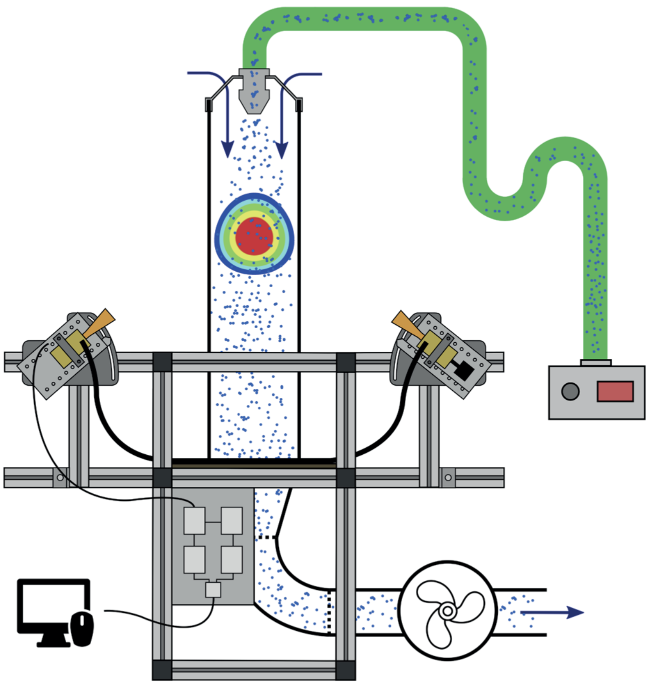
A Millimeter Wave Radar Sensor for Monitoring Solid and Liquid Aerosol Streams

Alwin Reinhardt



A Millimeter Wave Radar Sensor for Monitoring Solid and Liquid Aerosol Streams

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Abstract

This doctoral thesis deals with the development of sensors which are technologically capable of measuring aerosol streams and characterizing them with regard to the mass loading (mg/m^3), particle velocity (m/s), mass flow (mg/s) and average particle size. The sensors are based on radar technology in the high frequent millimeter wave range from 90 GHz to 150 GHz and therefore support the detection of microparticles down to particulate matter dimensions in comparatively large volumes and the retrieval of stream characteristics in real time.

These features make this technology suitable for existing and new applications. A big problem of today is critical air quality, mainly caused by human pollution of particulate matter. To comply with the limit values for atmospheric particulate matter concentration introduced by the EU, direct control at the source of pollution appears to be the most sensible solution. The millimeter wave radar sensors presented here could facilitate realization since they could be used, for example, to monitor emissions from combustion plants. However, there are also a number of application possibilities in industrial production processes, in which, for example, the technology could be used for mass flow measurements or as an analysis tool.

This dissertation takes up the current state of science and expands it to such an extent that applicable sensor technology is created. The focus is on theory as well as practice. With the so-called complex-source beam, an unconventional, analytical solution of the electromagnetic wave equation is adapted within the framework of antenna theory and used as incitation to solve the scattering problem of the particle ensemble. With the help of the derived models, the physics of particle scattering is extensively analyzed for various antenna arrangements, from which knowledge is drawn as to how antenna systems ideally have to be designed for different scenarios and information acquisition. At the same time, this work is written from a system engineer's point of view and focuses on the methodical design of the radar system architecture. From the physical relations technical requirements are derived. Building on this, it is described on system and component level how the required specifications are achieved. Finally, extensive measurements and field tests are carried out with the developed prototypes, in which solid and fluid particles of the size of milli- to micrometers are measured in indoor and outdoor measurement setups, whereby the established theories and techniques are validated.

Kurzzusammenfassung

Diese Doktorarbeit beschäftigt sich mit der Entwicklung von Sensoren, die technologisch in der Lage sind, Aerosolströmungen zu erfassen und hinsichtlich der Partikelmassenladung (mg/m^3), Partikelgeschwindigkeit (m/s), Massenflussrate (mg/s) und durchschnittlichen Partikelgröße zu charakterisieren. Die Sensoren basieren auf Radartechnik im hochfrequenten Millimeterwellenbereich von 90 GHz bis 150 GHz und können daher Kleinstpartikel im Mikrometerbereich in vergleichsweise ausgeprägten Volumen detektieren und Informationen in Echtzeit auswerten.

Durch diese Merkmale eignet sich diese Technologie für bestehende und neue Anwendungen. Ein großes Problem der heutigen Zeit ist die schlechte Luftqualität, maßgeblich verursacht durch menschengemachte Feinstaubemissionen. Um die seitens der EU darauf eingeführten Grenzwertsätze für atmosphärische Feinstaubkonzentration einhalten zu können, erscheint eine direkte Kontrolle beim Verursacher am sinnvollsten. Die hier vorgestellten Radarsensoren könnten eine Umsetzung möglich machen, da sich mit ihnen beispielsweise Ausstöße von Verbrennungsanlagen überwachen ließen. Doch auch für die Industrie gibt es eine Vielzahl an Anwendungsmöglichkeiten, in denen beispielsweise die Technik für Massenflussmessungen oder als Analysewerkzeug eingesetzt werden könnte.

Diese Doktorarbeit greift den bisherigen Stand der Wissenschaft auf und baut diesen soweit aus, dass einsatzbare Sensortechnik entsteht. Hierbei werden sowohl Schwerpunkte in der Theorie als auch Praxis gesetzt. Mit dem sogenannten Complex-Source Beam wird eine unkonventionelle, analytische Lösung der elektromagnetischen Wellengleichung im Rahmen der Antennentheorie adaptiert und für die Berechnung von Streuproblemen an den Partikelwolken eingesetzt. Mit Hilfe der aufgestellten Modelle wird die Physik der Partikelstreuung umfangreich für diverse Antennenanordnungen analysiert, woraus Erkenntnisse gezogen werden, wie Antennensysteme für unterschiedliche Szenarien und Informationsgewinnung idealerweise ausgelegt werden müssen. Gleichzeitig ist diese Arbeit aus der Sicht eines Systemingenieurs geschrieben und setzt einen Fokus auf die methodische Auslegung der Radarsystemarchitektur. Aus den physikalisch-technischen Beziehungen werden Anforderungsprofile erstellt. Darauf aufbauend wird auf System- und Bauteilebene beschrieben, wie diese Anforderungen technisch umgesetzt werden. Schließlich werden mit den entwickelten Prototypen umfangreiche Messungen und Feldversuche durchgeführt, in denen milli- bis mikrometergroße Fest- und Fluidpartikel in Innen- und Außen-Messaufbauten gemessen werden, wodurch die aufgestellten Theorien und Techniken validiert werden.

Declaration

Hereby I declare that I have produced the doctoral thesis

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independently and without improper external assistance and that I have identified all word-for-word quotations of other authors, as well as comments based closely on other authors' ideas, and I have listed the relevant sources. Furthermore, this thesis has not been, partially or completely, submitted to any other university or institute in the context of an examination procedure. I declare that the following work has been written in compliance with the rules of good scientific practice of the German Research Foundation.

(Place, Date)

(Alwin Reinhardt)

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List of Abbreviations and Symbols

The following list serves as a quick lookup-guide. It is not the intent to cover all abbreviations and symbols in full completion.

Abbreviation	Definition
ADC	Analog to digital converter
CDF	Cumulated distribution function
CSB	Complex-source beam
DRCS	Differential radar cross section
EEA	European environment agency
FEM	Finite element method
FFT	Fast Fourier transform
GUI	Graphical user interface
HFSS®	High Frequency Structure Simulator (software)
IF	Intermediate frequency
IMPATT	Impact avalanche transit time
LO	Local oscillator
MMIC	Monolithic microwave integrated circuit
PDF	Probability density function
PLA	Polylactic acid
PLL	Phase locked loop
PM	Particulate matter
PSD	Power spectral density
RADAR	Radio Detection and Ranging
RCS	Radar cross section
RF	Radio frequency
SiGe	Silicon-Germanium
SNR	Signal to noise ratio
SRCS	Specific radar cross section

Latin Symbol	**Definition**	**Unit**
A	Cross section of the particle stream	$[\mathrm{m}^2]$
a	Scale parameter (Weibull distribution)	
a_n	Complex coefficients (Mie theory)	
$a_{n,m}$	Multipole amplitudes	
b	Shape parameter (Weibull distribution)	
b_n	Complex coefficients (Mie theory)	
$b_{n,m}$	Multipole amplitudes	
c	Speed of light	$[\frac{\mathrm{m}}{\mathrm{s}}]$
d_p	Particle diameter	$[\mathrm{m}]$
$\mathbf{E}$	Electric field	$[\frac{\mathrm{V}}{\mathrm{m}}]$
e	Euler constant	
$\mathbf{E}_{inc}$	Incident electric field	$[\frac{\mathrm{V}}{\mathrm{m}}]$
$\mathbf{E}_{sca}$	Scattered electric field	$[\frac{\mathrm{V}}{\mathrm{m}}]$
$\mathbf{E}_{tot}$	Total electric field	$[\frac{\mathrm{V}}{\mathrm{m}}]$
$\mathbf{E}_{\infty}$	Electric far field	$[\frac{\mathrm{V}}{\mathrm{m}}]$
f	Frequency	$[\mathrm{Hz}]$
Δf	Band width	$[\mathrm{Hz}]$
f_d	Doppler frequency	$[\mathrm{Hz}]$
f_T	Transmission frequency	$[\mathrm{Hz}]$
F_T^2	Transmitting antenna power pattern	
F_R^2	Receiving antenna power pattern	
f_{Rp}	Particle size distribution function	
g	Gravitational constant	$[\frac{\mathrm{m}}{\mathrm{s}^2}]$
G_T	Transmitting antenna gain	$[\mathrm{dB}]$
G_R	Receiving antenna gain	$[\mathrm{dB}]$
G_{CSB}	Gain of the complex-source beam	$[\mathrm{dB}]$
$G_{0,T}$	Gain constant of the transmitting antenna	$[\mathrm{dB}]$
$G_{0,R}$	Gain constant of the receiving antenna	$[\mathrm{dB}]$
$\mathbf{H}$	Magnetic field	$[\frac{\mathrm{A}}{\mathrm{m}}]$
$\mathbf{H}_{inc}$	Incident magnetic field	$[\frac{\mathrm{A}}{\mathrm{m}}]$
$h_n^{(1)}$	Spherical Hankel functions of the first kind	
$\mathbf{H}_{sca}$	Scattered magnetic field	$[\frac{\mathrm{A}}{\mathrm{m}}]$
$\mathbf{H}_{tot}$	Total magnetic field	$[\frac{\mathrm{A}}{\mathrm{m}}]$
$\mathbf{H}_{\infty}$	Magnetic far field	$[\frac{\mathrm{A}}{\mathrm{m}}]$
I	Electric current	$[\mathrm{A}]$

Latin Symbol	**Definition**	**Unit**
j	Imaginary unit	
j_n	Spherical Bessel function of the first kind	
$\mathbf{k}$	Wave vector	$[\mathrm{m}^{-1}]$
k	Wave number	$[\mathrm{m}^{-1}]$
L	Half antenna distance	[m]
M	Mass loading	$[\frac{\mathrm{kg}}{\mathrm{m}^3}]$
$\mathbf{M}_{n,m}$	Vectorial multipole functions	
$\mathbf{m}_{n,m}$	Transversal vector functions	
$\mathbf{N}_{n,m}$	Vectorial multipole functions	
$\mathbf{n}_{n,m}$	Transversal vector functions	
m_k	Moment of distribution	
n_0	Particle concentration	$[\mathrm{m}^{-3}]$
P_n^m	Associated Legendre function of the first kind	
P_R	Received power	[W]
P_T	Transmitted power	[W]
Q_m	Mass flow	$[\frac{\mathrm{kg}}{\mathrm{s}}]$
R	Electrical resistance	[Ω]
$\mathbf{r_c}$	Complex location vector	[m]
r_p	Particle Radius	[m]
R_T	Distance between target and transmitting antenna	[m]
R_R	Distance between target and receiving antenna	[m]
S_1	Scattering plane amplitudes (Mie theory)	
S_2	Scattering plane amplitudes (Mie theory)	
s	Path length	[m]
s_{opt}	Optimal path length	[m]
T	Temperature	[K]
t	Time	[s]
U	Electric voltage	[V]
v	Velocity	$[\frac{\mathrm{m}}{\mathrm{s}}]$
V	Volume filled with particles	$[\mathrm{m}^3]$
V_{ef}	Effective Scattering Volume	$[\mathrm{m}^{-1}]$
v_p	Particle velocity	$[\frac{\mathrm{m}}{\mathrm{s}}]$
$Y_{n,m}$	Normalized surface spherical harmonic	
Z_0	Impedance of the free-space	[Ω]
z_n	Spherical Bessel functions	

Greek Symbol	**Definition**	**Unit**
δ	Dirac delta-function	
ϵ	Permittivity	$[\frac{\mathrm{As}}{\mathrm{Vm}}]$
ϵ_r	Relative Permittivity	
ϵ'	Real part of complex permittivity	
ϵ''	Imaginary part of complex permittivity	
λ	Wavelength	[m]
γ	Distribution moment ratio	
ϕ_m	Polarization angle (Mie theory)	$[^\circ]$
μ	Permeability	$[\frac{\mathrm{Vs}}{\mathrm{Am}}]$
μ	Mean of the logarithmic values (Log-n distrib.)	
μ_r	Relative permeability	
ρ_p	Material density of the particles	$[\frac{\mathrm{kg}}{\mathrm{m}^3}]$
σ	Radar cross section	$[\mathrm{m}^2]$
σ	Standard deviation (Log-n distribution)	
σ_d	Differential radar cross section	
σ_p	Radar cross section of an individual particle	$[\mathrm{m}^2]$
σ_0	Specific radar cross section	$[\mathrm{m}^{-1}]$
θ_m	Scattering angle (Mie theory)	$[^\circ]$
θ_{TR}	Bistatic angle (between the antennas)	$[^\circ]$

Natural Constants	**Definition**
Speed of light in vacuum	$c_0 = 299792458\ \frac{\mathrm{m}}{\mathrm{s}}$
Permittivity constant of vacuum	$\epsilon_0 = 8,854 \cdot 10^{-12}\ \frac{\mathrm{As}}{\mathrm{Vm}}$
Permeability constant of vacuum	$\mu_0 = 4\pi \cdot 10^{-7}\ \frac{\mathrm{Vs}}{\mathrm{Am}}$
Impedance of the free-space	$Z_0 = 120\pi\ \Omega$