Chapter 1
Introduction

1.1 Photon Transfer History and Application

Photon transfer (PT) is a valuable testing methodology employed in the design, operation, characterization, optimization, calibration, specification, and application of solid state imagers and camera systems (most notably CCD and CMOS). As far as the author knows, PT began its evolution during the era of vidicon tubes used by NASA's early planetary imaging missions. The noise floor for these imagers was typically constant with light level, although a slight noise elevation near saturation was occasionally observed. Researchers speculated that the noise increase was associated with photon shot noise and prepared rudimentary plots to graph the noise source and better understand its nature. These plots may have been the first photon transfer curves (PTCs) generated by an area array imager in which noise was plotted against signal.

In the mid-1970s the charge-coupled device (CCD) began to replace the vidicon to become the premier imager for NASA and the imaging world.[1] This new solid state imager exhibited a read noise floor considerably lower than that of the vidicon (40 times less at that time). Photon shot noise was clearly observed, and the title "shot noise limited" was given to the sensor to signify its ideal performance. At the same time the CCD and PTC were immediately married. Although the formal name "photon transfer curve" would come a few years later, the new testing technique was formally born and would become an important measurement standard for the imaging community. Today PT is routinely used and continues to evolve along with the multitude of new imaging technologies in development.

The PT technique is applicable to all imaging disciplines. For example, CCD and CMOS solid state physicists as well as design and fabrication/process engineers rely on PT feedback to assist in the development and production of quality imagers. Table 1.1 lists key sensor performance parameters that are measured and optimized by PT and the chapters in this book where they are discussed.

Camera companies and their customers also regularly use a PTC for trouble shooting, characterization, optimization, and calibration purposes. The system level performance parameters listed in Table 1.2 depend on PT results.

Table 1.1 Detector performance parameters.

Performance parameter	Symbol	Unit	Chapter
Interacting quantum efficiency	$\mathrm{QE_I}$	interacting photons/ incident photons	2
Quantum efficiency	QE	e^-/incident photons	2
Quantum yield	η_i	electrons/interacting photons	2
Fano factor	F_F		3
Pixel FPN quality factor	P_N		3
Charge collection efficiency	CCE		4
Effective quantum yield	η_E	e^-/photon	4
Sense node capacitance	C_SN	F	4
Sense node gain	A_SN	V/e^-	4
Charge capacity	S_FW	e^-	5
Dynamic range	DR		5
Image lag factor	I_LAG		5
Read noise	σ_READ	e^- rms	5
V/V nonlinearity	NL		7
V/e^- signal nonlinearity	$\mathrm{NL_S}$		7
V/e^- noise nonlinearity	$\mathrm{NL_N}$		7
Dark current figure of merit	D_FM	nA/cm^2 at 300 K	11
Dark current FPN quality factor	D_N		11
Dark current nonlinearity	$\mathrm{NL_D}$		11
Offset fixed pattern noise	σ_OFF	e^- rms	11
Pixel source follower noise	σ_SF	e^- rms	11
Reset noise	σ_RESET	e^- rms	11
Pixel responsivity	R_e	e^-/lux-sec	12

Note that the performance parameters listed in Tables 1.1 and 1.2 are specified in absolute units (e.g., electrons). In contrast, sensor and camera systems that use relative units to specify performance can be very puzzling. For example, it is impossible to discern if a pixel's charge capacity is satisfactory if it is specified in output volts. But there is no misunderstanding about a full-well specification given in electron units. Some parameters may be encountered that fool one's intuition. For example, a low read noise voltage generated by a detector may seem to achieve better signal-to-noise (S/N) performance relative to a higher noise floor. However, when the same noise is measured in electrons, the higher noise voltage may prove to be superior (e.g., refer to Chapter 11 on reset noise). The absolute scientific units provided by PT take the guesswork out of properly specifying performance.

Raw data generated by a camera system are measured in the form of relative digital numbers, or DNs (i.e., a pixel's signal is encoded in DN). The DN is phys-

Table 1.2 Camera system performance parameters.

Performance parameter	Symbol	Units	Chapter
Analog to digital converter (ADC) sensitivity	$K_{\mathrm{ADC}}(\mathrm{e^-/DN})$	$\mathrm{e^-}$/DN	4
ADC offset	$S_{\mathrm{ADC\_OFF}}(\mathrm{DN})$	DN	4
ADC sensitivity variance	σ_{K}	$\mathrm{e^-}$/DN rms	6
ADC noise sensitivity	$N_{\mathrm{ADC}}(\mathrm{e^-/DN})$	$\mathrm{e^-}$/DN	7
ADC signal sensitivity	$S_{\mathrm{ADC}}(\mathrm{e^-/DN})$	$\mathrm{e^-}$/DN	7
Flat-fielding quality factor	Q_{FF}	$\mathrm{e^-}$	8
Flat-field S/N	$(\mathrm{S/N})_{\mathrm{FF}}$		10
Image S/N	$(\mathrm{S/N})_{\mathrm{I}}$		10
Maximum image S/N	$(\mathrm{S/N})_{\mathrm{I\_MAX}}$		10
ADC quantizing noise	σ_{ADC}	$\mathrm{e^-}$ rms	11
System noise	σ_{SYS}	$\mathrm{e^-}$ rms	11
Absolute flat-field S/N	$[\mathrm{S/N}]_{\mathrm{L\_FF}}$		12
Absolute image S/N	$[\mathrm{S/N}]_{\mathrm{L\_I}}$		12
Minimum detectable luminance	L_{MIN}	lux	12
Image luminance required for S/N $= 10$	L_{Q}	lux	12

ically meaningless. Therefore, it is essential that a constant be found that converts DN units to absolute electron units. Deriving this constant may seem like a daunting task considering the multitude of transfer functions associated with a camera system, especially if the accuracy required for this constant must sometimes be better than 1% for scientific work. Luckily, PT can treat a camera system, no matter how complex it is, as a black box and determine the desired conversion constant with very little effort. The user needs only to expose the camera to a light source and measure the signal and noise output DN responses for a small group of pixels. From there PT is applied, and almost magically, the desired $\mathrm{e^-}$/DN constant is obtained.

Photon transfer is one of the first go/no-go tests performed to determine the health of a new camera system. Frequently, PTC plots are disappointing on the first try because a new camera may be filled with problems. PT aids troubleshooting with routines to identify issues ranging from solid state sensor problems to software data acquisition deficiencies. PT keeps everyone honest (including software engineers!) by providing absolute information each step of the way. Dozens of PTCs may be generated before a camera can be declared “operational,” and even more curves to title it “optimized.” But in the end, the efforts will be worthwhile to ensure that a camera is achieving the most reliable high performance possible.

Fortunately, testers have prior knowledge about what a PTC should look like before beginning the process. PTC “shape” is dictated by Mother Nature, who herself is described by a few PT relations. Many PTCs presented in this text are computer simulated using derived theoretical PT relations (e.g., refer to the appendix for example computer programs). Textbook experimental PTCs will precisely follow simulation results only when a system is in perfect working order as judged by PT.

When executing PT, initially it may seem like a lifetime before good results materialize. However, as experience is gained with PTC, data will be generated in short order (experts can generate PTCs in less than a minute). The necessity for high-speed PT testing is warranted because each camera modification requires a new e^-/DN calibration. For example, when attempting to lower the read noise through a camera change, the DN noise level must be converted to electrons through e^-/DN in order to verify if the fix worked (recall that a lower DN noise change could actually mean a higher electron noise level). Similar to peeling an onion, read noise sources are eliminated one by one through the routine. Therefore, it is desirable to run PT experiments quickly. PT also enables testers to tweak most other parameters for optimum performance with a fast turnaround.

The end user will also find PT valuable. For example, generating a PTC will verify if a camera purchase meets specifications before serious application in the field takes place. An application may require absolute calibration to measure signals with very high accuracy (a $<1\%$ photometry error is routine for astronomers). PTCs will demonstrate and confirm that a camera system is stable and reliable. Image processing algorithms are often applied to remove fixed pattern noise (FPN) sources to obtain high S/N performance, especially when working with low-contrast images. PTCs validate that the software and hardware for this important purpose are in order. As will be shown in Chapter 12, PT is also a valuable tool that joins commercial photometric and scientific radiometric measurement units.

1.2 Photon Transfer Family

It is remarkable that only two measurements—average signal and rms noise—can produce the amount of information contained in this book. In addition to the data products presented in Tables 1.1 and 1.2, different transfer curves can be generated from the same two parameters for further characterization results. As it turns out, format is an important factor in extracting the most information from a PTC; therefore, specific plotting routines have been invented for this purpose. Collectively, these routines are called the "photon transfer family." Tables 1.3–1.17 present the principal transfer curves contained for the family. By far the most exercised plot is the classical PTC (Table 1.3) and the variance PTC (Table 1.4). This data will give the user significant insight about whether a camera system is in proper working order as well as supply many of the performance parameters listed in Tables 1.1 and 1.2. Note that some PTCs are composed of multiple plots that differentiate noise sources (grouped as "sets"). Also, PTC data are usually plotted in both DN and electron units, which produces supplementary information.

Each performance parameter and transfer curve presented in Tables 1.1–1.17 will be encountered in this book, including many others. Theoretical PT relations are also derived for each curve to support the experimental data taken.

Table 1.3 Photon transfer curve (PTC).

Set	Plots	Units	Chapter
Set 1	read, shot, FPN (total noise) vs. signal	log rms DN vs. log DN	5
Set 1	read, shot noise vs. signal	log rms DN vs. log DN	5
Set 1	shot noise vs. signal	log rms DN vs. log DN	5
Set 1	FPN vs. signal	log rms DN vs. log DN	5
Set 2	read, shot, FPN (total noise) vs. signal	log rms e^- vs. log e^-	5
Set 2	read, shot noise vs. signal	log rms e^- vs. log e^-	5
Set 2	shot noise vs. signal	log rms e^- vs. log e^-	5
Set 2	FPN vs. signal	log rms e^- vs. log e^-	5

Table 1.4 Variance photon transfer curve (VPTC).

Set	Plots	Units	Chapter
Set 1	shot noise variance vs. signal	(rms DN)^2 vs. DN	5

Table 1.5 V/V nonlinearity.

Set	Plots	Units	Chapter
Set 1	K_{ADC}(e^-/DN) vs. signal	e^-/DN vs. log DN	7
Set 2	K_{ADC}(e^-/DN) vs. signal	e^-/DN vs. log e^-	7

Table 1.6 V/e^- nonlinearity.

Set	Plots	Units	Chapter
Set 1	S_{ADC}(e^-/DN) vs. signal	signal e^-/DN vs. log DN	7
Set 1	N_{ADC}(e^-/DN) vs. signal	noise e^-/DN vs. log DN	7
Set 2	S_{ADC}(e^-/DN) vs. signal	signal e^-/DN vs. log e^-	7
Set 2	N_{ADC}(e^-/DN) vs. signal	noise e^-/DN vs. log e^-	7

Table 1.7 Nonlinearity residuals.

Set	Plots	Units	Chapter
Set 1	nonlinearity vs. signal	% vs. log DN	7
Set 2	nonlinearity vs. signal	% vs. log e^-	7

Table 1.8 K_{ADC}(e^-/DN) histogram.

Set	Plots	Units	Chapter
Set 1	occurrences vs. K_{ADS}(e^-/DN)	occurrences vs. e^-/DN	6

Table 1.9 Quantum yield.

Set	Plots	Units	Chapter
Set 1	quantum yield vs. wavelength	e^-/interacting photon vs. wavelength	2

Table 1.10 Flat-fielding photon transfer curve (FFPTC).

Set	Plots	Units	Chapter
Set 1	read, shot, FPN (total noise) vs. signal	log rms DN vs. log DN	8
Set 1	read, shot noise vs. signal	log rms DN vs. log DN	8
Set 1	read, shot noise vs. signal (after FF)	log rms DN vs. log DN	8
Set 2	read, shot noise, FPN vs. signal	log rms e^- vs. log e^-	8
Set 2	read, shot noise (total noise) vs. signal	log rms e^- vs. log e^-	8
Set 2	read, shot noise vs. signal (after FF)	log rms e^- vs. log e^-	8

Table 1.11 Modulation photon transfer curve (MPTC).

Set	Plots	Units	Chapter
Set 1	image modulation vs. signal	log rms DN vs. log DN	9
Set 1	read, shot, FPN vs. signal	log rms DN vs. log DN	9
Set 1	read, shot noise vs. signal	log rms DN vs. log DN	9
Set 2	image modulation vs. signal	log rms e^- vs. log e^-	9
Set 2	read, shot, FPN vs. signal	log rms e^- vs. log e^-	9
Set 2	read, shot noise vs. signal	log rms e^- vs. log e^-	9

Table 1.12 Signal-to-noise transfer curve.

Set	Plots	Units	Chapter
Set 1	read, shot, FPN (total noise) S/N vs. signal	log S/N vs. log DN	10
Set 1	read, shot S/N vs. signal	log S/N vs. log DN	10
Set 2	read, shot, FPN (total noise) S/N vs. signal	log S/N vs. log e^-	10
Set 2	read, shot S/N vs. signal	log S/N vs. log e^-	10

Table 1.13 Flat-fielding signal-to-noise transfer curve.

Set	Plots	Units	Chapter
Set 1	S/N vs. signal (after FF)	log S/N vs. log DN	10
Set 2	S/N vs. signal (after FF)	log S/N vs. log e^-	10

Table 1.14 Image signal-to-noise transfer curve.

Set	Plots	Units	Chapter
Set 1	Image S/N vs. signal (with FPN)	log S/N vs. log DN	10
Set 1	Image S/N vs. signal (without FPN)	log S/N vs. log DN	10
Set 2	Image S/N vs. signal (with FPN)	log S/N vs. log e^-	10
Set 2	Image S/N vs. signal (without FPN)	log S/N vs. log e^-	10

Table 1.15 Dark transfer curve (DTC).

Set	Plots	Units	Chapter
Set 1	Dark read, shot, FPN (total noise) vs. signal	log DN vs. log DN	11
Set 1	Dark read, shot noise vs. signal	log DN vs. log DN	11
Set 2	Dark read, shot, FPN (total noise) vs. signal	log e^- vs. log e^-	11
Set 2	Dark read, shot noise vs. signal	log e^- vs. log e^-	11

Table 1.16 Lux transfer curve (LTC).

Set	Plots	Units	Chapter
Set 1	S/N vs. luminance (with FPN)	log S/N vs. log lux	12
Set 1	S/N vs. luminance (without FPN)	log S/N vs. log lux	12

Table 1.17 Modulation lux transfer curve (MLTC).

Set	Plots	Units	Chapter
Set 1	S/N vs. luminance (with FPN)	log S/N vs. log lux	12
Set 1	S/N vs. luminance (without FPN)	log S/N vs. log lux	12

1.3 Chapter Review

This section summarizes each chapter in this book:

Chapter 2, *Photon Interaction*, briefly reviews the photoelectric effect as applied to semiconductors stimulated with energetic particles. Although varieties of particles, carriers, and semiconductors can be involved in the PT process, this book assumes that photons, electrons, and silicon are responsible for generating electronic images. PT plays a role in measuring the number of photons that interact photoelectrically with the silicon, a performance parameter referred to as *quantum efficiency* (QE). For energetic photons, multiple electrons are generated, a performance parameter referred to as *quantum yield*. This characteristic is important because a PT response is dependent on photon wavelength, which allows incident photon energy and related quantum yield to be determined.

Chapter 3, *Photon Transfer Noise Sources*, introduces four fundamental noise sources measured by PT. Two sources, shot noise and Fano noise, are related to initial photo-carrier generation. Photon shot noise plays a major role in providing the information necessary to determine the e^-/DN conversion constant found by the PTC. The third noise source, pixel FPN, is present because charge collection from pixel to pixel is different. Although FPN seems to be insignificant (only 1% pixel nonuniformity is measured for CCD and CMOS detectors), the noise source dominates the sensor's dynamic range and has a dramatic limiting effect on S/N performance. The last noise source, read noise, limits the accuracy for all measurements made by PT.

Chapter 4, *Photon Transfer Theory,* presents transfer functions for a typical camera system with the photon as the input and DN as the output. General PT equations are derived for the various sensitivity functions internal to the system that relate DN, volt, electron, and photon measurement units (e.g., e^-/DN). We demonstrate how quantum efficiency, quantum yield, and charge collection efficiency (CCE) are measured by manipulating the sensitivity constants.

Chapter 5, *Photon Transfer Curve*, reviews camera and software setup requirements to perform PT experiments. Experimental data is used to show a step-by-step procedure used to generate a PTC. The classical PTC is introduced, showing four distinct noise regimes in the plots (read noise, shot noise, FPN, and full well). PTC computer simulations are employed to exercise PT equations derived for the plots. Various performance parameters are then extracted from the PTCs, including the important e^-/DN conversion constant. Common signal processing errors that add uncertainty to the ideal PTC response are reviewed and demonstrated. An advanced measuring technique is described that generates a full PTC from a single frame of data. The variance PTC, an alternate graphing format, is presented to graphically determine e^-/DN in the presence of read noise. The last section of the chapter includes many sample experimental PTC data products.

Chapter 6, e^-/DN *Variance*, theoretically derives the formulas required to determine the e^-/DN constant to a specific degree of accuracy. PTC simulations and data products verify the precision achieved for the relations presented. The analysis is also applicable to other camera sensitivity parameters that require a desired degree of accuracy.

Chapter 7, *Nonlinearity*, discusses V/V gain nonlinearity common to CCD and CMOS sensors. The problem is quantified by taking a standard PTC data set and plotting e^-/DN as a function of signal. Signal processing algorithms are presented that remove the nonlinearity problem. This chapter also deals with V/e^- nonlinearity, a more serious gain problem associated with CMOS detectors. Detailed analysis presents the impact of V/e^- gain nonlinearity on PTC results. The last section shows that PTC can separate the effects of V/V and V/e^- nonlinearity issues when both problems are present.

Chapter 8, *Flat Fielding*, demonstrates a popular image signal processing technique used to remove FPN in images to achieve shot noise limited performance (the best possible performance). The chapter begins by demonstrating the mechanics of the flat-fielding technique through simulation. A general formula is derived that predicts the resultant noise contained in an image after flat fielding is performed. Various before and after flat-field simulations are presented that demonstrate the flat-fielding routine. The PTC is then used to verify expected results.

Chapter 9, *Modulation Photon Transfer*, derives the response generated by a detector stimulated by a sinusoidal light source. Important results from analysis and simulations show that the average sinusoidal shot noise and FPN are approximately equivalent to a uniform light response with the same average signal level. Similar conclusions are extended to real images. The "modulation PTC" plots image modulation as a function of average signal. An "image modulation constant" is extracted from the curve, a product of incoming scene contrast and system modulation transfer function (MTF). The parameter is used to quantify image S/N performance in the following chapter.

Chapter 10, *Signal-to-noise Performance*, replots PTC data as S/N as a function of signal. Image S/N plots are generated from modulation PTC data. An important relation is also derived to show that S/N for an image is the product of the flat-field S/N and the image modulation constant. Simulated images are presented to demonstrate that quality images required S/N > 10. Analysis includes S/N improvements achieved when FPN is removed through flat fielding. The chapter closes by showing S/N improvements made when multiple frames of an image are averaged.

Chapter 11, *Read Noise*, discusses important noise sources found in CCD and CMOS cameras that are collectively called the read noise floor. Noise sources analyzed include pixel source follower noise, sense node reset noise, thermal dark current noise, ADC quantizing noise, offset FPN, and system noise. Relations are given for each source and show their unique influence on PTC results.

Chapter 12, *Lux Transfer*, describes a powerful extension of the PTC that plots S/N as a function of absolute light level. The LTC is a valuable standard that collects all detector and camera performance parameters into a single performance curve. Also presented is the "modulation LTC," an extension of modulation PTC that plots image S/N as a function of absolute light level. Numerous data products are derived from these two curves, including minimum detectable luminance level, luminance required for image S/N > 10, and pixel responsivity (e^-/lux-sec). Radiometric and photometric units are married by the LTC.

Appendix A presents tables containing raw experimental data generated by a CMOS imager. Discussions take the user through a step-by-step process to generate various PTC results from the data. Appendixes B, C, and D contain MatLab simulation programs that generate PTCs and LTCs.