Concepts, Terminology, and Notation for Optical Modulation

In the early 1960s, the National Bureau of Standards aided the photographic and printing industries by conducting research on precise measurement of optical transmission and reflection density, providing physical standards to calibrate instruments, and writing national and international documentary standards on optical density measurement. Optical density is a logarithmic measure of the darkness of a photograph or printed image. Although the science was hardly new, it suffered from loose concepts and imprecise terminology. The same problems were encountered in photometry, radiometry, colorimetry, and spectrometry. This publication [1] represented a major step forward in removing the confusion and promoting the use of precise concepts in optical measurements.

Physics textbooks defined "reflectance" as the ratio of the amount of light reflected from a surface to the amount of incident light. Workers who said they were measuring reflectance actually measured the ratio of the amount of reflected light to the amount of light reflected from a standard diffuse white surface. They generally regarded the measurement of the light reflected from the white surface as merely a convenient way of measuring the incident light. There was no generally accepted terminology to distinguish these two kinds of measurements. The concepts thus were blurred.

The degree of confusion may be illustrated by an example. Light incident on white paper is diffusely reflected in all directions, only a minute fraction being reflected to the pupil of the eye. The ratio of the amount reflected *in that direction* to the amount incident is a very small number, perhaps under 0.001. On the other hand, the ratio of the amount *reflected in that direction* to the amount reflected *in the same direction* from a standard diffuse white surface may be as much as 0.9. These are two different concepts—two different physical quantities, with vastly different numerical values. Such considerations led to a thorough analysis of the basic concepts and terminology in this field. The term "reflectance" was retained for the concept defined in textbooks. The measurement relative to a white standard was called "reflectance factor." That term is now used internationally in photography, printing, and color science.

Considerations of transmission measurements had even more important consequences. The textbook definition of "transmittance" is the ratio of the amount of transmitted light to the amount of incident light. The most important applications of transmission are motion-picture projection, slide projection, projection printing (enlarging), and the viewing of x rays and other transparencies on viewing boxes. A projector forms an image on a screen because the film absorbs or scatters some light, so the illumination at each point is some fraction of what it would be without the film. It might appear that one would need no more than the concept "transmittance" to quantify this process. However, some projectors were made to view microfilm images that scattered light. The light source was moved to one side, so the light beam passed through the film gate but was not directed toward the projection lens. With no film in the gate, the screen was dark. When film was inserted, some light was scattered in the direction of the projection lens and the screen became brighter. In *Concepts, Terminology, and Notation* McCamy defined "transmittance factor" as the ratio of the screen luminance with the film in place to the screen luminance without film. The concept called "transmittance factor" had not been previously differentiated from "transmittance." In the projector just described, the transmittance factor would be much greater than one. By definition, transmittance cannot be greater than one. "Transmittance" and "transmittance factor" are different concepts—two different physical quantities, with different numerical values.

There was no generally accepted collective term for ratios such as those describing reflection, transmission, or some combination of them, so the general term "modulation" was introduced, based on the idea that objects modulate the flow of light. The combination of light source and optics directing light to a specimen was called an "illuminator" or "irradiator" and the optical system collecting and evaluating the light reflected or transmitted in a specified direction was called a "receiver." Light flowing from an illuminator to a specimen was called "influx" and that evaluated by the receiver was called "efflux." A guiding principle was that the physical quantity measured was a function of the ratios measured *and* of the geometrical and spectral specifications of the illuminator and receiver. A well-known mathematical notation signifying a functional relationship was extended and formalized to provide a compact notation describing the geometrical and spectral conditions for such measurements.

Perhaps the most important contribution of this paper was the adoption of the fundamental "principle of simulation": To measure optical modulation, the geometrical and spectral conditions of measurement must simulate the geometrical and spectral conditions for the use of the modulation. Before this analysis, the standard method of measuring the optical density of a film was to measure the amount of light entering the entrance port of an integrating sphere and then measure the amount entering the sphere with the film covering the entrance port. This method assured purists that all the transmitted light would be measured. NBS provided precise calibrations by this method, relating the optical modulation to the inverse-square law of illumination. In practical densitometers the bulky integrating sphere was replaced with a piece of diffusing opal glass. At low values of density, it was impossible to correlate the standard sphere density with opal-glass density because there were interreflections between the film and the white opal glass. The principle of simulation demanded an answer to the question: "What is the use of the calibrated standards?" In this case they were used to calibrate densitometers. The physical quantity being calibrated so precisely was not the physical quantity being measured in practical applications. Either the calibration procedure had to be changed or the practical instruments had to be upgraded. Again applying the principle of simulation, it was realized that when a film was used for photographic contact printing there were interreflections between the film and the white printing paper. When films, such as x rays, were viewed on a viewing box, there were interreflections between the film and the diffuse illuminator screen. The practical opal-glass densitometers were measuring exactly the right physical quantity, so the "ideal" standard sphere method was abandoned and the opal-glass method was standardized. The same approach led to the development of the standard method of measuring projection density, using geometry simulating practical projectors. Great accuracy and precision are useless if the basic concept of the quantity to be measured is wrong [1].

During this analysis, McCamy was Chairman of the Densitometry Subcommittee of the American Standards Association, which later became the American National Standards Institute. The subcommittee was a sounding board during the work, so the whole system was readily adopted as a national standard [2]. That national standard was equally endorsed by the International Organization for Standardization (ISO), in an international standard [3]. The color measurement community recognized the need for a term and readily adopted "reflectance factor," but the rest of the terminology was only gradually assimilated and the system of notation was eventually standardized by the Committee on Color and Appearance of the American Society for Testing and Materials (ASTM) [4,5]. Further parts of the system are being adopted in the current revision of the International Lighting Vocabulary of the International Commission on Illumination (CIE) [6]. A method of greatly simplifying the geometric notation by reference to conical geometry, introduced in this paper, was called "McCamy's conical method" and recommended by later authors at NBS/NIST [7]. The paper was reprinted in NBS Special Publication 300, *Precise Measurement and Calibration,* Volume 7, *Radiometry and Photometry* [8] and Volume 10, *Image Optics* [9].

Calvin S. McCamy was born in 1924, received a B.Ch.E. in Chemical Engineering and an M.S. in Physics at the University of Minnesota. He taught there

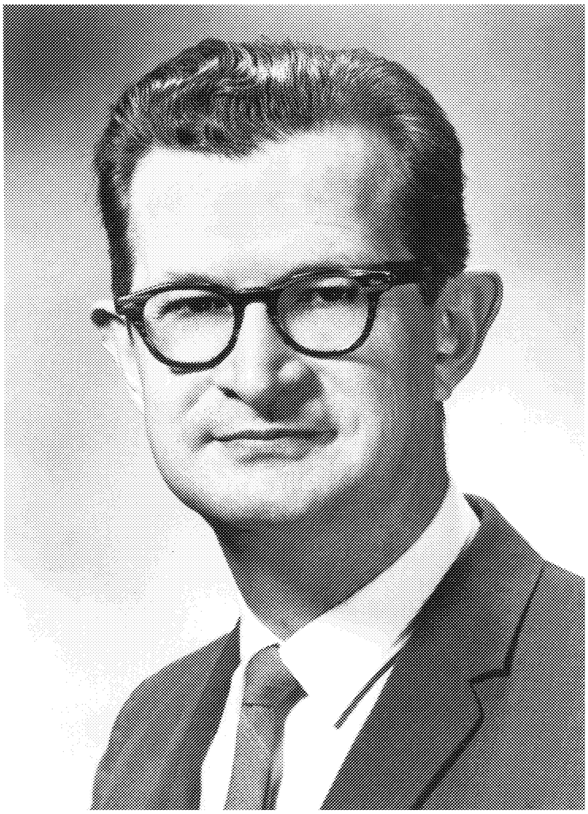

Fig. 1. Calvin S. McCamy at about the time *Concepts, Terminology, and Notation for Optical Modulation* was published.

and at Clemson University and then joined the Fire Research Section of NBS (1958-1964) and subsequently served as Chief of the Photographic Research Section (1958-1964) and Chief of the Image Optics and Photography Section (1964-1970).

In the Photographic Research Section and later the Image Optics and Photography Section, he designed a nomograph to compute the color filter required to take well-balanced colored pictures with a given film and illumination [11]. It was made available on a single sheet from the U.S. Government Printing Office or NBS and was very popular with amateur and professional photographers. It was the subject of many feature articles in popular and professional photographic magazines and became a common feature of color filter catalogs.

When demonstrations by Edwin Land led to widespread speculation that cheaper and better color television could be possible by using two primary colors rather than three, McCamy demonstrated to the Federal Communications Commission that a two-color system was not acceptable. That lecture-demonstration, by means of three projectors, allowed people to witness many visual phenomena. It generated such widespread interest that he was invited to present it fifty times at NBS, major universities, major industrial research laboratories, and scientific society meetings in 1959-1961 [12]. Among other phenomena, he demonstrated that under certain conditions, people perceive colors in black-and-white images. He was invited to repeat that lecture-demonstration forty years later, in February 2000 [13].

Photographic wedges are widely used in photographic science. The wedge may be straight, the density varying linearly with length, or it may be circular, the density varying linearly with rotational angle. Since density is the logarithm of the reciprocal of transmittance, the transmittance varies logarithmically. When the density is gradually changing and is measured over a finite area, it is difficult to know where on the wedge the actual density value is measured. Some finite area is required for measurement. NBS could measure uniform areas precisely, but wedges could not be calibrated because the required theoretical relationships were unknown. McCamy derived the mathematical relationship between the measured density and the location to which it may be assigned, for a rectangular aperture on a straight wedge, a circular aperture on a straight wedge, a sector aperture on a circular wedge, and a circular aperture on a circular wedge [14]. The last case was commonly encountered and, for that case, the mathematical derivation was remarkably complex.

McCamy also designed the resolution target used internationally to test microfilm cameras, and his laboratory made as many as 25,000 per year as standard reference materials for the industry. He designed and provided other test targets to calibrate instruments used to measure the image structure characteristics of optical and photographic systems. He developed a laboratory camera to measure how much information a photographic film or plate could record on a given area. Scientists involved in manufacturing electronic components came to the Bureau to study the camera, and the general features of it came into widespread use in the production of tiny electronic components. McCamy derived a formula to compute the information storage capacity of a photographic system, in bits per square millimeter, from the measured resolving power [15]. All these activities supported the development and utilization of the U.S. satellite reconnaissance system, which was highly classified during the cold war.

When it was discovered that the vast stores of federal and state government records on microfilm were developing blemishes that might destroy vital archival information, McCamy mustered the support of many government agencies and many private interests to conduct a wide-ranging investigation. His laboratory discovered the cause of the blemishes. The microfilms were stored in cardboard boxes and the aging cardboard emitted minute amounts of hydrogen peroxide, which attacked the film. The task was difficult because the concentration of peroxide was less than 10^{-9} mol/L and the molecules were so labile that they were dissipated on passing through two centimeters of air [16-19].

As Vice President for Research of the Macbeth Division of the Kollmorgen Corporation in 1970–1990, after leaving NBS, McCamy continued research on optical design, precise transmission measurements, color measurement, optical filter design, simulation of daylight for color inspection, geometric attributes of appearance, densitometry in photography and color printing, color order systems, color standards, and related mathematics. He substantially improved the classical absolute method of photometry based on the inverse-square law of illumination, and he designed the Macbeth ColorChecker Color Rendition Chart$^{\text{TM}}$, which is used internationally to evaluate color-imaging systems. At the request of Congress in 1978, he analyzed all known photographs and x rays related to the assassination of President Kennedy and testified before the House Select Committee on Assassinations. His method of analyzing images of long firearms is used routinely by the U.S. Federal Bureau of Investigation. He continued to be active in national and international standardization of photography, color printing, and color science, chairing committees of the American National Standards Institute, the American Society for Testing and Materials, the International Commission on Illumination (CIE), and the International Organization for Standardization (ISO). He wrote the spectral specifications for optical character recognition for the banking industry and the Universal Product Code for the grocery and other retail industries.

He is on the Advisory Board of the Munsell Color Science Laboratory at the Rochester Institute of Technology and was Adjunct Professor at Rensselaer Polytechnic Institute, President of the Kollmorgen Foundation, and Trustee of the Munsell Foundation. He was elected fellow of the Optical Society of America, Society of Photographic Scientists and Engineers, Royal Photographic Society of Great Britain, Society of Motion Picture and Television Engineers, and the Washington Academy of Sciences and has been honored for his lectures. He received the 1997 Bruning Award of the Federation of Societies for Coatings Technology and the 1999 Godlove Award of the Inter-Society Color Council.

Prepared by Calvin S. McCamy.

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