Infrared and Multispectral Imaging

TSBB21 Computational Photography

Jörgen Ahlberg

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Agenda

1.	Light & radiation
2.	Radiation & matter
3.	Thermal cameras
4.	Applications
5.	Multispectral imaging
6.	Camera demo

Part 1

Light & Radiation

From where comes the radiation that I see?

Emitted

Transmitted

Reflected

Absorbed

F. W. Herschel

Symphony No. 15 (1762)

https://open.spotify.com/track/0kQcVlkwv2LJQ49KXnklVe

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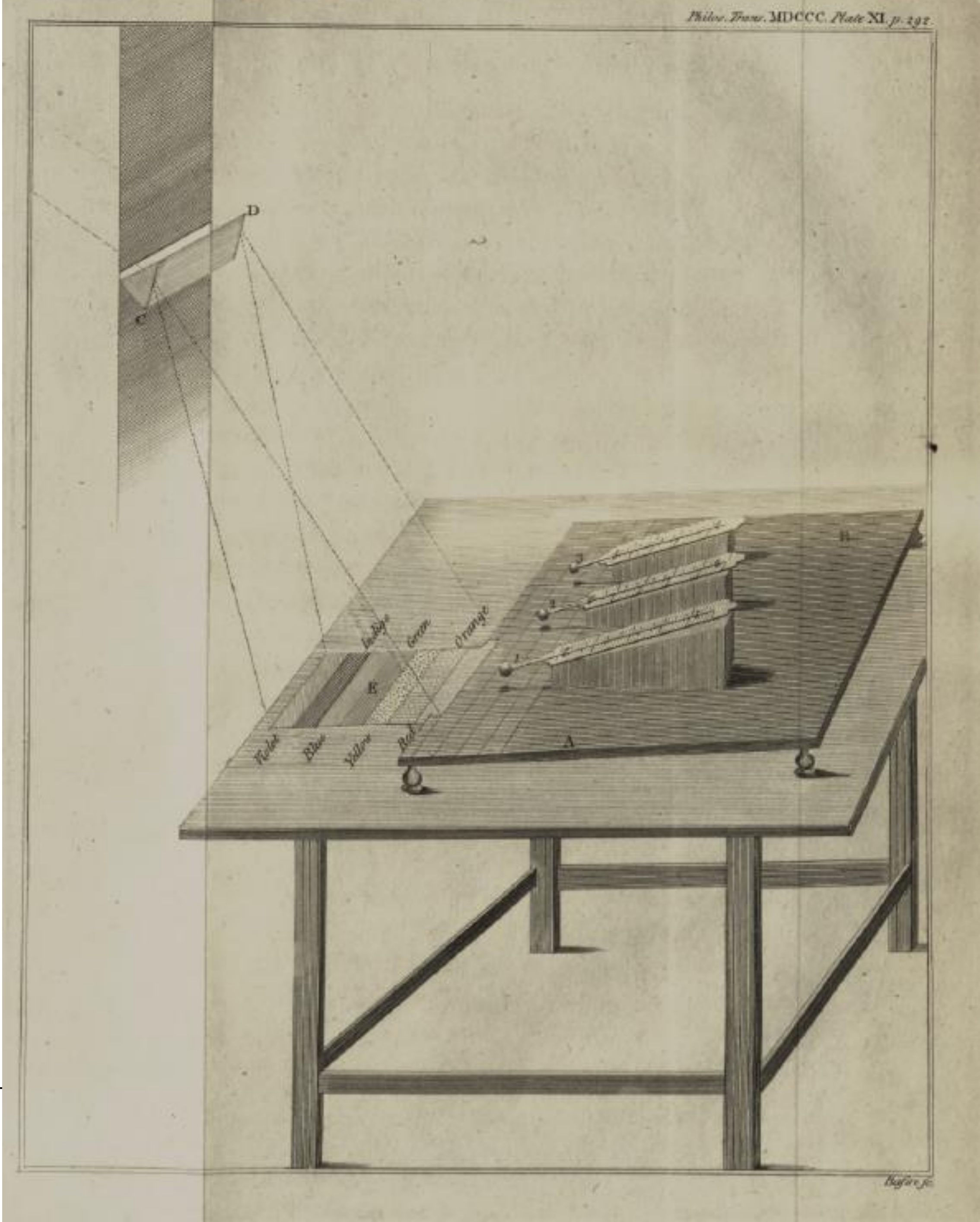
Caroline & William Herschel

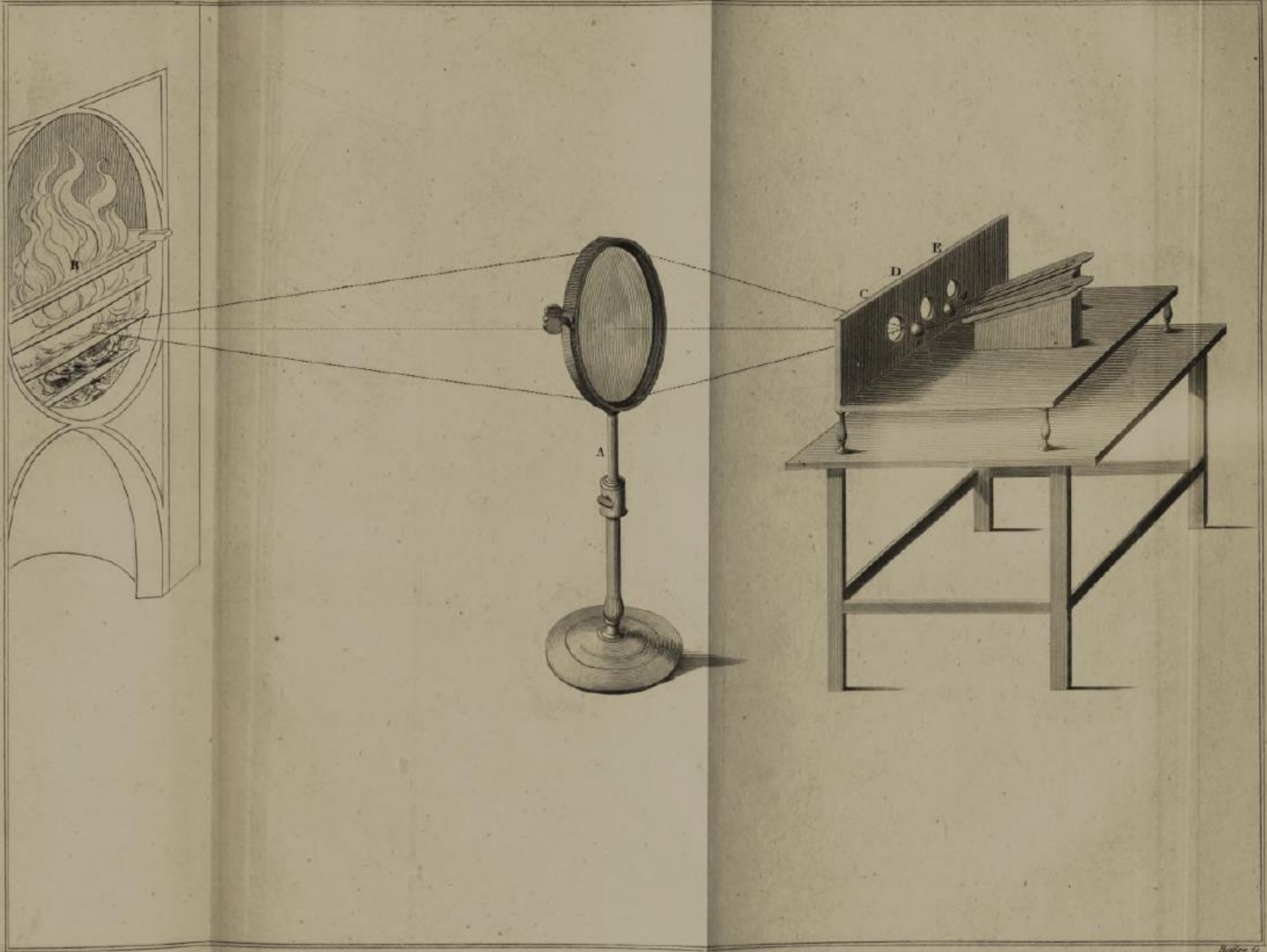
- 1 planet
- 4 moons
- 8 comets
- 5000 other objects

Herschel 1800a

"In this case, radiant heat will at least partly, if not chiefly, consist, if I may be permitted the expression, of invisible light; that is to say, of rays coming from the sun, that have such a momentum as to be unfit for vision."

F. W. Herschel, "Experiments on the refrangibility of the invisible rays of the Sun," *Philos. Trans. R. Soc.*, vol. 90, pp. 284–292, 1800.
doi: 10.1098/rstl.1800.0015



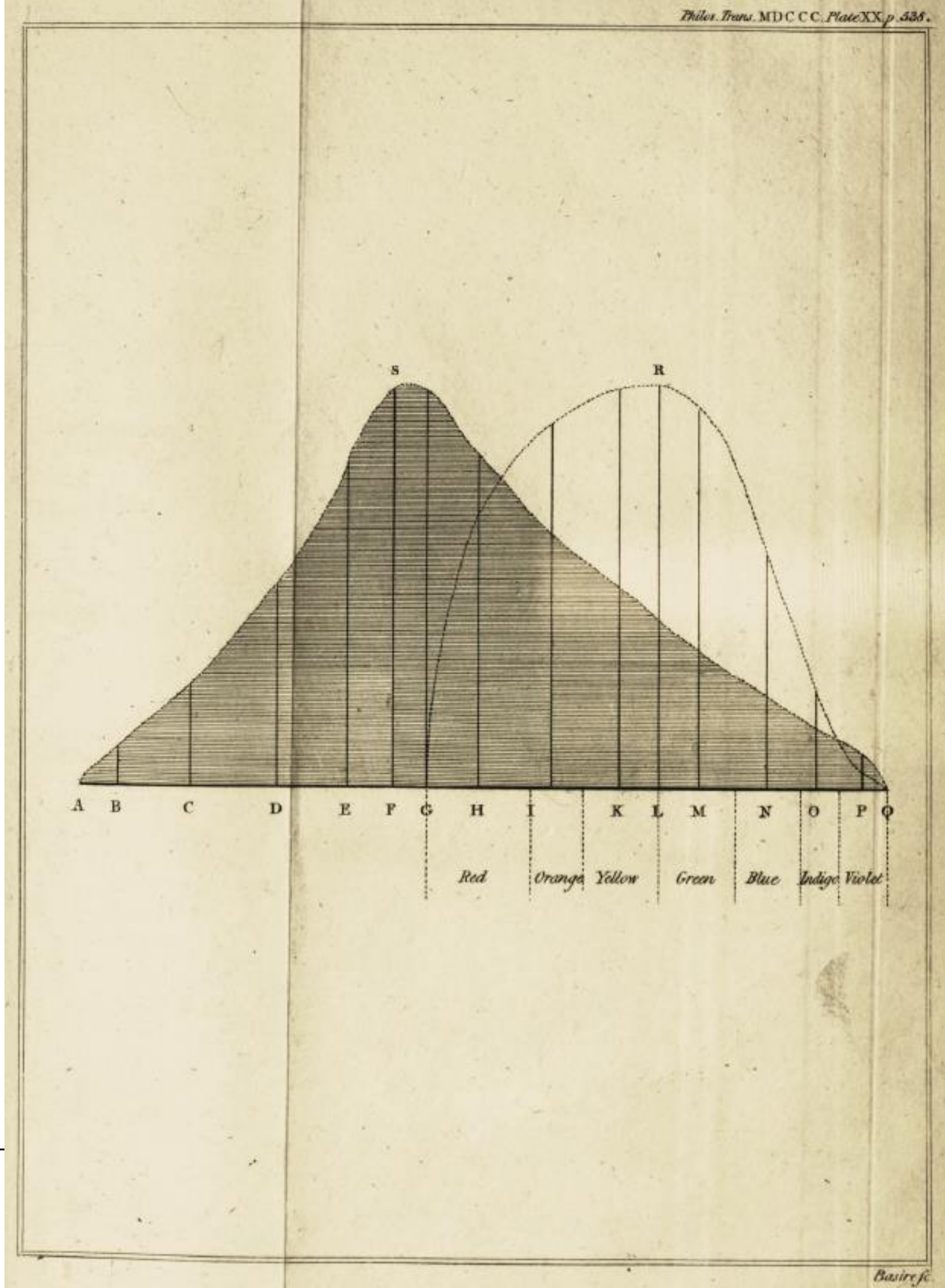


Basire sc.

Herschel 1800b, c

F. W. Herschel, “Experiments on the Solar, and on the Terrestrial Rays that Occasion Heat; With a Comparative View of the Laws to Which Light and Heat, or Rather the Rays Which Occasion Them, are Subject, in Order to Determine Whether They are the Same, or Different. Part I,” *Philos. Trans. R. Soc. London*, vol. 90, pp. 293–326, Jan. 1800.
doi: 10.1098/rstl.1800.0016

F. W. Herschel, “Experiments on the Solar, and on the Terrestrial Rays that Occasion Heat; With a Comparative View of the Laws to Which Light and Heat, or Rather the Rays Which Occasion Them, are Subject, in Order to Determine Whether They are the Same, or Different. Part II,” *Philos. Trans. R. Soc. London*, vol. 90, pp. 437–538, Jan. 1800.
doi: 10.1098/rstl.1800.0020



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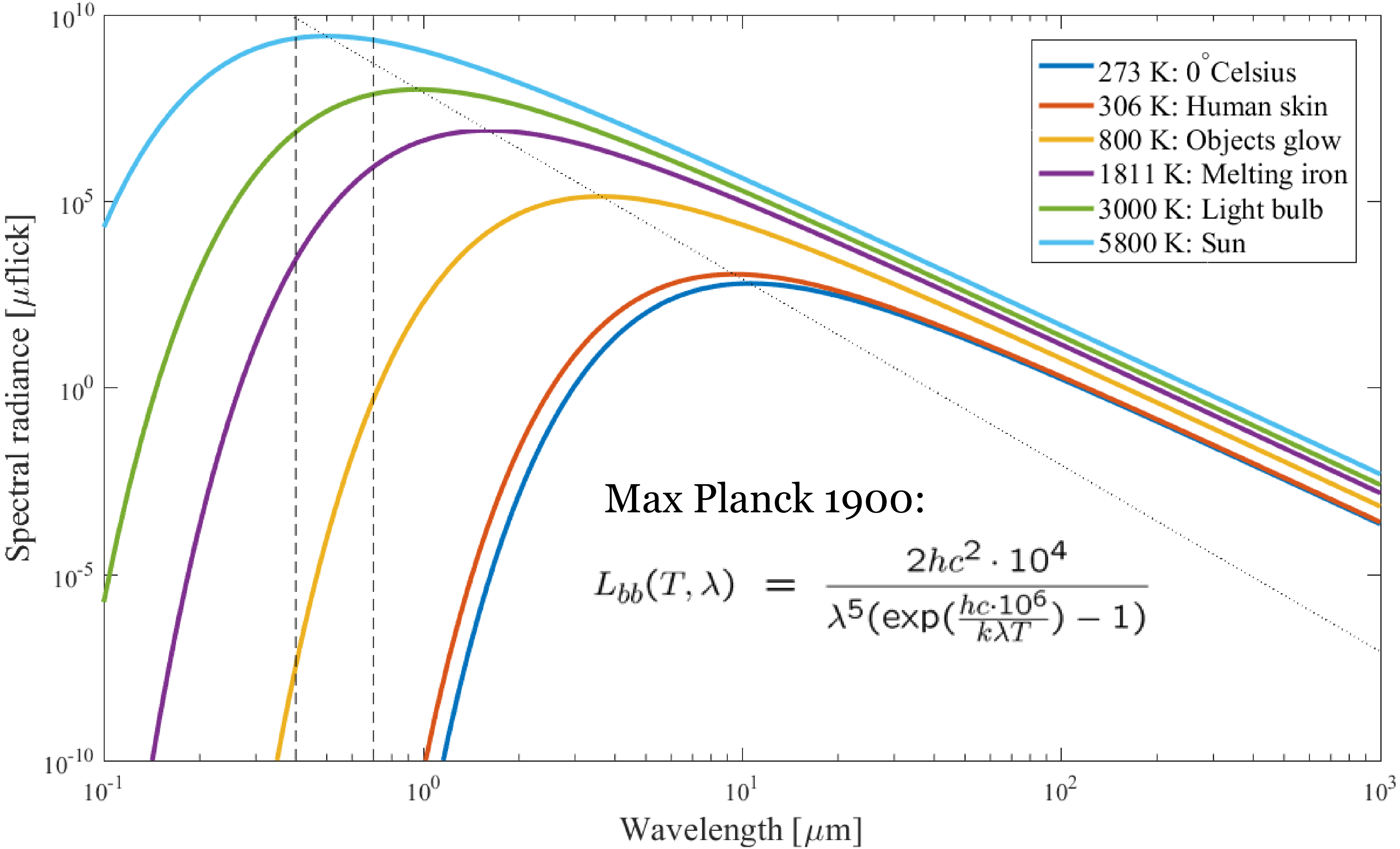
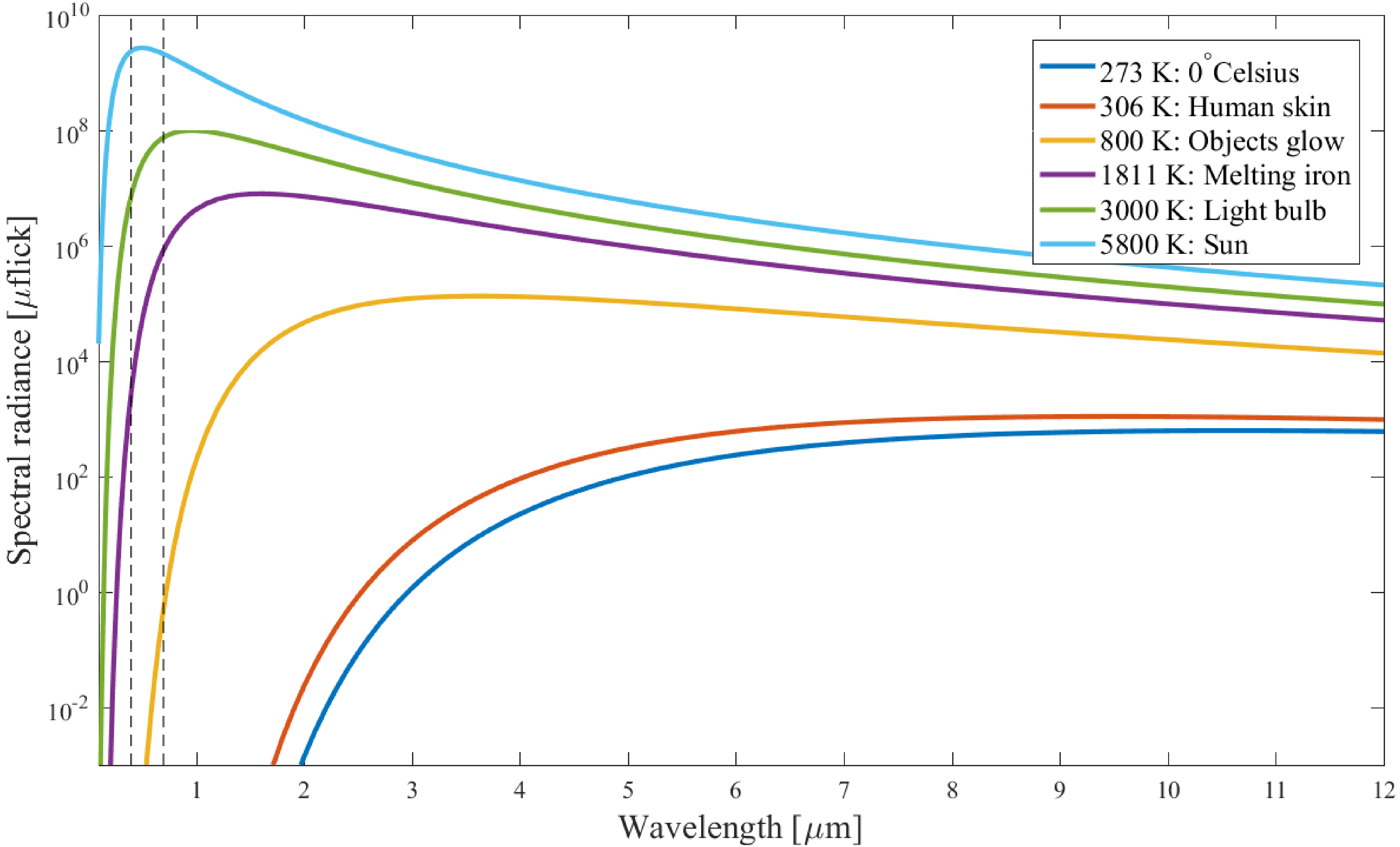
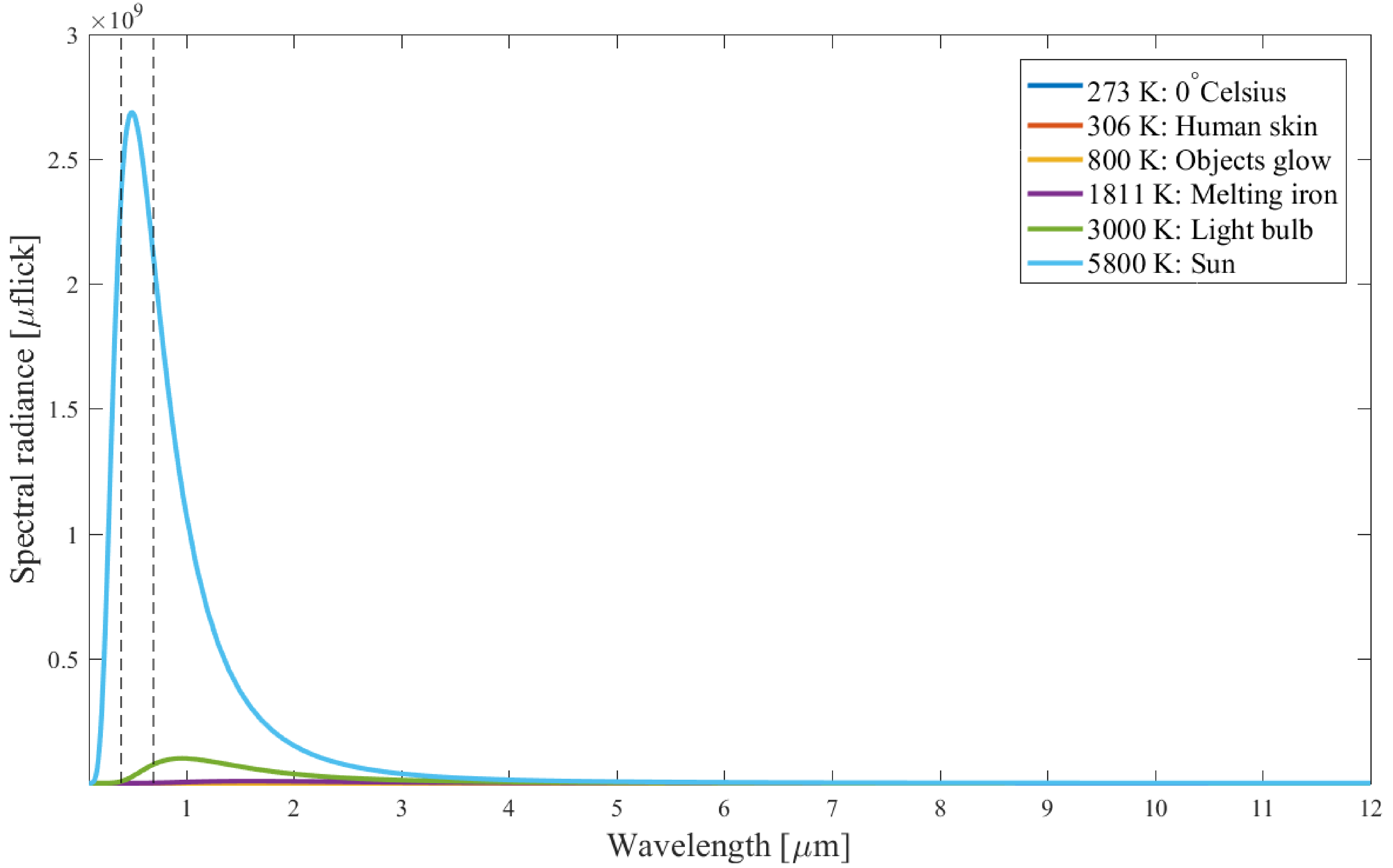


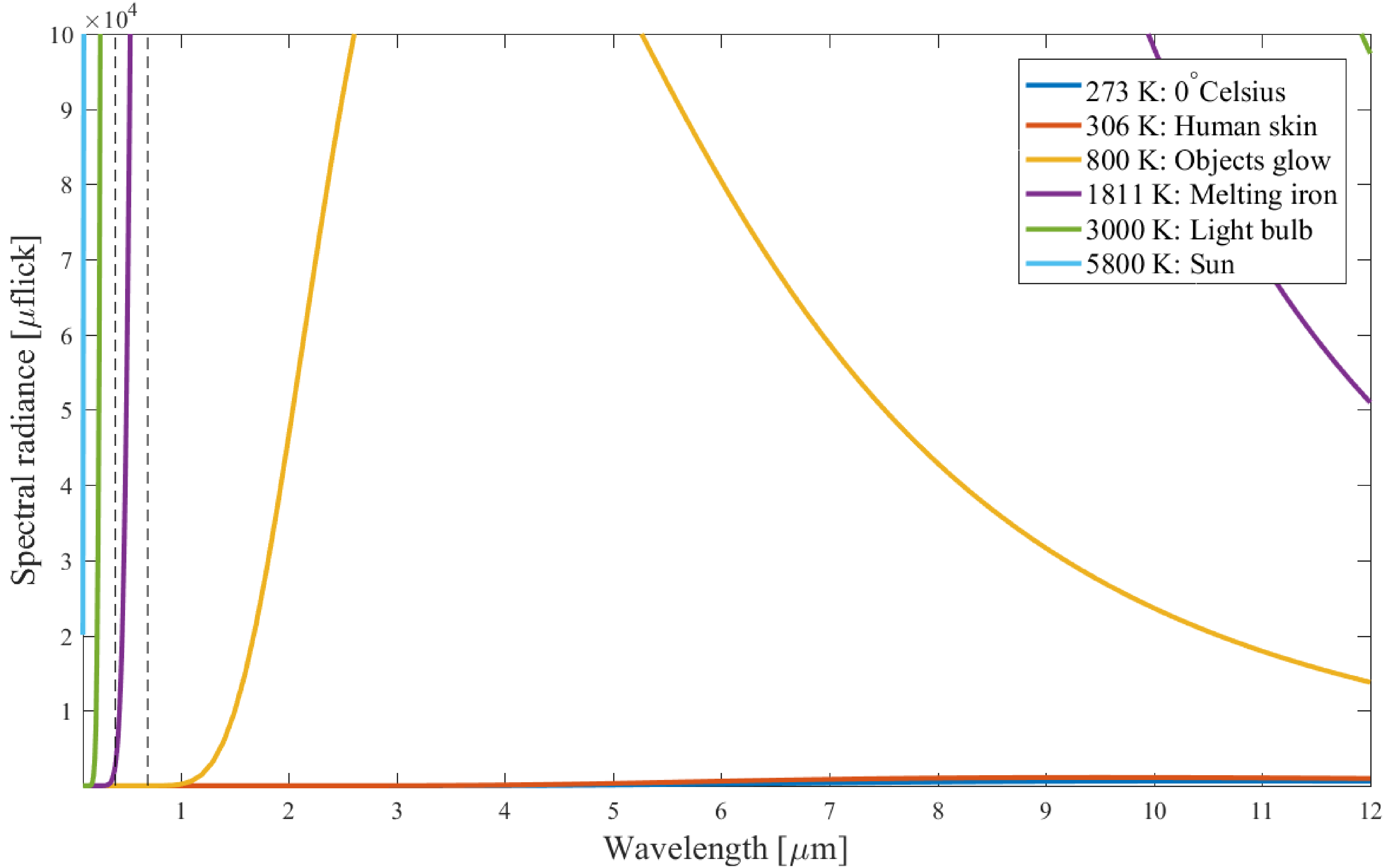
Spectral radiance [μflick]
Wavelength [μm]
10^{10}
10^{5}
10^{0}
10^{-5}
10^{-10}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
273 K: 0°Celsius
306 K: Human skin
800 K: Objects glow
1811 K: Melting iron
3000 K: Light bulb
5800 K: Sun
Max Planck 1900:
$L_{bb}(T,\lambda) = \frac{2hc^2 \cdot 10^4}{\lambda^5(\exp(\frac{hc \cdot 10^6}{k\lambda T}) - 1)}$



10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
Spectral radiance [μflick]
1 2 3 4 5 6 7 8 9 10 11 12
Wavelength [μm]
273 K: 0° Celsius
306 K: Human skin
800 K: Objects glow
1811 K: Melting iron
3000 K: Light bulb
5800 K: Sun

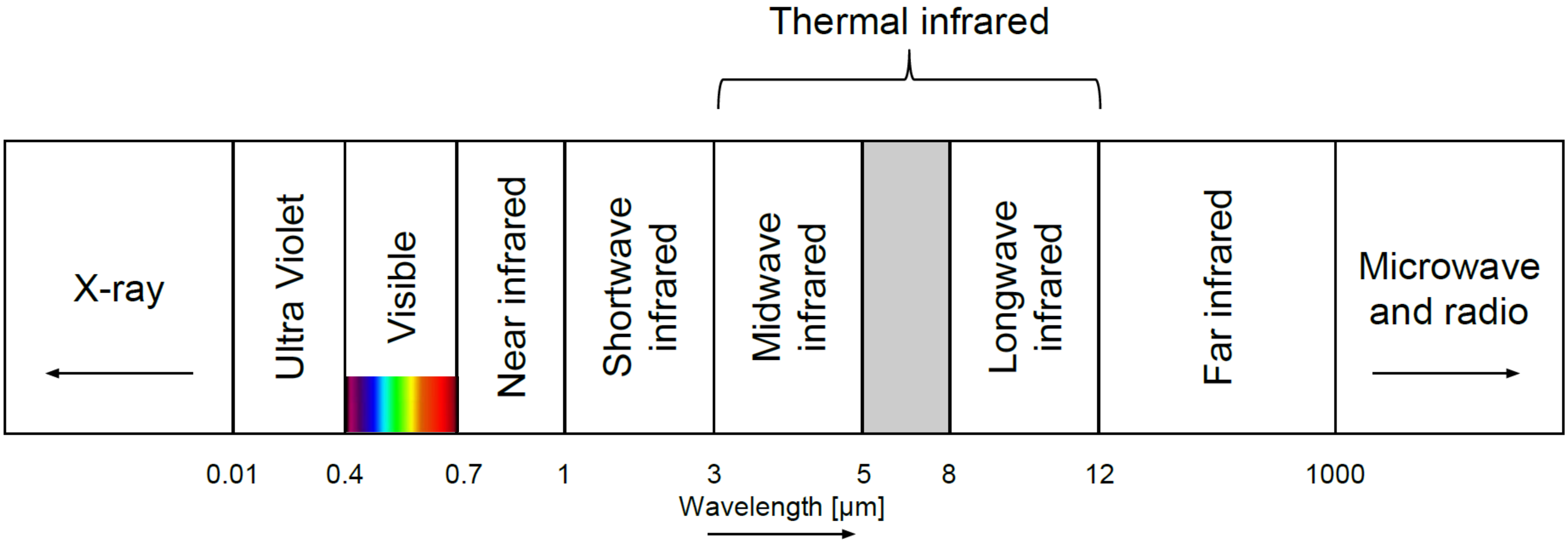


$\times 10^9$
3
2.5
2
1.5
1
0.5
Spectral radiance [μflick]
1
2
3
4
5
6
7
8
9
10
11
12
Wavelength [μm]
273 K: 0°Celsius
306 K: Human skin
800 K: Objects glow
1811 K: Melting iron
3000 K: Light bulb
5800 K: Sun



×10^4
10
9
8
7
6
5
4
3
2
1
Spectral radiance [μflick]
1
2
3
4
5
6
7
8
9
10
11
12
Wavelength [μm]
273 K: 0° Celsius
306 K: Human skin
800 K: Objects glow
1811 K: Melting iron
3000 K: Light bulb
5800 K: Sun

Domains and wavelengths and bands



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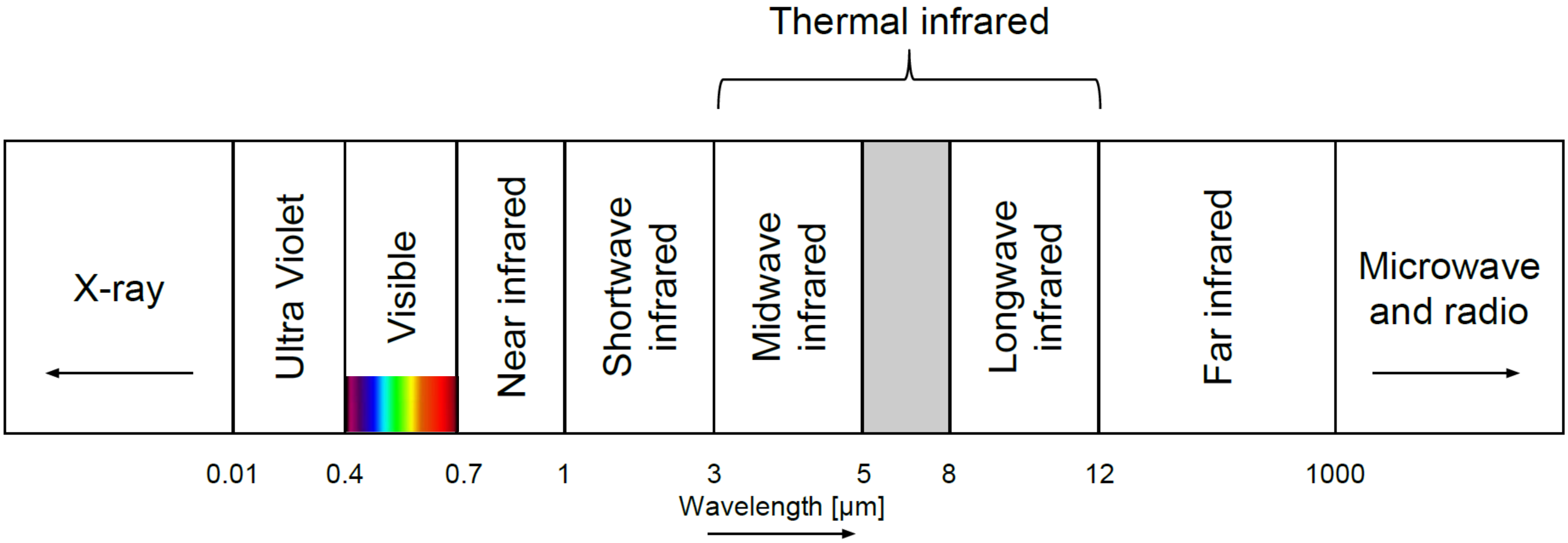
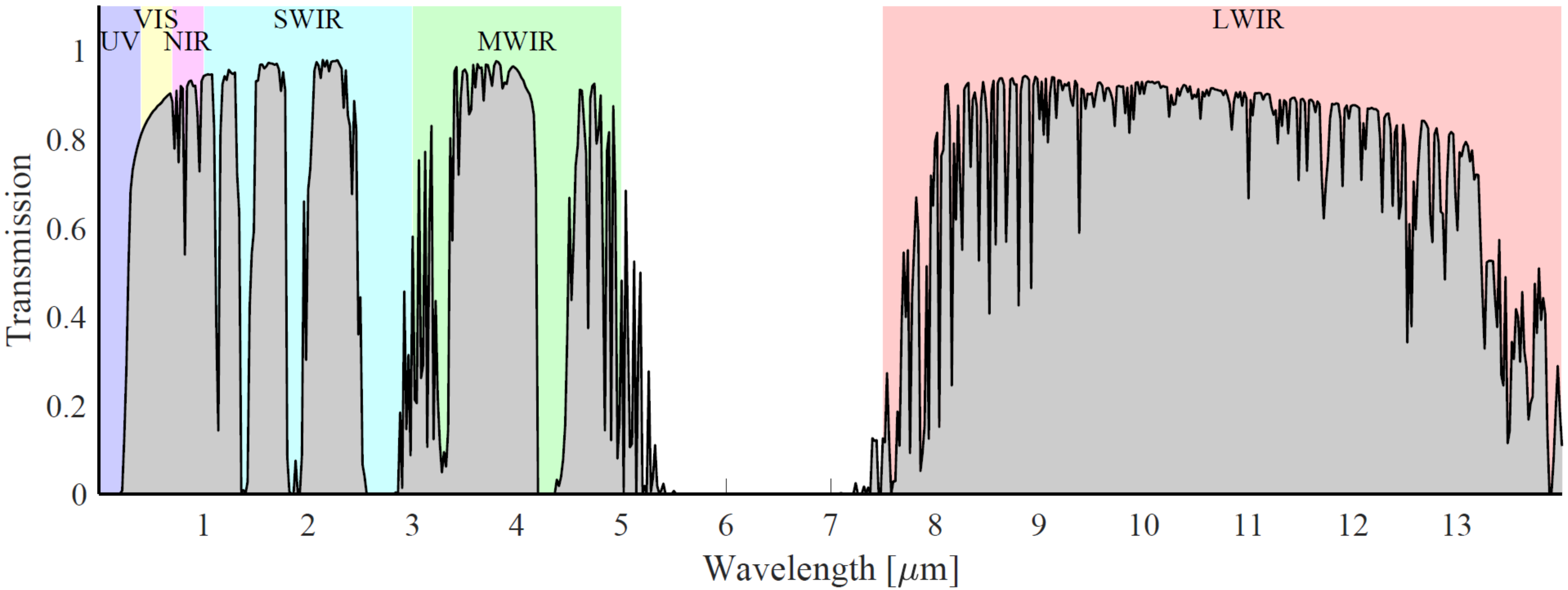
Why this particular division?



Reason 1: Atmospheric transmission



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Reason 2: Behaviour

- Reflective domain
- Emissive domain

Reason 3: Sensors

- VNIR: Silicon (CCD, CMOS)
- SWIR: InGaAs sensors
- MWIR: InSb and MCT sensors
- LWIR: MCT and bolometer sensors

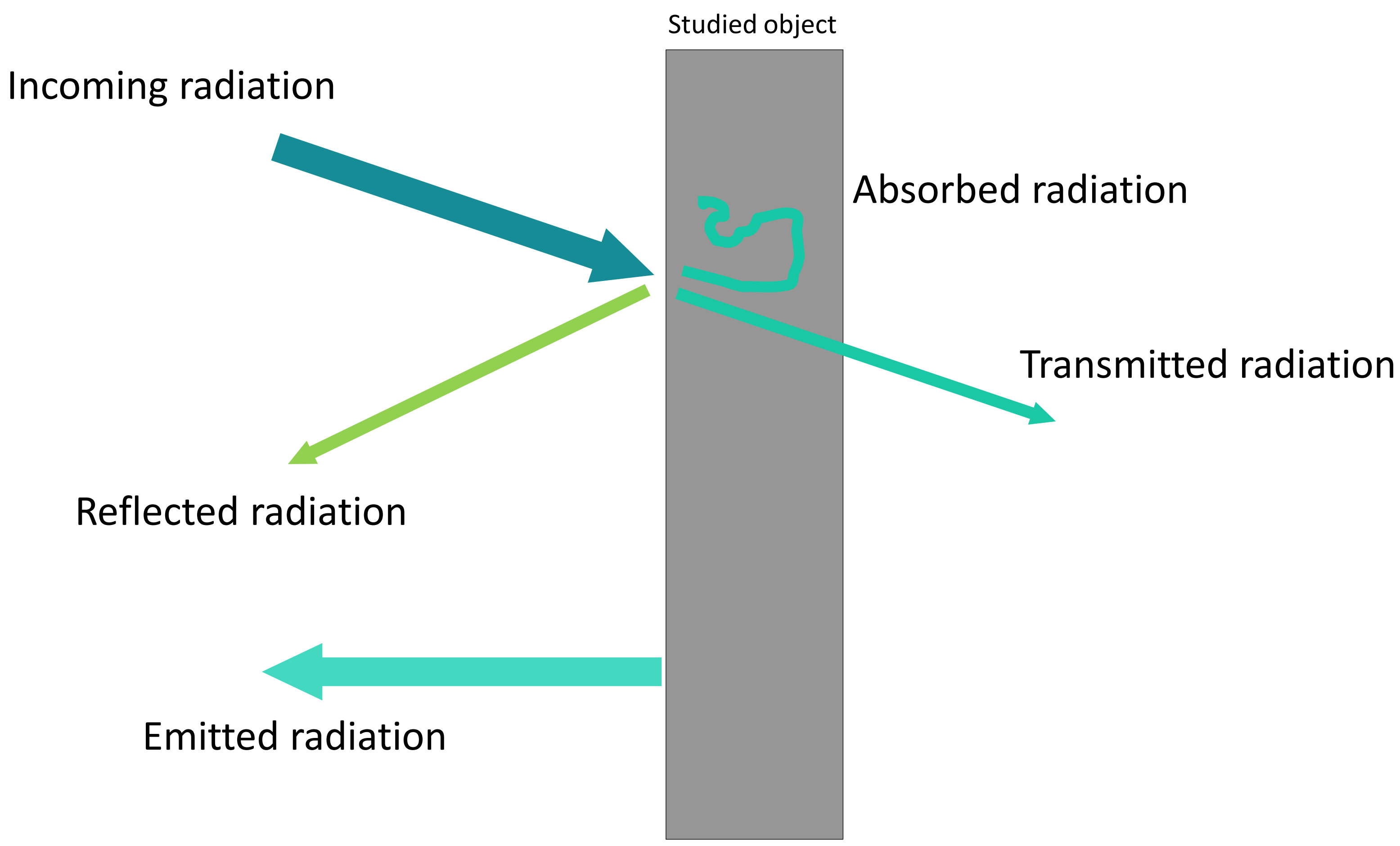
Note:
There are other subdivisions!
For example, astronomers use:
- NIR 0.7-5
- MIR: 5-(25…40)
- FIR: (25-40)-

Part 2

Radiation & Matter

Radiation and matter

- Absorbed
- Reflected
- Transmitted
- Emitted

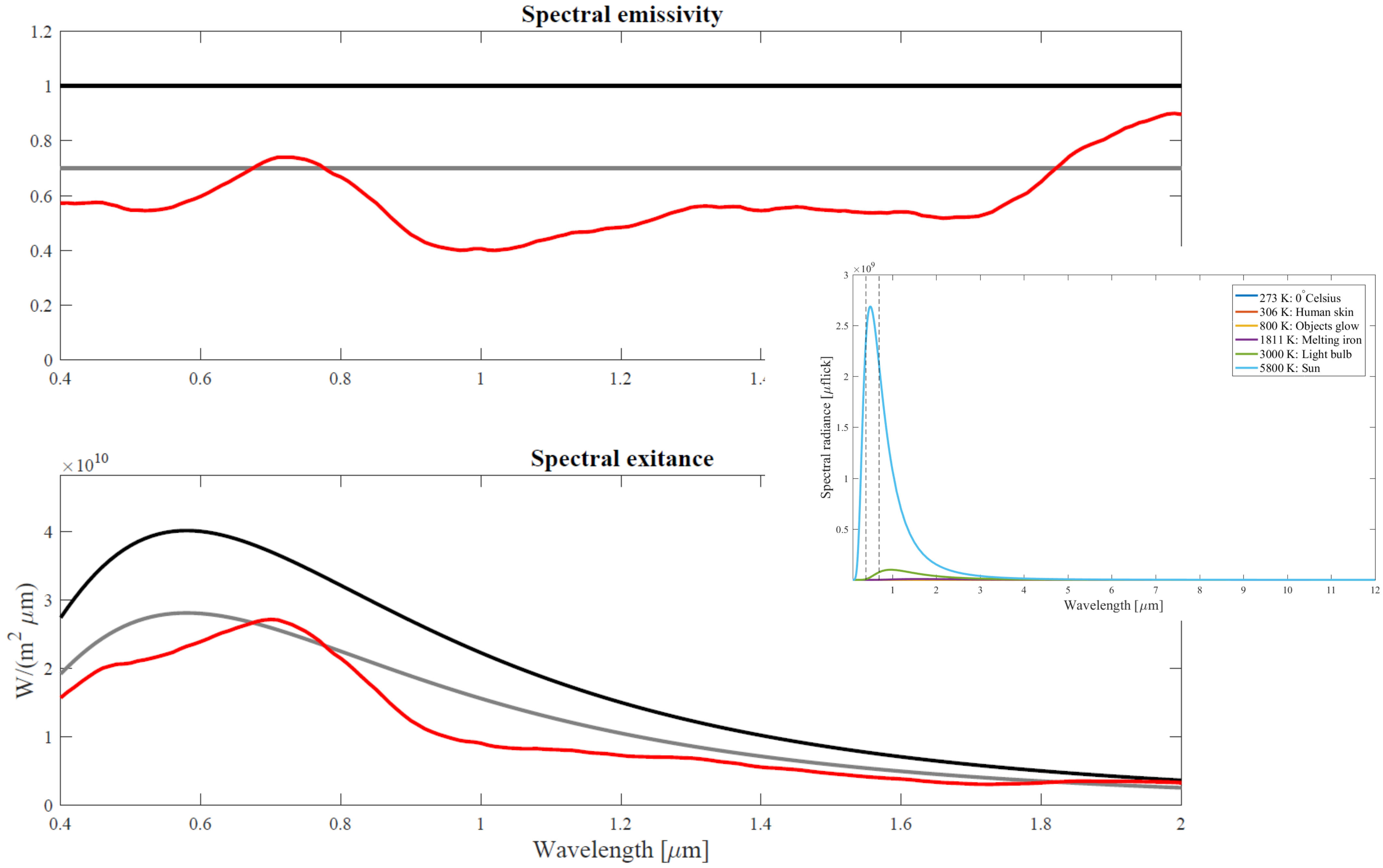


$$\alpha + \tau + r = 1$$

$$\alpha(\lambda) + \tau(\lambda) + r(\lambda) = 1$$

Emissivity (ε)

$$\alpha = \varepsilon$$



Spectral emissivity
Spectral exitance
W/(m^2 μm)
Wavelength [μm]
273 K: 0° Celsius
306 K: Human skin
800 K: Objects glow
1811 K: Melting iron
3000 K: Light bulb
5800 K: Sun
Spectral radiance [μflick]
Wavelength [μm]

Outgoing radiation

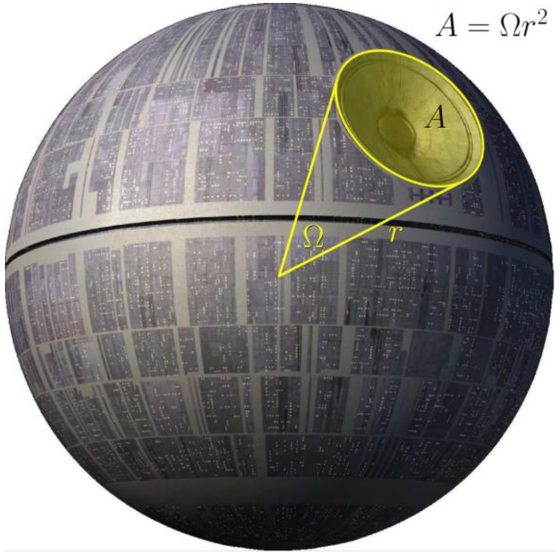
Incoming radiation

- Absorptivity α
- Emissivity ε
- Transmittance τ
- Reflectance r

- (Radiant) Flux Φ [W]
- Irradiance E [W / m²]
- Exitance M [W / m²]
- Radiance L [W / m² sr]

steradian

- α + τ + r = 1
- Dependent on wavelength and angle!
- Commonly: τ or r close to zero.



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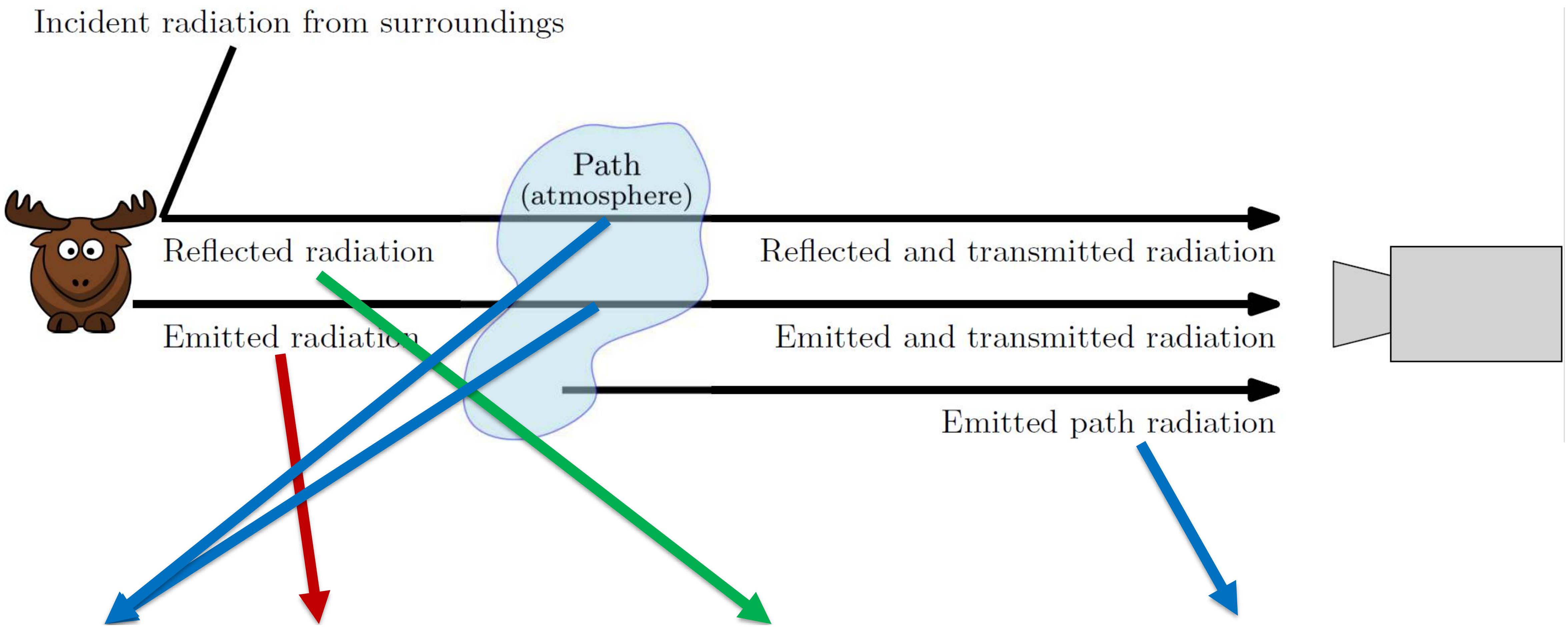
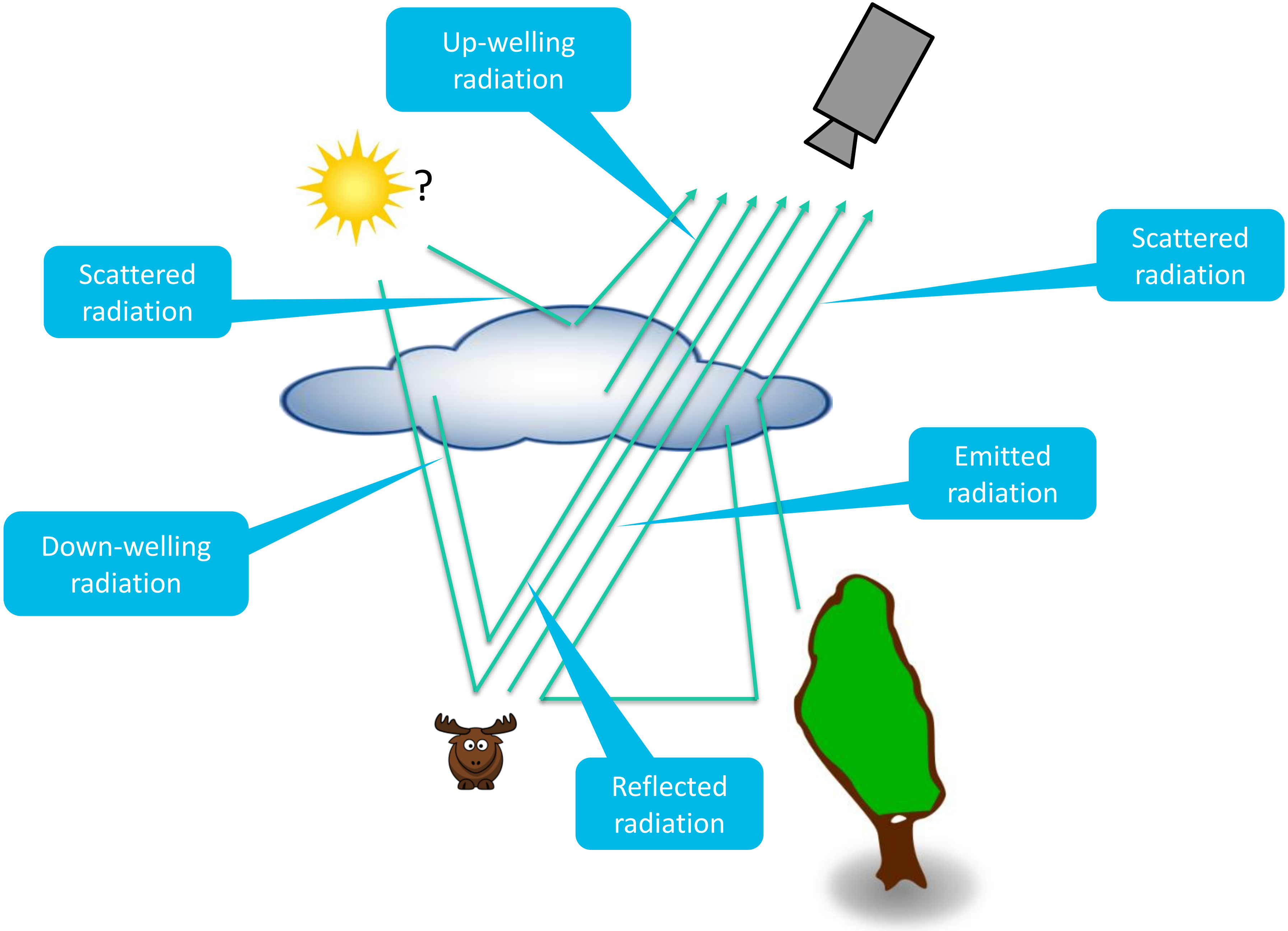

Incident radiation from surroundings
Path
(atmosphere)
Reflected radiation
Reflected and transmitted radiation
Emitted radiation
Emitted and transmitted radiation
Emitted path radiation



Up-welling radiation
?
Scattered radiation
Scattered radiation
Emitted radiation
Down-welling radiation
Reflected radiation

From object to sensor

- A sensor integrates the incoming energy over a certain bandwidth.
- The at-sensor radiance is (mainly and typically) the sum of
  1. Radiation emitted by the object and transmitted through the path;
  2. Radiation reflected by the object transmitted through the path;
  3. Radiation emitted by the path;
  4. Radiation scattered by the path.
- This does not equal the temperature of the object!

Summary: Light, radiation and matter

- Radiators: Blackbodies, greybodies, general objects.
- Properties: Emissivity, absorptivity, reflectance, transmittance.
- Radiation often measured as flux, radiance, and irradiance.
- Domains: Reflective vs emissive.
- Bands: UV, VIS, NIR, VNIR, SWIR, MWIR, LWIR, TIR, FIR.

Part 3

Thermal cameras

Thermal cameras

Defence

Civilian

Thermography

Imaging
(non radiometric)

Temperature measuring
(radiometric)

Handheld

Industrial

High-end (defence)

High-end (science)

Cooled and uncooled cameras

Sensor type / material		Used for
Cooled		
Mercury cadmium telluride	MCT	SWIR – LWIR
Indium antimonide	InSb	NIR – LWIR
Strained Layer Superlattice	SLS	MWIR, LWIR
Un-cooled		
Charged-coupled device	CCD	VNIR
Active-pixel sensor	APS / CMOS	VNIR
Indium gallium arsenide	InGaAs	NIR, SWIR
Microbolometer		LWIR

Uncooled cameras

- Pyro-electric detectors
- Microbolometers

The common detector in handheld and industrial IR cameras.

Internal radiation

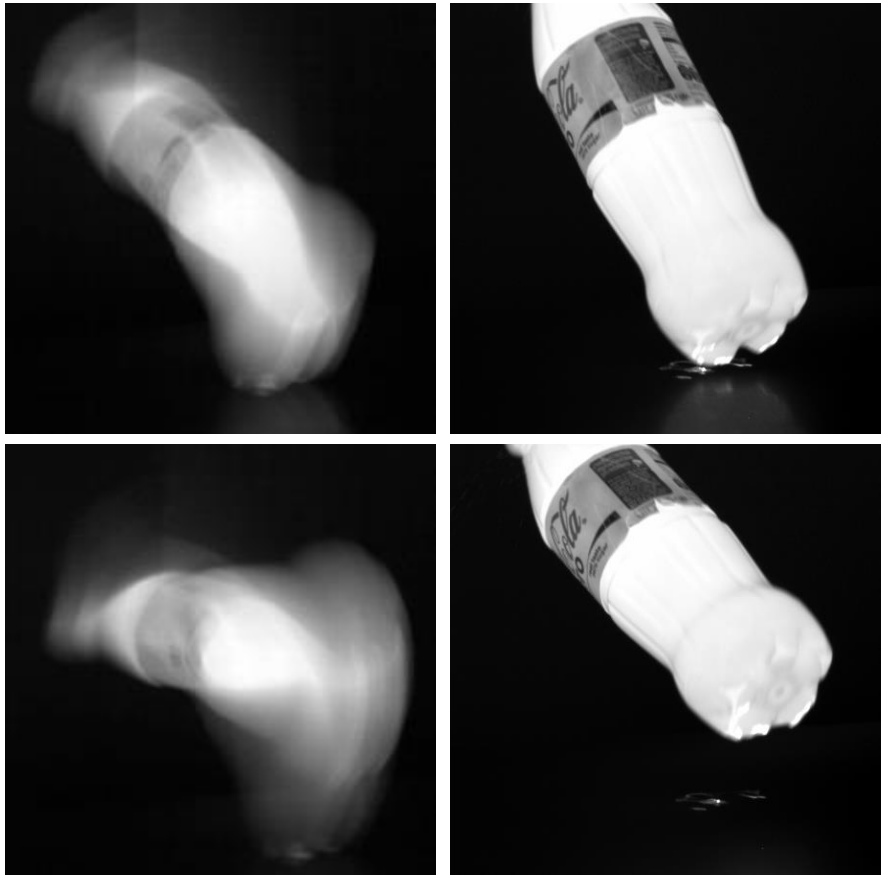
- Much of the radiation hitting the sensor is emitted by the camera
  - 90% is a realistic value
- Thus:
  - One or more internal thermometers
  - On-board processing

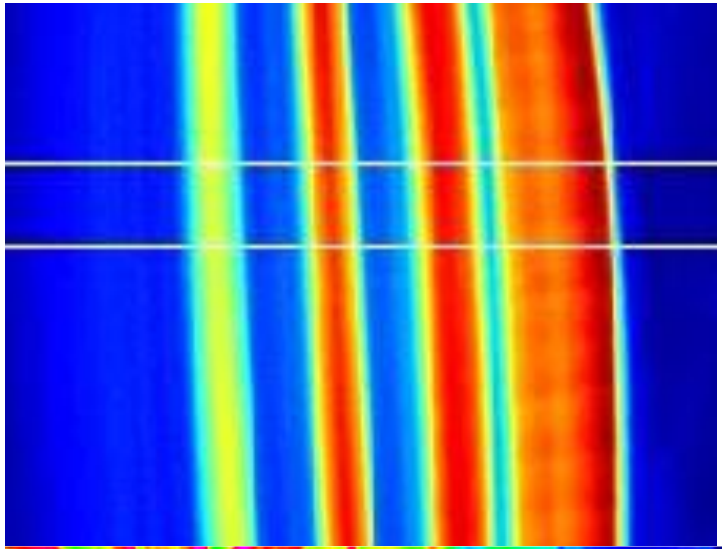
3 thermometers in this one!

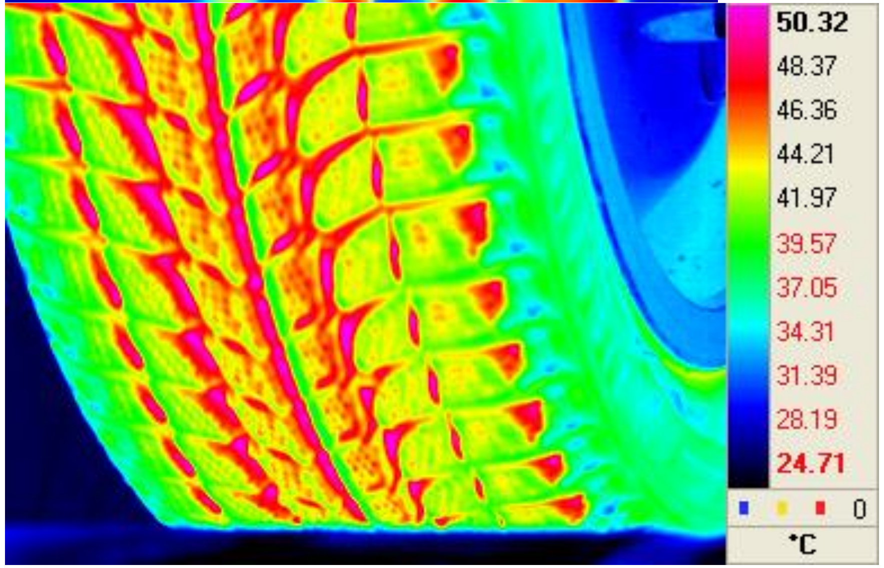
Cooled cameras

- High spatial resolution
- High temperature resolution
- Fast
- Loud
- Heavy
- Large
- Expensive

Cooled vs uncooled

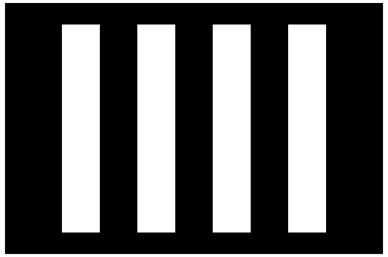






Performance measures

- NETD: Noise Equivalent Temperature Difference
- MRTD: Minimum Resolveable Temperature Difference



- NEP: Noise Equivalent Power

$$\mathrm{NEP} = \frac{\sigma^2}{R} \quad \left[\frac{\mathrm{W}}{\sqrt{\mathrm{Hz}}}\right]$$

- Normalized Detectivity D*
  - Indepedent of detector size and speed

$$\mathrm{D}^* = \frac{\sqrt{A\,\Delta f}}{\mathrm{NEP}} = \frac{R\sqrt{A}}{\sigma^2} \quad \left[\frac{\mathrm{cm}\sqrt{\mathrm{Hz}}}{\mathrm{W}} \text{ or Jones}\right]$$

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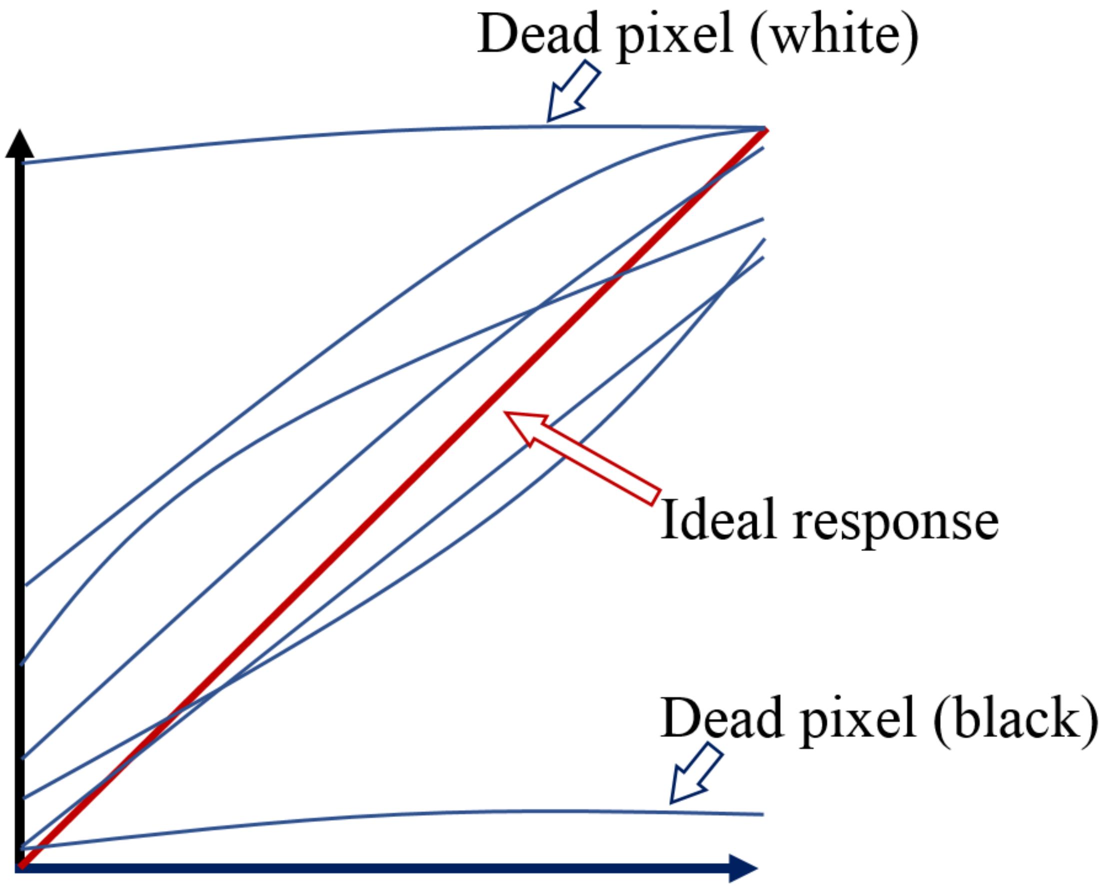
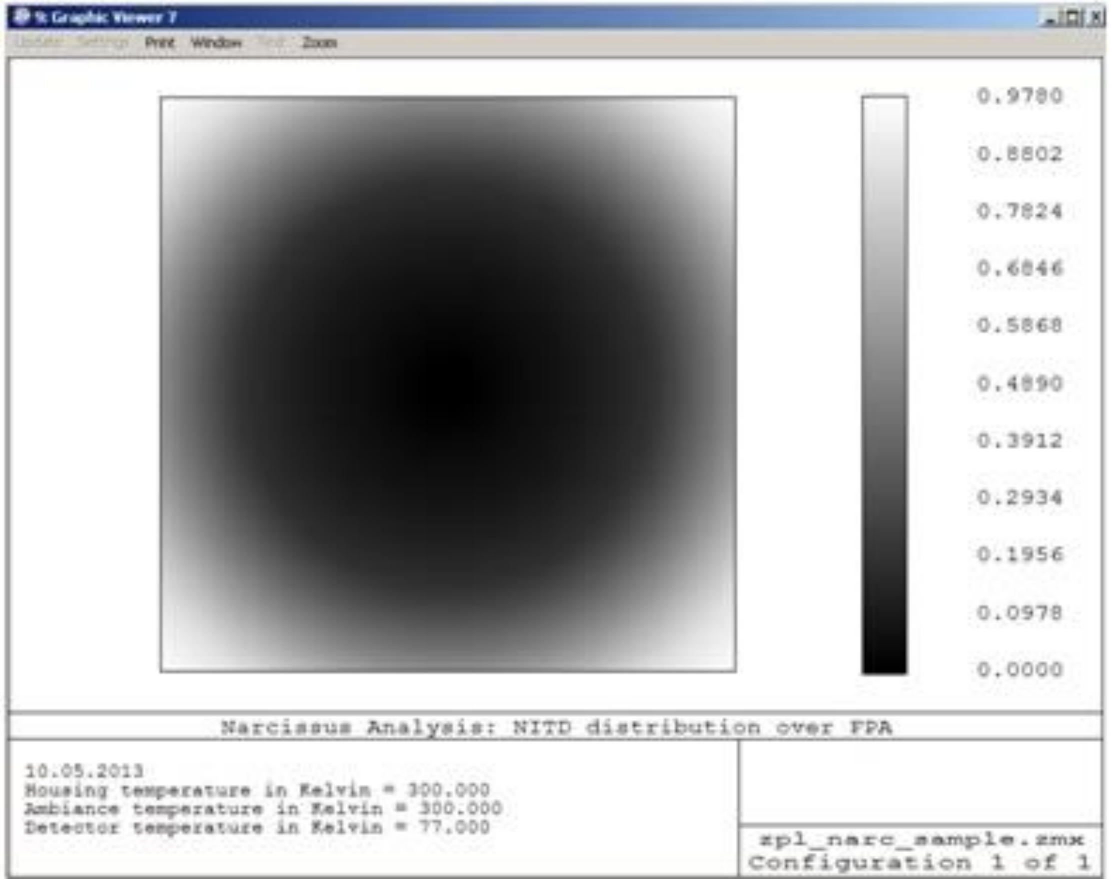
Calibration and NUC



Narcissus



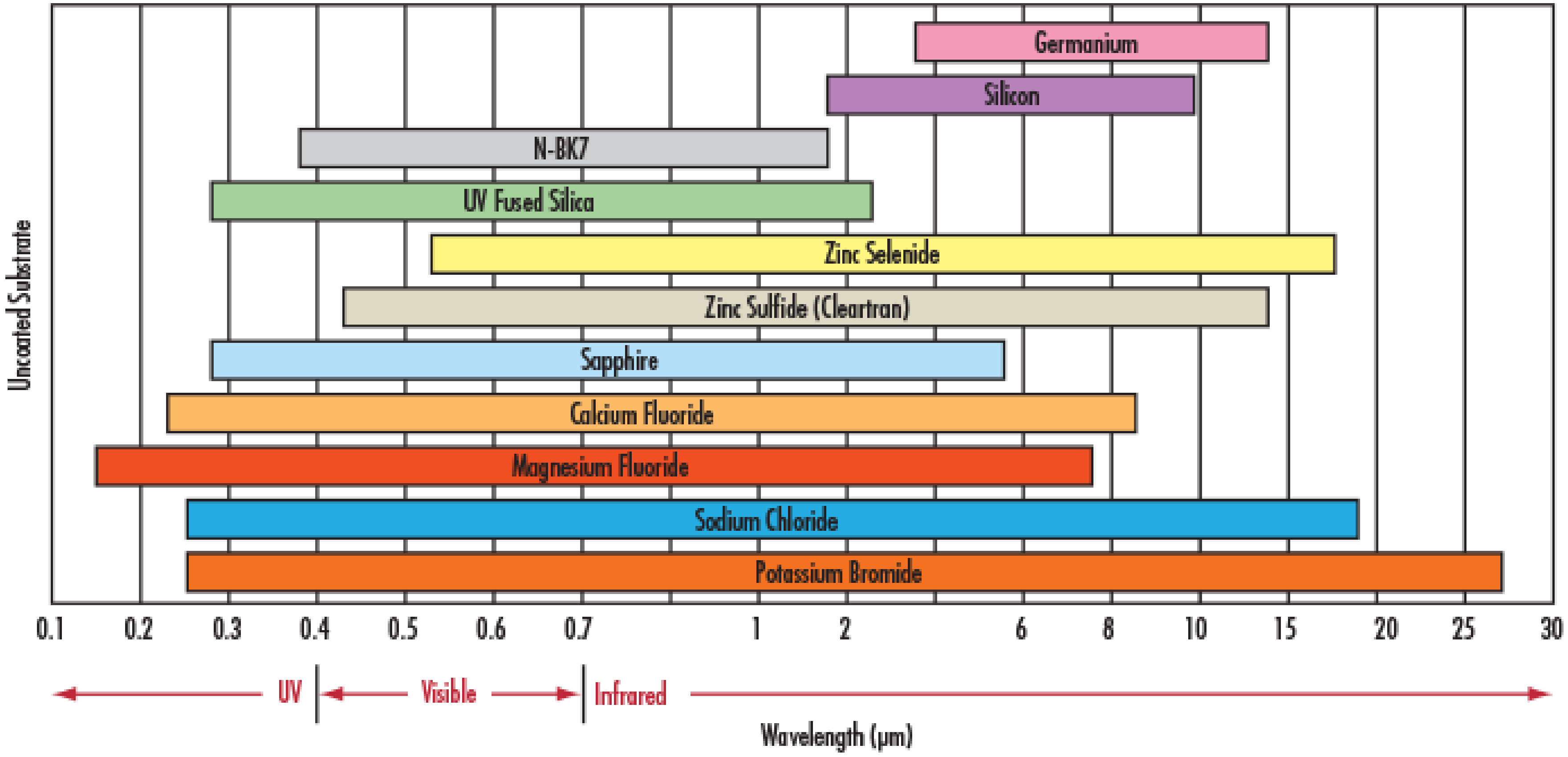
9: Graphic Viewer 7
Update Settings Print Window Text Zoom
0.9780
0.8802
0.7824
0.6846
0.5868
0.4890
0.3912
0.2934
0.1956
0.0978
0.0000
Narcissus Analysis: NITD distribution over FPA
10.05.2013
Housing temperature in Kelvin = 300.000
Ambiance temperature in Kelvin = 300.000
Detector temperature in Kelvin = 77.000
zpl_narc_sample.zmx
Configuration 1 of 1

Optics for thermal cameras

Parameters

- Durability
- Refractive index
- Variability due to heat
- Cost
- Transmittance

Materials



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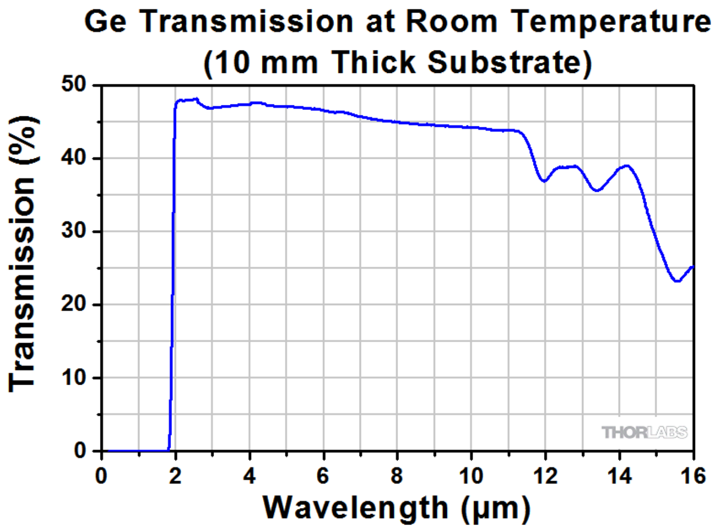
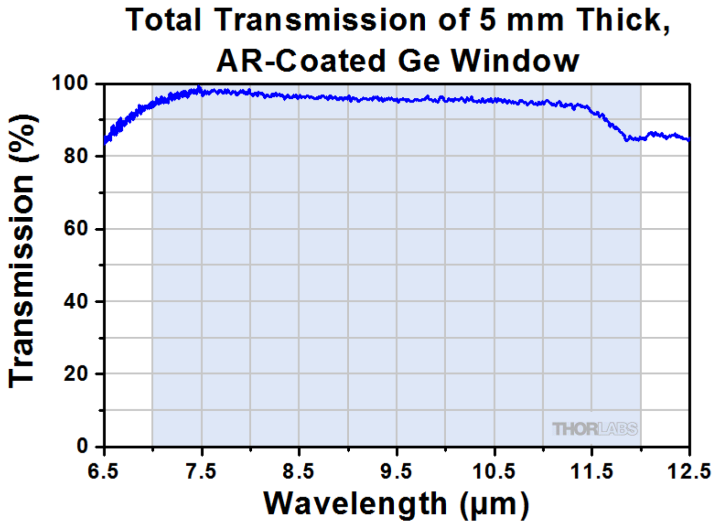
Lens materials: Germanium

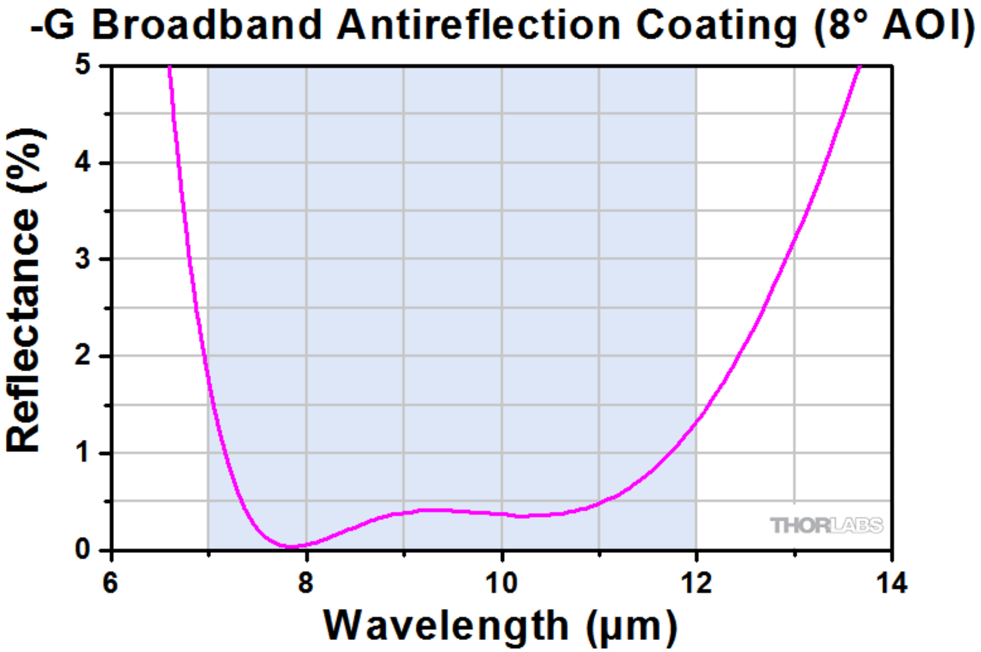
- Good for MWIR and LWIR (with AR coating)
- Durable (KH 780)
- High refractive index (4.0)
- Transmittance drops with temperature!





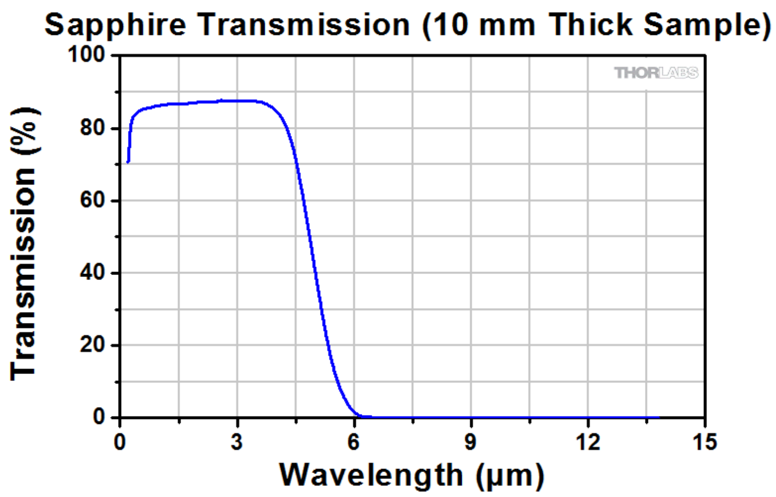
Lens materials: Zinc Selenide

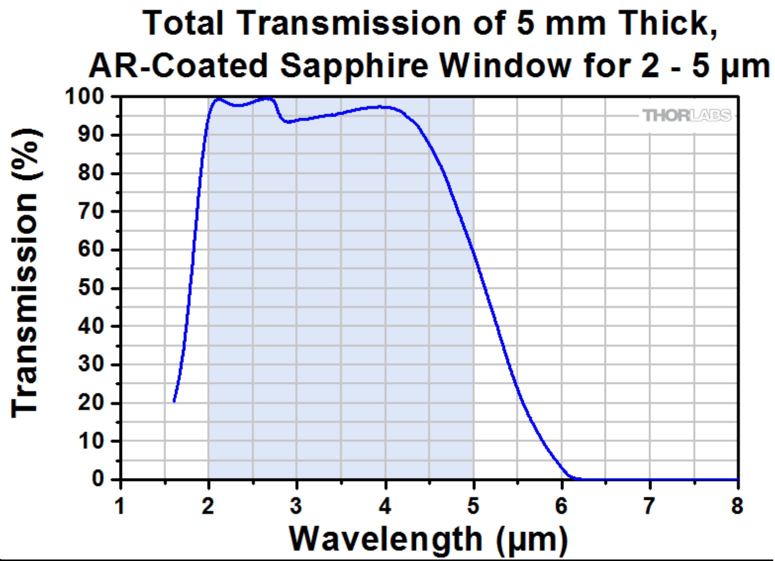
- Transmits even better than Germanium!
- KH 120 ☹
- Toxic



Lens materials: Sapphire

- Durable (KH 2200).
- Good transmittance in VIS-MWIR.





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A note on color

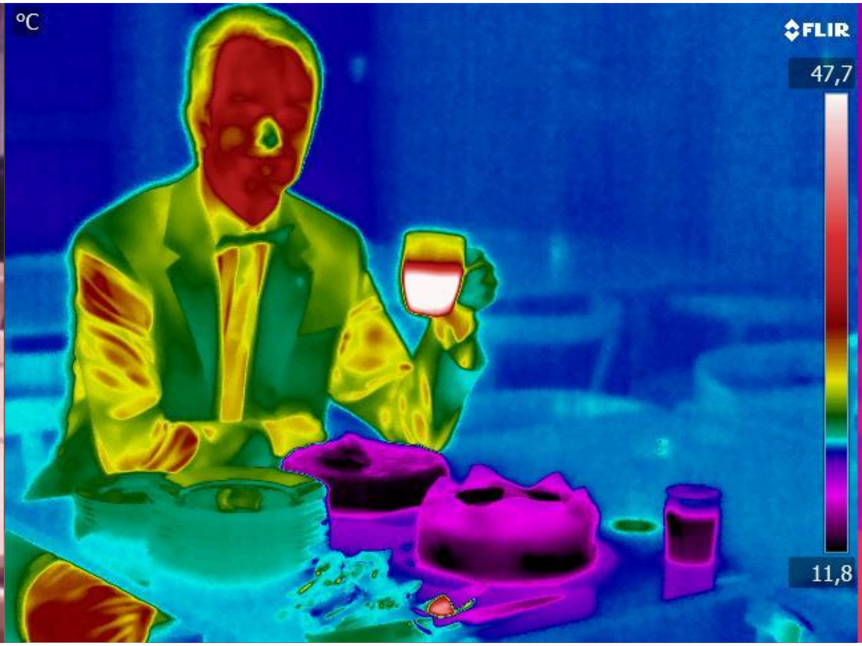
Visual

White hot

Black hot

A note on color

Visual



Rainbow

Iron

Summary: Thermal cameras

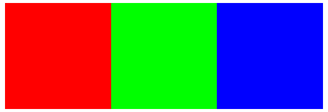
- Cooled vs uncooled
  - Cooled: Loud, cumbersome, expensive, fast, sensitive.
- Sensors: Thermal detectors vs photon detectors
- Optics: Transmitting in different bands
- The most common thermal camera: Uncooled bolometer camera for LWIR with Germanium lens.

Part 5

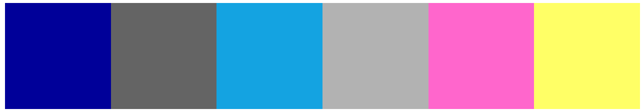
Multispectral imaging

What is multi/hyperspectral imaging?

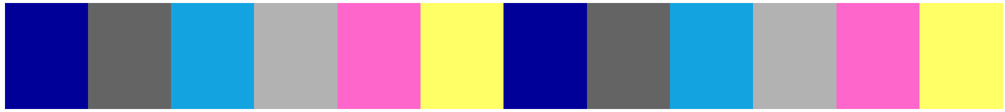
Greyscale image – one band



Color image – three bands



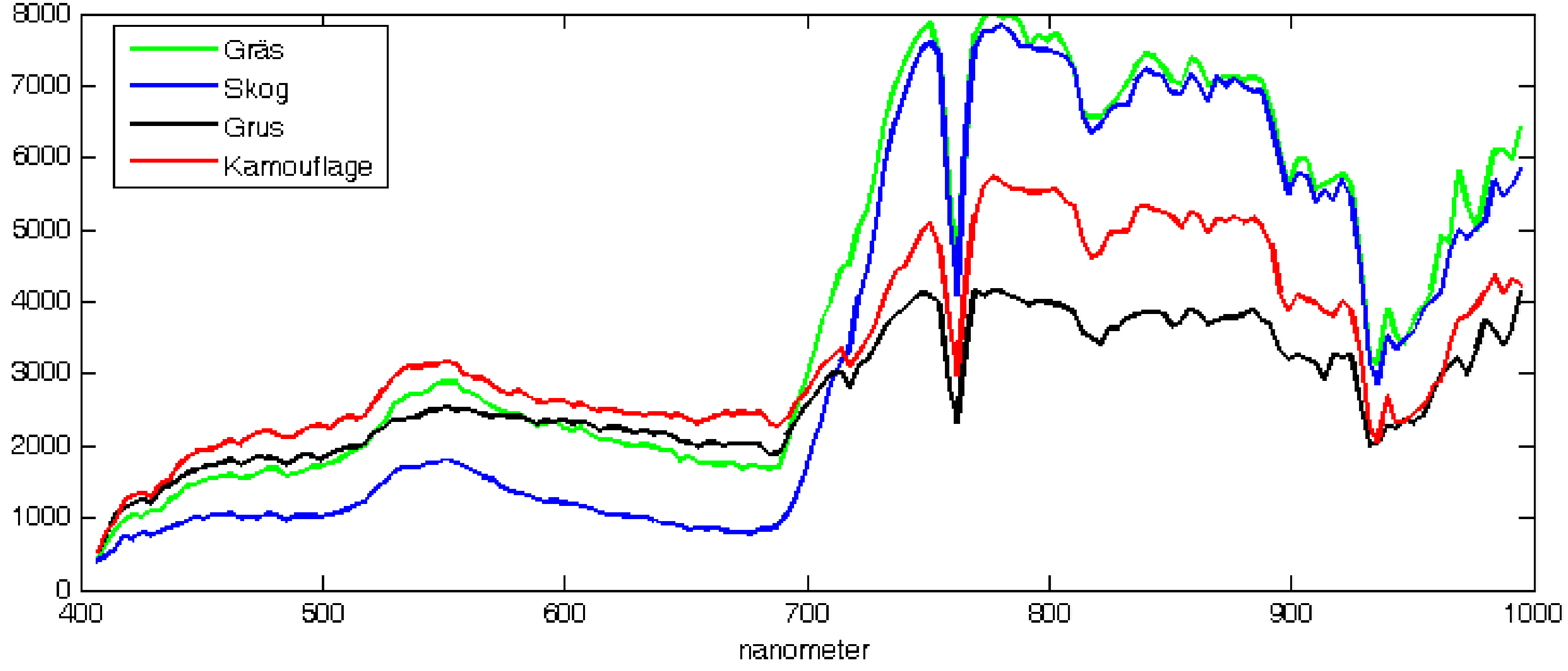
Multispectral image – several bands



…

Hyperspectral image –
many contiguous bands

Why multi/hyperspectral images?



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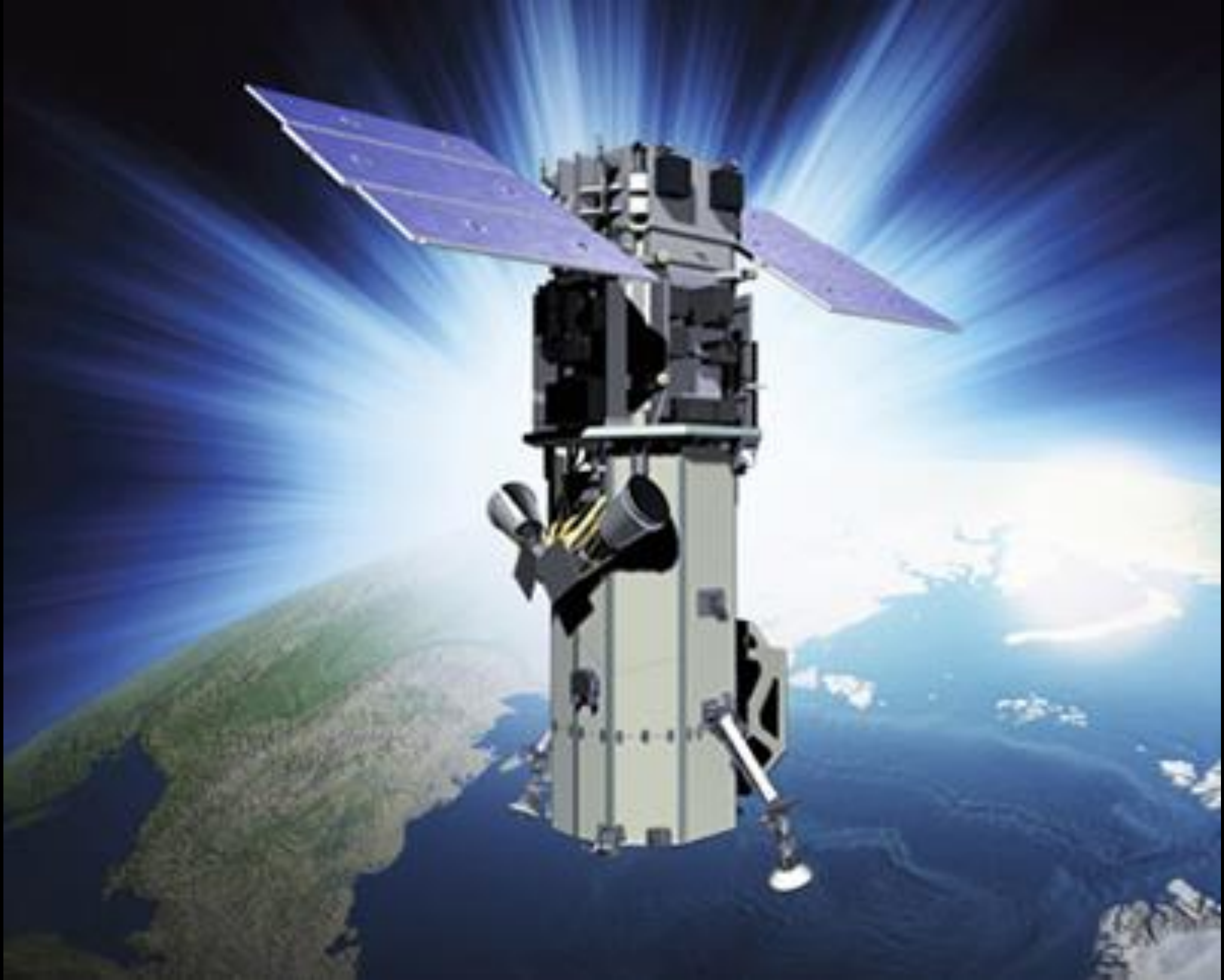
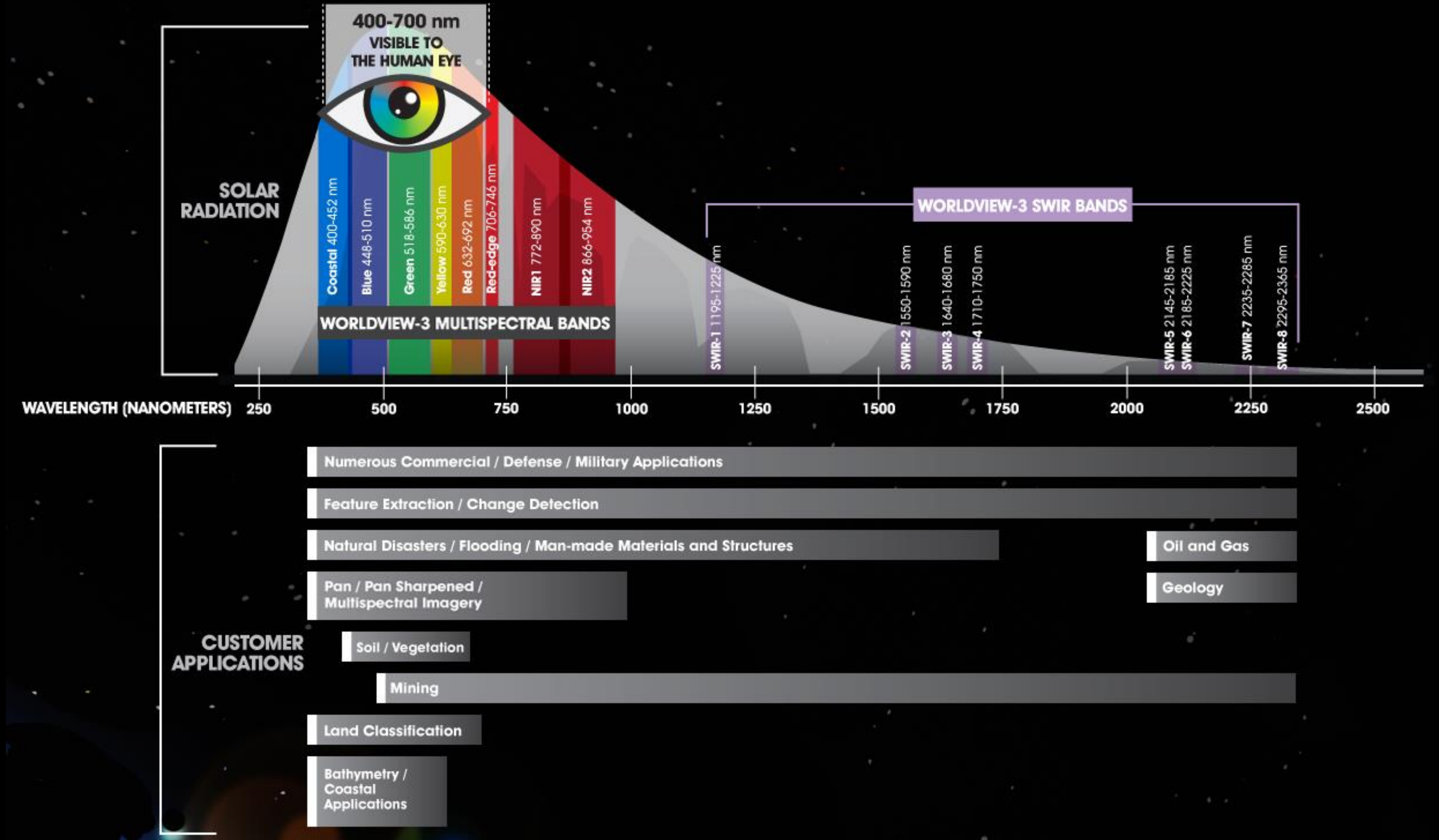
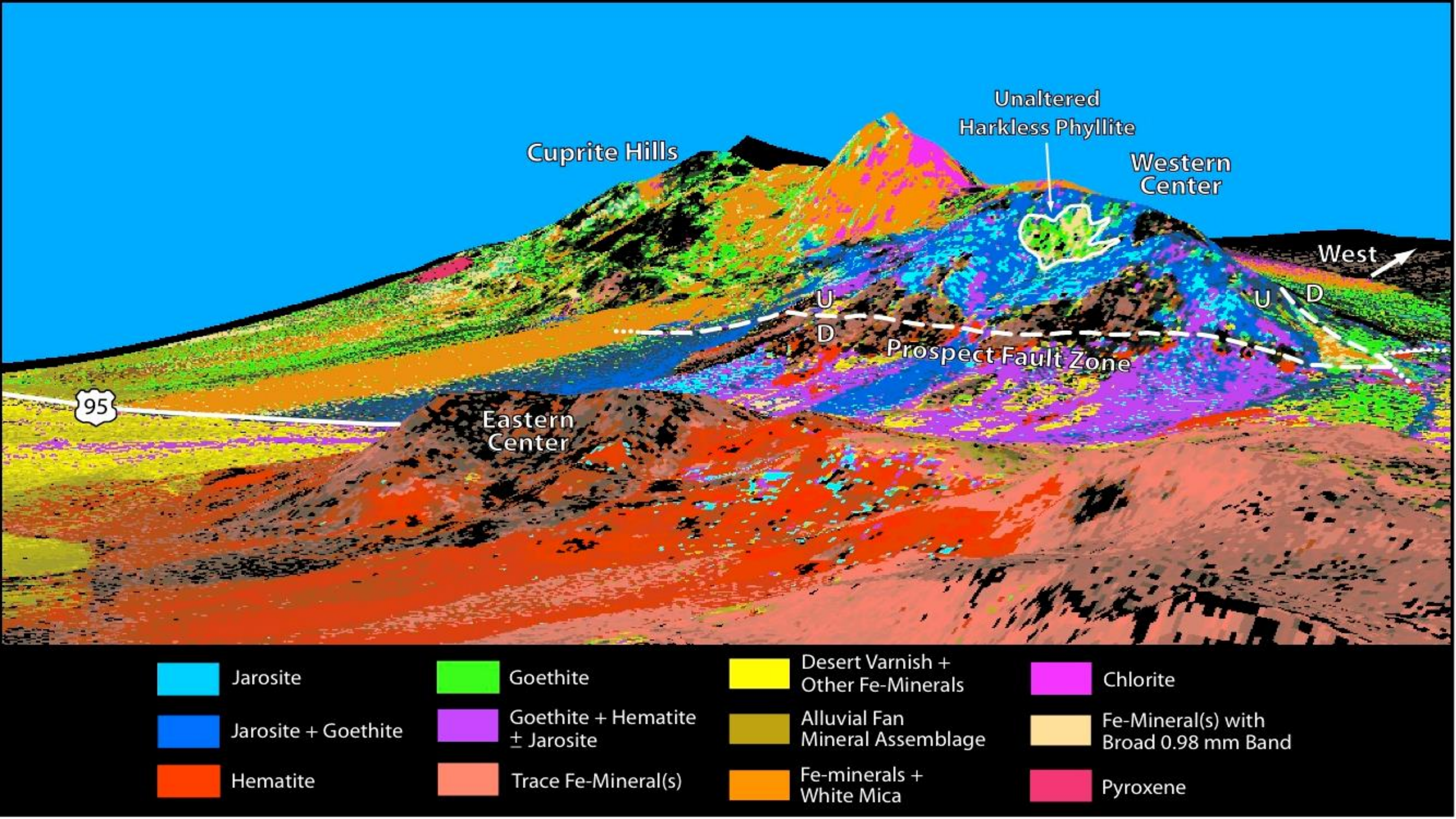
Applications

- Defence
- Mineralogy
- Land-use classification
- Precision farming
- Food inspection
- Environmental monitoring
- …



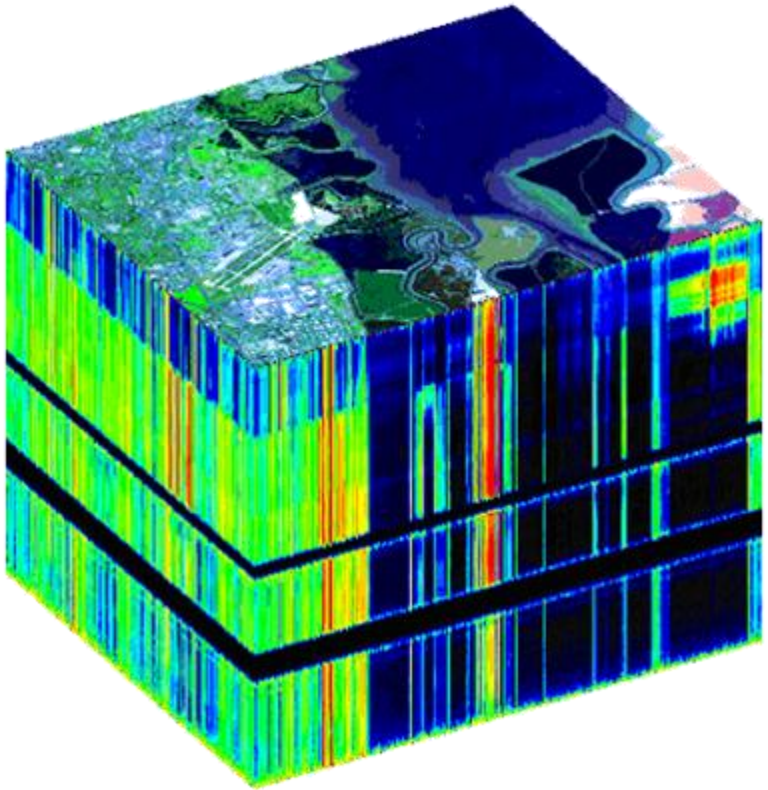


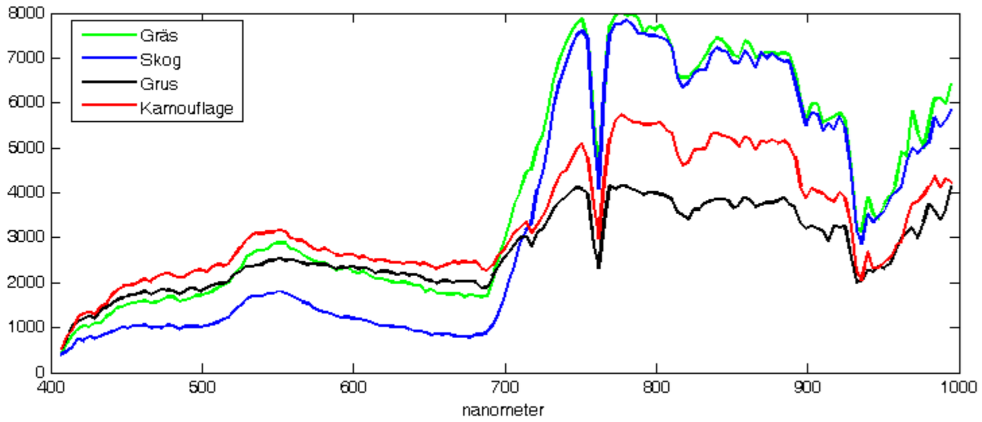
400-700 nm
VISIBLE TO THE HUMAN EYE
SOLAR RADIATION
Coastal 400-452 nm
Blue 448-510 nm
Green 518-586 nm
Yellow 590-630 nm
Red 632-692 nm
Red-edge 706-746 nm
NIR1 772-890 nm
NIR2 866-954 nm
WORLDVIEW-3 MULTISPECTRAL BANDS
WORLDVIEW-3 SWIR BANDS
SWIR-1 1195-1225 nm
SWIR-2 1550-1590 nm
SWIR-3 1640-1680 nm
SWIR-4 1710-1750 nm
SWIR-5 2145-2185 nm
SWIR-6 2185-2225 nm
SWIR-7 2235-2285 nm
SWIR-8 2295-2365 nm
WAVELENGTH (NANOMETERS)
250
500
750
1000
1250
1500
1750
2000
2250
2500
CUSTOMER APPLICATIONS
Numerous Commercial / Defense / Military Applications
Feature Extraction / Change Detection
Natural Disasters / Flooding / Man-made Materials and Structures
Oil and Gas
Pan / Pan Sharpened / Multispectral Imagery
Geology
Soil / Vegetation
Mining
Land Classification
Bathymetry / Coastal Applications



Cuprite Hills
Unaltered
Harkless Phyllite
Western
Center
West
U
D
U
D
Prospect Fault Zone
95
Eastern
Center
Jarosite
Jarosite + Goethite
Hematite
Goethite
Goethite + Hematite
± Jarosite
Trace Fe-Mineral(s)
Desert Varnish +
Other Fe-Minerals
Alluvial Fan
Mineral Assemblage
Fe-minerals +
White Mica
Chlorite
Fe-Mineral(s) with
Broad 0.98 mm Band
Pyroxene

The data cube





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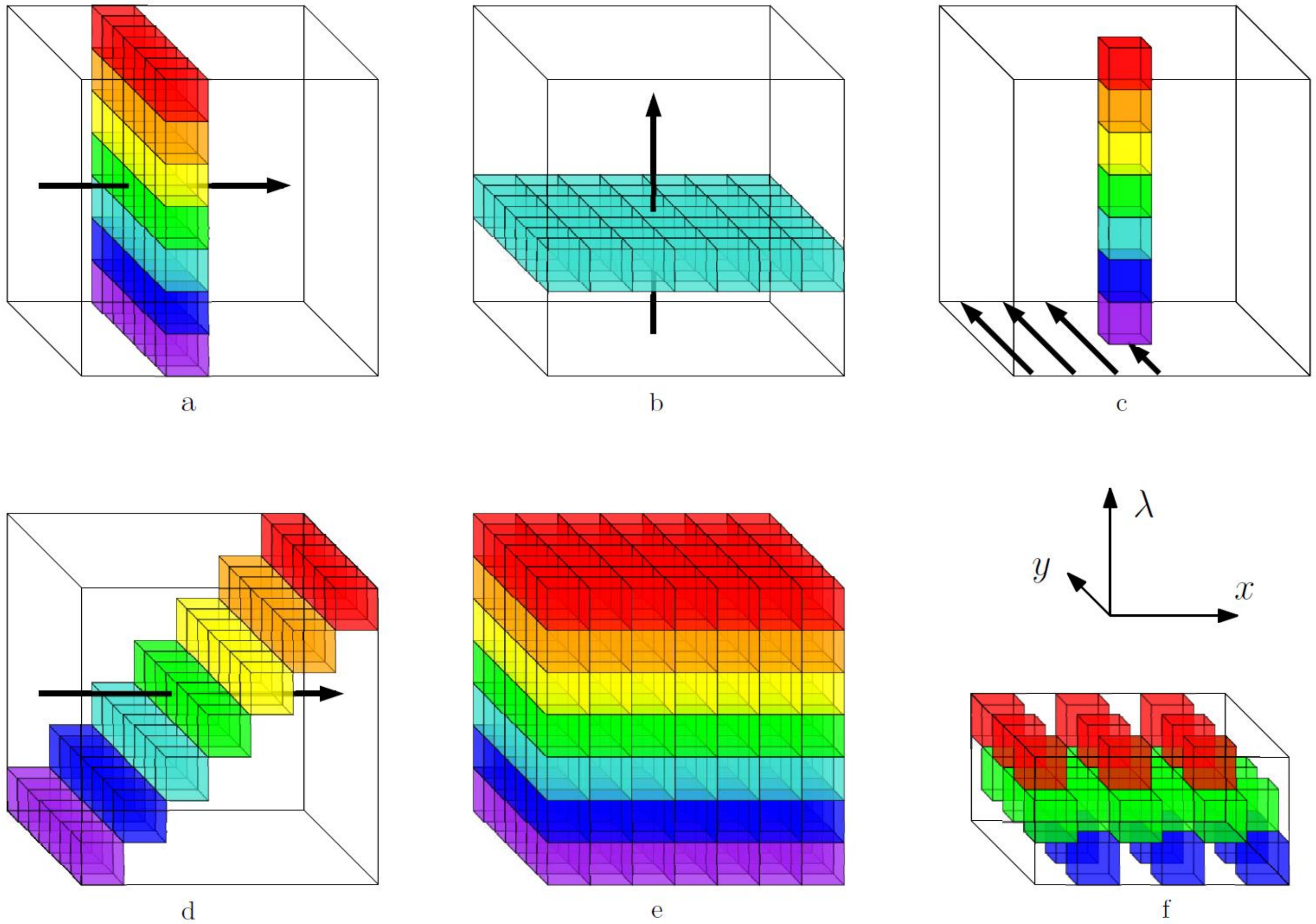
Acquiring the data cube

- Push-broom
- Wisk-broom
- Staring
- Scanning



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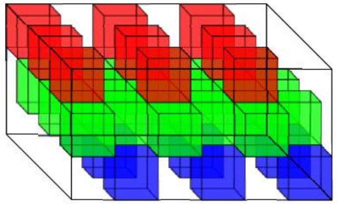
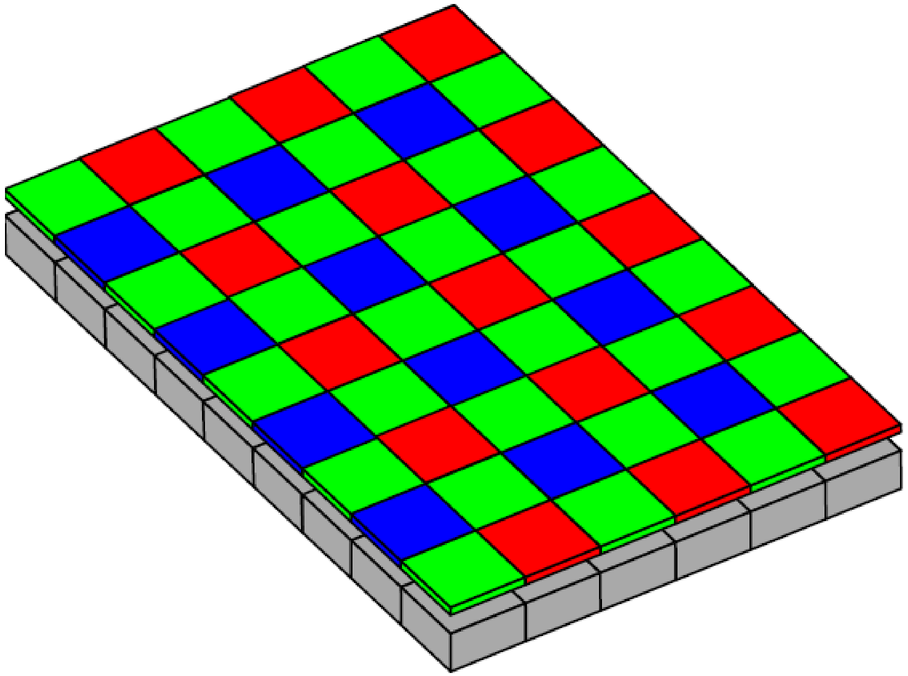
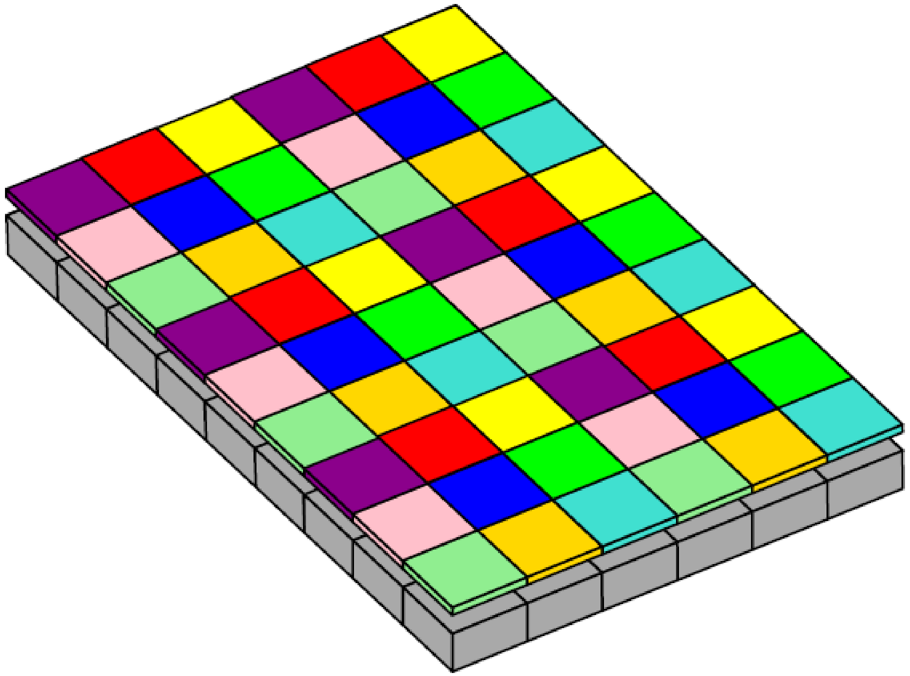
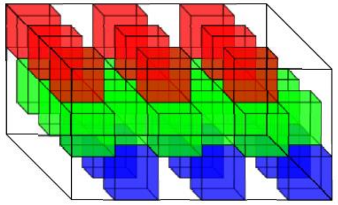
Multispectral cameras


f

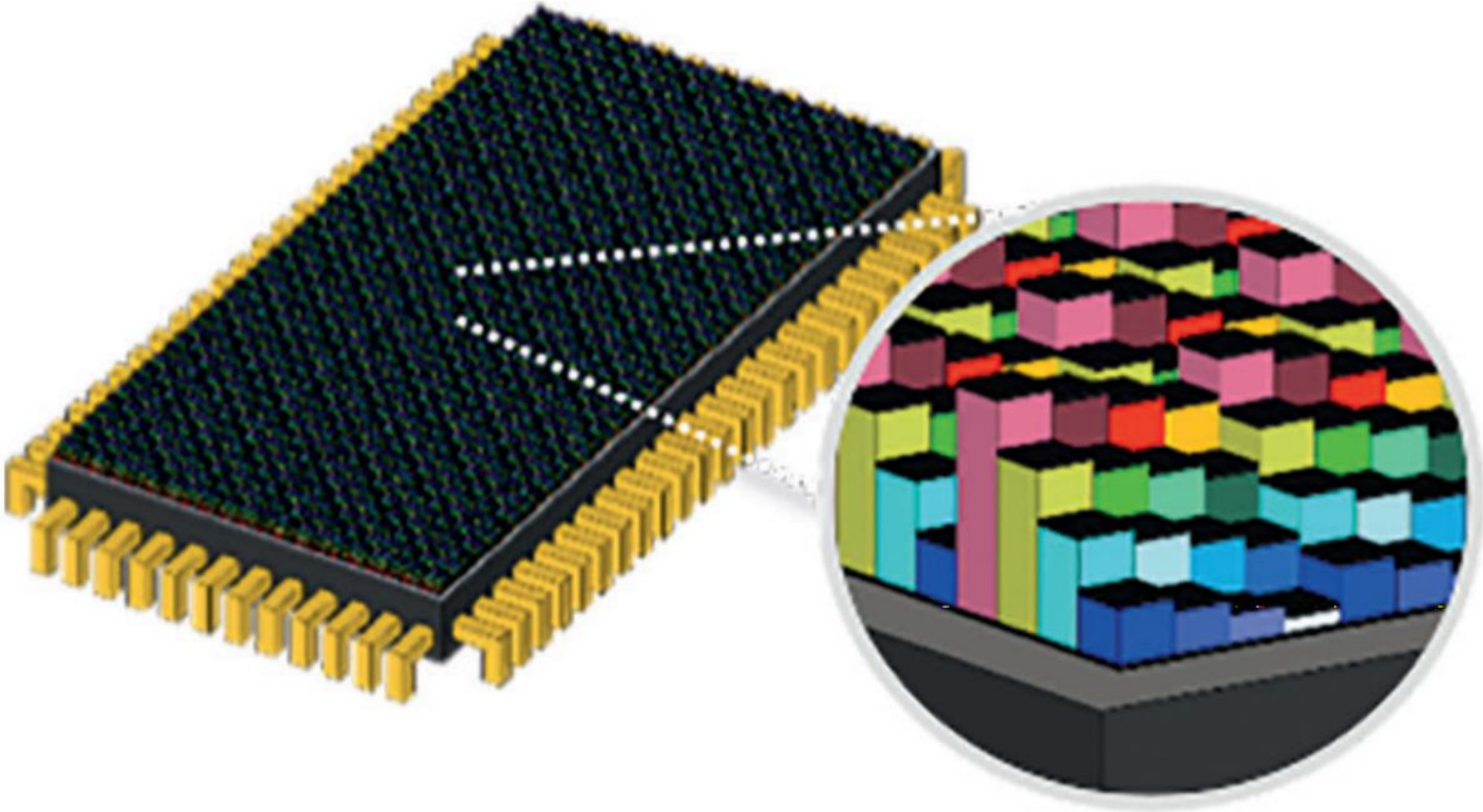
Filter mosaics



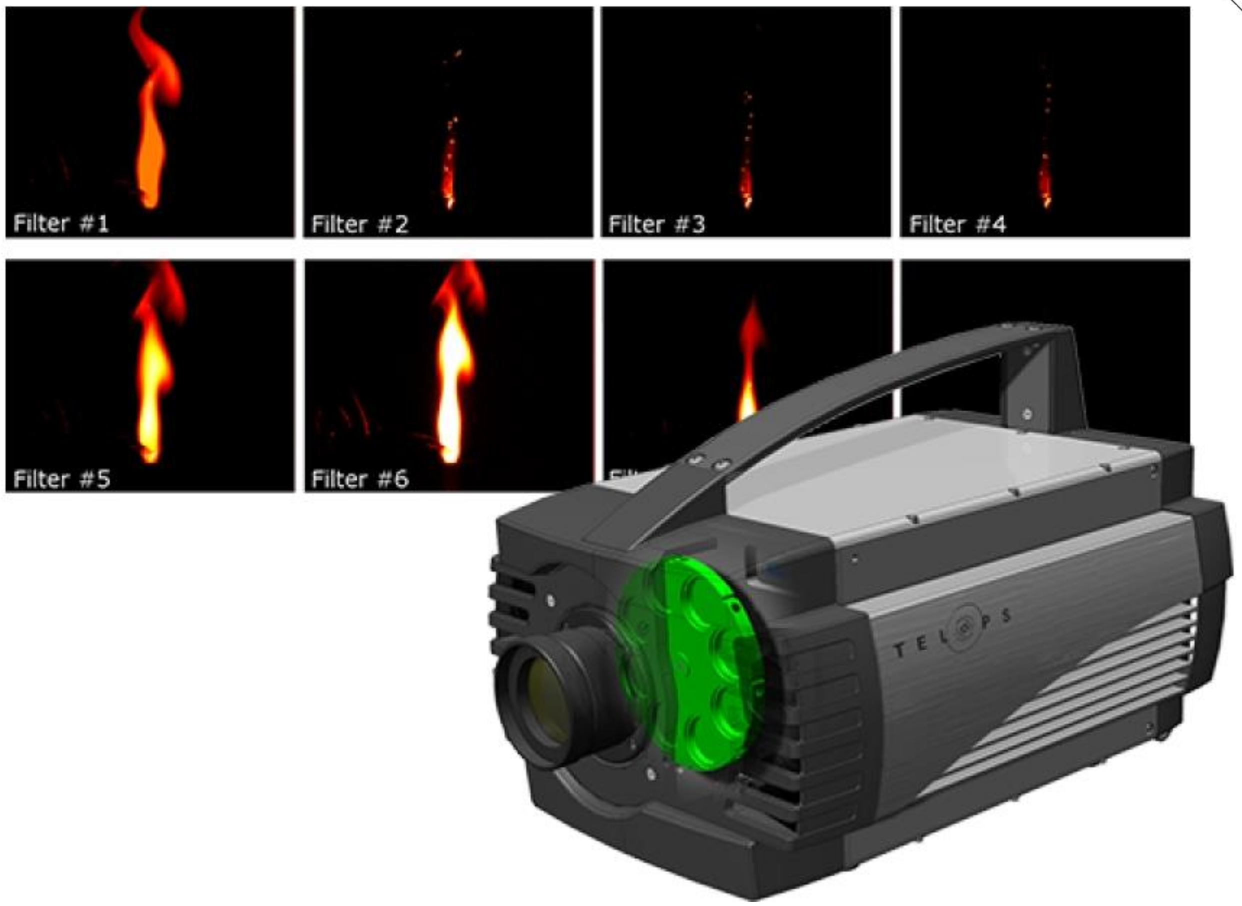


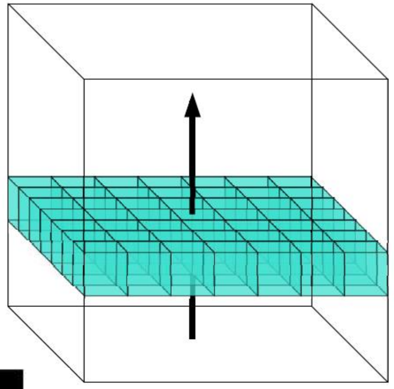


16-band sensor from IMEC

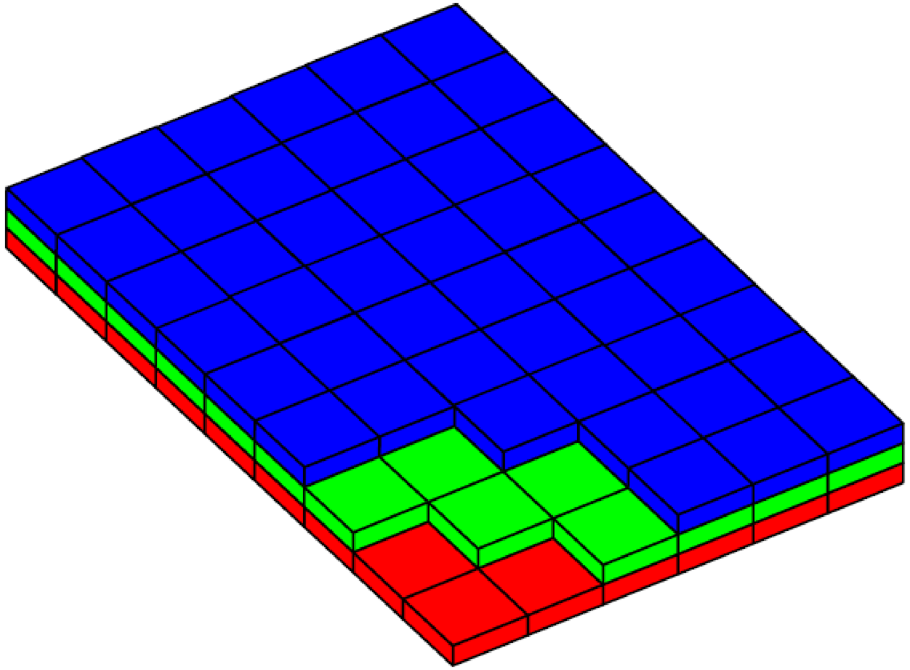


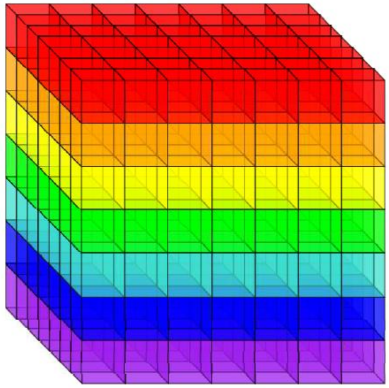
Filter wheels




b

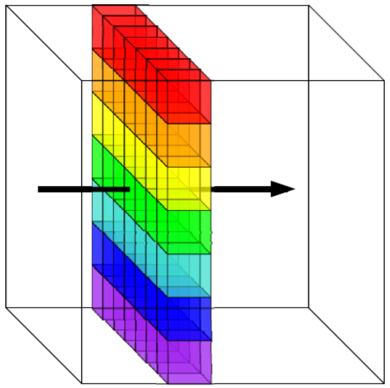
Multi-layer sensors

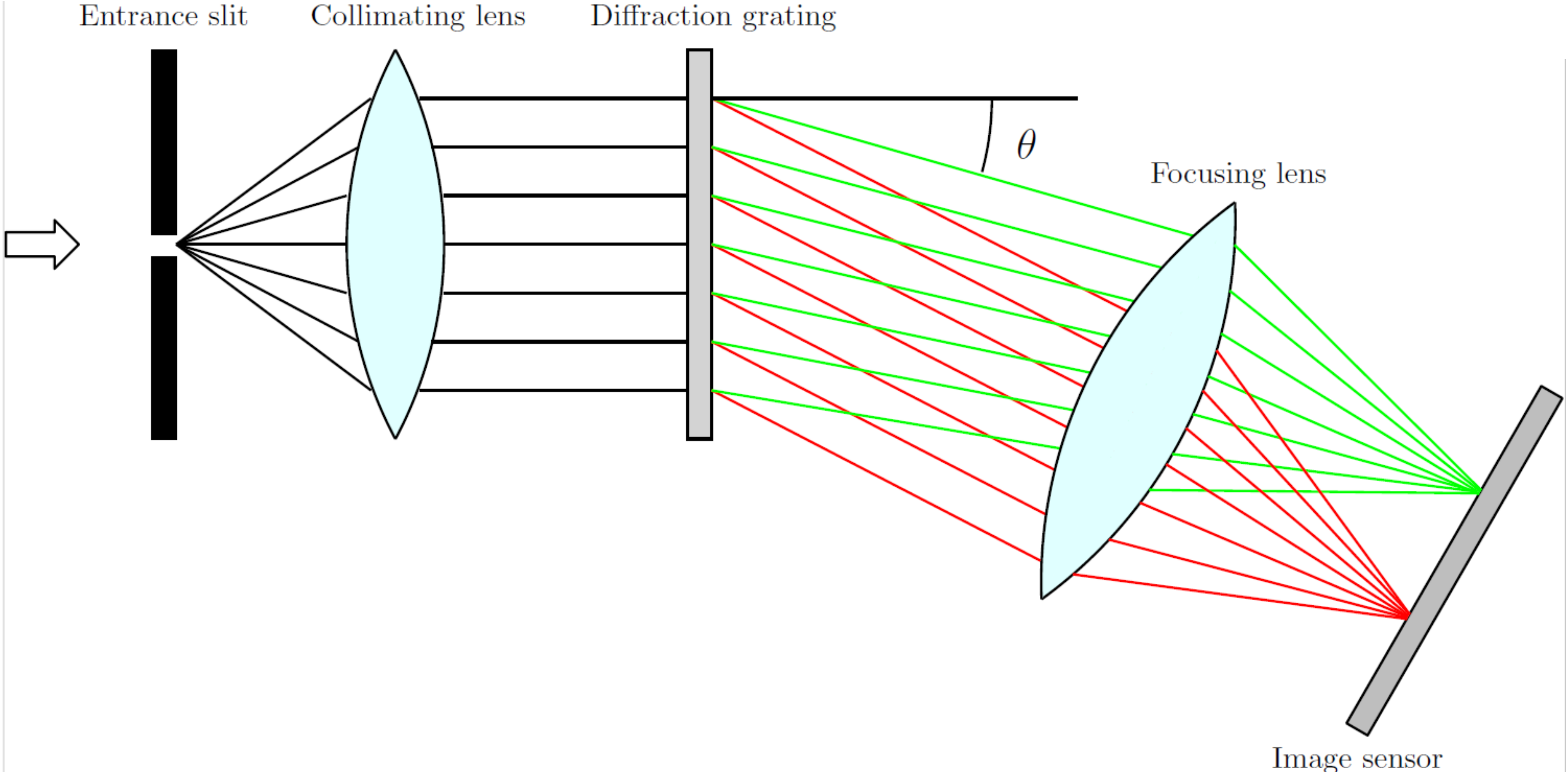




Hyperspectral cameras

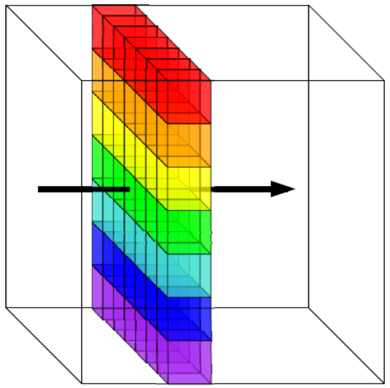
Diffraction grating





termisk

Specim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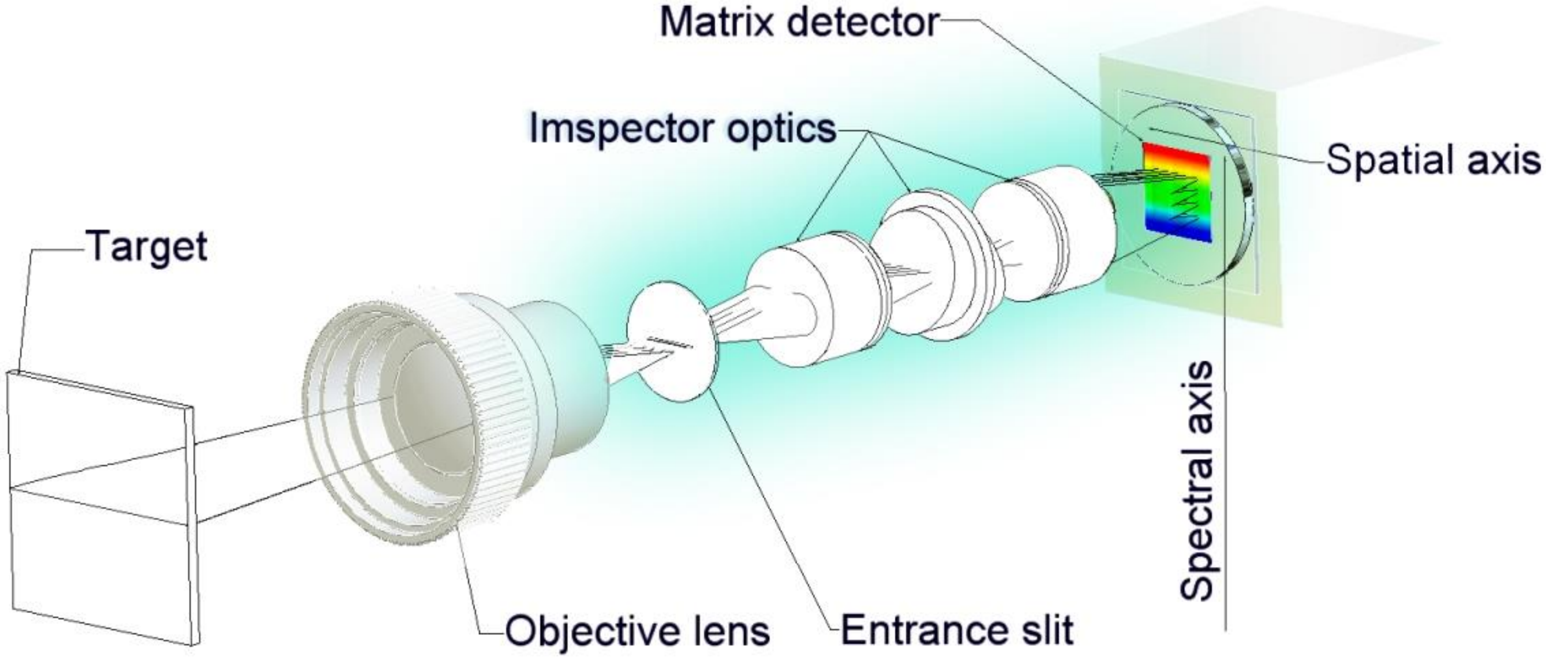
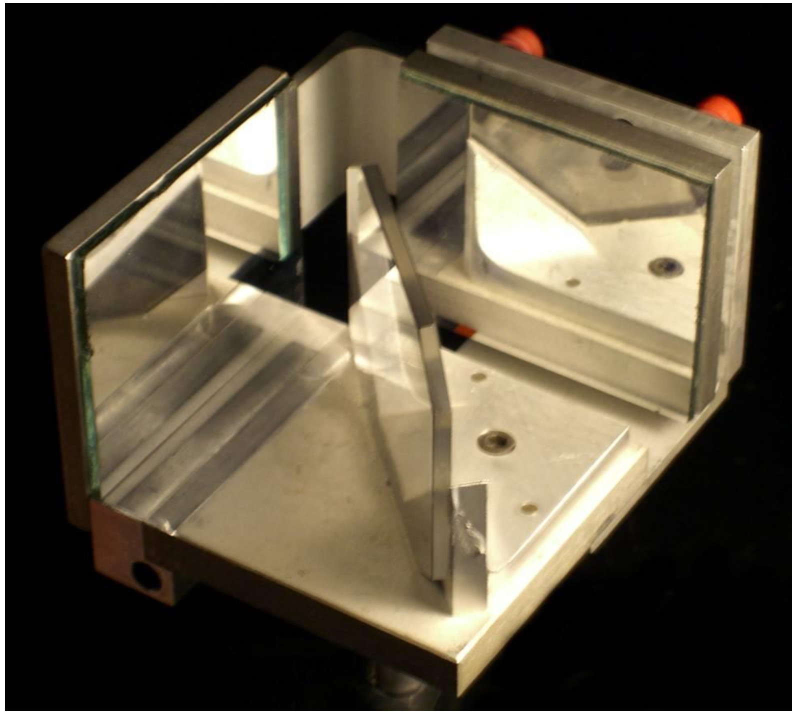
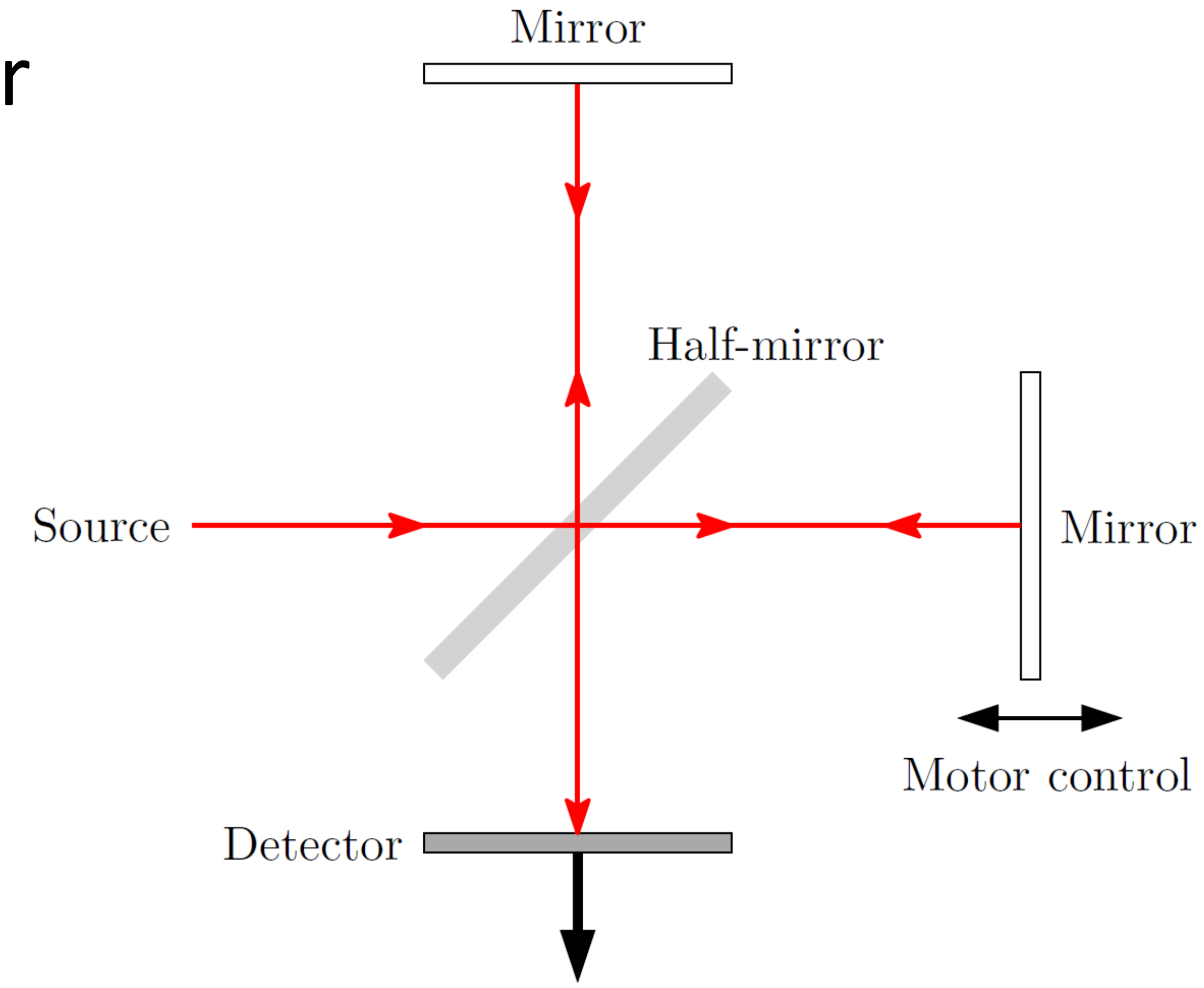
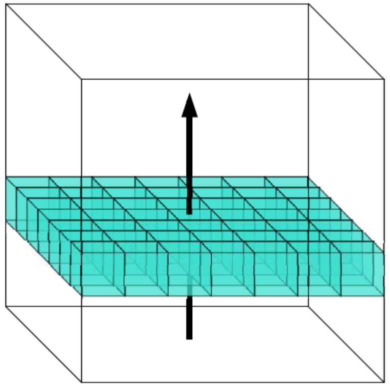

Matrix detector
Imspector optics
Spatial axis
Target
Spectral axis
Objective lens
Entrance slit

Michelson interferometer





Fabry-Perot interferometer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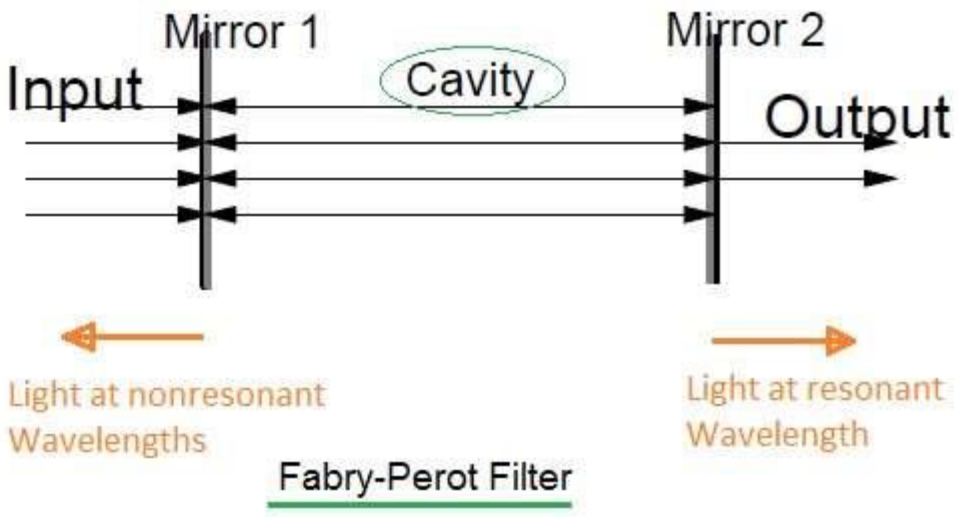
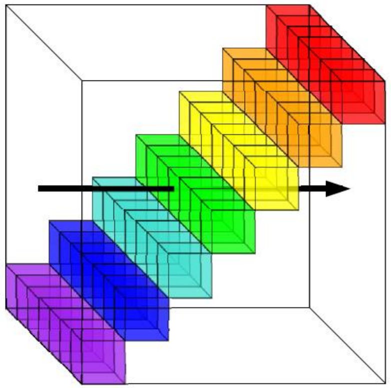


https://www.rfwireless-world.com/Terminology/Fabry-Perot-Filter-vs-Fabry-Perot-Interferometer-vs-Fabry-Perot-Cavity.html

Continuously variable optical band-pass filter



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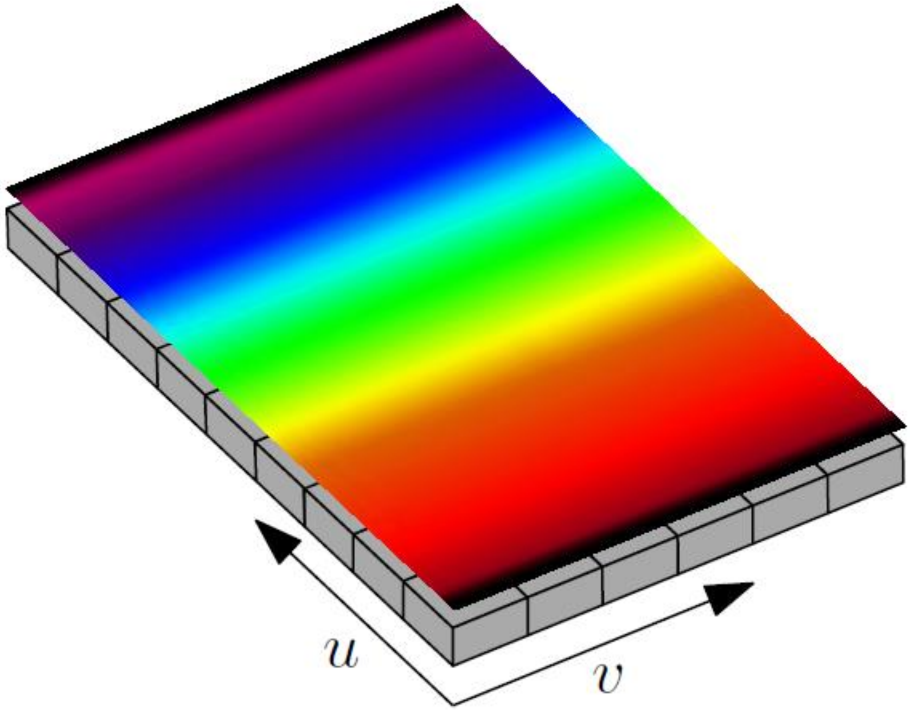

Summary: Multi/hyperspectral

- Use multiple wavebands to see better!
- Recognize materials in one pixel!
- Many ways of making M/HS cameras.
- Applications: Mostly remote sensing and military, others upcoming, especially life sciences and agriculture.

MSc thesis projects & summer internships

Contact:
mathias.kindstedt@termisk.se

Or visit our booth at LINK-dagarna October 23-24 (2023).