A Century of Image Quality

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Abstract

The development of individual and overall descriptors of image quality has been of concern to various branches of the imaging community for a century or more. Especially, the latter half-century has seen the evolution of an overall image-quality language spanning many practical areas of applied imaging, with major contributions from studies in fields as diverse as astronomy, photography, microscopy, radiation detectors, human vision, radar, statistical processes and information theory. A survey is given here of some key aspects of this evolution, including the roles of the earliest pioneers and their major contributions made over the course of the century.

Contemporary problems include the translation of techniques developed for the evaluation of analog imaging processes into the digital domain, for example in the development of digital photography systems.

Introduction

In all historical surveys one of the most vexing issues is often simply that of when the existence of the topic first entered the public domain. Within the photographic context - and in the sense of the posing of an obvious practical problem - Niepce may have been said to have clearly demonstrated the need to address the image-quality problem. His picture of the rooftops of his country house taken around 1826 (generally acknowledged to be the first photograph) shows marginal image quality in spite of an exposure which ran to several hours - or, in later photographic parlance, a practically unacceptable speed-to-grain ratio.

It was however in what at the time was the quite separate context of astronomical imaging that quantitative approaches were being made to problems posed by the limits of image quality. For example the diffraction pattern formed by plane waves from a point source passing through a circular aperture was of considerable interest in limiting the resolving power of telescopes and other optical instruments. This problem was first solved in 1835 by Sir George Airy,[1] with the solution expressed in terms of Bessel functions. In hindsight this provides an excellent example of the image-quality insight provided by system modeling. A criterion for optical resolution was first introduced in 1879 by Lord Rayleigh[2] in connection with prism and grating spectroscopes and the term *Rayleigh resolution criterion* survives to this day. In 1902 Strehl[3] proposed a more generally applicable quality criterion (*Strehl definition*), based on the observation that a slight defocusing or a small amount of spherical aberration in an optical system alters the distribution of light between the disk and rings in the diffraction pattern without much changing their sizes or their relative positions.

Stemming from these and other of the earliest studies, this present century has seen remarkable and well-documented advances in optical aberration theory, a topic beyond the present scope. However the explicit convergence with a general systems quality analysis of complex imaging systems awaited the arrival and general adoption of Fourier optics in the mid-part of the present century, to be touched on shortly.

Photographic Image Quality: Early Studies

Following the widespread commercialization of silver halide processes in the latter part of the nineteenth century, it would be true to say that the image quality problem was largely solved *de facto* in the absence of any scientific approach, and high quality photographs became commonplace. A practical picture-taking combination of format and exposure time had evolved which yielded sufficient light to overcome the inherently low quantum efficiency of the photographic grains, and the microscopic size of the latter combined with large-format cameras permitted what were essentially grain-free, high-resolution photographs. However to understand and advance the complex relationship between speed, grain and resolution, it was necessary to embark on series of quantitative studies which continue to the present day. With benefit of hindsight a few of the earliest studies were pivotal to the modern field, and are noted below.

The famous works of Ferdinand Hurter and Vero Driffield established the concept of the analytical study of photographic response,[4] and specifically the relationship between exposure and resulting image density. In 1913 Nutting[5] modeled the relationship between image density and the size and concentration of the grains forming the image. Silberstein[6] introduced the photographic community to the implications of a quantum theory of exposure, during a paper read at the 1921 meeting of the American Physical Society ("*From a recent conversation with Einstein* …"). For the next two decades or so Silberstein advanced these ideas in a remarkable series of papers, and although these were mainly in the context of latent image formation and the relationship to the characteristic curve, they formed the basis for many subsequent modern signal-to-noise studies of the quantum-limited aspects of silver-halide image formation.

From the many pre-Fourier-theory studies of photographic granularity, the Siedentopf relationship[7] deserves special mention since it has proved to be of lasting significance. By relating the aperture-scanned image noise to the grain size and concentration, Siedentopf essentially achieved in the fluctuation sense what Nutting had pioneered in the mean-level sense, and also provided a soundly-based insight of the role of the aperture in scaling the noise.

The Fourier Transform Revolution

Duffieux[8] is widely credited with introduction to the optics community of the advantages of the Fourier (spatial-frequency) domain in image evaluation studies. The advances brought about by widespread adoption of Fourier transforms led to a mid-century revolution in optical image evaluation which rapidly spilled over into other fields of imaging, including photography. In fact a decade previously Frieser[9] had demonstrated the utility and properties of sine-wave targets as measures of photographic resolution. Due to his lifetime contributions in almost every aspect of photographic image evaluation, Frieser can truly be said to be the father of the field, and his lifetime works are collected in a weighty volume[10] published towards the end of his career.

Others prominent in introducing the Fourier approach to imaging included Schade[11] who especially pioneered the study of "*the performance characteristics of electronic and photographic imaging systems in the same technology*" and subsequently published a substantial review of his many contributions in these and related image-quality fields[12]. Linfoot[13] published in textbook form a treatise noteworthy here in that it included the influences of both optical and photographic components within a comprehensive Fourier-based image-evaluation treatment. MTF analysis of image transfer is now universal.

Image Noise Analysis

As a preface to the widespread adoption of Fourier-based techniques for the description of image noise, the pioneering work of Wiener[14] during the 1930s concerning the analysis of stochastic processes was of crucial importance, with the associated implications of the Wiener-Khintchine theorem. During the 1950s classical treatments by Fellgett,[15] Jones[16] and Zweig,[17] among others, established the details necessary for the application to photographic granularity, including practical problems of measurement and scaling.

The confluence of these Fourier-based ideas during the 1950s as applied to a diversity of optical and imaging technologies made this an outstanding decade of general progress in image evaluation concepts. This progress was accompanied by several other fields of intense creative activity taking place within a similar time period, and these fields were also to play a long-term important role in understanding the fundamental quality associated with imaging devices.

Fundamental Detector Limits

Starting in the 1940s the question had been posed of the natural limits imposed on detection by the quantum nature of the exposing radiation itself. Likewise there was interest in comparing on an absolute basis a variety of radiation detectors, from photographic film to TV tubes and even human vision. Albert Rose[18] was prominent in this field, and along with Fellgett[19] and Jones[20] established detection and signal-to-noise ratio metrics which are scaled to the absolute limits imposed by the quantum nature of the exposure radiation. These metrics coalesced into what is now known as the *noise-equivalent* methodology of scaling image noise and establishing absolute signal-to-noise ratio scales, and thereby the universal metric of *detective quantum efficiency*.

This methodology has proved invaluable in identifying imaging systems limitations, especially when coupled with systems models in terms of component technologies. Resisted at first with some vigor by a substantial body of the traditional photographic community, who thought little of being told that in effect they were custodians of a technology rated at around one-percent efficiency in the noise-equivalent sense, the methodology has subsequently been used to great effect to explore the bounds of imaging performance and to compare competitive technologies, for example analog and digital photography systems.

"Vision, Human and Electronic" published later[21] by Rose remains a valuable introductory source to these topics, covers a wide variety and detector and imaging technologies, and provides a lasting testament to his own dominant role in the field.

The concept of detective quantum efficiency was elaborated on in detail by several authors[22-26] whose studies included further DQE comparisons among imaging technologies using different light-amplification mechanisms. Of these the most controversial were, surprisingly, elaborations on the truism that photographic grain is an amplified manifestation of the incoming photon noise,[23, 26] ideas again initially resisted with vigor by the traditional silver-halide community.

Other studies included the relationship between Fourier-based signal-to-noise ratio concepts and those emanating from the Rose-based photon-counting approach, leading to a more comprehensive definition of DQE in terms of Fourier components.[25] In this form it provides a fundamental definition of "photographic space", since it explicitly and fully includes the variables associated with resolution and noise as well as those defining the exposure constraints. In this global form it also provides an important link to the next applied field to be mentioned here, one which has had profound implications in many fields of science far removed from imaging.

Information Theory and Imaging

During the 1940s Claude Shannon had worked on fundamental problems of coding and decoding, leading to his landmark publications[27] and the coining of the term *information theory*. The important implications of his classical theorems were quickly evident to the optics and imaging communities, and in 1955 Fellgett and Linfoot[28] published an extensive analysis wherein they laid the groundwork for the information-theoretic approach to optical imaging systems. Continuous, two-dimensional spatial images subject to stochastic noise, with signal and noise expressed in the Fourier-domain, could now be assessed within a universal framework.

This universal nature was subsequently explored in great detail by Brillouin,[29] among others, leading to the concept of information as a natural extension of generalized entropy theory - somewhat akin to statistical thermodynamics and its ubiquitous second law. In similar vein the relationship between the information-theoretic and noise-equivalent approaches is then seen as converging naturally. The importance of Shannon's ideas in the context of communication and imaging was also explored by Tribus,[30] who considered the energy-cost of information in these terms.

Among the earliest practical photographic information-theoretic studies was that of Altman and Zweig,[31] who investigated the physical parameters limiting photographic bit-storage. Huck and co-workers[32] used Shannon's theorems to assess the performance of line-scan and sensor-array systems, and subsequently have been associated with a series of fundamental imaging studies along similar lines. These topics lead naturally to a further field of image concern and advancement.

Sampled, Scanned and Grid Imagery

The earliest quality studies were essentially concerned with pseudo-continuous (analog) images. From their work relating to television systems, Mertz and Gray published in 1934 their classical opus on two-dimensional scanned systems,[33] and especially the role of the aperture. Schade[34] later made his own many contributions to this field, and in 1973 Robinson extended these studies by considering multidimensional Fourier transforms and image processing with finite scanning apertures.[35] These and similar topics are naturally of great relevance in the present era of electronic imaging and digital imaging, and many comprehensive treatments now exist. Again, Huck and co-workers have been associated with substantial contributions[36] to the field.

An area of special interest within this field concerns the so-called halftoning method of image reproduction. Roetling and co-workers[37] addressed the problem of the Fourier spectrum of the halftone image as a function of the spectrum of the original continuous-tone image and the halftoning process, and among the many contributions from Allebach and co-workers was an early one concerning the elimination of moire patterns.[38]

The topic of applying stochastic noise theory to grid-like image structures has been studied in the context of analog electrophotographic halftones[39,40] showing that with suitable precautions Wiener spectrum techniques may still be used for noise scaling and comparison between imaging technologies. Latterly it has been demonstrated[41] that an absolute Wiener-based noise scale may be constructed directly linking digital and analog systems, even including the perceptual response, with only minor additions to techniques used for quality analysis of analog systems half-a-century ago.

Fields of Applied Imaging

Over the course of the century substantial contributions to the fundamental understanding of image quality issues have come from the various fields of applied imaging, as opposed to those contributions which have come from those concerned with proprietary imaging systems and processes themselves. Originally and consistently, as already noted, the field of astronomy often gave impetus to such understanding, and along the way other fields have likewise contributed. One good example of recent progress comes from that of medical diagnostic imaging, where recent years have shown an acceleration in the application of the most sophisticated approaches to systems image-quality studies, and also clearly demonstrated the benefits of to be gained.

During the 1960s Rossmann and co-workers[42,43] applied MTF and Wiener spectrum techniques to problems of radiographic imaging, and during the 1970s these techniques became well-established in the field.[44-47] Wagner and co-workers[48-50] have played a leading role in advancing these techniques, including extensions to other diagnostic-imaging modalities. The noise-equivalent approach has proved crucial[51] not only in the absolute signal and noise scaling exercises which are vital in this field, but also indicating proximity to fundamental limits in imaging systems approaching the quantum-limited ideal.

Other topics actively pursued in the medical imaging domain include that of transfer of signal and noise power spectra through imaging system chains,[52-54] with resulting general solutions applicable to similar problems in other imaging fields, digital or analog. These modern advances, especially as translated into the digital domain, offer solutions to problems in fields such as digital photography.

Digital Photography

Image quality studies of the potential capabilities of digital photography systems[56-59] have been of increasing practical interest, especially as practical consumer systems become widely available, with natural interest in the comparison of performance (speed, resolution, noise) with traditional analog photography. For this the modern language of image quality, which has evolved as outlined above, can play a central role, all indications are that the infusion of Fourier/noise-equivalent/information-theoretic metrics into this field will be of benefit to all.

Detailed problems of application are inevitable, but indications are that most of these have already been satisfactorily addressed in other fields of applied imaging.

The remaining problems of assessing image quality are thus largely ones of translation rather than invention, and we can all be grateful to those original pioneers who did such a thorough job, often against the odds, in bringing us to this enviable position. We stand on their broad shoulders.

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