Direct-Detection LADAR Systems

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Introduction to the Series

Since its inception in 1989, the Tutorial Texts (TT) series has grown to more than 80 titles covering many diverse fields of science and engineering. The initial idea for the series was to make material presented in SPIE short courses available to those who could not attend and to provide a reference text for those who could. Thus, many of the texts in this series are generated by augmenting course notes with descriptive text that further illuminates the subject. In this way, the TT becomes an excellent stand-alone reference that finds a much wider audience than only short course attendees.

Tutorial Texts have grown in popularity and in the scope of material covered since 1989. They no longer necessarily stem from short courses; rather, they are often generated by experts in the field. They are popular because they provide a ready reference to those wishing to learn about emerging technologies or the latest information within their field. The topics within the series have grown from the initial areas of geometrical optics, optical detectors, and image processing to include the emerging fields of nanotechnology, biomedical optics, fiber optics, and laser technologies. Authors contributing to the TT series are instructed to provide introductory material so that those new to the field may use the book as a starting point to get a basic grasp of the material. It is hoped that some readers may develop sufficient interest to take a short course by the author or pursue further research in more advanced books to delve deeper into the subject.

The books in this series are distinguished from other technical monographs and textbooks in the way in which the material is presented. In keeping with the tutorial nature of the series, there is an emphasis on the use of graphical and illustrative material to better elucidate basic and advanced concepts. There is also heavy use of tabular reference data and numerous examples to further explain the concepts presented. The publishing time for the books is kept to a minimum so that the books will be as timely and up-to-date as possible. Furthermore, these introductory books are competitively priced compared to more traditional books on the same subject.

When a proposal for a text is received, each proposal is evaluated to determine the relevance of the proposed topic. This initial reviewing process has been very helpful to authors in identifying, early in the writing process, the need for additional material or other changes in approach that would serve to strengthen the text. Once a manuscript is completed, it is peer reviewed to ensure that chapters communicate accurately the essential ingredients of the science and technologies under discussion.

It is my goal to maintain the style and quality of books in the series and to further expand the topic areas to include new emerging fields as they become of interest to our reading audience.

James A. Harrington
Rutgers University

To my wife, Linda, who has always been my strongest supporter.

R.R.

To my wife, Karen, and kids, Asher, Josiah, and Tobias, who make all my days worth living.

S.C.

Contents

Preface

The field of 3D LADAR (LAser Detection And Ranging) is growing steadily with new advances in focal plane readout technology driving ever-faster image capture and readout capabilities. This text is designed to introduce engineers to the basic concepts and operation of 3D imaging LADAR systems. The book facilitates the instruction of junior and senior year student engineers as well as graduate students who have a background in statistics and linear systems through a single-term course in LADAR systems. The book begins with the laser range equation and follows with discussions of sources of noise in LADAR signals, LADAR waveforms, the effects of wavefront propagation on LADAR beams through optical systems and atmospheric turbulence, algorithms for detecting, ranging, and tracking targets, and finally, comprehensive system simulation.

This book also provides computer code for accomplishing the many examples appearing throughout the text. Exercises at the end of each chapter allow students to apply concepts studied throughout the text to fundamental problems encountered by LADAR engineers. The exercises closely follow the examples so that guidance is available for successfully solving these problems. Students in both academia and industry can use the book as part of a formal course or a self study to acquire a basic understanding of LADAR systems. The book relates how to simulate realistic LADAR data as well as how to process it to extract target-related information.

Many thanks are due to Karen Cain, who provided many of the illustrations found in Chapter 1. Thanks are also due to both Karen and Asher Cain, who aided in the initial editing of the text.

Mathematical Notation

α	tilt in the horizontal direction caused by atmospheric turbulence
A	aperture transmittance function
A_g	amplitude of a Gaussian beam
β	tilt in the vertical direction caused by atmospheric turbulence
B	average number of photoelectrons contributed by the background
c	speed of light in a vacuum
C	capacitance of the detector circuit in Farads (F)
Δ	size of the LADAR receiver detector in meters (m)
Δ_y	sample size in the source plane of an optical field in meters (m)
Δ_x	sample size in the distant plane of an optical field in meters (m)
Δ_{det}	sample size in the detector plane dictated by propagation rules
Δ_λ	passband width of the background rejection filter in microns (μm)
Δt	detector integration time
dA	effective target surface area
D	total number of photoelectrons collected by a LADAR system
D_α	horizontal tilt structure function
D_B	number of photoelectrons contributed by the background
D_θ	phase structure function
D_s	number of photoelectrons contributed by the laser pulse
D_t	diameter of the aperture of the LADAR transmitter optics
D_R	diameter of the aperture of the LADAR receiver optics
f	frequency in Hertz (Hz)
f_c	maximum spatial frequency of an optical field in inverse meters
f_l	focal length of the LADAR receiver optics
f_o	fundamental frequency of the discrete Fourier transform in Hertz (Hz)
γ	angular field of view of the LADAR receiver
G_{apd}	avalanche photodiode gain
η	quantum efficiency of the LADAR detector
h	Planck's constant
h_{tot}	point spread function of the LADAR system
H_{atm}	atmospheric transfer function
H_{det}	detector transfer function
H_{opt}	optical transfer function
H_{tot}	total system transfer function, the Fourier transform of h_{tot}
ν	frequency of the laser light in Hertz (Hz)

v_x horizontal wind speed across the LADAR receiver aperture
v_y vertical wind speed across the LADAR receiver aperture
I_{target} intensity of the LADAR beam at the target in watts per square meter (W/m^2)
$I_{receiver}$ intensity of the returned pulse at the receiver aperture in watts per square meter (W/m^2)
k_b Boltzmann's constant
K number of photons incident on the LADAR detector
λ wavelength of the laser light processed by the LADAR system
Λ likelihood ratio test
L_r size of an optical field in the distant plane in meters (m)
L_s size of an optical field in the source plane in meters (m)
M coherence parameter; large for incoherent light, 1 for fully coherent
N index of refraction of the atmosphere
n_{sr} average index of refraction of the atmosphere along a path
Δn perturbation in the index of refraction about the average value
N_{signal} number of electrons measured by the LADAR system
N_b number of electrons measured by the LADAR system due to background
N_{dark} number of electrons contributed by the detector dark current
$N_{speckle}$ number of electrons measured by the LADAR system with speckle noise
$N_{thermal}$ number of noise electrons contributed by thermal noise effects
P_d probability of detection
P_{fa} probability of false alarm
P_{det} total laser power incident on the LADAR detector in watts (W)
P_{det_diff} laser power incident on the LADAR detector with diffraction effects
P_{det_tot} geometrically predicted laser power incident on the LADAR detector
P_{ref} total reflected laser power from the target in watts (W)
P_t transmitted laser power in watts (W)
p_w pulse width parameter for the negative parabola model in seconds (s)
q_e elementary charge in coloumbs (C)
Q_n readout noise standard deviation in electrons (e.u.)
ρ_t target surface reflectivity
r_o Fried's seeing parameter in centimeters (cm)
ΔR distance between two surfaces viewed by a LADAR system
R range between the laser RADAR system and the target
R_1 range between the LADAR system and the first target in a two-target case
R_2 range between the LADAR system and a second target in a two-target case
R_{ff} range from the LADAR system that the far-field approximation is valid
R_θ phase correlation function
R_α horizontal tilt correlation function
R_β vertical tilt correlation function
σ_α standard deviation of the tilt in the horizontal direction

σ_β	standard deviation of the tilt in the vertical direction
σ_{pc}	photo-current standard deviation in amperes (A)
$\sigma_{speckle}$	photon standard deviation due to photon counting noise and laser speckle
σ_w	pulse width parameter for the Gaussian pulse model in seconds (s)
S	average number of photoelectrons contributed by the laser pulse
S_{IR}	background intensity in watts per square meter (W/m^2)
τ	difference in the time of flight between two surfaces at ranges R_1 and R_2
τ_a	atmospheric transmission
τ_o	LADAR receiver optics transmission
t	time of flight in seconds (s) through a vacuum
t_Δ	change in the time of flight due to changes in index of refraction
t_{lens}	lens transmittance function including optical delays
t_o	time of flight in seconds (s) through an atmospheric path with no turbulence
t_{sr}	time of flight in seconds (s) through the atmosphere
T	crcuit temperature in Kelvin (K)
T_p	target profile: the surface area of the target as a function of range
t_{ns}	time of flight in nanoseconds (ns)
θ_{atm}	phase error introduced by atmospheric turbulence
θ_R	target surface angular dispersion in steradians (sr)
θ_t	beamwidth of the LADAR transmitter in radians (rad)
ω_o	beam waist parameter for the Gaussian beam
Z	distance between the target plane and the plane of the LADAR aperture