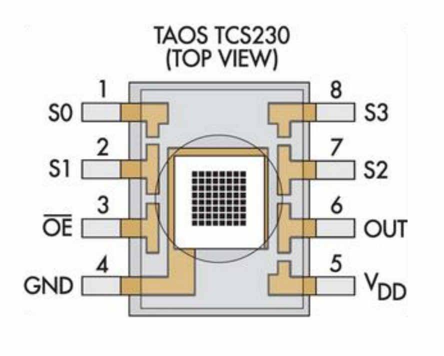
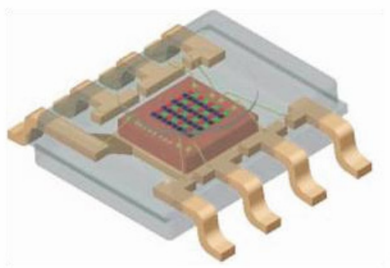
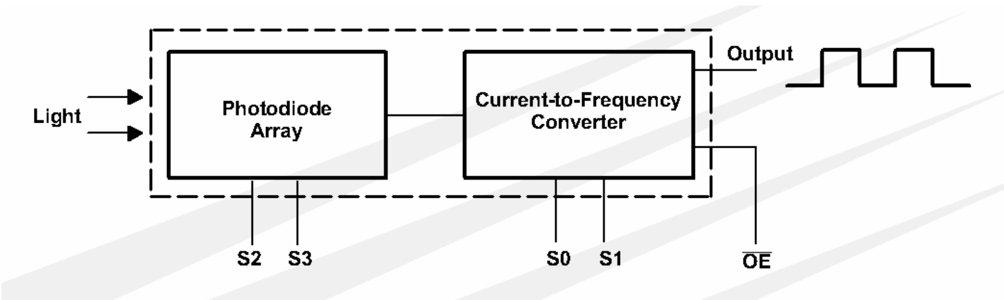
อุปกรณ์ตรวจวัดค่าสี

(color light-to-frequency converter)

ET-TCS230 เป็นผลิตภัณฑ์ที่ได้นำเอาอุปกรณ์เซนเซอร์ตรวจวัดค่าระดับความสว่างของสี คือ TCS230 ซึ่งอุปกรณ์ตัวดังกล่าวนี้สามารถที่จะเปลี่ยนแปลงค่าความสว่างของสีที่มาตกกระทบตัวมันให้ออกมาเป็นสัญญาณ-ความถี่เอาต์พุต สี่เหลี่ยม (Square wave) โดยมีค่า duty cycle เป็น 50% ซึ่งความถี่เอาต์พุตดังกล่าวจะมีผลความสัมพันธ์โดยตรงกับค่าความสว่างของสีที่มาตกกระทบตัวเซนเซอร์ โดยโครงสร้างของ TCS230 นั้นจะประกอบไปด้วย โฟโต้ไดโอดขนาด 8x8 ตัว ซึ่งมีการจัดเรียงกันแบบ อาร์เรย์ โดยโฟโต้ไดโอดเหล่านี้จะแบ่งออกเป็น 4 กลุ่มด้วยกัน คือ โฟโต้ไดโอดที่มีฟิลเตอร์ สีแดง (Red) , เขียว (Green) , น้ำเงิน (Blue) และ แบบไม่มีฟิลเตอร์ (Clear) จำนวนชุดละ 16 ตัว ซึ่งแต่ละกลุ่มก็จะตอบสนองต่อสนองต่อความสว่างของสีแตกต่างกันไปตามแต่ชนิดของฟิลเตอร์นั้นๆ



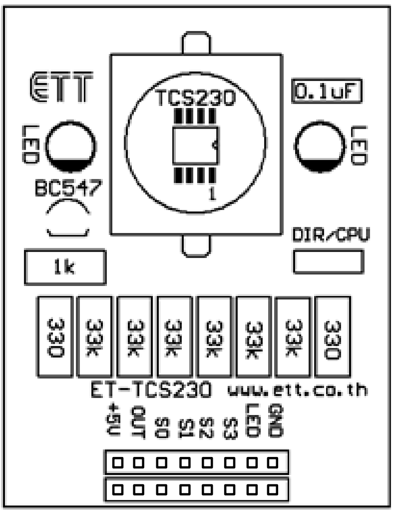




จากรูปบล็อกไดอะแกรม แสง(Light) จะเข้ามาตกกระทบที่โฟโต้ไดโอด (Photodiode Array) ซึ่งเราสามารถเลือกชนิดฟิลเตอร์ของโฟโต้ไดโอด ได้จากขาสัญญาณ S2 และ S3 โดยผลที่ได้จะอยู่ในรูปของกระแสไฟฟ้า และ จะถูกส่งไปยังภาค Current-to-Frequency Converter เพื่อทำหน้าที่แปลงกระแสไฟฟ้าให้เป็นสัญญาณความถี่ออกไปที่ขาสัญญาณ Output โดยมี S0 และ S1 เป็นตัวกำหนดช่วงของสัญญาณความถี่ที่เราต้องการ ส่วนขาสัญญาณ OE ทำหน้าที่ควบคุมการ Enable และ Disable ของสัญญาณ Output ซึ่งจะแอคทีฟที่สัญญาณลอจิก “0”

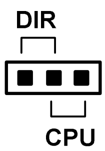
คุณสมบัติบอร์ด ET-TCS230

- ให้ค่าความละเอียดของผลลัพธ์สูง (ค่าจากการแปลงความเข้มของแสงไปเป็นความถี่ fo)
- สามารถโปรแกรมเลือกตรวจวัดค่าสีจากฟิลเตอร์ (RED, Green ,Blue และ Clear) ตามต้องการ และ กำหนดกระดับสัญญาณของเอาต์พุต fo (Frequency Output) ได้
- สามารถทำการเชื่อมต่อสัญญาณต่างๆ เขากับไมโครคอนโทรลเลอร์ได้โดยตรง
- ทำงานที่แรงดัน 2.7 V ถึง 5.5V
- TCS230 เป็นชิพที่มีคุณสมบัติกินกำลังงานต่ำ
- ค่าความคลาดเคลื่อน 0.2% ที่ความถี่ 50kHz
- มีหลอดไฟ LED สำหรับทำการสะท้อนสีของวัตถุ



รายละเอียดของบอร์ด

- DIR/CPU เป็นจัมเปอร์สำหรับเลือกการทำงานของหลอดไฟ LED ซึ่งมีหน้าที่ในการสะท้อนแสงสีของวัตถุมายังเลนส์ของตัวเซนเซอร์ TCS230 โดยสามารถเลือกได้สองลักษณะคือ

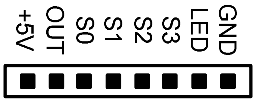


DIR = การเชื่อมต่อวงจร LED ให้ทำงาน (ติดสว่าง) ตลอดเวลาโดยไม่ต้องมีการควบคุมใดจาก CPU

CPU = คือ การควบคุมการทำงานของ LED ด้วย CPU หรือ ไมโครคอนโทรลเลอร์ภายนอก ซึ่งจะควบคุมที่ขาสัญญาณ LED ของคอนเนกเตอร์ 8 PIN

- **<u>ขาสัญญาณต่างๆ</u>**

จะถูกจัดเรียงเป็นคอนเนคเตอร์ขนาด 8 PIN โดยมีทั้งตัวผู้และตัวเมีย เพื่อความสะดวกในการต่อใช้งาน ซึ่งขาสัญญาณต่างๆ มีหน้าที่ดังนี้



- +5V คือ ขาสัญญาณไฟเลี้ยงแรงดันไฟบวก 5 โวลท์
- OUT คือ ขาสัญญาณเอาต์พุต โดยให้ค่าออกมาเป็นความถี่ (fo) เป็นรูปคลื่นสี่เหลี่ยม Duty cycle 50% ซึ่งค่าความถี่จะแปรผันตามค่าของแสงที่ตกกระทบ ชนิดของฟิลเตอร์
- S0 และ S1 เป็นขาสัญญาณเลือกระดับของสัญญาณความถี่เอาต์พุต (fo) โดยสามารถเลือกได้ 4 ระดับดังตารางต่อไปนี้

ตารางที่ 1 การกำหนดระดับสัญญาณความถี่เอาต์พุต (fo)

S0	S1	OUTPUT FREQUENCY SCALING (fo)
0	0	Power down (ไม่ผลิตสัญญาณความถี่)
0	1	2% (ความถี่ต่ำ)
1	0	20% (ความถี่ที่ 20%)
1	1	100% (ความถี่สูงสุด)

- S2 และ S3 เป็นขาสัญญาณที่ใช้เลือกชนิดของฟิลเตอร์ของโฟโต้ไดโอดที่เราต้องการอ่านค่าดังตารางต่อไปนี้

ตารางที่ 2 การกำหนดชนิดของฟิลเตอร์ของโฟโต้ไดโอดที่ต้องการวัดสัญญาณ

S2	S3	PHOTODIODE TYPE
0	0	แดง (Red)
0	1	น้ำเงิน (Blue)
1	0	ไม่มีฟิลเตอร์ (Clear : no filter)
1	1	เขียว (Green)

- LED เป็นขาสัญญาณที่ใช้ในการควบคุมหลอดไฟ LED ให้ติดสว่าง หรือ ดับ ทั้งนี้หากต้องการที่จะควบคุมการทำงานของ LED จากขาสัญญาณนี้จะต้องทำการเลือกจัมเปอร์ DIR/CPU มาอยู่ที่ตำแหน่ง CPU ด้วย จึงจะสามารถทำการควบคุมการทำงานของหลอด LED ได้

ตารางที่ 3 สรุปหน้าที่ของขาสัญญาณต่างๆของ IC TCS230

ขาสัญญาณ	I/O	คำอธิบาย
GND		Power supply ground
OE	Input	ขาสัญญาณ Enable สัญญาณความถี่เอาต์พุต (fo) ทำงานที่ลอจิก "0" โดยในบอร์ด ET-TCS230 ได้ทำการต่อ Enable ไว้ให้แล้ว
OUT	Output	ขาสัญญาณความถี่เอาพุต(fo) ที่เปลี่ยนแปลงตามค่าความสว่างของสี
S0,S1	Input	ขาสัญญาณอินพุต กำหนดระดับสัญญาณความถี่เอาต์พุต(สามารถดูรายละเอียดได้ในตารางที่ 1)
S2,S3	Input	ขาสัญญาณเลือกประเภทของ Photodiode หรือ สีของฟิลเตอร์ที่ต้องการ (สามารถดูรายละเอียดได้ในตารางที่ 2)
VDD		Supply Voltage

การนำไปใช้งาน

ขาสัญญาณ S0 และ S1 ได้มีการต่อตัวต้านทาน Pull-Up ไว้ (S0=1,S1=1) ซึ่งจะทำให้ระดับสัญญาณความถี่เอาต์พุตอยู่ในระดับ 100% อยู่แล้ว ซึ่งถ้าหากต้องการระดับสัญญาณที่ 100% ก็ไม่จำเป็นต้องต่อสัญญาณมาควบคุม (แต่ถ้าต้องการที่ระดับต่างๆจะต้องต่อสัญญาณมาควบคุมดูรายละเอียดในตารางที่ 1) ซึ่งขาสัญญาณที่จำเป็นต้องควบคุมก็คือขาสัญญาณ S2 และ S3 โดยวิธีการในการอ่านค่าสีจากตัวเซนเซอร์ดังกล่าวนี้สามารถทำได้โดยการเลือกฟิลเตอร์ของสีที่เราต้องการอ่านจากนั้นทำการนับสัญญาณความถี่ (fo) ที่ขาสัญญาณ OUT แล้วทำการเก็บค่าไว้ซึ่งควรจะทำการแยกเก็บตัวแปรออกเป็น 3 ตัวแปร คือ ตัวแปรเก็บค่าสี แดง (Red) , เขียว (Green) และ น้ำเงิน (Blue) ซึ่งสามารถสรุปตามตัวอย่างขั้นตอนต่างๆ ดังนี้

- ตัวอย่างขั้นตอนการอ่านค่าสี RGB

(1). กำหนดลอจิกให้กับ S0 และ S1 เพื่อกำหนดระดับสัญญาณความถี่เอาต์พุตในช่วงที่ต้องการ (ดูรายละเอียดจากตารางที่ 1)

(2). กำหนดลอจิกให้ **S2=0 , S3=0** เพื่อเลือกฟิลเตอร์สีแดง

(3). นับสัญญาณความถี่ที่ขาสัญญาณ OUT เก็บผลลัพธ์ลงตัวแปร Red_result

(4). กำหนดลอจิกให้ **S2=0 , S3=1** เพื่อเลือกฟิลเตอร์สีน้ำเงิน

(5). นับสัญญาณความถี่ที่ขาสัญญาณ OUT เก็บผลลัพธ์ลงตัวแปร Blue_result

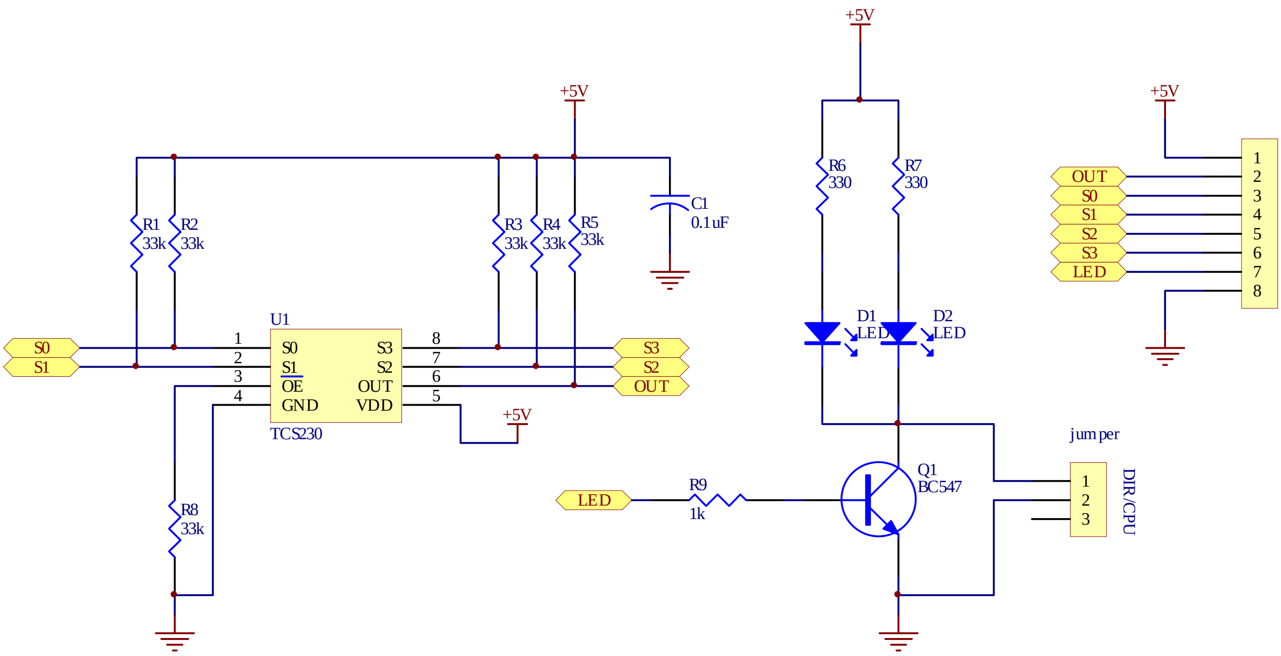
(6). กำหนดลอจิกให้ **S2=1 , S3=1** เพื่อเลือกฟิลเตอร์สีเขียว

(7). นับสัญญาณความถี่ที่ขาสัญญาณ OUT เก็บผลลัพธ์ลงตัวแปร Green_result

หมายเหตุ : จะต้องทำการ On หรือ ส่งลอจิกให้ LED ติดสว่างทุกครั้งที่ทำการอ่านค่าสัญญาณสีเพื่อให้แสงของ LED สะท้อนแสงของสีวัตถุเขามาหาตัวเซนเซอร์ หรือ ถ้าหากต้องการให้หลอดไฟ LED ติดสว่างตลอดเวลาก็ให้เลือกจัมเปอร์ DIR/CPU มาที่ตำแหน่ง DIR

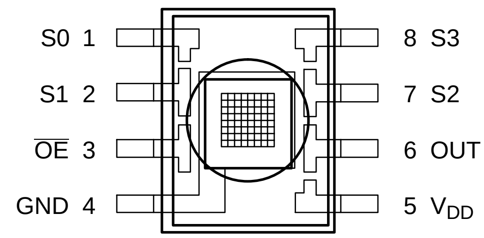
จากตัวอย่างในขั้นต้นเราจะได้ผลลัพธ์ออกมา 3 ค่า คือ Red_result, Blue_result และ Green_result ซึ่งค่าทั้ง 3 นี้จะเป็นความสัมพันธ์ของสีที่เกิดขึ้น หรือ เรียกได้เป็นค่าของแม่สี RGB (Red,Green,Blue) โดยสีทั่วๆไปจะมีค่าสี RGB แตกต่างกันไป เราจึงสามารถจำแนกสีออกเป็นสีต่างๆ ได้จากความสัมพันธ์ของค่า RGB ที่ได้นี้

วงจร ET-TCS230



- **High-Resolution Conversion of Light Intensity to Frequency**
- **Programmable Color and Full-Scale Output Frequency**
- **Communicates Directly With a Microcontroller**
- **Single-Supply Operation (2.7 V to 5.5 V)**
- **Power Down Feature**
- **Nonlinearity Error Typically 0.2% at 50 kHz**
- **Stable 200 ppm/°C Temperature Coefficient**
- **Low-Profile Surface-Mount Package**

PACKAGE D
8-LEAD SOIC
(TOP VIEW)

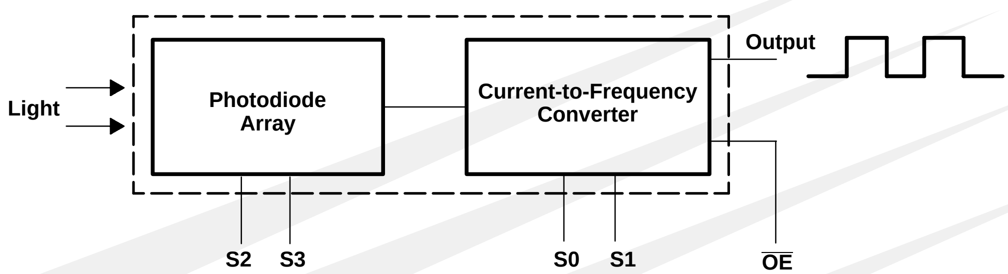


Description

The TCS230 programmable color light-to-frequency converter combines configurable silicon photodiodes and a current-to-frequency converter on single monolithic CMOS integrated circuit. The output is a square wave (50% duty cycle) with frequency directly proportional to light intensity (irradiance). The full-scale output frequency can be scaled by one of three preset values via two control input pins. Digital inputs and digital output allow direct interface to a microcontroller or other logic circuitry. Output enable ($\overline{OE}$) places the output in the high-impedance state for multiple-unit sharing of a microcontroller input line.

The light-to-frequency converter reads an 8 x 8 array of photodiodes. Sixteen photodiodes have blue filters, 16 photodiodes have green filters, 16 photodiodes have red filters, and 16 photodiodes are clear with no filters. The four types (colors) of photodiodes are interdigitated to minimize the effect of non-uniformity of incident irradiance. All 16 photodiodes of the same color are connected in parallel and which type of photodiode the device uses during operation is pin-selectable. Photodiodes are 120 µm x 120 µm in size and are on 144-µm centers.

Functional Block Diagram



Terminal Functions

TERMINAL NAME	TERMINAL NO.	I/O	DESCRIPTION
GND	4		Power supply ground. All voltages are referenced to GND.
$\overline{OE}$	3	I	Enable for f_o (active low).
OUT	6	O	Output frequency (f_o).
S0, S1	1, 2	I	Output frequency scaling selection inputs.
S2, S3	7, 8	I	Photodiode type selection inputs.
V_{DD}	5		Supply voltage

Table 1. Selectable Options

S0	S1	OUTPUT FREQUENCY SCALING (f_o)		S2	S3	PHOTODIODE TYPE
L	L	Power down		L	L	Red
L	H	2%		L	H	Blue
H	L	20%		H	L	Clear (no filter)
H	H	100%		H	H	Green

Available Options

DEVICE	T_A	PACKAGE − LEADS	PACKAGE DESIGNATOR	ORDERING NUMBER
TCS230	−40°C to 85° C	SOIC−8	D	TCS230D

Absolute Maximum Ratings over operating free-air temperature range (unless otherwise noted)†

Supply voltage, V_{DD} (see Note 1) . . . . 6 V
Input voltage range, all inputs, V_I . . . . −0.3 V to V_{DD} + 0.3 V
Operating free-air temperature range, T_A . . . . −40°C to 85°C
Storage temperature range . . . . −40°C to 85°C
Solder conditions in accordance with JEDEC J−STD−020A, maximum temperature . . . . 240°C

† Stresses beyond those listed under “absolute maximum ratings” may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated under “recommended operating conditions” is not implied. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.

NOTE 1: All voltage values are with respect to GND.

Recommended Operating Conditions

		MIN	NOM	MAX	UNIT
Supply voltage, V_{DD}		2.7	5	5.5	V
High-level input voltage, V_{IH}	V_{DD} = 2.7 V to 5.5 V	2		V_{DD}	V
Low-level input voltage, V_{IL}	V_{DD} = 2.7 V to 5.5 V	0		0.8	V
Operating free-air temperature range, T_A		−40		70	°C

Electrical Characteristics at T_A = 25°C, V_{DD} = 5 V (unless otherwise noted)

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
V_{OH}	High-level output voltage	I_{OH} = −4 mA	4	4.5		V
V_{OL}	Low-level output voltage	I_{OL} = 4 mA		0.25	0.40	V
I_{IH}	High-level input current				5	μA
I_{IL}	Low-level input current				5	μA
I_{DD}	Supply current	Power-on mode		2	3	mA
		Power-down mode		7	15	μA
	Full-scale frequency (See Note 2)	S0 = H, S1 = H	500	600		kHz
		S0 = H, S1 = L	100	120		kHz
		S0 = L, S1 = H	10	12		kHz
	Temperature coefficient of output frequency	λ ≤ 700 nm, −25°C ≤ T_A ≤ 70°C		±200		ppm/°C
k_{SVS}	Supply voltage sensitivity	V_{DD} = 5 V ±10%		±0.5		%/V

NOTE 2: Full-scale frequency is the maximum operating frequency of the device without saturation.

Operating Characteristics at V_{DD} = 5 V, T_A = 25°C, S0 = H, S1 = H (unless otherwise noted) (See Notes 3, 4, 5, 6, and 7).

PARAMETER	TEST CONDITIONS	CLEAR PHOTODIODE S2 = H, S3 = L			BLUE PHOTODIODE S2 = L, S3 = H			GREEN PHOTODIODE S2 = H, S3 = H			RED PHOTODIODE S2 = L, S3 = L			UNIT
		MIN	TYP	MAX	MIN	TYP	MAX	MIN	TYP	MAX	MIN	TYP	MAX	
f_O Output frequency	E_e = 47.2 μW/cm², λ_p = 470 nm	16	20	24	11.2	16.4	21.6							kHz
f_O Output frequency	E_e = 40.4 μW/cm², λ_p = 524 nm	16	20	24				8	13.6	19.2				kHz
f_O Output frequency	E_e = 34.6 μW/cm², λ_p = 640 nm	16	20	24							14	19	24	kHz
f_D Dark frequency	E_e = 0		2	12		2	12		2	12		2	12	Hz
R_e Irradiance responsivity (Note 8)	λ_p = 470 nm		424			348			81			26		Hz/(μW/cm²)
	λ_p = 524 nm		495			163			337			35		
	λ_p = 565 nm		532			37			309			91		
	λ_p = 640 nm		578			17			29			550		
Saturation irradiance (Note 9)	λ_p = 470 nm		1410			1720								μW/cm²
	λ_p = 524 nm		1210						1780					
	λ_p = 565 nm		1130						1940					
	λ_p = 640 nm		1040									1090		
R_v Illuminance responsivity (Note 10)	λ_p = 470 nm		565			464			108			35		Hz/lx
	λ_p = 524 nm		95			31			65			7		
	λ_p = 565 nm		89			6			52			15		
	λ_p = 640 nm		373			11			19			355		
Nonlinearity (Note 11)	f_O = 0 to 5 kHz		±0.1%			±0.1%			±0.1%			±0.1%		% F.S.
	f_O = 0 to 50 kHz		±0.2%			±0.2%			±0.2%			±0.2%		% F.S.
	f_O = 0 to 500 kHz		±0.5%			±0.5%			±0.5%			±0.5%		% F.S.
Recovery from power down			100			100			100			100		μs
Response time to output enable ($\overline{OE}$)			100			100			100			100		ns

NOTES:
3. Optical measurements are made using small-angle incident radiation from a light-emitting diode (LED) optical source.
4. The 470 nm input irradiance is supplied by an InGaN light-emitting diode with the following characteristics: peak wavelength λ_p = 470 nm, spectral halfwidth $\Delta\lambda$½ = 35 nm, and luminous efficacy = 75 lm/W.
5. The 524 nm input irradiance is supplied by an InGaN light-emitting diode with the following characteristics: peak wavelength λ_p = 524 nm, spectral halfwidth $\Delta\lambda$½ = 47 nm, and luminous efficacy = 520 lm/W.
6. The 565 nm input irradiance is supplied by a GaP light-emitting diode with the following characteristics: peak wavelength λ_p = 565 nm, spectral halfwidth $\Delta\lambda$½ = 28 nm, and luminous efficacy = 595 lm/W.
7. The 640 nm input irradiance is supplied by a AlInGaP light-emitting diode with the following characteristics: peak wavelength λ_p = 640 nm, spectral halfwidth $\Delta\lambda$½ = 17 nm, and luminous efficacy = 155 lm/W.
8. Irradiance responsivity R_e is characterized over the range from zero to 5 kHz.
9. Saturation irradiance = (full-scale frequency)/(irradiance responsivity).
10. Illuminance responsivity Rv is calculated from the irradiance responsivity by using the LED luminous efficacy values stated in notes 4, 5, and 6 and using 1 lx = 1 lm/m².
11. Nonlinearity is defined as the deviation of f_O from a straight line between zero and full scale, expressed as a percent of full scale.

TYPICAL CHARACTERISTICS

PHOTODIODE SPECTRAL RESPONSIVITY

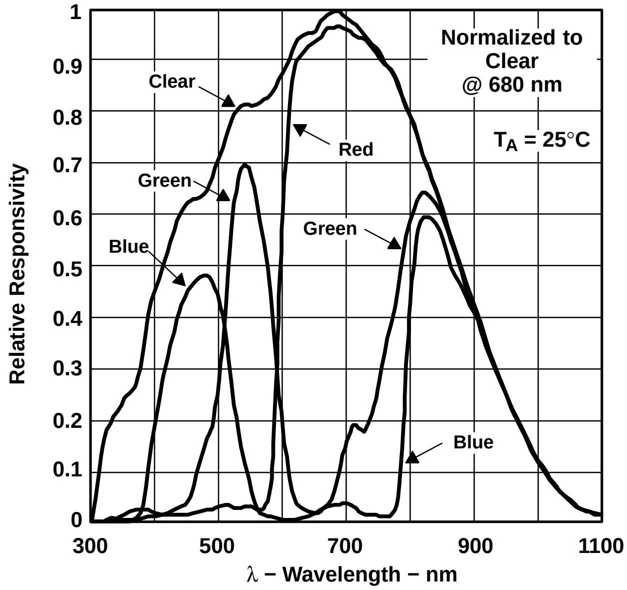


Figure 1

PHOTODIODE SPECTRAL RESPONSIVITY WITH EXTERNAL HOYA CM500 FILTER

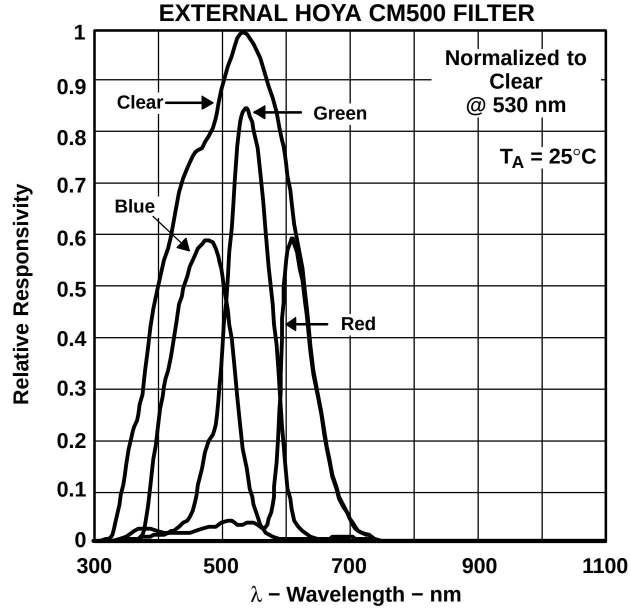


Figure 2

NORMALIZED OUTPUT FREQUENCY
vs.
ANGULAR DISPLACEMENT

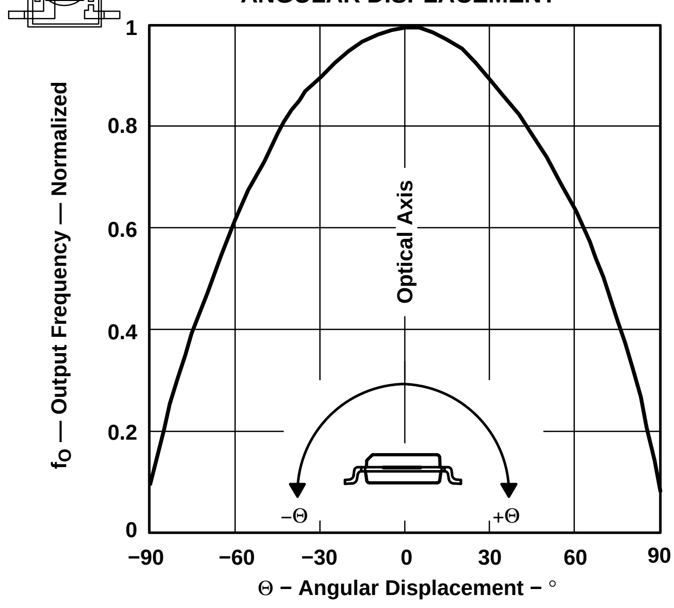


Figure 3

APPLICATION INFORMATION

Power supply considerations

Power-supply lines must be decoupled by a 0.01-μF to 0.1-μF capacitor with short leads mounted close to the device package.

Input interface

A low-impedance electrical connection between the device $\overline{\text{OE}}$ pin and the device GND pin is required for improved noise immunity.

Output interface

The output of the device is designed to drive a standard TTL or CMOS logic input over short distances. If lines greater than 12 inches are used on the output, a buffer or line driver is recommended.

Photodiode type (color) selection

The type of photodiode (blue, green, red, or clear) used by the device is controlled by two logic inputs, S2 and S3 (see Table 1).

Output frequency scaling

Output-frequency scaling is controlled by two logic inputs, S0 and S1. The internal light-to-frequency converter generates a fixed-pulsewidth pulse train. Scaling is accomplished by internally connecting the pulse-train output of the converter to a series of frequency dividers. Divided outputs are 50%-duty cycle square waves with relative frequency values of 100%, 20%, and 2%. Because division of the output frequency is accomplished by counting pulses of the principal internal frequency, the final-output period represents an average of the multiple periods of the principle frequency.

The output-scaling counter registers are cleared upon the next pulse of the principal frequency after any transition of the S0, S1, S2, S3, and $\overline{\text{OE}}$ lines. The output goes high upon the next subsequent pulse of the principal frequency, beginning a new valid period. This minimizes the time delay between a change on the input lines and the resulting new output period. The response time to an input programming change or to an irradiance step change is one period of new frequency plus 1 μS. The scaled output changes both the full−scale frequency and the dark frequency by the selected scale factor.

The frequency-scaling function allows the output range to be optimized for a variety of measurement techniques. The scaled-down outputs may be used where only a slower frequency counter is available, such as low-cost microcontroller, or where period measurement techniques are used.

Measuring the frequency

The choice of interface and measurement technique depends on the desired resolution and data acquisition rate. For maximum data-acquisition rate, period-measurement techniques are used.

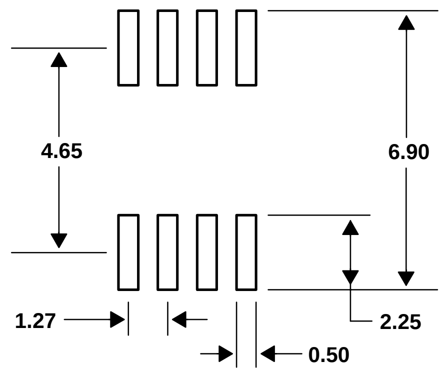
Output data can be collected at a rate of twice the output frequency or one data point every microsecond for full-scale output. Period measurement requires the use of a fast reference clock with available resolution directly related to reference clock rate. Output scaling can be used to increase the resolution for a given clock rate or to maximize resolution as the light input changes. Period measurement is used to measure rapidly varying light levels or to make a very fast measurement of a constant light source.

Maximum resolution and accuracy may be obtained using frequency-measurement, pulse-accumulation, or integration techniques. Frequency measurements provide the added benefit of averaging out random- or high-frequency variations (jitter) resulting from noise in the light signal. Resolution is limited mainly by available counter registers and allowable measurement time. Frequency measurement is well suited for slowly varying or constant light levels and for reading average light levels over short periods of time. Integration (the accumulation of pulses over a very long period of time) can be used to measure exposure, the amount of light present in an area over a given time period.

APPLICATION INFORMATION

PCB Pad Layout

Suggested PCB pad layout guidelines for the D package are shown in Figure 4.



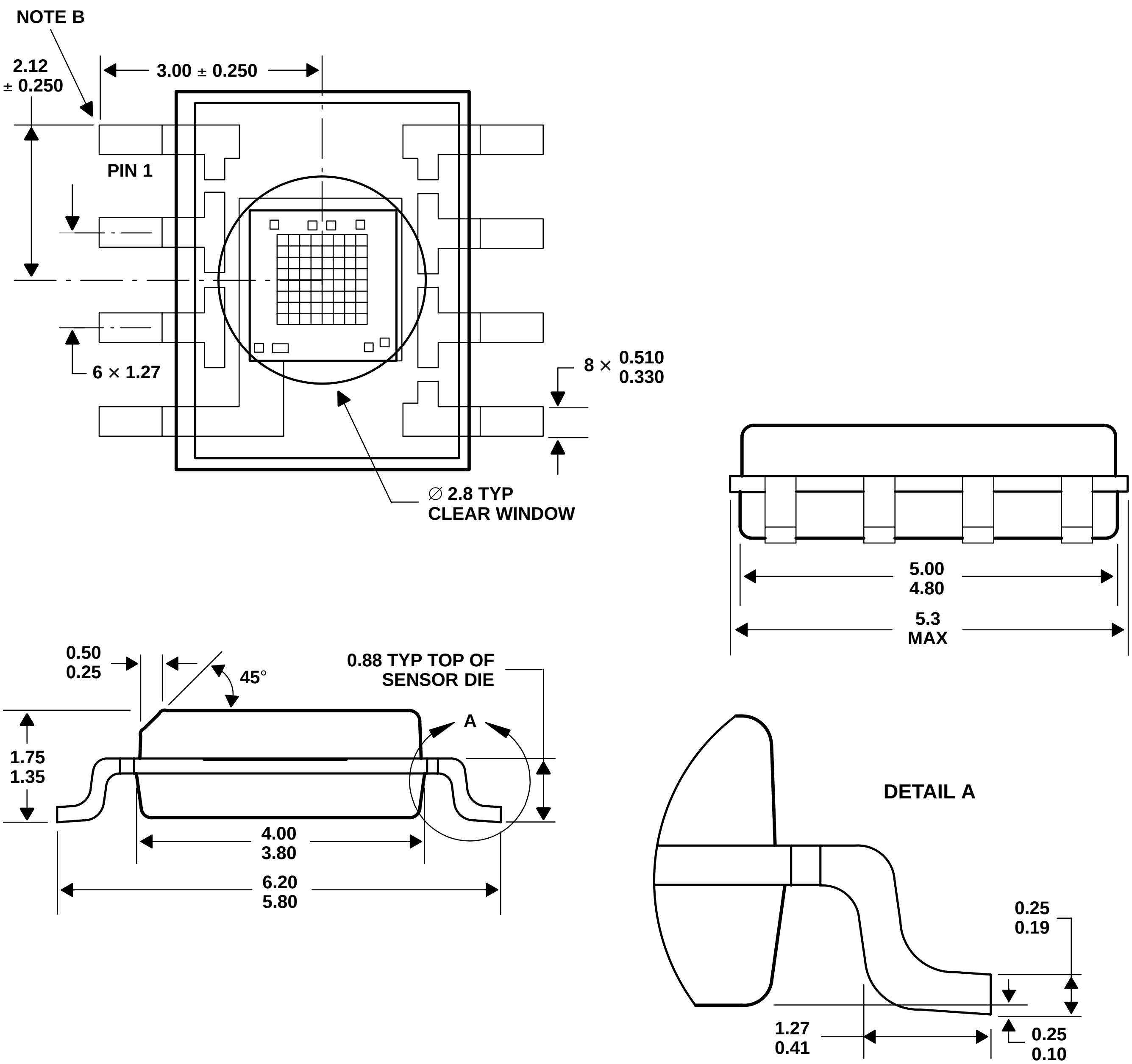
NOTES: A. All linear dimensions are in millimeters.
B. This drawing is subject to change without notice.

Figure 4. Suggested D Package PCB Layout

MECHANICAL INFORMATION

This SOIC package consists of an integrated circuit mounted on a lead frame and encapsulated with an electrically nonconductive clear plastic compound. The TCS230 has an 8 × 8 array of photodiodes with a total size of 1.15 mm by 1.15 mm. The photodiodes are 120 µm × 120 µm in size and are positioned on 144 µm centers.

PACKAGE D **PLASTIC SMALL-OUTLINE**



NOTES: A. All linear dimensions are in millimeters.
B. The center of the 1.15-mm by 1.15-mm photo-active area is referenced to the upper left corner tip of the lead frame (Pin 1).
C. Package is molded with an electrically nonconductive clear plastic compound having an index of refraction of 1.55.
D. This drawing is subject to change without notice.

Figure 5. Package D — Plastic Small Outline IC Packaging Configuration

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Sensing color with the TAOS TCS230

The TAOS TCS230 is a small, highly integrated color sensing device packaged in a clear plastic 8-pin SOIC. It reports, as analog frequency, the amount of shortwave (blue), mediumwave (green), longwave (red), and wideband (white) optical power incident onto the device. It can be used in a variety of color sensing applications. Details of the device can be found in its datasheet. This white paper details the concepts and calculations involved in color sensing using the TCS230.

www.gretagmacbeth.com

We will use the ColorChecker chart as an optical stimulus to work through a numerical example of color sensing. The chart, depicted in Figure 1, is manufactured and distributed by GretagMacbeth. The chart measures approximately 13 inches by 9 inches; it contains 24 colored patches arranged in a 6 by 4 array. Figures 2 through 5 overleaf show the spectral reflectance of the patches in each of the four rows of the chart – that is, the fraction of incident light that is reflected, as a function of wavelength from 350 nm to 740 nm.

Figure 1 **The ColorChecker** has 24 colored patches on a 13 by 9 inch card.

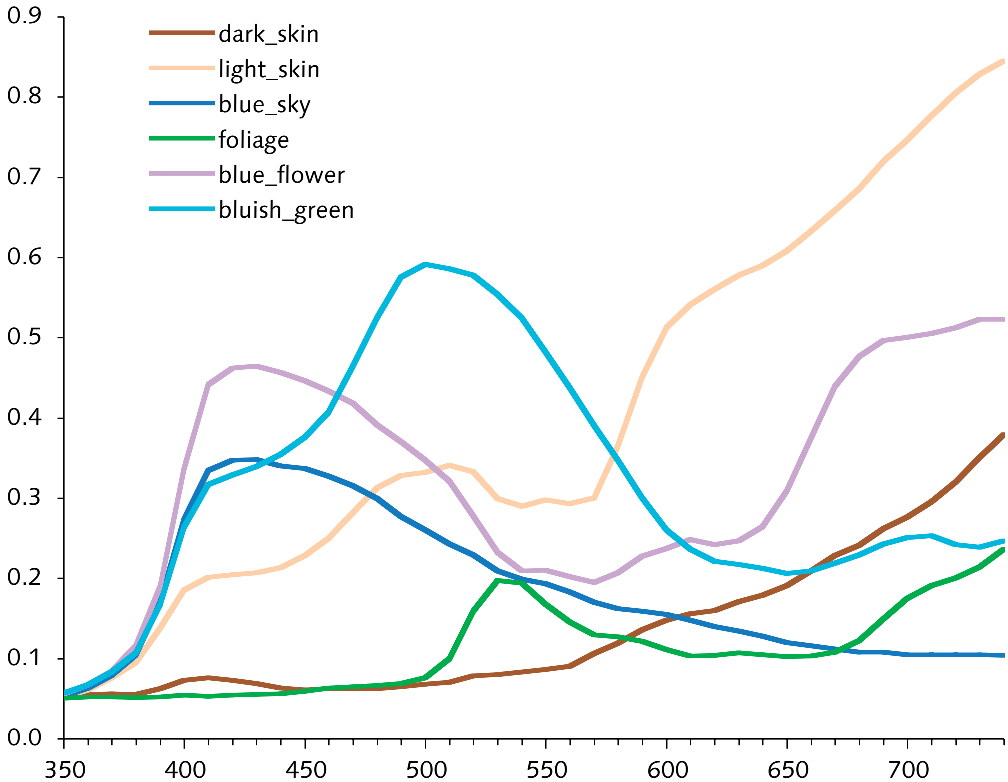

Figure 2 **ColorChecker spectra, top row.**

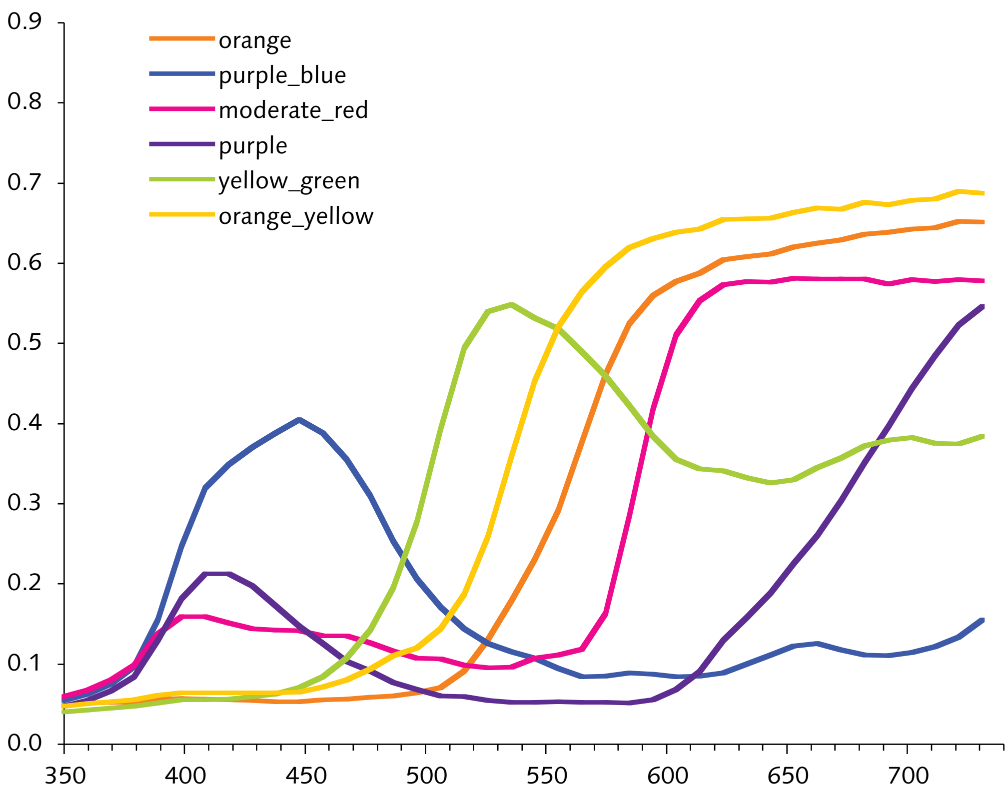

Figure 3 **ColorChecker spectra, second row.**

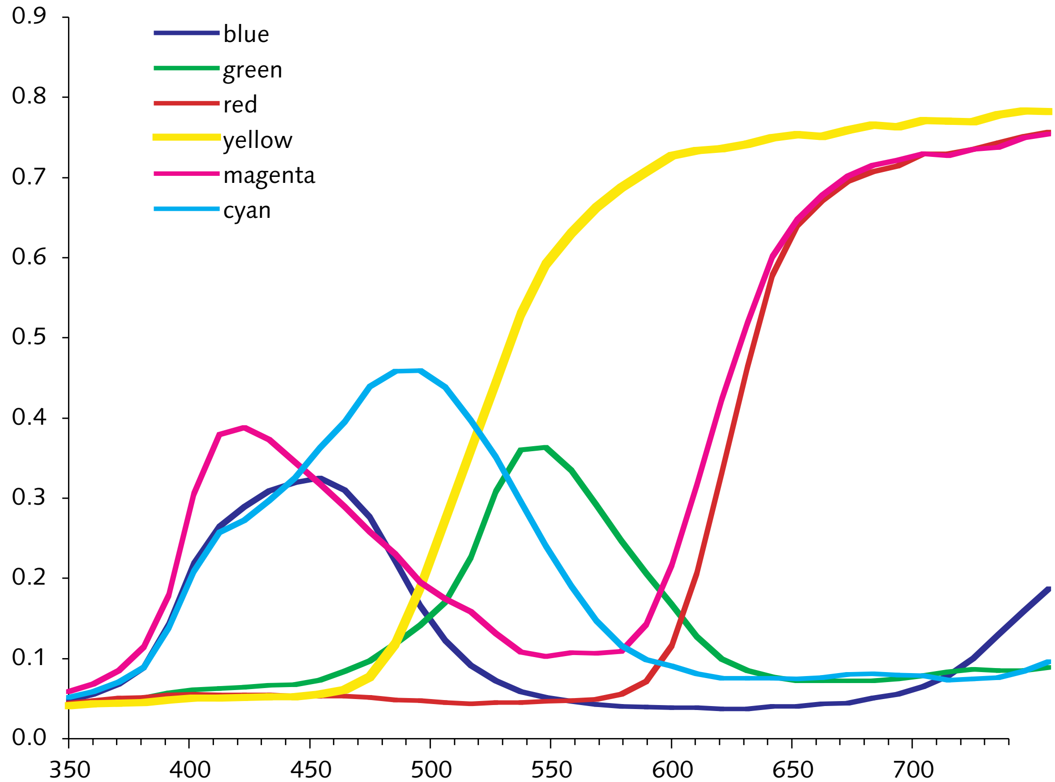

Figure 4 **ColorChecker spectra, third row.**

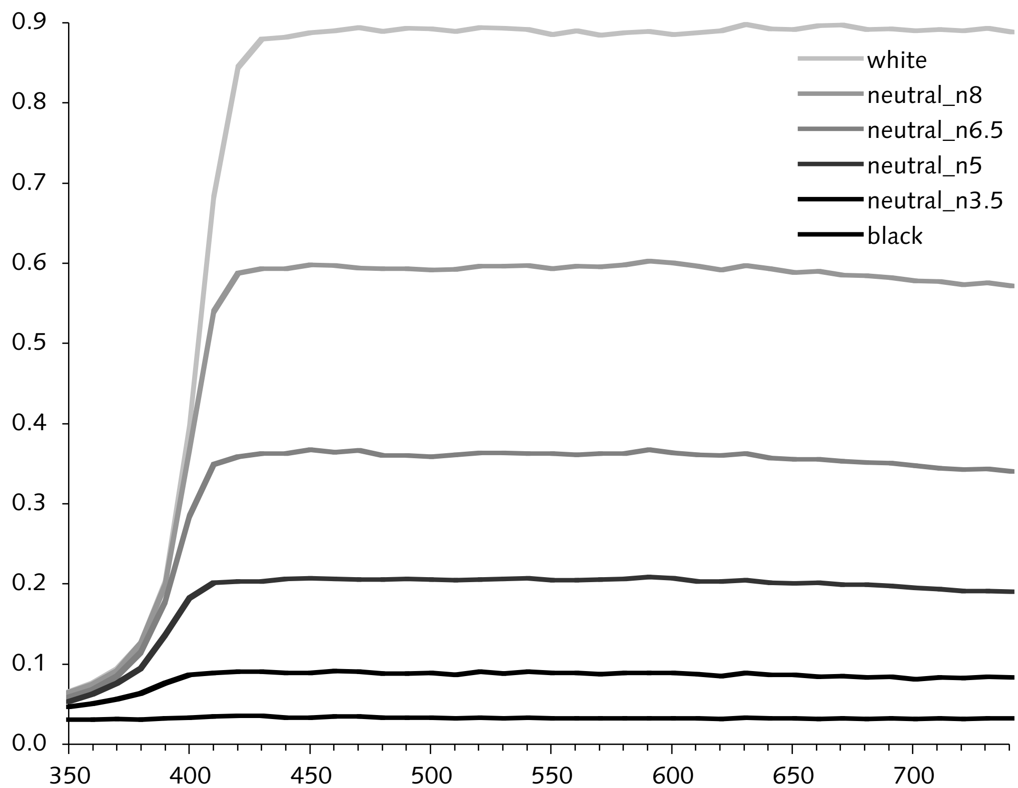

Figure 5 **ColorChecker spectra, bottom row** (neutral series)

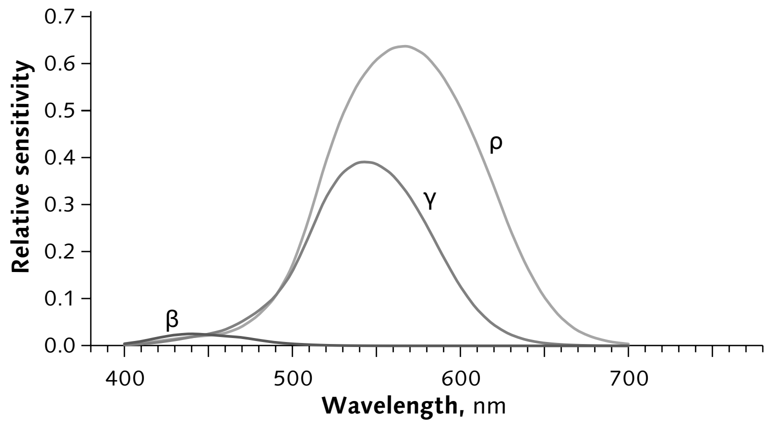

Figure 6 **Cone sensitivities** of cone photoreceptors are shown. The shortwave-sensitive photoreceptors are much less sensitive than the other two types. The responses of the mediumwave and longwave photoreceptors have a great deal of overlap. Vision is not sensitive to the precise wavelength of the stimulus: What matters is optical power integrated under each response curve.

Introduction to color vision

Photoreceptor cells called *cones* in the retina are responsible for human color vision. There are three types of cone cells, sensitive to longwave, mediumwave, and shortwave radiation within the electro-magnetic spectrum between about 400 nm and 700 nm. Because the cone sensitivities are very roughly in the parts of the spectrum that appear red, green, and blue, color scientists denote the cell types as ρ, γ, and β, the Greek letters for r, g, and b. (To denote the sensors *R, G,* and *B* would wrongly suggest a closer correspondence.) Estimates of the spectral response of the cone types are graphed in Figure 6 above.

Sometimes the designations *S, M,* and *L* – for shortwave, medium-wave, and longwave – are used.

Light in the physical world can be characterized by spectral power distributions (SPDs). Colored objects can be characterized by spectral reflectance curves, such as those of the ColorChecker. However, vision is insensitive to the exact wavelength of a stimulus: All that matters is the integral of optical power integrated underneath each response curve. That there are three types of cone cells leads to the property of *trichromaticity:* Three components are necessary and sufficient to characterize color as sensed by the eye.

Interpreted in one way, the phrase “color as sensed by the eye” is redundant at best, and misleading at worst: Color is *defined* by vision, so there is no need to use the qualifying phrase “as sensed by the eye,” or to use the adjective *visible* when referring to color.

Overview of CIE Colorimetry

The spectral responses of the cone cells that I graphed in Figure 6 were unavailable to researchers in the 1920s. Researchers at the time used psychophysical experiments, such as the famous color matching experiment, to tease out the data. The CIE is the international body responsible for color standards. In 1931, that organization adopted the *color matching functions* graphed in Figure 7 opposite.

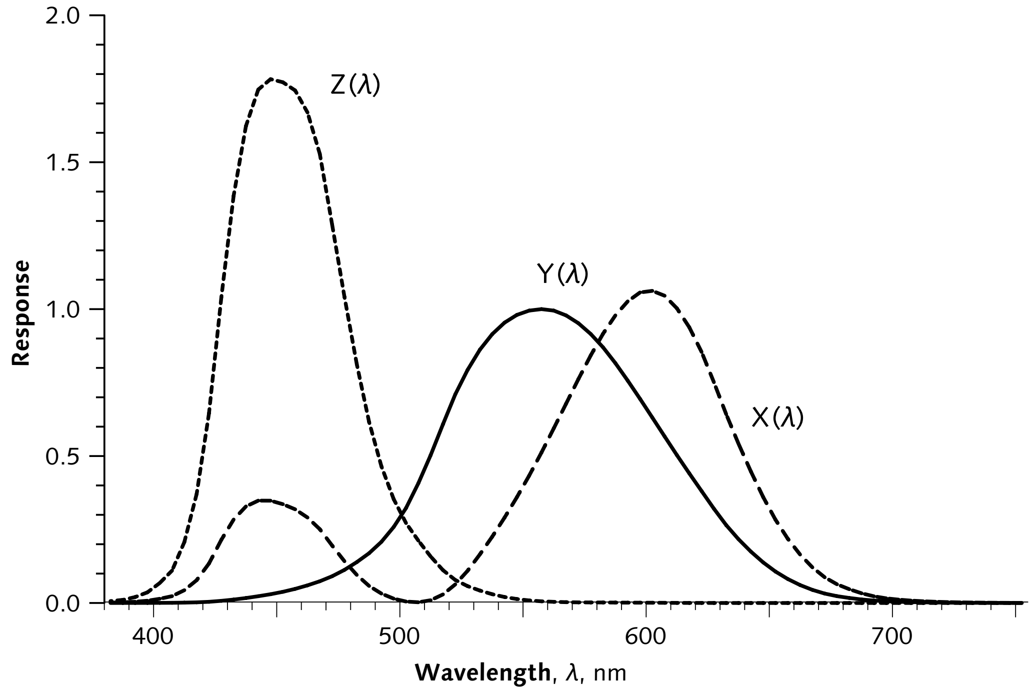

Figure 7 **CIE 1931, 2° color-matching functions.** A camera with 3 sensors must have these spectral response curves, or linear combinations of them, in order to capture all colors. However, practical considerations make this difficult. These analysis functions are *not* comparable to spectral power distributions!

A description of the application of color science to color imaging is contained in Poynton, Charles, *Digital Video and HDTV Algorithms and Interfaces* (San Francisco: Morgan Kaufmann, 2003).

Weighting a physical SPD under each of these three curves (that is, forming the wavelength-by-wavelength product), and summing the results, forms a triple of three numbers, denoted *X, Y,* and *Z.* In continuous mathematics, this three integrals need to be computed; in discrete math, a matrix product is sufficient. The *X, Y,* and *Z tristimulus values* characterize color. They are linear-light quantities, proportional to optical power, that incorporate the wavelength sensitivity of human vision. The *Y* value is *luminance,* which is ordinarily expressed in units of candelas per meter squared ($cd \cdot m^{-2}$). If you are measuring reflectance, the reflected tristimulus values depend upon the spectral characteristics of the illuminant, and their amplitudes scale with the power of the illumination. *Relative luminance* is the ratio of reflected luminance to the luminance of the illumination; it is also known as the *luminance factor.*

The X(λ), Y(λ), and Z(λ) color matching functions of Figure 7 are obviously different from the ρ, γ, and β spectral sensitivities of Figure 6. Not even subjecting the X(λ), Y(λ), and Z(λ) curves to a 3×3 linear transform can bring them into good agreement with Figure 6. The reasons and consequences of the discrepancy are complex; this issue remains a research topic among color scientists. For our purposes, the best explanation is this: Despite the fact that the photoreceptor cells respond as indicated in Figure 6, the high-level properties of vision – by which vision relates SPDs to color – are best approximated by the CIE curves. It is difficult to implement these curves or even close approximations to them. Furthermore, in most applications the range of colors that need to be distinguished is limited, and it is not necessary to closely approximate the CIE curves.

Luminance is proportional to intensity, but is weighted by the spectral response of vision's lightness sensation. The perceptual response to luminance is complex, but it can be approximated by a power function. The CIE has standardized the computation of *lightness*, denoted L^*, as approximately the 0.4-power of relative luminance. Because of the subtle relationships among intensity, luminance, and lightness, you should take care to use these terms correctly.

$$x = \frac{X}{X+Y+Z}$$

$$y = \frac{Y}{X+Y+Z}$$

Eq 1 Chromaticity coordinates

In many applications, tristimulus signals (including luminance) scale with the illumination, and are otherwise uninteresting in themselves. What is more interesting is the ratios among them, which characterize color disregarding luminance. The CIE has standardized the projective transformation of Equation 1, in the margin, to transform [X, Y, Z] values into a pair of [x, y] *chromaticity coordinates* that represent color disregarding luminance. These coordinates are suitable for plotting in two dimensions on a *chromaticity diagram.*

Illumination

A nonemissive object must be illuminated in order to be visible. The SPD reflected from an illuminated object is the wavelength-by-wavelength product of the illuminant's SPD and the spectral reflectance of the object. Before light reaches the eye, the interaction among light sources and materials takes place in the spectral domain, not in the domain of trichromaticity. To accurately model these interactions requires spectral computations. When applying the TCS230, attention must be paid to the spectral content of the illumination and to potential interaction between the illumination and the samples to be sensed. Generally, the less spiky the spectra, the better. Figure 8 graphs several illuminants.

Your application may involve sensing color, in which case the preceding description applies. However, some applications of the TCS230 involve not so much estimating color as seen by the eye but rather sensing physical parameters associated with optical power in the visible range. In such applications, to approximate the visual response may not be the best approach: It may be more effective to take a more direct approach to estimating the parameters of the underlying physical process.

The Color Checker

Equipped with knowledge of how spectra are related to colors, the plotting of chromaticity coordinates, and the dependence of colors upon illumination, we can return to the ColorChecker. GretagMacbeth doesn't publish or guarantee the spectral composition of the patches of the ColorChecker. However, nominal CIE [X, Y, Z] values are published. The patches in the bottom row of the ColorChecker contain neutral colors; the numeric notations in the legends of Figure 5 reflect one tenth of the lightness (L^*) values of those patches.

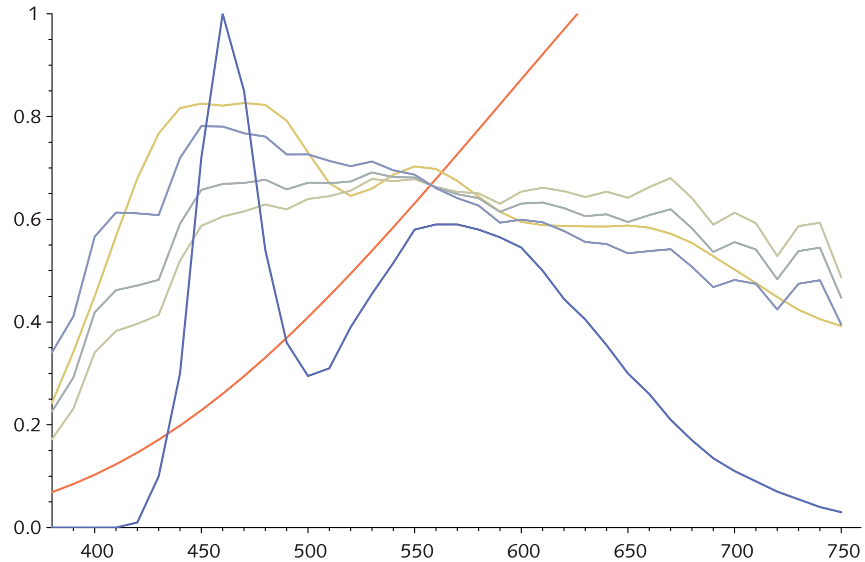

Figure 8 **SPDs of various illuminants** are graphed here. Illuminant A, shown in orange, is representative of tungsten light sources; it is deficient in shortwave power, and may cause errors in sensing blue colors. The blue line graphs the SPD of a Nichia white LED. There is a peak in the blue portion of the spectrum: Uncorrected, the sensor would report excessive blue values. The other four lines represent CIE standard illuminants C, D_{50}, D_{55}, and D_{65}.

The spectra graphed on pages 2 and 3 represent the physical wavelength-by-wavelength reflectance of the patches. These spectral reflectances have been measured by color measurement instrument called a *spectrophotometer.* If you had access to a light source having perfectly even distribution of power across the visible spectrum, then the reflectance curves graphed here could simply be scaled to represent the reflectance in your application. Practical light sources do not have perfectly even spectral distributions, so compensation is necessary: You must compute the wavelength-by-wavelength product of the illuminant's SPD with the spectral reflectance of the chart.

We will first calculate the CIE [*X*, *Y*, *Z*] values from the chart. (These values should agree with the figures provided by Gretag.) Then we will calculate the [*R*, *G*, *B*] values that will be detected by a TCS230.

To calculate CIE [*X*, *Y*, *Z*], we take the 31×3 matrix representing the color matching functions (CMFs) of the CIE Standard Observer, and perform a matrix product with 31 spectral response values as corrected for illumination. This produces the [*X*, *Y*, *Z*] tristimulus values. When chromaticity coordinates [*x*, *y*] are computed from [*X*, *Y*, *Z*] through the projective transform in Equation 1, then plotted, the chromaticity diagram in Figure 9 results. The horseshoe-shaped figure, closed at the bottom, contains all colors: Every non-negative spectral distribution produces an [*x*, *y*] pair that plots within this region. The lightly-shaded triangle shows the region containing all colors that can be produced by an additive *RGB* system using sRGB (Rec. 709) primary colors. This region typifies video and desktop

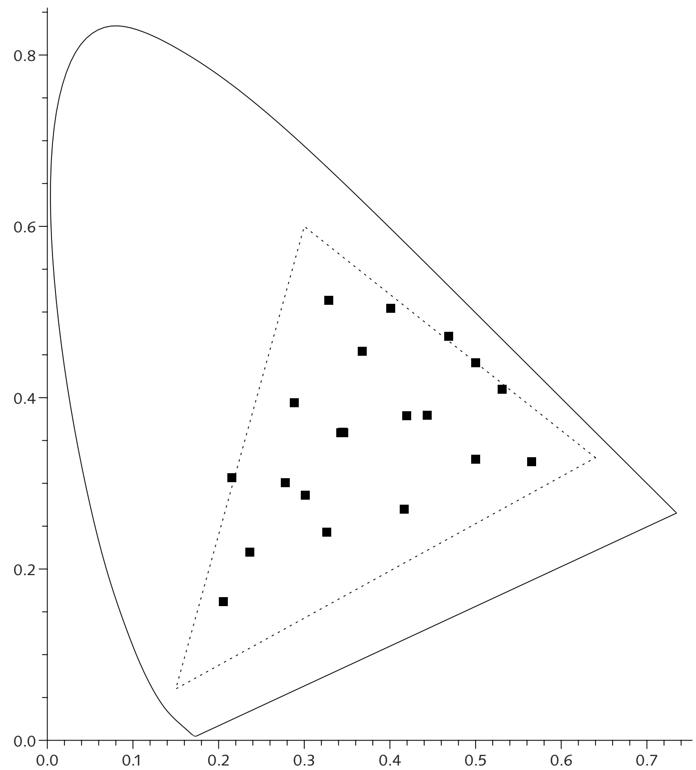

Figure 9 **Coordinates of ColorChecker patches** are graphed on the CIE [*x*, *y*] chromaticity diagram. The horseshoe encloses all colors; the triangle encloses the colors that can be represented in video (Rec. 709) and in desktop computing (sRGB).

computing (sRGB). The points plotted in Figure 9 are the colors of the ColorChecker. White and gray values are clustered near the center of the chart.

The TCS230

Figure 10 shows the responses of the four channels of the TCS230. The black curve shows the response of the unfiltered sensor elements. The red, green, and blue curves show the responses of the longwave-sensitive, mediumwave-sensitive, and shortwave-sensitive elements respectively.

As I mentioned on page 5, the CIE model of color vision involves integrating an SPD under the X(λ), Y(λ), and Z(λ) color matching functions (graphed in Figure 7), producing *X, Y,* and *Z* values. To use the TCS230 to estimate color we perform an analogous calculation, but using the TCS sensitivity functions instead of the CIE CMFs: We integrate the SPD under the TCS230's sensitivity curves, and produce *R, G,* and *B* values. The device *R, G,* and *B* values will depend upon several factors: the spectral content of the illuminant, the spectral reflectance of the sample, the spectral attenuation of any intervening optical components (such as the lens), and finally, the spectral response functions of the TCS230. The various spectral phenomena are modelled by computing wavelength-by-wavelength products.

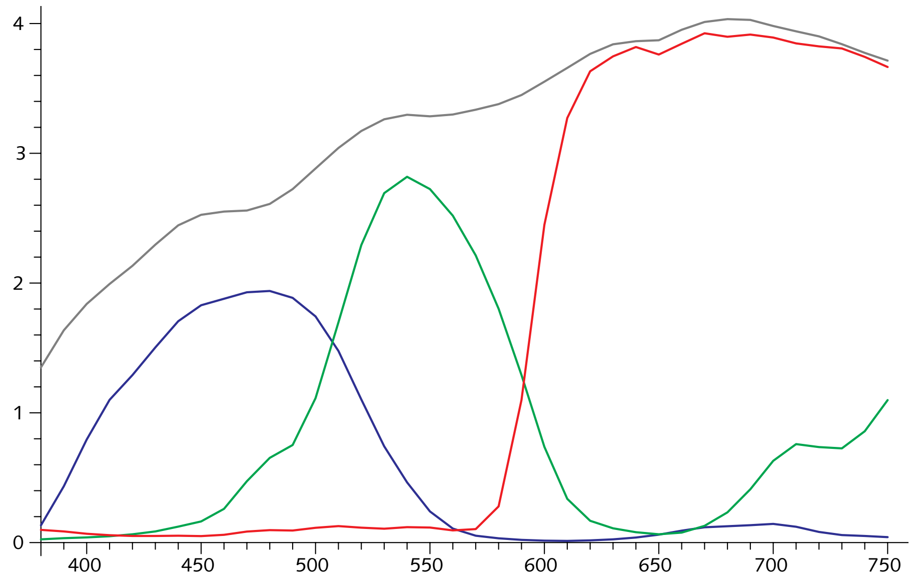

Figure 10 **TCS230 spectral sensitivities** are graphed here. The red, green, and blue channels are graphed in the corresponding colors; the gray line reflects the sensitivity of the clear (unfiltered) channel. Because these responses are different from the CIE standard observer, the values reported by the TCS230 are not colorimetric. However, suitable signal processing yields color information that is sufficiently accurate for many industrial applications.

Owing to the fact that the TCS230 is sensitive to infrared light (having wavelengths above 700 nm), and the fact that most light sources produce power in the infrared region, typical applications include an IR cut filter in front of the TCS230. Figure 11 shows the response of a typical IR cut filter.

Continuing our modelling of the ColorChecker, we illuminate the ColorChecker with the CIE D_{65} illuminant, integrate the resulting spectral reflectances under the TCS230 sensitivity curves, and finally transform to CIE [*x*, *y*] coordinates. The relative luminance values obtained through this process are fairly accurate; however, the chromaticity coordinates are not very accurate. Figure 12 graphs the CIE chromaticities of the uncorrected *R*, *G*, and *B* values. The results differ from the coordinates of the ColorChecker graphed in Figure 9.

The reason for the disagreement is that the TCS230's sensitivity functions differ quite substantially from the CIE color matching functions. Even if the TCS230 sensitivities were in close agreement with the CIE functions, the effect of the spectral power distribution of the illuminant, and the spectral effect of intervening optical components, would cause some divergence.

To form a more accurate estimate of color requires processing the raw TCS230 *R*, *G*, and *B* values through a linear 3×3 matrix whose coefficients are optimized with respect to the spectrum of the illuminant, the spectral response of intervening optical components, and the

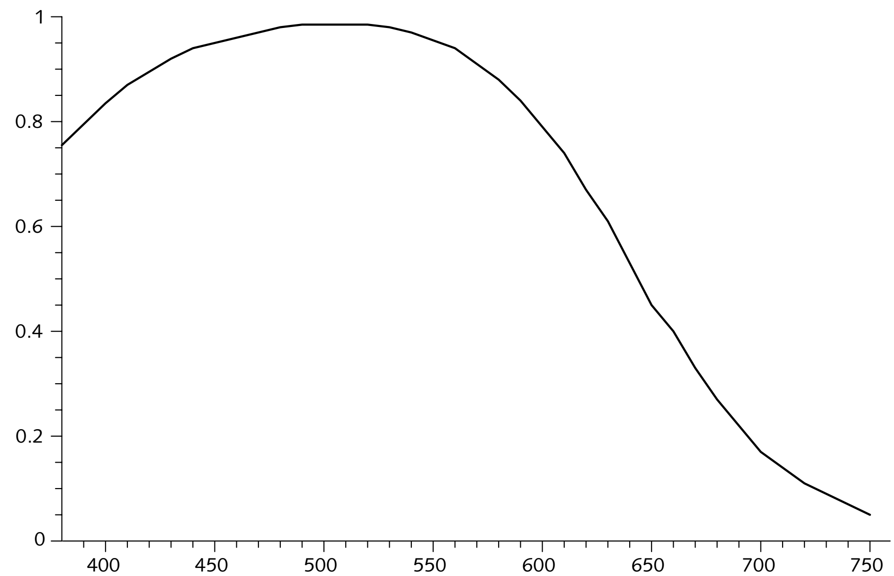

Figure 11 **An IR cut filter** is necessary in most sensor systems. Most silicon sensors are sensitive to IR, most light sources emit substantial amounts of power in the IR region, and many colored objects reflect in the IR range. If IR response were left unattenuated, the sensor would report excessively high red components. This graph reflects the IR filter incorporated into the Argus lens of the TCS230 evaluation module.

response curves of the TCS230. The data processing operation can be represented in matrix form as follows:

$$\boldsymbol{x} = \boldsymbol{M} \bullet \boldsymbol{t} \qquad \text{Eq 2}$$

The symbol ***t*** represents a three-element vector containing the device values captured from a color patch. ***M*** represents the 3×3 color correction matrix that we will apply to these values through matrix multiplication, denoted by the • symbol. The symbol ***x*** represents the resulting vector of estimated [*X, Y, Z*] values. (I conform to the usual mathematical convention of representing a vector by a lowercase bold italic letter and a matrix by an uppercase bold letter.)

We can use matrix notation to symbolize processing a set of three color patches at once, by arranging the three sets of device values into successive columns of a 3×3 matrix ***T***. Successive rows of ***T*** contain red, green, and blue data respectively. Upon matrix multiplication by ***M***, the columns of the resulting matrix ***X*** contain *XYZ* values of the successive samples; the rows of ***X*** contain *X*, *Y*, and *Z* values respectively. One equation expresses the mapping of three patches at once:

$$\boldsymbol{X} = \boldsymbol{M} \bullet \boldsymbol{T} \qquad \text{Eq 3}$$

Given a matrix ***T*** whose columns contain three sets of device samples, and a matrix ***X*** containing the corresponding set of three ideal *XYZ* triples, there is a unique matrix ***M*** that maps from ***T*** to ***X***. It is found

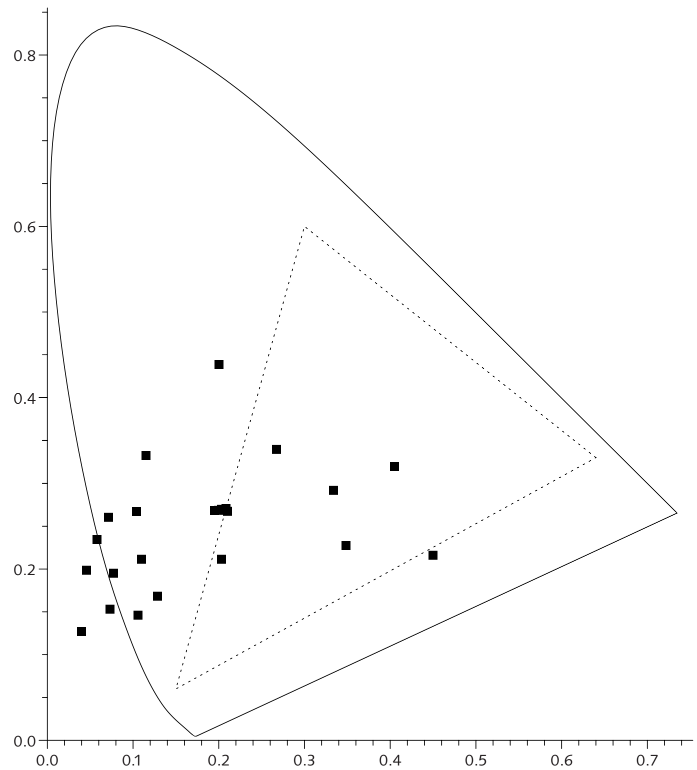

Figure 12 **Uncorrected TCS230 values,** illuminated by CIE Illuminant D_{65}, are graphed here as if the TCS230 were colorimetric. Signal processing can be used to bring these values into closer agreement with the values obtained using the CIE Standard Observer.

by computing the matrix inverse of ***T***, then computing the matrix product (by premultiplication) with ***X***:

$$\boldsymbol{M} = \boldsymbol{X} \bullet \boldsymbol{T}^{-1} \qquad \text{Eq 4}$$

Matrix multiplication is non-commutative: $\boldsymbol{A} \cdot \boldsymbol{B}$ is generally unequal to $\boldsymbol{B} \cdot \boldsymbol{A}$. *Premultiplication by* ***X*** means that ***X*** is on the left.

The resulting 3×3 color correction matrix ***M*** exactly maps the each of the chosen three sets of device values to the corresponding set of tristimulus values. It is not necessary to invert matrices at the time of sensing! The matrix ***M*** can be computed in advance, based upon the samples that are expected to be presented to the sensor in the intended application. To process three device values upon sensing a sample, all that is necessary is computation of the matrix product of Equation 3.

Here is the optimum transform to CIE [*X, Y, Z*] for the ColorChecker's red, green, and blue patches, illuminated by CIE D_{65} and sensed by the TCS230:

$$\begin{pmatrix} \hat{X} \\ \hat{Y} \\ \hat{Z} \end{pmatrix} = \begin{pmatrix} 0.3240 & 0.2072 & 0.0350 \\ 0.0243 & 0.5491 & -0.0555 \\ 0.0813 & -0.2364 & 0.5838 \end{pmatrix} \bullet \begin{pmatrix} R_{TCS230} \\ G_{TCS230} \\ B_{TCS230} \end{pmatrix} \qquad \text{Eq 5}$$

The "hats" on *X, Y,* and *Z* indicate that these quantities are estimates. The matrix in Equation 5 was optimized for three particular sample values (patches). The approach is suitable for applications where the TCS230 is used to distinguish among a set of three colors. However, exact mapping is guaranteed for just those three samples. The mapping from a set of device values outside that set is likely to be far from optimal. Attempting to optimize the mapping for more than three samples, to a set of more than three corresponding ideal tristimulus values, leads to an overdetermined system. If your application involves more than three stimuli, further work is necessary.

A color correction matrix that produces good results across more than three samples can be computed through a numerical optimization procedure. When this is done, no particular sample is likely to map exactly to its ideal tristimulus set, but a linear matrix can be constructed that minimizes the error across a range of samples (where the error is measured in a least-squares sense). The color correction operation is still accomplished exactly as in Equation 2.

The mathematical details of the pseudoinverse are explained in Strang, Gilbert, *Introduction to Linear Algebra*, Second Edition (Boston: Wellesley-Cambridge, 1998). For a highly technical description of the construction of color transforms, see Sharma, Guarav, Ed., *Digital Color Imaging Handbook* (Boca Raton, Fl., U.S.A.: CRC Press, 2003).

To describe the mapping of more than three patches using just one equation, matrix ***T*** is extended to have more than three columns. In this example, we will use the 24 patches of the ColorChecker chart, so ***T*** is a 3×24 matrix and ***X*** is a 3×24 matrix. The numerical optimization procedure takes exactly the form of Equation 4; however, the system is overdetermined, and the matrix inverse of ***T*** cannot be computed. The best least-squares mapping is obtained by computing the *pseudoinverse* of ***T*** instead of the inverse. Pseudoinverse is related to the *singular value decomposition* (SVD). Systems for doing mathematics using computers, such as Mathematica and Matlab, have built-in provisions for computing the pseudoinverse of a matrix.

When the pseudoinverse is formed and premultiplied by the ideal tristimulus values – that is, multiplied on the left of the pseudoinverse – the optimum transform for the ColorChecker illuminated by CIE D_{65} and sensed by the TCS230 is determined to be this:

$$\begin{pmatrix} \hat{X} \\ \hat{Y} \\ \hat{Z} \end{pmatrix} = \begin{pmatrix} 0.3131 & 0.8022 & -0.0767 \\ -0.0836 & 1.2567 & -0.1450 \\ 0.0514 & -0.3283 & 1.0710 \end{pmatrix} \bullet \begin{pmatrix} R_{TCS230} \\ G_{TCS230} \\ B_{TCS230} \end{pmatrix} \quad \text{Eq 6}$$

Euclidean distance is the square root of the sum of the squares of a set of values. In engineering, this is the *root-mean-square* (RMS) value. For color differences, we deal in three dimensions. In the two-dimensional case, this computes the length of the hypotenuse of a right triangle. (Upon receiving his diploma, the Scarecrow in *The Wizard of Oz* offers Dorothy a garbled description of this calculation; he has gained self-confidence, but not mathematical knowledge!)

ColorChecker patches processed through this optimized transform produce the chromaticity coordinates that are plotted in Figure 13.

The usual way to describe the visual magnitude of color differences is to use the the *delta-E* scale defined by the CIE. This scale is defined by Euclidean distances between CIE *L*a*b** triples, where *L*a*b** values – sometimes denoted *CIELAB,* or just *LAB* – are obtained by a nonlinear transformation of CIE *XYZ.* Transforms among *XYZ, Yxy, L*a*b*, RGB,* and many other color systems are detailed in Poynton's book, cited in the margin of page 5.

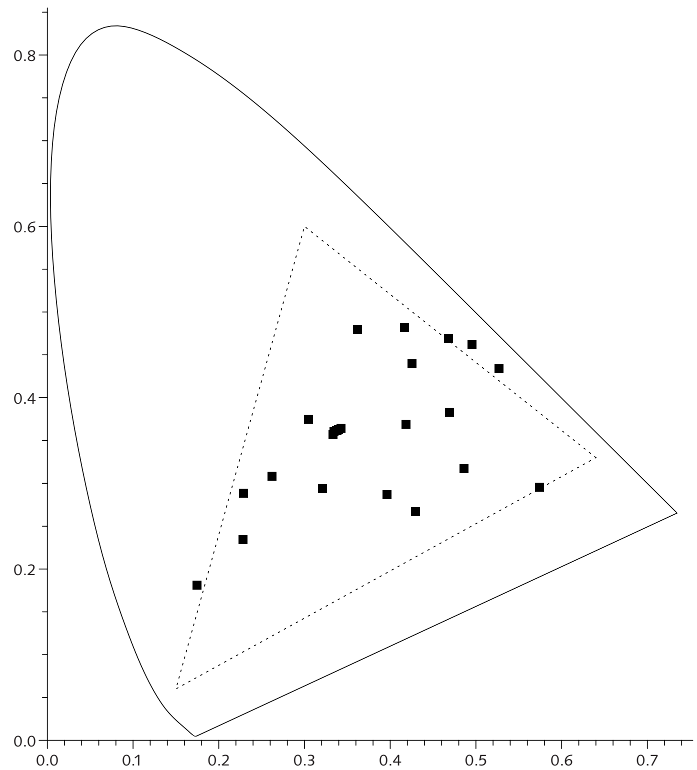

Figure 13 **Corrected TCS230 values,** illuminated by CIE Illuminant D_{65}, are graphed here. The chromaticity values are reasonably close to those of Figure 9.

When color-corrected TCS230 values are transformed to *L*a*b** coordinates through the optimized matrix of Equation 6, then compared to the published *L*a*b** values of the ColorChecker (as measured by instrumentation), the average magnitude of the error is about 8 delta-*E* units. In high-quality image reproduction, a delta-*E* value of unity is taken to lie approximately on the threshold of perceptibility, and a value of 2 is taken to be acceptable. A color measurement instrument is expected to have an error of *a* fraction of *a* delta-*E.* In TCS230 applications, we are not sensing images. An average error of 8 is quite respectible for *a* low-cost sensor device, and is comparable to the color error present in image data sensed by consumer digital still cameras.

The optimum 3×3 matrix depends upon the TCS230 responses, which are published by TAOS, and upon the spectral absorbance of optical components such as the lens and any IR filter. In most applications, reflected color is measured; the optimum matrix also depends upon the spectral content of the illuminant, and upon the spectral reflectance of the samples to be estimated. Because these latter factors depend upon the application, the system designer will probably have to compute his or her own optimized matrix. In the example presented above we have used the ColorChecker as a proxy for colors that might be enccountered in an application that deals with a wide array of color stimuli. If you intend to use the TCS230 to distinguish among a small handful of different colored items, the linear matrix should be optimized for the spectral reflectances of just those items. If you intend to use an illuminant having spectral properties different from CIE D_{65}, then you should optimize for that illuminant.

The TCS230 evaluation module is equipped with a pair of Nichia white LEDs to illuminate the sample. The evaluation module mounts the TCS230 device behind a lens that incorporates an IR cut filter whose response is shown in Figure 11. Here is the optimum matrix for the twenty four ColorChecker patches as reported by the evaluation module:

$$\begin{pmatrix} \hat{X} \\ \hat{Y} \\ \hat{Z} \end{pmatrix} = \begin{pmatrix} 1.2471 & 0.4099 & 0.0014 \\ 0.3658 & 0.8087 & -0.0592 \\ 0.1629 & -0.2418 & 0.8712 \end{pmatrix} \bullet \begin{pmatrix} R_{TCS230} \\ G_{TCS230} \\ B_{TCS230} \end{pmatrix} \qquad \text{Eq 7}$$

The average magnitude of the error of this transform across the 24 patches of the ColorChecker is about 6 delta-*E* units.

Should you wish to transform TCS230 color estimates to sRGB values suitable for use in desktop computing and computer graphics, use the standard textbook technique. First, transform the estimated [*X, Y, Z*] values to linear-light *R, G,* and *B* tristimulus values having the appropriate primary chromaticities and white reference chromaticity, using this linear matrix:

$$\begin{pmatrix} R_{sRGB} \\ G_{sRGB} \\ B_{sRGB} \end{pmatrix} = \begin{pmatrix} 3.240454 & -1.537139 & -0.498531 \\ -0.826029 & 1.759877 & 0.023179 \\ 0.043396 & -0.198899 & 1.063208 \end{pmatrix} \bullet \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \qquad \text{Eq 8}$$

An *XYZ* triple may represent a color that is out of gamut for Rec. 709 primaries. Such a color cannot be represented in sRGB code values between zero and unity: An out of gamut color will transform to an *RGB* triple where one or more components is outside the range zero to one – that is, a component may be less than zero, or may exceed unity. You may need to clip such excursions to the range zero to one.

Combining the matrix of Equation 8 with the optimized color correction matrix of Equation 6 (for the D_{65} illuminant, and no IR cut filter) yields this transform of linear-light values:

$$\begin{pmatrix} \hat{R}_{sRGB} \\ \hat{G}_{sRGB} \\ \hat{B}_{sRGB} \end{pmatrix} = \begin{pmatrix} 1.1174 & 0.8316 & -0.5594 \\ -0.4045 & 1.5413 & -0.1671 \\ 0.0849 & -0.5641 & 1.1642 \end{pmatrix} \bullet \begin{pmatrix} R_{TCS230} \\ G_{TCS230} \\ B_{TCS230} \end{pmatrix} \qquad \text{Eq 9}$$

Following this transformation, sRGB gamma correction – approximately a 0.45-power function, similar to a square root – is applied to the linear *RGB* values to obtain *R'G'B'*. See Poynton's book, cited in the margin of page 5, for details.