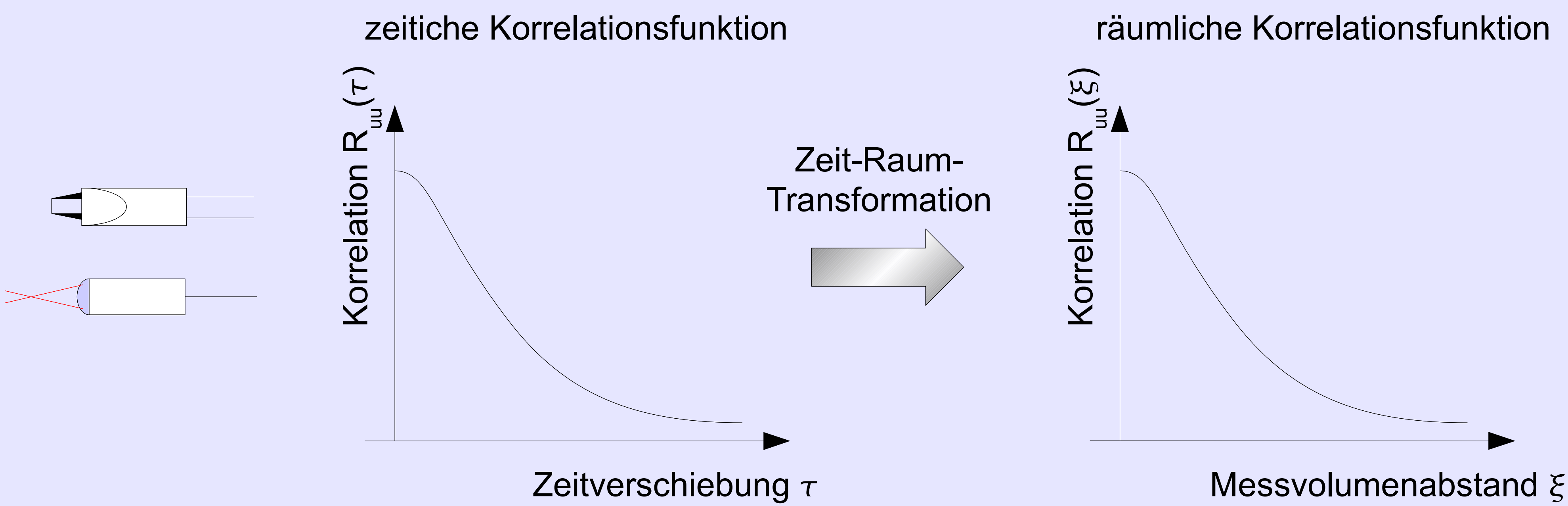
- Auswirkung und Korrektur wie Datenrauschen

- Multi-Punkt-Messung

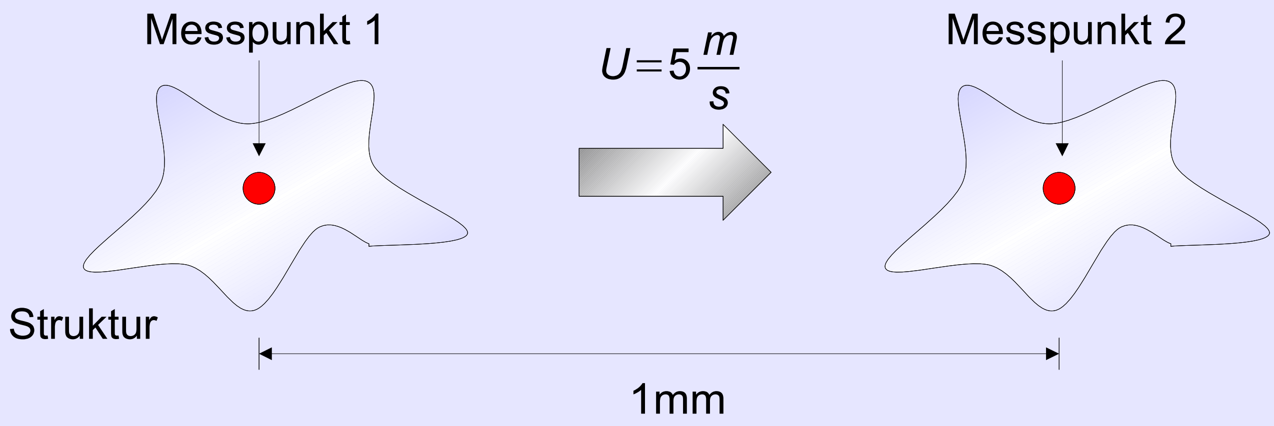


- Vorteil:
  - direkte Messung der räumlichen Korrelation
- Nachteile:
  - zwei oder mehr Sensoren
  - begrenzte räumliche Auflösung
  - zeitliche Korrelationen bleiben ungenutzt
  - hoher Justage- und Kalibrieraufwand
  - hoher zeitlicher Aufwand (mechanische Traversierung und wiederholte Messung)
  - hohe Anforderungen an die Langzeitstabilität
  - Probleme durch Rückwirkung der Sonden

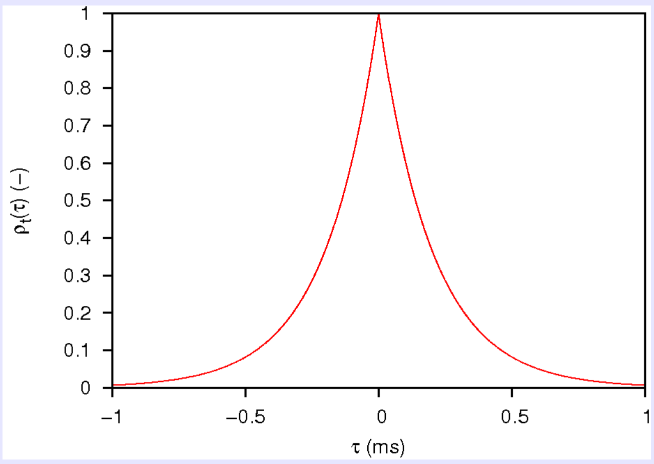
- Zeit-Raum-Transformation
  - Vorteile:
    - schnelle Messwertaufnahme
    - nur eine Sonde erforderlich
    - hohe zeitliche und räumliche Auflösung
    - einfache Bestimmung von Raum-Zeit-Korrelationen
  - Nachteile:
    - Annahme von bestimmten Voraussetzungen
    - nur Längskorrelationen (bei einkomponentiger Messung)



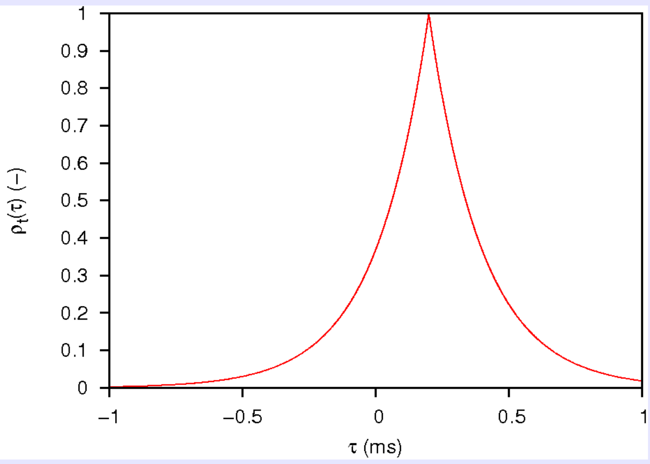
- Taylor-Hypothese



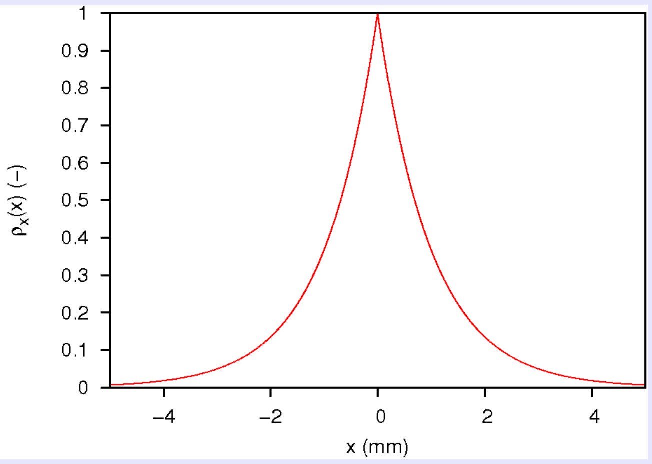
Zeitliche Autokorrelationsfunktion



Zeitliche Kreuzkorrelationsfunktion

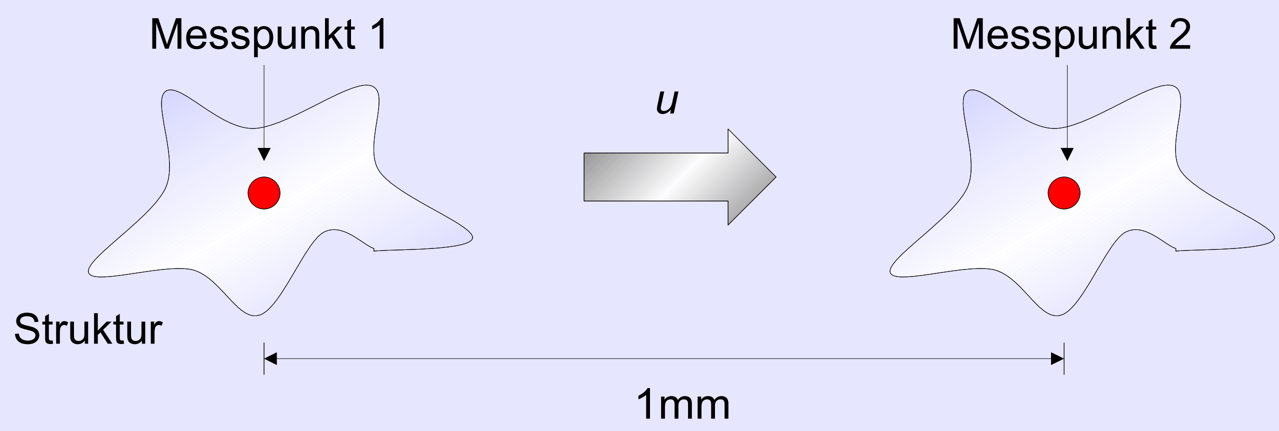


Räumliche Autokorrelationsfunktion

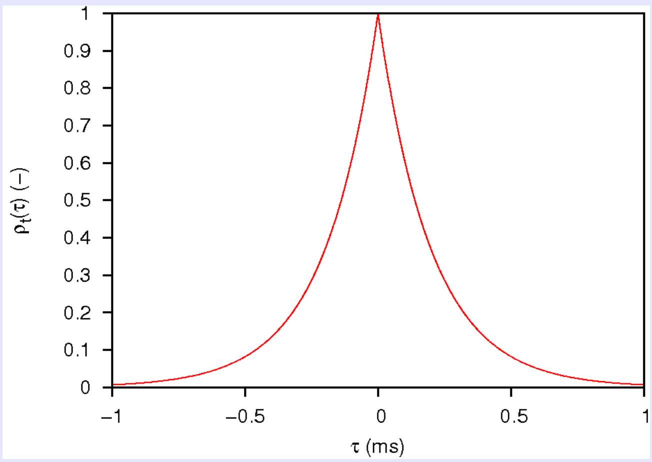


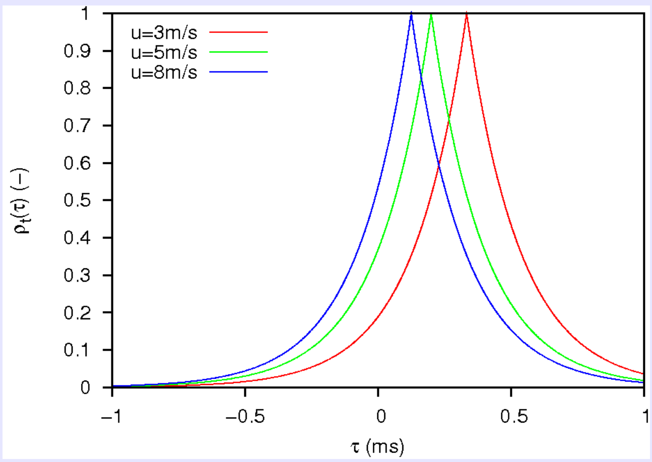
$1\text{ms} \Rightarrow 5\text{mm}$

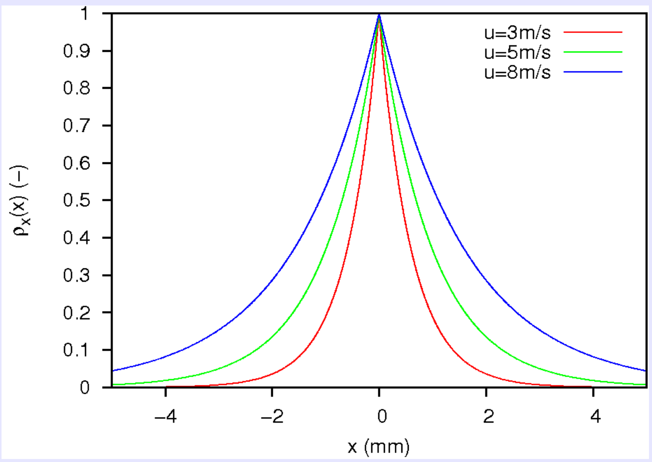
- veränderliche Geschwindigkeit



Zeitliche Autokorrelationsfunktion	Zeitliche Kreuzkorrelationsfunktion	Räumliche Autokorrelationsfunktion

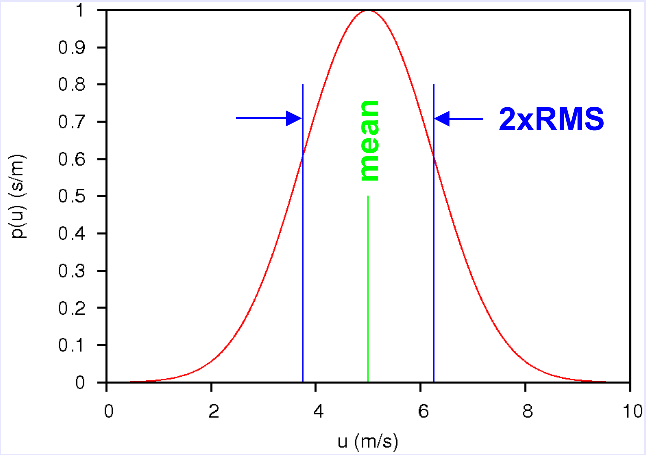




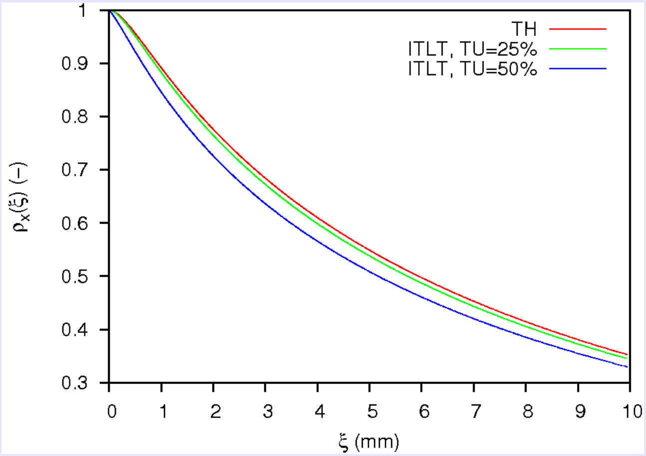


$$1\text{ms} \Rightarrow u \cdot 1\text{mm}$$

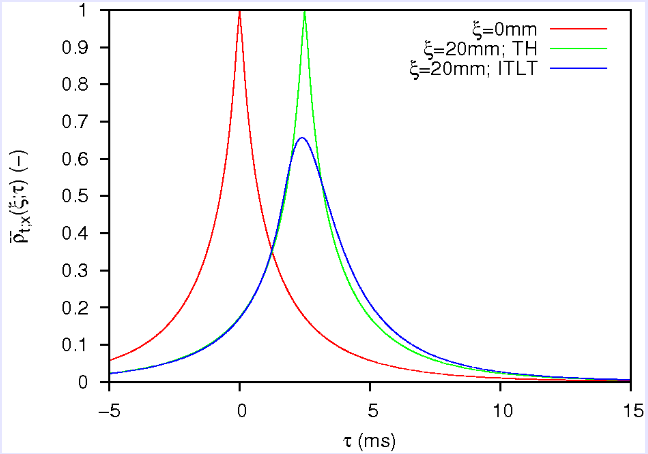
- Geschwindigkeitsstatistik
  - für jedes u:
    - Transformation $\rho(\xi)=\rho(\tau) \quad (\xi=u\,\tau)$
    - Wahrscheinlichkeitsdichte $p(u)$



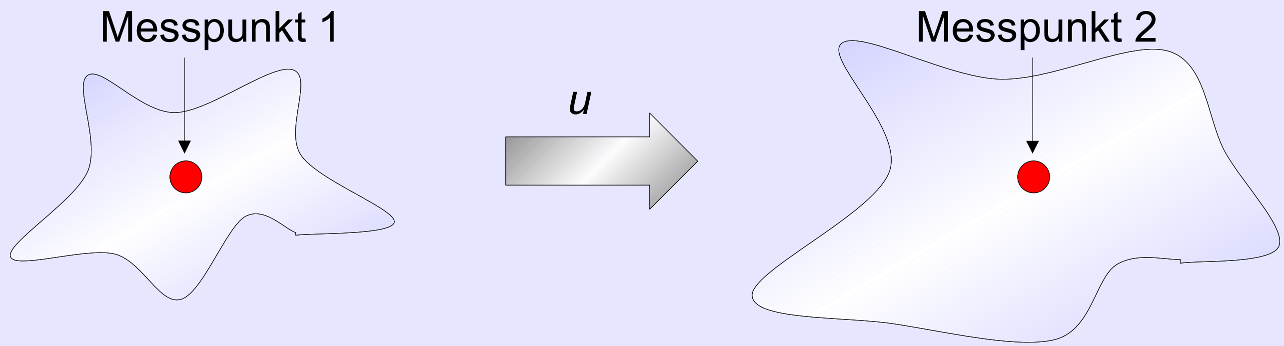
  - ganze räumliche Korrelationsfunktion:
    - Integration über alle u $\bar{\rho}(\xi)=\int_{-\infty}^{+\infty}\rho(\xi)\big|_u\,p(u)\,du$

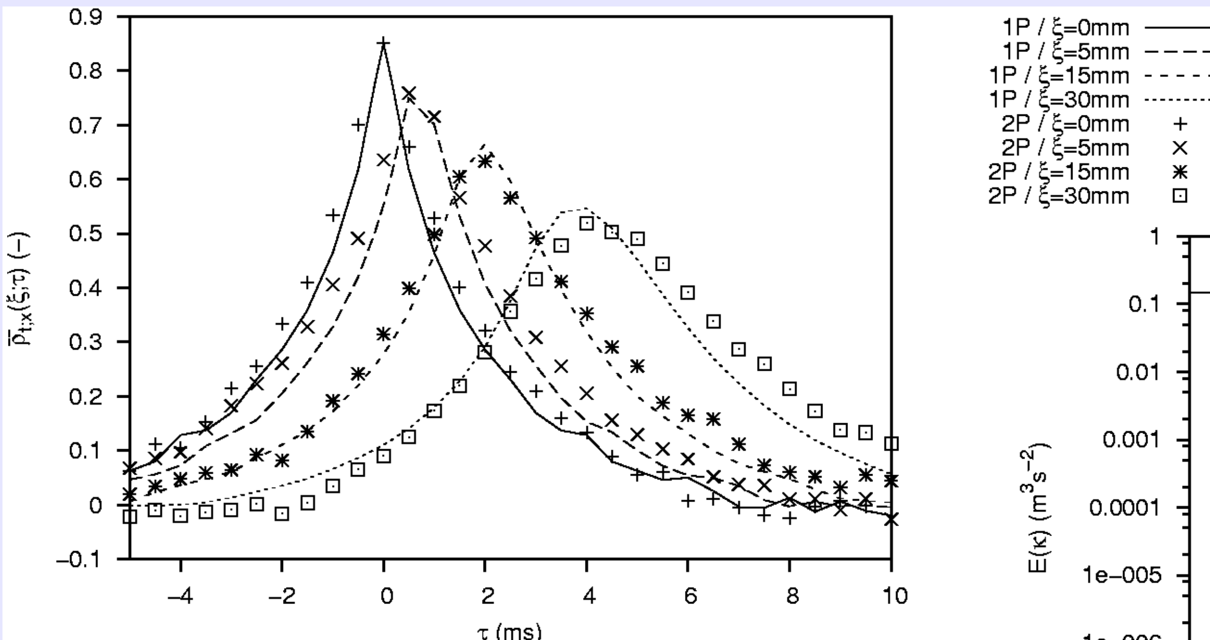


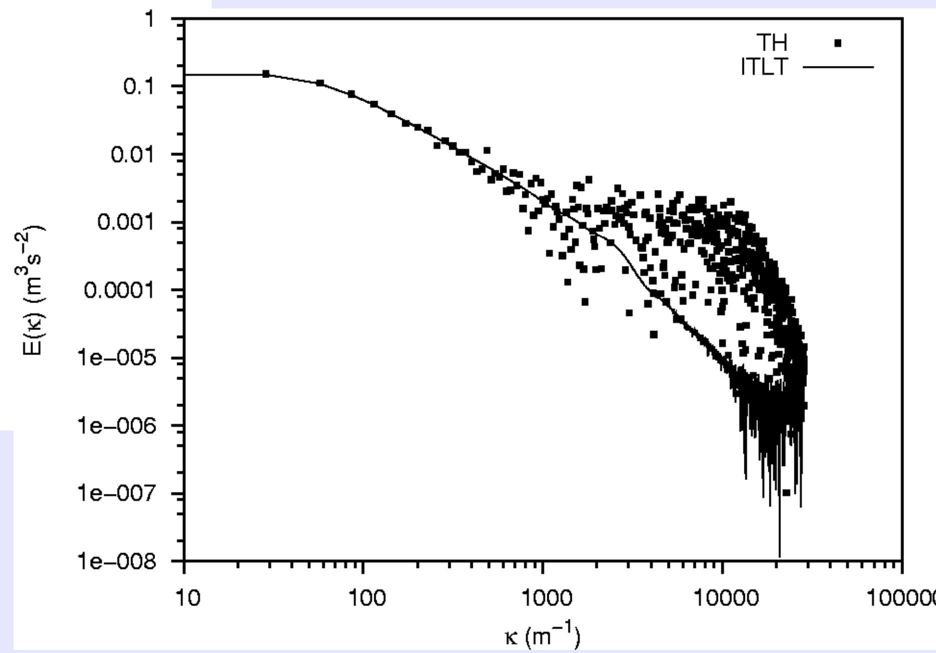
    - zusätzliche Zeitverschiebung für zweidimensionale Raum-Zeit-Korrelation $\bar{\rho}(\xi,\tau)=\int_{-\infty}^{+\infty}\rho(\xi,\tau)\big|_u\,p(u)\,du$ $\rho(\xi,\tau)\big|_u=\rho(\tau+\xi/u)$



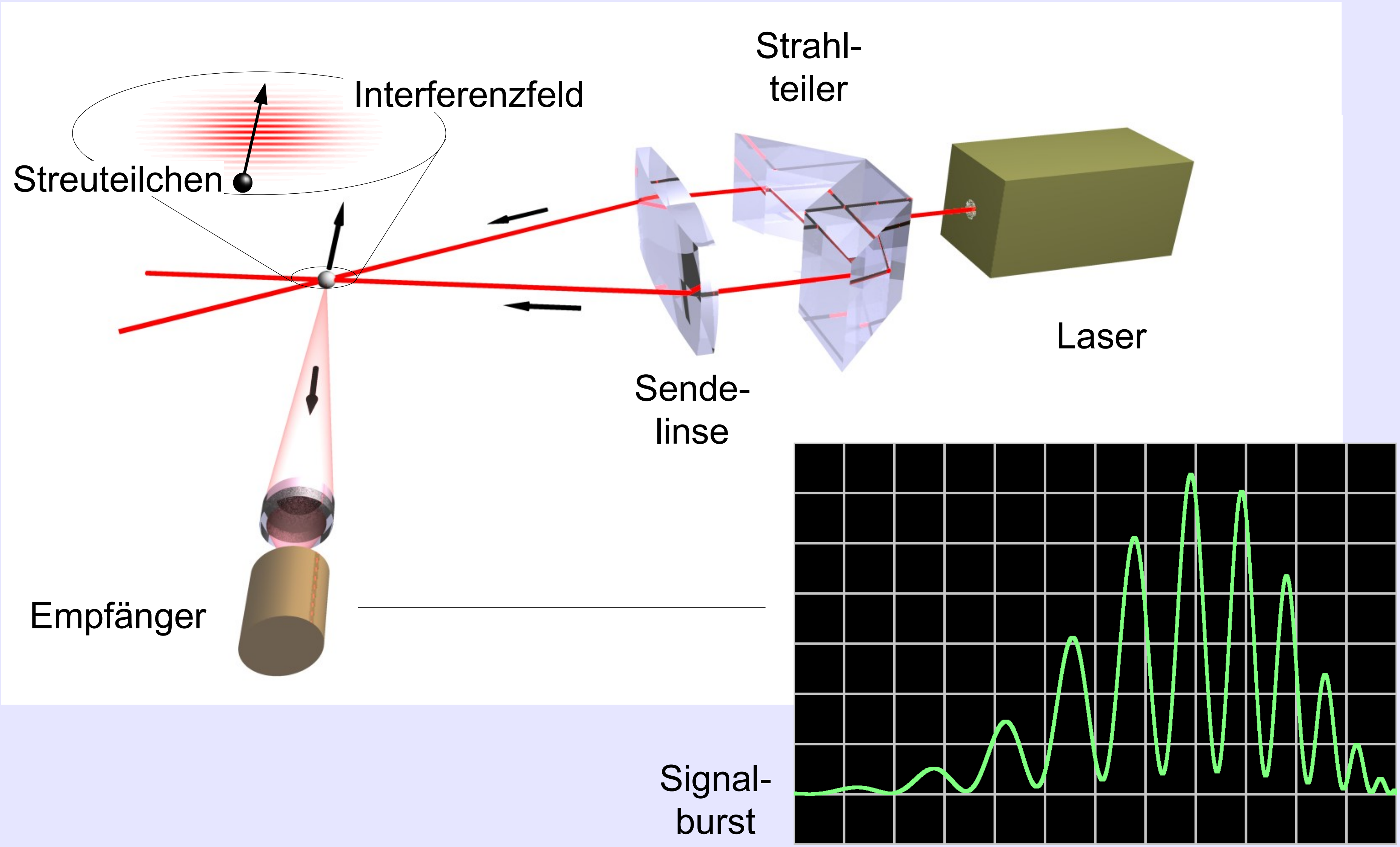
- Raum-Zeit-Korrelation



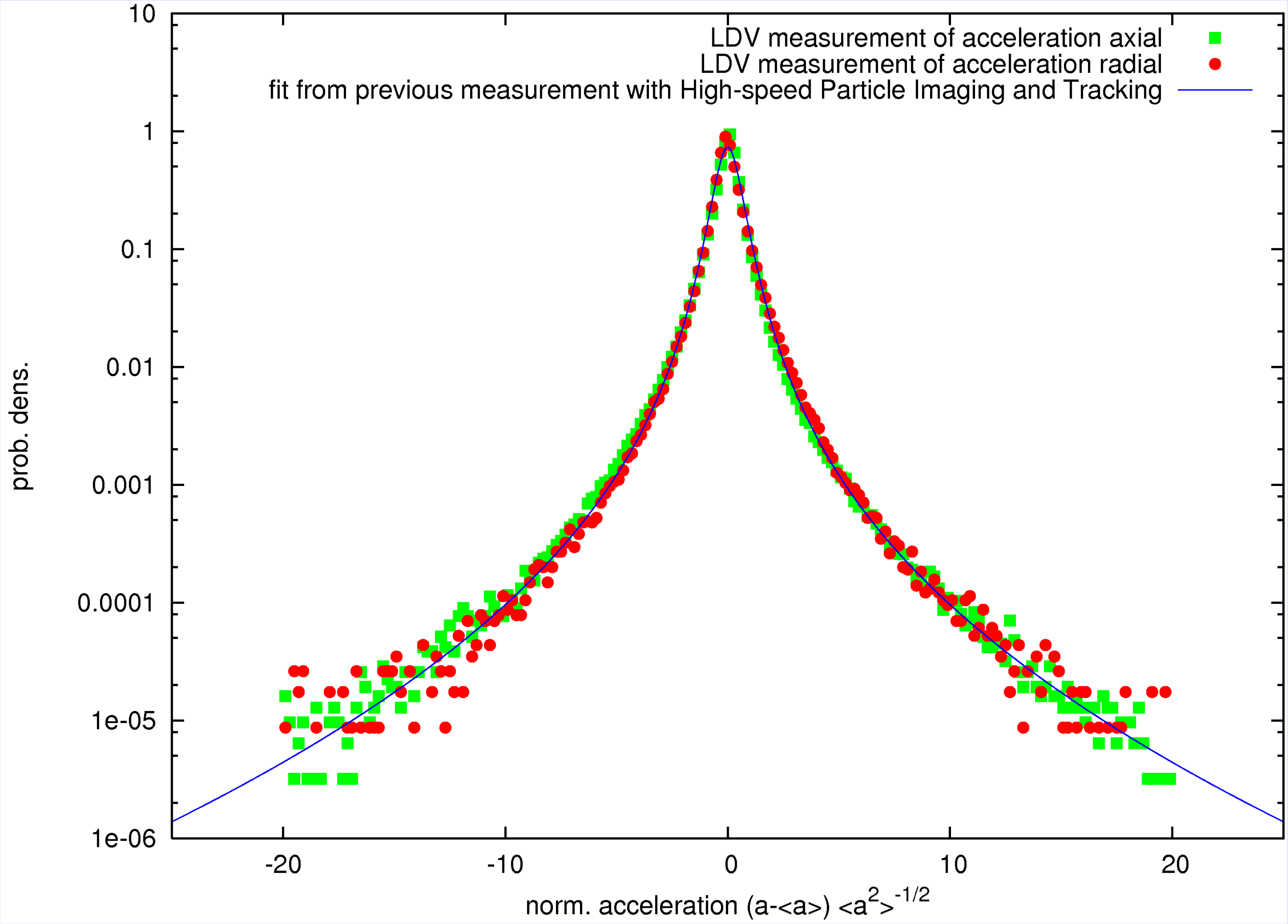




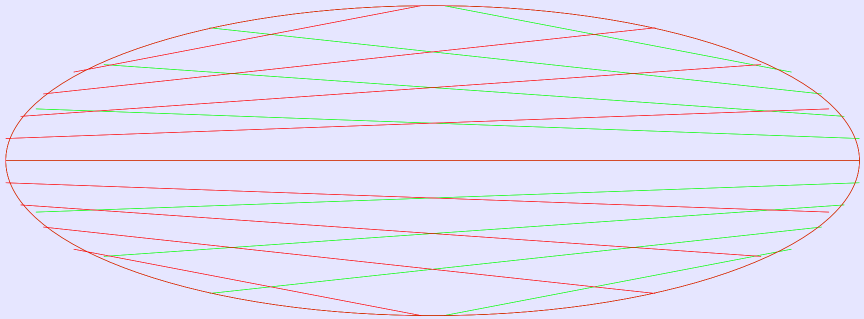
LDA-Beschleunigungsmessung



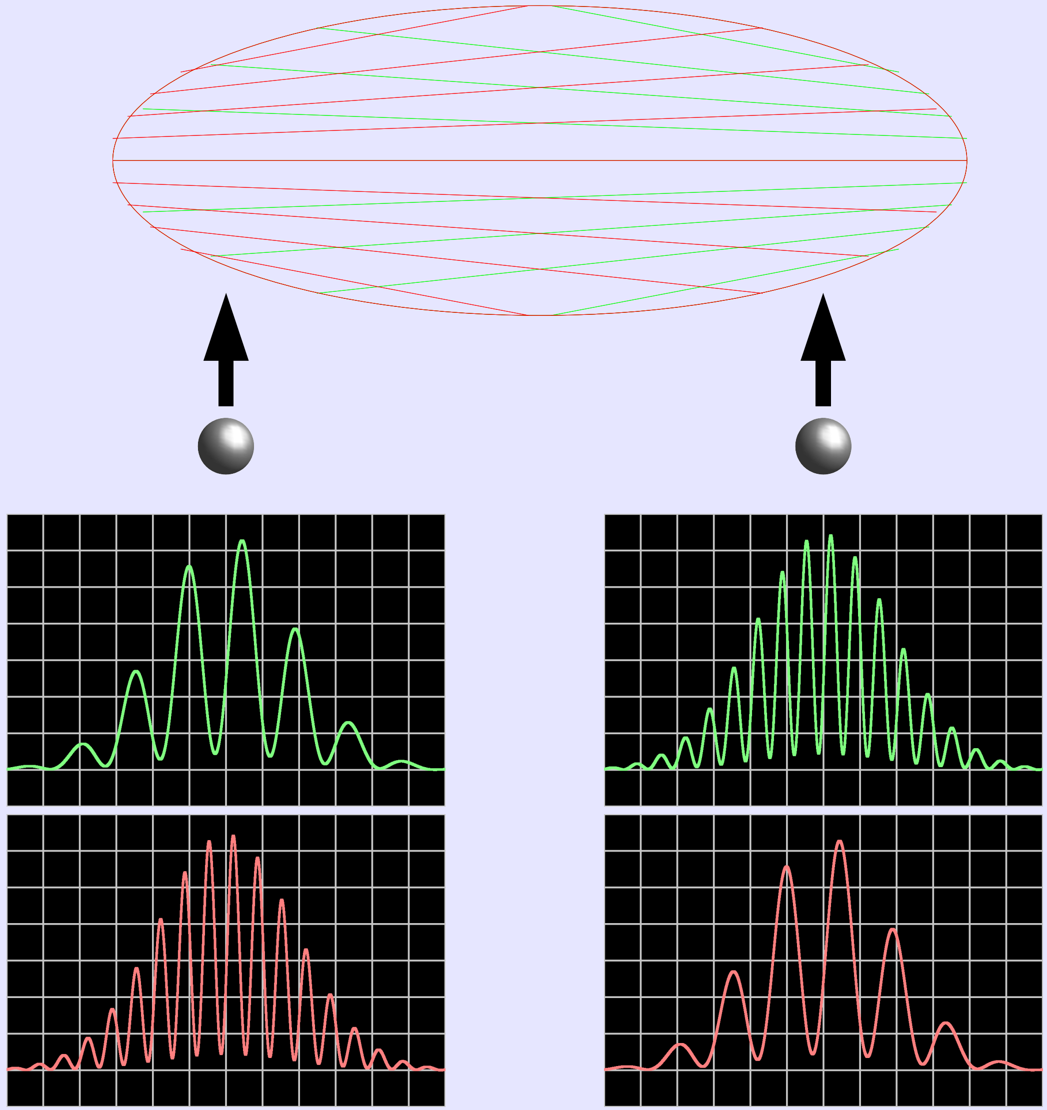
LDA-Beschleunigungsmessung



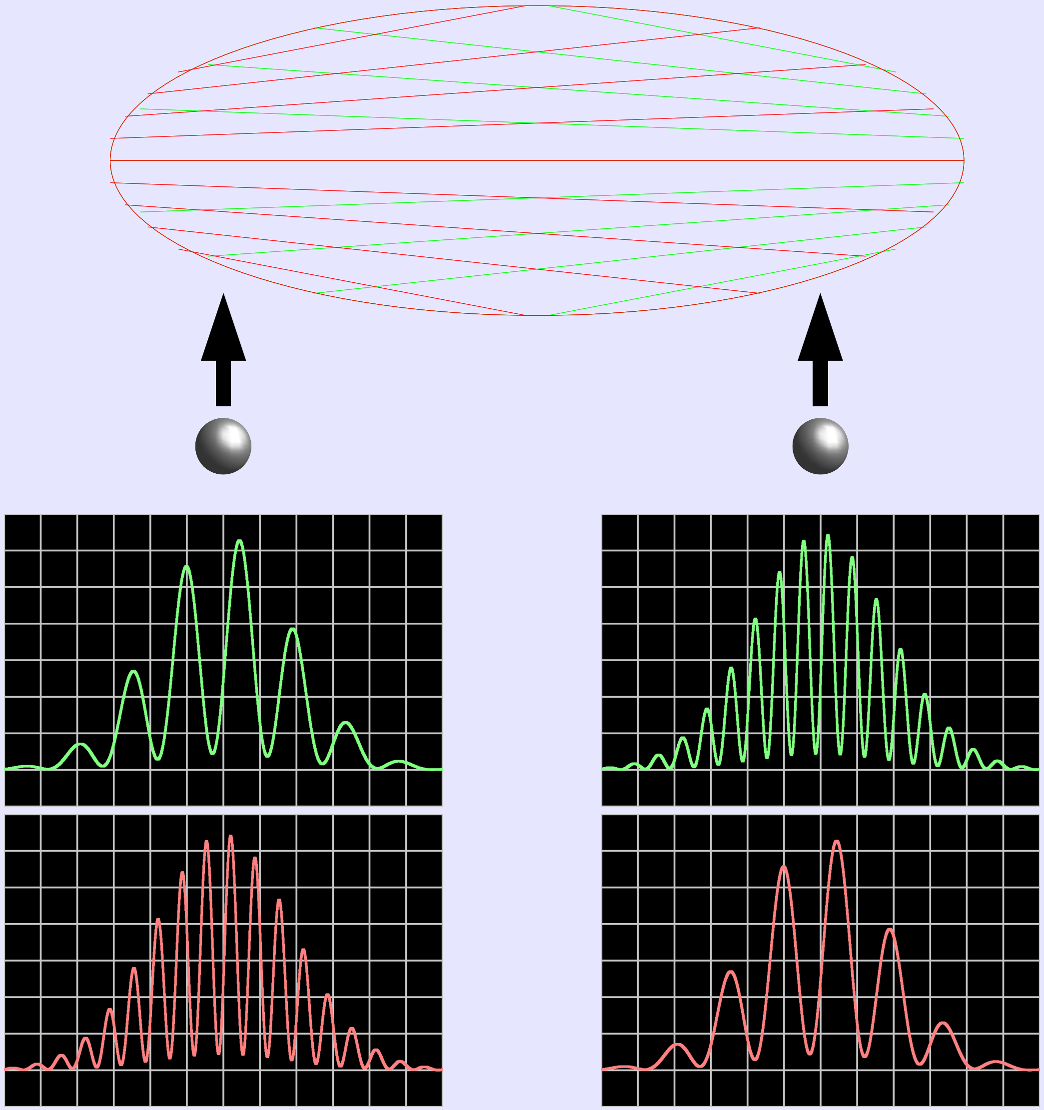
LDA-Profilsensor



LDA-Profilsensor



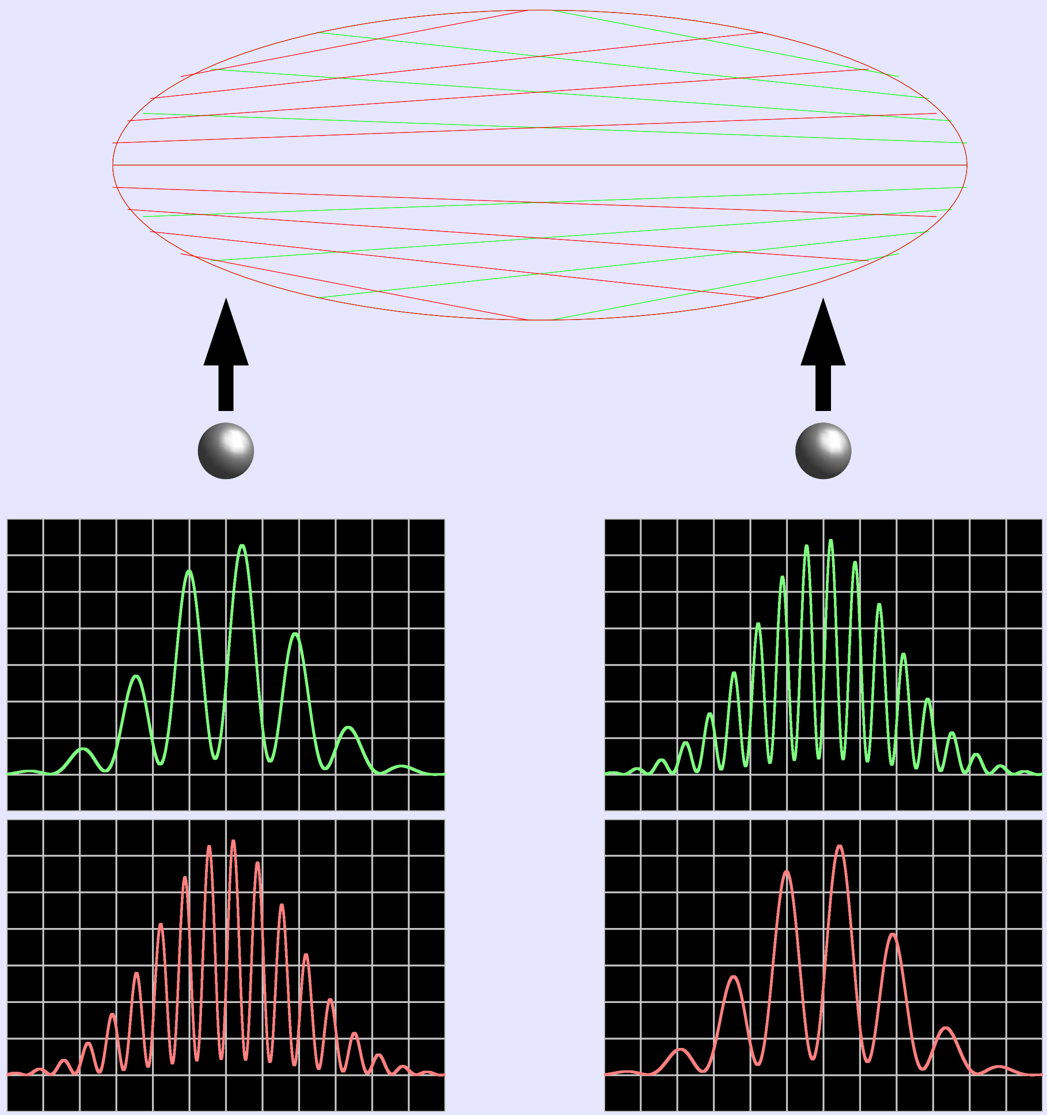
LDA-Profilsensor



LDA-Datensatz

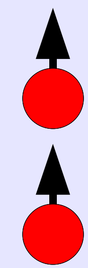
t u x

LDA-Profilsensor

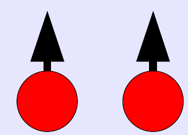


LDA-Datensatz

t u x

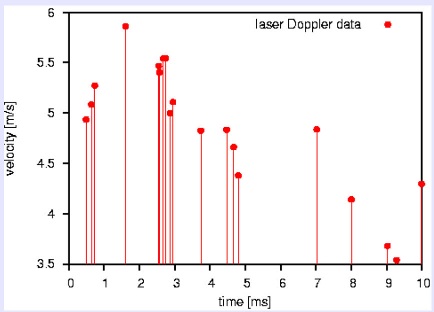


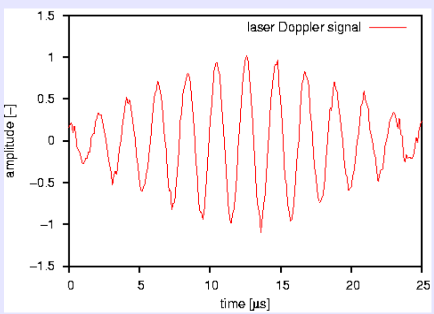
f-Korrelation
durch Transformation

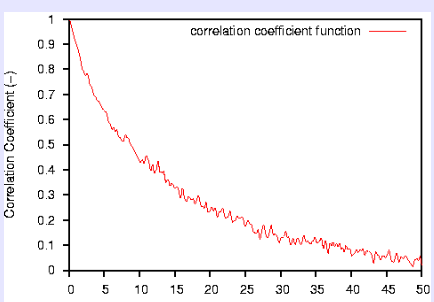


g-Korrelation
durch x-Auflösung

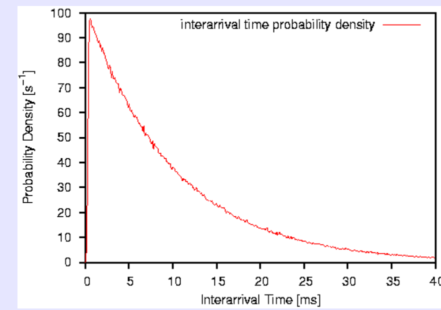
Laser Doppler and Phase Doppler Signal and Data Processing Site
http://ldvproc.nambis.de

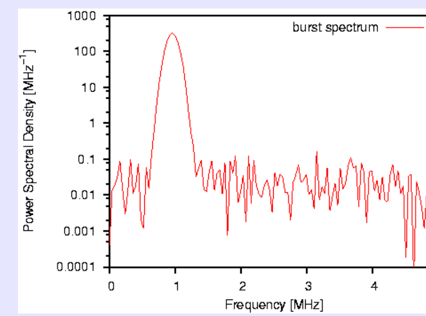


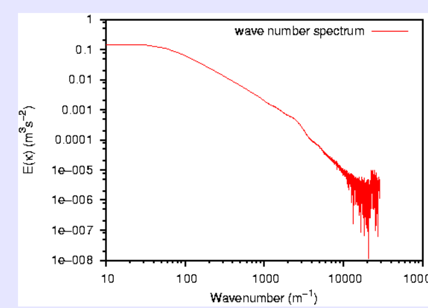




- News-Service
- Literatur
  - LDA-Signalverarbeitung
  - LDA-Datenverarbeitung
- Downloads
  - Simulationsprogramme
  - Experimentelle Referenzdaten (HDA und LDA)
  - Analyseprogramme







[BEN95] L H Benedict and R D Gould 1995: Experiences Using Kalman Reconstruction for Enhanced Power Spectrum Estimates, Proc. ASME/JSME Fluids Eng. and Laser Anemometry Conf., FED-Vol. 229, Hilton Head Island, South Carolina, USA, pp. 1-7

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