A Century of Imaging Science

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Abstract

The performance of imaging systems and pictorial recording and printing processes has been of concern within various branches of the diverse technical communities for a century or more. Especially, the latter half-century has seen the evolution of an overall quantitative imaging language, latterly formalized within the generic description of *imaging science*. Major contributions came from fundamental studies in fields as diverse as astronomy, photography, microscopy, radiation detectors, human vision, radar, statistical processes and information theory. As a result, imaging science now spans many practical areas of applied technology. Here a summary is presented of some key aspects of this historical evolution, including the roles of the earliest pioneers and their major contributions made over the course of a century or so.

Contemporary problems include the translation of universal imaging knowledge developed for the evaluation of analog imaging processes into the digital domain, for example as an important tool in the development of sophisticated digital printing systems.

Introduction

While there may have been a steady evolution rather than a definitive genesis of what we now term imaging science, Niepce can be said to have clearly provided a demonstration of 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 known photograph), while revolutionary, demonstrates marginal image properties in spite of an exposure which ran to several hours. In later imaging parlance we might say that he achieved a practically unacceptable signal-to-noise ratio in spite of having access to a powerful signal.

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 image limitations. 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.

Although these developments are now largely only of historical interest, the century which followed has seen remarkable and well-documented advances in optical imaging theory. However an explicit convergence of this theory with that used to evaluate image recording, printing and display systems awaited the arrival and general adoption of Fourier optics in the mid-part of the present century, to be touched on shortly.

Photography as an Imaging Process

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. Properly translated and suitably modified, the Siedentopf relationship can be of daily utility in the quantification of digital printing systems.

Fourier Transforms in Imaging

Duffieux[8] is widely credited with introducing to the optics community of the advantages of the Fourier (spatial-frequency) domain in the analysis and evaluation of imaging systems. 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.

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 generalization of problems such as those posed by 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, and in turn these and other advances led naturally to the questions of the signal-to-noise ratio associated with image detection. 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 and were formalized into what is now known as the *noise-equivalent* methodology of scaling image noise and establishing absolute signal-to-noise ratio scales. Far from an esoteric exercise, this methodology has proved invaluable in identifying imaging systems limitations, especially when coupled with systems models in terms of component technologies, and has subsequently been used to great effect to explore the bounds of imaging performance and to compare competitive technologies, for example analog and digital photographic systems.

The textbook "Vision, Human and Electronic" published later[21] by Rose as a summary of his work in this field remains a valuable introductory source to these topics, covering a wide variety and detector and imaging technologies, and providing a lasting testament to his own dominant role in the field. These concepts have also been extended and elaborated on by a number authors.[22-26]

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 consistent 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 – and in that senses somewhat analagous 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, including copying and printing activities.

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, and one that by nature has crucial implications in the field of digital printing.

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[36] have been associated with a number of substantial contributions 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 the absolute scaling and comparison of noise between imaging technologies, analog or digital.

Digital Printing

Over the last several years the author has attempted to translate important results form these earlier studies into a systematic set of image quality descriptors appropriate for example to ink-jet printing.[41-45] In this way an absolute scale has been described for digital noise and a similar scale developed for digital sharpness. The digital noise scale (*DNS*) has both a direct visual-science Fourier-basis yet lends itself to practical physical measurement, and in addition has the advantage that it is directly related to long-established granularity metrics in analog photography, and can also be simply translated into key digital printing parameters such as *dpi* and number of gray-levels. In similar fashion an absolute scale has been described for digital sharpness (*DSS*) that can be directly related to the sharpness associated with other imaging technologies (such as analog photography) and translated into pixel-size/enlargement terms as for example appropriate for printing of digital photographs using thermal ink-jet processes.

An Absolute Scale for Digital Noise

As first developed for photographic granularity and later extended to electrophotography,[46] then translated into convenient digital form, the digital noise may be expressed in the form

$$DN = \sqrt{\left\{ \iint WS_R(u,v)\, VTF^2(u,v)\, du\, dv \right\}} \qquad (1)$$

where $WS_R(u,v)$ represents the Wiener Spectrum of the noise fluctuations measured *in units of print reflectance*, and $VTF(u,v)$ denotes the transfer function associated with human vision. The visual transfer function, as assumed for normal print viewing conditions[46] is as shown in Figure 1.

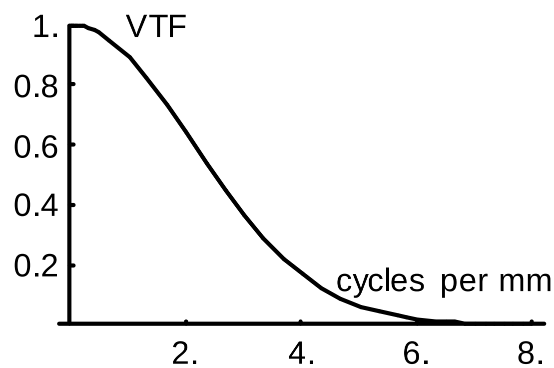

Figure 1. Visual transfer function for typical print viewing.

In many practical cases it is possible to simplify this expression to

$$DN = \sqrt{WS_R(0,0)} \qquad (2)$$

The author has also indicated that existing empirical descriptors for photographic grain fall on the *DNS* as below, implying a gamut of physical values in the range *1* to *10* for practical photography, with categories as shown.

DNS	Photo-Grain
10	*off-scale*
8	*very coarse*
6	*coarse*
5	*moderately coarse*
4	*medium grain*
3	*fine grain*
2	*very fine*
1	*extremely fine*
<1	*microfine*

A simple model for the image noise associated with ink-jet printing may be approximated on the digital noise scale in terms of *dpi* according to

$$DN(max) = 12{,}700 / (m\ dpi) \qquad (3)$$

where *m* denotes the number of available gray-levels expressed in reflectance-space.

Equation (3) demonstrates the equivalent roles played by *dpi* and the availability of print gray-levels in reducing digital noise.

An Absolute Scale for Digital Sharpness

In constructing this scale we assume the same visual transfer function, but must now consider the introduction of a spatial-frequency spectrum that will act as a global surrogate for those aspects of the input (scene) which convey the impression of sharpness. For this we assume a flat (white) scene-spectrum and the resulting product of this spectrum and the visual transfer function is shown in Figure 2. Note that due to an assumption of circular symmetry we have reduced the spatial frequency from two-dimensions (*u,v)* to one (*w*), by effectively changing to polar coordinates and hence introducing the radial multiplier (*w*) in the product. The same result is obtained by assuming a one-dimensional (line) scene-spectrum and assuming a linearly-increasing scene-spectrum.

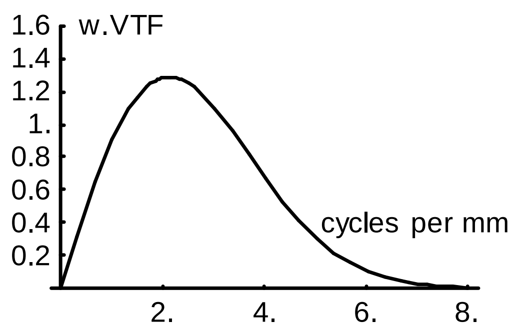

Figure 2. The visual spatial-detail-detection function

The transfer function associated with the digital printing process is considered to be due entirely to the pixel grid structure and can therefore be represented by a *sinc* function based on the pixel dimensions. This transfer function is now combined with that of Figure 2 to yield an overall spectrum for the spatial-detail detection function, as shown in Figure 3 for a range of pixel sizes.

Since the smaller pixel-sizes have spatial frequency band-passes far beyond that of the visual system, the curves shown in Figure 3 crowd together for the smaller pixel sizes, the limiting curve of course being simply that of Figure 2.

We now hypothesize that the spatial-frequency integral of the above curves as a metric of perceived print sharpness, or the digital sharpness scale (DSS). In other words we define digital sharpness (DS) according to the integral

$$DS = \int pixTF(w)\ VTF(w)\ w\ dw \qquad (4)$$

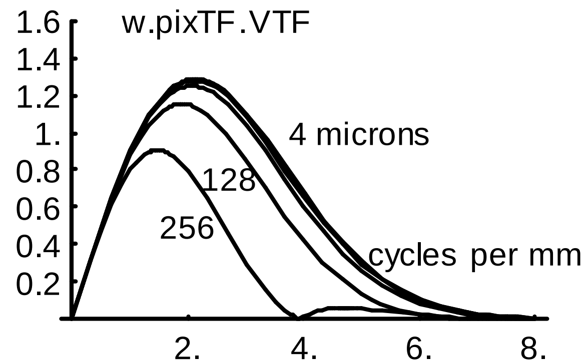

Figure 3. The overall spatial-detail detection-function

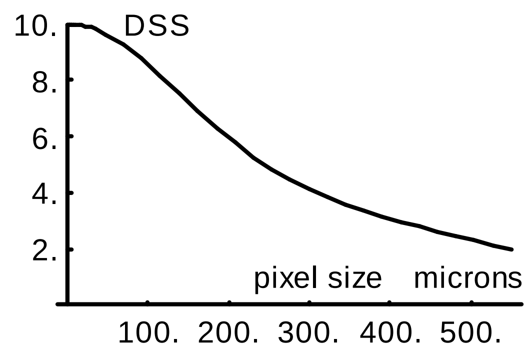

Figure 4. Digital sharpness as a function of print pixel size

In the absence of a closed-form solution, numerical integration yields the digital sharpness curve shown in Figure 4 as a function of print pixel size.

For convenience the scale has been normalized to 10 for an arbitrarily small pixel (ie, the integral of the function shown in Figure 2), yielding a convenient 0 to 10 scale for the complete gamut of sharpness values. It should be stressed here that the pixel size refers to that effective in the viewed print, and in digital photography this may be greater than the basic print-resolution dimension - and is always almost greater than the pixel dimension associated with image acquisition in the camera.

Figure 5 shows the result of Figure 4 expressed in the more familiar print terms of pixel resolution (*ppi*). From this we note that according to this new scale there is an almost linear increase in sharpness up to around 150*ppi.* Thereafter further increases in *ppi* bring diminishing sharpness benefits, while beyond 600 ppi print sharpness approaches its upper limit in asymptotic manner.

For the sake of context the range of this scale can be illustrate by estimation of the sharpness values associated with consumer analog photography. For this the equivalent pixel-size in the negative is assumed to fall within the range of 5 to 10 microns - practical values estimated from spread function diameters of typical modern negative materials. Secondly, the practical format/enlargement range of interest is assumed to fall between the extremes of APS format enlarged to 8" inch prints and 35mm format to 3.5"prints. Combining all these assumptions leads to an estimation for the practical range of spread-functions as falling between 20 and 120 microns in the analog print, with corresponding sharpness values varying between 8 and 9.95 according to the digital sharpness scale.

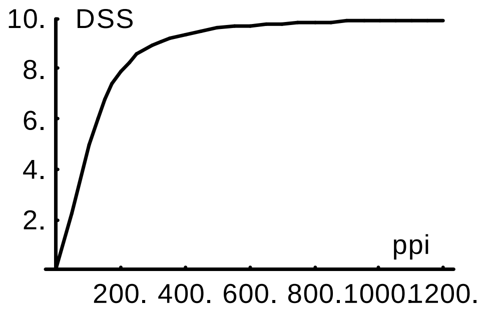

Figure 5. Digital sharpness as a function of print ppi.

A useful way of scaling these analog values alongside key parameters in digital photography is as shown in figure 6. Here the number of acquisition pixels on a side and the physical size of the print on this same side have been used as surrogates for print pixel size, and plotted according to sharpness criteria in the analog photography sharpness range. Thus according to any desired sharpness criterion it is possible to understand the maximum print size that will meet this criterion for a specific acquisition array size. For example, we see that a low sharpness value of 8 for an 12" print implies around 2000 pixels on a side.

Simultaneous Resolution and Noise Criteria

The simple analysis developed above from general imaging principles allows us consider the *mutual* properties of digital noise and digital sharpness in the print *ppi* and *gray-level* domain, since we have reduced both these image-quality attributes to simple models within this same domain. Figure 7 shows *gray-level/ppi* performance curves on the digital noise scale, where each *ppi* is now associated with a specific value of digital sharpness, as shown.

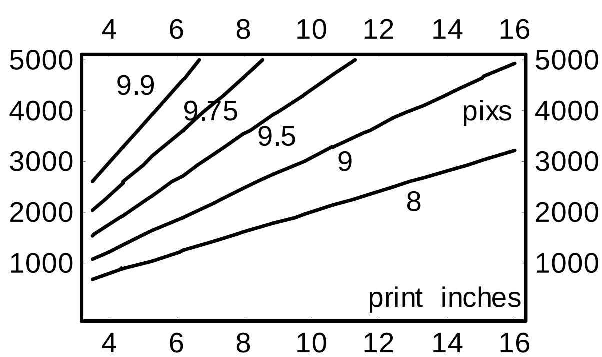

Figure 6. Relationship between number of sensor x-pixels and print x-dimension in order to conform to the range of sharpness values typical for analog photography.

Figure 7 thus acts as a means of understanding the implications when simultaneously setting print image-quality targets for noise and sharpness. An example of this is given in Figure 8. For this example it has been assumed that achieving a noise level of 1.5 or less is desired, along with a sharpness level of 8.5 or higher.

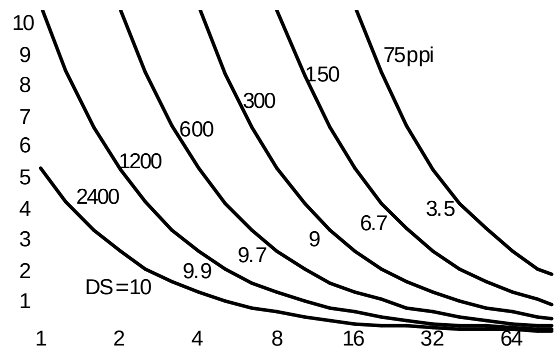

Figure 7. Digital noise (y-axis) as a function of available gray-levels (x-axis) for a range of print ppi values as shown. Also shown are the corresponding digital sharpness values.

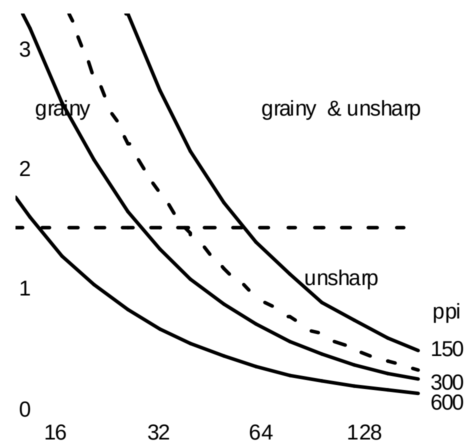

Figure 8. Digital noise (y-axis) as a function of available gray-levels (x-axis) for print ppi values as shown. The horizontal line denotes DN=1.5 while the dashed curve is for DS =8.5.

From Figure 8 we see that the imposition of these joint noise and sharpness criteria results essentially in four regions as bounded by the dashed lines. The top left region constitutes a region of excessive noise, although meeting the sharpness criterion, while the top right region implies both excessive noise and lack of requisite sharpness: the bottom right region represents lack of sharpness, although the noise is satisfactorily low. Only within the bottom left region can both the sharpness and noise criteria be met simultaneously, thus defining the appropriate combinations of *ppi* and gray levels which may be used to stay within specification. Other practically appropriate sharpness and noise criteria can of course be readily imposed in the format of Figure 8, as required.

Summary and Conclusions

A review has been presented of the major advances over the past century or so that have led to the unified body now commonly referred to as *imaging science*. In particular, the pioneers associated with the more significant historical advances have been identified within this historical context. These advances came from within a wide variety of applied fields, and covered a highly diverse set of imaging problems spanning many recording, printing and display technologies. Nevertheless … and in hindsight unsurprisingly … due to constraints and limitations imposed by the common laws of nature and their encapsulation in theories relating to detection, information, human vision, and so on, this unified body of science has the benefits not only of absolute rigor but also of immediate practical utility.

Some of the more simple and general results have been used here to illustrate the imaging science approach to the analysis and description of printing systems, and in this way it has been demonstrated how the fundamental limitations to image sharpness and noise are imposed in a closely-related way by the inherent parameters relating to *dpi* and gray levels.

References

1. G. B. Airy, *Trans. Camb. Phil. Soc.,* **5**, 283 (1835).
2. Lord Rayleigh, *Phil. Mag.,* **8,** 261 (1879).
3. K. Strehl, *Z. fur Instrumentenkunde,* **22**, 213 (1902).
4. F. Hurter & V. C. Driffield, *J. Soc. Chem. Ind.,* **9**, 455 (1890).
5. P. G. Nutting, *Phil. Mag.,* **26**, 423 (1913).
6. L. Silberstein, *Phil. Mag.,* **44**, 257 (1922).
7. H. Siedentopf, *Physik Zeit.*, **38**, 454 (1937).
8. P. M. Duffieux, *L'Integrale de Fourieret ses Applications a l'Optique*, private publication, Rennes, 1946.
9. H. Frieser, *Kinotechnik,* **17**, 167 (1935).
10. H. Frieser, *Photographic Information Recording,* Focal Press, London, 1975.
11. O. H. Schade, *Nat. Bur. Stands. Circular* **526** (1954).
12. O. H. Schade, *J. S.M.P.T.E.*, **73**, 81 (1964).
13. E. H. Linfoot, *Fourier Methods in Optical Image Evaluation* Focal Press, London, 1964.
14. N. Wiener, *Acta Math.,* **55**, 117 (1930).
15. P. B. Fellgett, *J. Opt .Soc. Amer.*, **43**, 271 (1953).
16. R. C. Jones, *J. Opt .Soc. Amer.*, **45**, 799 (1955).
17. H. J. Zweig, *J. Opt .Soc. Amer.*, **46**, 805 (1956).
18. A. Rose, *J. S.M.P.T.E.,* **47**, 273 (1946).
19. P. B. Fellgett, *J. Opt .Soc. Amer.*, **39**, 970 (1949).
20. R. C. Jones, *Nature,* **170** 937 (1952).
21. A. Rose, *Vision, Human and Electronic,* Plenum Press, New York (1974).
22. R. C. Jones, *Advances in Electronics and Electron Physics,* **11**, 87 (1959).
23. P. B. Fellgett, *J. Photogr. Sci,* **9,** 201, (1961).
24. H. J. Zweig, *Photogr. Sci. Eng.*, **5**, 142, (1961).
25. R. Shaw, *J. Photogr. Sci,,* **11,** 199, (1963).
26. J. C. Dainty & R. Shaw, *Image Science,* Academic Press, London, 1974.
27. C. E. Shannon, *Bell Syst. Tech. J.,* **27**, 379 (1948).
28. P. B. Fellgett & E. H. Linfoot, *Phil. Trans. Roy. Soc*., **A 247**, 369, (1955).
29. L. Brillouin, *Science and Information Theory,* Academic Press, New York, 1961.
30. M. Tribus & E. C. McIrvine, *Scient. Amer.* **224**, #3, (1971).
31. J. H. Altman & H. J. Zweig, *Photogr. Sci. Eng.,* **7**, 173, (1963).
32. C. L. Fales, F. O. Huck and R. W. Samms, *Appl. Opt*., **23**, 872 (1984).
33. P. Mertz & K. Gray, *Bell Syst. Tech. J.*, **13**, 464 (1934).
34. O. H. Schade, (a) *J. S.M.P.T.E.,* **64**, 593 (1955). (b) *Image Quality: a Comparison of Photographic and Television Systems*, RCA Labs, Princeton NJ, 1975
35. A. Robinson, *Appl. Opt*., **12**, 2344 (1973).
36. F. D. Huck, N. Halyo & S. K. Park, *Appl. Opt*., **19**, 2174 (1980).
37. D. Kermish & P. G. Roetling, *J. Opt .Soc. Amer.,* **65**, 716 (1975).
38. J. P. Allebach & B. Lui, *J. Opt. Soc. Amer.*, **66**, 909 (1976).
39. R. Shaw, *J. Appl. Phot. Eng*., **1**, 1 (1975).
40. R. Shaw, P. D. Burns & J. C. Dainty, *SPIE Proc*, **310**, 137 (1981).
41. R. Shaw, *IS&T Procs **NIP 12***, 162 (1996).
42. R. Shaw, *IS&T Procs **NIP 13***, 562 (1967)
43. R. Shaw, *IS&T Procs **NIP 14***, 582 (1968)
44. R. Shaw, *IS&T Procs **NIP 15***, 446 (1999).
45. R. Shaw, *IS&T Procs **NIP 17***, 705 (2001)
46. R .Dooley & R. Shaw, *J. Appl. Phot. Eng.,* **5**, 190 (1979).

Biography

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