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TAOS TCS230 Spreadsheet description

TAOS has created an Excel workbook to accompany the white paper entitled *Sensing color with the TAOS TCS230.* The workbook implements the calculation of the optimum 3×3 matrix that minimizes the color error when translating TCS230 device values to estimated CIE tristimulus values. The present document is *a* description of that spreadsheet. I assume that you are familiar with the white paper. Using the workbook will require only casual familiarity with Excel; however, if you wish to enter new data you will have to be reasonably familiar with Excel, and in particular, with array formulas.

The workbook contains macros. When you open the workbook, you may be presented with a dialog that states this fact and invites you to enable or disable macros. If you choose to disable macros, the pop-up menus in the workbook will not function (but everything else will).

The workbook contains spectral data, sampled at 10 nm intervals over the wavelength range from 380 nm through 750 nm inclusive. Spectral data comprises the CIE color matching functions, spectral radiance for various illuminants, spectral reflectance of the 24 patches of the GretagMacbeth ColorChecker, spectral transmittance data for a representative infrared cutoff filter, and spectral responses of a reference TCS230 sensor. The workbook is organized so that spectral data in each of these categories is provided on sheets named *CMF, Illuminant, ColorCheckerSR, IRcut,* and *TCS230* (respectively). A sheet named *Optical* provides for the insertion of the spectral transmittance of additional optical components; the reference design has no such components, so the sheet is delivered with unity data in that sheet.

Based upon the spectral data that I have mentioned, and upon a chosen illuminant and IR cut filter, the spreadsheet computes two 3×3 matrices that are presented in columns D through F at the bottom of the first sheet. One 3×3 matrix is entitled *Exact3: Matrix to map R, G, B exactly;* this matrix exactly maps the red, green, and blue patches of the Macbeth chart to their reference colorimetric values: The resulting delta-*E* values of red, green, and blue will be zero. The second 3×3 matrix is entitled *Opt24: Optimum matrix (pseudoinverse);* it minimizes the average delta-*XYZ* across all 24 patches. (In most cases, the optimum 3×3 matrix minimizes the average delta-*E*.)

The *Exact3* and *Opt24* matrices are computed by the spreadsheet based upon the illuminant and the IR cut filter indicated in the pop-up menus labelled *Illum* and *IR cut*. When you change the chosen illuminant or IR cut filter, the matrices will be recomputed. The calculation also depends upon any additional components that may be present in the optical path; the spectral transmittance of additional optical components can be entered on sheet 6 (entitled *Optical*).

Selecting either *Exact3* or *Opt24* from the pop-up at the bottom of sheet 1 copies the chosen matrix into the adjacent *Color correction matrix*. The *Average* ΔE_{ab} across all of the patches of the Macbeth chart is computed from this matrix and displayed in the bottom right cell of sheet 1. If you experiment by alternately choosing *Exact3* and *Opt24,* you will notice that optimizing across all 24 patches yields a lower average ΔE_{ab}. You can manually enter matrix coefficients to see how the average ΔE_{ab} responds; in the Opt24 case, changing any coefficient in either direction will almost certainly yield a larger error.

The worksheet entitled *ColorCheckerSR* contains cells to implement the calculation of average ΔE_{ab}. If on sheet 1 you choose *Exact3* and then consult the ColorCheckerSR sheet (4), you will see that the ΔE_{ab} of the red, green, and blue patches is made zero. If on sheet 1 you choose the *Opt24* matrix, the ΔE_{ab} of the red, green, and blue patches will (in all likelihood) become nonzero, but the average ΔE_{ab} across all 24 patches will be reduced compared to the *Exact3* case.

The 560 nm row of sheet 1 is highlighted to represent the approximate peak luminance sensitivity of vision, and as a reminder that the standard CIE illuminants are normalized to unity at 560 nm.

Rows 2 through 39 of the summary sheet (1) present, in successive columns, the reference wavelengths (380 through 750 nm), the spectral radiance for the chosen illuminant, the spectral reflectance for a chosen target patch, the spectral transmittance for the chosen IR cut filter, the spectral transmittance for any additional optical component(s), and finally the wavelength-by-wavelength (spectral) product of all of these contributions. Do not edit any of these values on sheet 1; instead, edit the corresponding values in column 2 of the associated sheet.

You can choose a Macbeth patch using the pop-up at the left edge of the first sheet; the spectral calculation for this patch is then represented in the spectral data displayed on that sheet. The CIE chromaticity coordinates of the target patch are computed, and displayed under the title *Colorimetric* at the bottom-right of sheet 1 (page 2, when printed). These coordinates would be reported if the patch were measured by a colorimeter. The chromaticity coordinates of the target patch as sensed by the TCS230 and transformed through the chosen color correction matrix are displayed under the title *Estimated.*

A chromaticity diagram is plotted at the upper right of sheet 1; the familiar horseshoe-shaped spectral locus is evident. The circle (**o**) on the chart represents the CIE chromaticity values of the target patch as computed colorimetrically. The cross (+) on the chart represents the chromaticity coordinates of the target patch, as estimated from TCS230 device values after transformation by the color correction matrix. The line joining the two points represents the direction and the magnitude of the color correction that was imposed on that color. If you choose the *Exact3* matrix and then choose either red, green, or blue as the target patch, you will see that the circle and the cross are precisely overlaid (representing zero error).

Advanced topics

When using this document, please ensure that its revision date (in the footer of page 1) matches the version date of the workbook.

The remainder of this document discusses various advanced topics that are not likely to be important to most users of the workbook. At the end of this document, you will find notes concerning the implementation of the spreadsheet.

CMFs

If you view the CMF sheet, sheet 2, you'll see the CIE color matching function data represented numerically, and *x* and *y* chromaticity values at 10 nm intervals computed from the CMFs. You'll also see the classic CIE chromaticity diagram derived from this data. The sums of the *x*-bar, y-bar, and z-bar data are provided to allow verification against the sums provided on page 58 of CIE Pub. 15.2 (1986).

Illuminants

On sheet 3 you'll find spectral radiance (SPDs) for several illuminants. The spectrum of the chosen illuminant is represented in column B (highlighted orange); the *Illuminant* column (B) of sheet 1 is a duplicate of column B on this sheet. Illuminant selection can be made on this sheet; the pop-up menu here duplicates the illuminant pop-up on sheet 1. A graph of the chosen illuminant is found on this sheet. (The samples at 10 nm intervals are joined by straight lines. These lines are not to be taken literally; they are merely suggestive.)

Should you wish to add an illuminant, do so in one of the *User1*, *User2*, *User3*, or *User4* columns provided. If you provide a name in row 1 of the appropriate column, this name will be reflected in the illuminant pop-up menu.

ColorCheckerSR

On sheet 4 you'll find spectral reflectance values for the 24 patches of the Macbeth ColorChecker, and a patch selection pop-up menu. The pop-up menu here duplicates the illuminant pop-up on sheet 1. When a patch is selected, its spectrum is copied into column B (highlighted orange); the *Target* column (B) of sheet 1 is then duplicated from column B on this sheet. A graph of the chosen illuminant is found on this sheet.

Should you wish to compute a custom target, enter its spectral reflectance into column B. The workbook is constructed so that those values will be reflected in the appropriate cells of sheet 1.

If on sheet 1 you choose the D_{50} illuminant, the *Xcc*, *Ycc*, and *Zcc* rows on the ColorCheckerSR sheet will reflect the published CIE tristimulus values of the Macbeth chart; the rows *L*cc*, *a*cc*, and *b*cc* immediately below will reflect the published LAB values.

IR cut

On sheet 5 you'll find spectral transmittance values a representative IR cut filter, from Arcus. Also included is a set of unity values, representing the absence of an IR cut filter. A graph of the spectral transmittance of the chosen IR filter is found on this sheet. There are also potential choices for *User1, User2,* and *User3.* As on the Illuminant sheet, you can enter your own data into the *User1, User2,* or *User3* columns; if you insert *a* title into row 1, that name will appear in the IR cut pop-up menu.

Optical

Sheet 6 provides for specification of the spectral transmittance of any optical components apart from the IR cut filter. The values entered into the highlighted column (2) will be reflected on sheet 1.

TCS230

Sheet 7 supplies representative TCS230 spectral sensitivity data. Normally you will not need to modify anything on this sheet.

Spreadsheet implementation notes

There is a hidden sheet named *private* that contains data that produces the pop-up menus. Should you wish to view the hidden sheet, choose *Format → Sheet → Unhide … .* Row 1 contains the numerical index of the pop-up choice for each of the 4 menus (Illuminant, Target, Matrix, and IR cut). Remaining rows of the sheet provide the pop-up choices; these values are copied (as transposed array references) from the headings in row 1 of the corresponding sheets. The *private* sheet also carries the Visual Basic code that implements the pop-up menus. Should you wish to view the Visual Basic code, choose *Tools → Macro → Macros … .*

The chromaticity diagram on sheet 1 plots data corresponding to the spectral locus, taken from the *CMF* sheet. The colorimetric "aim" point (o) and the estimated target chromaticity coordinates (+) are plotted as sole points in two series; a fourth series comprises just the line between them.

Normalization strategy

On sheet 1, the 3-element column vector named *RefWhiteXYZ* represents CIE illuminant D_{65}; this illuminant is the reference for the calculation of LAB values that is performed on the ColorCheckerSR sheet. The x and y chromaticity values for that illuminant are computed immediately below.

The *IllNorm* column vector on sheet 1 is computed as the tristimulus (*XYZ*) values of the chosen illuminant illuminating the white patch of the ColorChecker, scaled by the reference illuminant.

On the TCS230 sheet, the raw device sensitivity values in columns B, C, and D are as measured at TAOS. For purposes of matrix computation, we assume that the sensor system developer will implement gain adjustment in the device channels: We assume that gain will be adjusted to produce equal signal values – here, assumed to be unity – when sensing a white patch illuminated by the chosen illuminant. That calculation produces the values in columns E, F, and G. The column sums are formed in row 40, and the reciprocals of those sums are formed and placed in a diagonal matrix (named *DevNorm*) in F41:G43. The raw device sensitivities are matrix-multipled by this diagonal matrix so as to scale the columns and form the normalized device sensitivities (*DevSS*) in I2:K39. The 3-element row vector in I41:K41 is compted by simulating use of the chosen illuminant to illuminate the white patch, to propagate this spectrum through the chosen IR cut filter, then sense the resulting spectrum through the notrmalized device sensitivities. Computed values of unity serve to verify the device normalization computations.

The upper portion of the ColorCheckerSR sheet, rows 2 through 39, contain spectral reflectance values. Row 40 contains the patch names. The rows labelled *Xcc*, *Ycc*, and *Zcc* compute the CIE tristimulus values of the patches as illuminated by the chosen illuminant; the rows *L*cc*, *a*cc*, and *b*cc* immediately below compute the LAB values.

The rows labelled *Rraw*, *Graw*, and *Braw* compute the raw, normalized values of the patches as illuminated by the chosen illuminant. The rows labelled *Xcorr*, *Ycorr*, and *Zcorr* below compute the estimated tristimulus values of the patches through matyrix multiplication of the device triplets by the chosen 3×3 color correction matrix. The rows *L*corr*, *a*corr*, and *b*corr* immediately below compute the corresponding LAB estimates.

Finally, the *DeltaE* row computes the Euclidean distance between the colorimetric LAB values and the estimated LAB values for each patch; the average delta-*E* is then computed in cell A63. This value is copied onto sheet 1.

A border is drawn around the *XYZ*, colorimetric *LAB*, device *RGB*, estimated *XYZ* and *LAB*, and delta-*E* values of the red, green, and blue patches. The border represents the grouping of these three patches in the computation of the *Exact3* matrix. A border is drawn around the values in the column corresponding to the white patch; the border represents the use of this patch in the illuminant normalization calculations. ■