A Spectral Reflectance Measuring System which Corrects for Lateral Diffusion Error and Effects of Adjacent Surface Colors

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Abstract

Lateral diffusion error (LDE) is defined and the conventional methods of instrument configuration which minimize it are discussed. In 1999 it was discovered that the amount of light that laterally diffuses from an illuminated sample area to the adjacent unilluminated area is related to the spatial distribution of the light reflected by the illuminated area of the sample. A breadboard spectro-reflectometer which makes use of this relationship to correct for LDE has been built and test results are reported. Papers presented at the 2000 & 2001 TAGA meeting reported that printed colored areas adjacent to an unprinted area can affect the measured spectral reflectance value. This problem was attributed to bilateral diffusion of light between the area being measured and the adjacent printed colored area. The breadboard instrument was tested to determine if its capability to correct for LDE would result in correction of errors due to adjacent colors.

Introduction

Instrumental measurements of spectral reflectance, color, and density can be compromised by errors from a number of interactions of instrument components with the light reflected by the sample being measured.[1] Lateral diffusion errors[2-4] (LDE) can occur when translucent samples are measured and some of the illuminating light from the instrument diffuses laterally in the sample to locations outside of the area viewed by the instrument detection system. In some of the literature, LDE is referred to as translucent blurring error,[5] translucency error,[6] edge loss error,[7] and stray darkness.[8] Figure 1 gives a schematic illustration of an idealized 45°/0° geometry instrument in which the sample is illuminated by a beam of light incident at 45° from the surface normal and the detection system is viewing the illuminated area from above the sample (i.e. 0° from the sample surface normal). In this configuration, the light measuring system cannot detect the light that is diffused laterally beyond the common edge of the illumination and detector view areas. The light that diffuses beyond the area viewed by the detector represents the LDE - thus, the measured value reported by the instrument is the *true value*[9] less the light that has laterally diffused out of the area viewed by the detector.

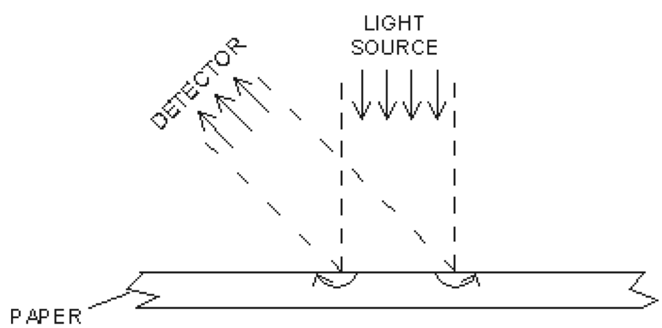

Figure 1.

The value of the LDE is a first order function of lateral penetration of light in the sample. In general, more translucent samples will have greater LDE when measured with a given instrument. Also, the backing of thinner samples can affect the LDE value - the LDE with a black sample backing is usually less than the LDE obtained when the same sample is measured with a white backing.The dimensions of the illuminated and viewed areas on the sample also affect the LDE value. For example, if the instrument uses circular illumination and viewing areas, the light not seen by detector is in an annular ring surrounding the circular area viewed by the detector. If the diameter of the illumination and viewing is doubled, the area of this annular ring roughly doubles and the area viewed by the detector quadruples. This result in the LDE being about one-half the values that it was with the smaller apertures. The ANSI[10] and ISO[11] standards defining the measurement geometries for photographic reflectance density functionally recognize the lateral diffusion error problem: they both specify that the illuminated area should be 2mm on the side larger than the area viewed. Most, if not all, densitometers used for measurement of photographic and printed materials do not meet these standards.[12] The method specified in the standards is normally termed "over-illumination". If the viewed area is larger than illuminated area, it is called "overviewing". Helmholtz optical reciprocity, as defined in a paper by Clarke & Parry,[13] indicates that both methods are equivalent. Note that both methods are "passive" in that the reduction of LDE as a function of sample translucency is fixed by the instrument apertures.

Most real world 45°/0° and 0°/45° instruments use some sort of annular illumination or viewing. This reduces the sensitivity to any grain or other azimuthal non-uniformities on the sample surface. As a sample is moved away from the port of a 45°/0° instruments which employs annular illumination, the area illuminated increases and the edge of the illuminated area begins to dim. When the sample is at a distance of about one quarter of the normal illumination diameter, there is a noticeable bright spot in the center of the lighted area. As the sample is moved further away, this bright spot decreases in diameter and the diameter of the dimly illuminated area increases. When the sample is at a distance of about one-half the diameter of the illumination aperture, this bright spot disappears. With further movement, a dark spot develops at the center. When the sample is brought to a distance equal to the normal, on-port, illumination diameter, this dark spot is approximately the same diameter as the illumination aperture. A function of the values measured on-port and at some constant off-port distance can be related to the LDE.[14]

A 1996 paper[15] described implementation of this method for correcting LDE. In this work, samples of various translucencies were measured with a Byk-Gardner Color Machine (BGCM) equipped with a 4mm diameter illumination aperture and a 3mm diameter viewing aperture (hereafter termed a 4/3 configuration). This data was compared to measurement data taken with the instrument equipped with a 38 mm diameter illumination aperture and a 3 mm diameter viewing aperture (hereafter termed a 38/3 configuration) and the LDE for each sample was calculated. Next, a series of measurements were made using the 4/3 configuration with the samples moved back from the instrument port. Reflectance data from seven white samples of varying translucencies were then used to fit a function to 600 nm wavelength on-port and off-port measurements to the relative or normalized LDE (nLDE) of the seven samples. This function was then used to derive LDE corrected values for 4/3 measurements of 14 colored samples. The LDE corrected values for these samples were then compared to the 38/3 measurements of the samples. This correction procedure reduced the CIE L*a*b* color differences between the 4/3 and 38/3 data by 75% or more.

Papers presented at the 2000 and 2001 TAGA meetings,[16,17] illustrated that lateral diffusion can result in colored areas adjacent to the measured area affecting measured color value even though these areas are neither illuminated or viewed by the instrument. The 2001 paper further illustrated that the color of an instrument aperture plate or other part in contact with the paper surface can affect the measured value.

Making the Illuminated and Viewing Areas Identical

The over-illumination and over-viewing methods of LDE reduction and the on-port - off-port correction method all assume that the area adjacent to the area being measured is the same color as the measured area (e.g. if the over-illuminated area is a different color than the central area being viewed, the measured value will be affected). A LDE correction method which allowed the use of identical illumination and viewing areas would be more desirable than the present methods which require uniformity beyond the area being measured.

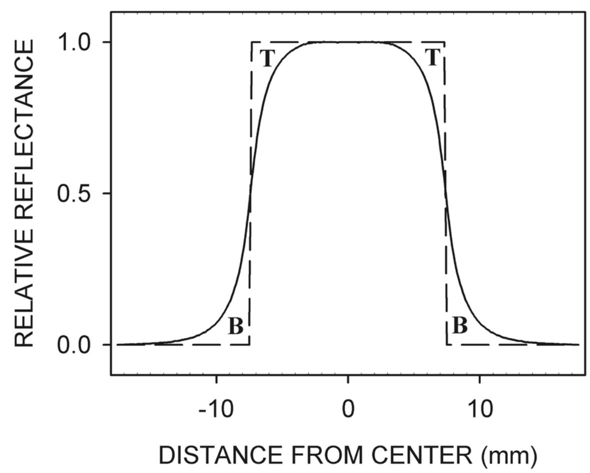

Figure 2. Narrow slit scan of a lighted area on a 0.1% TiO2 loaded polystyrene exhibit (solid line) compared to an idealized scan of an opaque exhibit (dashed line).

A paper presented at the 1999 TAGA meeting in Vancouver, BC,[18,19] discussed the relationship of the spatial distribution of the light reflected from the illuminated area of the sample to the light that diffused out of the illuminated area into the surrounding unilluminated area. Figure 2 is a plot of data derived from a narrow slit scan of an approximately 15 mm wide lighted area on a black backed polystyrene chip loaded with 0.1% rutile TiO_2. (Note that this data was modified to compensate for measurement differences caused by small non-uniformity in the illuminating source.) The lighted area was measured at 0.1 mm intervals with a 0.75 mm vertical slit focused on to an integrated filter (540 nm center wavelength and eight nm bandwidth) and silicon photodiode. The solid plot line shows the peak normalized results of this scan. The dashed line curve is what the scan would have looked like if the sample had exhibited little or no lateral diffusion. The areas marked **T** represent the amount of light that laterally diffused out of the lighted area into the unlighted area of the sample. The areas marked **B** represent the amount of light that was lost from the lighted area in the lateral diffusion process. Note that the **B** areas are exactly equal in size and, when rotated, in shape to the **T** areas. The normal method for getting the true value of the reflectance of the sample would be to make the aperture of the detector system large enough to see all of the light coming from the **B** areas.

On the basis of this data, an alternative method for getting the true value would be to make the area viewed by the detector equal to that of the illuminated area and then make a second measurement which would determine a value for the **T** areas. The two measurements could then be added together to get the correct reflectance value. While there is no simple way of measuring the value of the **T** areas, it is possible correlate the value of the **B** areas, which are equal to the **T** areas, to the difference of measurements made at the center and inside edges of the lighted area. To get data for this correlation, a 45°/0° narrow spectral band (540 nm with 8 nm bandwidth) reflectometer using single beam illumination was set up on an optical bench. Seventeen samples of various translucencies were measured using 38 and 8 mm diameter illumination and 8 mm viewing. The differences between the measurements made with the 38 and 8 mm illumination gave a LDE_{38-8} for each sample. Each of these values was divided by the 38 mm illuminated reflectance to give a relative or normalized LDE value which is designed as nLDE. Next, light viewed from the surface normal of each sample illuminated with 8 mm diameter lighting was focused onto a fiber optic assembly which consisted of a center circular bundle and a ring bundle surrounding the center bundle. The two bundles had approximately equal areas. The center bundle viewed a circular area of the sample approximately 4.6 mm diameter and the ring bundle viewed a ring area on the sample with an 8 mm OD and a 6.5 mm ID (a ferule in the fiber bundle assembly separated the center bundle from the ring bundle; this resulted in the ID of the area viewed by the ring being approximately 1.1 mm greater than the diameter of the center bundle). For reference, the center bundle in the fiber optic assembly is designated C and the ring bundle is designated R. Measurements of the light from each of these bundles for each of the samples were adjusted using the measured values of the relatively opaque Chrome Green pigmented plastic plaque (Opal glass, which is often used as a reflectance reference for instrument calibration was previously found to be too translucent for use in the determination of LDE[20]).

Figure 3 is a graph of the normalized difference between the center and ring bundle, (C-R)/R, for each of the eighteen samples plotted against the nLDE. The solid curve on the graph is a fit to the set of data. The curvature in the fitted curve results from the center bundle viewing some of the reflectance fall off area in samples with greater translucency.

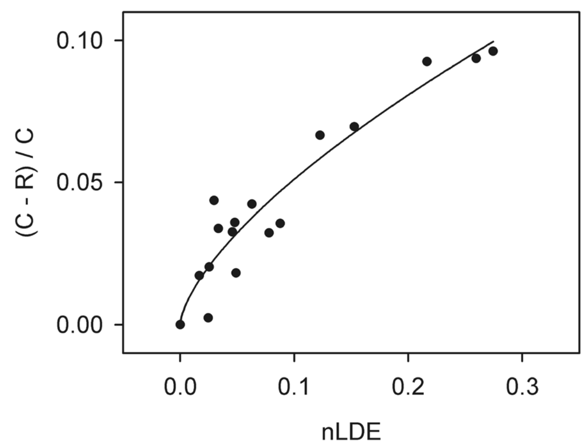

Figure 3. Measurements of 17 samples with the two channel detector system. Plot is the relative LDE versus the normalized center to ring values of the measurements. The solid line curve is a three parameter fit to the data.

A Spectral Reflectometer which Uses Spatial Distribution LDE Correction

A breadboard spectral reflection measuring instrument was built to test the validity of this LDE correction method. The measuring head from a BGCM was used to provide annular 45° illumination. The sample area illuminated is defined by a circular aperture plate. The normally used viewing fiber bundle has been removed from the head and replaced with a lens and a fiber optic assembly which views a 4mm diameter area on a sample placed face down on the aperture plate. The fiber assembly consist of <u>three</u> components, a center bundle, C, surrounded by two concentric rings, an inner ring, I, and an outer ring, O. A 45° prism and stepping motor assembly allows the output ends of the bundles to be sequentially viewed by the grating-diode array detection system of a BGCM. The calibration of the channels is accomplished by measuring a $BaSO_4$ pressed pellet using a 31mm illumination aperture. Appropriate procedures are employed to minimize the effects of light source and detector drift on the measured values.

The nLDE for each sample is determined by first summing the three measurement values at each of 35 wavelength bands for the 4mm illumination. These values are then compared to similar data obtained using 31mm illumination and the spectral LDE is determined. These LDE values are then normalized using the 31mm reflectance. A normalized spatial distribution value at each wavelength for the sample is determined by subtracting the two ring reflection value from two times that of the center bundle and dividing the result by two times the center bundle value (i.e. (2*C-IO)/2*C). Thirty-one sets of measurements of samples with black backing were made and the nLDE and spatial function for each sample set at each of the 35 wavelengths was calculated from the reduced data. Point plots of the results for 450, 550, and 650nm were made and a linear regression function was derived from each plot.

Figure 4 is a point and regression plot of the 550nm data (note the axes are different from those of figure 3 – nLDE is now the vertical axis). The regression parameters derived from this 550nm data along with the parameters from the 450 and 650nm data were used with the 4mm illumination spectral reflectance of each sample to compute LDE corrected reflectances. Figure 5 gives an example plot of the 4mm, 31mm, and LDE corrected reflectance curves of HP Brochure & Flyer matte finish inkjet paper.

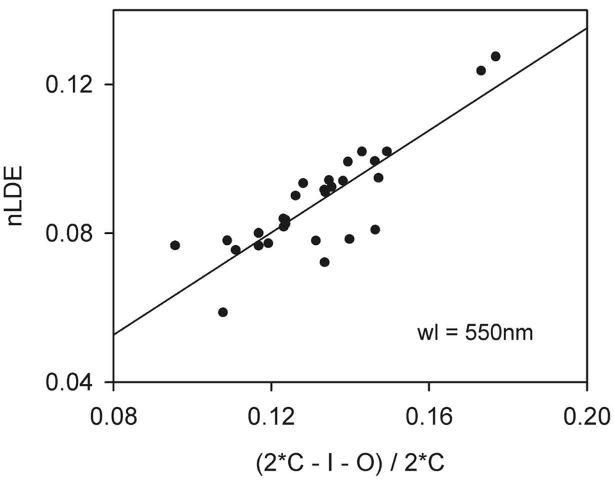

Figure 4.

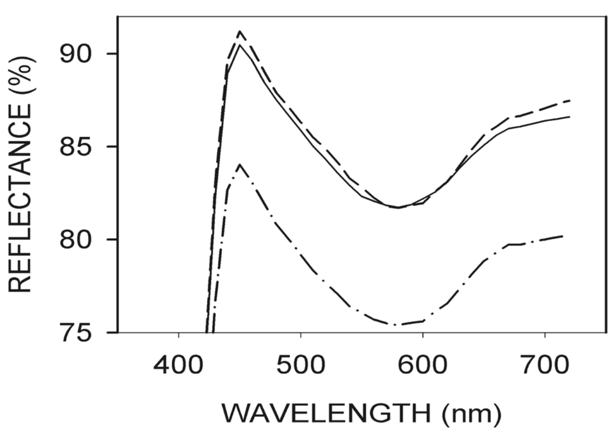

Figure 5. Corrected reflectance (upper dashed line) compared to 31mm illumination reflectance (solid line) and 4mm reflectance (lower dot-dashed line)

The process of computing the corrected reflectance was accomplished by first deriving linear regression parameters for each wavelength by combining the parameters obtained from the 450, 550, and 650nm. In particular, for wavelengths from 380 to 450nm the regression parameters for 450nm were used. Likewise, for wavelengths from 650 to 720nm, the 650nm parameters were used. The parameters for wavelengths between 450 to 550nm were derived by combining the 450 and 550nm parameters with a linear weighting based on the distance of the wavelength from 450 and 550nm points. The parameters for wavelengths between 550 and 650nm were derived from the 550 and 650 parameters in a similar manner. This resulted in a set of regression parameters for each of the 35 wavelengths between 380 and 720nm. These parameters were used to calculate a set of 35 nLDE values from the measured wavelength by wavelength spatial functions for the sample. The corrected spectral reflectance values were then corrected from these nLDE values.

The table below gives the CLab D50-2 degree observer color differences for eleven paper samples:

Paper	$DE_{31\text{-}4}$	$DE_{31\text{-corrected}}$
duP inkjet	2.94	0.56
duP waterproof	3.13	0.24
HP brochure	2.91	0.32
HP premium	3.10	0.13
HP premium+	3.11	0.12
JetPrint photo	2.88	0.16
JetPrint ultra	2.83	0.19
Kodak ultima	3.45	0.14
Copier paper	2.71	0.07
Whatman #1 filter	2.82	0.41
70# TiO_2 paper	3.18	0.21
Average	3.01	0.23

Correcting Errors Caused by Colored Areas Adjacent to the Area Being Measured

Papers presented at the 2000 and 2001 TAGA annual meetings[16,17] demonstrated that adjacent printed colored area surrounding an unprinted paper area can affect the measured reflectance of the paper area. The papers attributed these effects to the bidirectional lateral diffusion of light within the body of the paper. If this is so, it would seem that a method which corrects for errors caused by the lateral diffusion of light should also correct for errors caused by adjacent colors.

To test this, targets were printed which had a center circular unprinted area surrounded by a 100% yellow printed area. Three targets with center areas 6, 8, and 10mm in diameter were printed on duPont inkjet (D), JetPrint Ultra(J), and Whatman filter(F) papers. Each of the targets was measured with the 4mm illumination aperture in place on the instrument. Measurements of the 8 and 10mm targets were also made at a point near the edge but within the unprinted area.

Figure 6 is a graph of the 4mm illumination reflectance of Whatman filter with no surround (solid line) and of a 6mm diameter white area with yellow surround (dashed line). The effects of the short wavelength light absorption by surrounding yellow is clearly apparent.

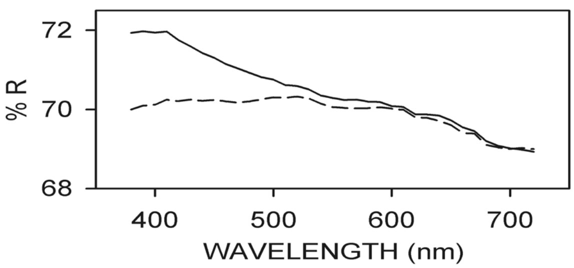

Figure 6.

A total of 15 measurements were made on the 9 targets. The table below gives the Clab color differences of the 4mm illuminated target white/yellow surrounded areas vs the 31mm illuminated plain paper (DE_{Y4-31}) and the LDE corrected 4mm illuminated target white/yellow surrounded areas vs the 31mm illuminated plain paper ($DE_{Y4CORR\ 31}$) :

SAMPLE	DE_{Y4-31}	$DE_{Y4CORR-31}$
D-6Y	4.02	0.98
D-8Y	3.85	0.67
D-8Y-OFF-1	3.94	0.65
D-10Y	3.84	0.32
D-10Y-OFF-2	3.50	0.40
F-6Y	2.96	0.90
F-8Y	2.84	0.80
F-8Y-OFF-1	2.62	0.88
F-10Y	3.44	0.32
F-10Y-OFF-2	3.39	0.37
J-6Y	3.50	0.99
J-8Y	3.52	0.66
J-8Y-OFF-1	3.48	0.36
J-10Y	4.58	0.64
J-10Y-OFF-2	4.73	0.70
AVERAGE	4.02	0.98

In this table, the sample paper stock is designated by first letter; the second term (number and letter) designates the diameter of the white area and surrounding color; the OFF and number, when present, indicates that the measurement was made one (OFF-1) or two (OFF-2) millimeters off from the center of the white area.

Discussion

Even though the data taken with this breadboard measuring system is somewhat noisy, it shows that the algorithm used to correct for LDE is useful. This work demonstrates that it may be possible to design a colorimeter or densitometer which can illuminate and view a 4mm area of a 5mm square print control strip and obtain measured values that are corrected for LDE and adjacent color effect errors.

The work reported in the 2001 TAGA paper showed that an instrument aperture plate in contact with the sample surface can cause measurement errors similar to those caused by adjacent colors printed on the surface of the paper. In this demonstration, a Gretag SPM-100 was used in the normal manner to measure a paper sample. Next, an adhesive label coated with yellow ink and with a hole slightly larger than the aperture plate aperture was affixed to the bottom side of the instrument aperture plate and a second measurement of the paper was made. The first measurement data was subtracted from the second measurement. Figure 7 is a plot of this difference. The effect of the yellow in contact with the paper surface is clear. Yellow was used in this experiment because it is easily identified on plots. No doubt the underside of the black aperture affected the measured value too! If the aperture plate was slightly removed (e.g. 5 or so micrometers) from the sample surface, the measured value would be different. Thus, it can be surmised that the degree of optical contact, as modified by surface roughness or curvature, can affect the measured value. It may be furthered inferred that with translucent samples, the degree of optical contact between the back of the sample and the typical black backing can modify the measured value.

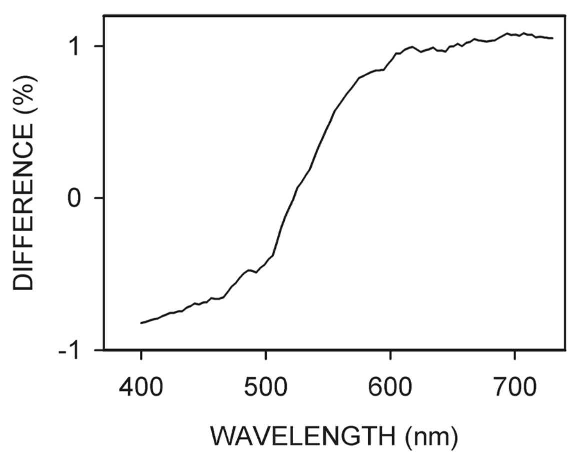

Figure 7.

Admittedly, much of the noise in the data taken with this breadboard instrument setup comes from inadequately compensated temporal variations in the light source intensity and photometric systems sensitivity. However, some amount comes from variations in the degree of contact between the sample surface and the surface of the 4mm aperture plate.

Ongoing Work

The Byk-Gardner color machine automatically does a zero and white standard calibration every time that it makes a measurement. At present, the breadboard instrument does not have this capability. The inclusion of additional optical components in the instrument head has prevented mounting of the motor which moves the calibrator components into position for automatic calibration readings. Within the next month or so, the measurement head will be modified to accommodate the parts which will allow automatic calibration with each measurement.

The process of measuring sample reflectance with the present optical bench instrument involves running two computer programs under control of a QuicKeys script. Once the data is logged, the reduction process involves six or so manually initiated operations with a spread sheet/plotting program. These processes in total can often be subject to equipment malfunctions and operator inattention. An upgrade effort is underway to integrate all of these manual operations into an automated, computer controlled, system. Once this effort is completed, it will be possible to readily observe the effects of changes to the correction algorithm and optical design changes on a near real-time basis.

Some method is needed for insuring that all samples have the same degree of optical contact with the aperture plate. It seems that keeping the sample off of the plate a very small distance may be the best solution. Pressurizing the measurement head so that the sample floats on a cushion would be a possible solution, but this would require sealing the measurement head assembly. At present, using a porous vacuum plate to hold the sample flat with 5 or so micrometer spacers at the outside edges of the aperture plate seems the most appropriate interim solution.

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Biography

David L. Spooner received a BSEE from Washington University, St. Louis in 1953 and was registered as a PE (professional engineer) in Ohio in 1957. He has worked extensively in the development of governmental and industrial electronic and optical instrumentation and data analysis. Early in his career he participated in the ARPA Vela-Uniform program where he investigated the use of spectral remote sensing to detect underground nuclear tests. At Lockheed, Houston, he was associated with the NASA Apollo program where he used the lunar goniophotometric properties to derive lunar cartography from Lunar Orbiter photography and did exact lighting simulations for lunar landing training. He joined the DuPont Pigments department in 1973 to work on the development of computer color matching techniques and the evaluation of pigmented products. During the four years prior to his retirement by DuPont in 1994, he was engaged in the measurement and modeling of the color of prepress proofing and printed products. He is presently associated with rhoMetric Associates, Ltd., where he consultants on the measurement and application of color and appearance data. His most recent work has included design of automated scanning color measuring systems and development of a method for correction of lateral diffusion error. He has eight U. S. patents and a ninth applied for. Since his retirement he has on average presented two papers at technical each year.