RIT Rochester Institute of Technology

TELELUMEN
The Recording and Playback of Light

Programmable Spectrum Luminaires and Measuring Daylight

Steve Paolini
President, Telelumen LLC
March 2023

Agenda

- Introduction
- Products in action
- Light sources, Objects, Observers
- Daylight – graphs and pictures including Como and Yosemite
- Software, Content, and Controls
- Summary

Steve Paolini
President
Telelumen LLC

Bio: Steve earned a BSEE from Penn State University in 1981 and joined Hewlett Packard, Optoelectronics Division. While at HP he held a variety of engineering and management positions in California, Japan, and Malaysia. In 2000 he joined Lumileds as a founding member. In 2007 he founded Telelumen, where he is currently the President. He was also the CTO at Lunera Lighting and the CTO at NEXT Lighting. He speaks frequently on a variety of topics related to solid state lighting, particularly daylight replication, and holds 25 issued patents.

- Founded 2007 – Saratoga, CA
- Purpose – Replicate any spectral power distribution
  - Products and services to record and playback light
- Privately owned
- Products:
  - Octa (various 8 color light player luminaires)
  - Dittosizer (24 channel light player luminaire)
  - Spectraloc – control software
  - Content – spectrometer recordings, Lumenscripts

Programmable Spectrum Markets

- Consumer electronics – cameras, displays, sensors
- University and hospital labs – circadian health
- University and government labs – lighting research
- Supply chain – Critical color control

Programmable Spectrum vs. Color Tuning

- Telelumen focuses on spectrum and change with time
  - Replicate actual daylight SPD not just CCT
  - Render human skin accurately
- Others focus on static RGB color
- Telelumen focuses on radiometry (physics)
- Others focus on photometry (standard observer)
- Telelumen focuses on efficiency, peak wavelength, SPD
- Others focus on efficacy, dominant wavelength, CCT

Octa Light Players 20000K to 1500K

LESA Lighting Enabled Systems & Applications

A National Science Foundation Engineering Research Center

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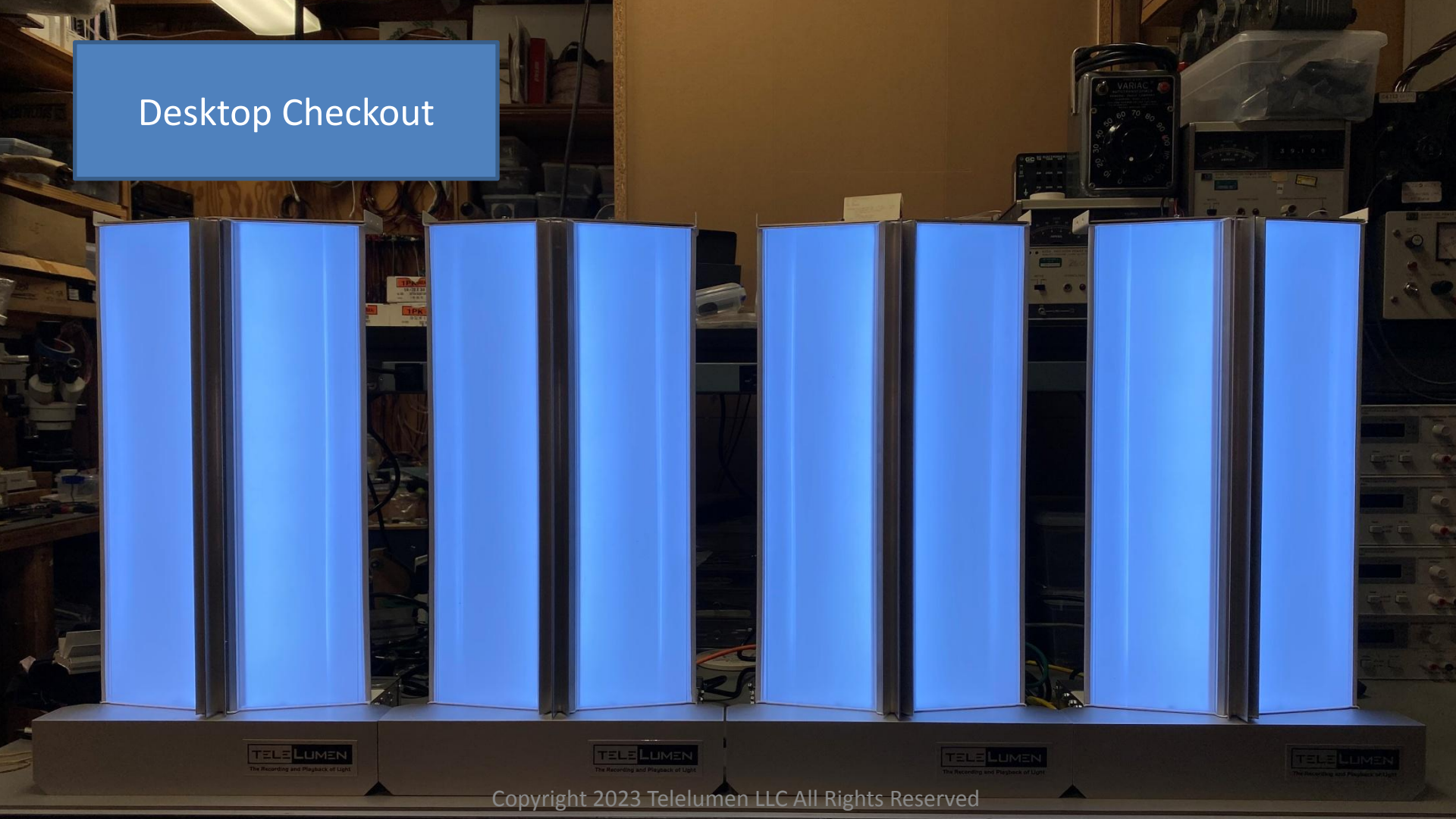
A National Science Foundation Engineering Research Center

THE UNIVERSITY OF NEW MEXICO
HEALTH SCIENCES CENTER

Shown above left are Telelumen Octa Light Players set to a mode enriched in short wavelengths and above right is the same system enriched in long wavelengths at an intensive care unit (ICU) in the Jefferson Hospital for Neuroscience in Philadelphia, PA (2019).

Octa Checkout

Desktop Checkout



Light Booth Checkout

Association of Textile, Apparel & Materials Professionals

What is Daylight?

- Circadian, Human Centric, Healthy, but…
- A fundamental aspect is the overall experience.
- Daylight is complex. The SPD changes with:
  - time of day
  - the weather
  - time of year
  - place on earth
  - your immediate environment – window, sidewalk, park, …
  - It’s processional – sun, shadows move during the day

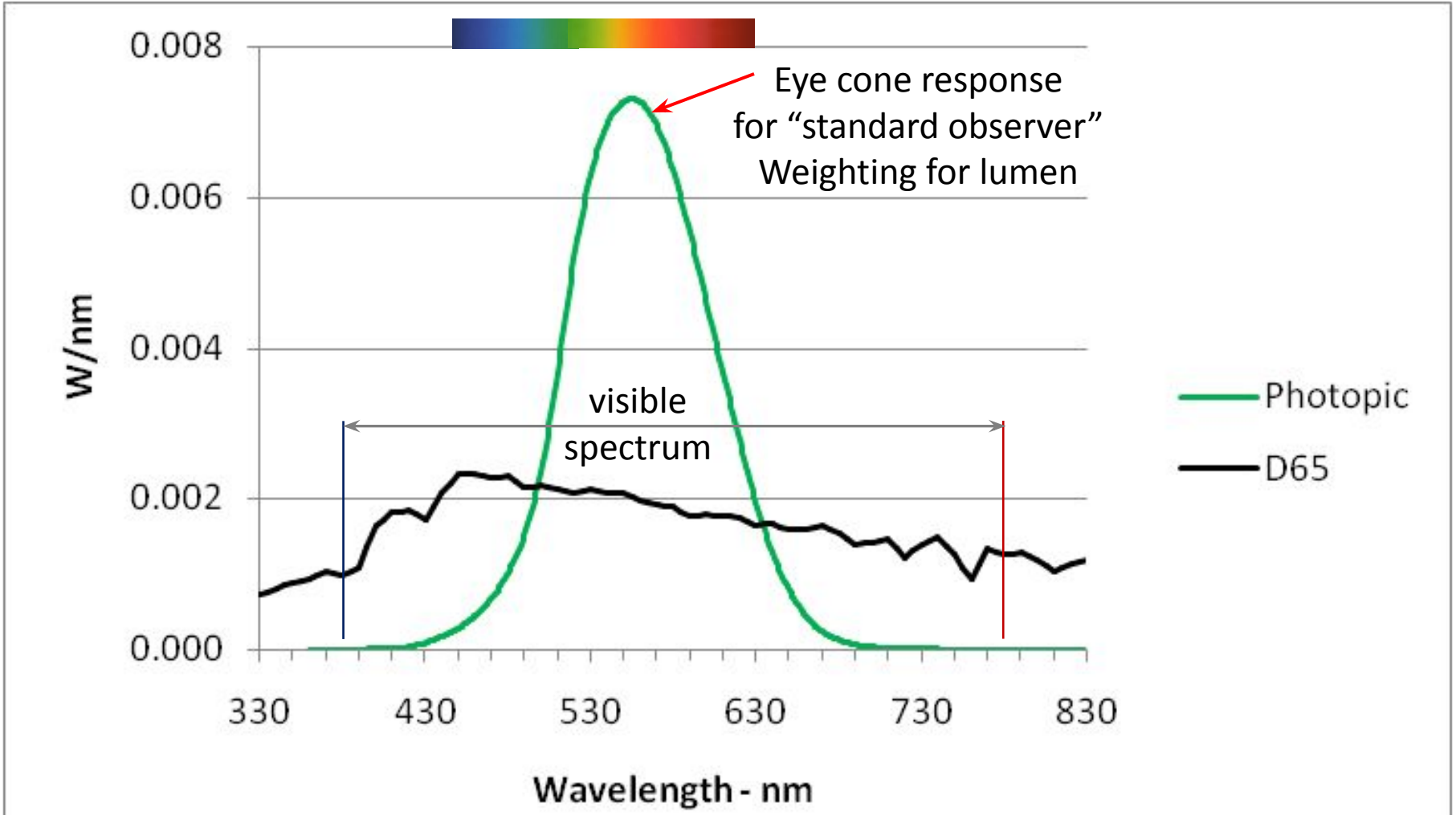
Sun ring (halo)
Saratoga, CA

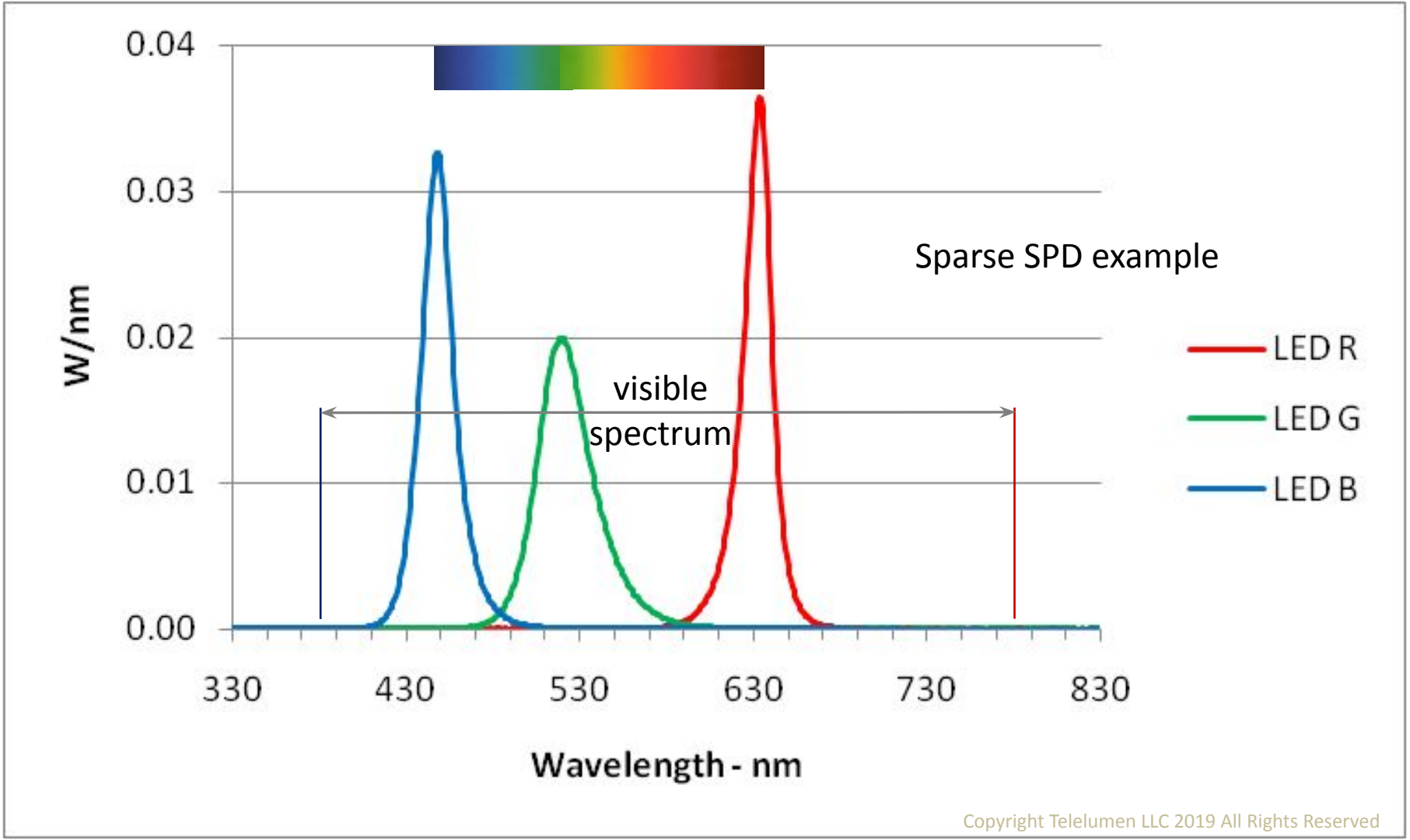
Fish tank refracting daylight on wood floor – Oak Park, CA

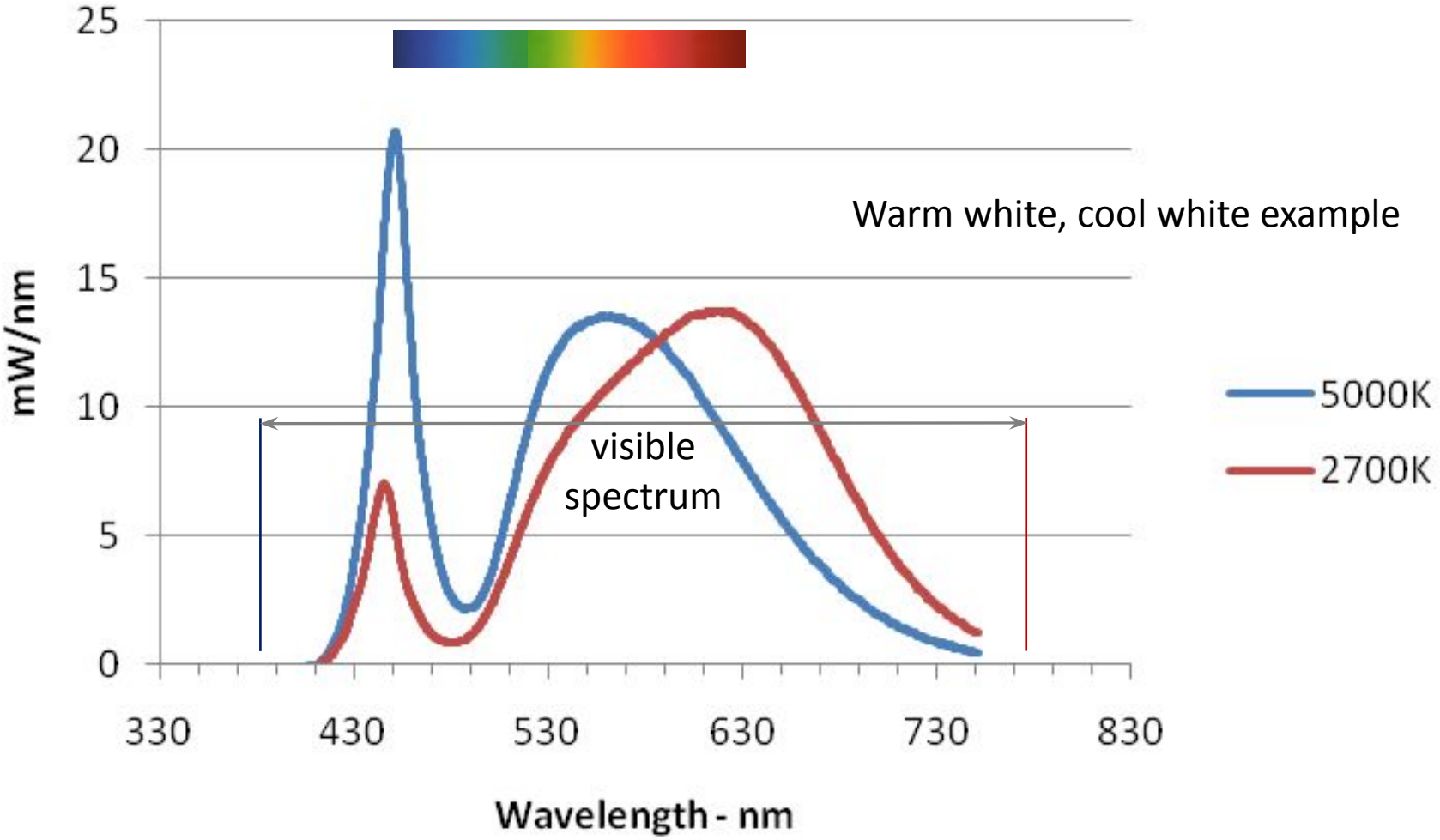
NOTE: Some colors in this image are false because they lie outside the camera and display gamut.

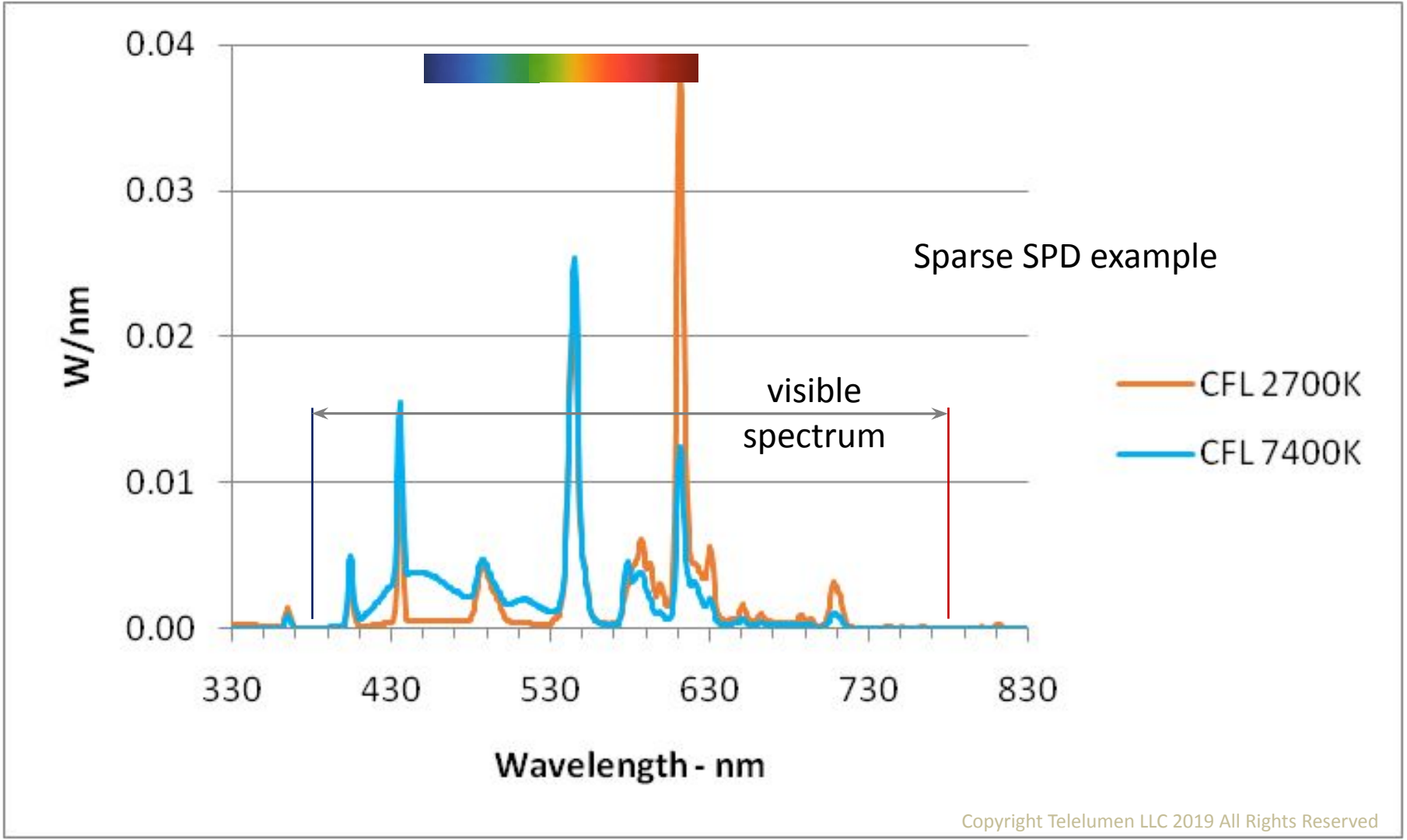
Daylight Experience

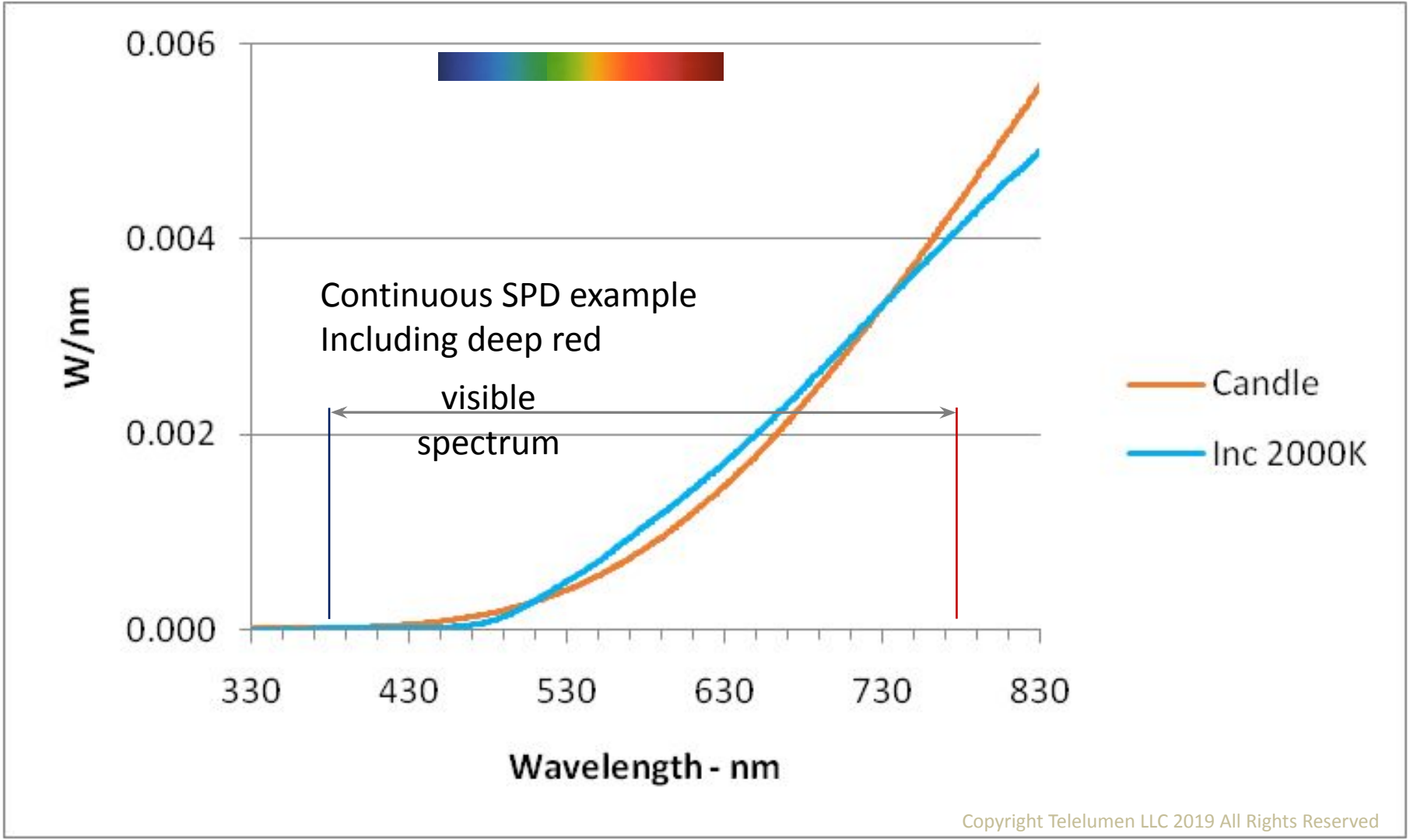
- Continuous SPD in the visible spectrum (380 – 780 nm) and beyond
- Continuous change with time
  - Both daylight itself and personal location/gaze
- Color temperatures are much higher than typical electric light
  - Deep red >650 nm is critical
- Photometrics are not sufficient to represent the daylight experience.
  - Chromaticity is typically not on the black body or daylight locus
  - CCT does not define the SPD
- When energy use is important efficiency is better than efficacy
  - Optical Watts vs. Lumens per Watt



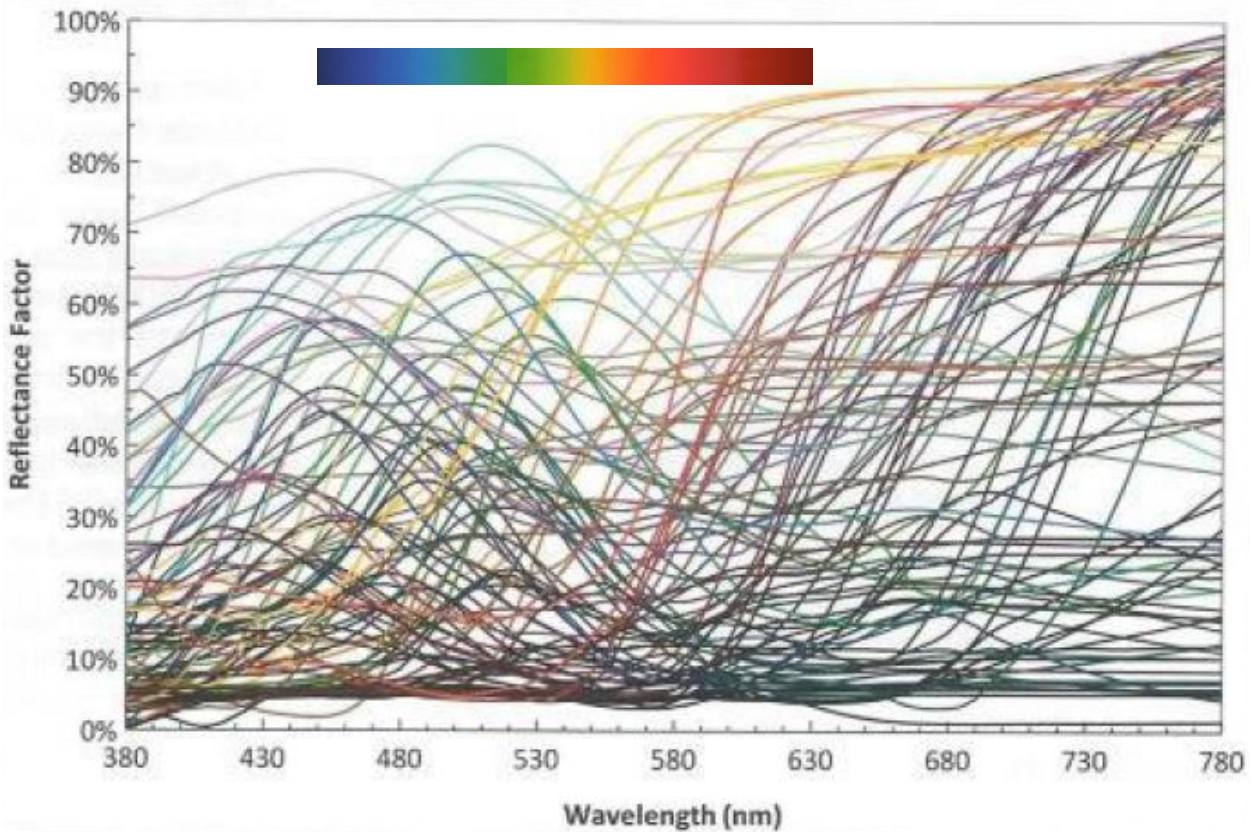








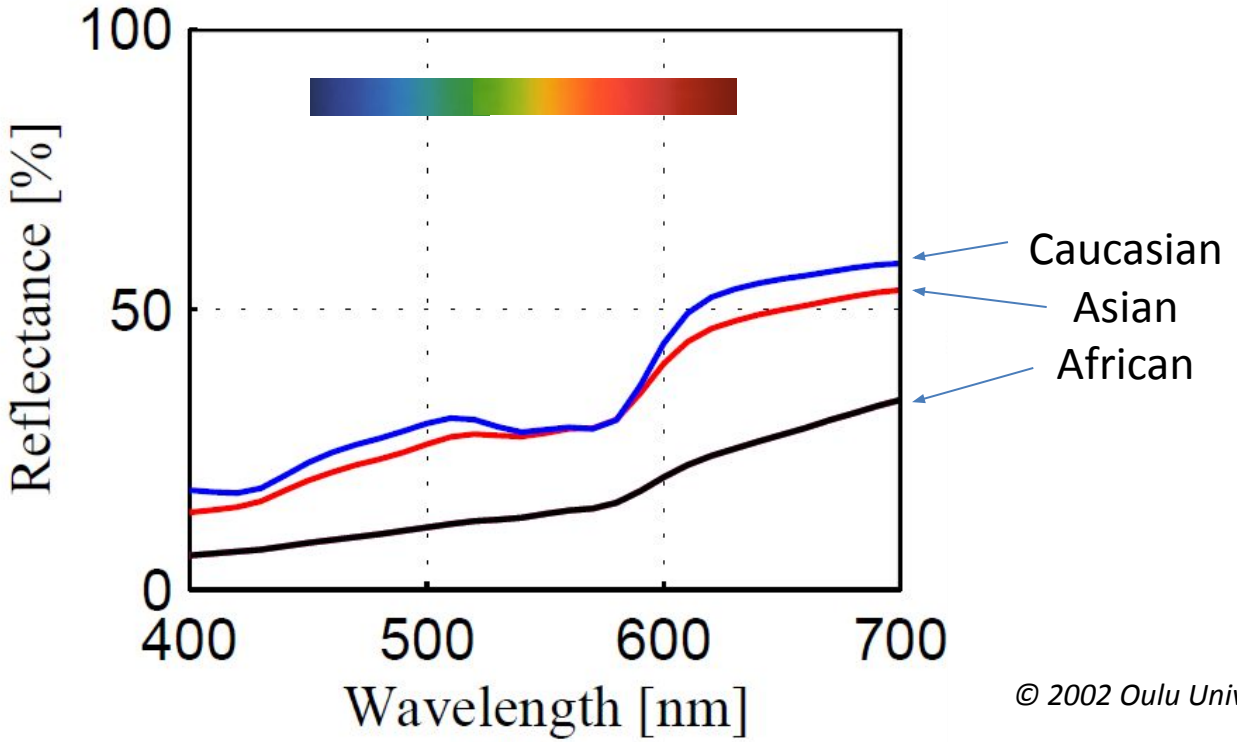
TM-30 Objects



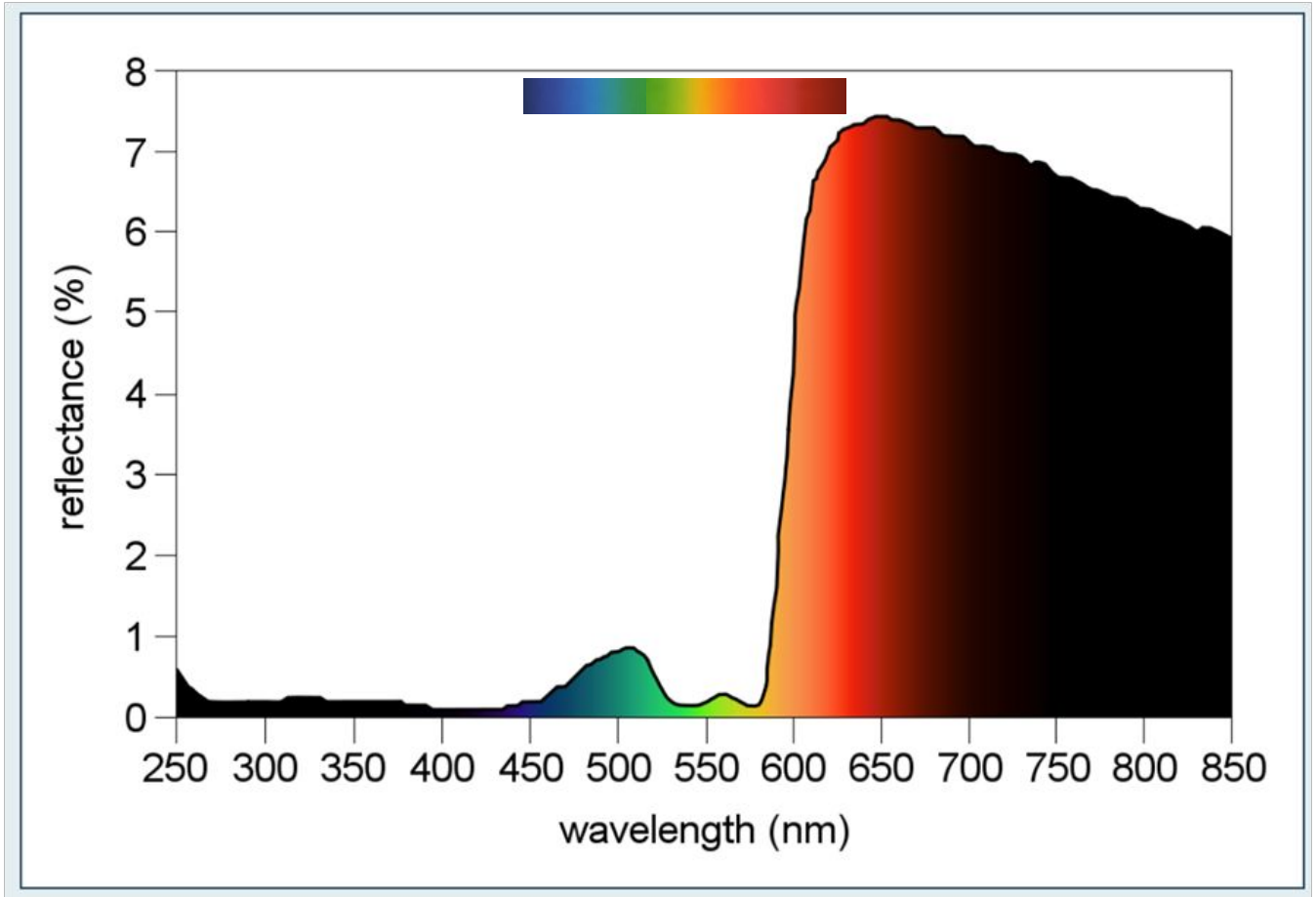
Courtesy of Michael Royer, PNNL

Deep Red is Key to Proper Skin Rendition

About half the response is >600nm

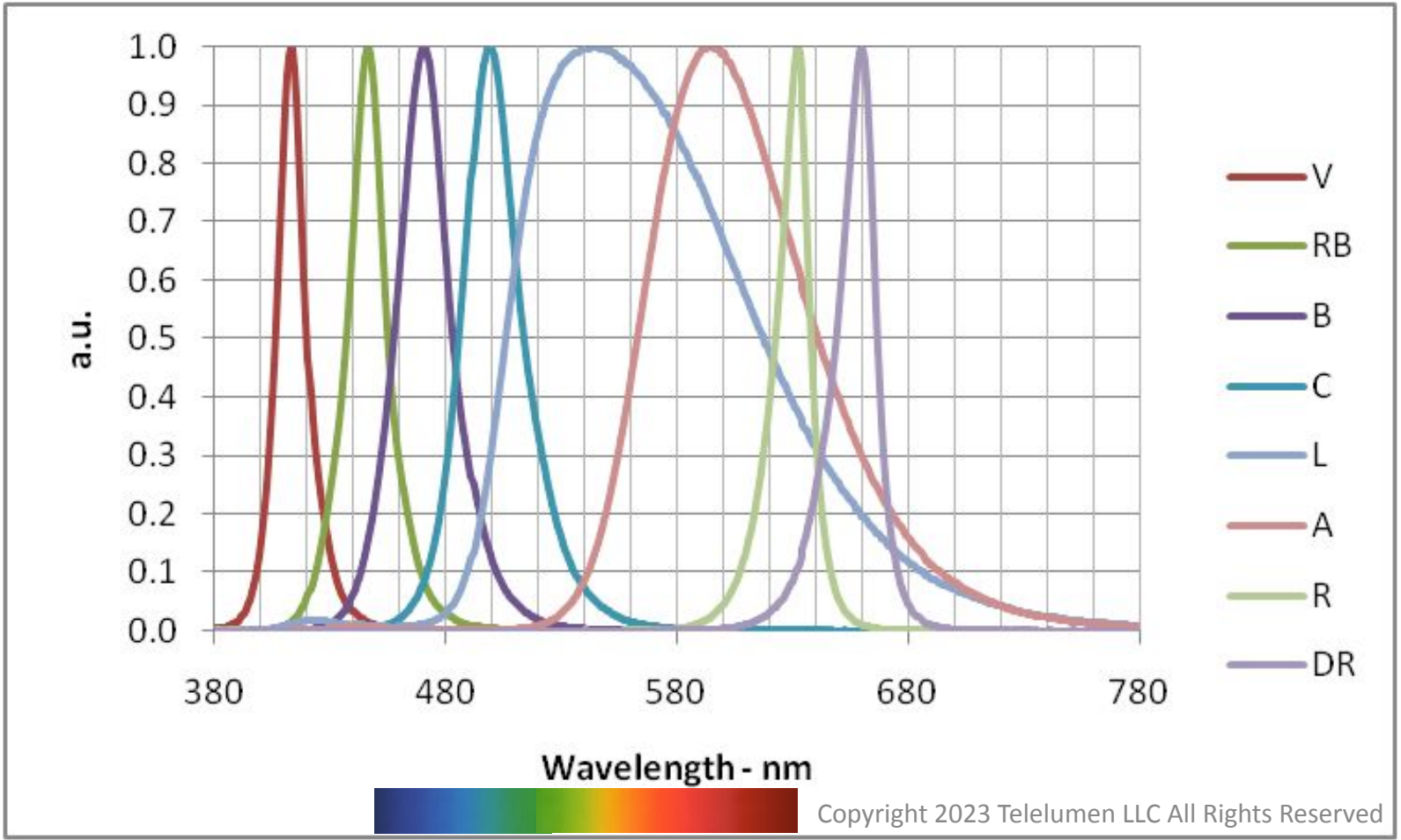


From: ”Face colour under varying illumination”, Chapter. 4; http://herkules.oulu.fi/isbn9514267885/html/i1030756.html

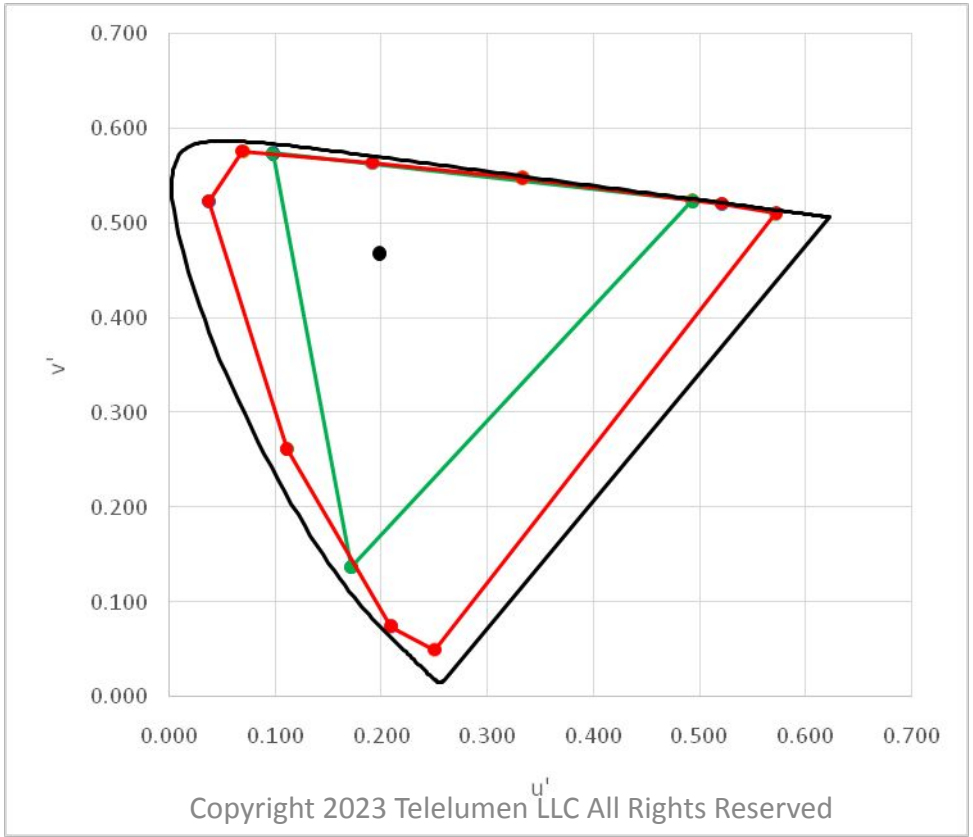


Diffuse reflectance of human blood with a hematocrit of 33%, oxygen saturation of 100%, and mean cell volume of 83 femtoliters. Public Domain Image, data source: M. Meinke, image source: Christopher S. Baird.

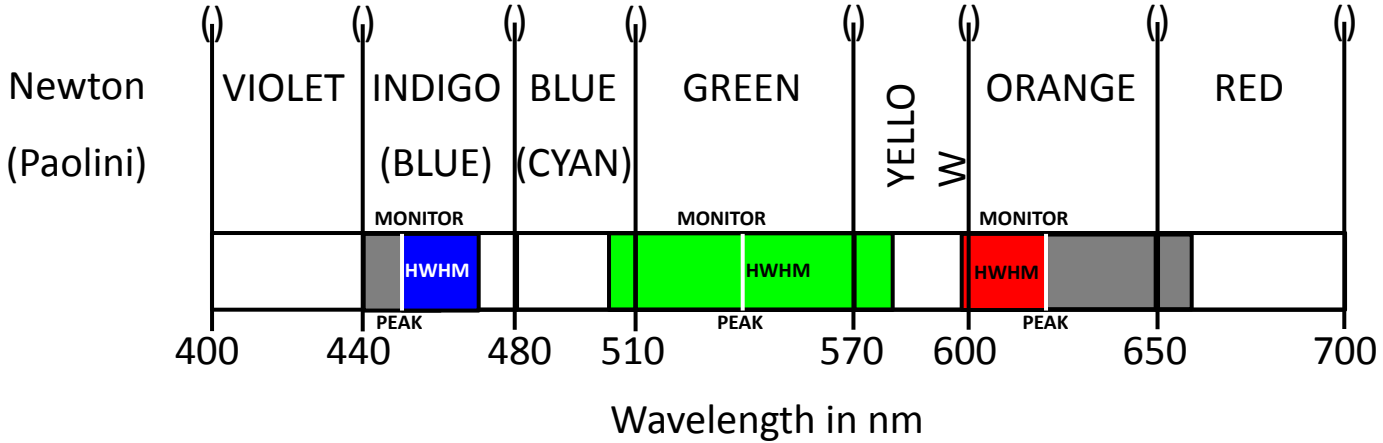
“Continuous” SPD means 7 or more colors – ROYGBIV



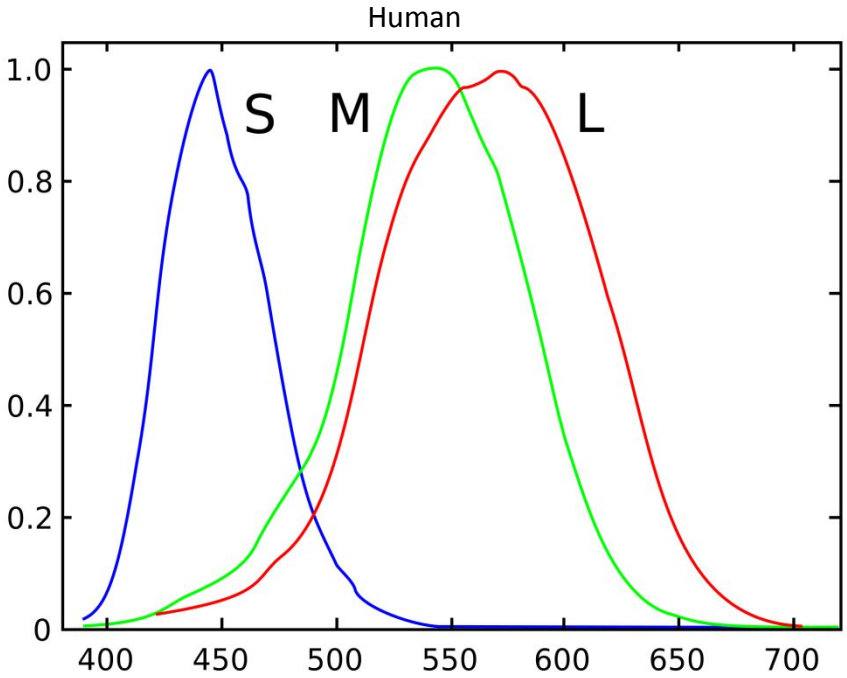
OLED Display vs. “Continuous” Luminaire



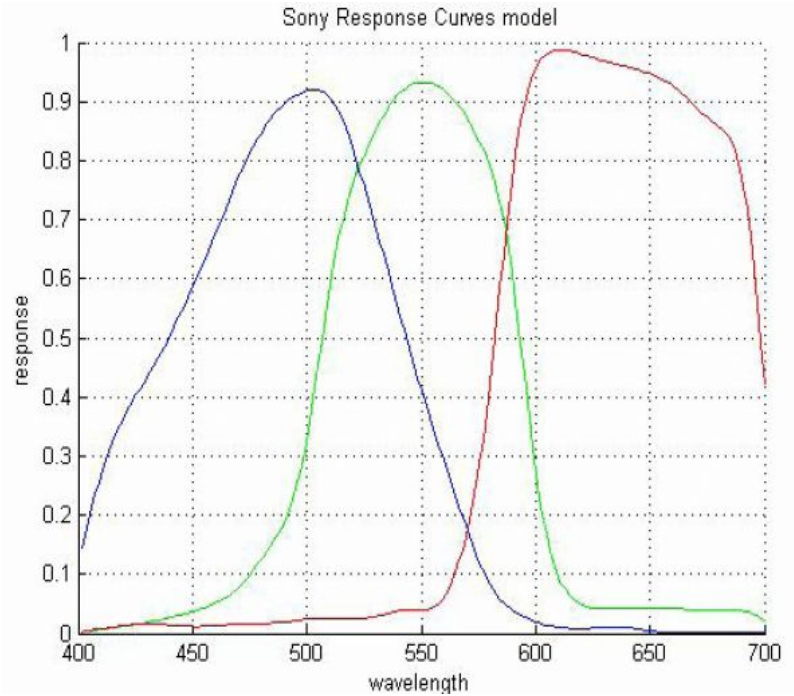
Color Words and Wavelength



Observers

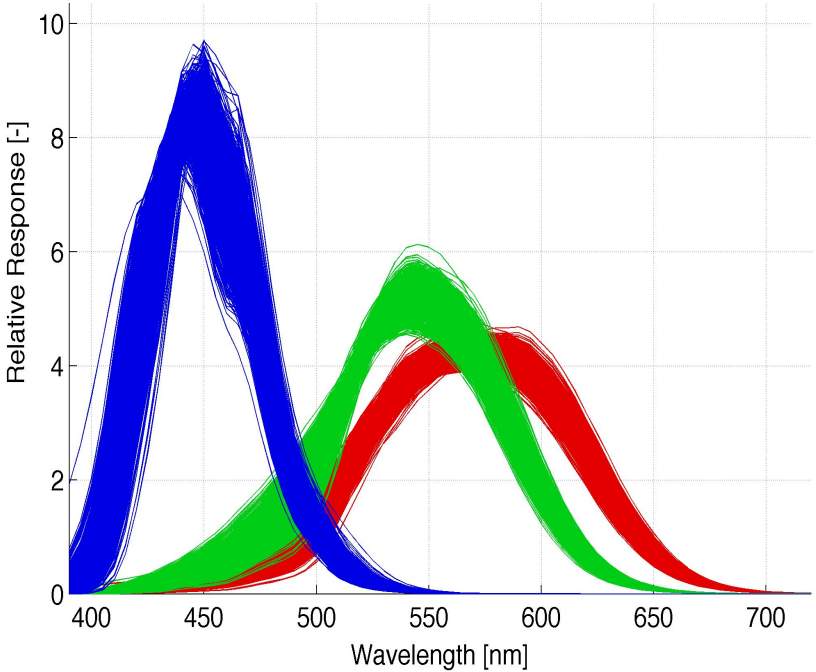


https://en.wikipedia.org/wiki/LMS_color_space

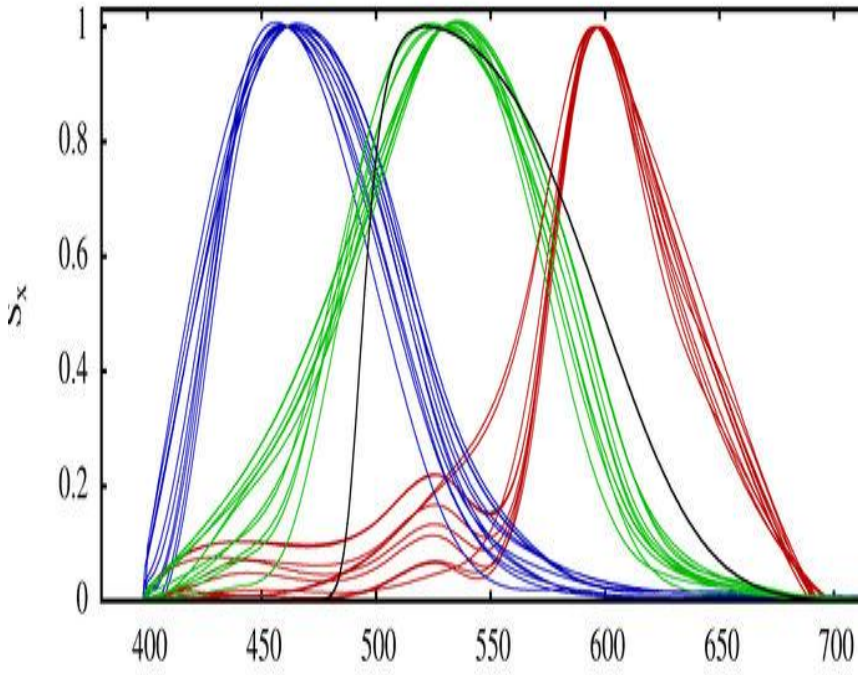


https://www.researchgate.net/figure/Spectral-sensitivity-of-the-CCD-in-a-Sony-digital-camera_fig6_285821904

Observers



https://www.rit.edu/science/sites/rit.edu.science/files/2019-01/MCSL-Observer_Function_Database.pdf



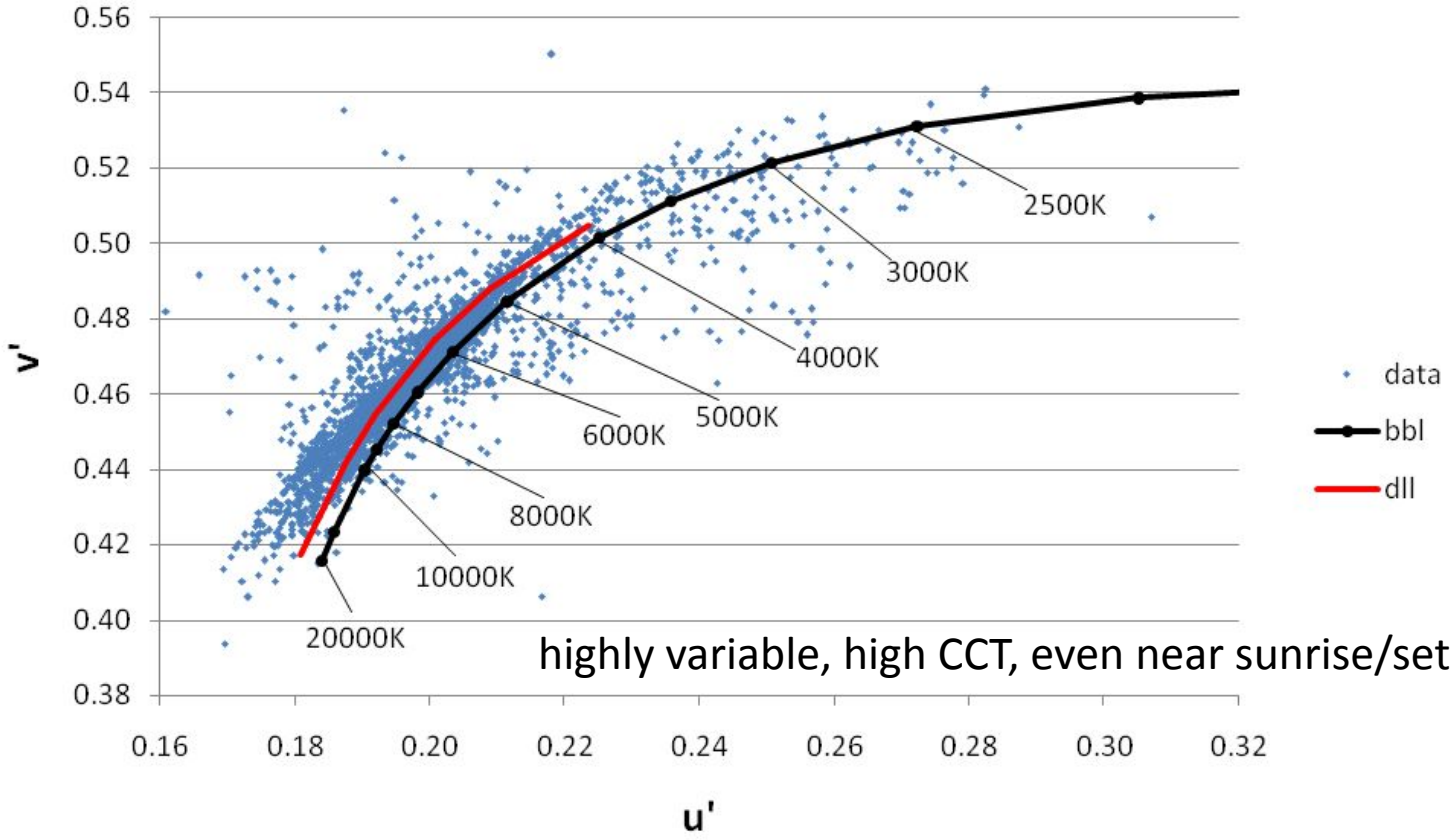
https://www.researchgate.net/figure/Typical-spectral-sensitivity-curves-of-commercial-digital-cameras-with-RGB-bands-The_fig1_342113086

Handheld Spectrometer examples

Latest Addition –
Waiting for Someone to Start Making Recordings

Daylight Data

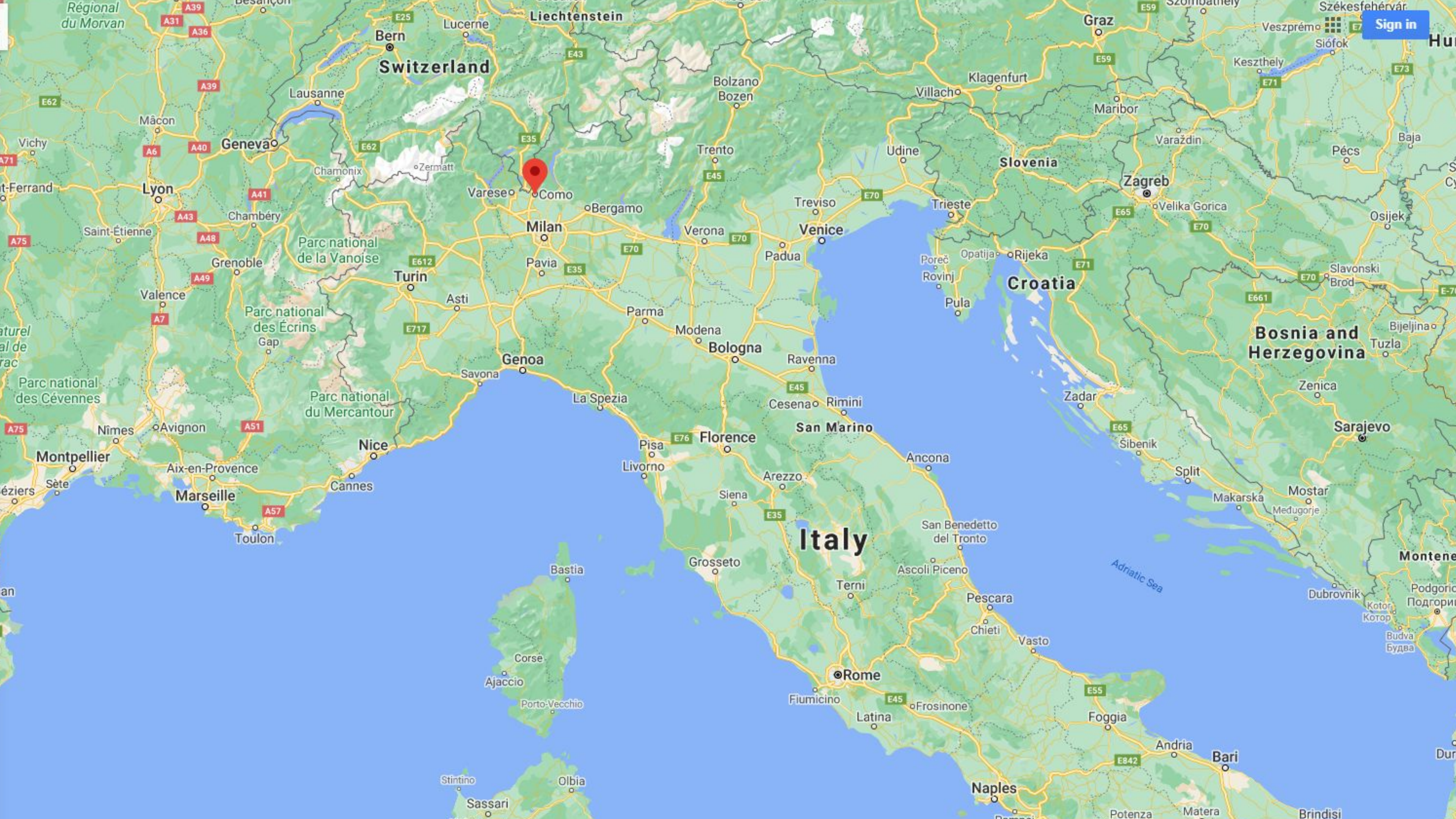
Aug15 to Jun20 (2700 recordings)



highly variable, high CCT, even near sunrise/set

Sample of Recording Locations

Abisko, Sweden	Göteborg, Sweden	Newark airport	Shinagawa, Japan
Akihabara, Japan	Guzhen, China	Newport Beach, CA	Shinjuku, Japan
Banglore, India	Houston airport	Orlando, FL	Singapore
Bolonga, Italy	Irvine, CA	Palo Alto, CA	Sishane, Turkey
Brännö Island, Sweden	Istanbul, Turkey	Panama City	Somerset, PA
Bregenz, Austria	Kingsten, Sweden	Penang, Malaysia	Stockholm, Sweden
Burbank airport	Kuala Lumpur, Malaysia	Point Vicente, CA	Styrsö Island, Sweden
Charlotte, NC	Lapland, Norway	Raleigh-Durham airport	Sunnyvale, CA
Cleveland, OH	Las Vegas, NV	Saltholmen, Sweden	Taipei, Taiwan
Como, Italy	Malpensa airport	San Diego, CA	Taoyuan airport
Dallas, TX	Melbourne, FL	San Jose, CA	Uppsala, Sweden
Deep Creek, MD	Millbrae, CA	Santa Clara, CA	Various airplane windows in flight
Del Garda, Italy	Monterey Bay aqurium, CA	Santa Cruz, CA	Wexford, PA
Delhi, India	Mt. Hamilton, CA	Santa Monica, CA	Wilmington, NC
Denver airport	Munich, Germany	Saratoga, CA	Woodside, CA
Frankfurt, Germany	Narita airport	San Francisco airport	Yokohama, Japan
Gaithersburg, MD	Nashville, TN	San Francisco bay bridge	Yosemite, CA
Garching, Germany	New Market, MD	Shanghai, China	


Sign in
Switzerland
Liechtenstein
Bern
Lucerne
Lausanne
Geneva
Zermatt
Chamonix
Varese
Como
Bergamo
Milan
Pavia
Turin
Asti
Genoa
Savona
La Spezia
Parma
Modena
Bologna
Ravenna
Cesena
Rimini
San Marino
Verona
Padua
Venice
Treviso
Trento
Bolzano
Bozen
Udine
Trieste
Villach
Klagenfurt
Graz
Maribor
Slovenia
Zagreb
Velika Gorica
Varaždin
Croatia
Rijeka
Opatija
Poreč
Rovinj
Pula
Zadar
Šibenik
Split
Makarska
Mostar
Međugorje
Dubrovnik
Kotor
Budva
Sarajevo
Zenica
Tuzla
Bijeljina
Bosnia and Herzegovina
Osijek
Slavonski Brod
Pécs
Baja
Keszthely
Siófok
Veszprém
Székesfehérvár
Florence
Pisa
Livorno
Arezzo
Siena
Grosseto
Italy
Ancona
San Benedetto del Tronto
Ascoli Piceno
Terni
Pescara
Chieti
Vasto
Rome
Fiumicino
Latina
Frosinone
Foggia
Andria
Bari
Naples
Potenza
Matera
Brindisi
Adriatic Sea
Bastia
Corse
Ajaccio
Porto-Vecchio
Olbia
Sassari
Stintino
Nice
Cannes
Marseille
Toulon
Aix-en-Provence
Avignon
Nîmes
Montpellier
Sète
Lyon
Saint-Étienne
Grenoble
Chambéry
Valence
Gap
Mâcon
Vichy
Parc national de la Vanoise
Parc national des Écrins
Parc national du Mercantour
Parc national des Cévennes
du Morvan
E25
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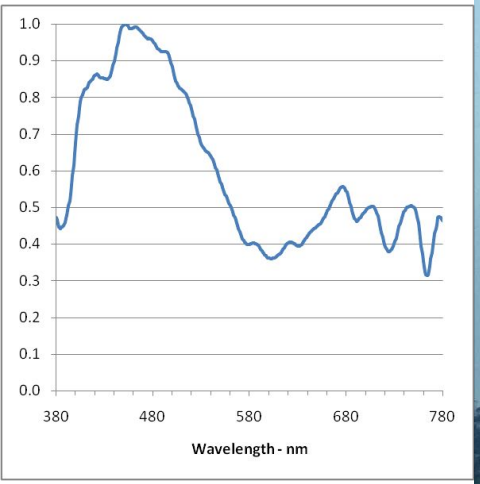
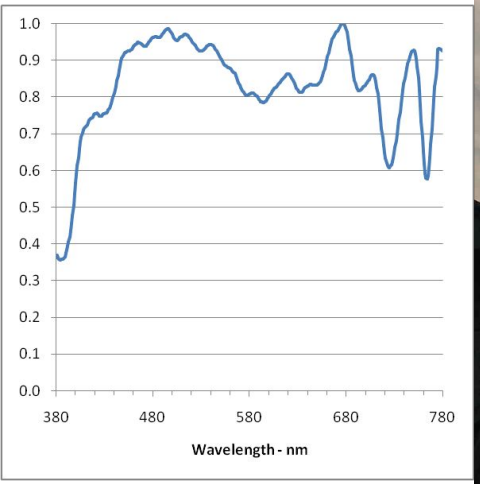
E65
E661
A39
A31
A36
A6
A40
A41
A43
A48
A49
A7
A75
A51
A57

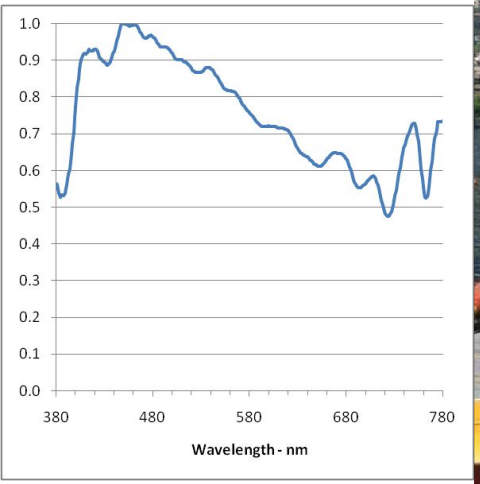
Place	Como, Italy
Date	28-May-16
Time	0537
Lux	159
CCT	14292
CRI	93
u	0.176
v	0.431
duv	0.010



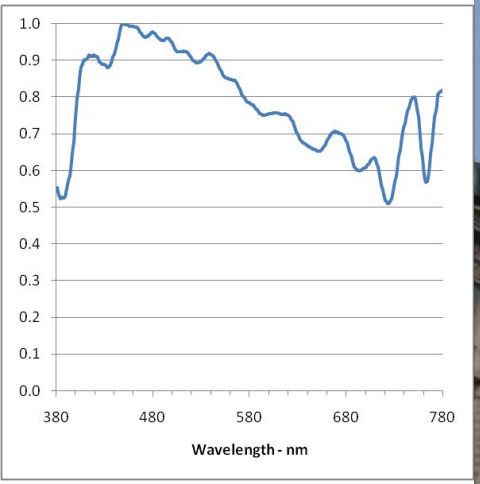
Place	Como, Italy
Date	28-May-16
Time	0631
Lux	2990
CCT	5868
CRI	97
u	0.202
v	0.475
duv	0.003



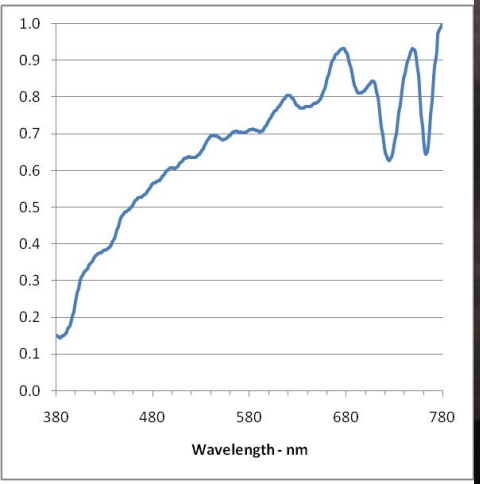
Place	Como, Italy
Date	28-May-16
Time	1042
Lux	9616
CCT	7052
CRI	99
u	0.196
v	0.462
duv	0.002



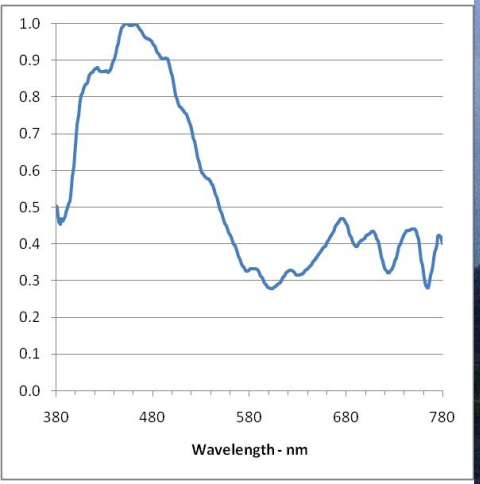
Place	Como, Italy
Date	28-May-16
Time	1726
Lux	6051
CCT	6753
CRI	99
u	0.197
v	0.465
duv	0.003

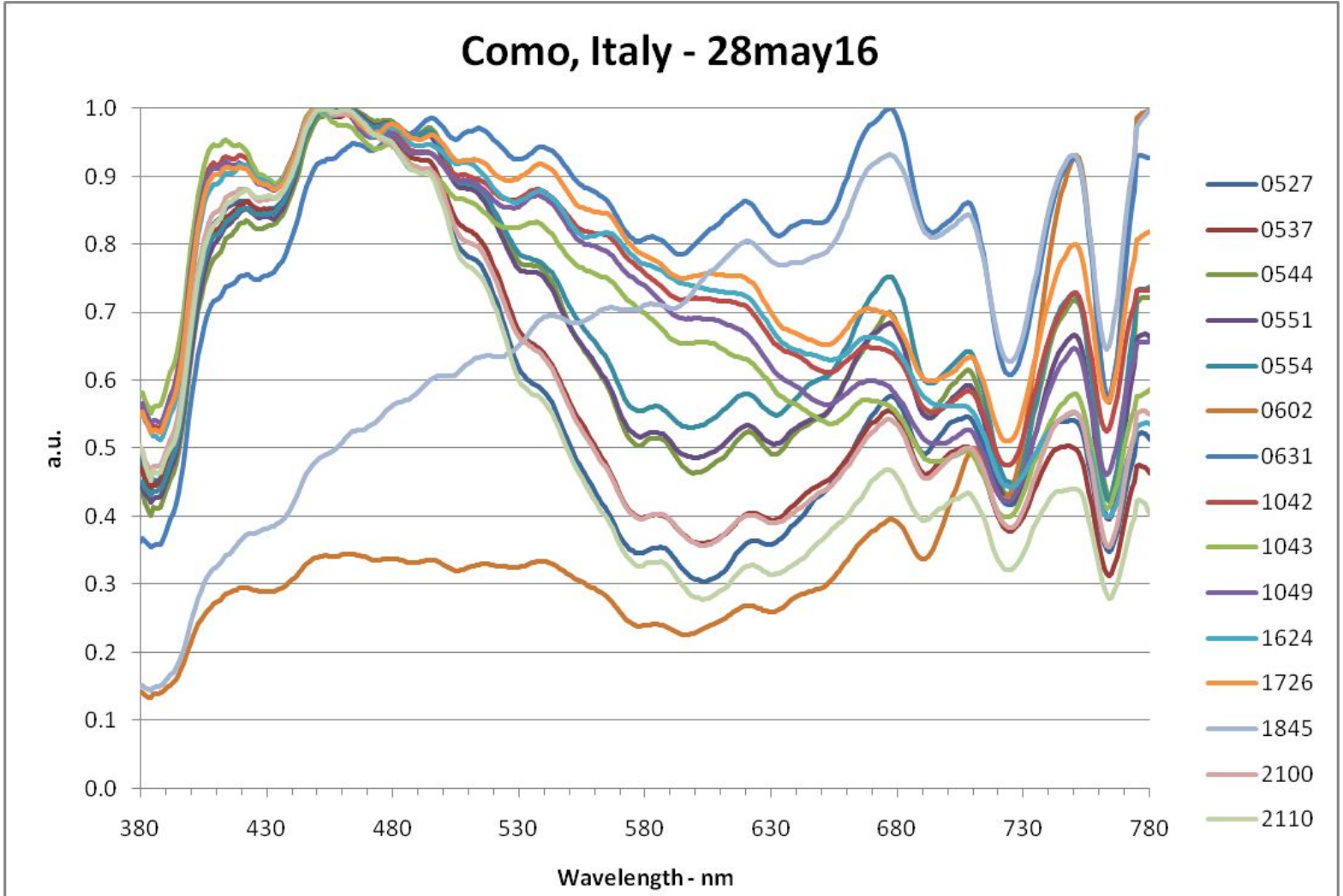


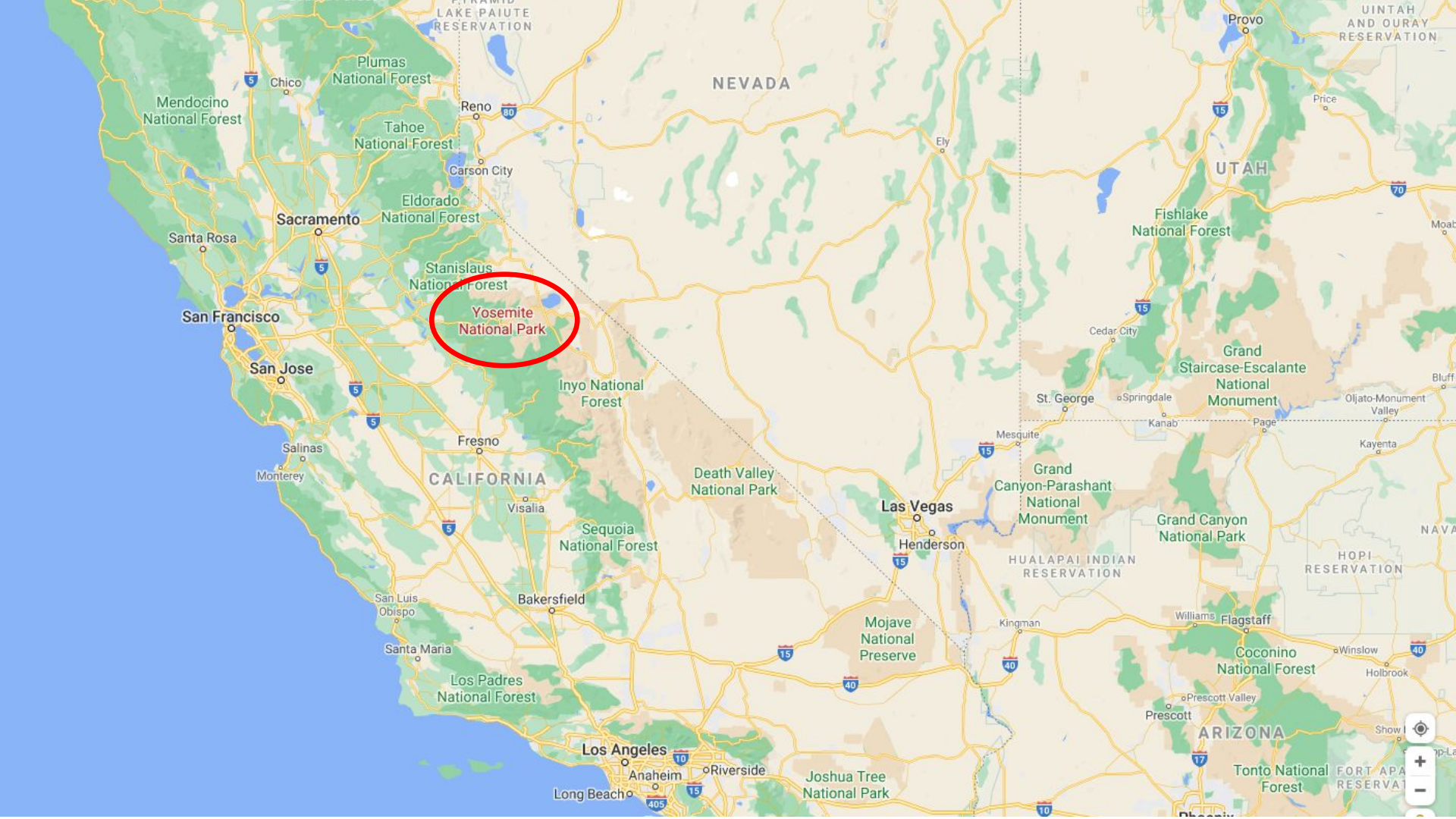
Place	Como, Italy
Date	28-May-16
Time	1845
Lux	33150
CCT	4188
CRI	98
u	0.222
v	0.498
duv	0.000

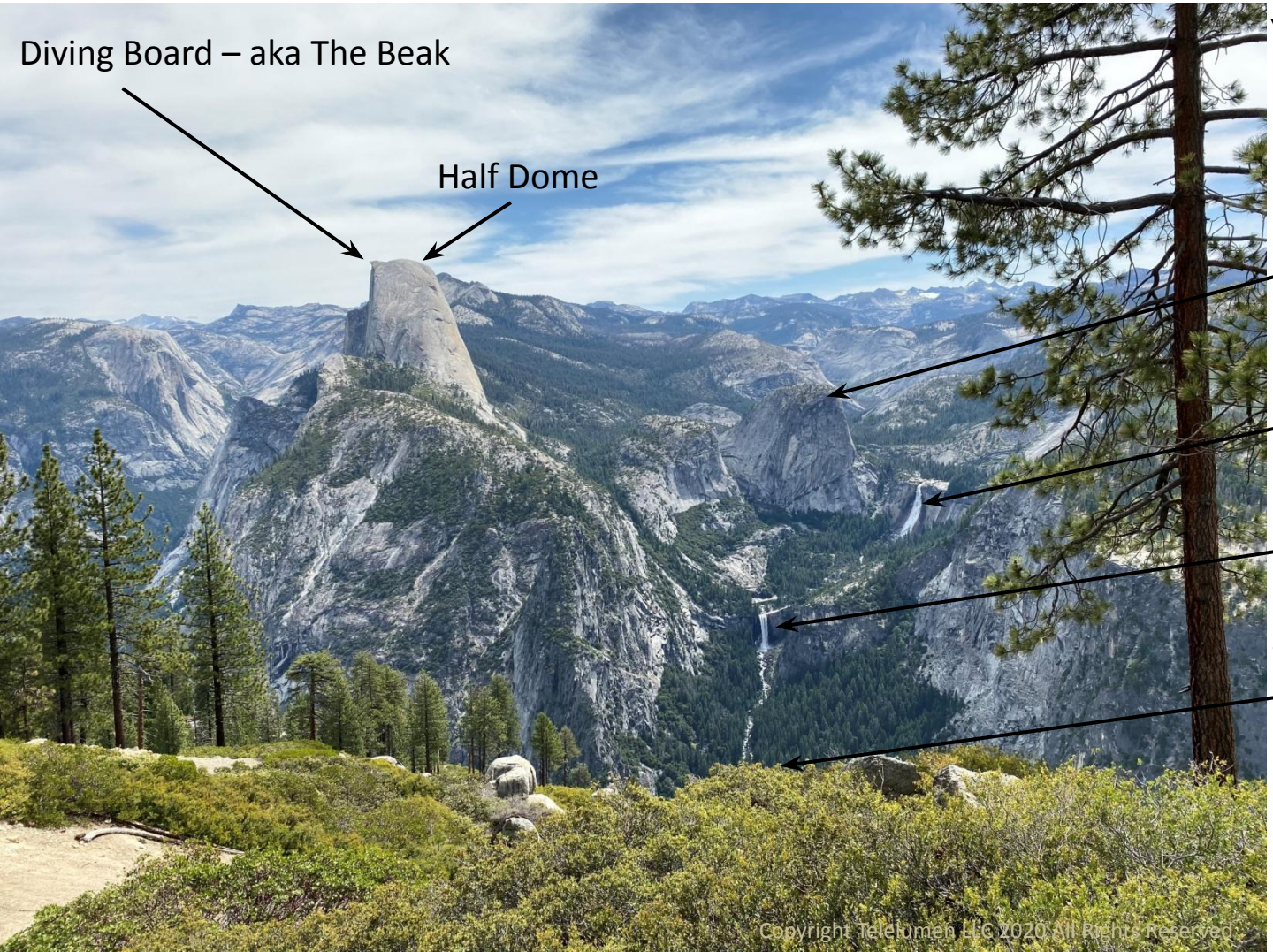


Place	Como, Italy
Date	28-May-16
Time	2110
Lux	55
CCT	25127
CRI	91
u	0.171
v	0.417
duv	0.013





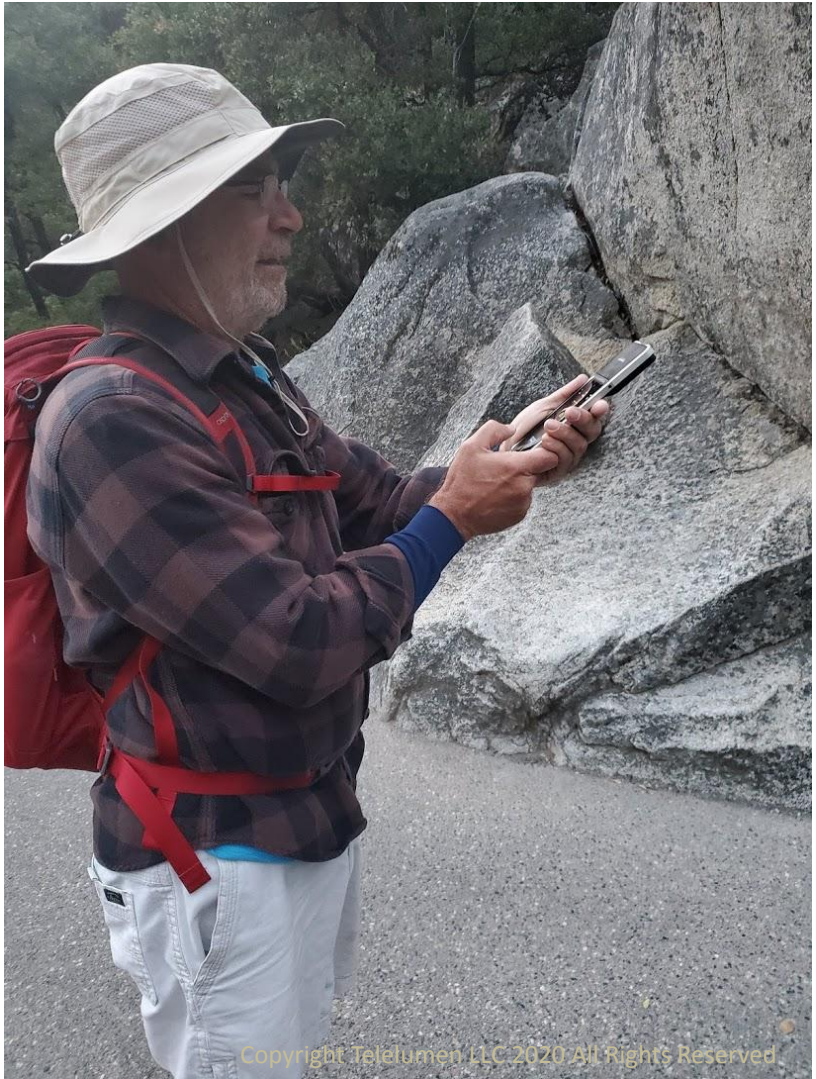

LAKE PAIUTE RESERVATION
Plumas National Forest
Chico
Mendocino National Forest
Reno
NEVADA
Tahoe National Forest
Carson City
Eldorado National Forest
Sacramento
Santa Rosa
Stanislaus National Forest
Yosemite National Park
San Francisco
San Jose
Inyo National Forest
Salinas
Monterey
Fresno
CALIFORNIA
Visalia
Death Valley National Park
Las Vegas
Henderson
Sequoia National Forest
Bakersfield
San Luis Obispo
Santa Maria
Los Padres National Forest
Mojave National Preserve
Los Angeles
Anaheim
Riverside
Long Beach
Joshua Tree National Park
Provo
UINTAH AND OURAY RESERVATION
Price
Ely
UTAH
Fishlake National Forest
Cedar City
Grand Staircase-Escalante National Monument
St. George
Springdale
Kanab
Page
Mesquite
Kayenta
Grand Canyon-Parashant National Monument
Grand Canyon National Park
HUALAPAI INDIAN RESERVATION
HOPI RESERVATION
Kingman
Williams
Flagstaff
Coconino National Forest
Winslow
Holbrook
Prescott Valley
Prescott
ARIZONA
Tonto National Forest



Yosemite National Park, California 14jun20

June 14, 2020

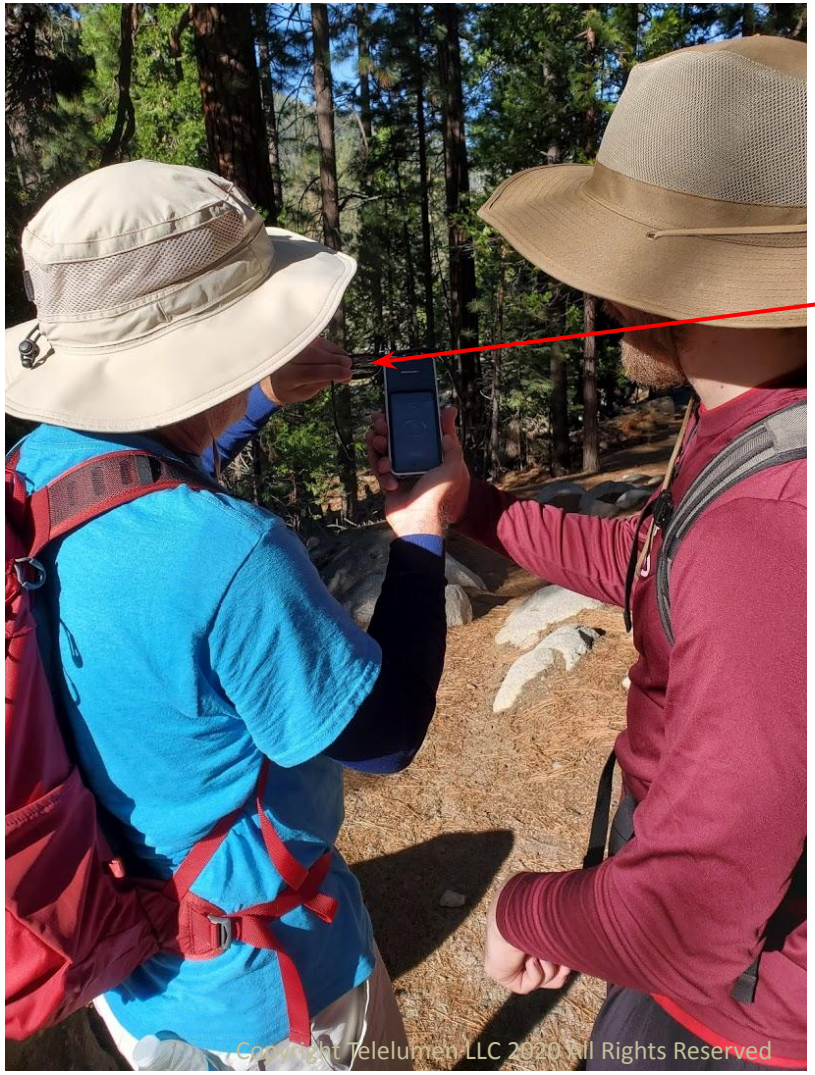
0503 – The hike begins.



0526 – Typical recording posture.

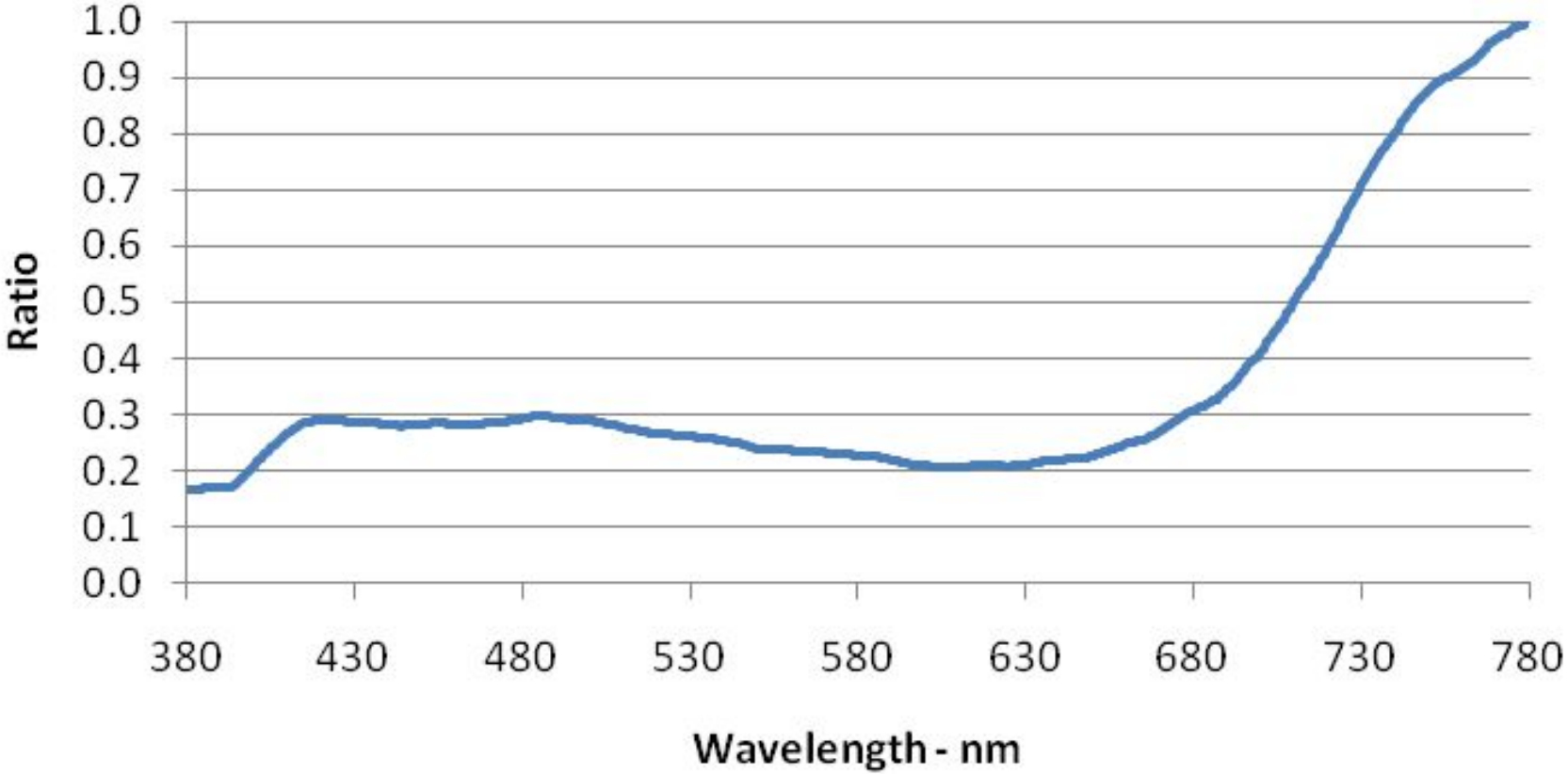
Lighting Passport Spectrometer

0728 – Day is heating up.



0800 – Measuring sunglasses.

Sunglasses/No Glasses



0944 – Taking it in.

1051 – Need to gather courage.

1054 – Out on the beak.

1529 – Measuring clear green water.

1915 – Back where we started.

By the numbers

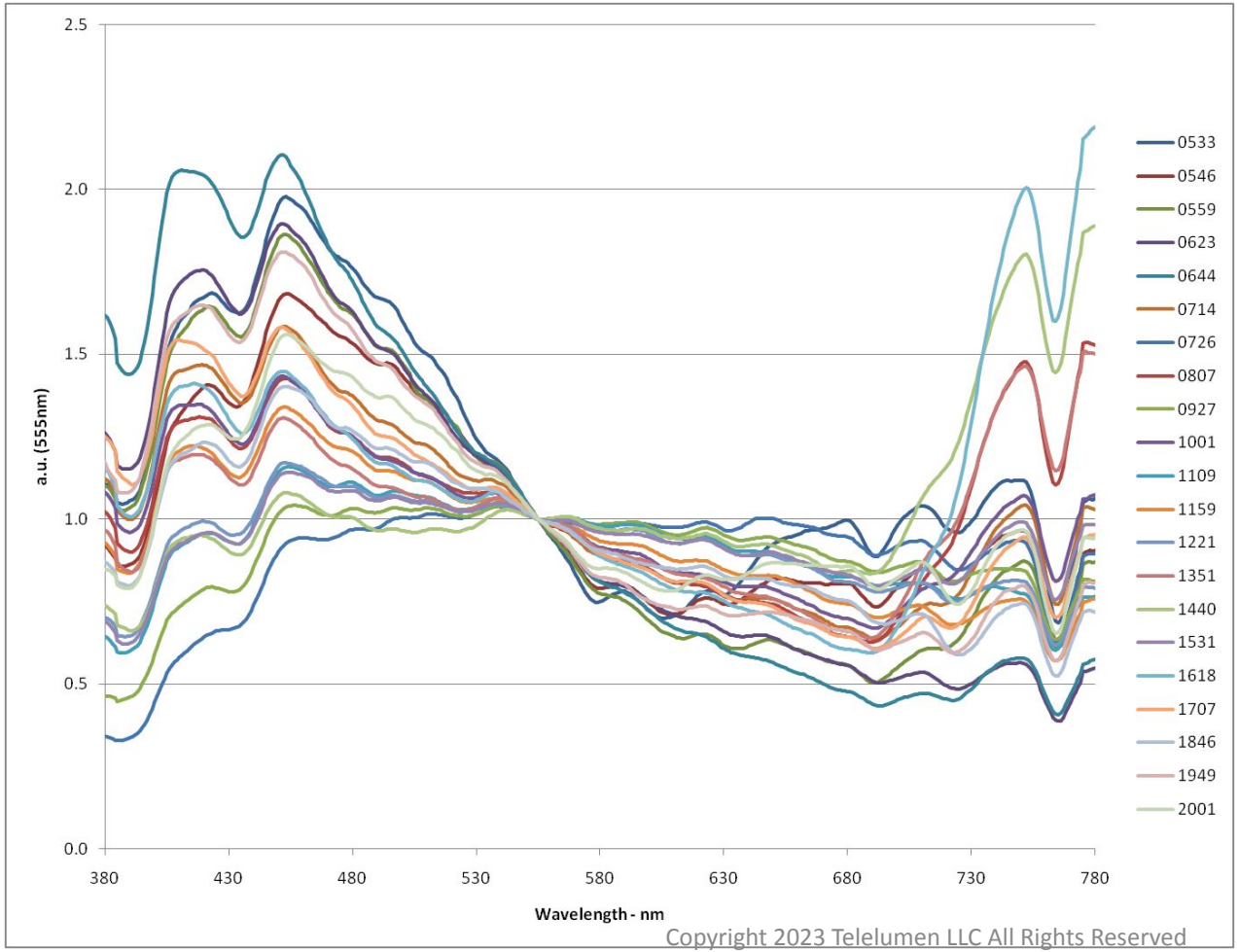
- Starting elevation – 4,000 feet (1,200 m)
- Ending elevation – 8,800 feet (2,700 m)

- According to Fitbit:
  - 45,000 steps
  - 19 miles (30 km)
  - 4,910 calories burned

- Weather: low 50 F – high 77 F (10 C – 25 C)

- Total time: 14 hours 15 mins

Yosemite National Park, Half Dome Hike, 14jun20



Max, Min CCT – 14jun20

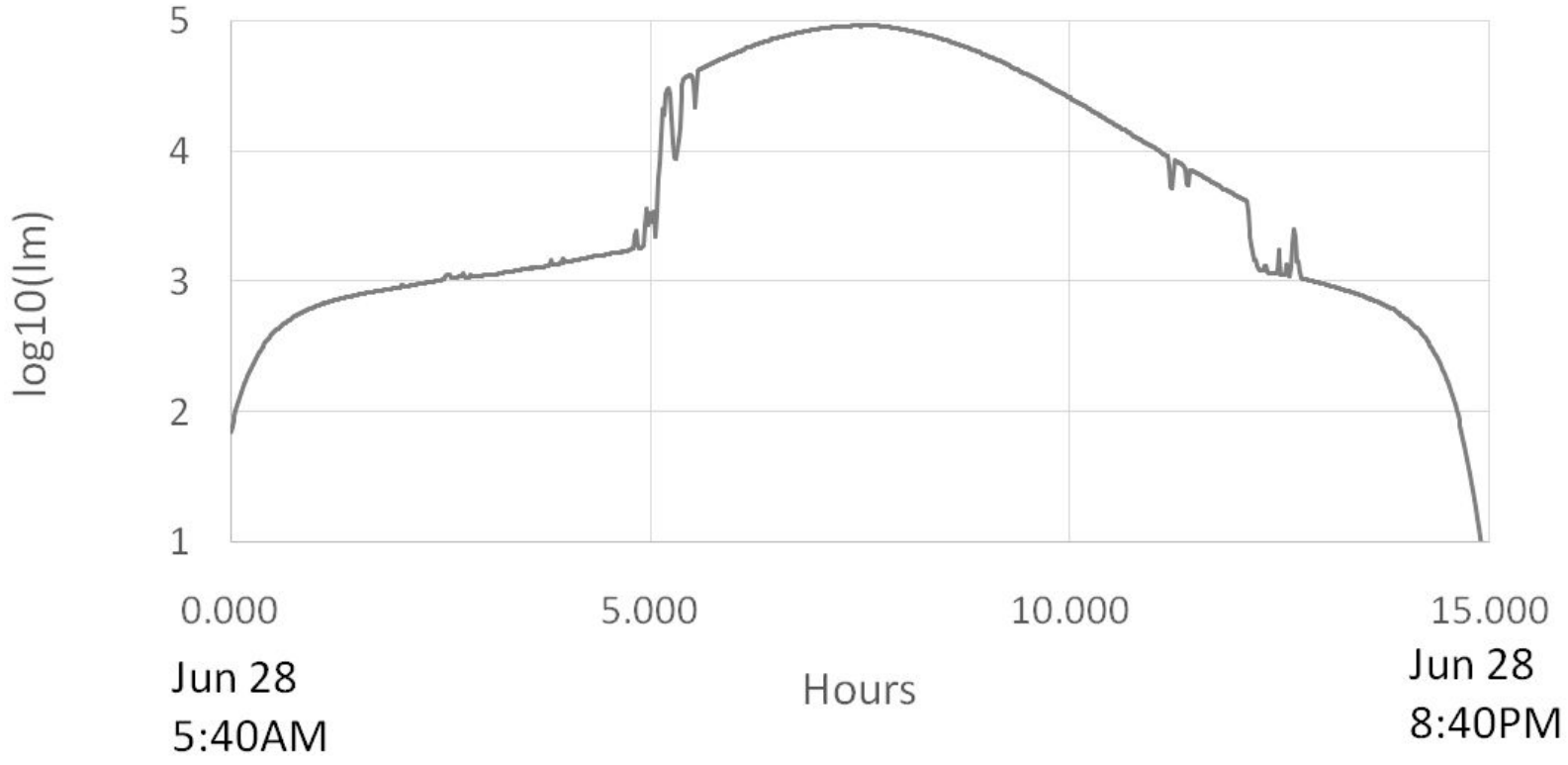
21,600K, 0644

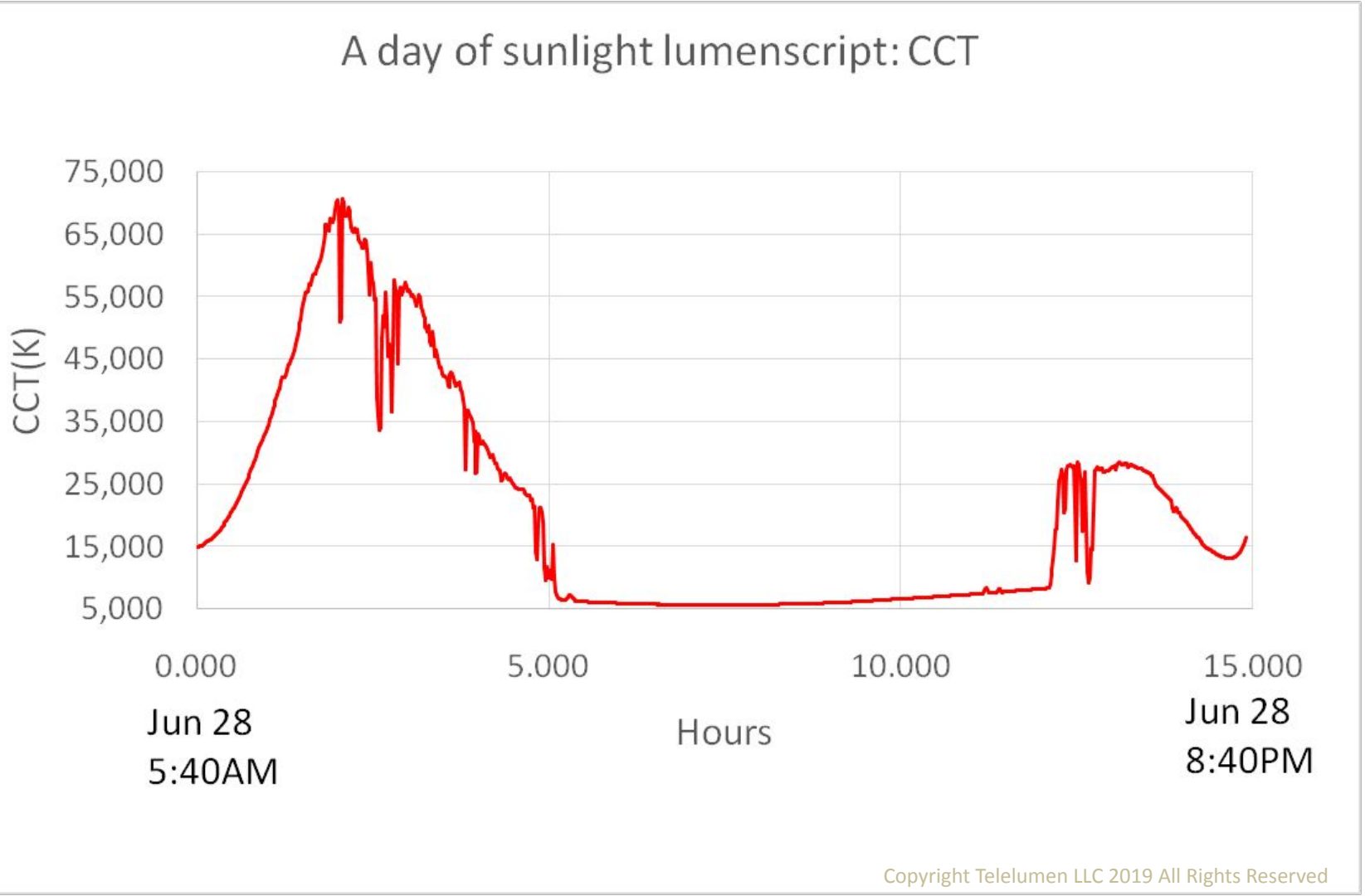
5,100K, 0726

Day of sunlight

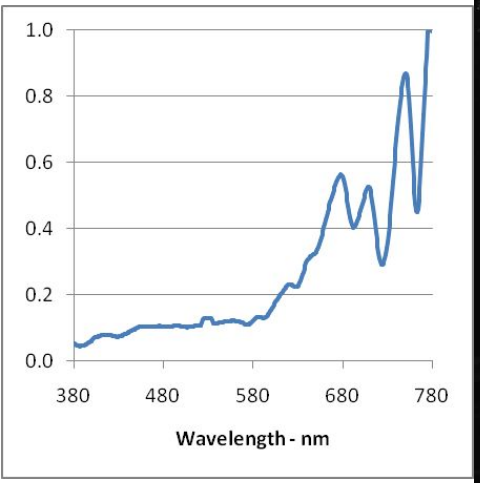
- Illuminance sensor pointed up at a mostly blue sky in Saratoga, California
- Starts: 28JUN18 at 05:48
  Ends: 28JUN18 at 20:48
- Lux range in actual recording: 10,000:1
- Color temperature range: 5,700K to 70,000K

A day of sunlight lumenscript: log luminous output

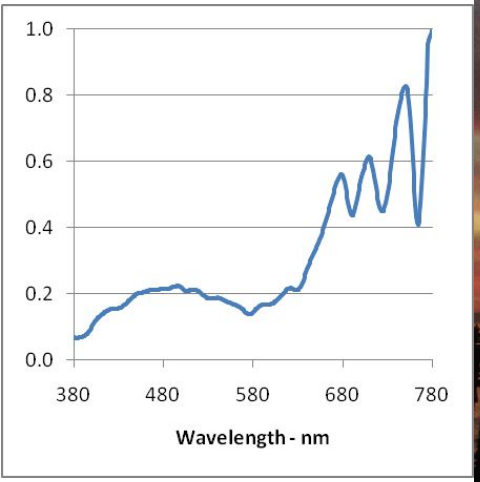




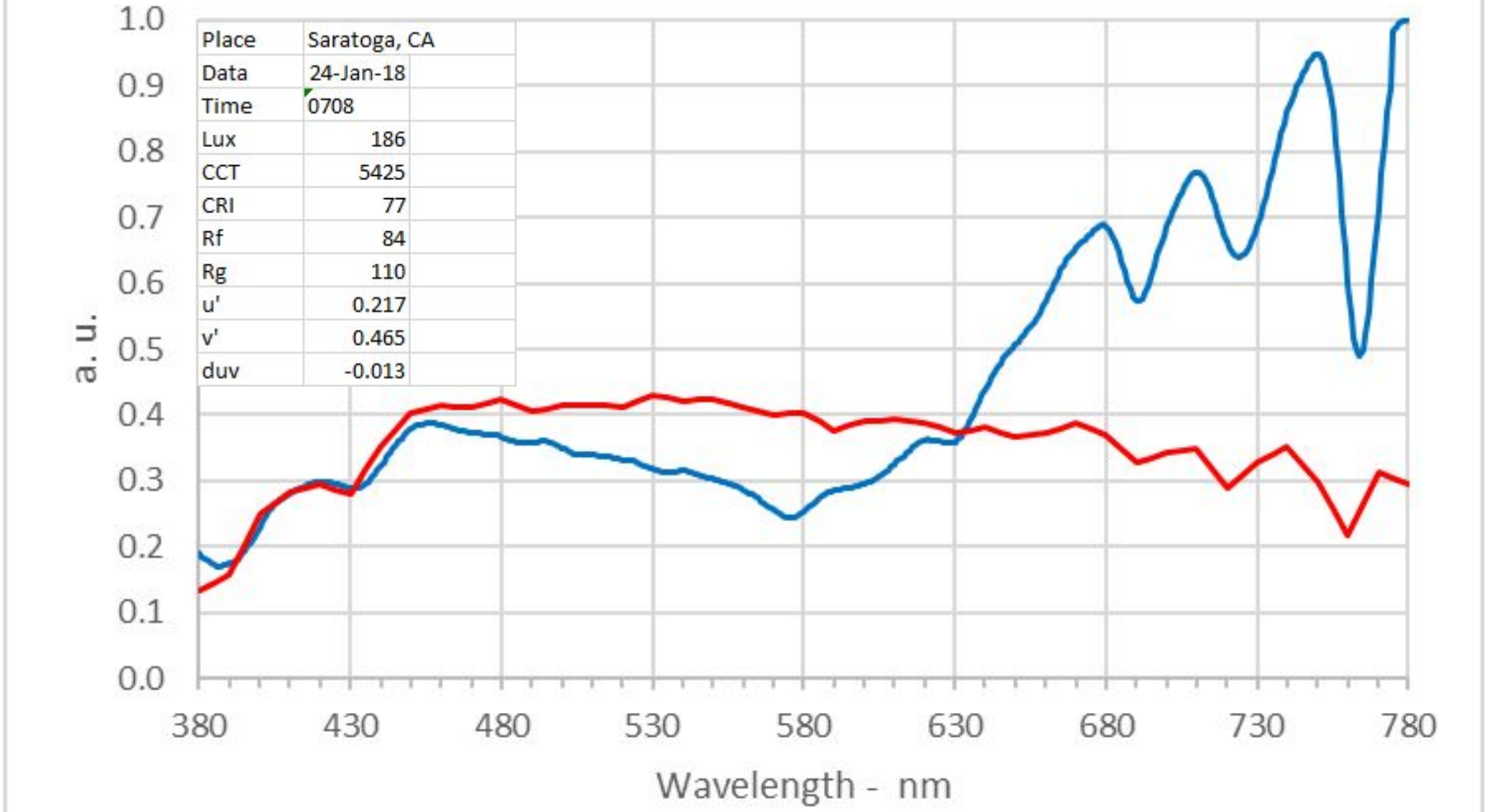
Place	Panama City
Date	13-Jul-18
Time	0552
Lux	89
CCT	2872
CRI	71
u'	0.262
v'	0.494
duv	-0.021



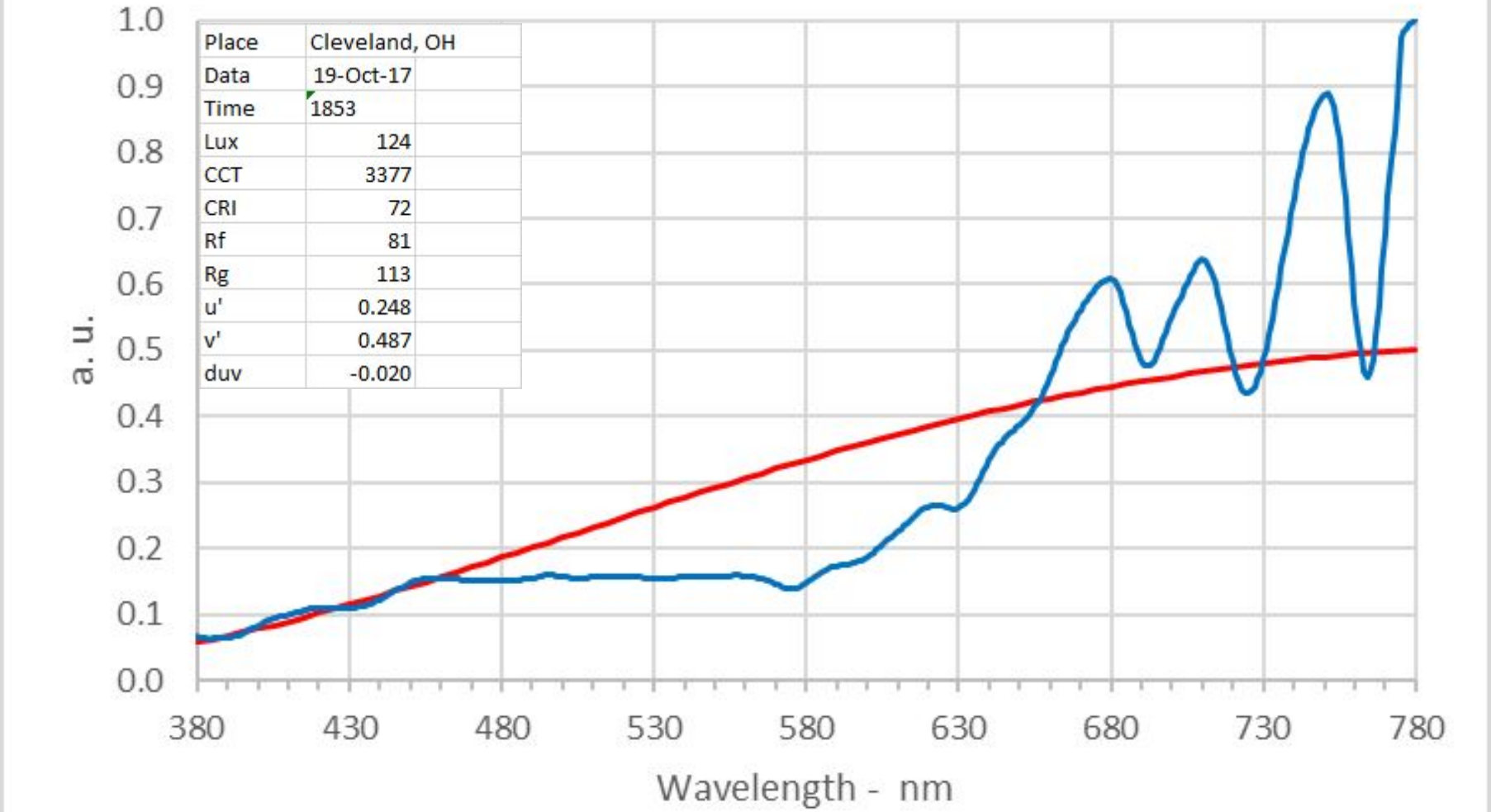
Place	Newport Beach, CA
Date	24-Feb-16
Time	1755
Lux	90
CCT	5056
CRI	73
u'	0.219
v'	0.471
duv	-0.012

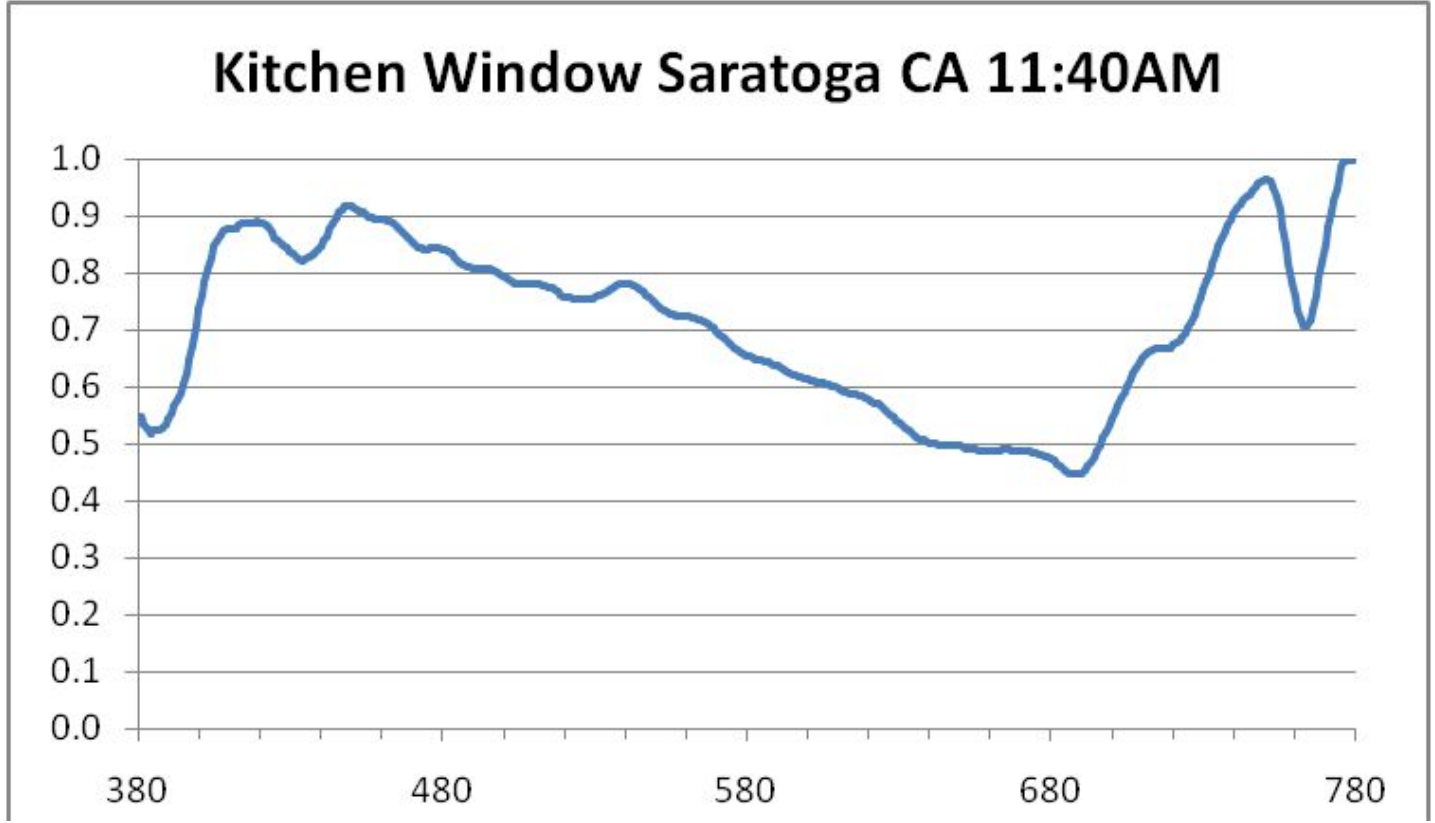


Saratoga morning sky, 7:11AM, 24jan18



Cleveland evening sky, 18:53PM, 19oct17



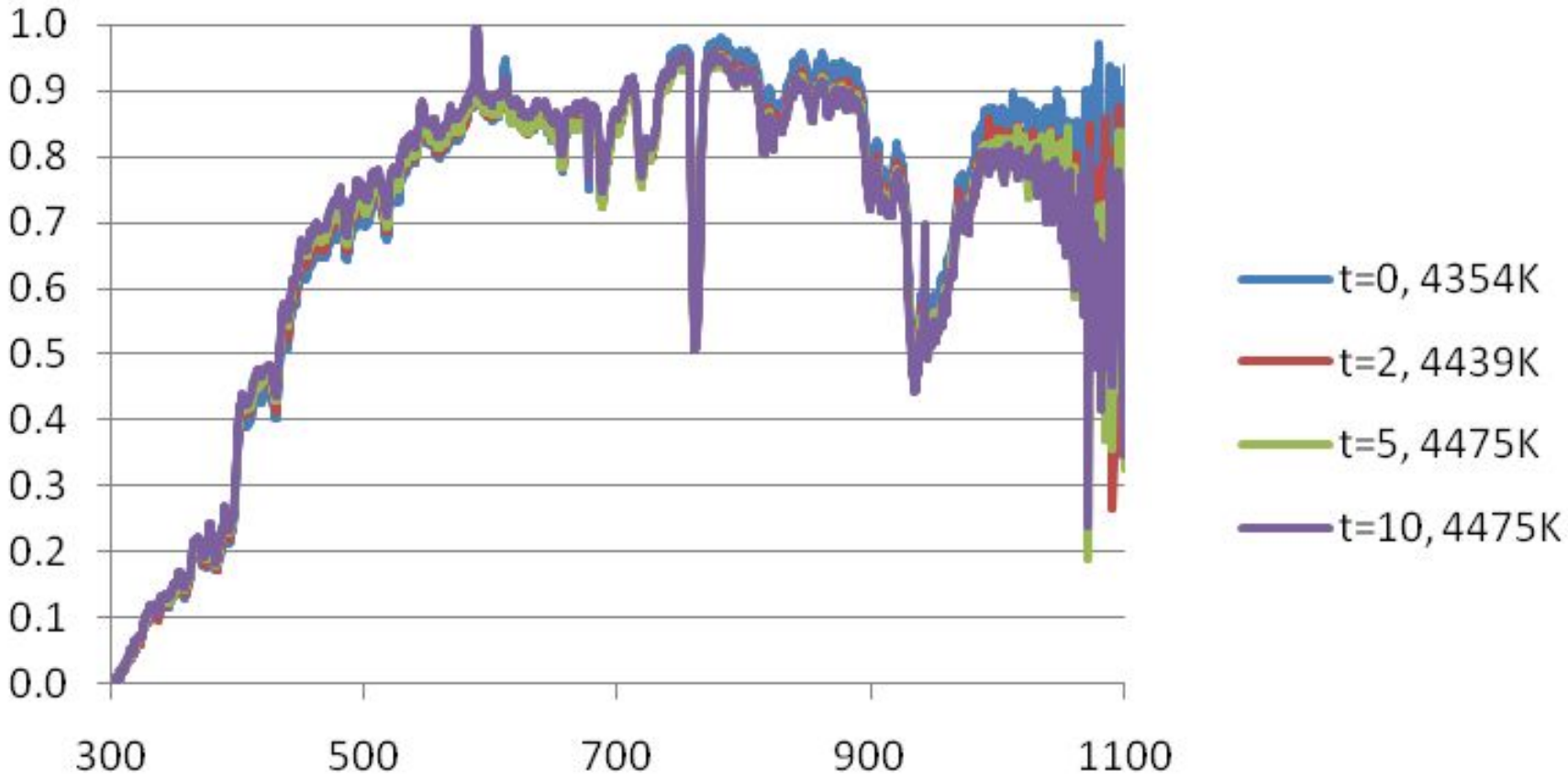


Beautiful high CCT daylight with non-standard SPD.

7526K, 300 lux

13nov15

Moonlight - 0.2 lux, Saratoga, CA, 14nov16



Claude Monet – “Haystacks”

The series shows differences in perception of light across various times of day, seasons, and types of weather

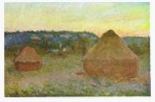
http://en.wikipedia.org/wiki/Haystacks_(Monet)

1890-1891 series [edit]

Grainstacks in the Sunlight, Morning Effect, 1890. Oil on canvas. Private collection.

Haystacks, (Midday), 1890-91, National Gallery of Australia

Wheatstacks (End of Summer), 1890-91. Oil on canvas. Art Institute of Chicago



Wheatstacks, 1890-91. Oil on canvas. Art Institute of Chicago.

Wheatstacks, Snow Effect, Morning, 1891. Oil on canvas. J. Paul Getty Museum

Haystacks at the End of Summer, Morning Effect, 1891. Oil on canvas. Musée d'Orsay, Paris, France.

Haystacks on a Foggy Morning, 1891. Oil on canvas. Private collection.

Haystack, Morning Snow Effect (Meule, Effet de Neige, le Matin), 1891. Oil on canvas. Museum of Fine Arts, Boston.

Grainstacks Snow Effect, (Meules, effet de neige), 1891. Oil on canvas. National Gallery of Scotland, Edinburgh, Scotland

Wheatstacks (Sunset, Snow Effect), 1890-91. Oil on canvas. Art Institute of Chicago.

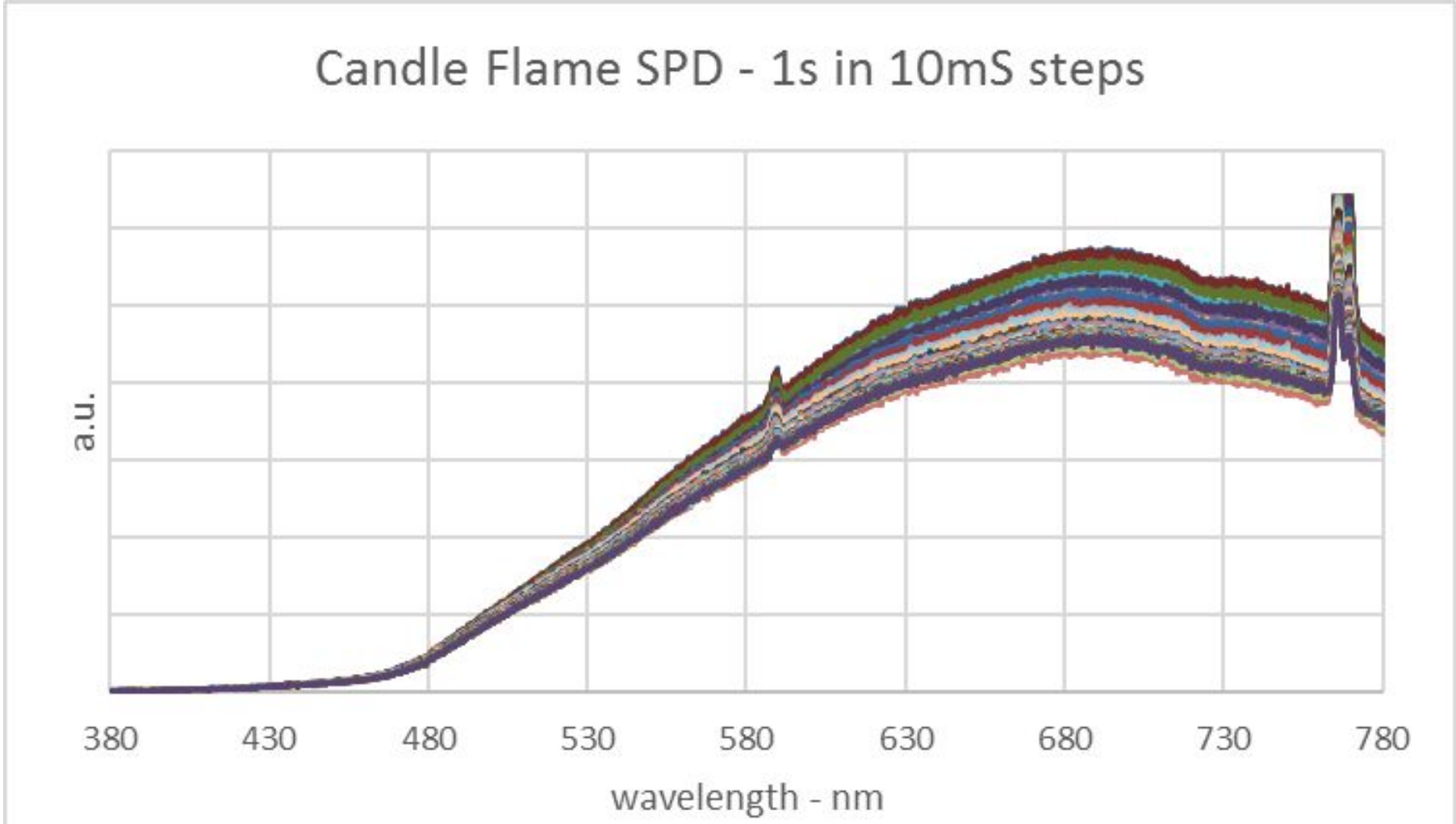
Wheatstack (Snow Effect, Overcast day) (Meule, effet de neige, temps couvert), 1890-91. Oil on canvas. Art Institute of Chicago.

Wheatstack, 1890-91. Oil on canvas. Art Institute of Chicago.

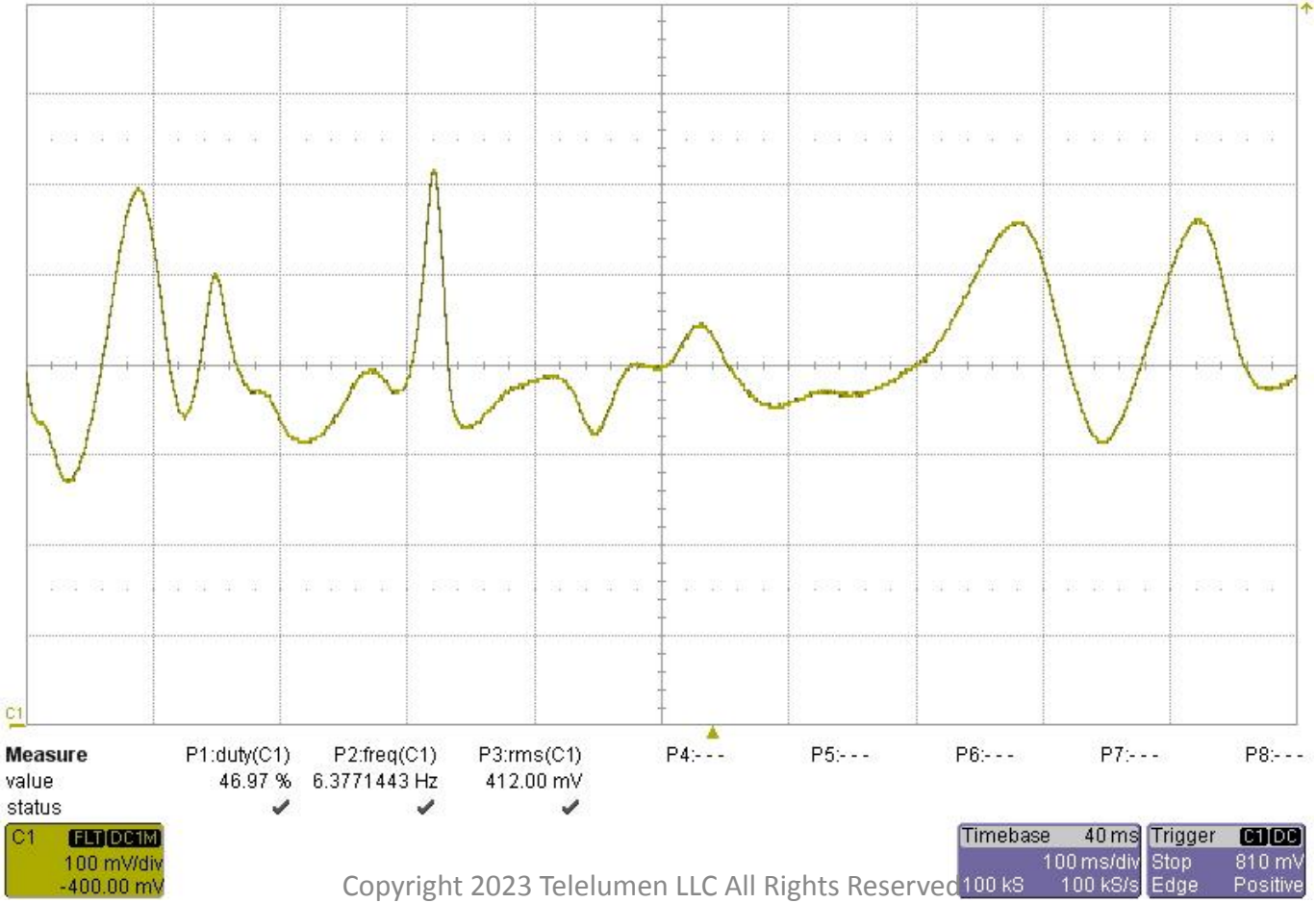
Wheatstack (Thaw, Sunset), 1890-91. Oil on canvas. Art Institute of Chicago.

Wheatstack (Sun in the Mist), 1891. Oil on canvas. Minneapolis Institute of Arts.

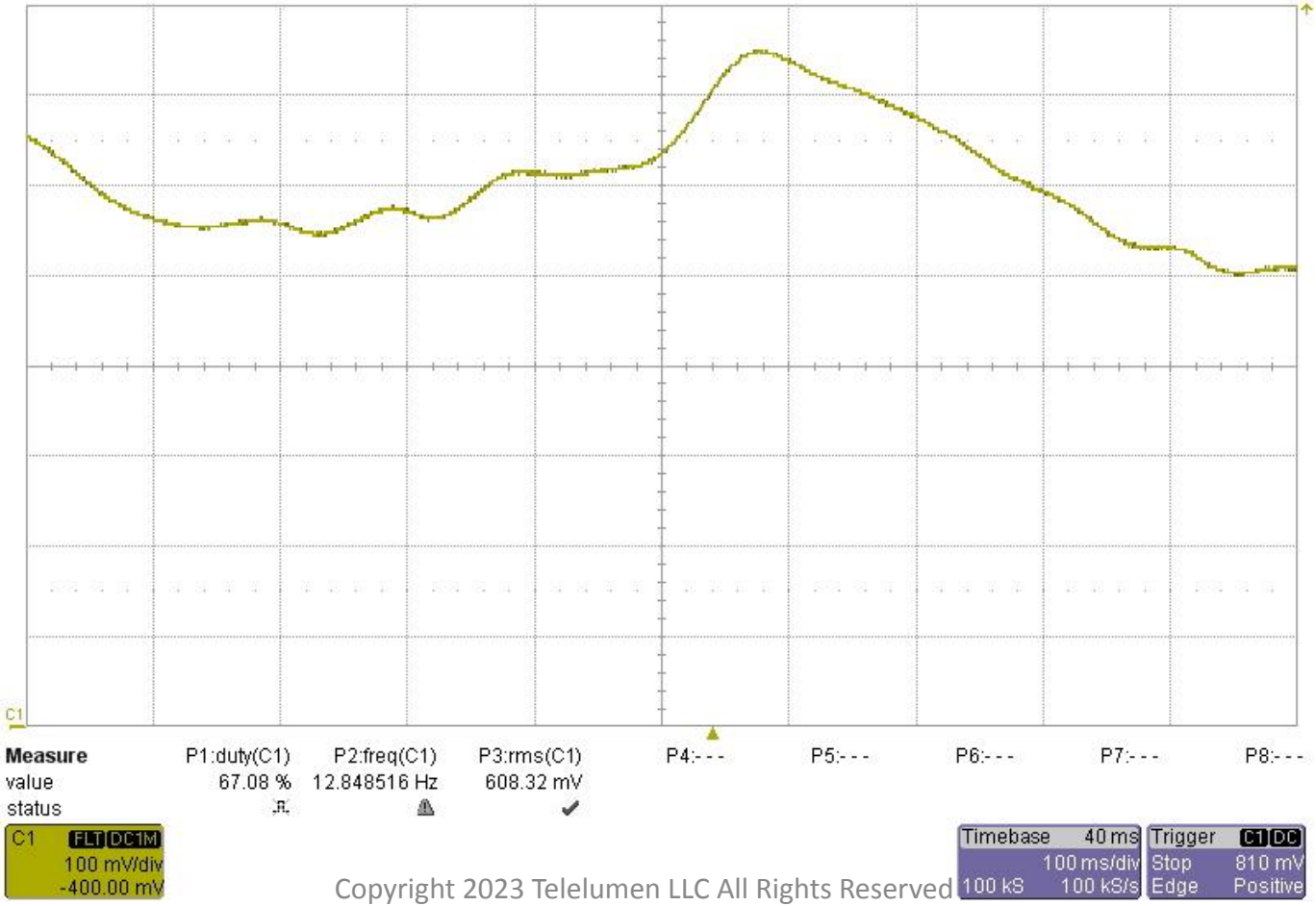
Grainstacks. (Snow effects; sunlight.), 1890-91. Oil on canvas. National Gallery of Scotland, Edinburgh, Scotland.



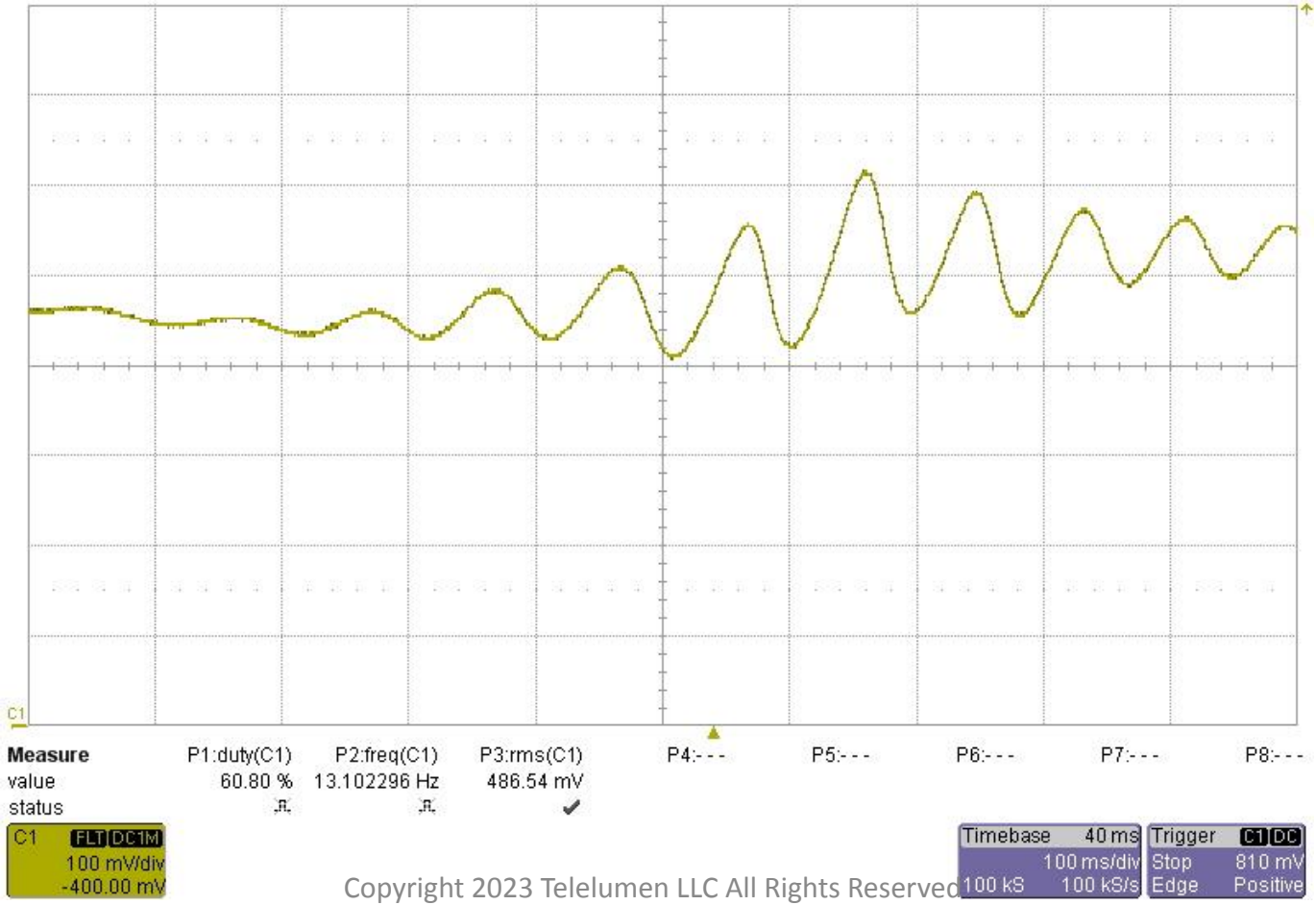
Candle Flame from Photometer – 1 sec



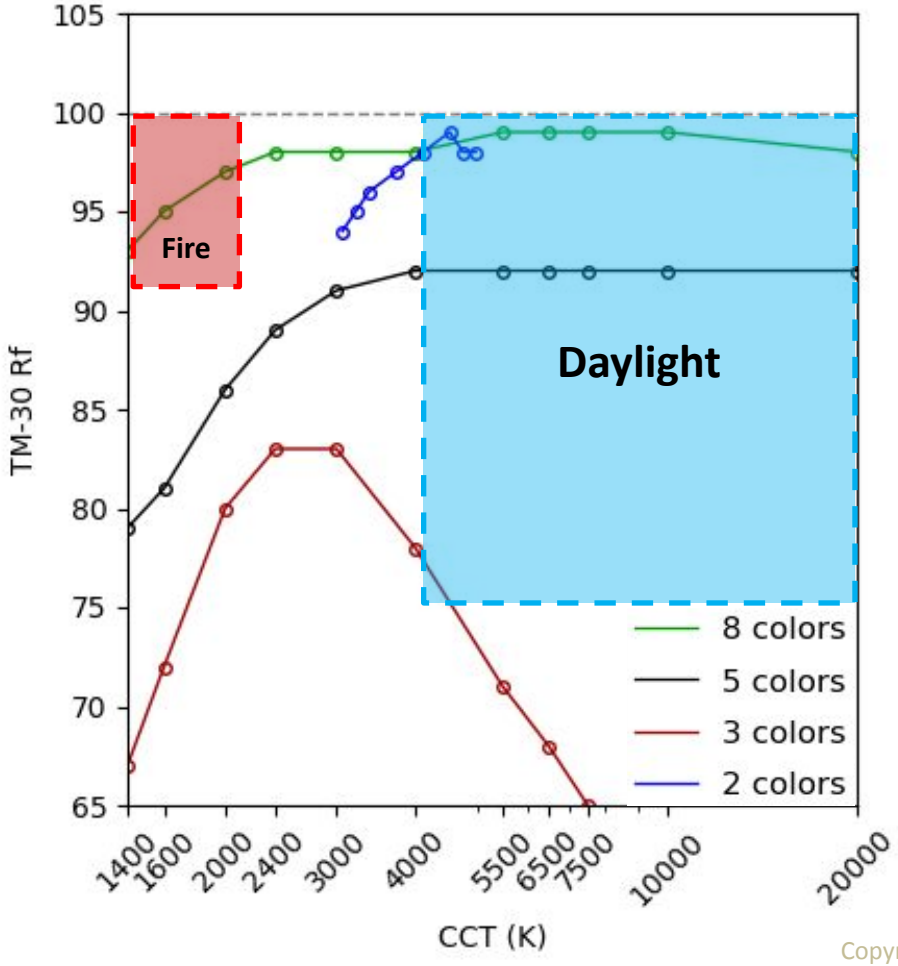
Candle Flame from Photometer – 1 sec



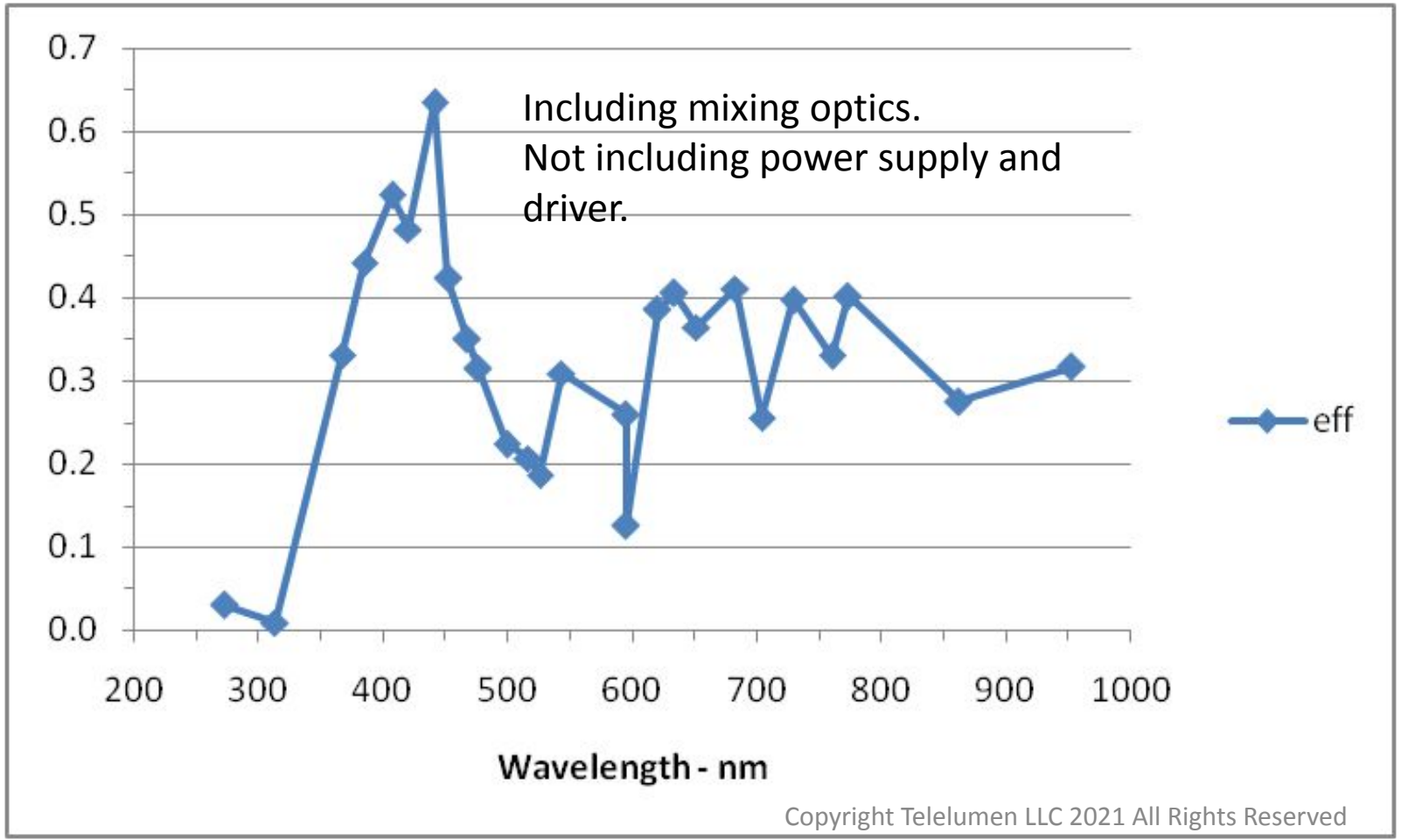
Candle Flame from Photometer – 1 sec



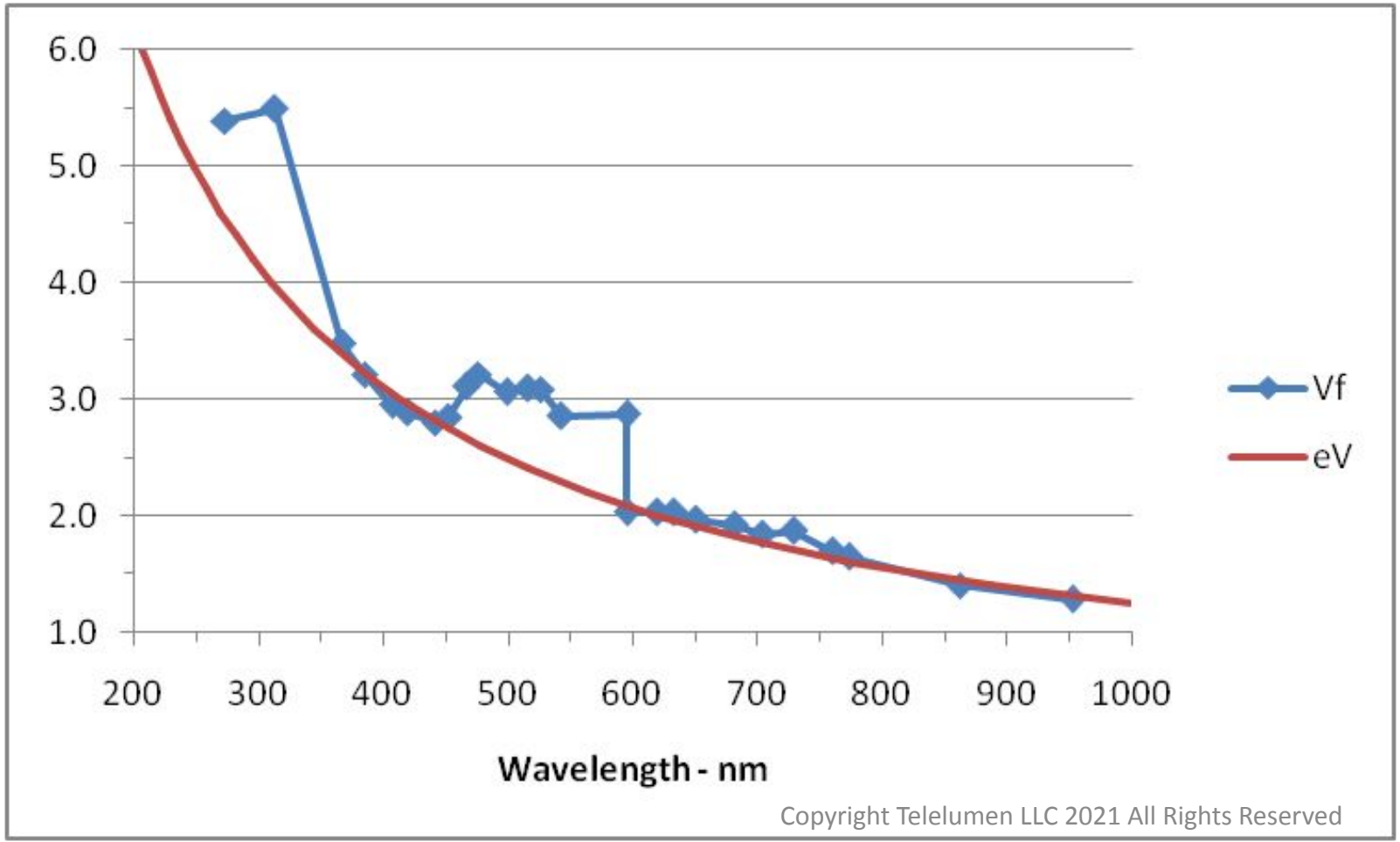
Rf (Color Quality), CCT, and # of colors



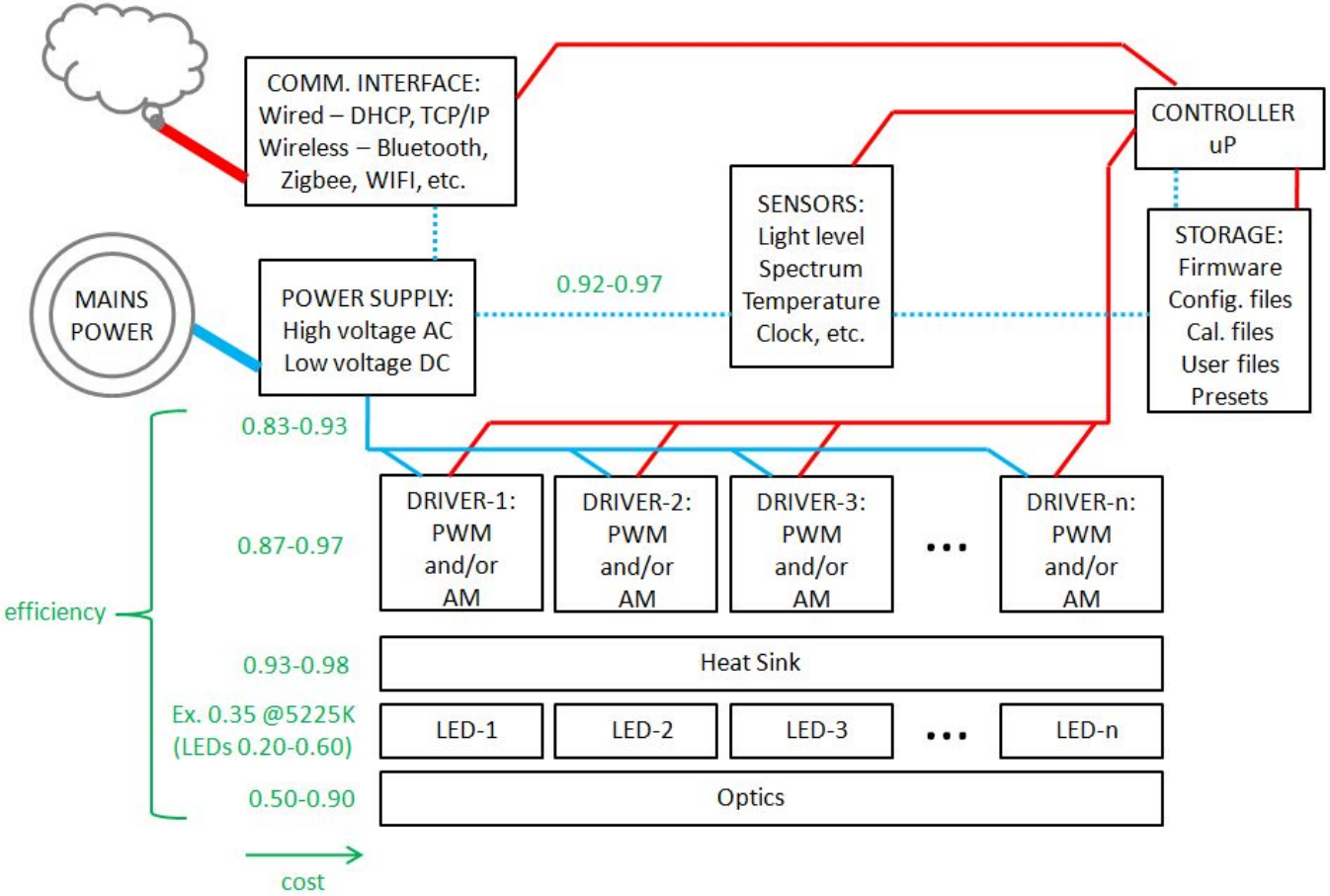
Efficiency vs. Wavelength



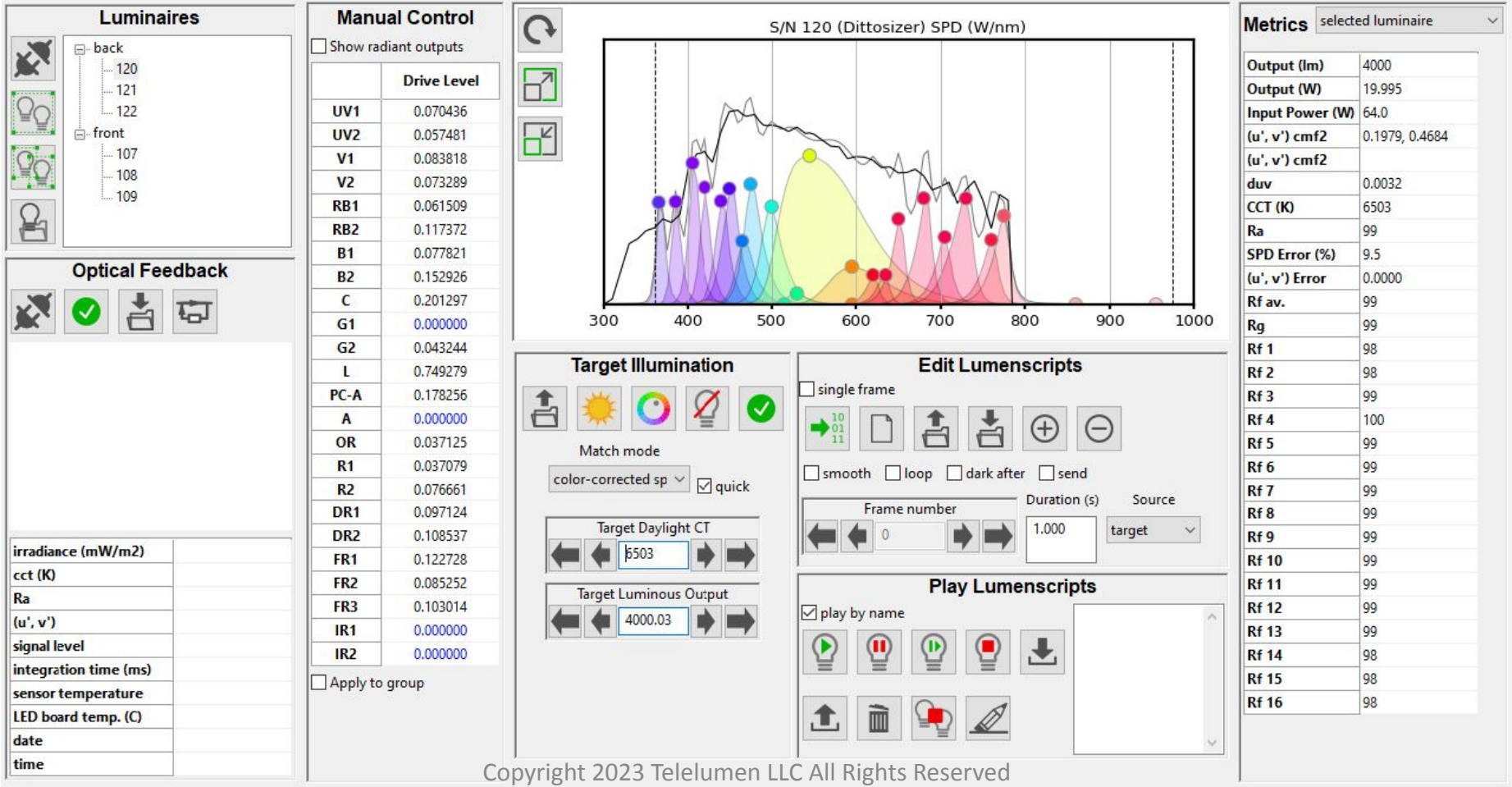
Photon Energy and Vf vs. Wavelength



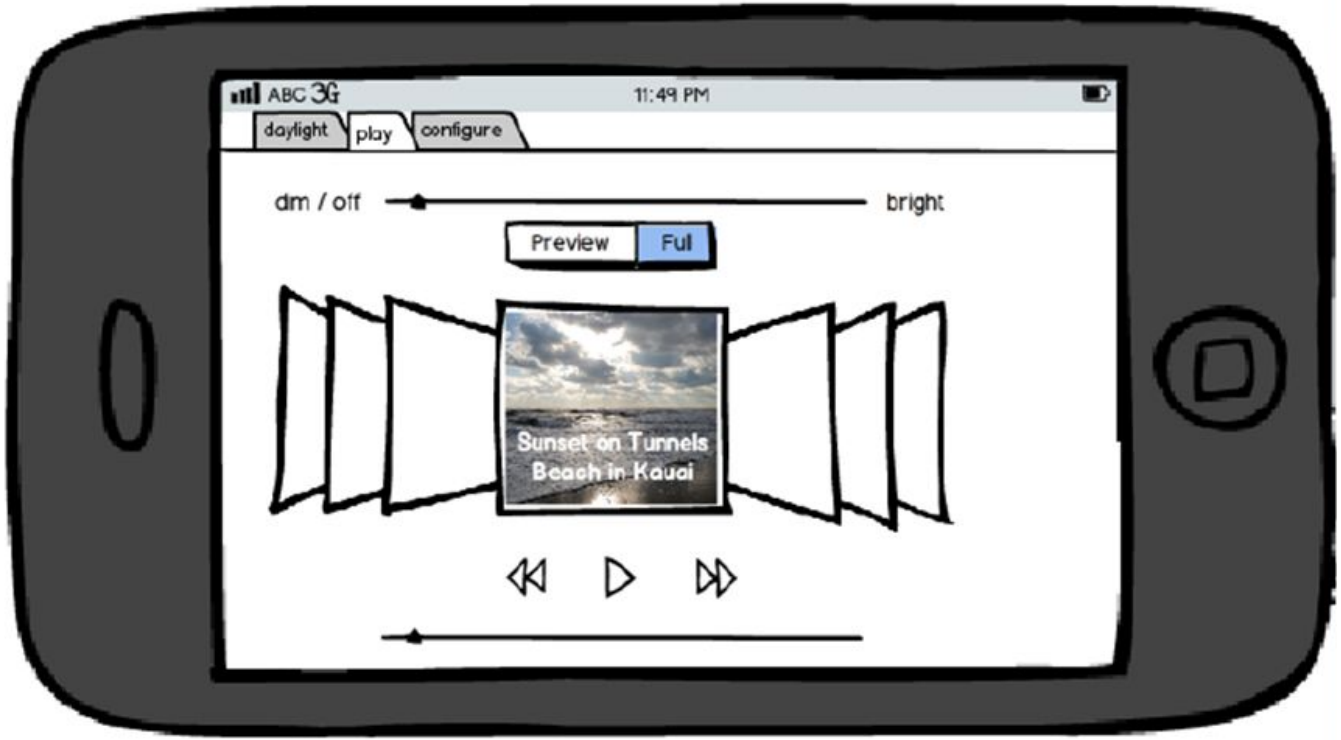
Spectrally Tunable Architecture



Telelumen Spectraloc Software GUI Operating the 24-channel Dittosizer



Intuitive Light Player Control Example



Summary

- Programmable spectrum light players are 21st century luminaires.
- Programmable spectrum sources facilitate more solutions than traditional photometry.
- Focus on radiometry
  - SPD, efficiency, peak wavelength
  - NOT efficacy, dominant wavelength, and CCT
- Daylight is the gold standard for lighting.
  - Fire is the silver standard.
- Daylight is complex – continuous changing spectrum over time.
  - The daylight locus is a very approximate representation of actual daylight.
- Daylight CCTs are much higher than typical electric lights.
- Deep red light (>650nm) is essential to skin rendition and high CCT acceptance.
- Fixed spectrum phosphor converted sources will be the most efficacious.

RIT | Rochester Institute of Technology

TELELUMEN

The Recording and Playback of Light

Questions, Comments, Demo…

steve@telelumen.com