Swux: A new radiometric unit of measure to characterize SWIR irradiance

CORM 2018

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Why a new SWIR specific radiometric unit of measure ?

- SWIR imaging results frequently referred to lux measurement

- But: VIS- and InGaAs-band irradiances behave differently:
  - Ratio varies by factor 100 for natural sources (sun, moon, stars: direct and indirect)
  - by factor 10^6 for artificial sources (fires, flames, fluorescent lighting, LEDs…)

- VIS and SWIR scatter differently in atmosphere (sharper shadows in SWIR)

→ Propose commercial SWIR-equivalent of luxmeter to log SWIR-specific irradiance background for InGaAs-type cameras

→ **Meter must be traceable and conform to NIST standard**

Swux unit of measure

- Swux introduced in 2017 at SPIE DCS – reference SPIE 10178-12
- Combination of “SWIR” and “lux”
- Spectrally-weighted unit of SWIR-specific irradiance (analogous to illuminance): irradiance convolved with $S(\lambda)$ function
- $S(\lambda)$: Average SR of various lattice-matched InGaAs detectors @ T_{amb}
- Swux: single-number metric for InGaAs camera performance in different lighting scenarios
- Swux has already been incorporated into NV-IPM and various software packages across industry (Labsphere, SBIR)

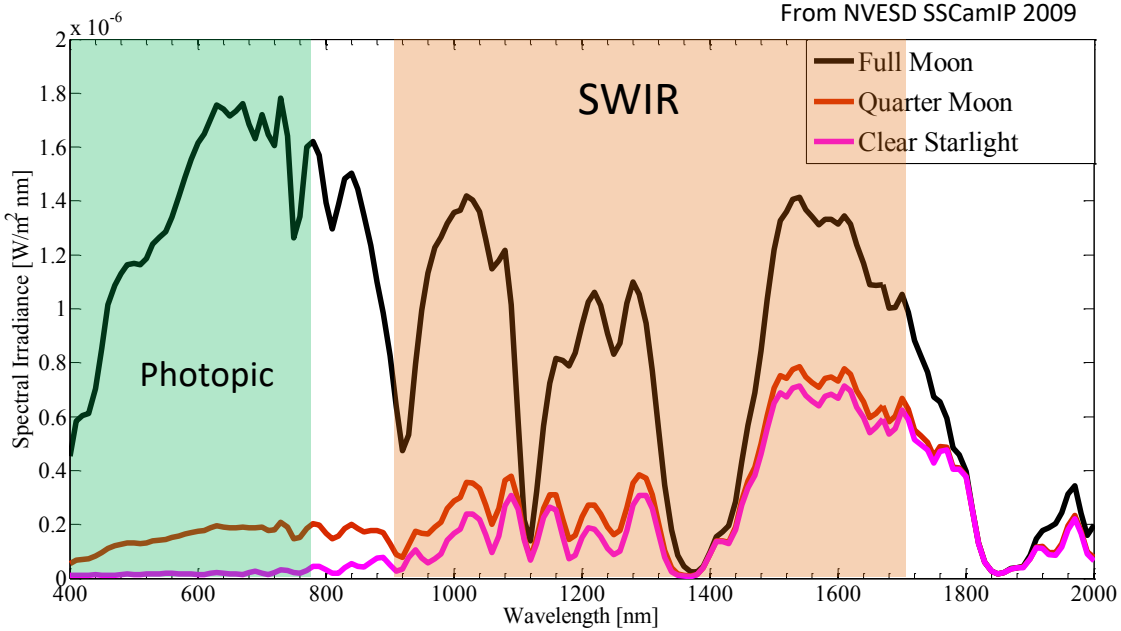
Motivation for a new SWIR specific radiometric unit of measure

Detailed measurements can show the actual irradiance levels:

Spectroradiometers (VIS-SWIR):

- Not portable
- High Price
- SNR
- Complex

From NVESD SSCamIP 2009



- SWIR imaging technology requires devices like “lux-meters“, capturing a **single number parameter called “swux“**.

- “Swux-meter“ : time- and site-independent **comparison** in the field.

- Better prediction of imager performance .

SWIR-Specific Radiometric Quantities

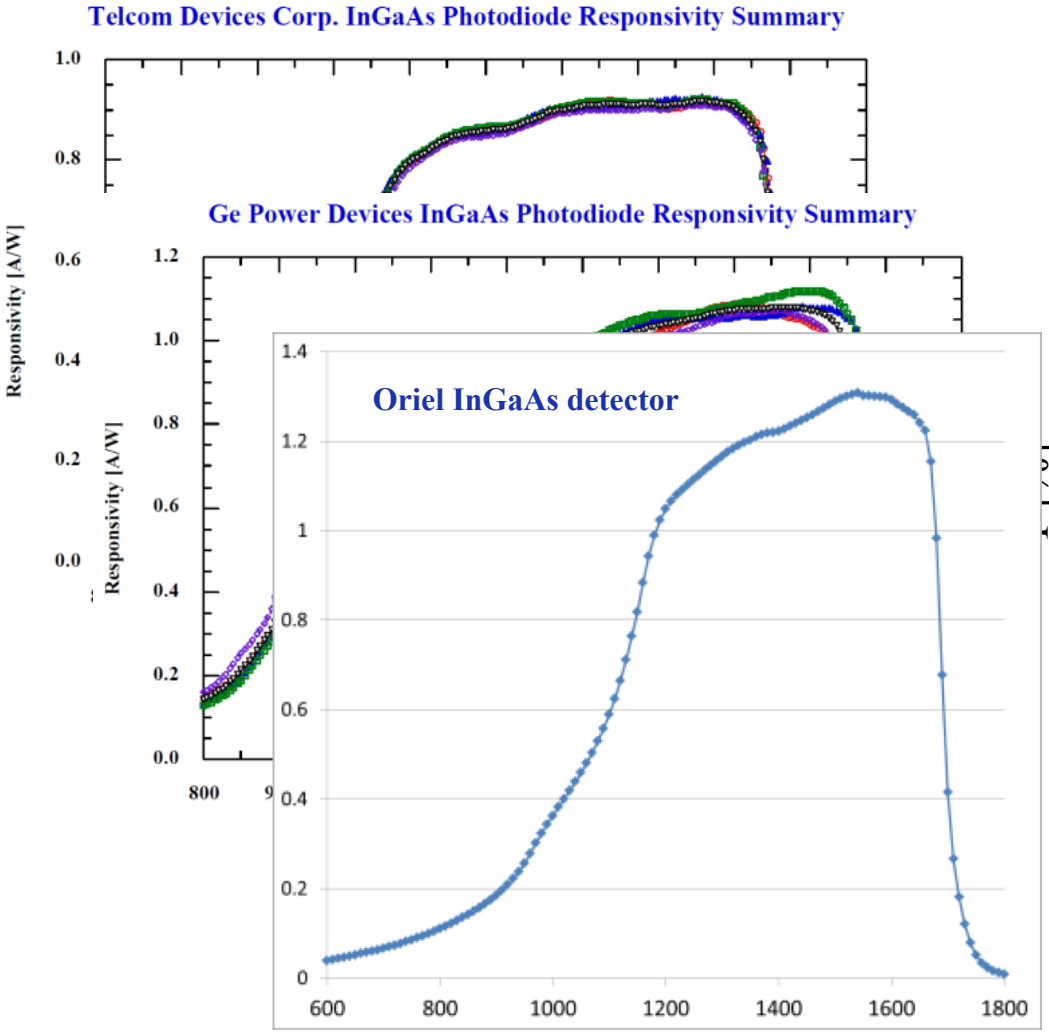
Proposal for an analogous framework

Photometric (VIS)	SWIR specific (SWIR)
Candela $(1/cd = 683)$ lm/W	SWIR-Candela $(1/sc)$ swir-lumen/W
$V(\lambda)$ photopic vision	$S(\lambda)$
$lux = K_m \cdot \int_\lambda E_e(\lambda) \cdot V(\lambda) d\lambda$ $K_m = 1/cd = 683$	$swux = A_m \cdot \int_\lambda E_e(\lambda) \cdot S(\lambda) d\lambda$ $A_m = 1/sc$

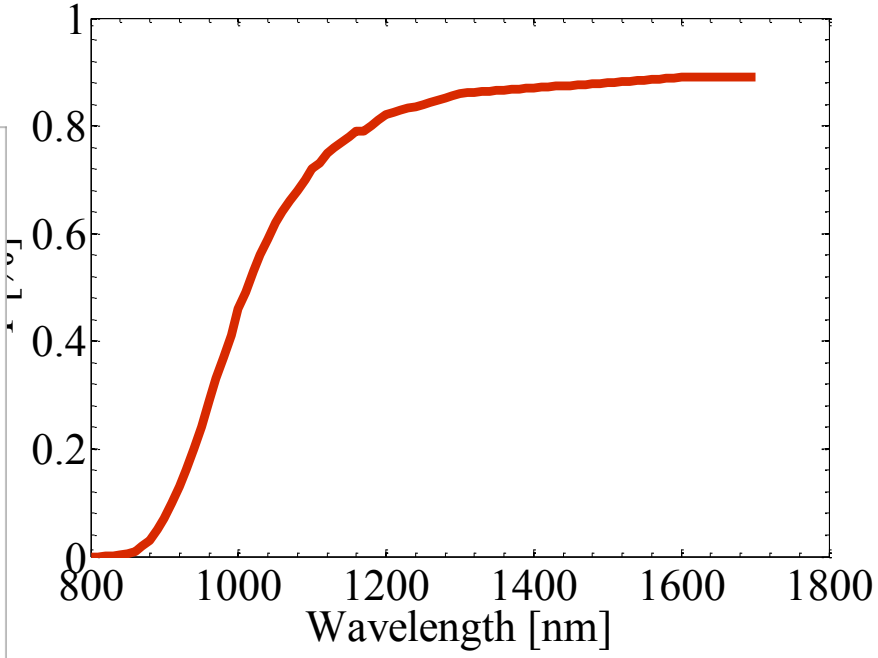
$E_e(\lambda) = \text{Spectral irradiance}$

Spectral radiant efficiency function for SWIR sensing = $S(\lambda)$

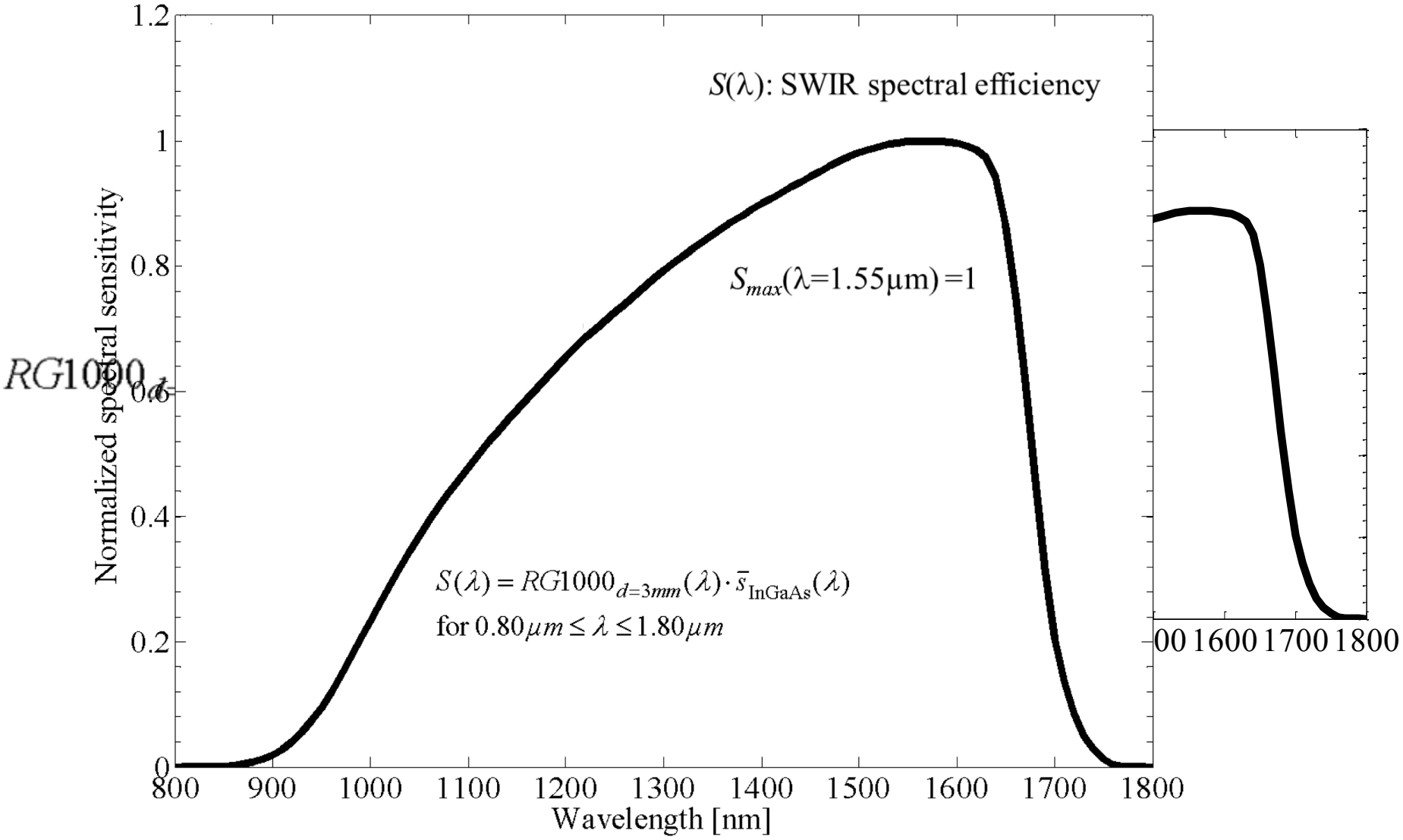
Basis for $S(\lambda)$ = spectral sensitivity of lattice matched InGaAs:



RG 1000 $_{3mm}$ cut-on filter glass



Spectral radiant efficiency function for SWIR sensing = $S(\lambda)$



SWIR-Specific Radiometric Quantities

Main issues tbd.:

S(λ) : Spectral radiant efficiency function for SWIR sensing

sc : setting the new quantity scale

The SWIR-candela is proposed to be the radiant intensity, in a given direction, of a source that emits monochromatic radiation of frequency 193.413 E+12 Hz (λ =1.55µm in vacuum),

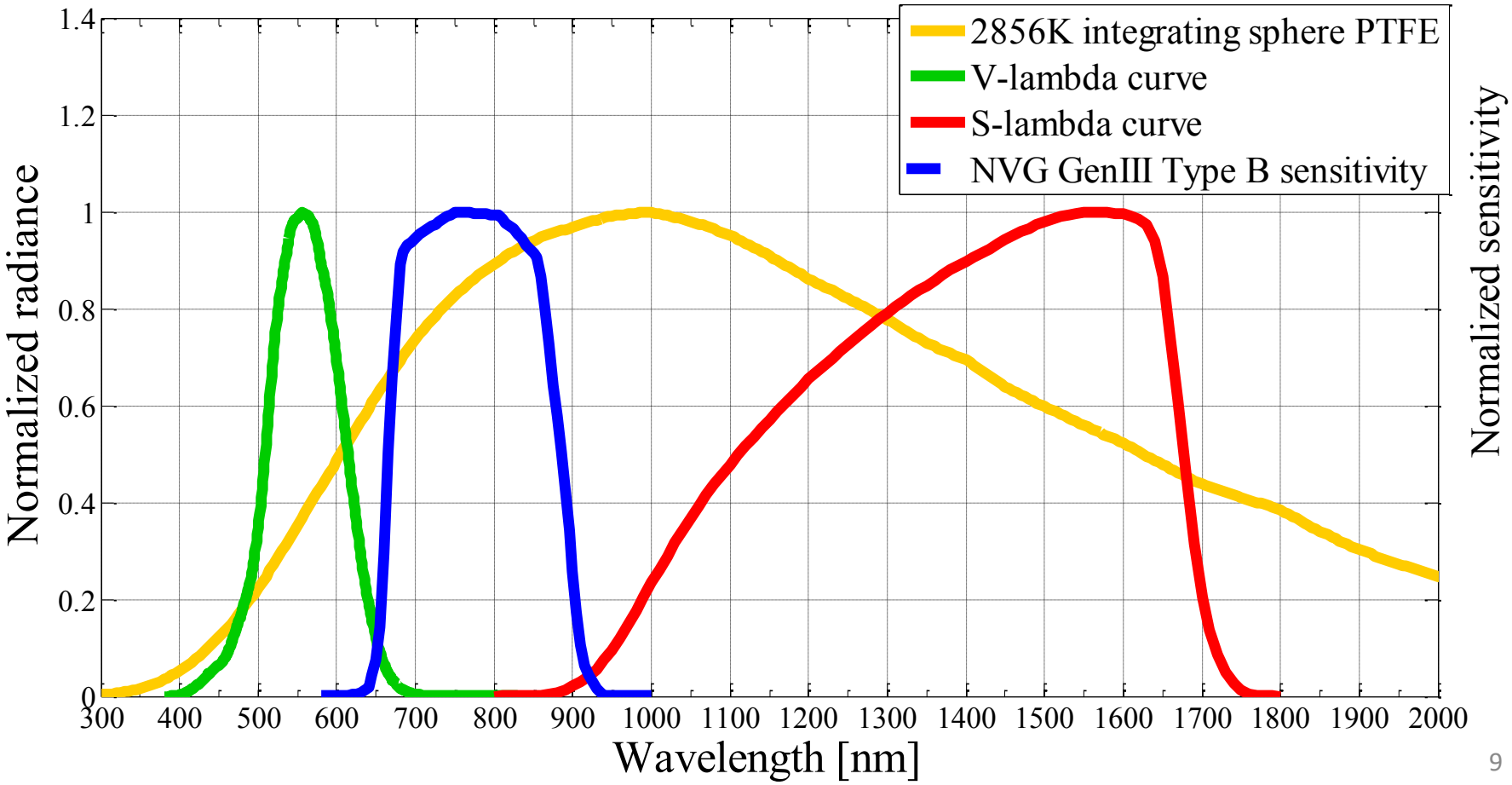
with a radiant intensity in that direction of ***SC*** watt per steradian.

Proposal for setting the new SWIR quantity scale

2856K Illuminant A: “bridge“ between VIS /NIR/SWIR radiometric quantities of measure:

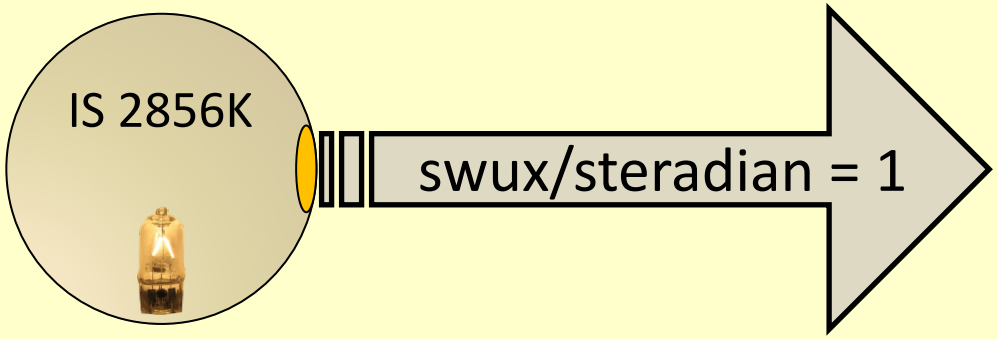
Used in photometry, colorimetry, SWIR and NVG gain calibration.

But: CIE Illuminant A only defined as standard up to 820nm! Or, extend with FEL spectral radiance/irradiance.



Approach for scale setting based on Illuminant A:

Set SWIR-specific radiance quantity level =! **1** with **NVG Type B gain calibration source**



$$A_m = {}^{1}\!/_{sc} \approx 210{,}000$$

IS-Radiance level: equivalent NVG gain such as 2.48E-10 W $sr^{-1}cm^{-2}$ @820nm LED.

lux

$$V(\lambda)$$

$$K_m = {}^{1}\!/_{cd} = 683$$

swux

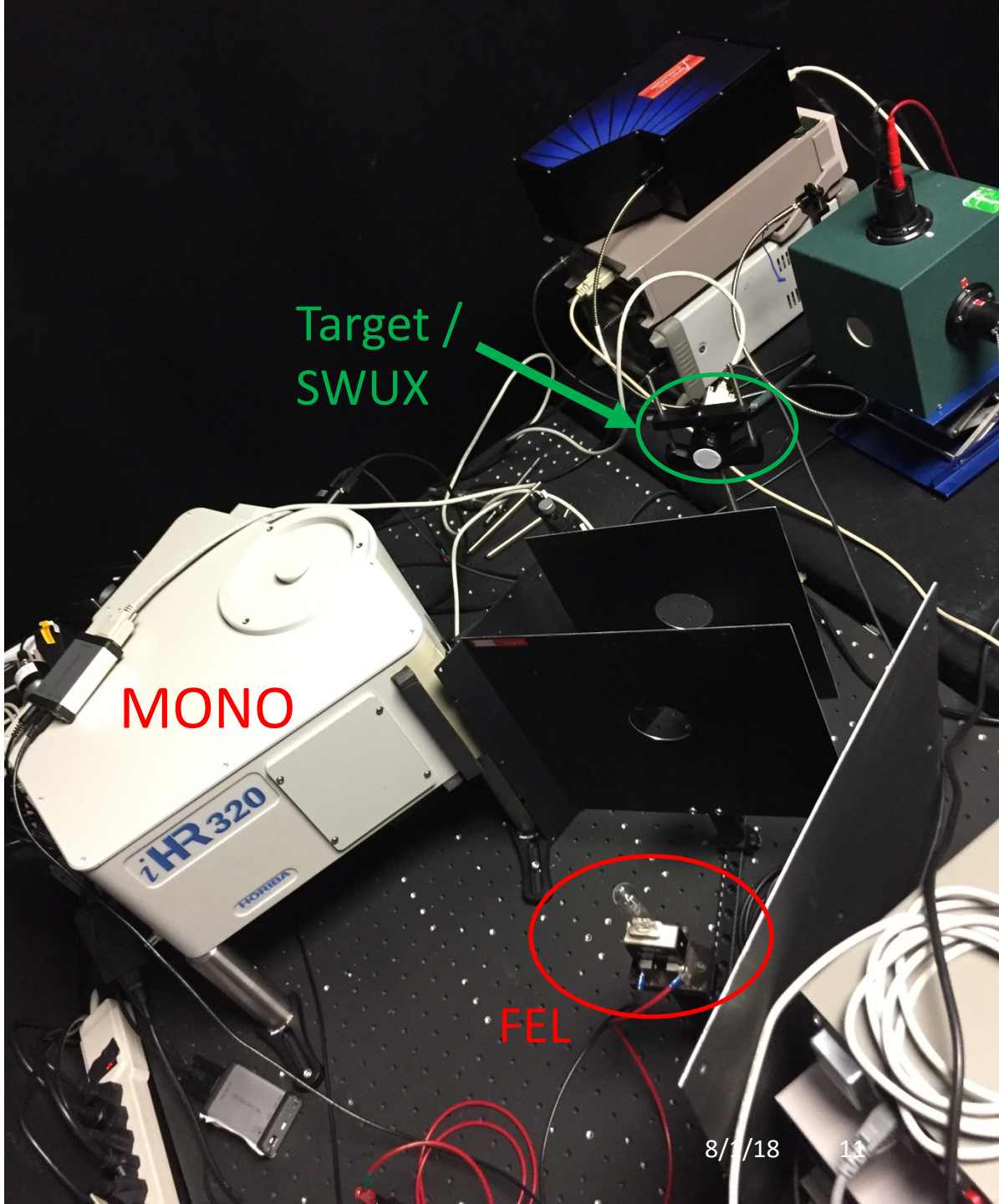
$$S(\lambda)$$

$$A_m = {}^{1}\!/_{sc} = 210{,}000$$

Now we can calibrate a Swux-meter…

Direct FEL Lamp SWUX meter Irradiance calibration

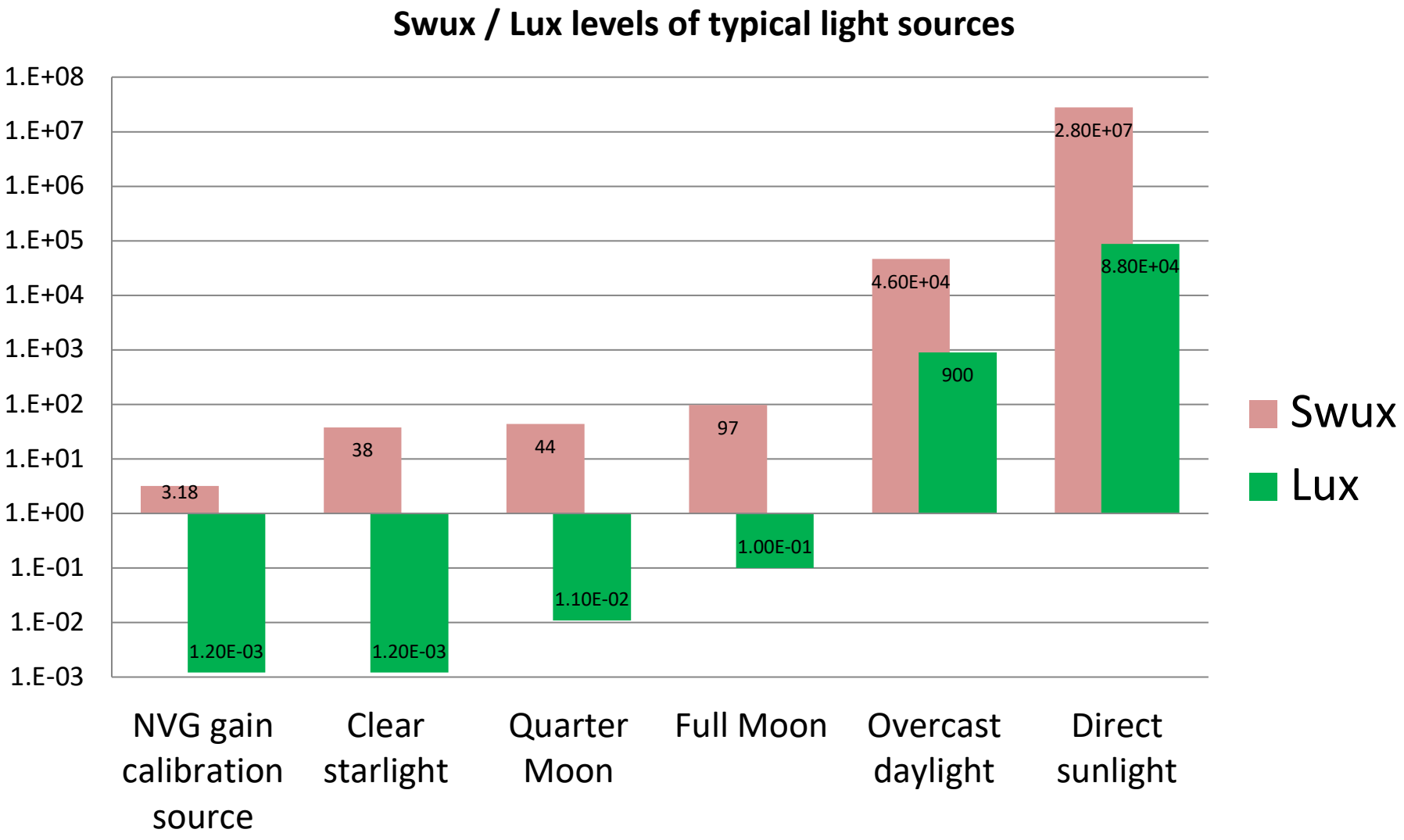
- Follows classic lux-meter calibration technique
  - FEL 1000W (or other W)
  - Spectralon Target
  - Monochromator
  - Cosine-corrected swux meter @ 50cm



Predicted irradiance backgrounds in nature:

Illumination condition: NVESD 2009 SSCamIP	**Swux level**	**Swux/Lux** Ratio	**Lux level**
Clear starlight	38	**3.2E+4**	1.2E-3
Quarter Moon	44	**4.0E+3**	1.1E-02
Full Moon	97	**970**	0.1
Overcast daylight	4.6E+04	**51**	900
Direct sunlight	2.8E+07	**320**	8.8E+4

Predicted irradiance backgrounds in nature:

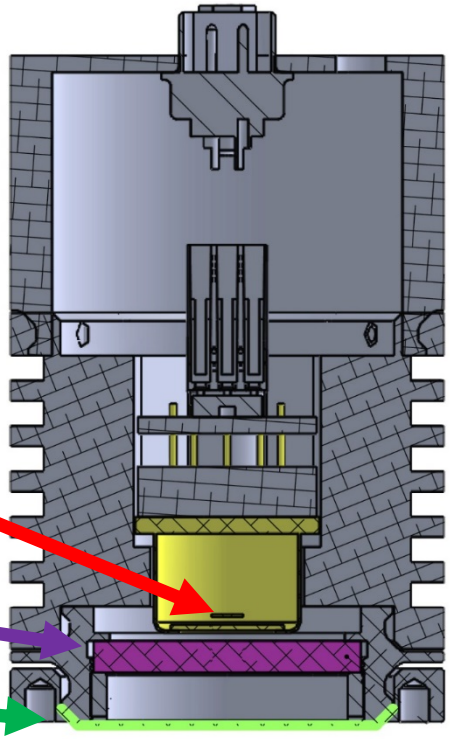


Swuxmeters

Three different swuxmeters

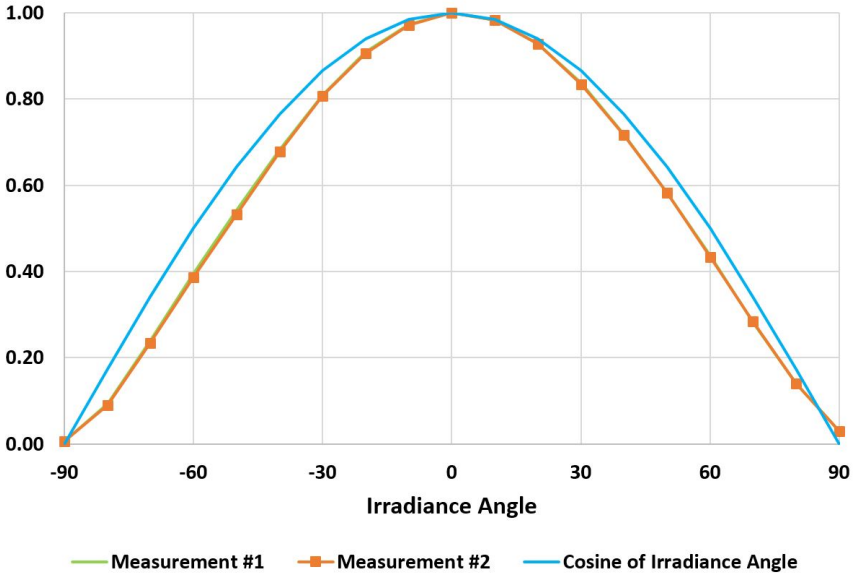
Best one by Labsphere:

- 3mm InGaAs detector @ -40°C
- RG1000 filter
- Spectralon diffuser for cos(θ) response

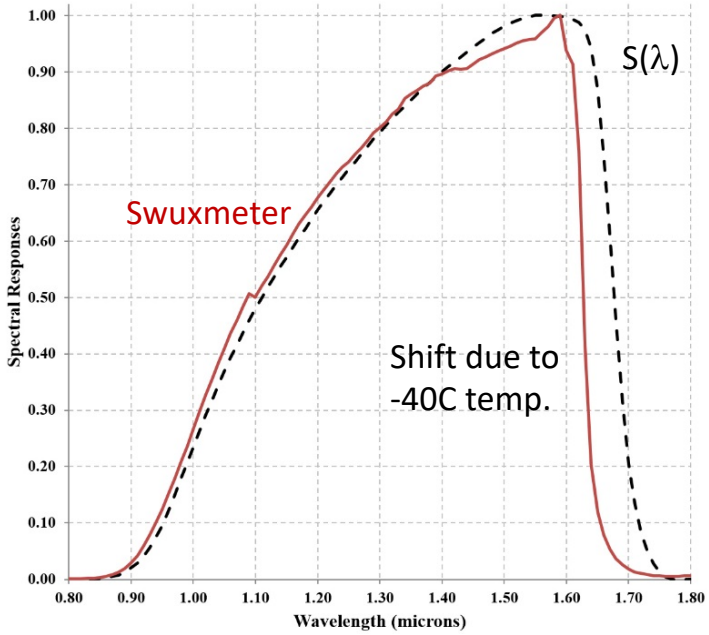


Labsphere Swuxmeter

Angular response



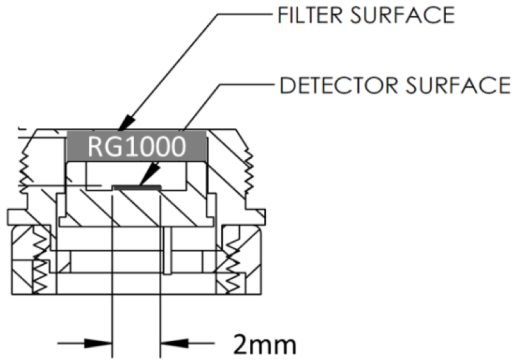
Spectral response

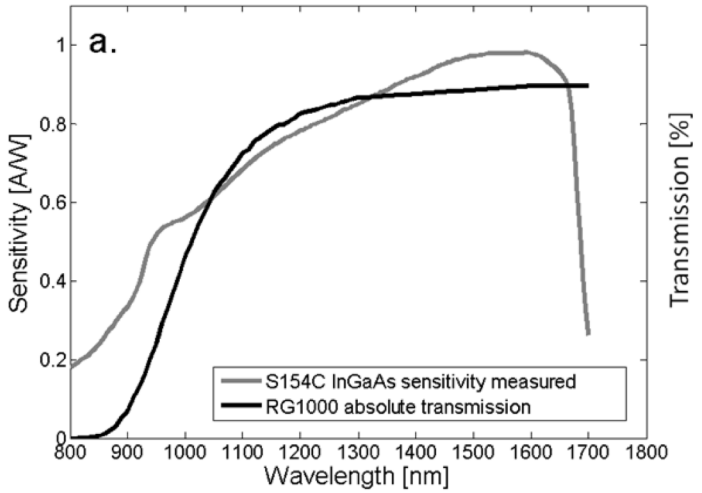


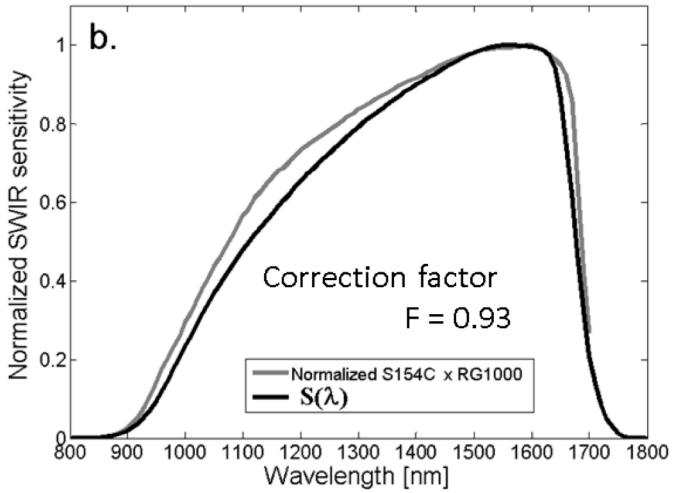
Calibration: FEL Lamp/ NIST-traceable Ge detector

→ **Conversion factor = 4.917 x10^{10} swux/amp**

Thorlabs Swuxmeter







Calibration: Integrating sphere calibr. stand. OL455-6→ **Conversion factor = 26.9 x10^{10} swux/amp**

Measured backgrounds

Examples of lighting conditions:

1. Artificial indoor lighting (residential/industrial)
2. Outdoors: natural sources
3. Outdoors: combustion-based sources
4. Urban/suburban artificial backgrounds
5. Diurnal patterns
6. Total solar eclipse

Prototype SWUX Meter Measurements

Incandescent lighting
TURNED ON

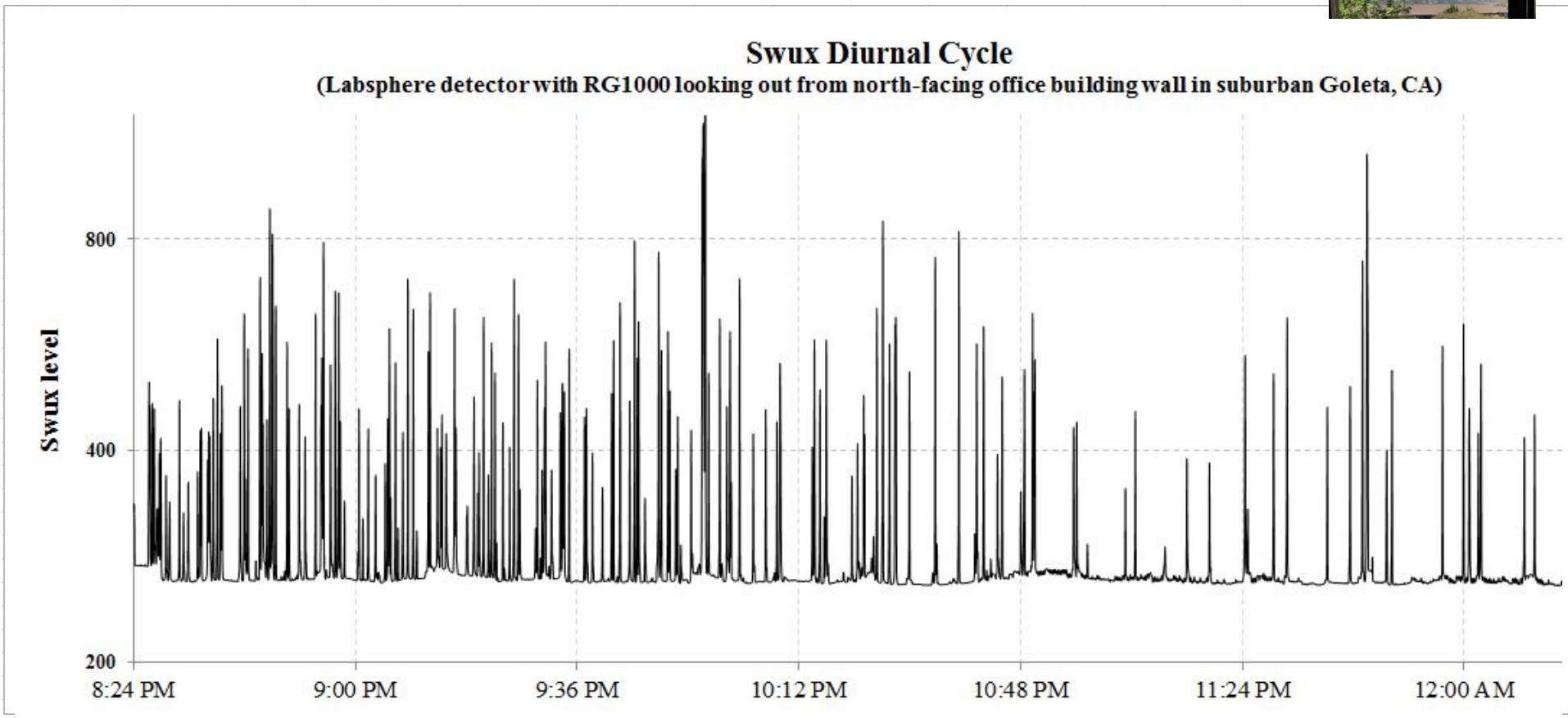
Swux meter: 33,000 swux
Lux meter : 192 lux

Incandescent lighting
TURNED OFF

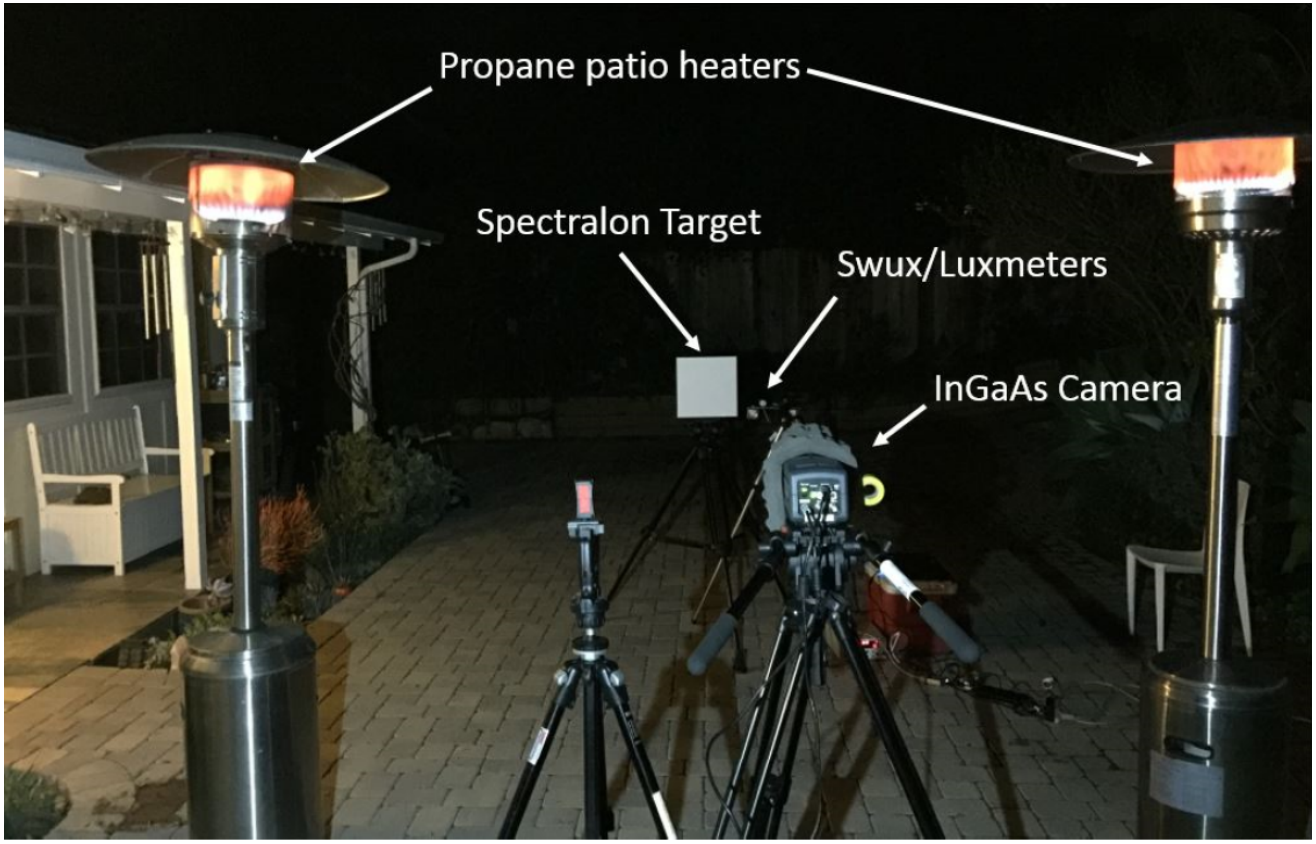
Swux meter: 15,000 swux
Lux meter : 164 lux

The human eye and Lux meters are both ***terrible*** Swux meters!

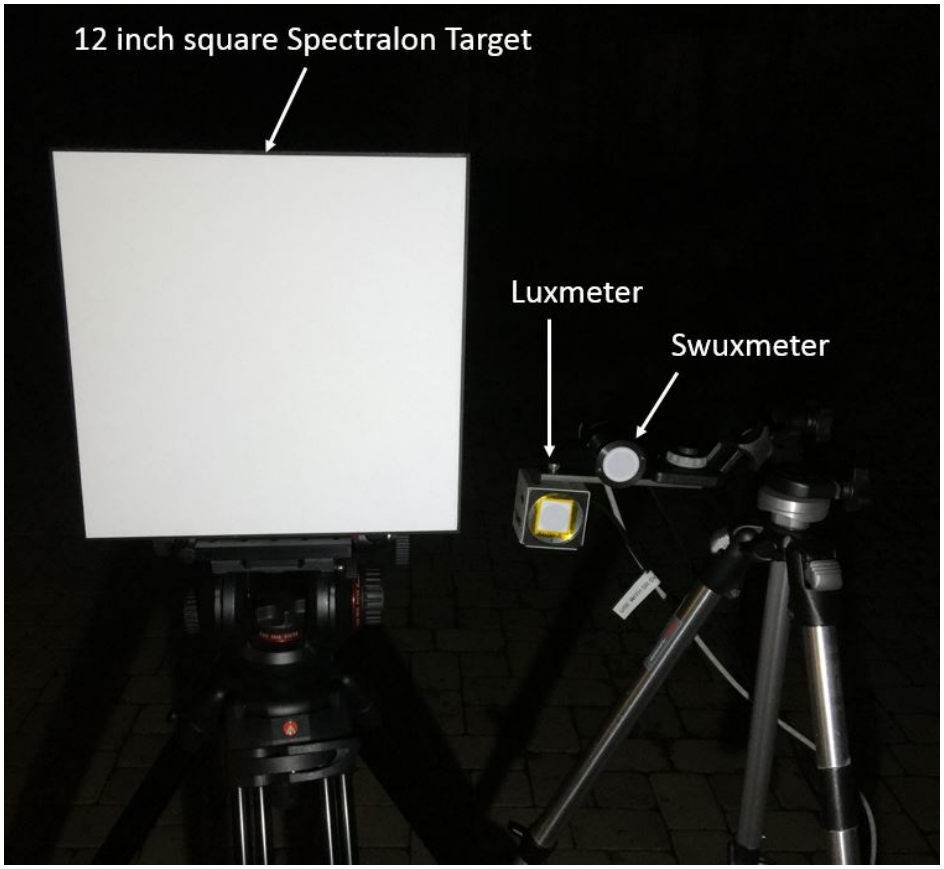
48 hours of swux logging:



Propane patio heaters as sources



Reference target and two meters



Two patio heaters at 650C provide the only irradiance of this scene

Illuminance = 3.10 x 10^{-2} lx
SWIR-specific irradiance = 4.47 x 10^{5} swux

SWUX/LUX RATIO = 1.4 x10^{7}

Large irradiance for InGaAs camera, small one for VIS camera

Canon 5D, 3.2 seconds, f/4, ISO 6400

FLIR A6261sc, 2ms, low gain, f/1.6

This kitchen has starlight swux irradiance level from CFL lighting!

Illuminance ≈ 0.8 lx
SWIR-specific irradiance ≈ 47 swux (slightly above clear starlight)

SWUX/LUX RATIO = 60

Large irradiance for VIS camera, small one for InGaAs camera

Urban swux and lux background measurements

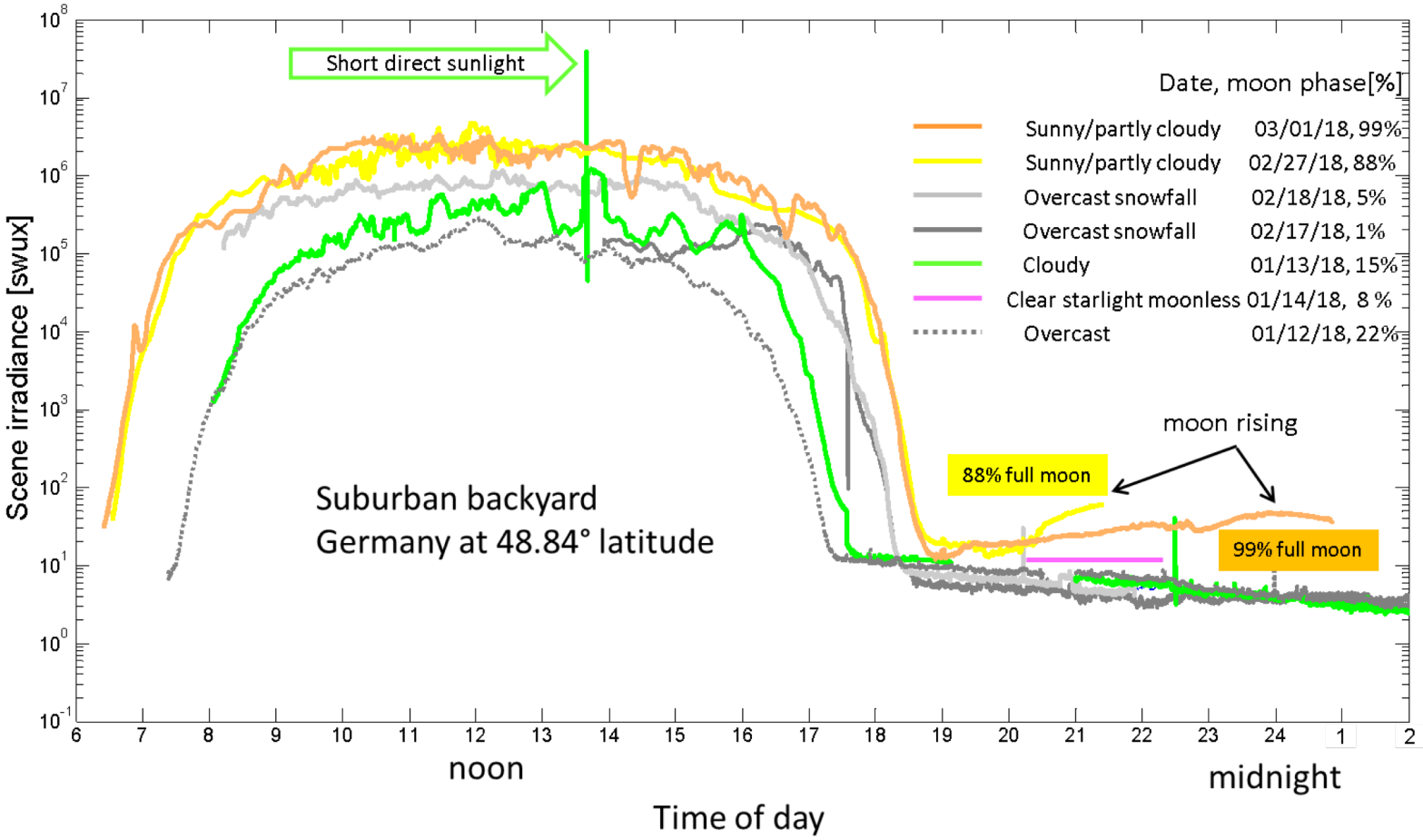
a

b

Illuminance levels several hours after sunset 10-60 lux on streets/parking lots

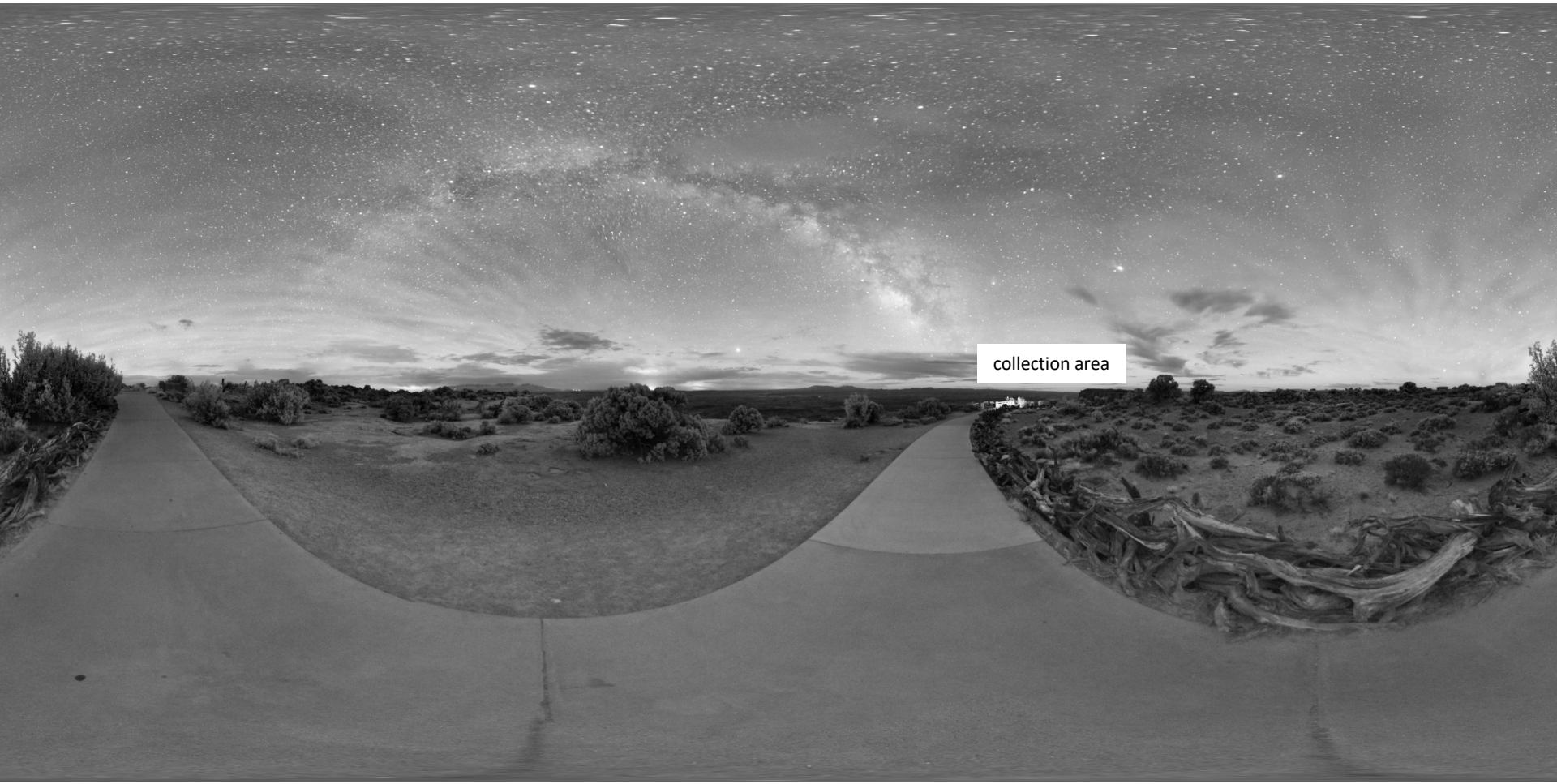
c

Diurnal measurements with the Thorlabs swuxmeter



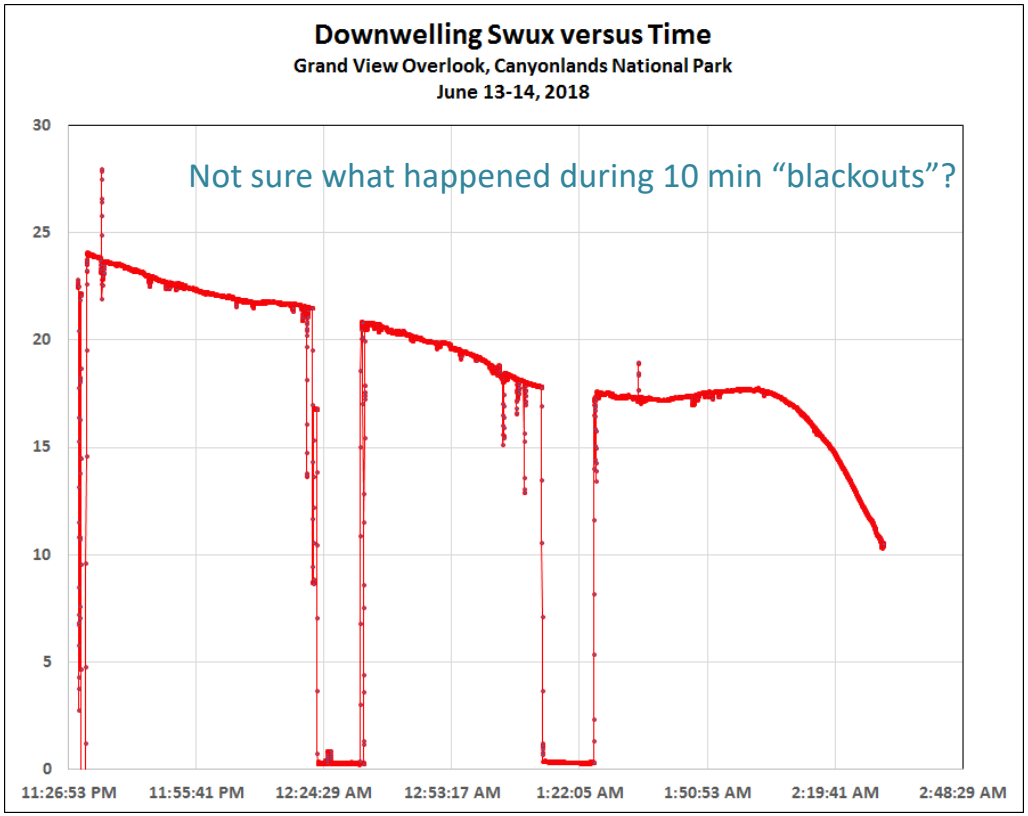
Moab, UT: Swux data collection in a true starlight-only outdoor environment

NIR Panorama shot by John Wood with Nikon and NIR filter

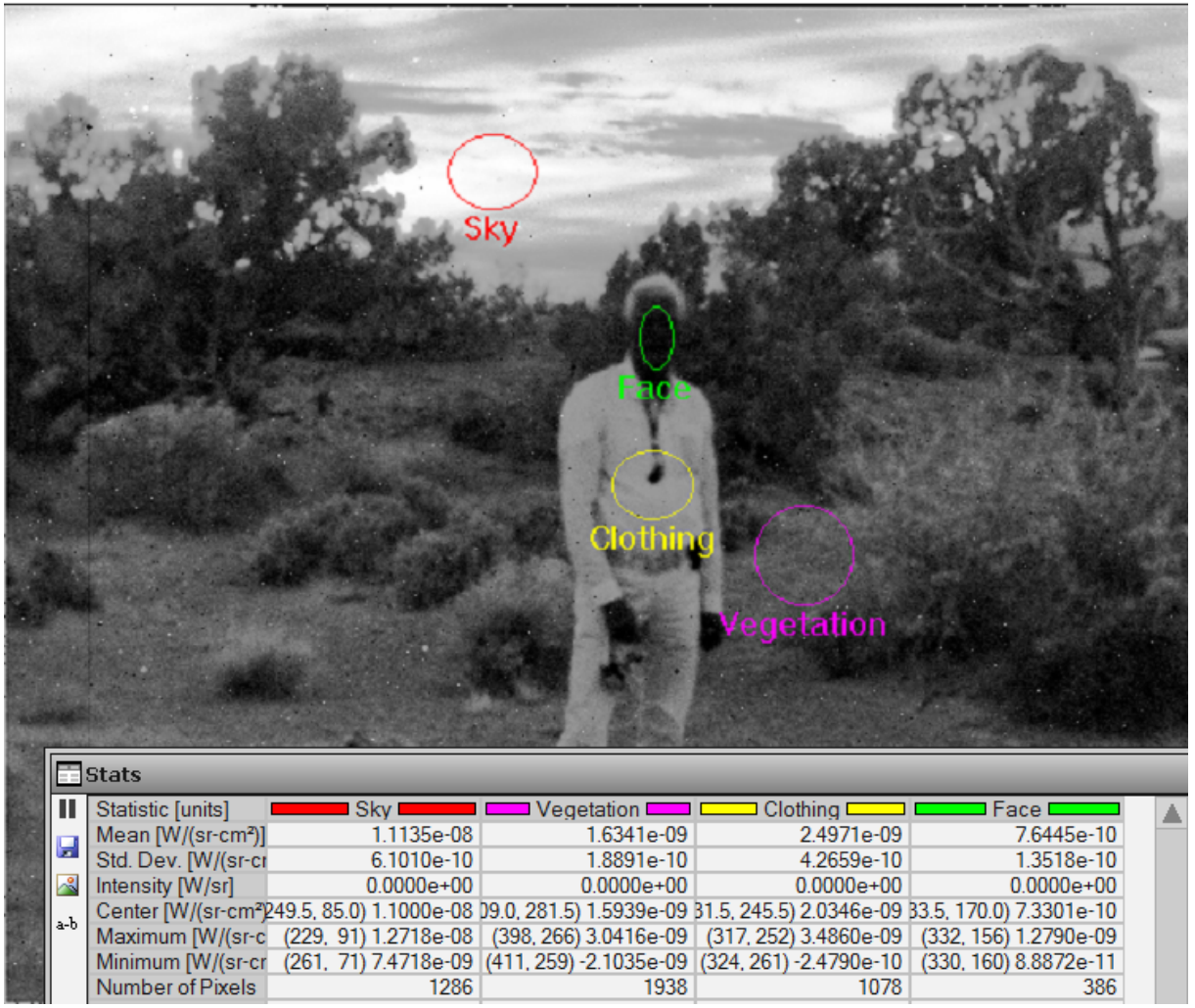


Swux meter with periodic collection (lux meter was too noisy due to inverter power noise). Nightglow swux decreased as expected over hours.

Observed swux was ~50% of clear starlight model prediction

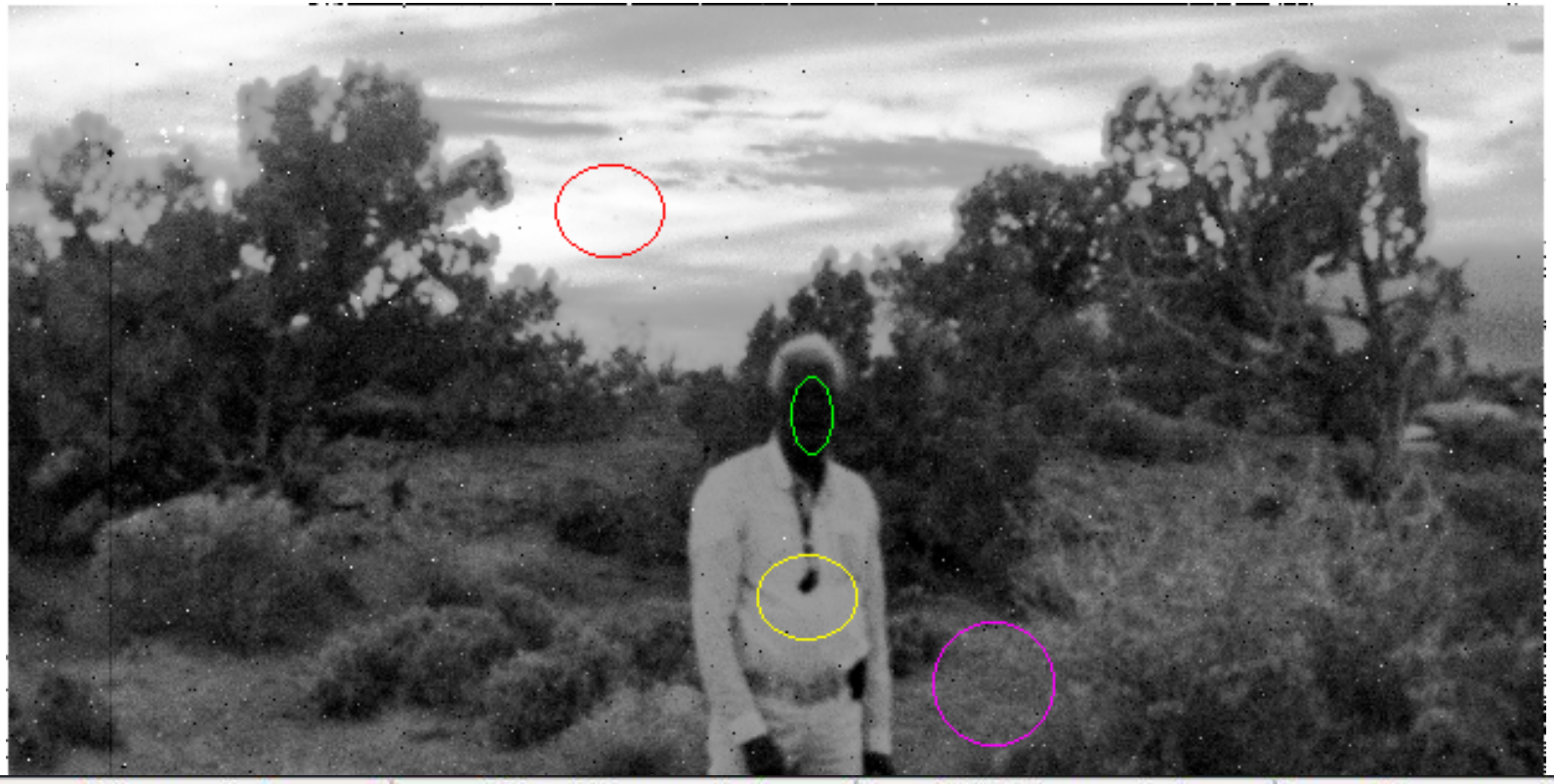


Starlight Radiometric Image of Person: In-Band Radiance (W/sq.cm/sr)



A6261sc InGaAs camera, Tint = 200msec, medium gain, f/1.4, 16-frame average

Starlight Radiometric Image of Person: swux/steradian



Sky swux/sr	Vegetation swux/sr	Clothing swux/sr	Face swux/sr
22.2675	3.26789	4.9937	1.52875

Conclusion

- A new set of SWIR specific radiometric units of measure has been proposed
- Definition way in analogy to photometric detector based units of measure, all based on source independent SWIR-candela unit.
- S-lambda curve proposed as spectral radiant efficiency function for SWIR sensing based on standard InGaAs sensitivity smoothed by RG1000 filter glass.
- Scale setting of SWIR units by relating VIS/NIR specific quantities over the standard 2856K Illuminant A.
- Strong recommendation to extend CIE Illuminant A standard up to 1800nm!
- First Prototype implementation of a Swux meter demonstrated.
- **HOW TO GET NIST (and other NMIs) INTERESTED/INVOLVED in this industry-driven unit?**

Conclusion

- Different swuxmeter implementations now built and calibrated
- Swux/lux ratio measurements essential for full characterization of VIS/SWIR imaging conditions
- First swux results for artificial lighting situations
- Goal: Create commercial field swux/luxmeter systems
- Goal: Create a reference library of swux/lux measurements
- This info vital for VIS/SWIR imaging systems design
- InGaAs sensor price dropping, more and more applications all the time (ADAS)
- Driverless vehicles, drones with InGaAs sensors and passive/active lighting

Thank you!