Analysis and Evaluation of

Sampled Imaging Systems

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Introduction to the Series

Since its inception in 1989, the Tutorial Texts (TT) series has grown to more than 85 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

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Preface

This tutorial is written for the design engineer or system analyst interested in quantifying the performance of electro-optical imagers. Advancing technology in detector arrays, flat panel displays, and digital image processing provide new opportunities to expand imaging applications and enhance system performance. Technical managers and design engineers are faced with evaluating the cost, weight, and performance of an ever-expanding selection of technology options. This book provides the theory and procedures for performance assessment.

This text supersedes *Analysis of Sampled Imaging Systems*, which was published by SPIE Press in 2000. Part I updates the earlier work. Part II discusses performance evaluation of electro-optical imagers. Part III provides computer programs and up-to-date information on detector arrays, optics, and display options. This book provides the theory, procedures, and information needed to evaluate and compare the performance of available imaging technologies.

Our prior work *Analysis of Sampled Imaging Systems* focused on the mathematical formulism needed to analyze sampled imagery. That book described the sampled imager response (SIR) function. SIR quantified sampled imager aliasing as well as the system transfer response. Fourier transform theory was used to describe and quantify sampling artifacts such as display raster, blocky images, and the loss or alteration of image detail due to aliasing.

However, the metrics provided by the earlier book were "rules of thumb." Sampled imager design rules were based on experience and experimentation. No theory existed to quantify the effect of aliasing on visual task performance. The earlier work provided guidance on how to optimize sampled imagers by minimizing aliasing. *Analysis of Sampled Imaging Systems* did not provide a procedure to quantify the impact of aliasing on performance.

In the intervening years since the first book, we have discovered that the effect of aliasing on targeting performance is predictable by treating aliasing as noise. This book presents a resolution metric that predicts the effect of imager blur, noise, and sampling on the probability of correctly identifying targets. This new publication includes quantitative procedures for evaluating target acquisition performance.

Part I of this book includes all of the pertinent material from *Analysis of Sampled Imaging Systems*. The first five chapters remain substantially the same as the previous work. These chapters introduce sampling concepts and describe the differences between shift-variant and shift-invariant systems. Chapter 2 on Fourier optics is extensively rewritten. The errors associated with assuming

separability in Cartesian coordinates are discussed, and examples are provided. The blurs associated with vibration and electronic stabilization are described. In Chapter 3, additional examples are added to better describe the SIR function. The focus of Chapters 1 through 5 remains the same, however. These chapters provide the mathematical tools needed to analyze sampled imagers.

Part II of this new book includes Chapters 6 through 10. This new material describes electro-optical imager evaluation. Chapter 6 describes target identification experiments. These experiments quantify visual task performance. Chapter 7 describes a resolution metric that predicts the probability of identifying targets. Chapter 7 also discusses the relationship between imager resolution and field performance. Chapter 8 explains aliasing as noise theory. For some years, we have known how to predict the effect of noise on target acquisition. Aliasing as noise theory predicts the effect of aliasing on target acquisition. Chapters 9 and 10 provide details on analyzing thermal imagers and imagers of reflected light, respectively.

Part III provides computer programs that implement the theory. These programs calculate the resolution of thermal and reflected light imagers. The programs are used to evaluate expected target acquisition performance and to compare imagers and assess the benefit or penalty of design changes.

Information is also provided to help make realistic assessments of imager performance. The book discusses optical performance and provides the characteristics of typical, good, and ideal lens systems. The book also contains information on a variety of display formats and interfaces, as well as detailed information on available focal plane arrays (FPAs). The information is presented in written form and is also coupled to the computer programs.

Particular emphasis is placed on theory and practice for the wide variety of available infrared FPAs. Technologies represented include InSb, HgCdTe, QWIP, and uncooled thermal arrays. Information is provided on the quantum efficiency, blur, crosstalk, and noise characteristics of each technology. The detector and array dimensions of available FPAs are provided. The availability of current information on optics, display, and FPA subassemblies allows the model user to make quick and realistic performance assessments of electro-optical imager designs.

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February 2010

Acronyms and Abbreviations

2afc	two alternative forced choice
A	ampere
Å	angstrom
AAN	aliasing as noise
AR	antireflection
A/W	units (amperes/watt) for spectral current responsivity
BDI	buffered direction injection
BLIP	background-limited photoconductor
CCD	charge-coupled device
CMOS	complementary metal-oxide semiconductor
CRT	cathode ray tube
CSF	contrast sensitivity function
CTF	contrast threshold function
CTIA	capacitive transimpedance amplifier
DC	direct current
DI	direct injection
DLHJ	double-layer heterojunction
erf	error function
E field	electric field
E-stab	electronic stabilization
ezoom	electron zoom
FF	fill factor
FOV	field of view
FPA	focal plane array
FPN	fixed pattern noise
FWHM	full width at half maximum
HDTV	high-definition television
HgCdTe	mercury cadmium telluride
HUD	head-up display
IFOV	instantaneous field of view
InSb	indium antimonide
IR	infrared
LACE	local-area contrast enhancement
LCD	liquid crystal display
LOS	line of sight
LSI	linear and shift invariant

LWIR	long-wave infrared
MHz	megahertz
MKS	meter-kilogram-second
MRT	minimum resolvable temperature
MTF	modulation transfer function
MWIR	midwave infrared
NEP	noise equivalent power
NETD	noise equivalent temperature difference
NIR	near infrared
NUC	nonuniformity correction
OTF	optical transfer function
Pf	picofarad
PID	probability of correct identification
psf	point spread function
PSQ	square of the Pearson's coefficient
PV	photovoltaic
QE	quantum efficiency
QWIP	quantum well infrared photoconductor
RC	resistor-capacitor
rms	root mean square
ROIC	readout integrated circuit
RSS	square root of the sum of squares
SGR	sky-to-ground ratio
SIR	sampled imager response
SIT	system intensity transfer
SMAG	system magnification
S/N	signal-to-noise ratio
SOM	specific object model
SRH	Shockley-Read-Hall
SSD	signal spectral density
str	steradian
SWIR	short-wave infrared
TCR	temperature coefficient of resistance
tgt	target
TOD	triangle orientation discrimination
TTP	targeting task performance
UAV	unmanned aerial vehicle
VFOV	vertical field of view
W	watt
WFOV	wide field of view