



STT51

The 51st International Congress on Science,
Technology, and Technology-based Innovation

11th–13th November 2025

Faculty of Science, Chulalongkorn University
Bangkok, Thailand

SP7 - COLOUR SCIENCE/TECHNOLOGY, LIGHT AND APPLICATIONS

SP7_INV01: PROGRAMMABLE MULTICHANNEL LIGHTING FOR ACCURATE SPECTRAL CONTROL AND DAYLIGHT EMULATION

Steve Paolini
President, Telelum LLC
November 12, 2025

Agenda

- Introduction
- Light sources
- Daylight – graphs and pictures including Como and Yosemite
- Programmable Luminaires and Control Software
- Summary

Steve Paolini
President
Telumen 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 Telumen, 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.



The Recording and Playback of Light

- Founded 2007 – Saratoga, CA
- Purpose – Replicate any spectral power distribution
 - Products and services to record and playback light
- 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 – sleep, vision
- University and government labs – lighting research
- Supply chain – Critical color control

Programmable Spectrum

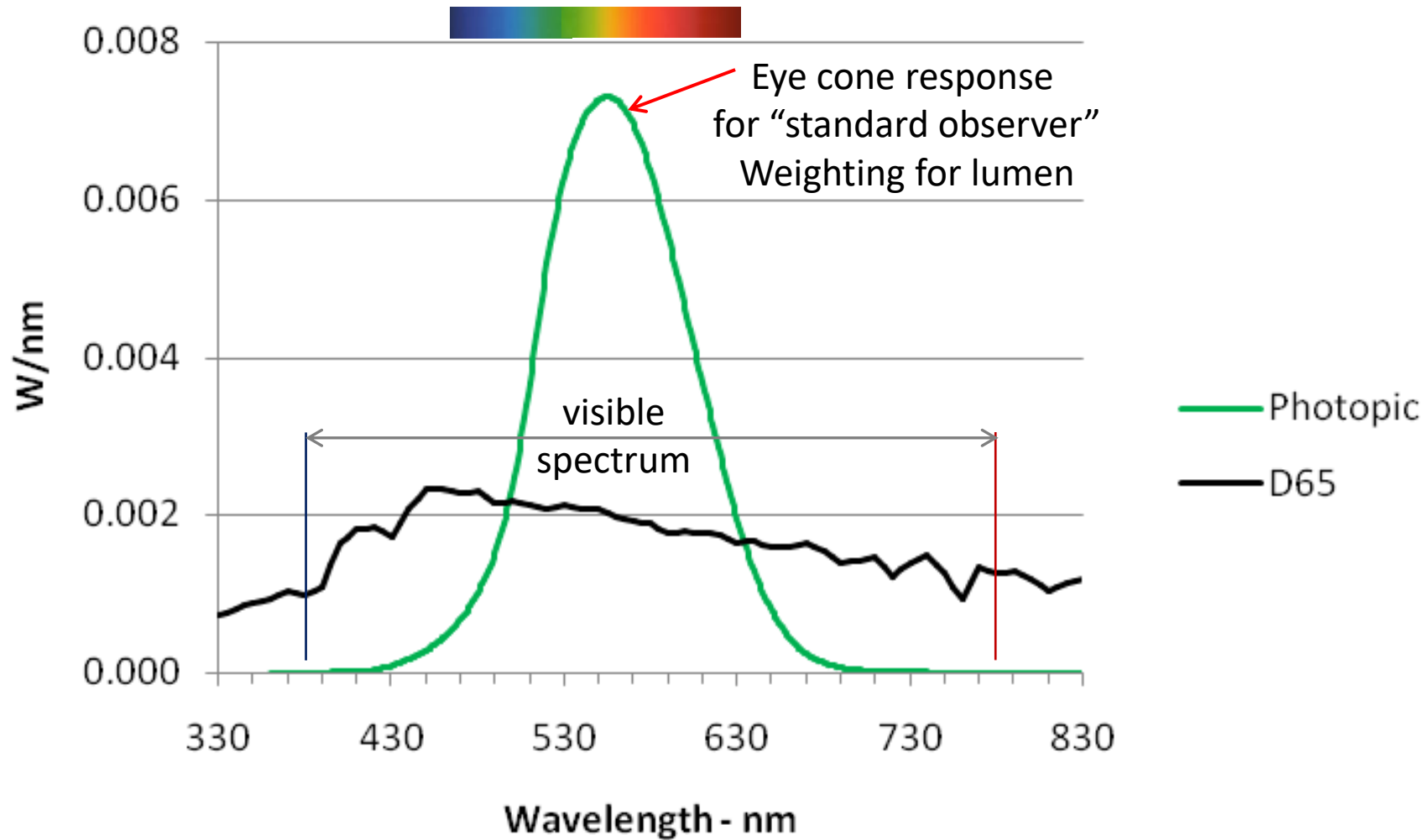
- Telumen focuses on spectrum and time
 - Goal is to replicate actual daylight SPD not just CCT
- Telumen focuses on radiometry vs. photometry

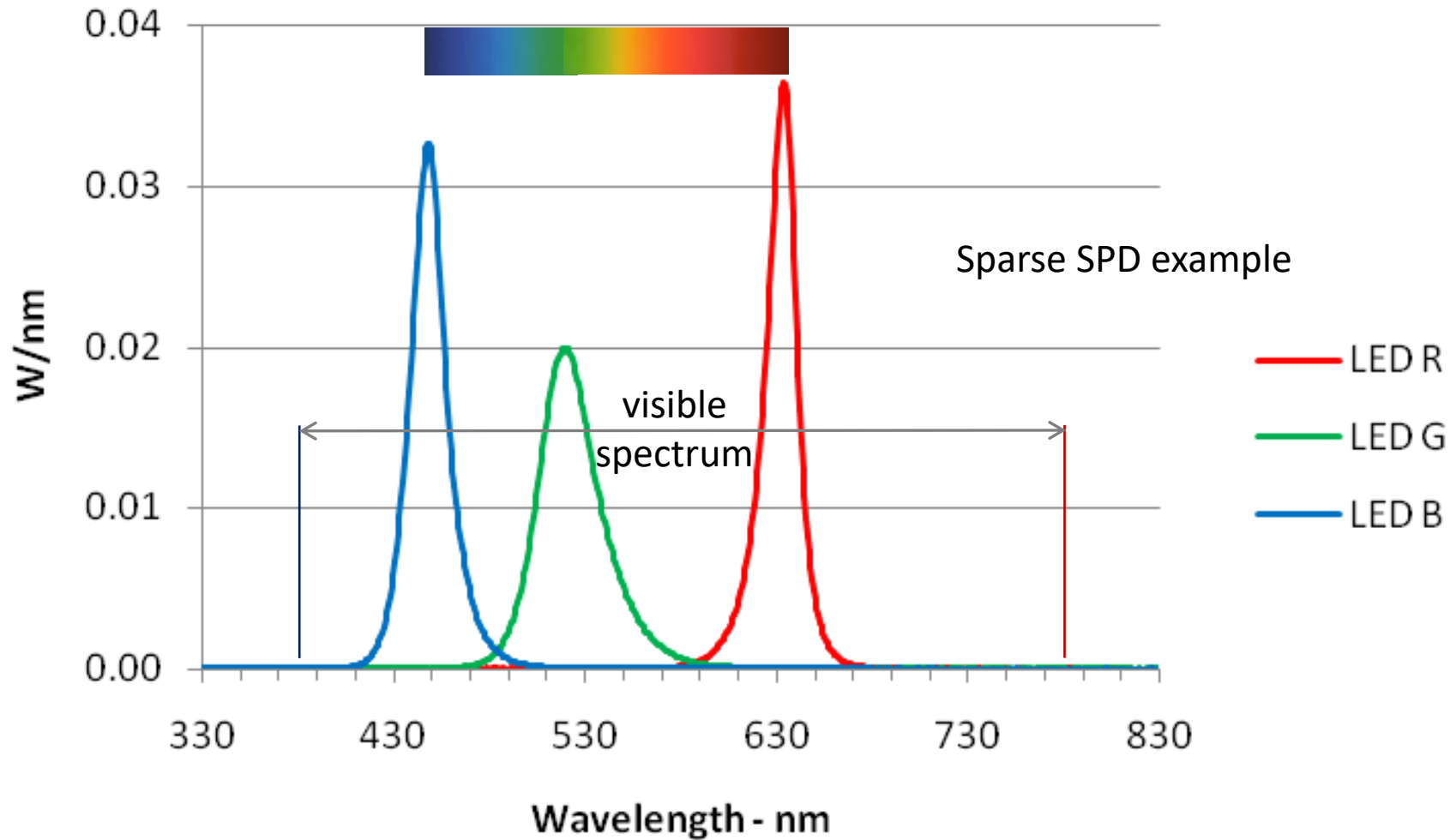
What is Daylight?

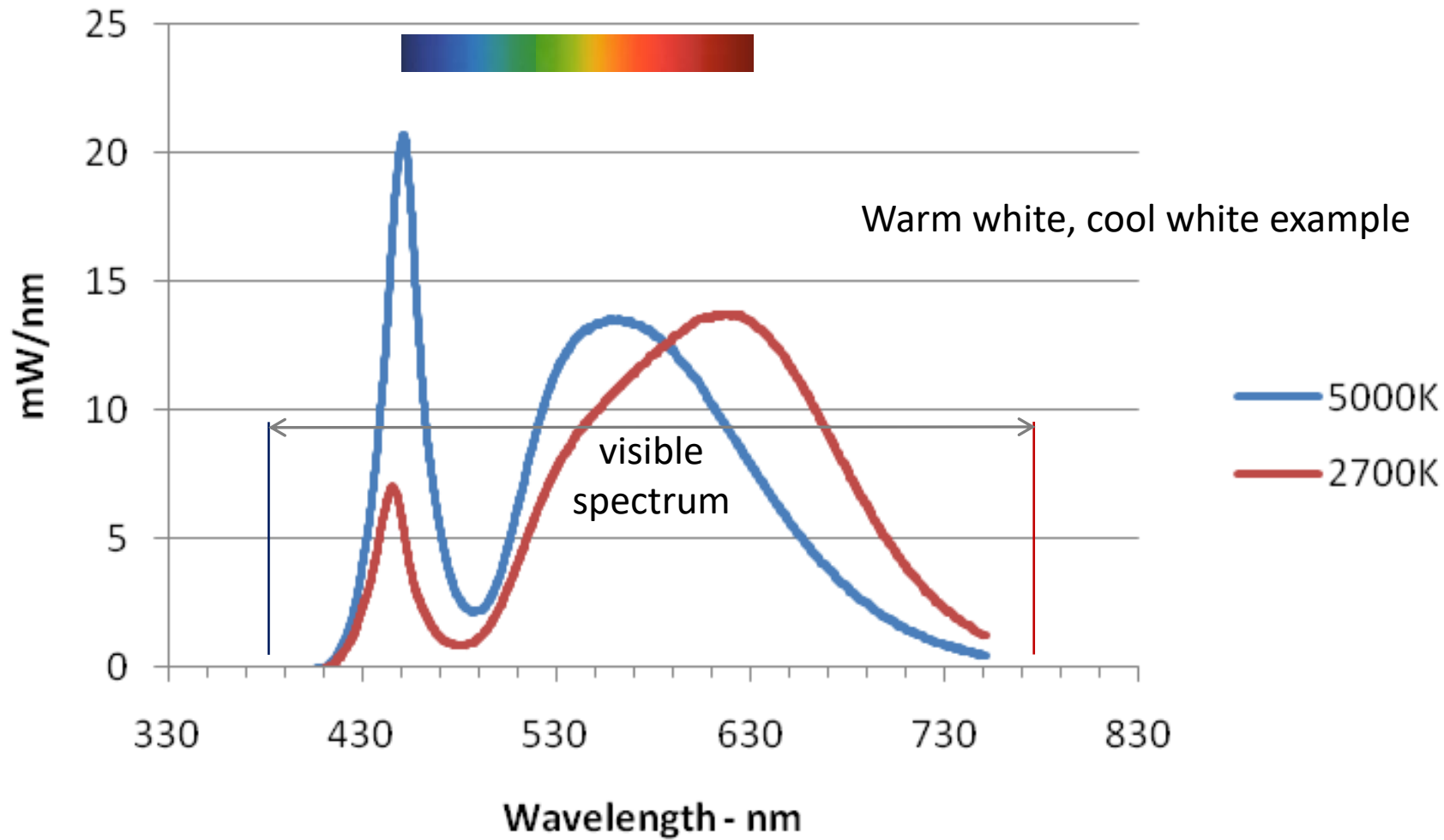
- Circadian, Human Centric, Healthy, but...
- A fundamental aspect is the overall experience.
- Daylight is complex. The SPD changes with:
 - time of day
 - the weather
 - time of year
 - place on earth
 - your immediate environment – window, sidewalk, park, ...
 - It's processional – sun, shadows move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

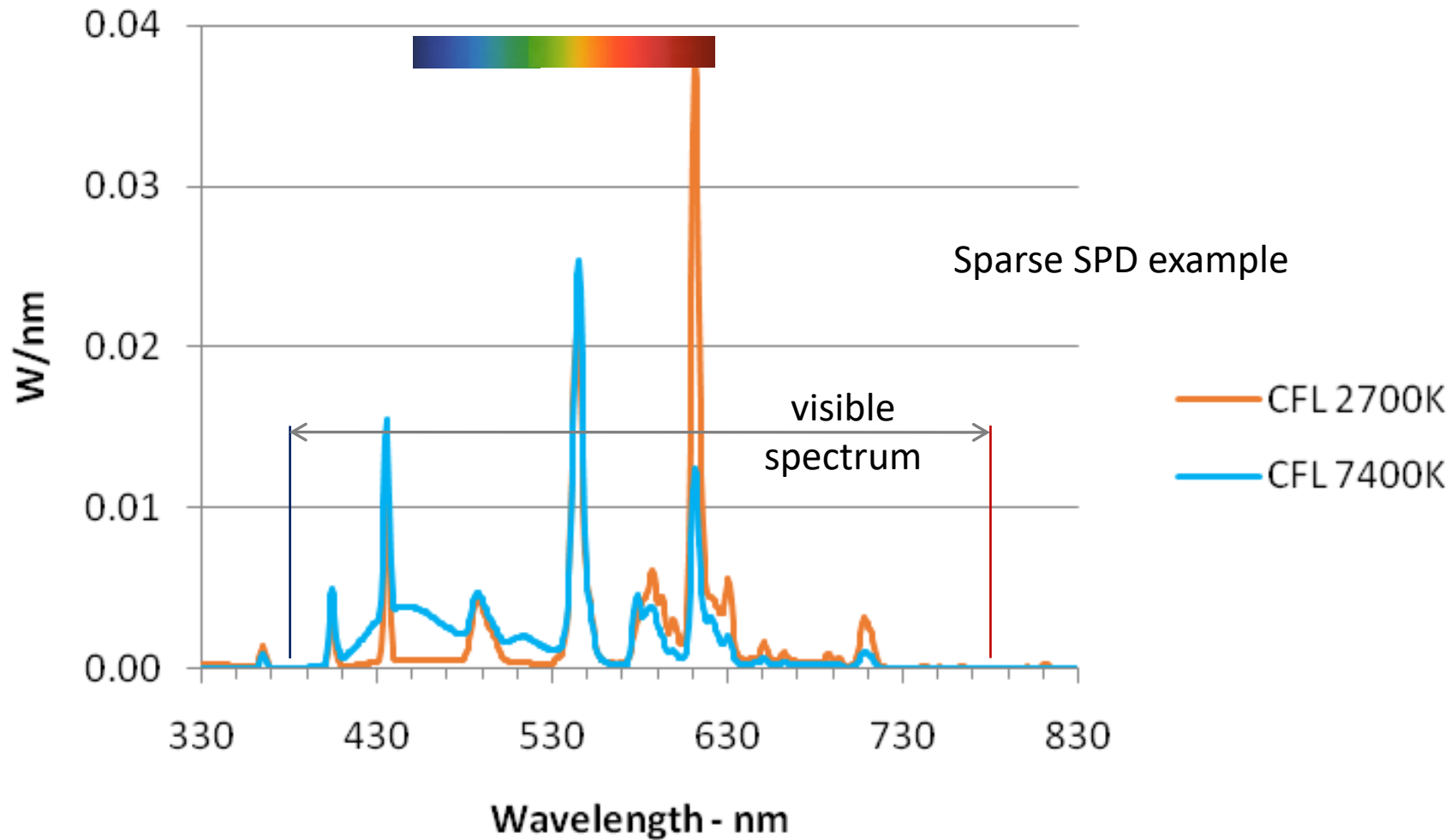
Daylight Experience

- 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 >650nm 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 metric than efficacy
 - Optical Watt per Electrical Watt vs. Lumens per Watt

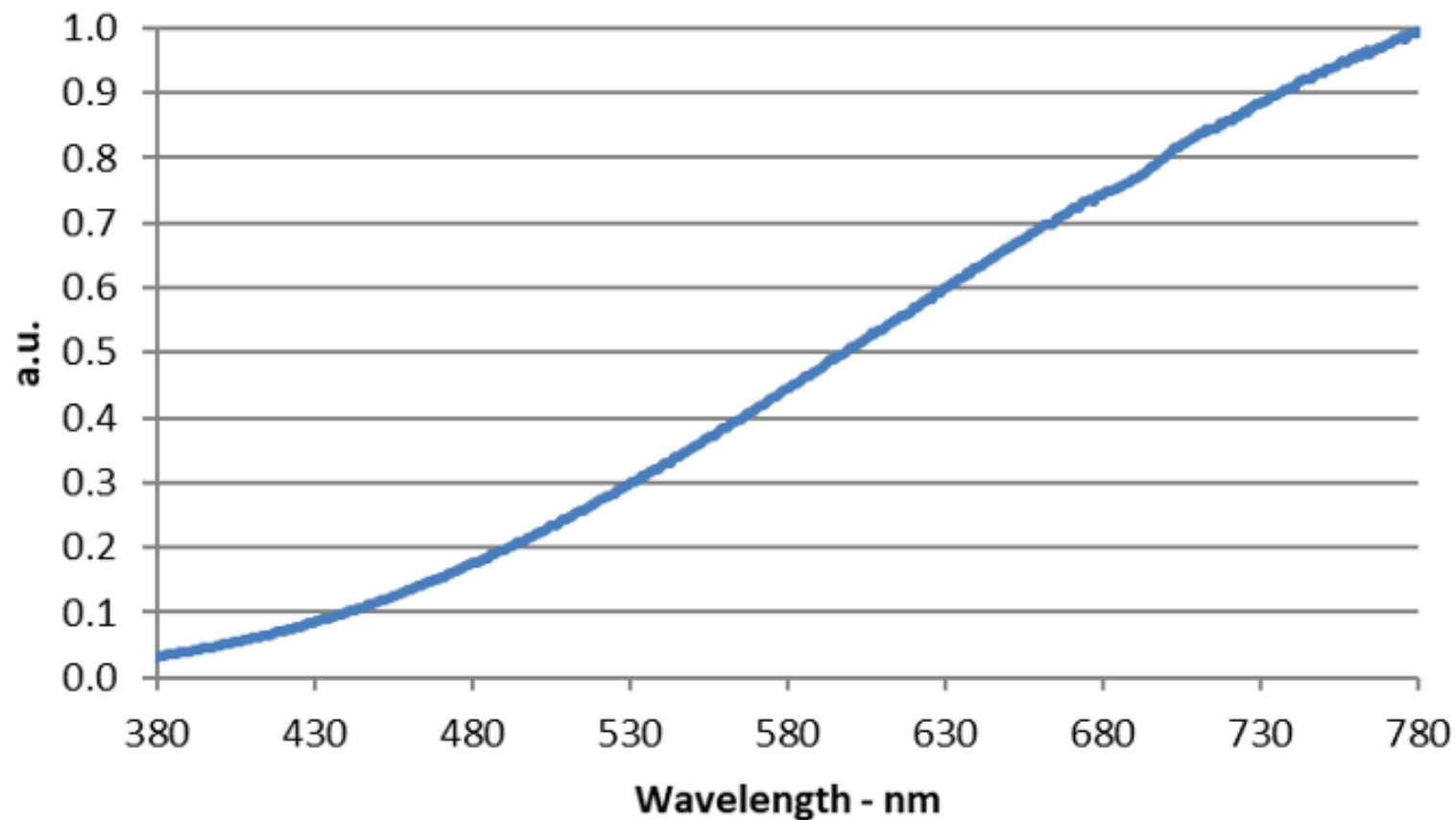




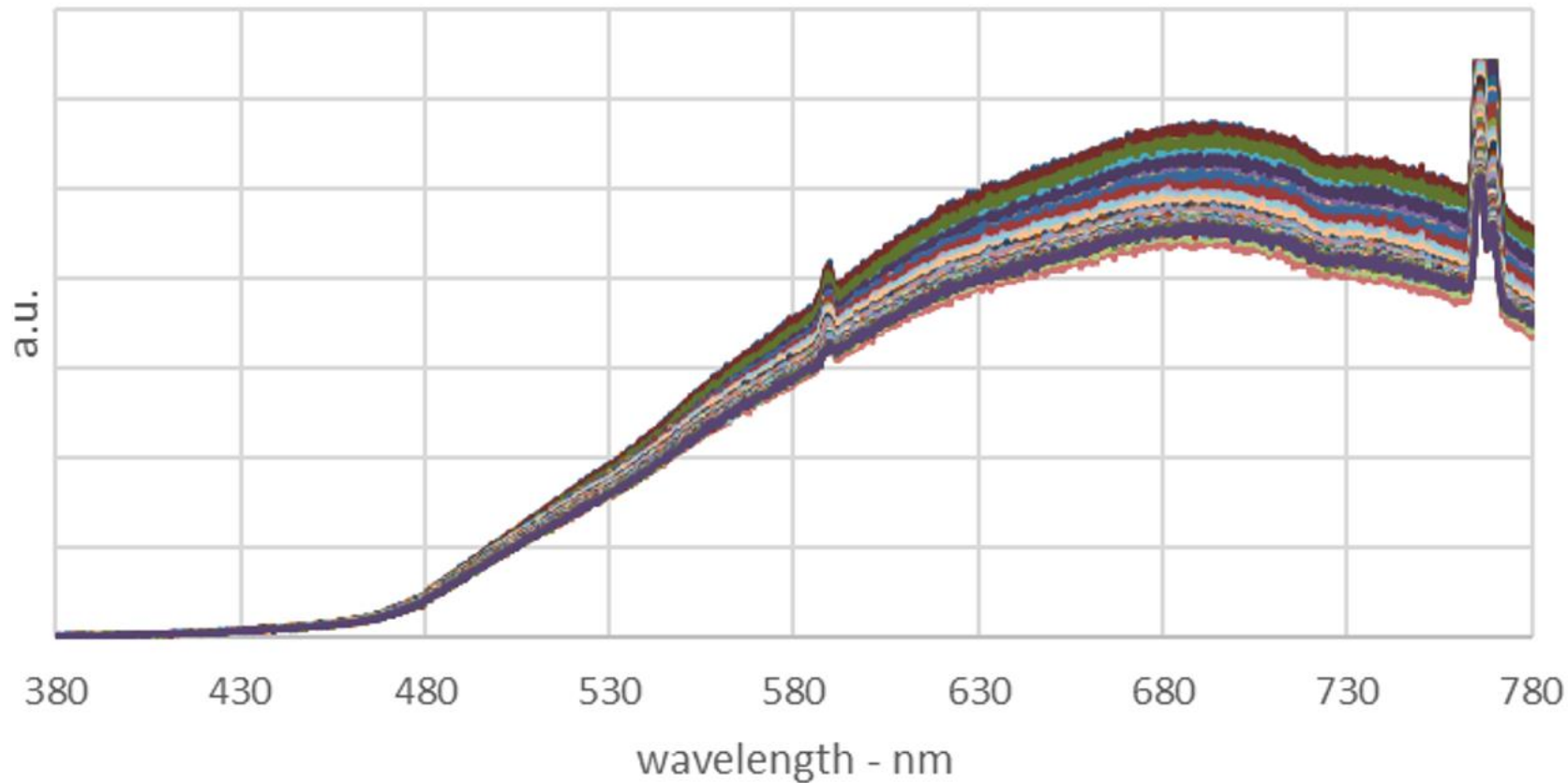




60W Incandescent Lamp - 2755K

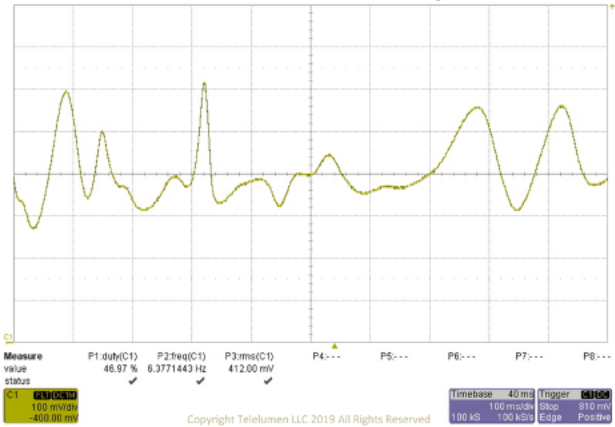


Candle Flame SPD - 1s in 10mS steps

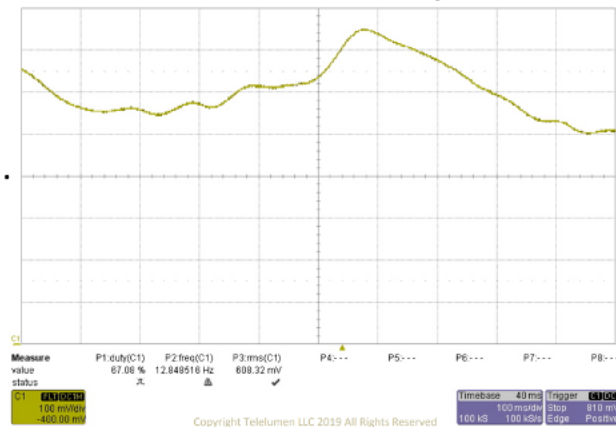


Same Flame, 3, 1 s Samples

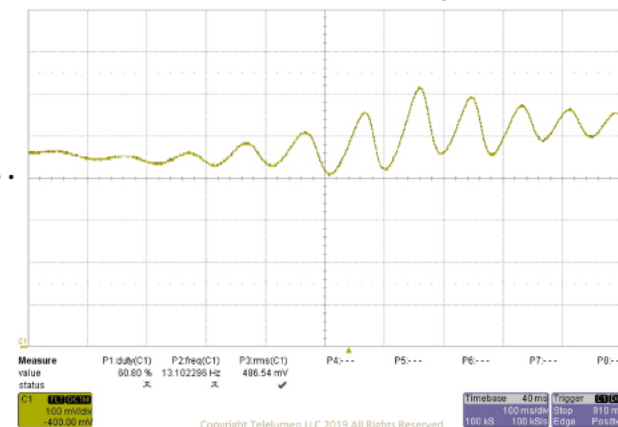
Candle Flame, 1 s Sample – t=a



Candle Flame, 1 s Sample – t=b

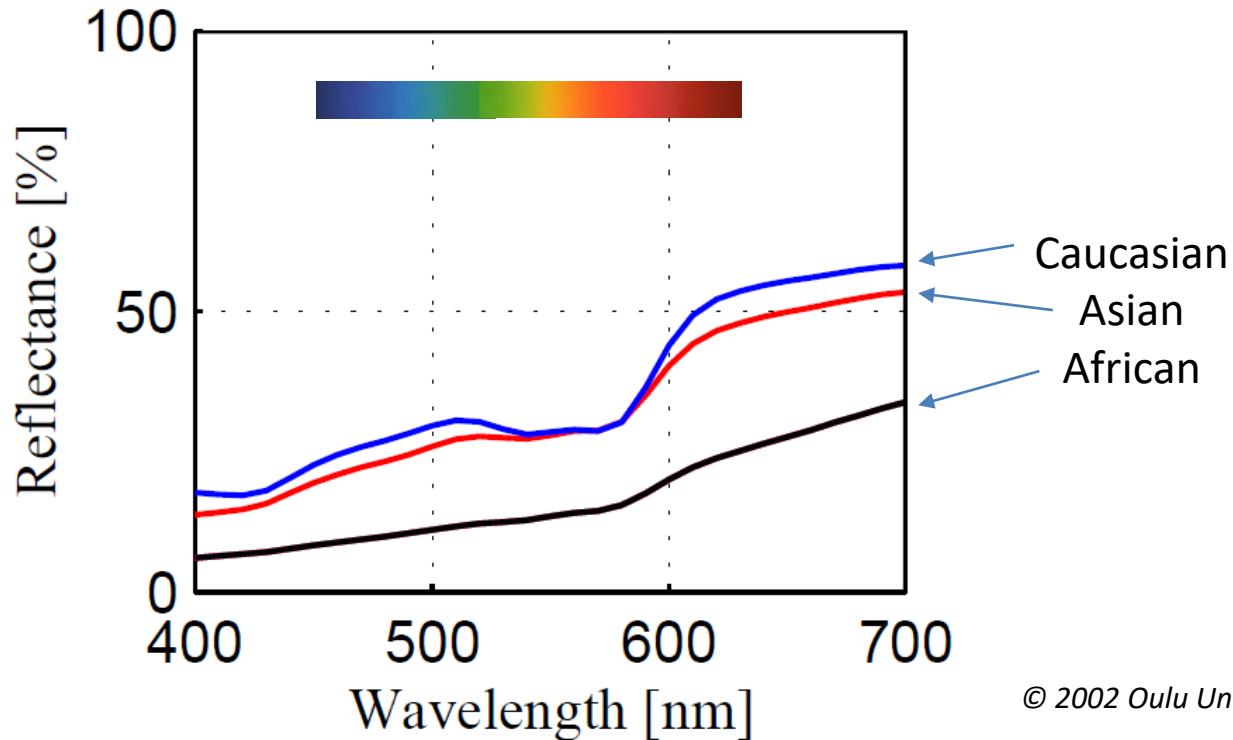


Candle Flame, 1 s Sample – t=c



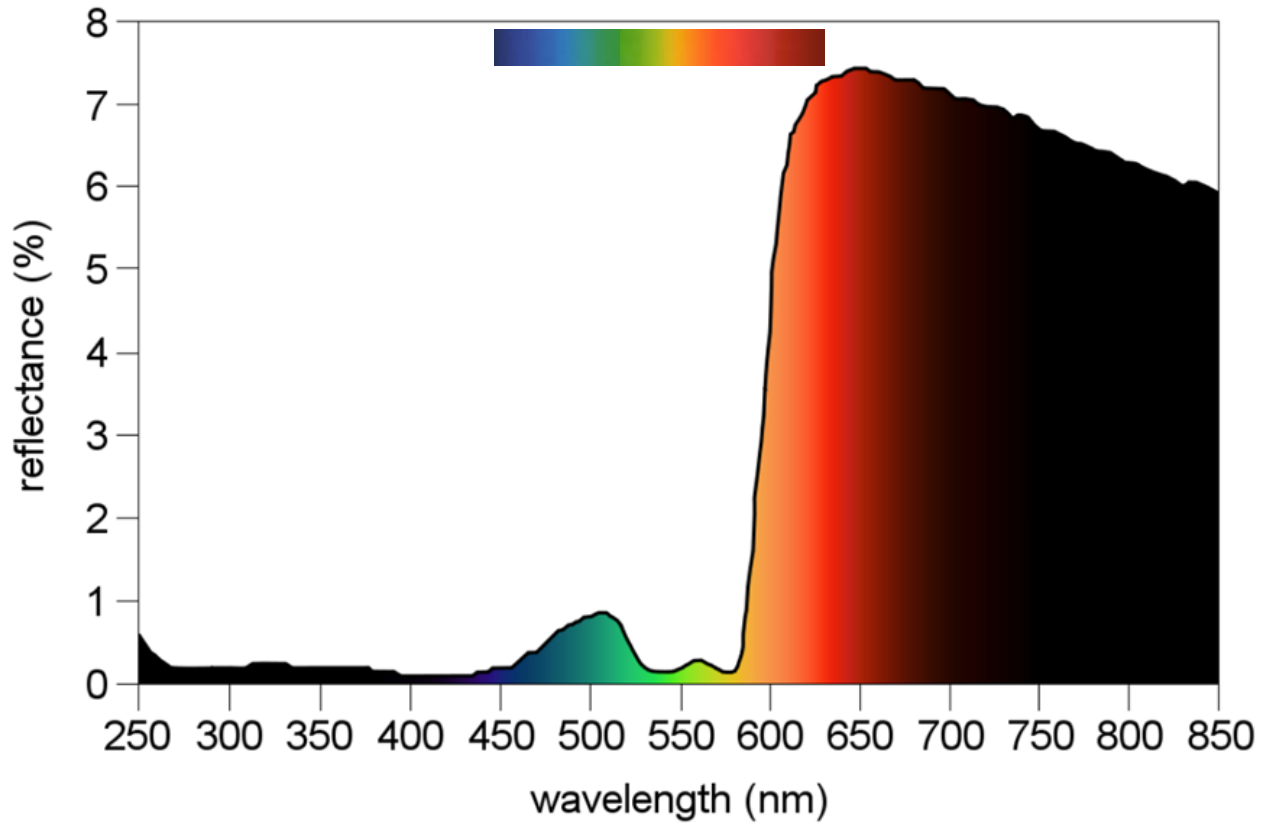
Deep Red is Key to Proper Skin Rendition

About half the response is >600nm



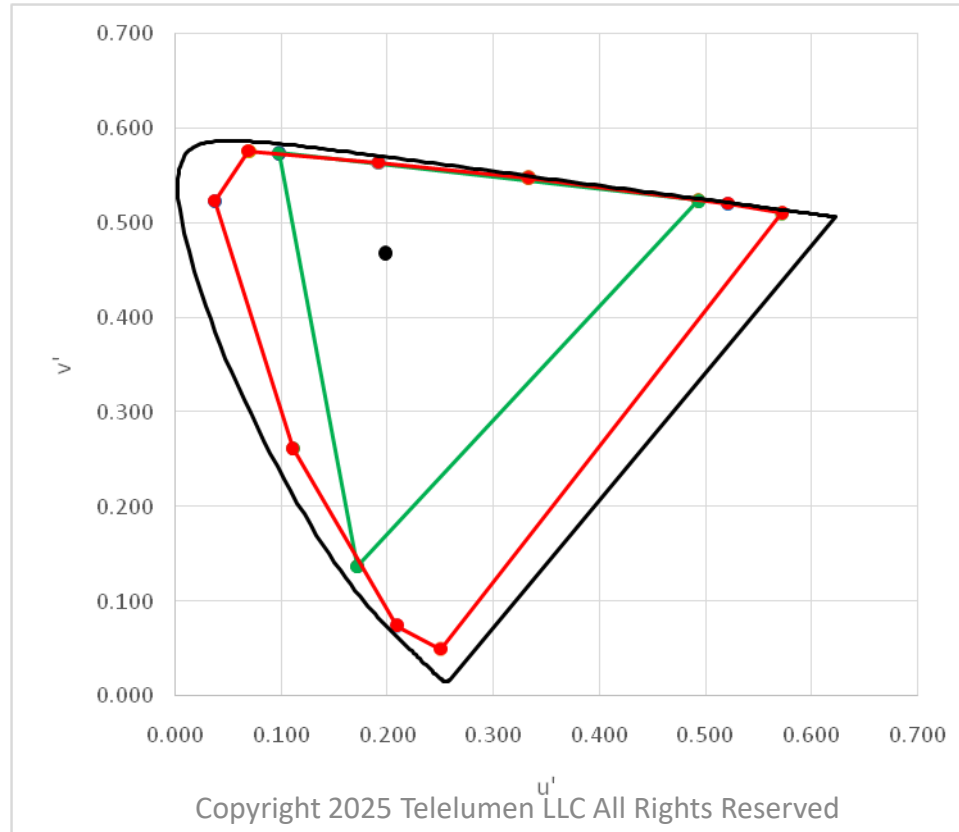
© 2002 Oulu University Library

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.

OLED Display vs. “Continuous” Luminaire



Handheld Spectrometer examples

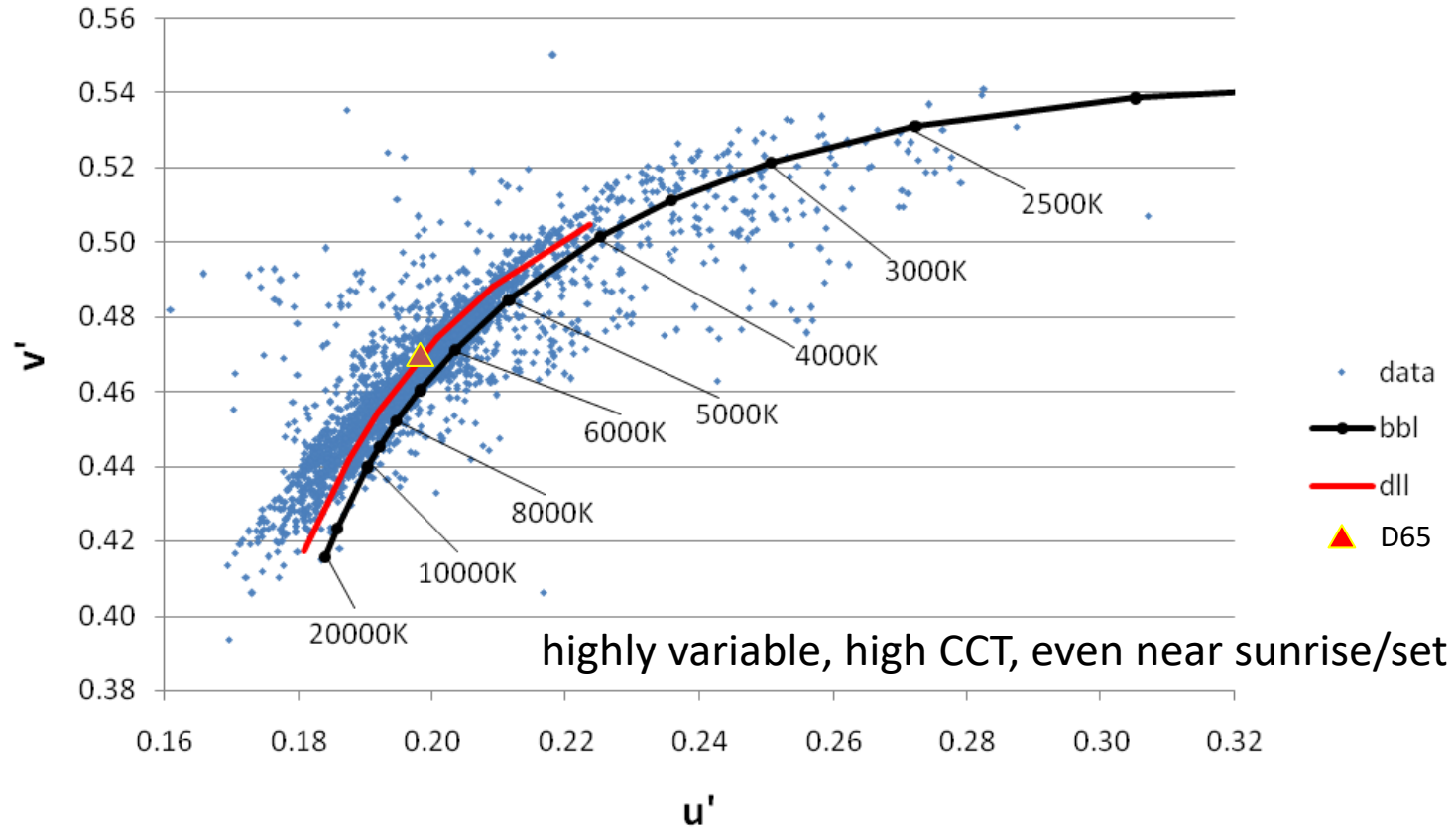


Latest Addition – Future Recordings

SPECIM IQ
HYPERSENSITIVE GOES MOBILE

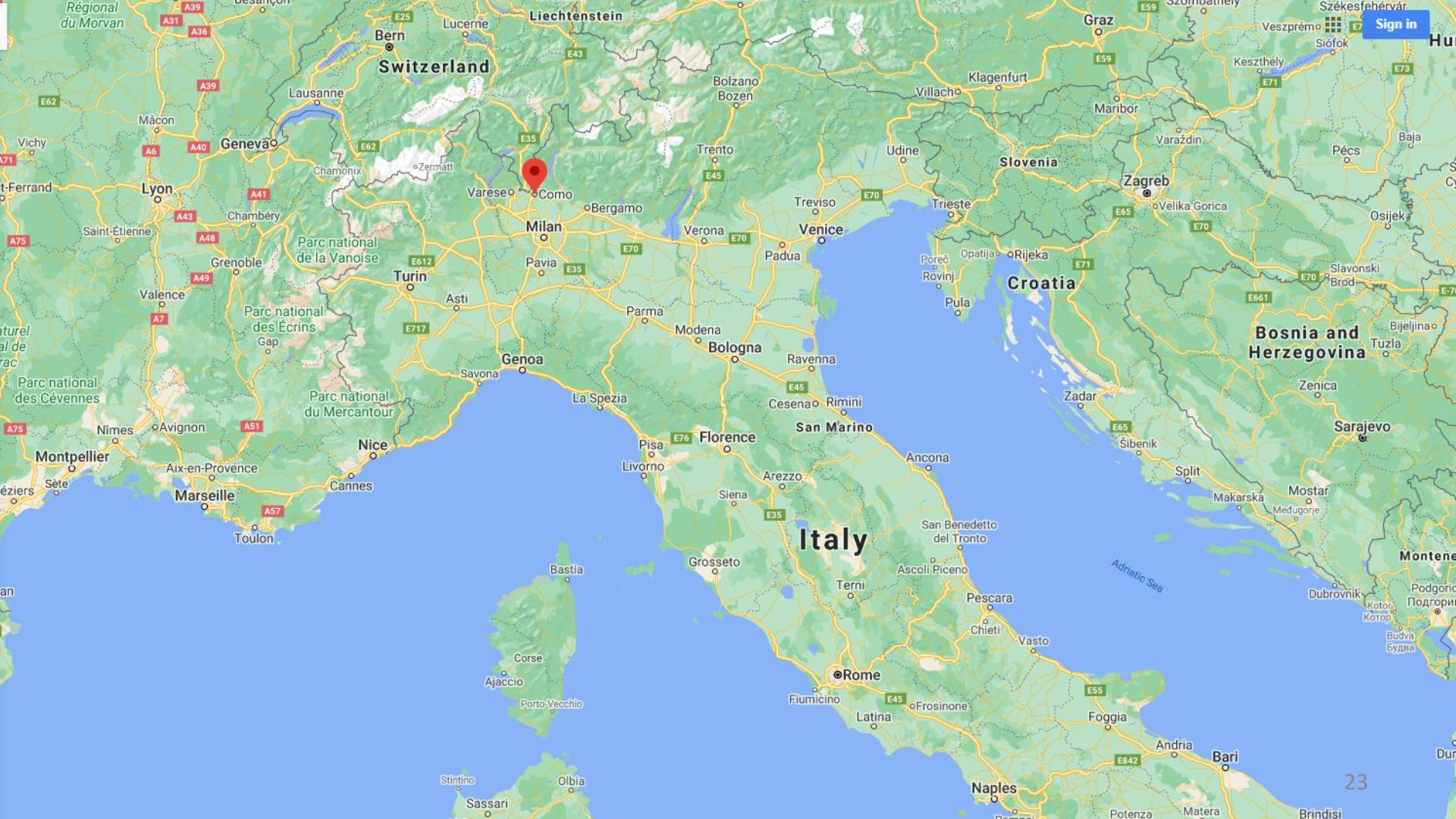


2700 Daylight Recordings



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
Bologna, 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 aquarium, 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	



Switzerland

Geneva

Como

Milan

Venice

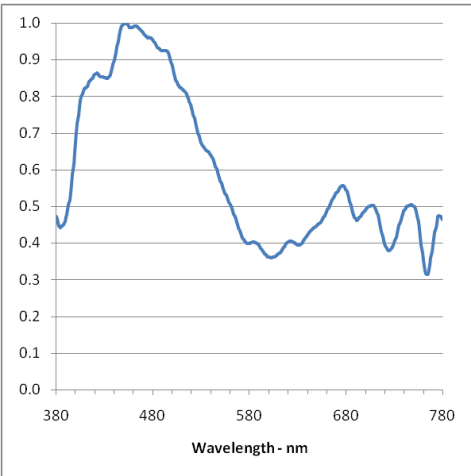
Croatia

Bosnia and Herzegovina

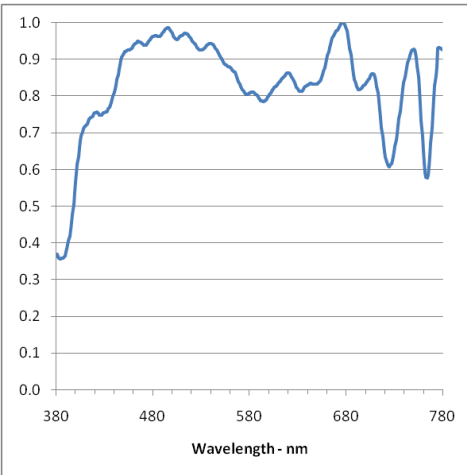
Italy

Rome

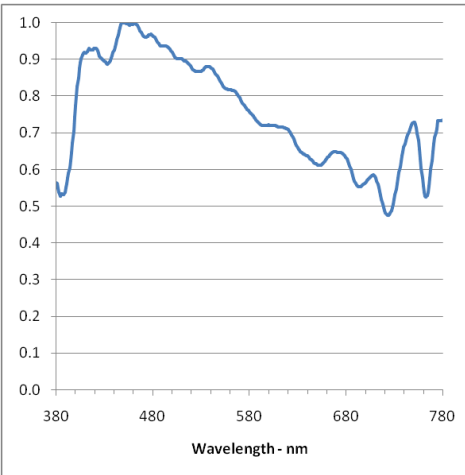
Place	Como, Italy
Date	28-May-16
Time	0537
Lux	159
CCT	14292
CRI	93
u	0.176
v	0.431
duv	0.010



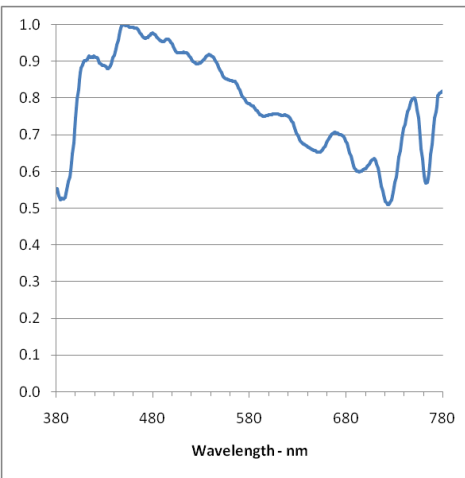
Place	Como, Italy
Date	28-May-16
Time	0631
Lux	2990
CCT	5868
CRI	97
u	0.202
v	0.475
duv	0.003



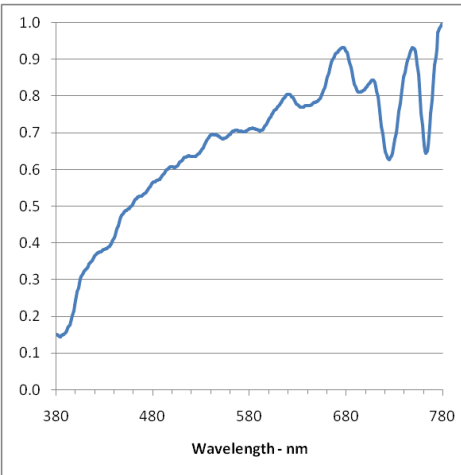
Place	Como, Italy
Date	28-May-16
Time	1042
Lux	9616
CCT	7052
CRI	99
u	0.196
v	0.462
duv	0.002



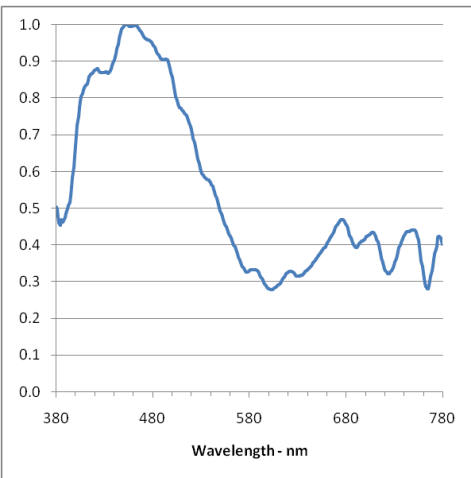
Place	Como, Italy
Date	28-May-16
Time	1726
Lux	6051
CCT	6753
CRI	99
u	0.197
v	0.465
duv	0.003



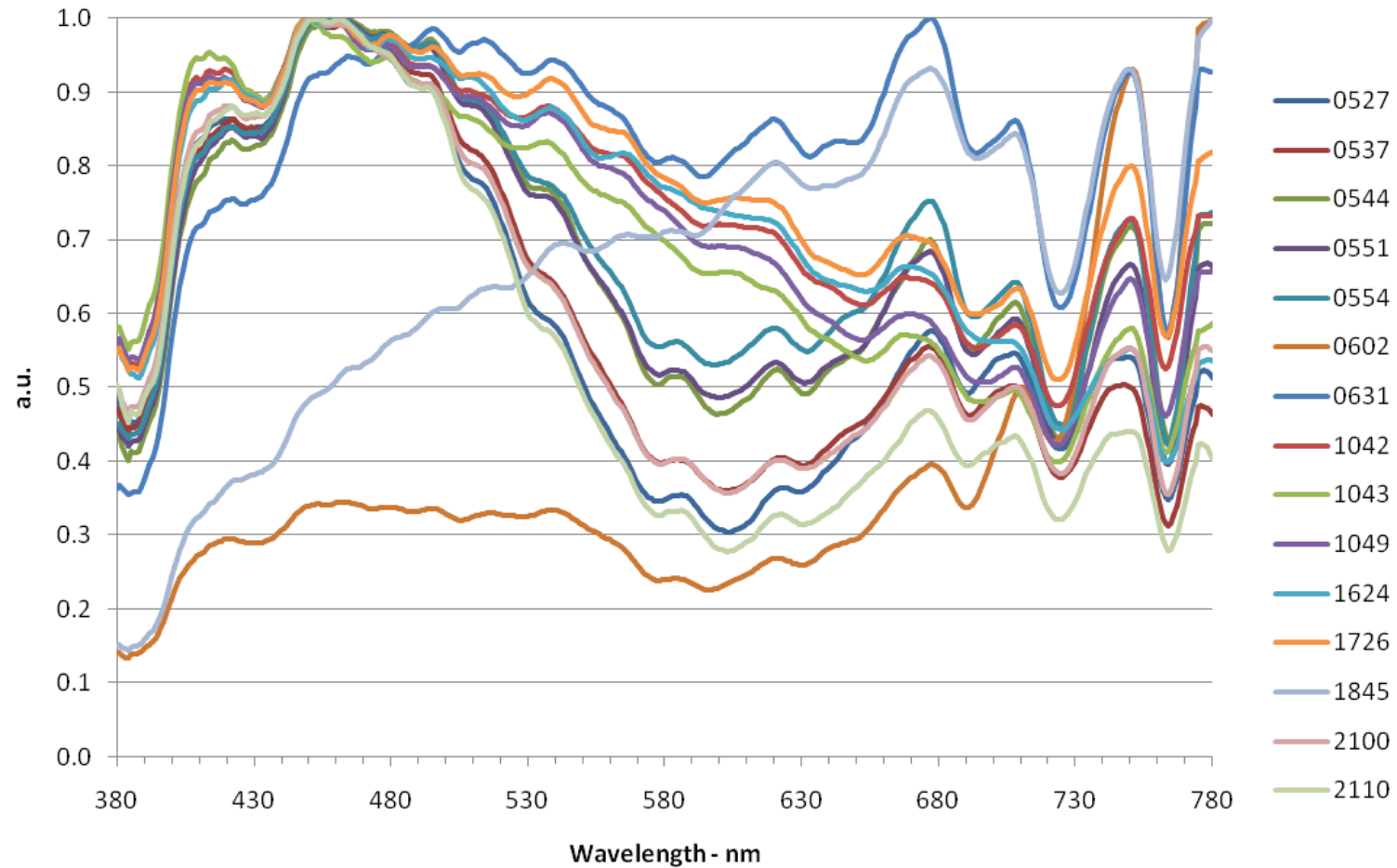
Place	Como, Italy
Date	28-May-16
Time	1845
Lux	33150
CCT	4188
CRI	98
u	0.222
v	0.498
duv	0.000

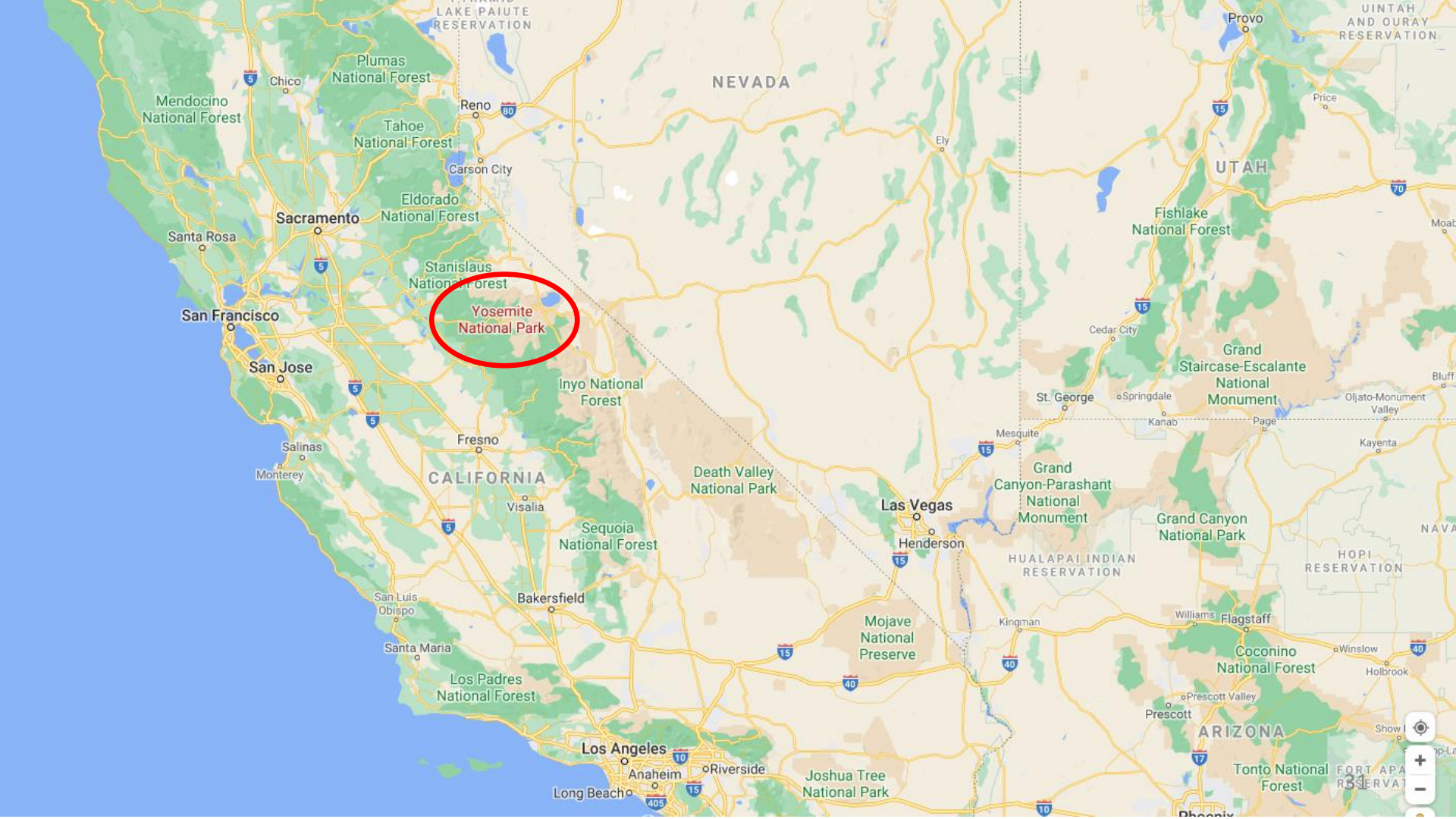


Place	Como, Italy
Date	28-May-16
Time	2110
Lux	55
CCT	25127
CRI	91
u	0.171
v	0.417
duv	0.013



Como, Italy - 28may16





Yosemite National Park

San Francisco

San Jose

Salinas

Monterey

CALIFORNIA

Fresno

Visalia

Sequoia National Forest

San Luis Obispo

Santa Maria

Los Padres National Forest

Bakersfield

Los Angeles

Anaheim

Riverside

Long Beach

Joshua Tree National Park

Death Valley National Park

Inyo National Forest

NEVADA

Las Vegas

Henderson

Mojave National Preserve

Grand Canyon-Parashant National Monument

Grand Canyon National Park

HUALAPAI INDIAN RESERVATION

Kingman

ARIZONA

Williams

Flagstaff

Coconino National Forest

Prescott

Prescott Valley

Tonto National Forest

FORT APACHE RESERVATION

Grand Staircase-Escalante National Monument

St. George

Springdale

Kanab

Page

Kayenta

Fishlake National Forest

UTAH

Provo

Price

Moab

Bluff

Ojito-Monument Valley

Bluff

Kayenta

NAVAJO RESERVATION

HOPI RESERVATION

Winslow

Holbrook

Prescott

Show Low

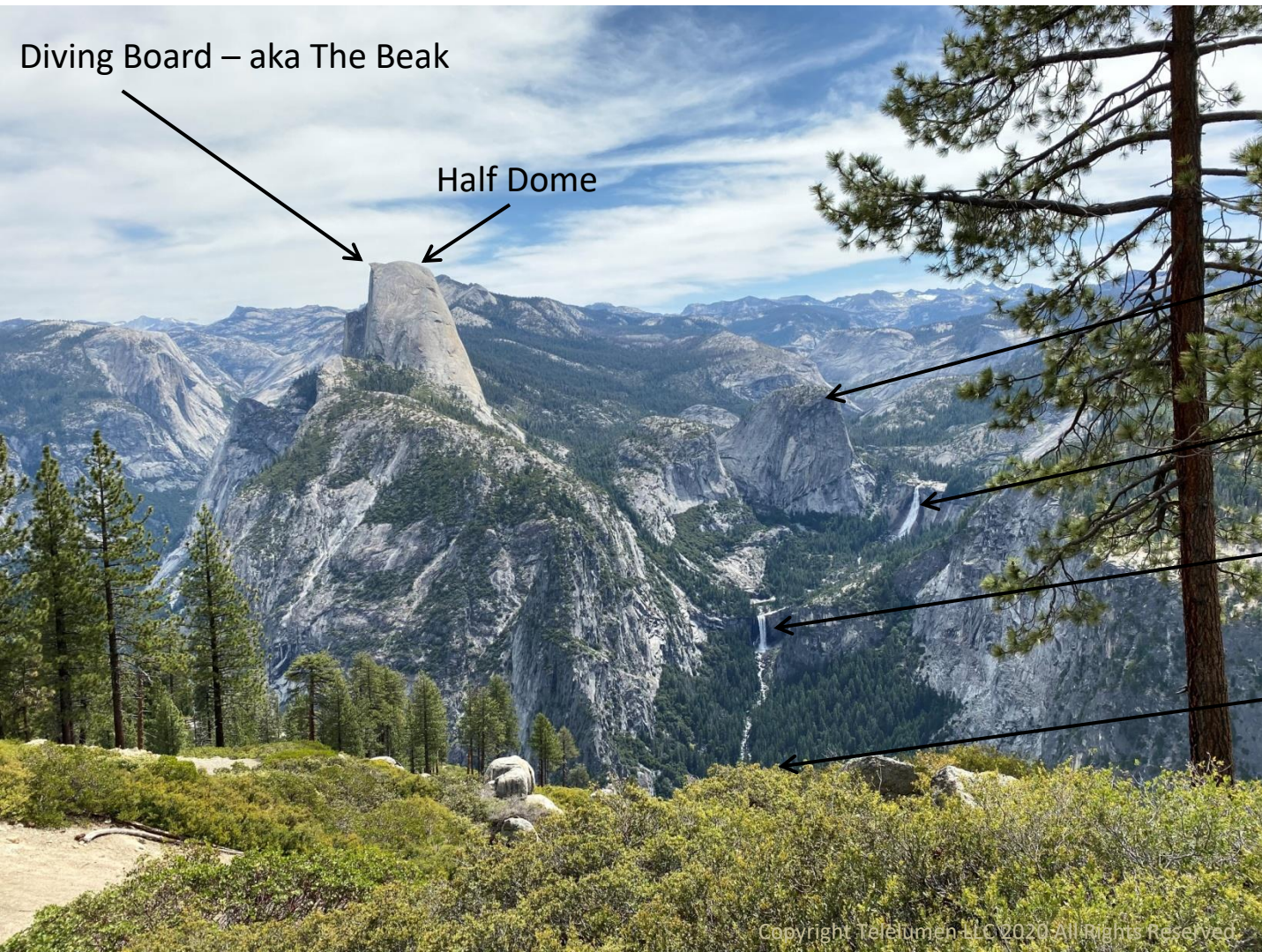
Flagstaff

Phoenix

Phoenix

Phoenix

Phoenix



Diving Board – aka The Beak

Half Dome

Yosemite National Park,
California
14jun20

Liberty Cap

Nevada Falls

Vernal Falls

Start/Finish – Curry Village



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June 14, 2020

0503 – The hike begins.



0526 – Typical recording posture.

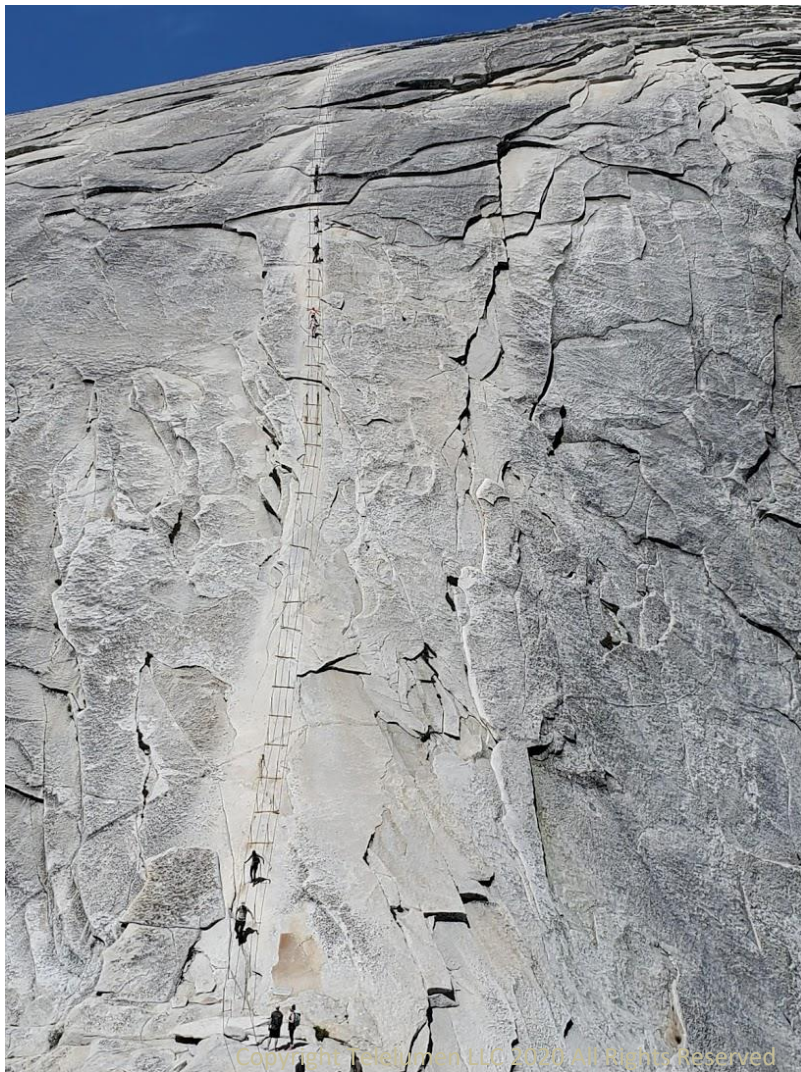
Lighting Passport Spectrometer



0728 – Day is heating up.



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

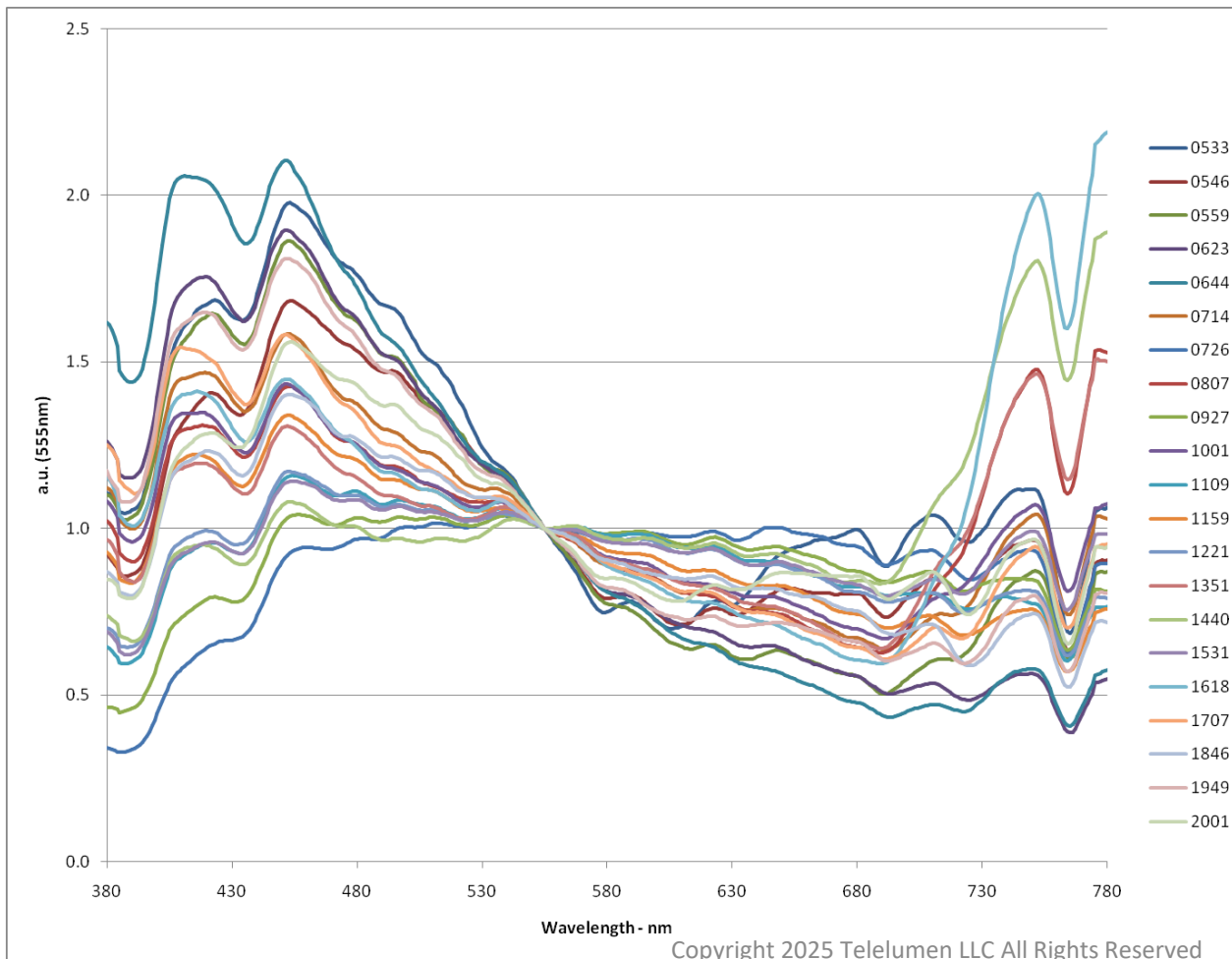
- Starting elevation – 4,000 feet (1,200 m)
- Ending elevation – 8,800 feet (2,700 m)

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

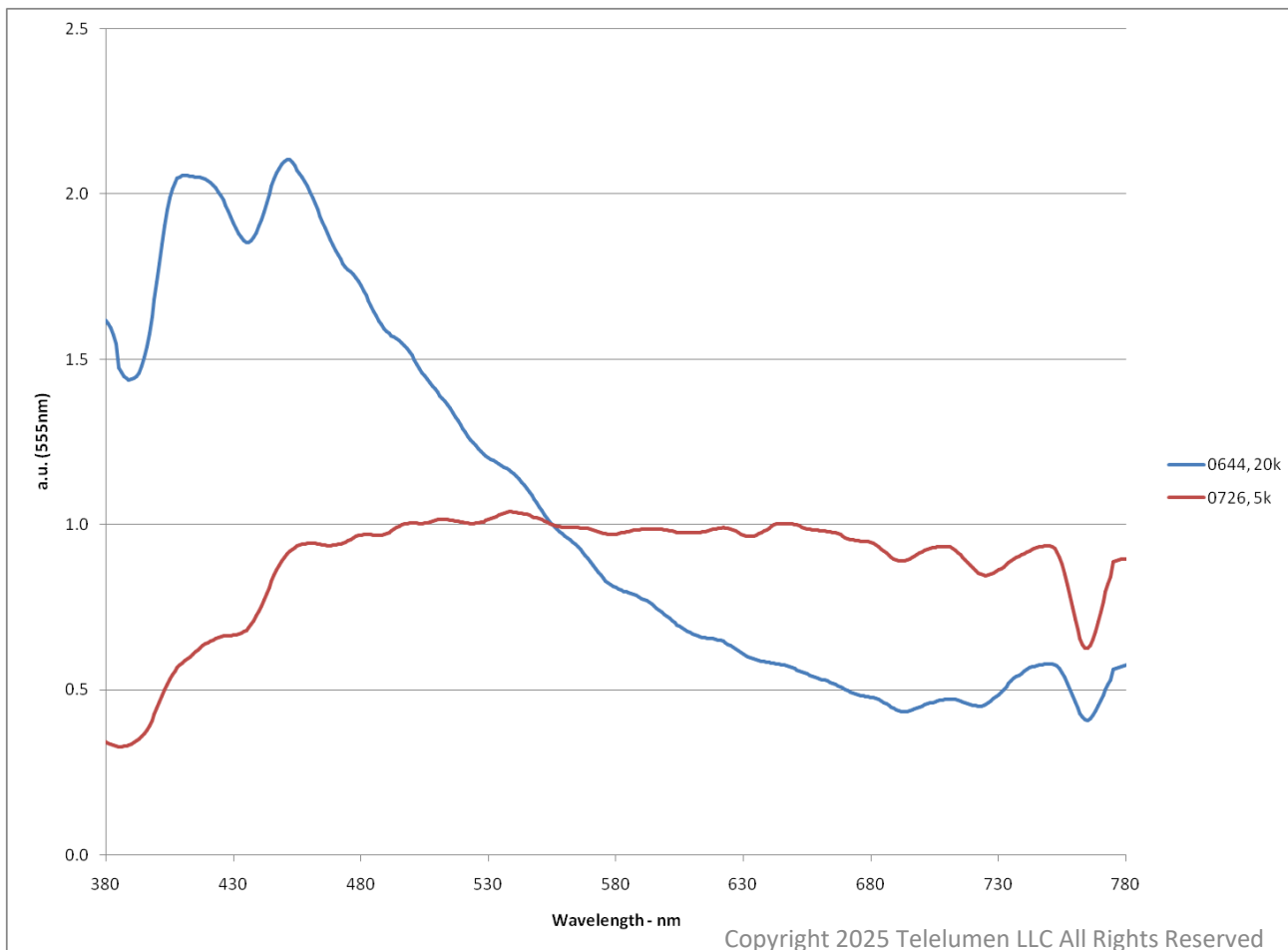
- Weather: low 50 F – high 77 F (10 C – 25 C)

- Total time: 14 hours 15 mins

Yosemite National Park, Half Dome Hike, 14jun20



Max, Min CCT – 14jun20



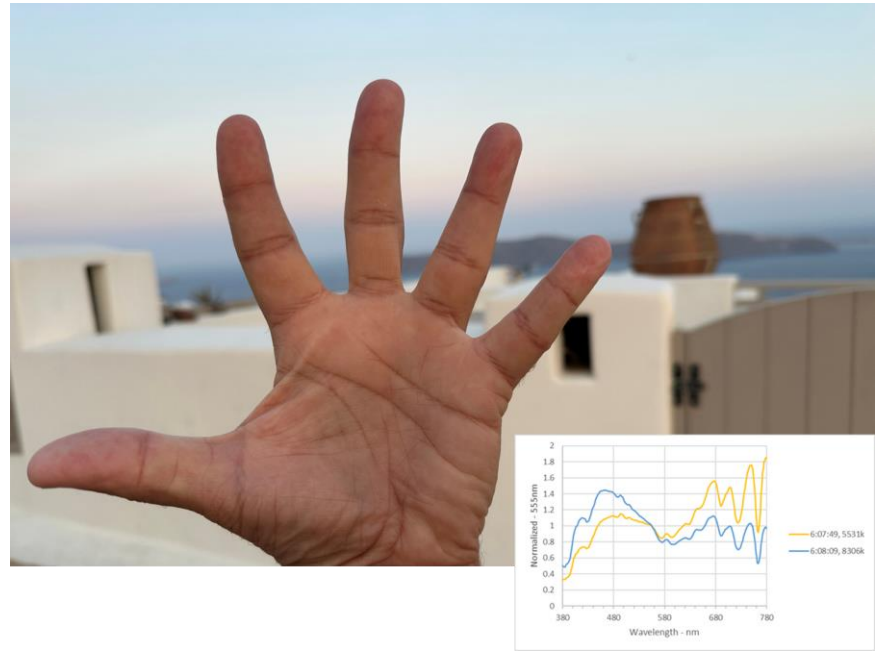
21,600K, 0644



5,100K, 0726



Santorini, Greece – 29jun25

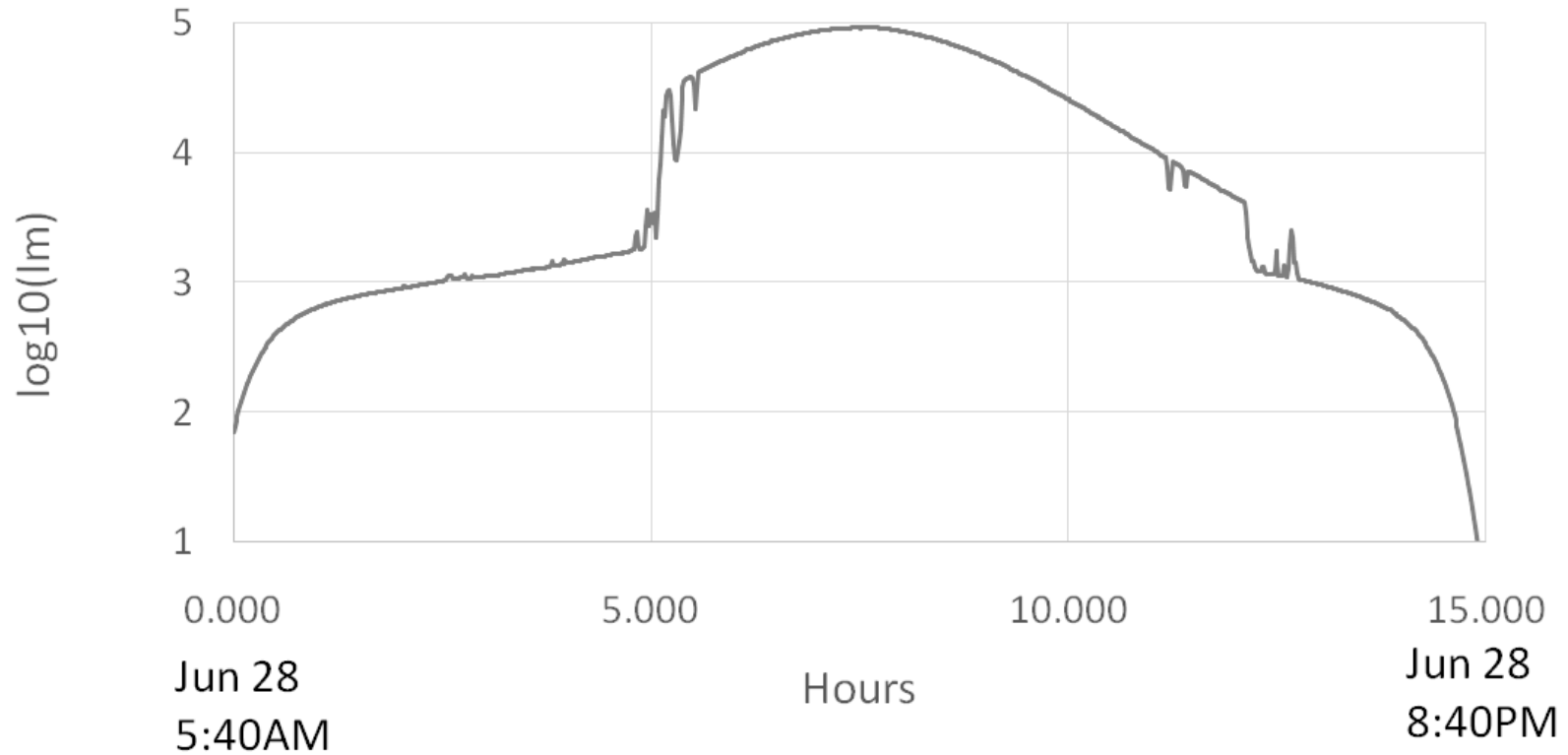


Day of sunlight

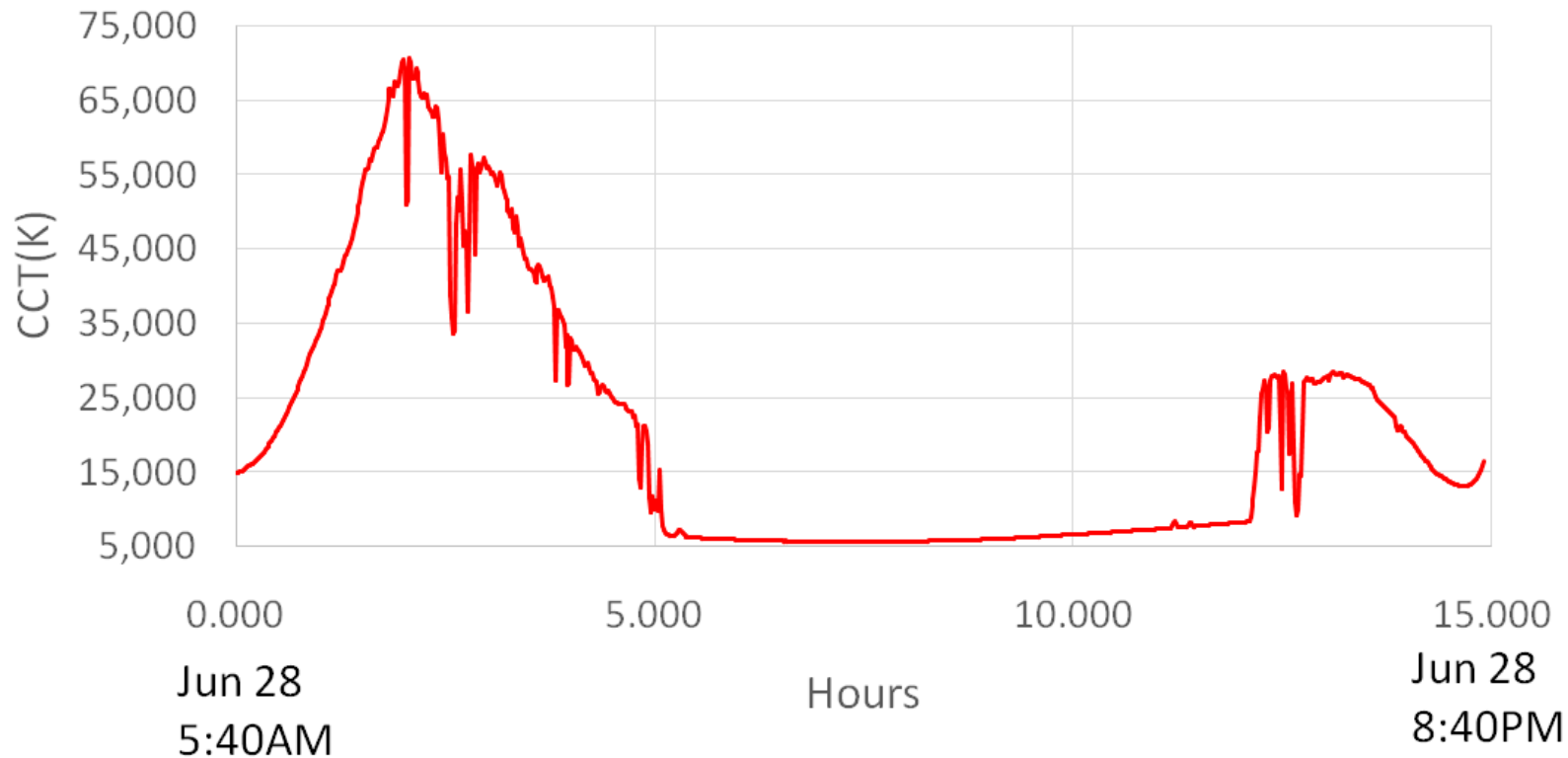
- Illuminance sensor pointed up at a mostly blue sky in Saratoga, California
- Starts: 28JUN18 at 05:48
Ends: 28JUN18 at 20:48
- Lux range in actual recording: 10,000:1
- Color temperature range: 5,700K to 70,000K



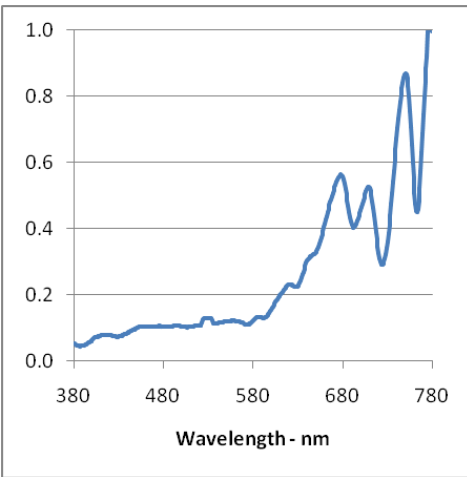
A day of sunlight lumenscript: log luminous output



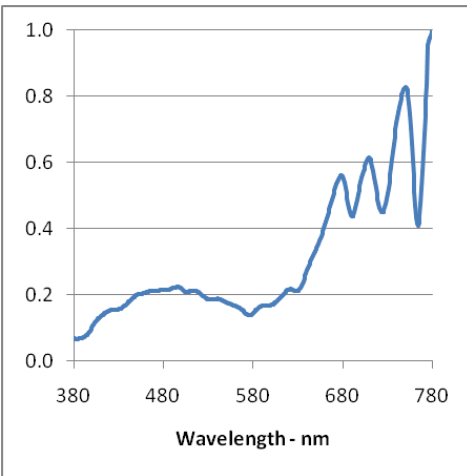
A day of sunlight lumenscript: CCT



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

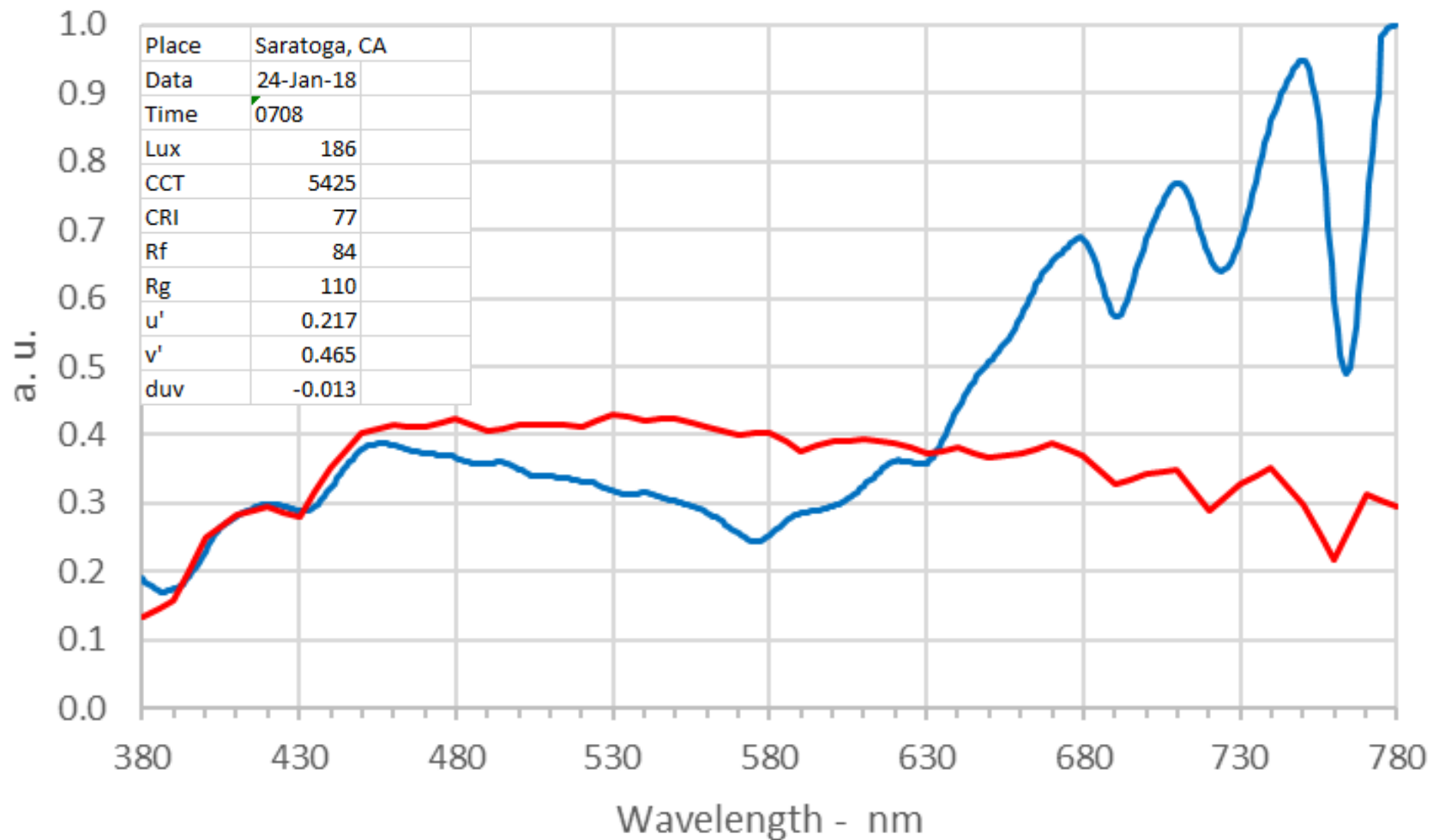


Place	Newport Beach, CA
Date	24-Feb-16
Time	1755
Lux	90
CCT	5056
CRI	73
u'	0.219
v'	0.471
duv	-0.012



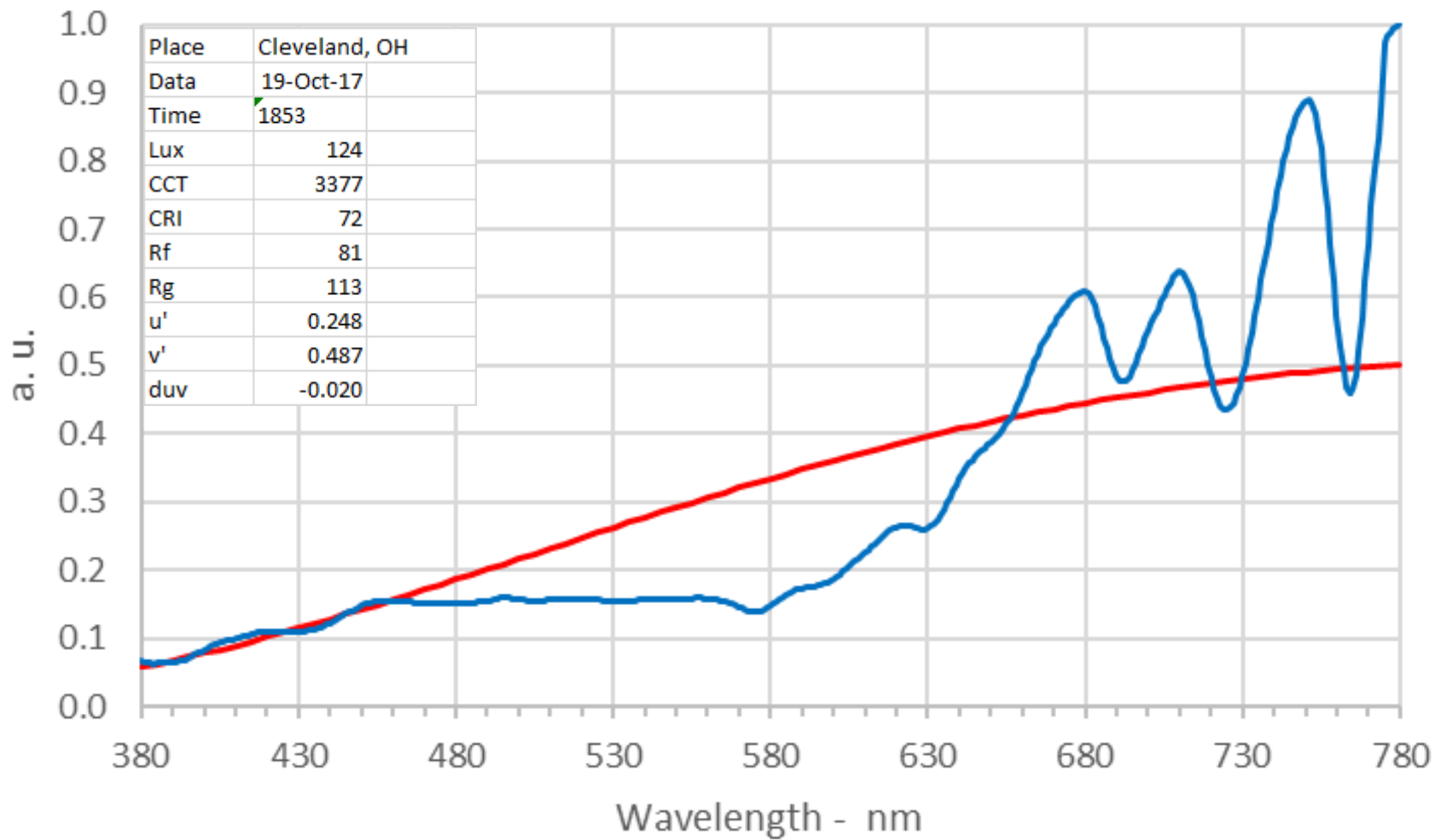
Saratoga morning sky, 7:11AM, 24jan18



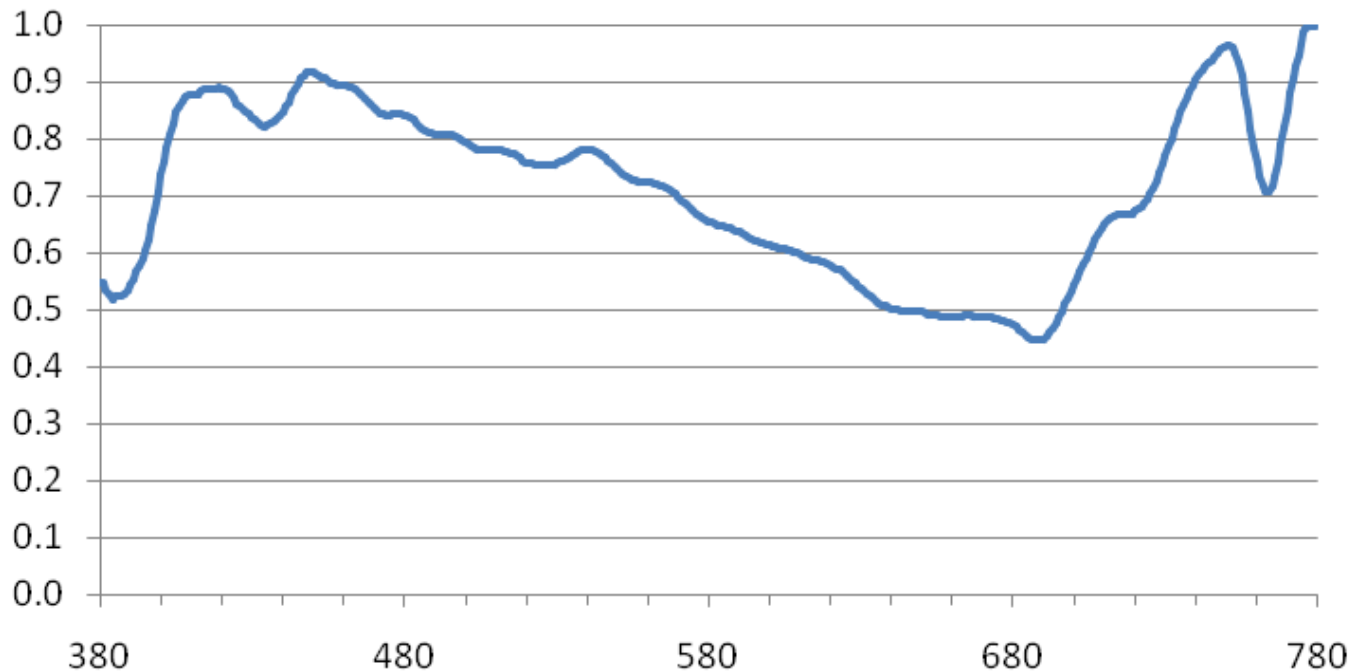


Cleveland evening sky, 18:53PM, 19oct17





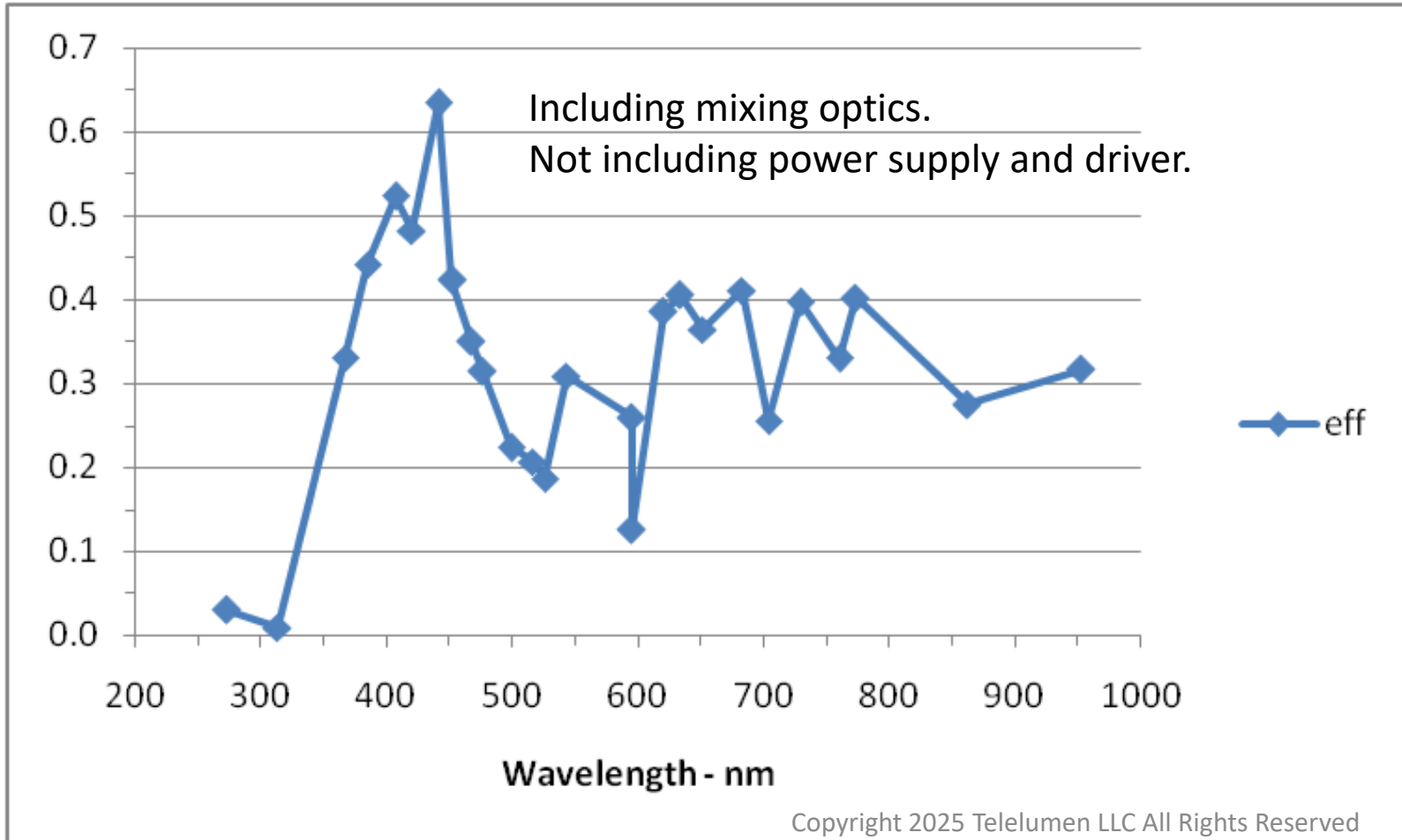
Kitchen Window Saratoga CA 11:40AM



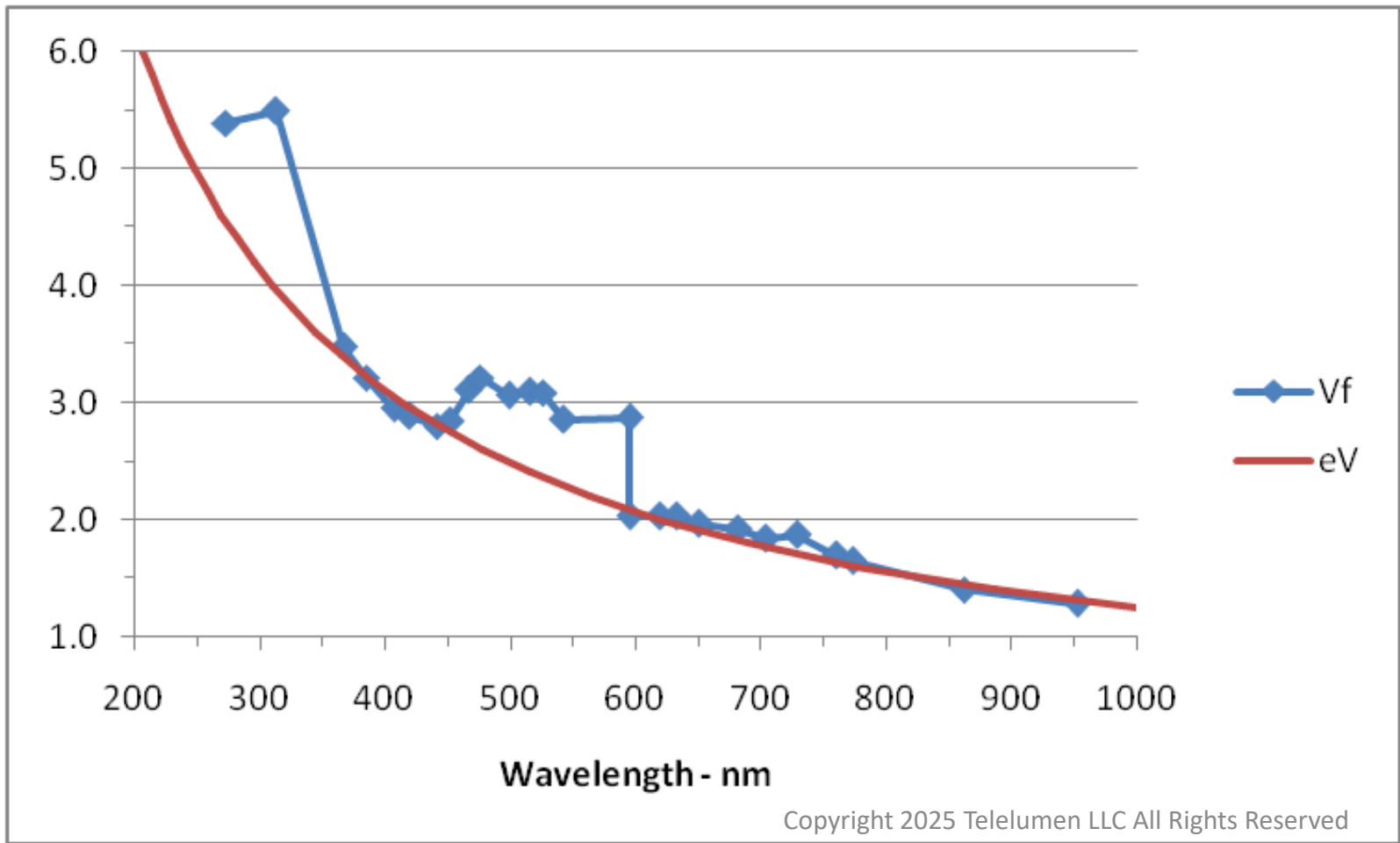
Beautiful high CCT daylight with non-standard SPD.

7526K, 300 lux
13nov15

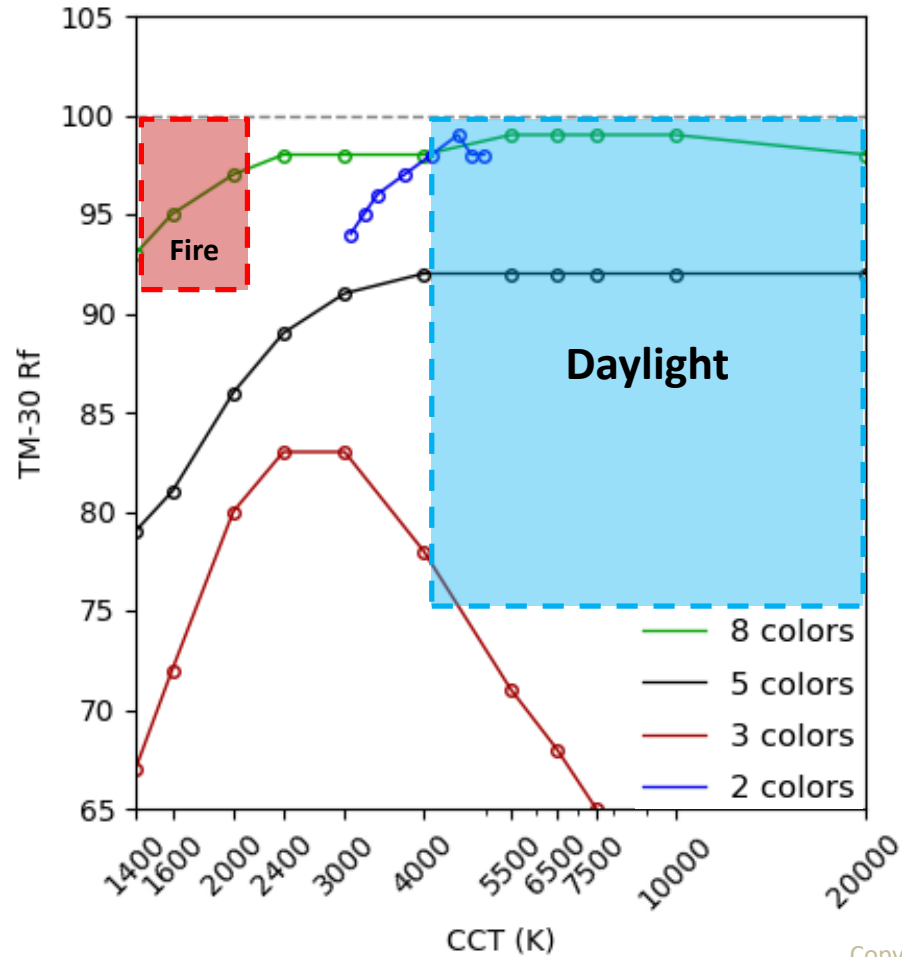
Efficiency vs. Wavelength



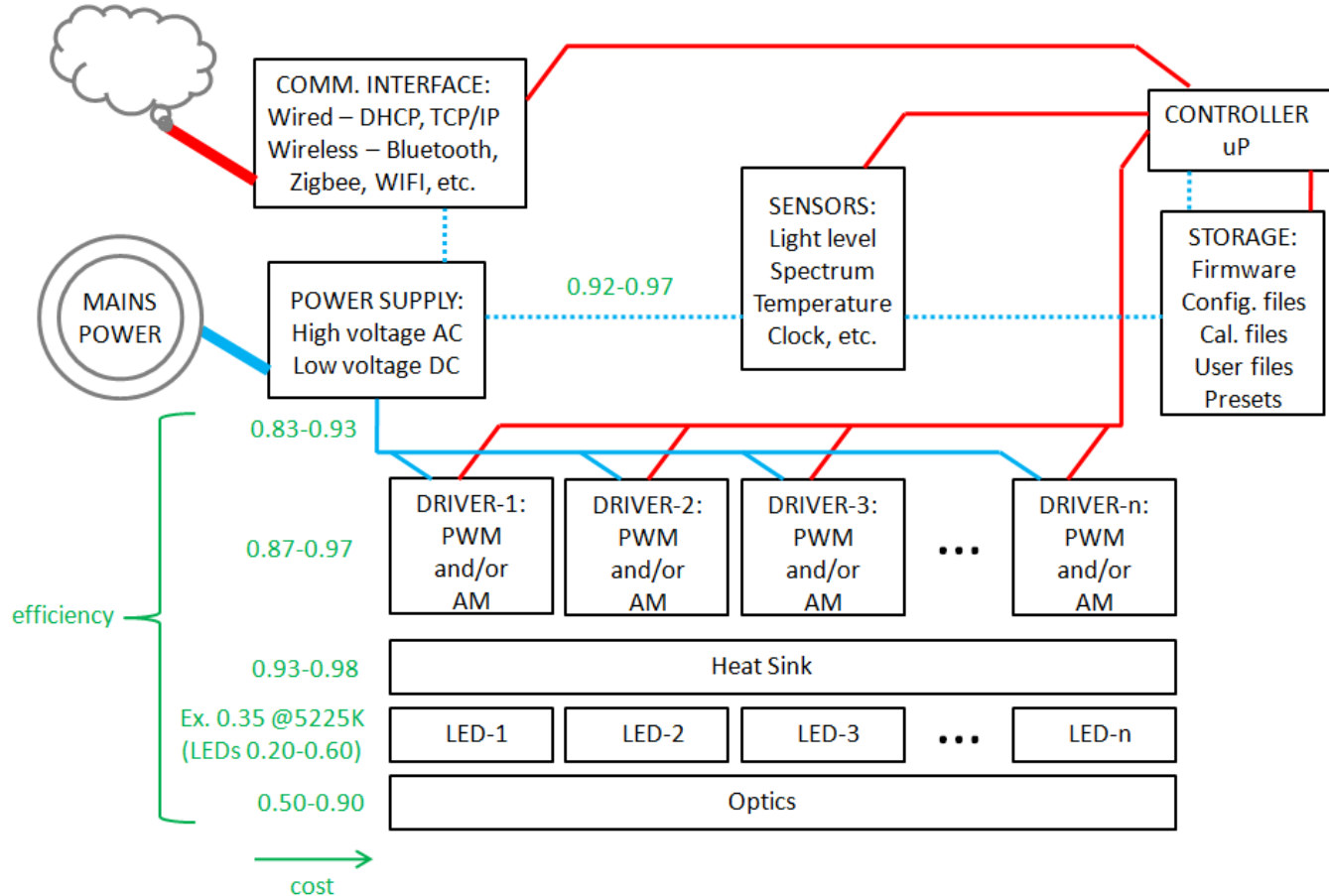
Photon Energy and Vf vs. Wavelength



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



Spectrally Tunable Architecture



Spectraloc Control Software

Telumen Spectraloc 25.01.29.0

Luminaires

201
2641

forced discover

Target Illumination

Match mode
spectrum

Target Thermal CT
3097

Target Luminous Output
1699.38

Manual Control

Level apply to group

	Level
UV1	0.0175
UV2	0.0190
V1	0.0205
V2	0.0219
RB1	0.0207
RB2	0.0322
B1	0.0193
B2	0.0516
C	0.0555
G1	0.0000
G2	0.0449
L	0.2288
PC-A	0.2538
A	0.0000
OR	0.0252
R1	0.0340
R2	0.0635
DR1	0.0863
DR2	0.0732
FR1	0.1455
FR2	0.0773
FR3	0.1767
IR1	0.3949
IR2	0.4555

Metrics

luminaire

Output (lm)	1699
Output (W)	16.773
Input (W)	56.6
(u', v') cmf2	0.247, 0.520
duv	0.0006
CCT (K)	3097
Ra	98
SPD Error (%)	28.7
(u', v') Error	0.0011
Rf av.	98
Rg	99
Board T (C)	

S/N 201 (Dittosizer) SPD (W/nm)

Full scale: 8.9e-02

Edit Lumenscripts

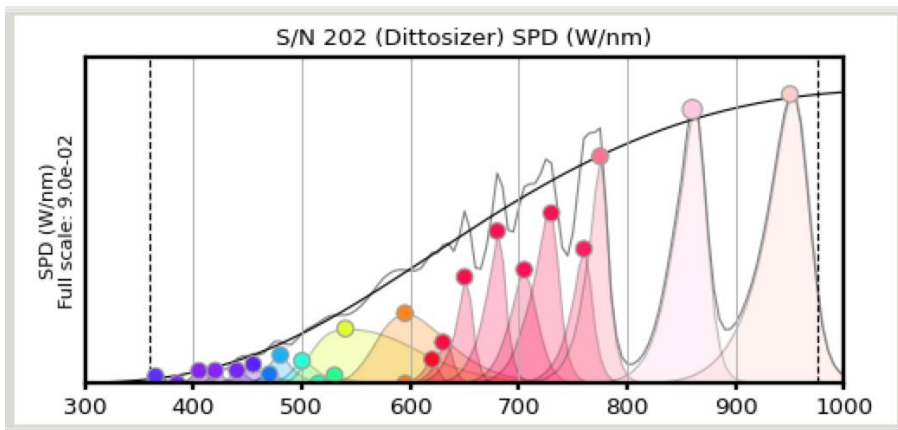
Next Frame # 1 | Duration 1.000 | Source target

single frame smooth loop dark after send

play by name

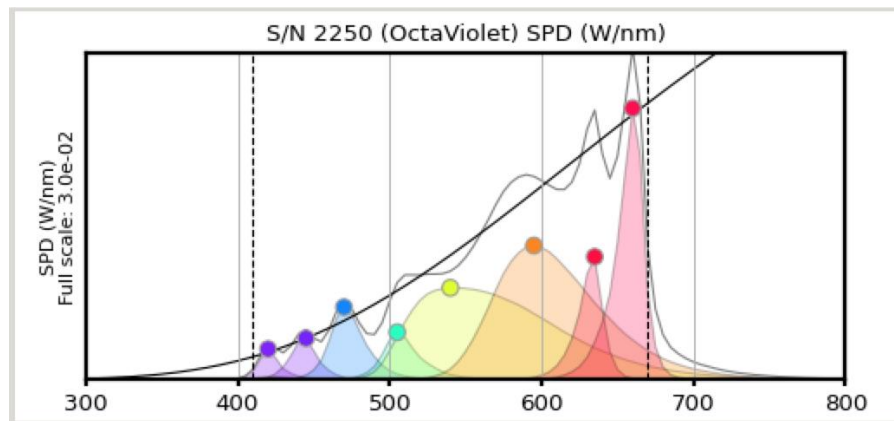
Play Lumenscripts

24-channel

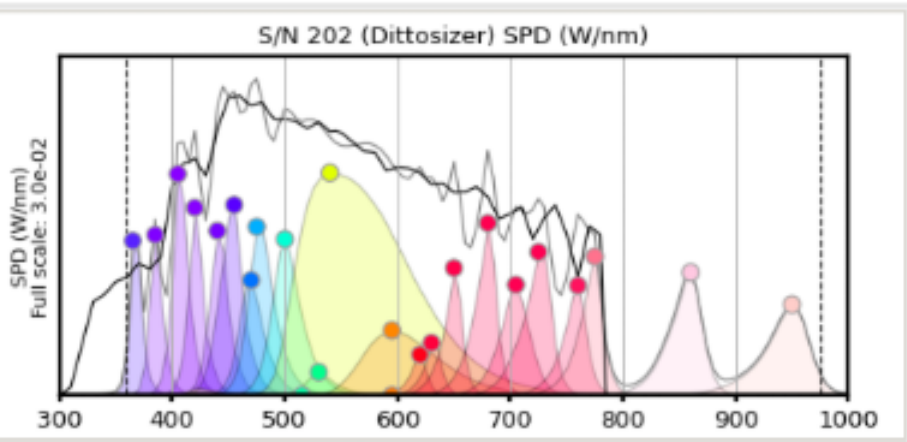


2755K Incandescent Target

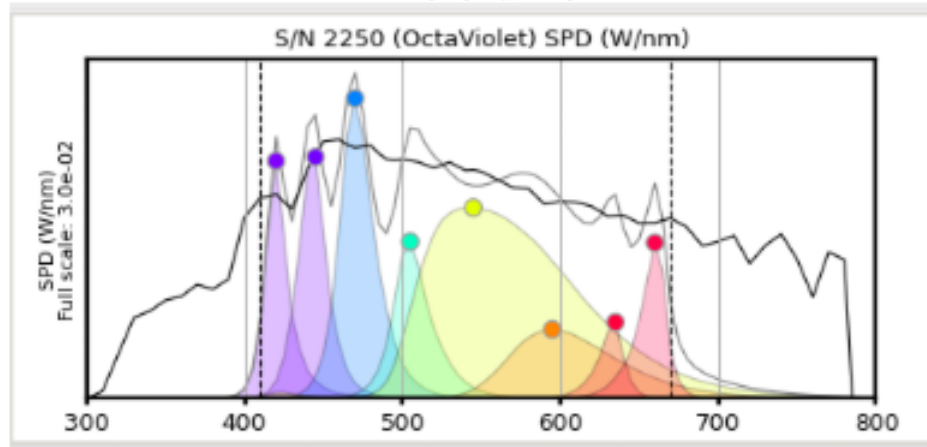
8-channel



24-channel

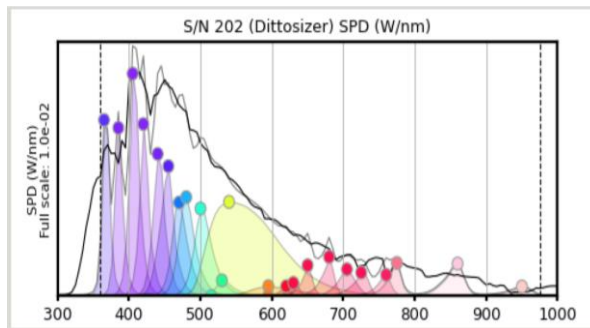


8-channel

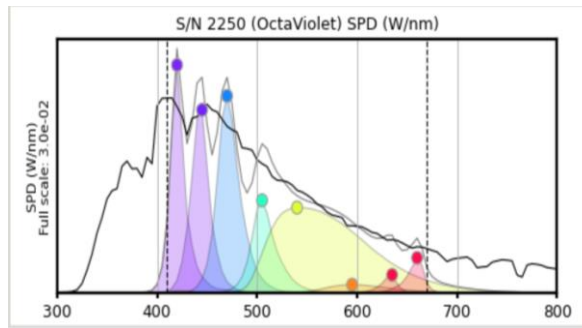


6500K Daylight Target

24-channel

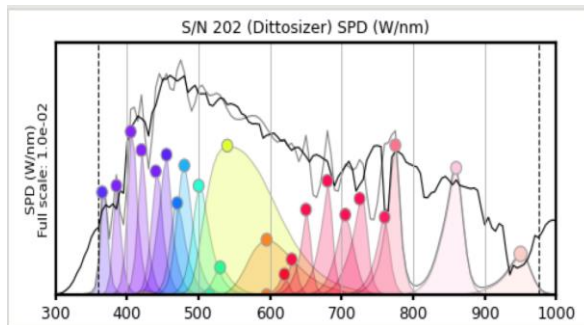


8-channel

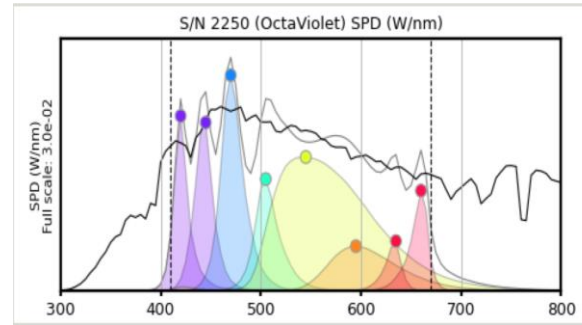


Daylight Recorded at 1712, 18440K

24-channel



8-channel



Daylight Recorded at 1714, 6657K

Octa Light Players 20000K to 1500K





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).

Claude Monet – “Haystacks”

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

1890-1891 series [\[edit\]](#) [http://en.wikipedia.org/wiki/Haystacks_\(Monet\)](http://en.wikipedia.org/wiki/Haystacks_(Monet))



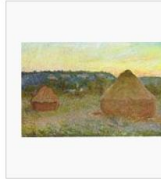
Grainstacks in the Sunlight, Morning Effect, 1890. Oil on canvas. Private collection.



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.



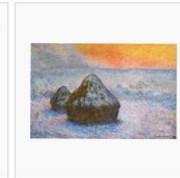
Haystacks on a Foggy Morning, 1891. Oil on canvas. Private collection.



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



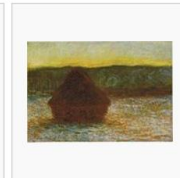
Wheatstacks (Sunset, Snow Effect), 1890-91. Oil on canvas. Art Institute of Chicago.



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



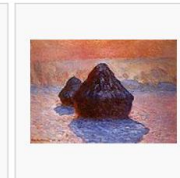
Wheatstack, 1890-91. Oil on canvas. Art Institute of Chicago.



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.

Summary

- Daylight is the gold standard for lighting.
- Daylight is complex – continuous spectrum, changing over time.
 - Daylight locus is only occasionally representative of daylight.
- Daylight CCTs are much higher than most electric lights.
 - Typically, even at sunrise and sunset.
- Programmable spectrum sources allow many solutions for the same CCT.
- Deep red (>650nm) is essential for high CCT acceptance and skin color.
- Focus on radiometry, photometry is not sufficient for daylight.



The Recording and Playback of Light

SP7 - COLOUR SCIENCE/TECHNOLOGY, LIGHT AND APPLICATIONS

Questions, Comments

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