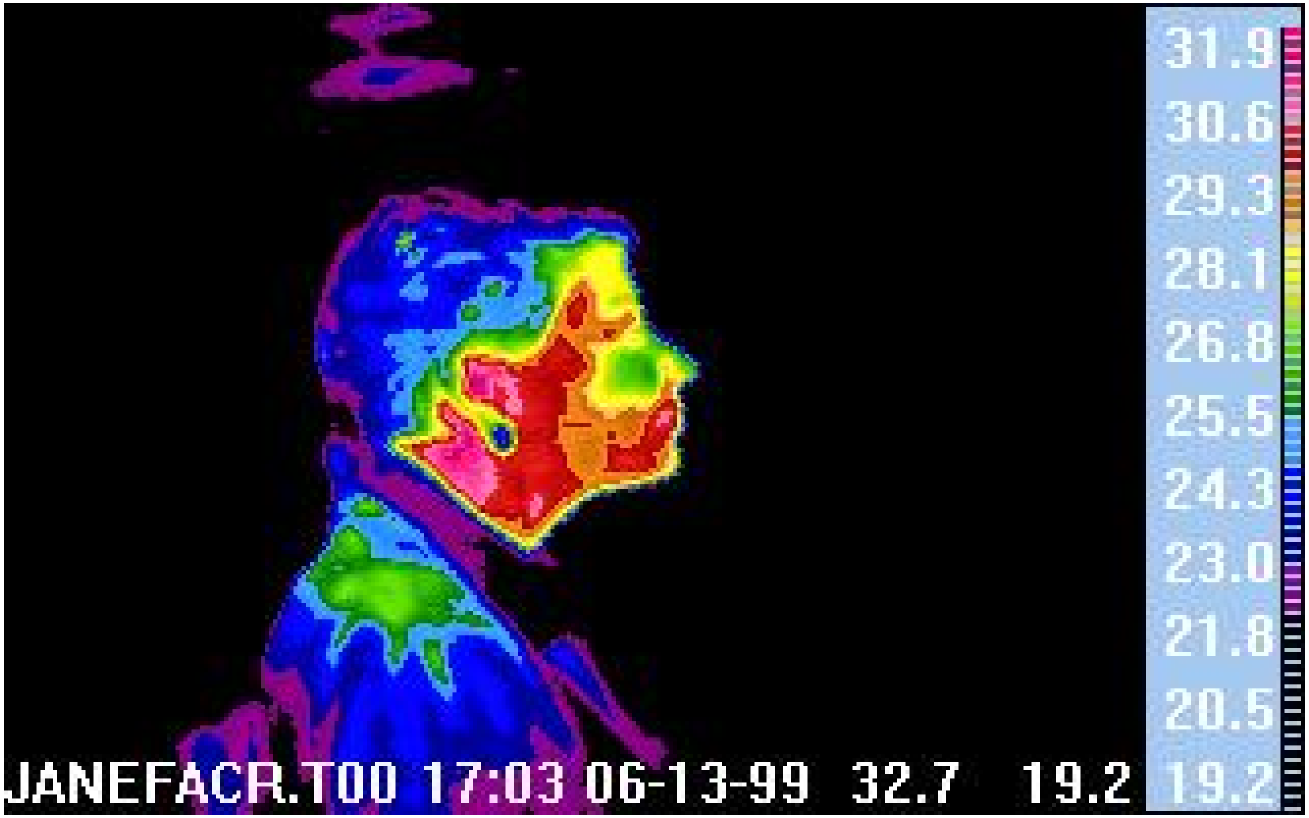
Thermal Infrared Systems

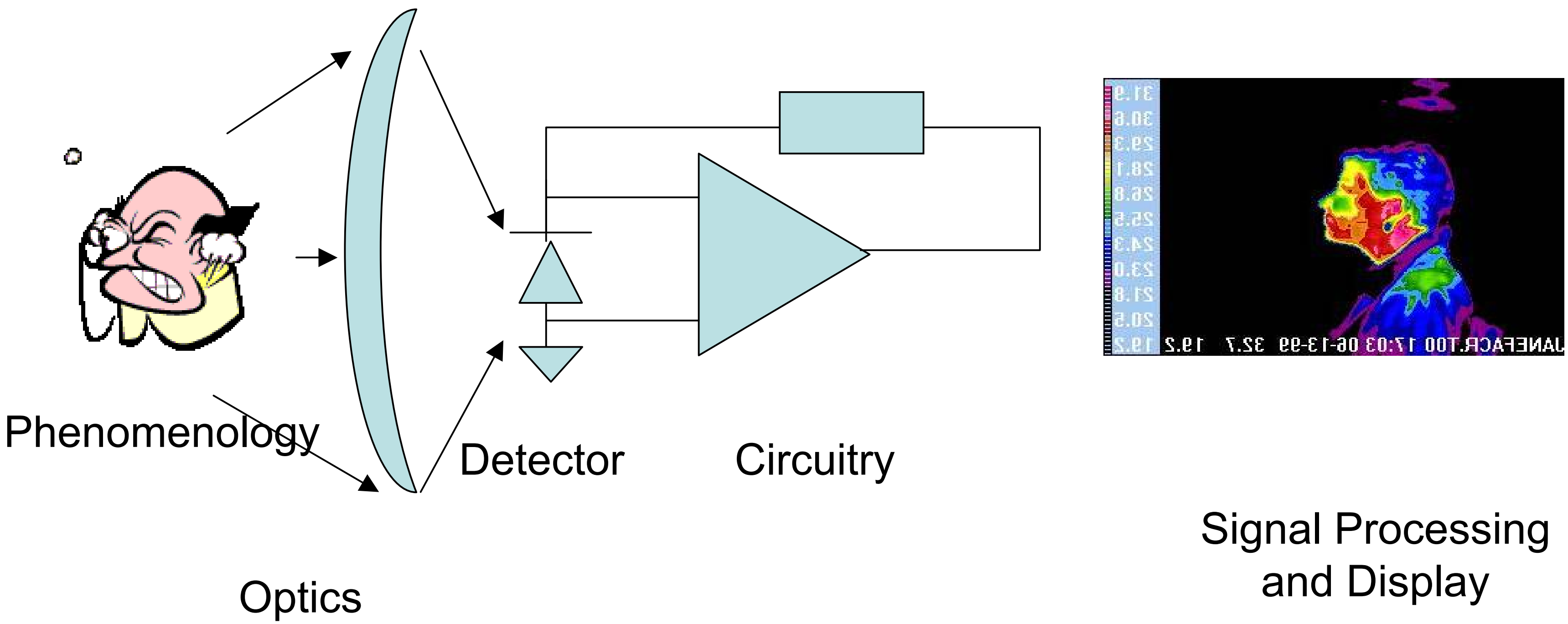
Lecturer: B T Yang 楊丙郇 March 2005 NTU



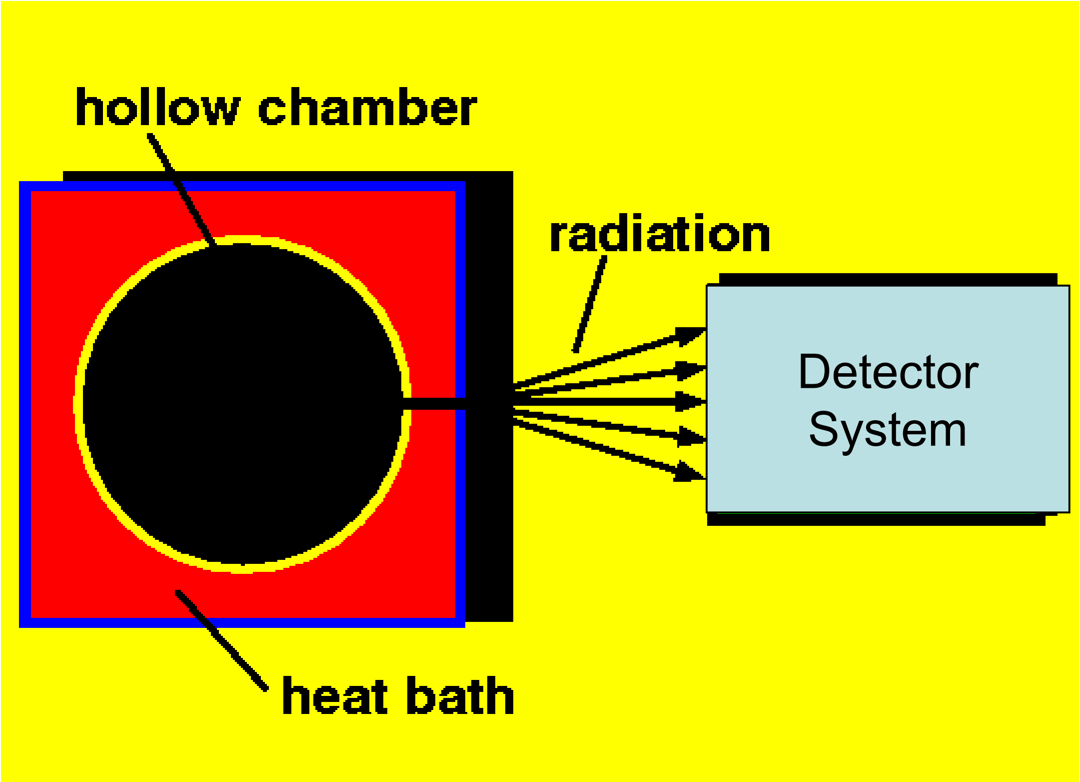
Lecture Outline

1. Phenomenology: “What is”
2. Optics
3. IR Detectors: Thermal, PC, PV
4. IR Detector Circuitry and Noises
5. IR Systems and Applications

Typical IR System



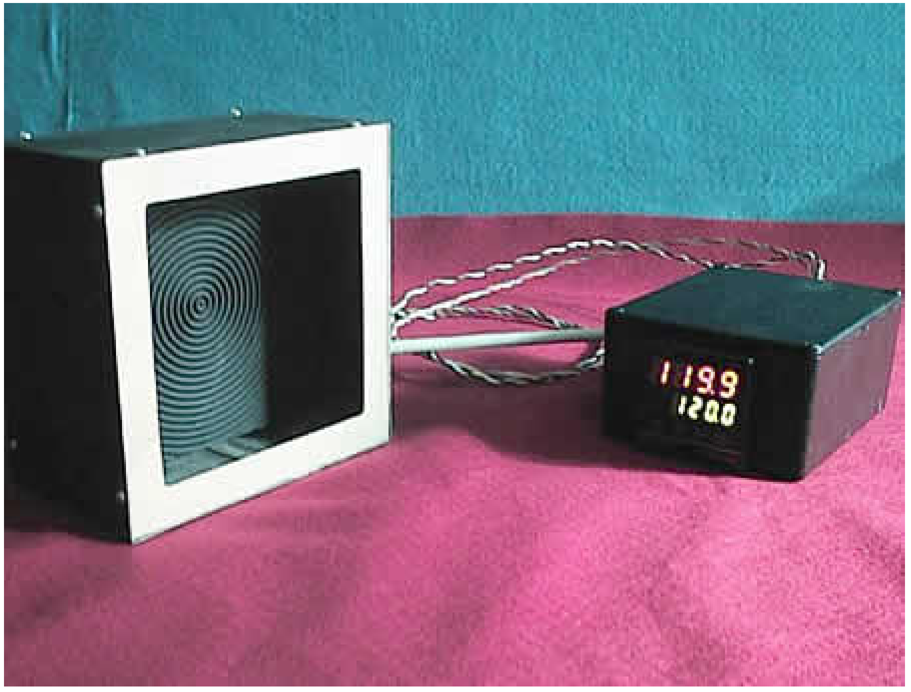
IR is Never Complete without Introducing the "Blackbody"



"Black" means No Light is Reflected, but "Light" can be emitted!

Grooved Planar Black Body Source

- “Grooved surface enhancing the emissivity

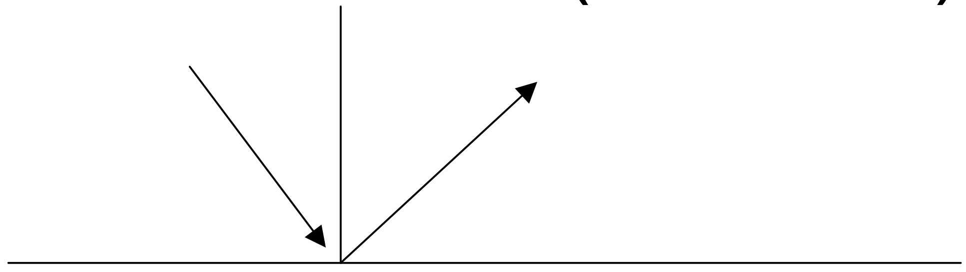


Definition of a Black Body

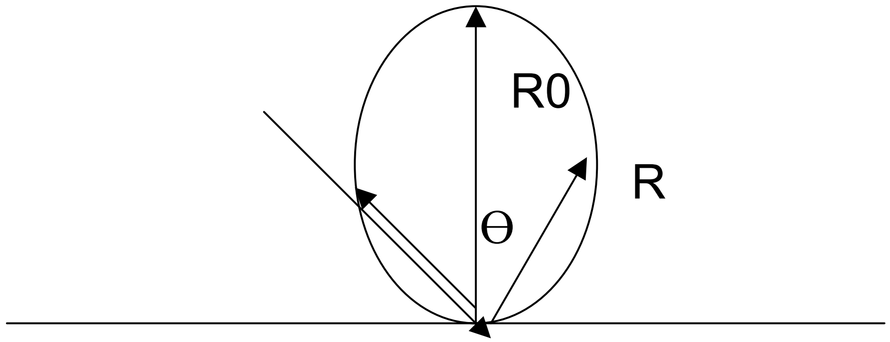
- **A blackbody absorbs all incident radiation; r=0**
- **At a given temperature, no surface can emit more energy than a blackbody**
- **A blackbody is a “diffuse” emitter that follows the “Lambertian Laws”**

Lambertian Law

- Specular Surface (reflective)



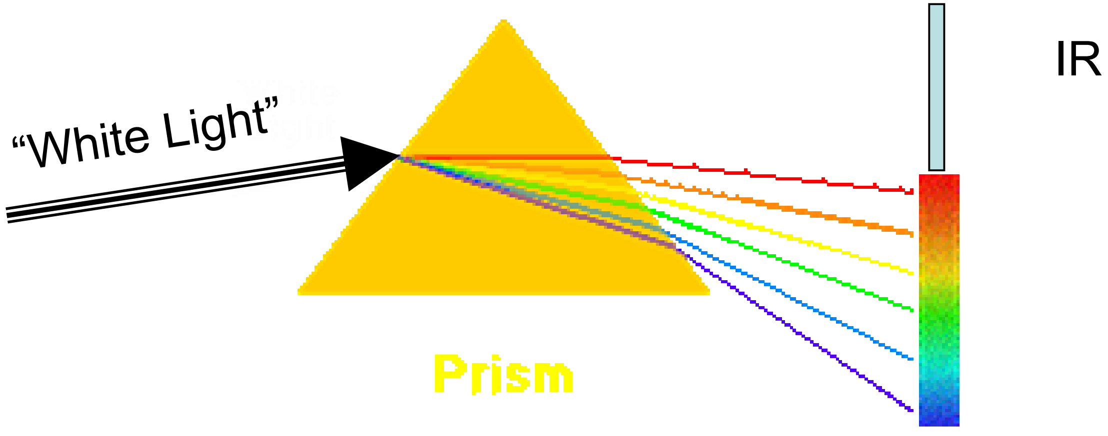
- Lambertian Surface (diffuse surface)



$R=R_0 \cos\Theta$

The beginning of Infrared
Infra= Ln. below

- In 1800, Sir William Herschel, using a prism to spread sunlight, observed the heating “beyond the red end” of the visible light spectrum



IR: Heat?

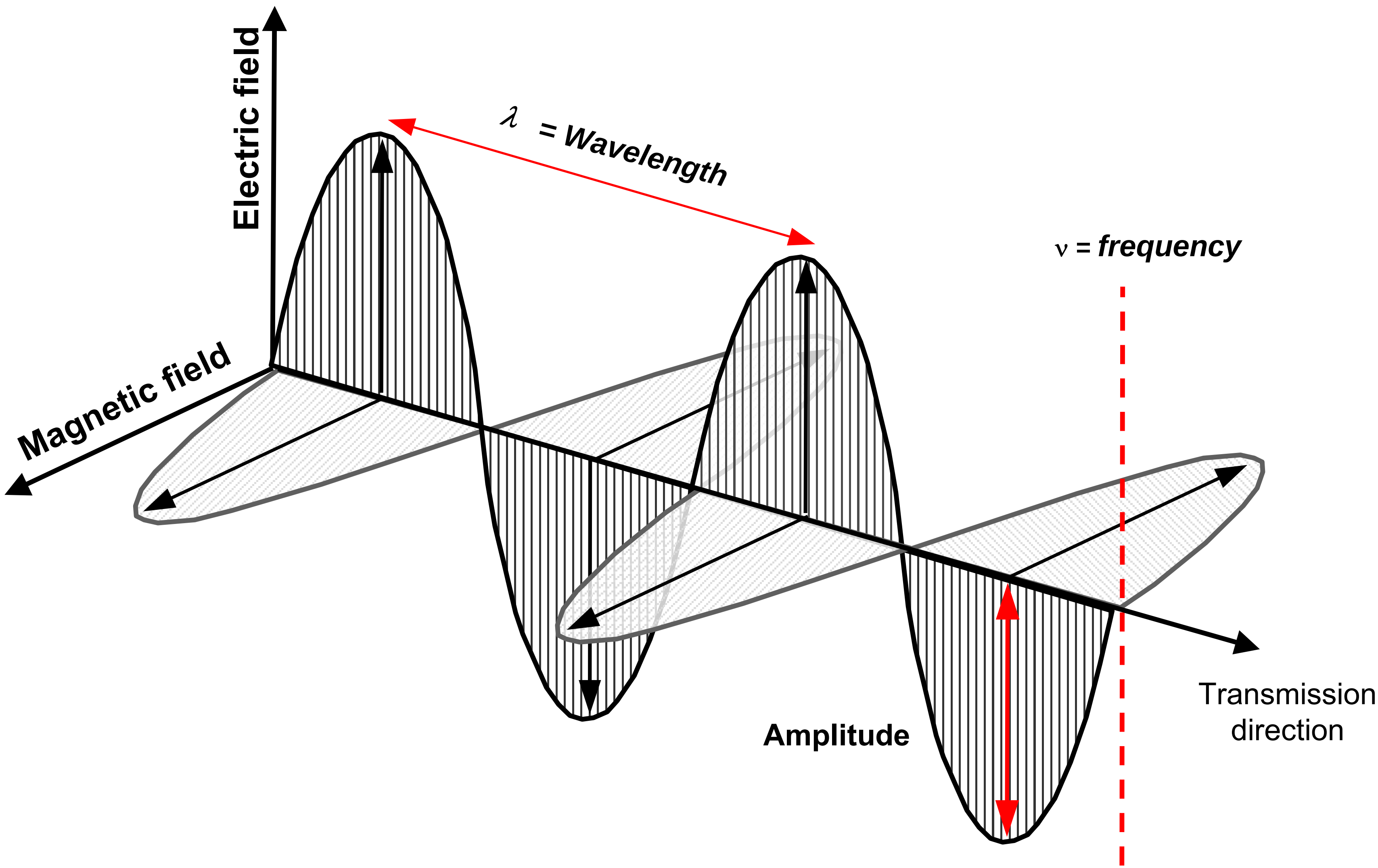
- A known effect of infrared light on skin is dilation of blood vessels that transport blood to and from the skin for cooling=> sensation of heat!

- According to Kirchhoff Law, if r=0

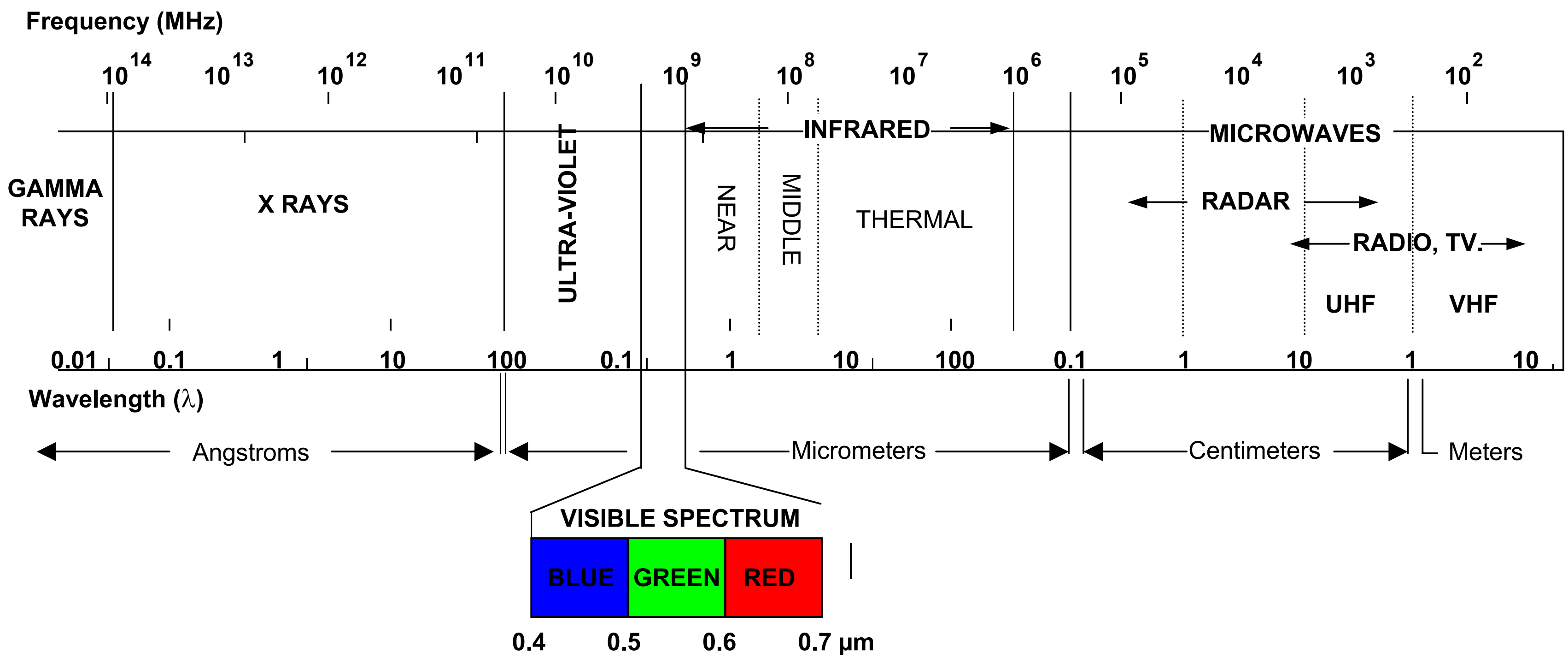
$$\varepsilon(\text{absorptivity}) = \sigma(\text{emissivity})$$

- Since skin is a good IR emitter then it must be a good IR absorber!

Light: An Electromagnetic wave



The Electromagnetic Spectrum



IR Frequency and Energy

- Frequencies: $.003 \times 10^{14}$ to 4×10^{14} Hz
- Wavelengths: 1 mm – 0.7 μm
- Quantum energies: 0.0012 - 1.65 eV

Planck's Equation

M_λ: Spectral Exitance [W·cm^{-2} · μm^{-1}]

λ: wavelength [μm]

T: absolute temperature [K]

h= Planck's constant =6.63x10^{-34} W sec^{2}

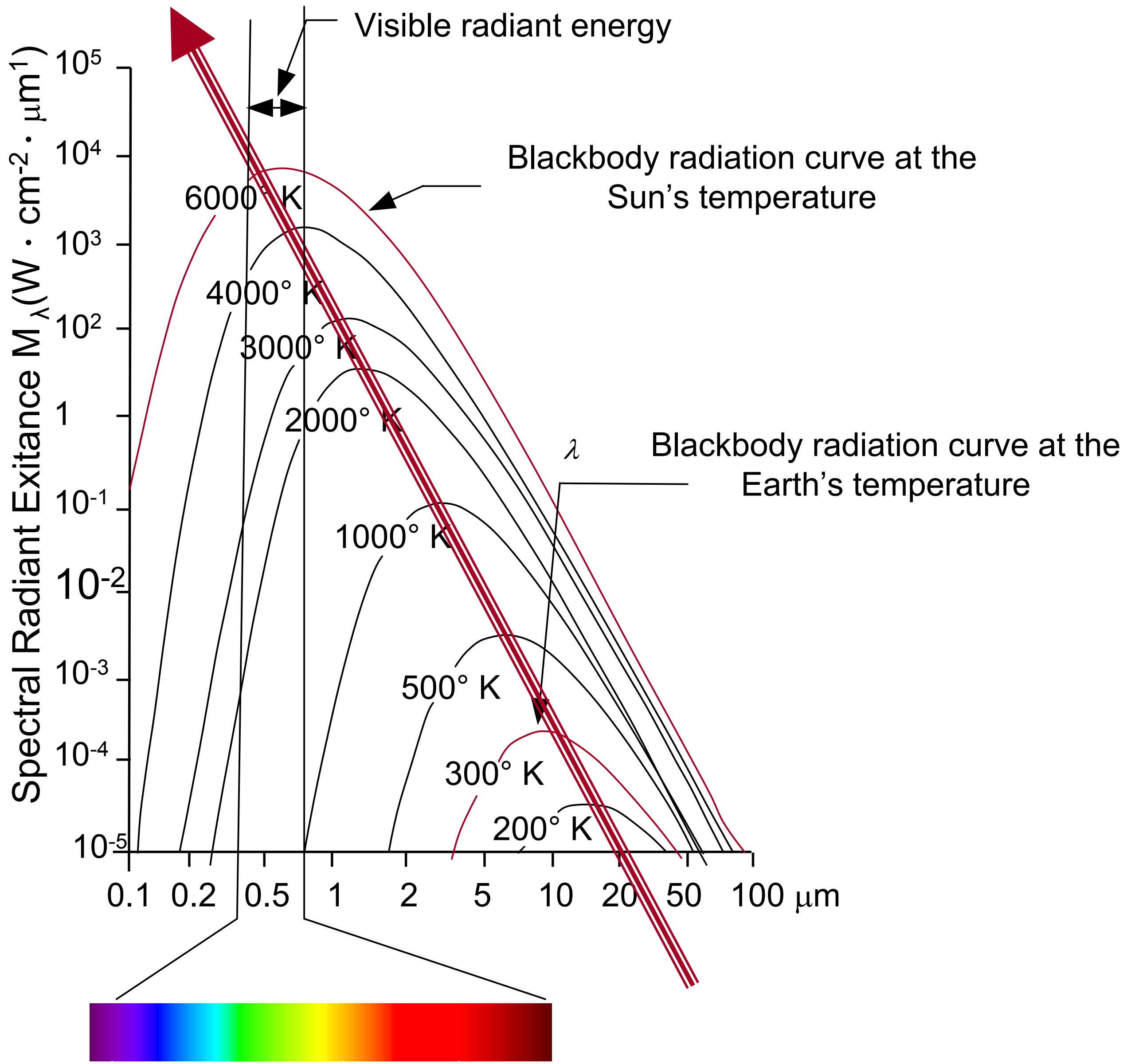
C= 3x10^{14} μm /sec

k= Boltzmann's constant 1.38x10^{-23} W sec K^{-1})

$$M_\lambda(\lambda, T) = \frac{2\pi hc^2}{\lambda^5}\frac{1}{e^{\frac{hC}{\lambda kT}} - 1}$$

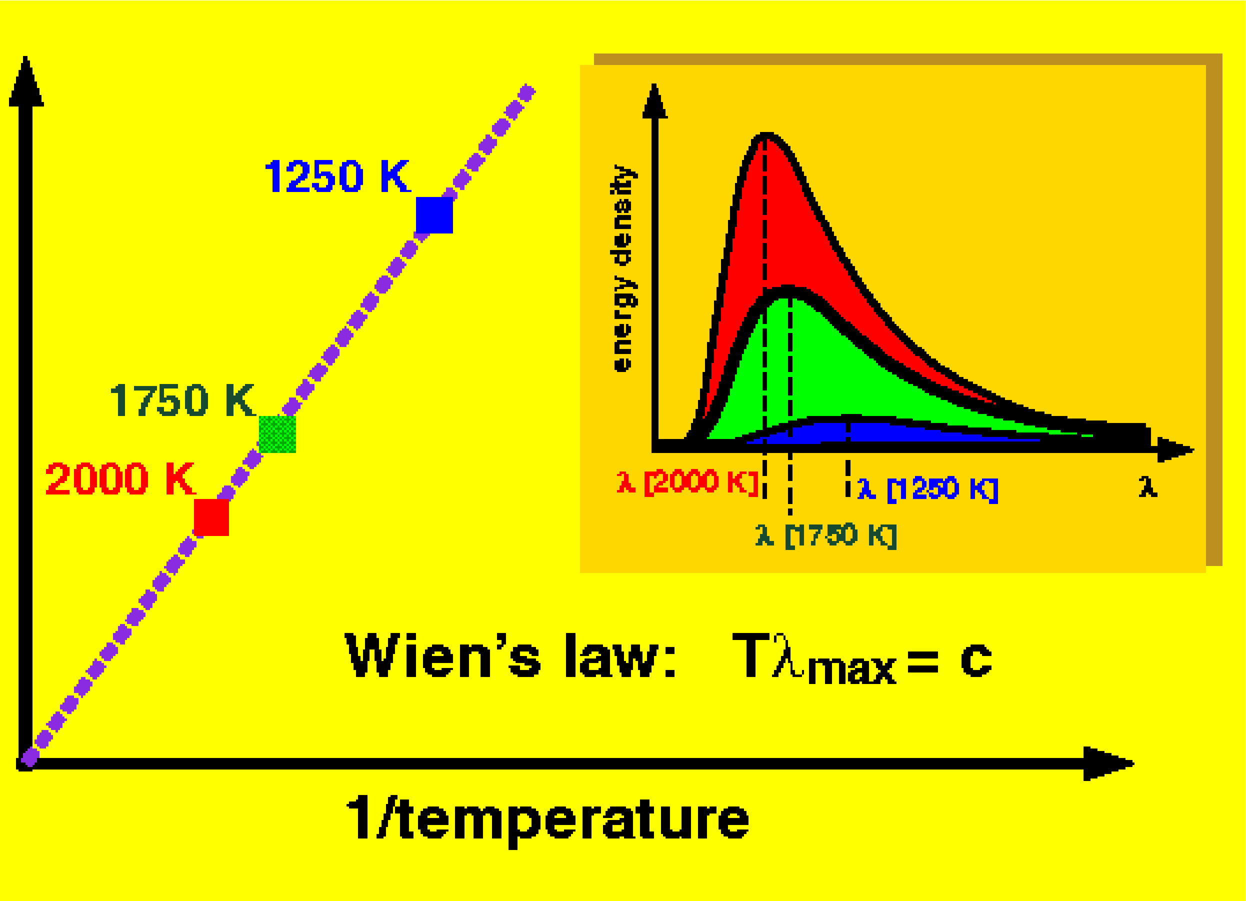
$$= \frac{3.74 x 10^4}{\lambda^5 [e^{1.44 x 10^4 / \lambda T} - 1]}$$

Spectral exitance of a blackbody



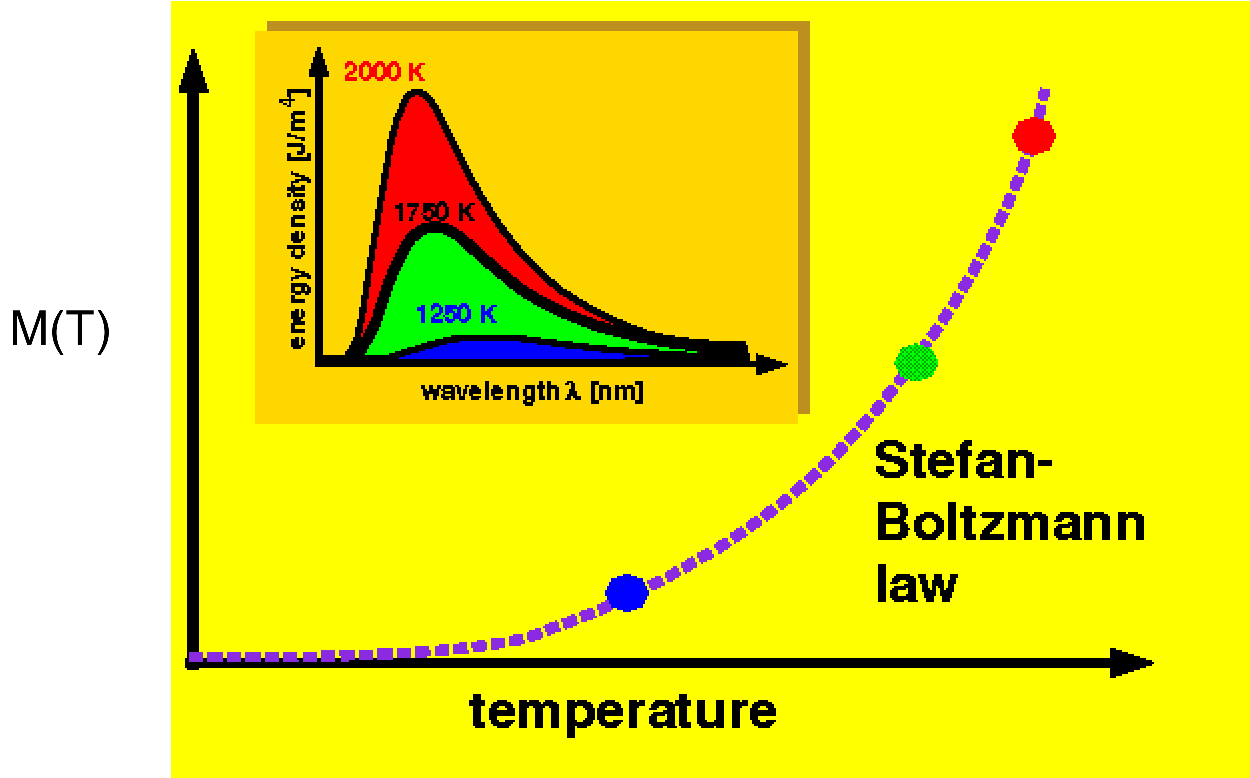
Wien's Law

- $\lambda_{max}T \sim 3000\ \mu m\text{-}K$



Stefan-Boltzmann's Equation of Radiation

- **$M(T) = \int M_\lambda(\lambda, T)\, d\lambda = \sigma T^4$ [$W \cdot cm^{-2}$]**
- **M(T): Exitance (not Spectral Exitance)**
- σ **: Stefan-Boltzmann's constant $5.67 \times 10^{-12}\ W \cdot cm^{-2} \cdot K^{-4}$**



Grey Body?

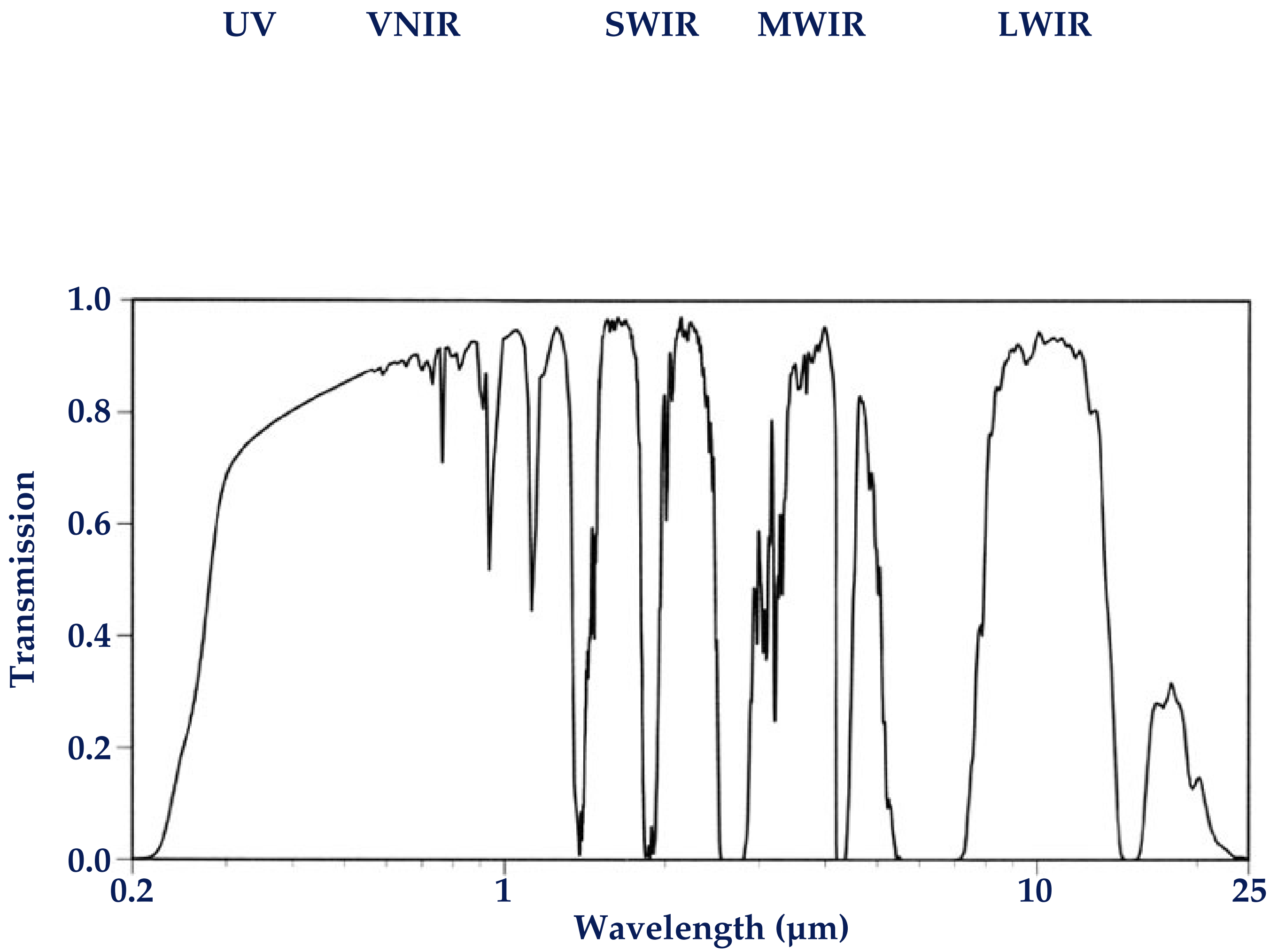
- When emissivity ε is not unity
- Most physical surfaces are grey bodies

ε_{skin} ~ 0.95, then it must be "Approximated as a Blackbody

$M_{\lambda} = \varepsilon M_{\lambda}$

$M = \varepsilon \sigma T^4$

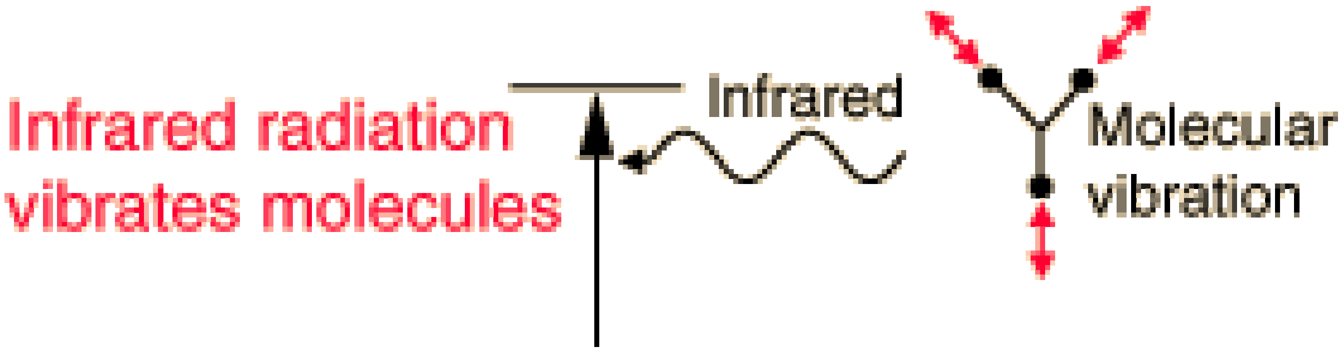
Atmospheric Transmission Spectra



Infrared Interactions

http://hyperphysics.phy-astr.gsu.edu/hbase/mod3.html#c3

- . The result of infrared absorption is heating of the tissue since it increases molecular vibrational activity..



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Discrete Energy State

- Planck's 1900's "lucky Guess" $\Delta E = h\nu$

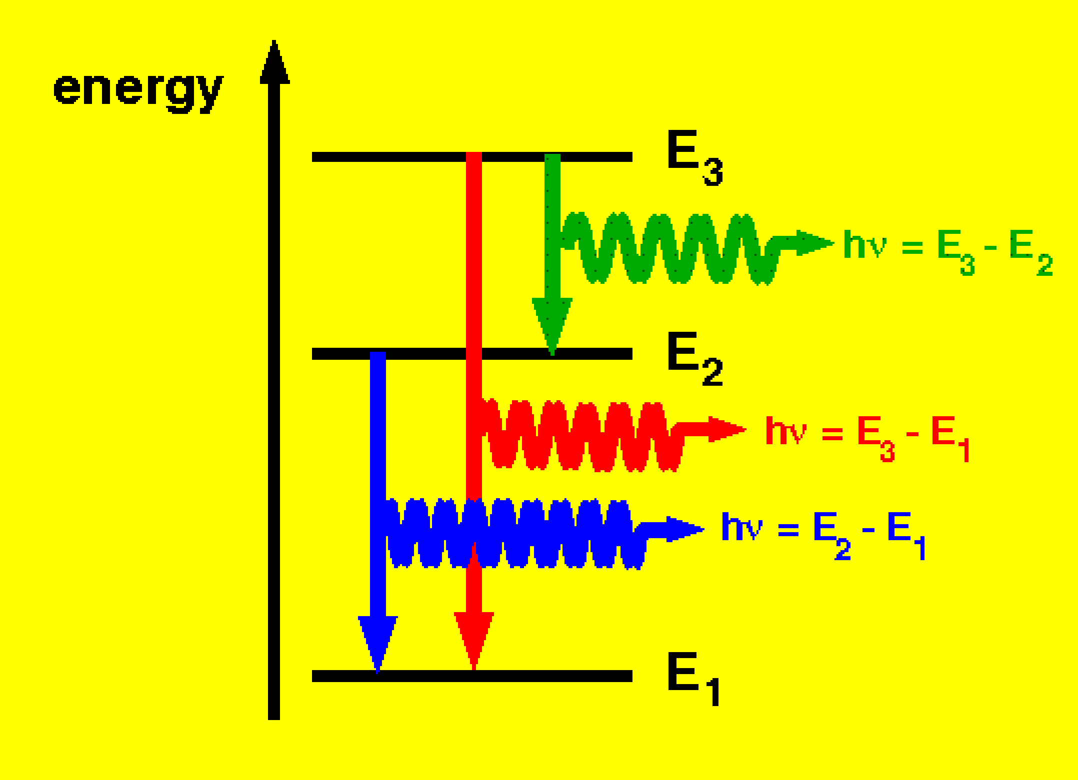
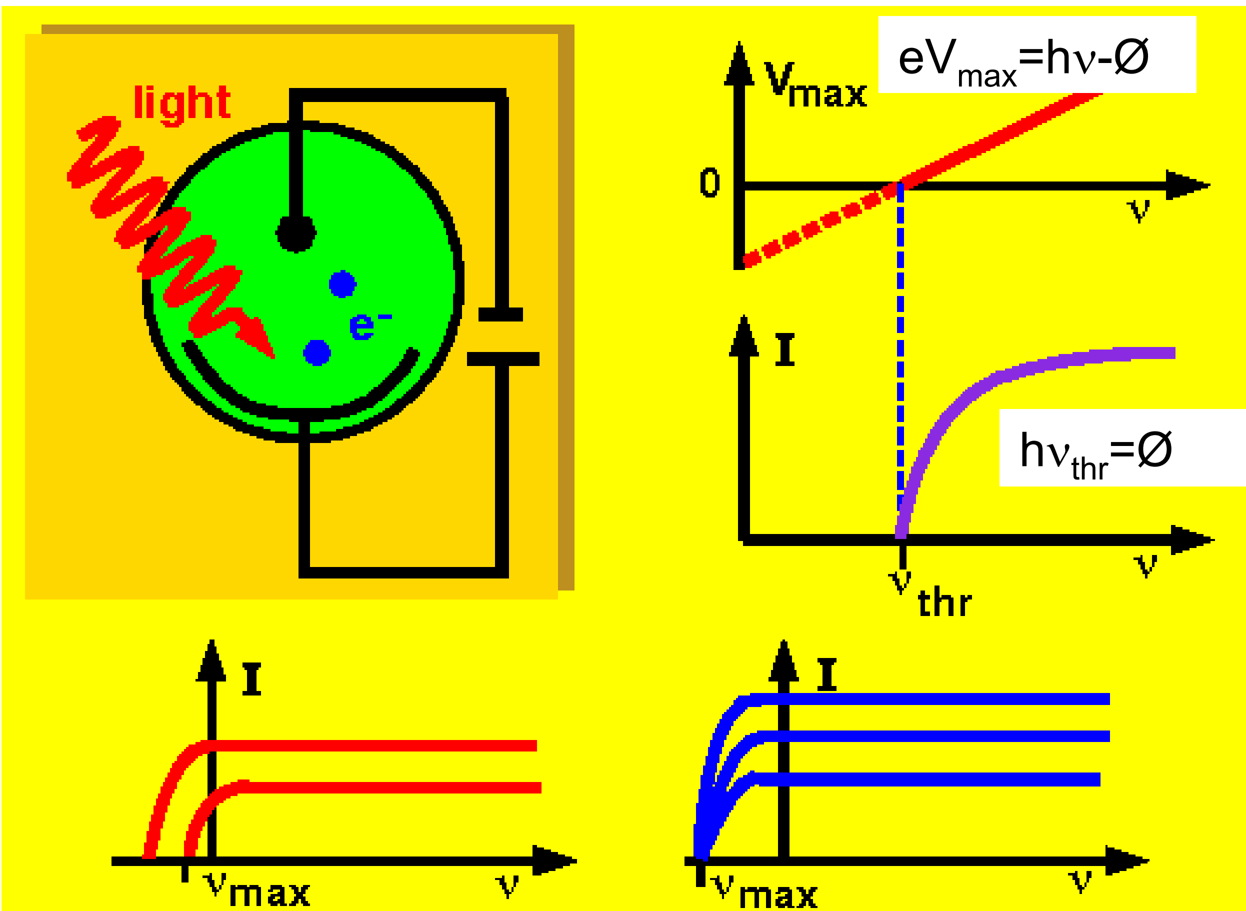


Photo-Electric Effect

- Eienstein 1905's Paper Confirming the Discret Energy

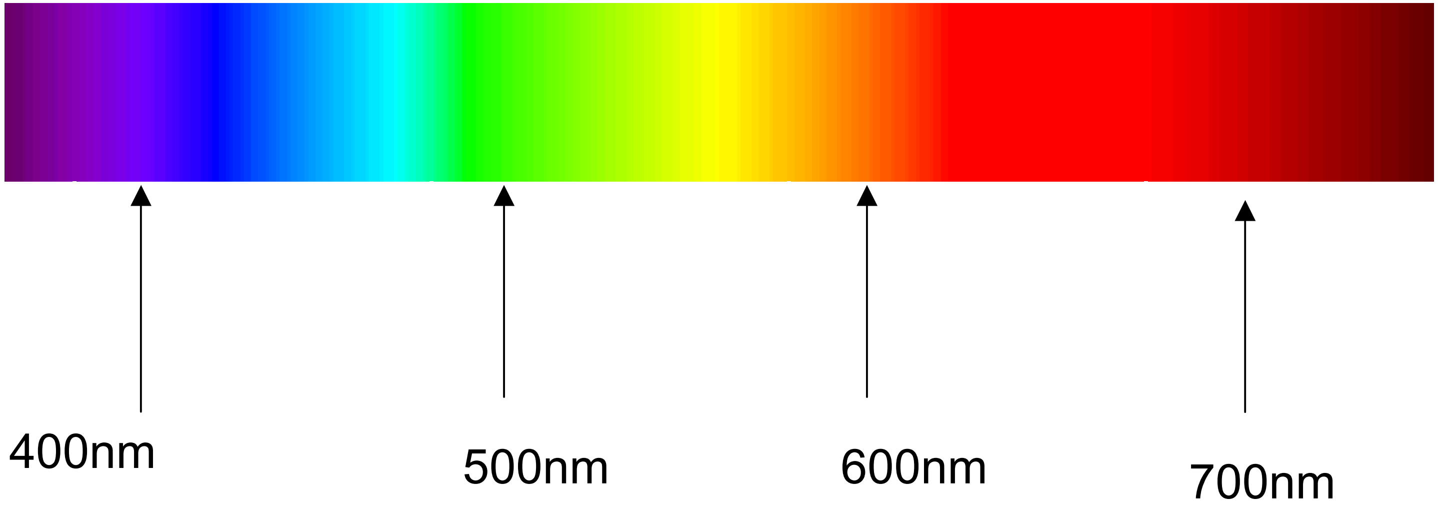


Varying ν

Same ν, varying intensity

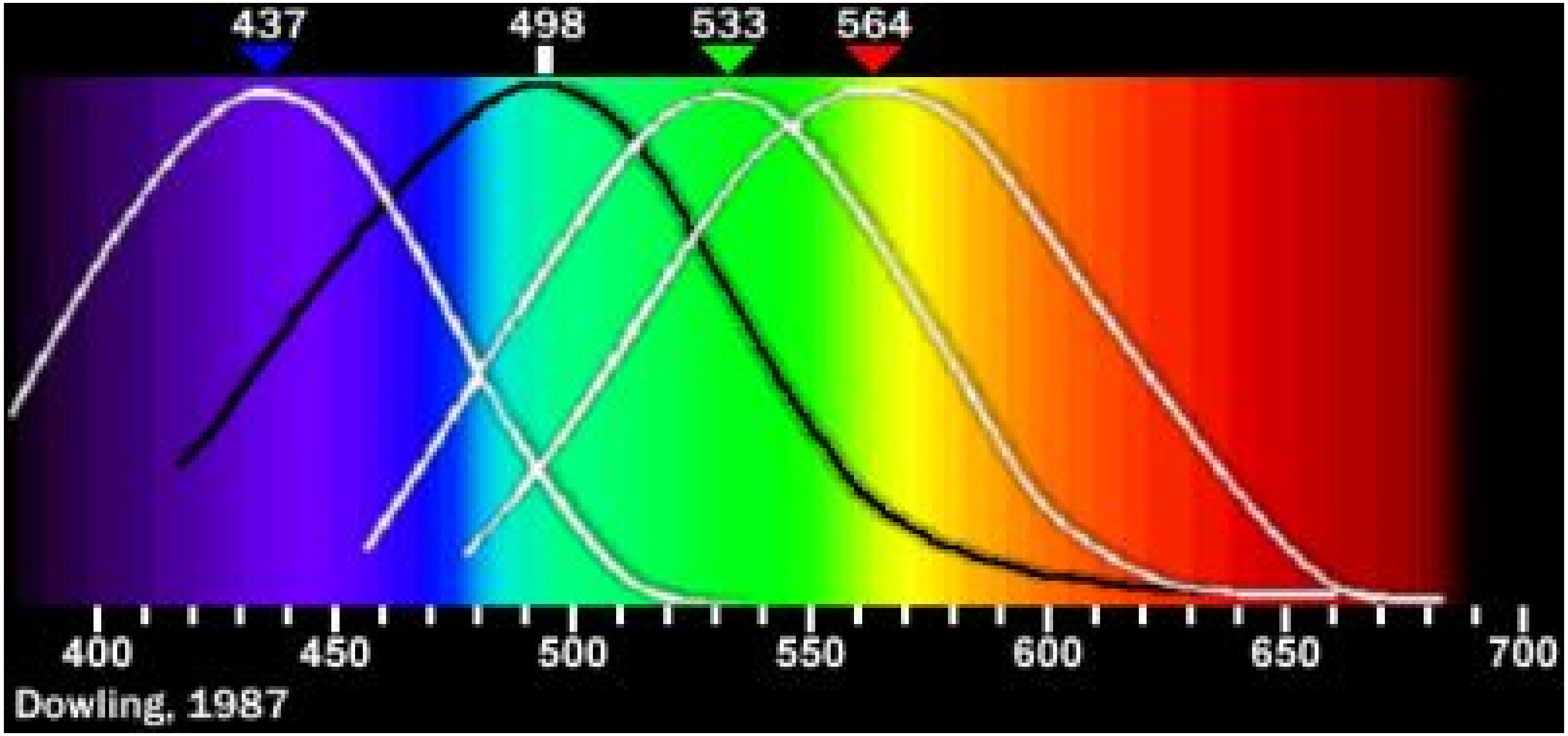
Visible Spectral Range

- Visible Band: 400nm to 700nm



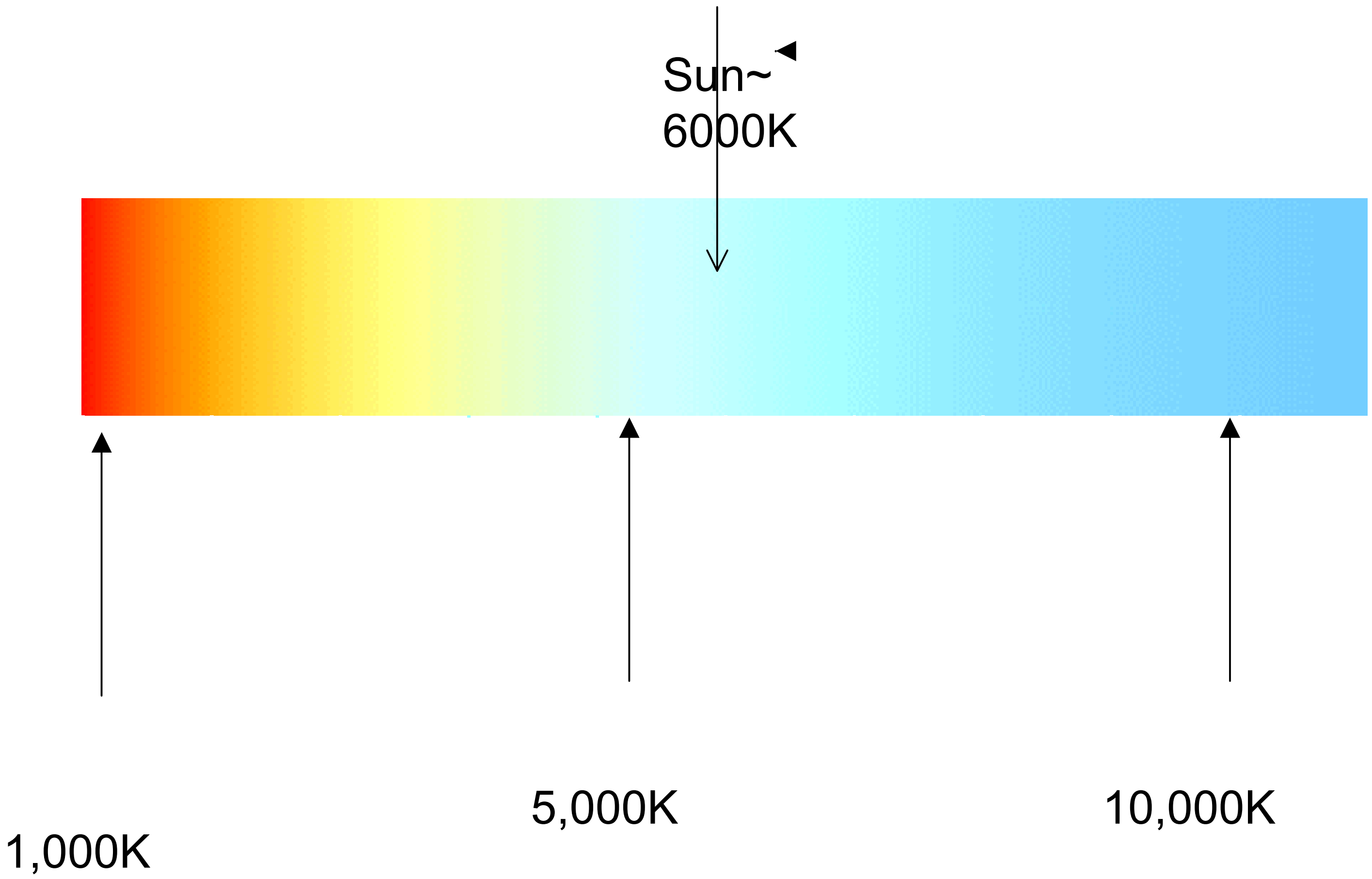
Eye's Cones' (3) and Rods' Responses

- Rods for night vision (more sensitive)
- Cones for color day vision



“Color” Temperature

An Apparent Visible Color of a Blackbody at T



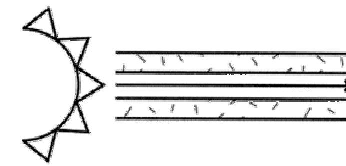
Night Goggles are "not" true Thermal Images

- Night Goggle Images are "Reflected NIR Images", not "Emitted Thermal images"

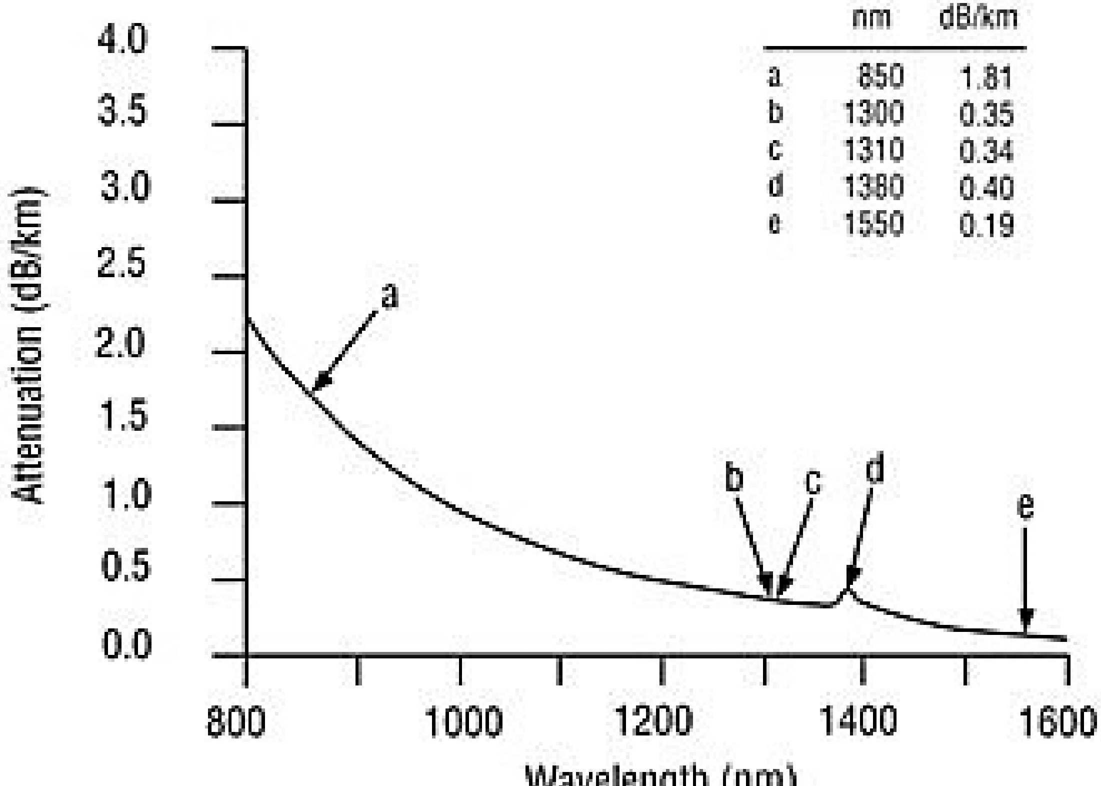
Many Low-Cost Low-Light Detection Systems are NIR Systems

"Near IR Wavelength Used for Optical Communications

"Single mode fiber"
single path through the fiber



Spectral Attenuation (typical fiber):

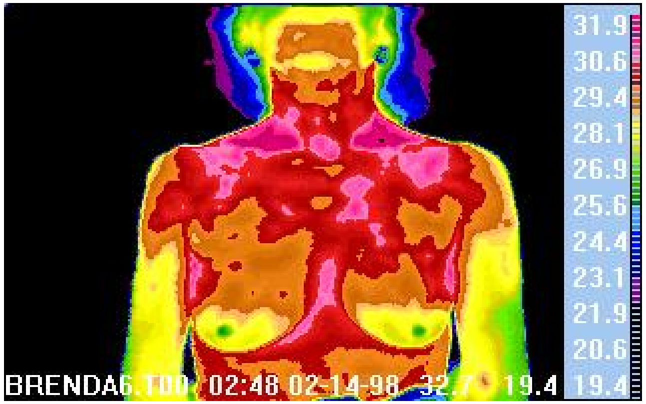


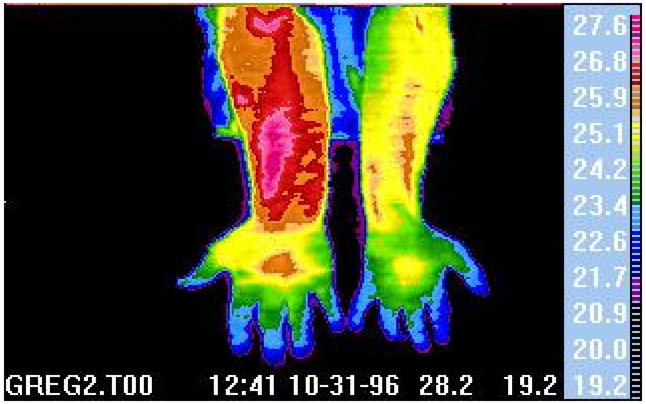
	nm	dB/km
a	850	1.81
b	1300	0.35
c	1310	0.34
d	1380	0.40
e	1550	0.19

Singlemode Fibre 10/125

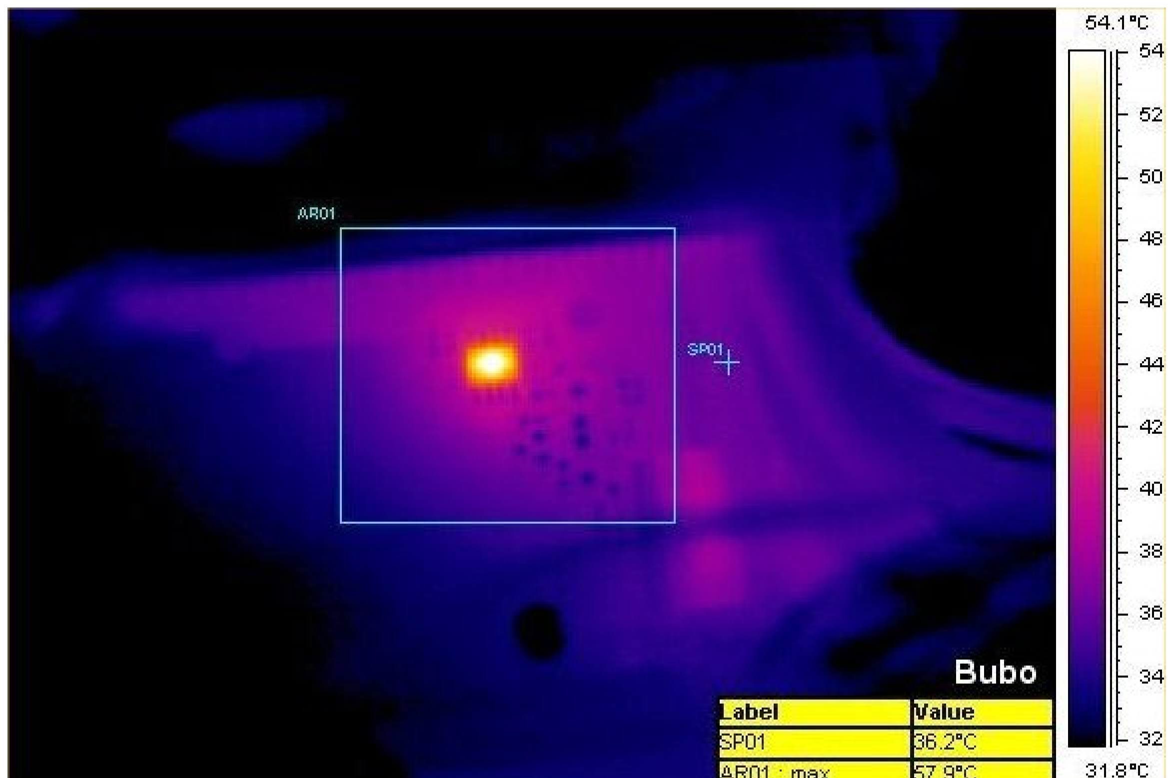
Human Thermal Images

- http://www.ir55.com/infrared_IR_camera.html

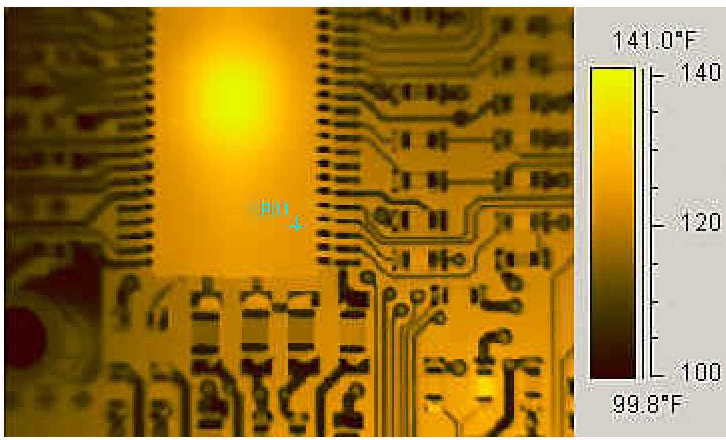


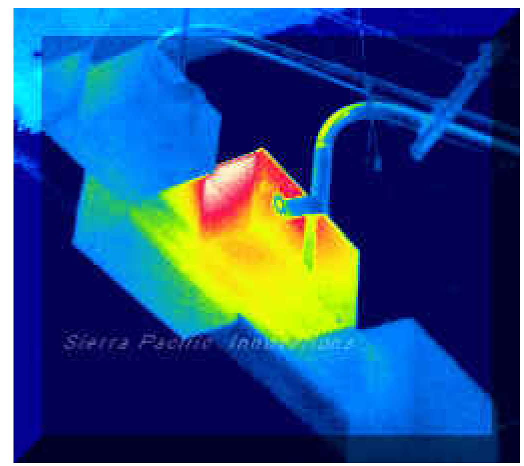


PC Board Localized Heating



Localized IC Chip Detection





Burglar Detection

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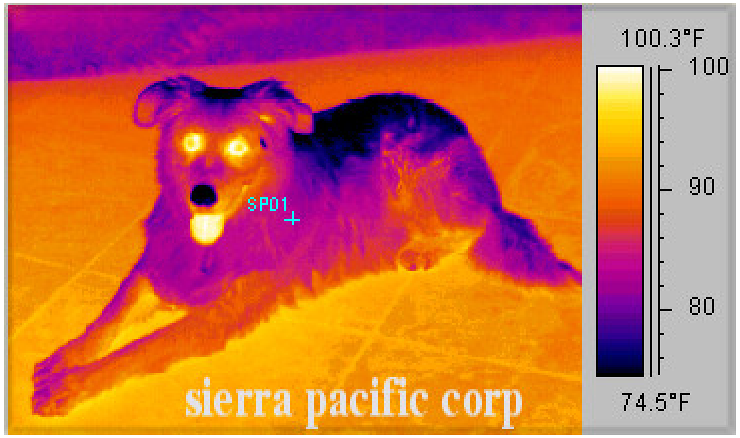

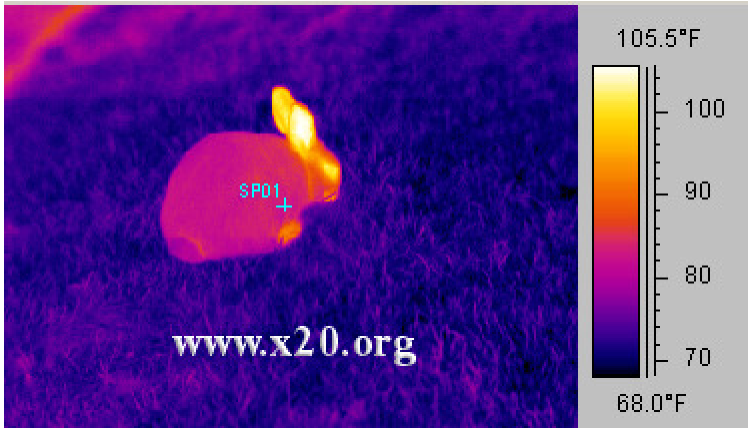

Underside Celeron Chip

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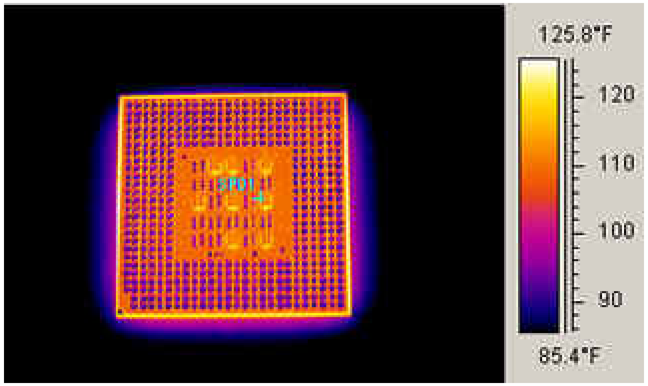

SARS Temperature Screening

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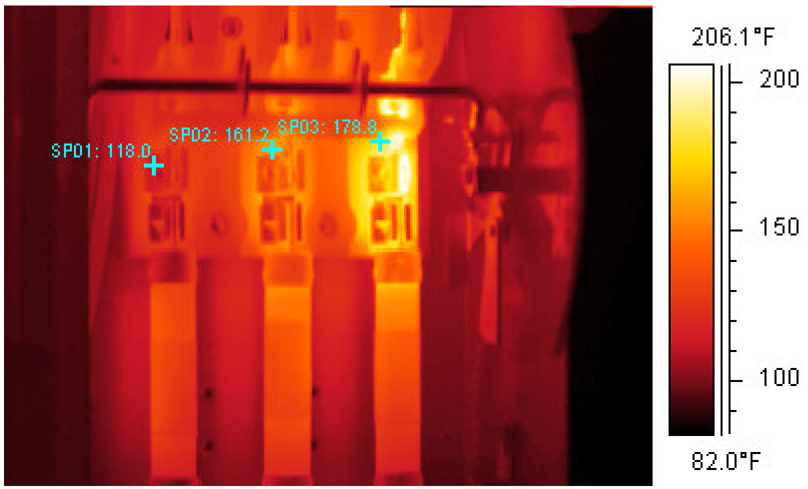
Preventive Maintenance

- Electrical Fuse Thermal Image



Thermal Management

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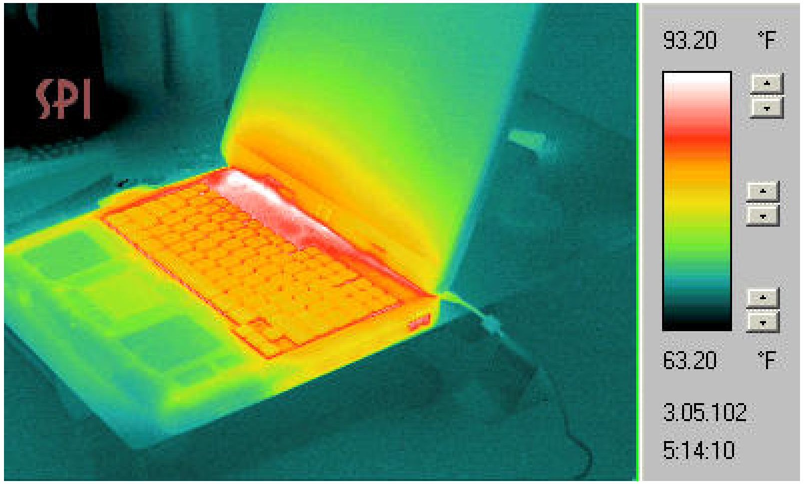
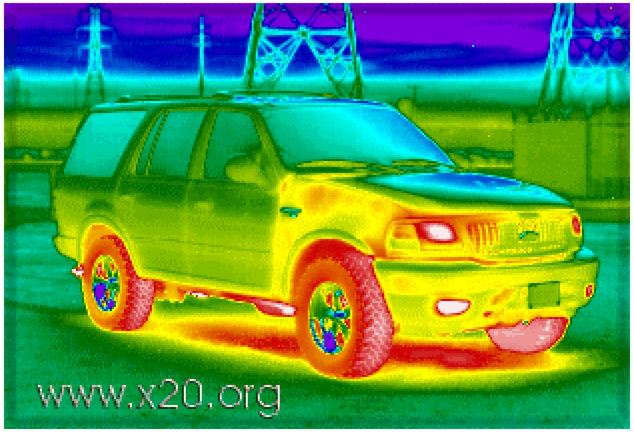
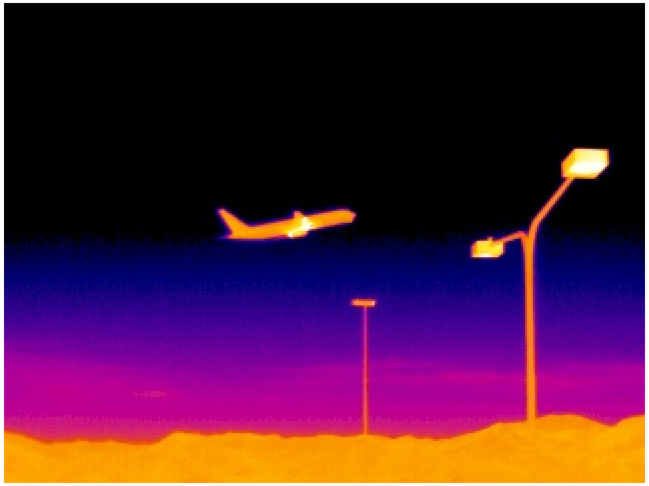


Defense Applications



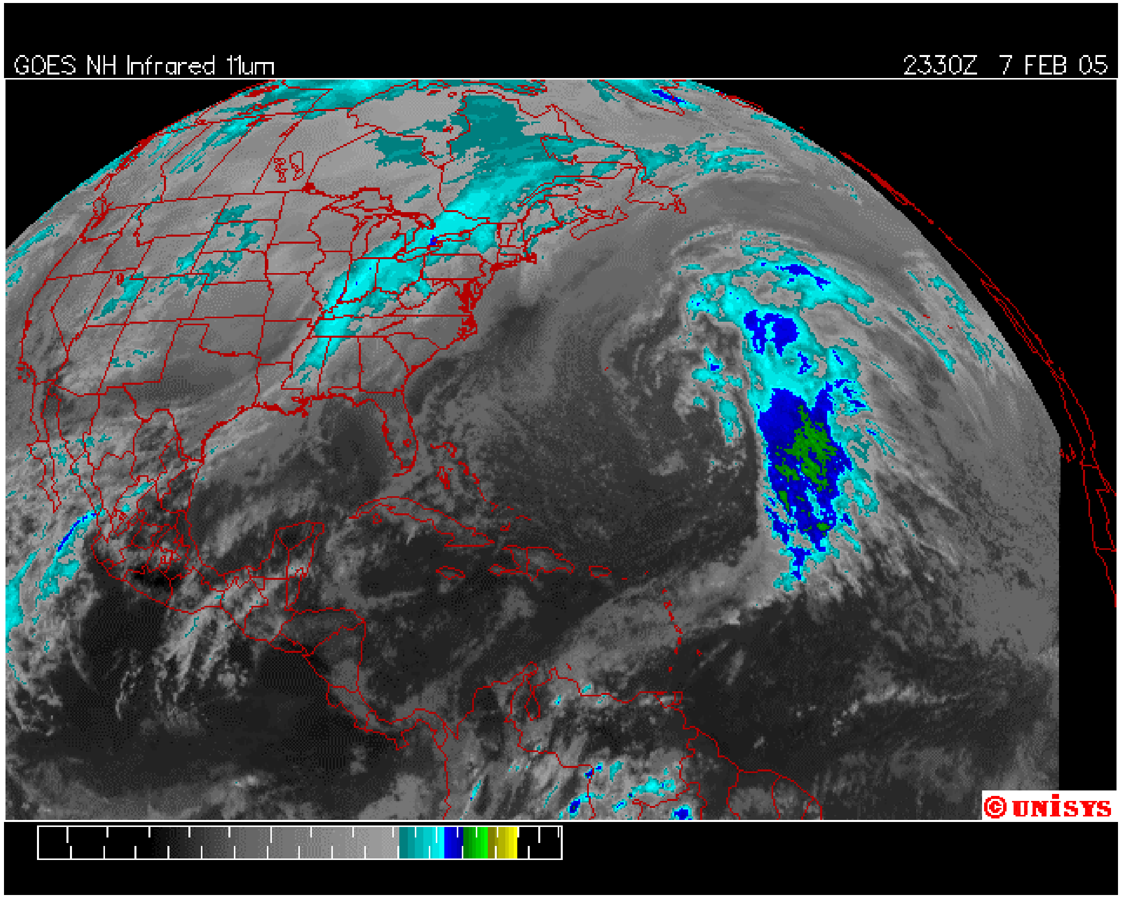
Sky Surveillance

- Collision Prevention



Weather Monitoring

- Geosynchronous Weather Satellite Application



What “Limits” Your Measurements?

1. Spatial (How Small an Area Can the System Resolved?):

   Optics

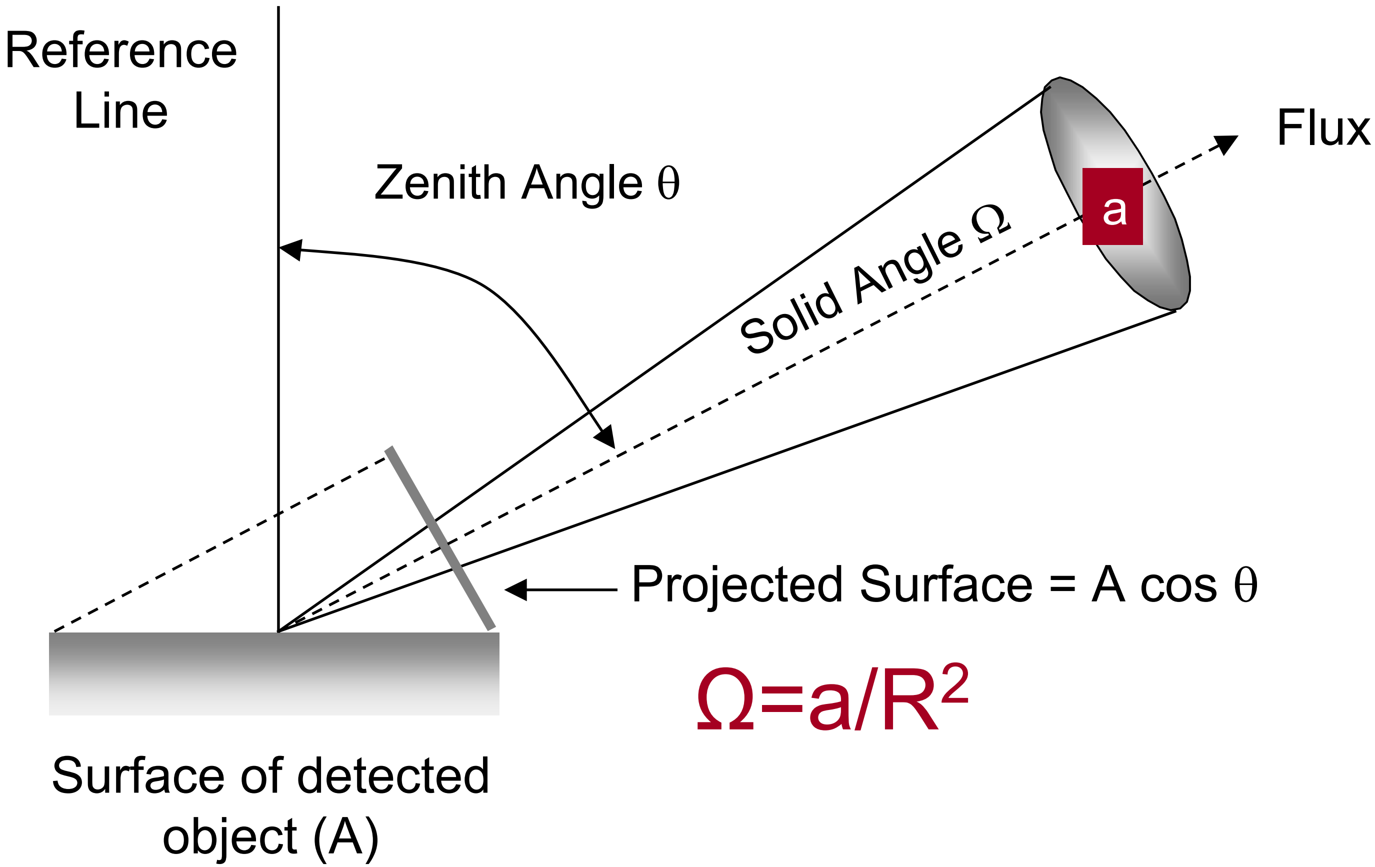
2. Temporal (How Fast Can the System Do?):

   Detector and Electronics Responses

3. Resolution of the System (What is the Samllest Temperature the System can resolve?):

   NEP

Solid Angle Concept



$\Omega = a/R^2$

Radiance L

- Radiance is Defined as the Power per Unit Area per Steradian(Sr)

$$L[W\ m^{-2}\ Sr^{-1}]=M(T)/\pi$$

Solar Constant K_{solar}(Example)

- Solar disk "subtends" 1/2º(or 9 mRadian) in view, the solar constant is the total Radiance Power per unit area
- Since the Radiance is

$L=1/\pi M(6000K)=(\sigma/\pi)x6000^4=2.34x10^7 W \cdot m^{-2}$ Sr^{-1}

- The solid angle of the sun is
- $\Omega=(\pi/4)(0.009/2)^2 \sim 6.4x10^{-5}$ Sr
- The Solar Constant is then:
- K_{solar} $=L \cdot \Omega \sim 1.5$ KW/M^2
- σ : **Stefan-Boltzmann's constant $5.67x10^{-8}$ W · m-2 · K^{-4}**

Equilibrium Temperature Concept

- The Total Power Absorbed by a $1M^2$ Plate Perpendicular to Sun Rays is a Solar Constant K_{solar} of 1.5KW
- The Radiated Power is
- The Equilibrium Thermodynamic Condition Stipulates:
- $\sigma T_{plate}^4 = K_{solar}$
- $T_{plate} = (1500/\sigma)^{1/4} \sim 403K = 130^oC$

$$T_{equi} = \sqrt[4]{\frac{\alpha K_{solar}}{\varepsilon \sigma}}$$

How to Manipulate the Equilibrium Temperature T_{equi}

- By varying Surfaces Solar Absorption Coefficient $\alpha$and ε
- For α of 0.2 and $\varepsilon$of 0.9, T_{equi}~277K=>4ºC!
- $\alpha K_{solar} = \varepsilon \sigma T_{plate}^4$

$$T_{equi} = \sqrt[4]{\frac{\alpha K_{solar}}{\varepsilon \sigma}}$$

•For α of 0.2 and ε of 0.9, T_{equi}~277K=>4ºC!

Why is a Metal Surafce so Warm in the Sun?

Polished Metal Surfaces have low αandε

Assume α=ε=0.2

$$T_{equi} = \sqrt[4]{\frac{\alpha K_{solar}}{\varepsilon\sigma}} = \sqrt[4]{\frac{0.2X1500}{0.2X5.67X10^{-8}}} = 403K!$$

- σ **: Stefan-Boltzmann's constant 5.67x10^{-8} W · m-2 · K^{-4}**

Does "Absolute Temperature" Have to Do with Heat Transfer?

- Conduction

$\Delta Q \sim \Delta T$

- Convection

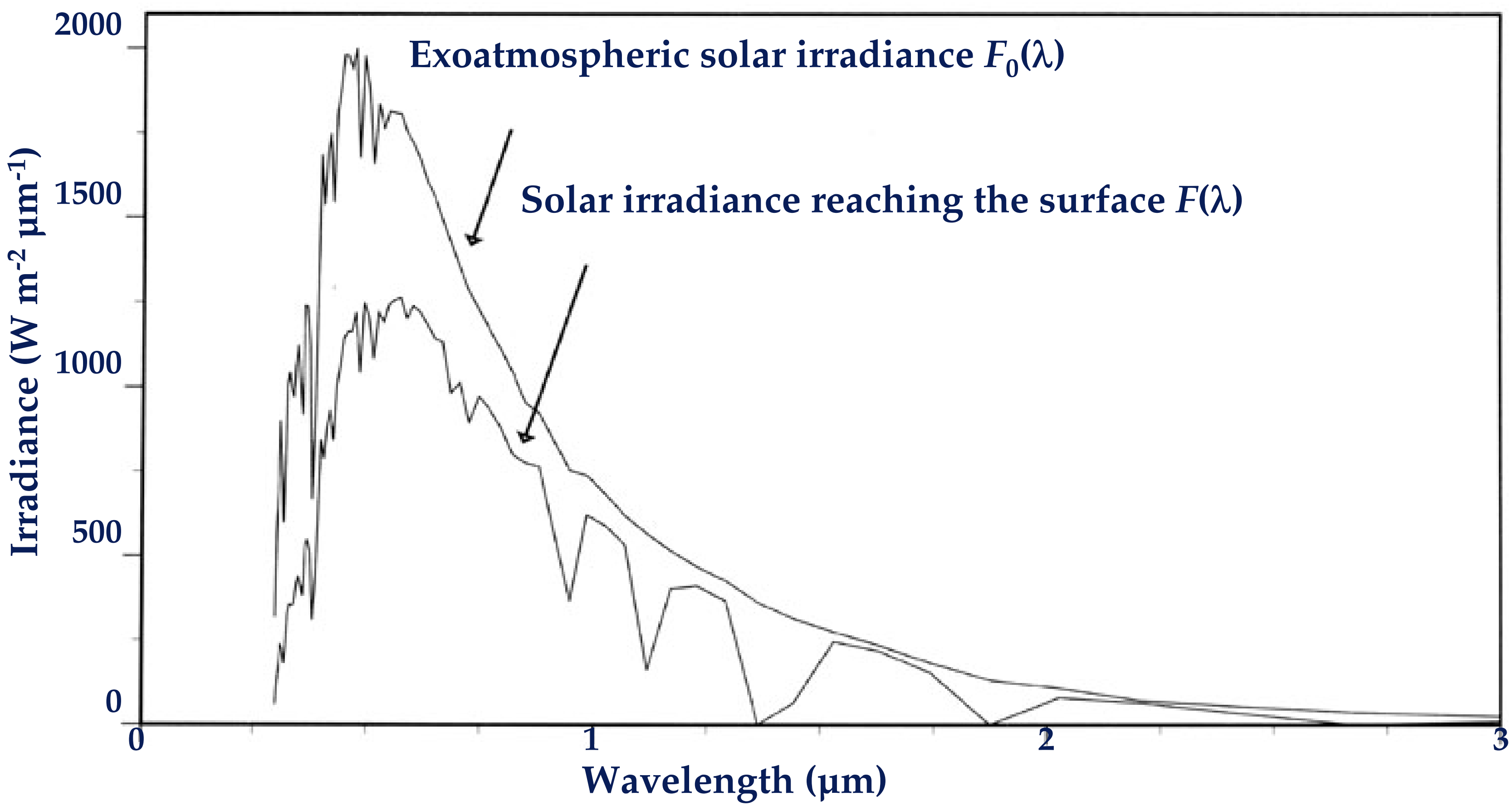
$\Delta Q \sim \Delta T^{n}$; $n \neq 1$

- Radiation

$\Delta Q \sim \Delta\ (T_1^4 - T_2^4)$

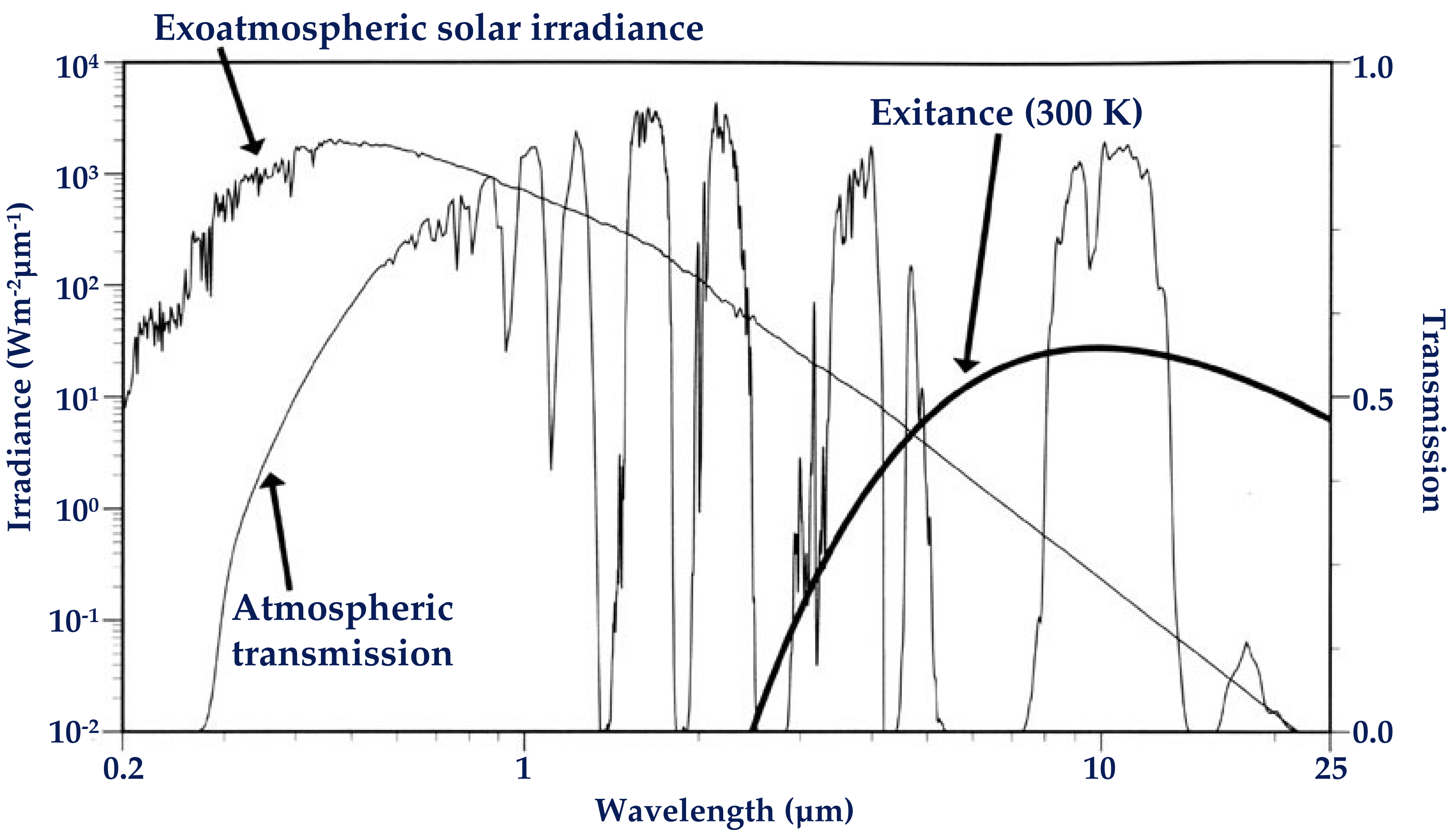
Radiative Heat Transfer is the Only Form of Heat Transfer that requires Absolute Temperature instead of Temperature Difference

Scattering of Sunlight by the Earth-Atmosphere-Surface System



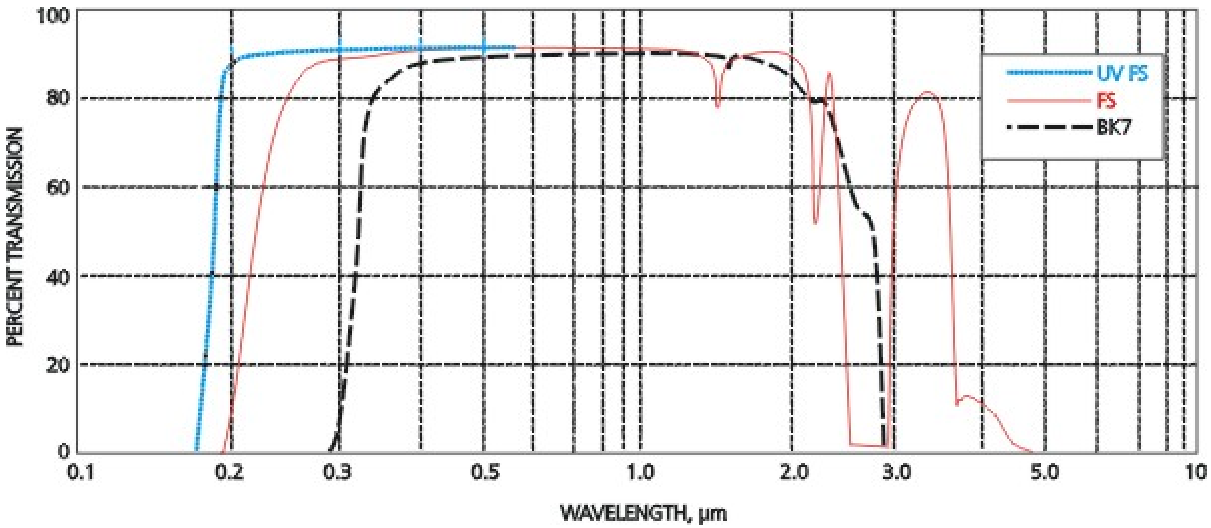
Atmospheric Transmission and Greenhouse Effects

http://tbrs.arizona.edu/education/553-2004/2004/Lect083104_Ch2.ppt-link.ppt#21



BK-7 Transmission Curve

- Most Plate Glass, Similar to BK7
- Plate Glass is Opaque to LWIR

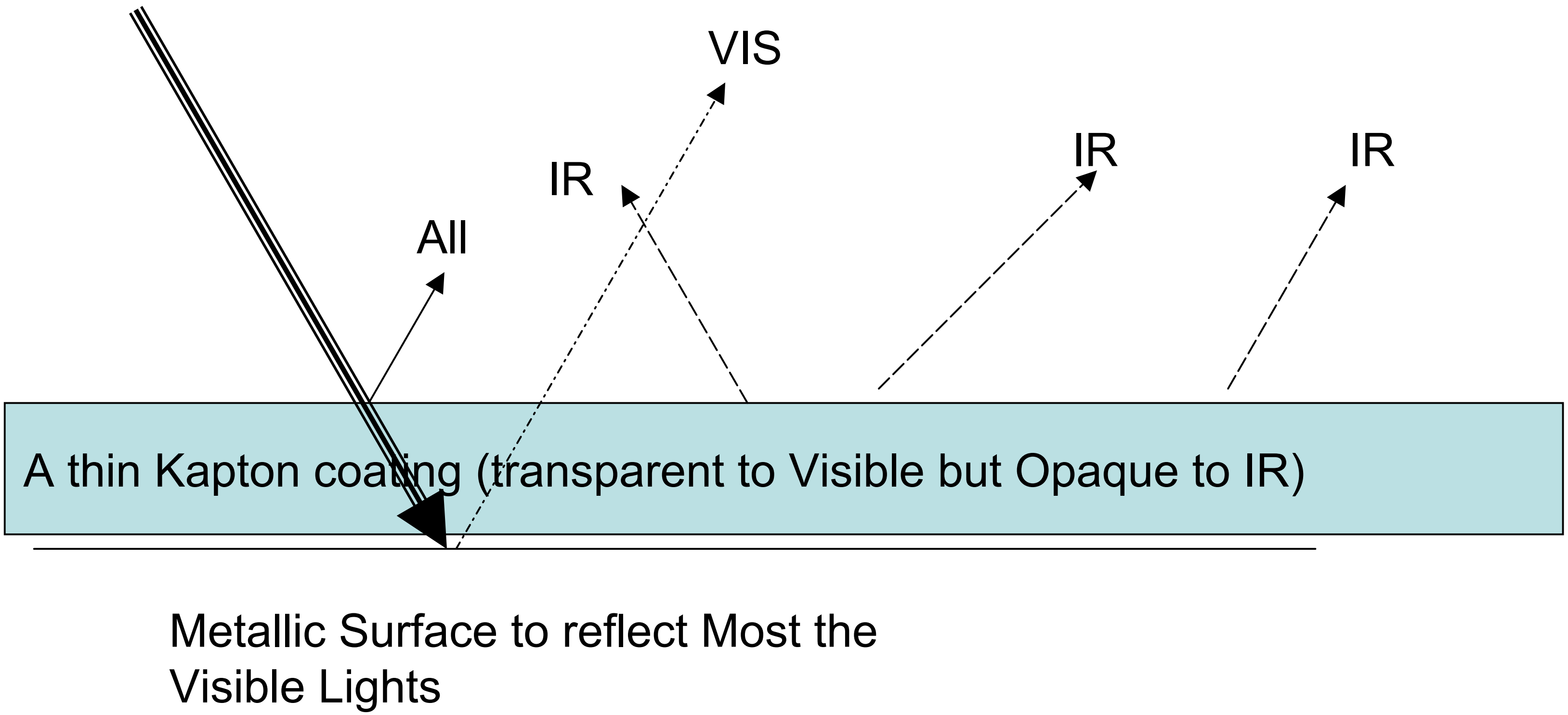


Why is the Interior of a Car so Warm in the Sun?

- Sun(6000K) warms a car with all wavelengths, but the interior of the car (300K-400K) emits IR that can not pass through the glass.

So How Does a Space Suit Work in the Sun?

- By a "Secondary Mirror" Surface!



Si and Ge IR Transmissions

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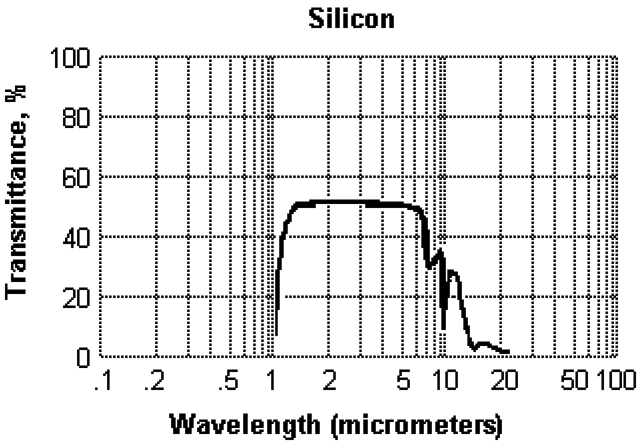
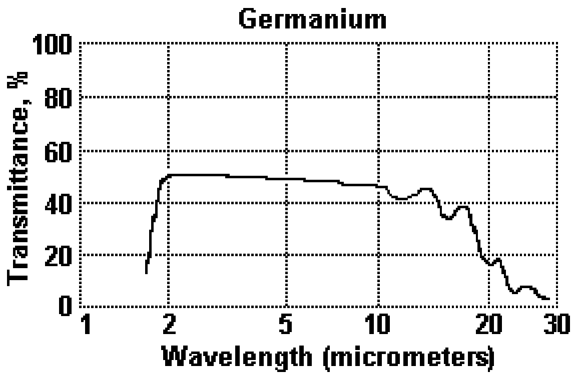
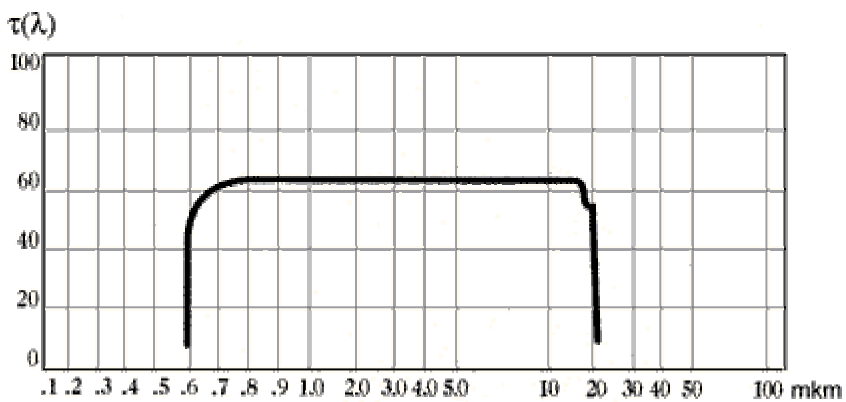




ZnSe Transmission

- http://www.almazoptics.com/ZnSe.html



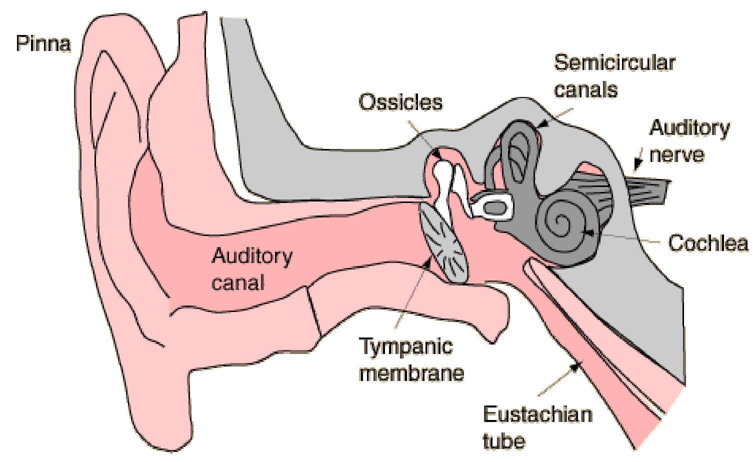
Regardless the “skin tone” difference, all men are equal in Infrared

- Yes, about 0.98; almost black!

What is an Aural Thermometer", or Infrared Aural sensor

- Tympanic cavity as a blackbody cavity
- Emissivity~1.00
- Readily calibrated

- **Must be in a cavity!!

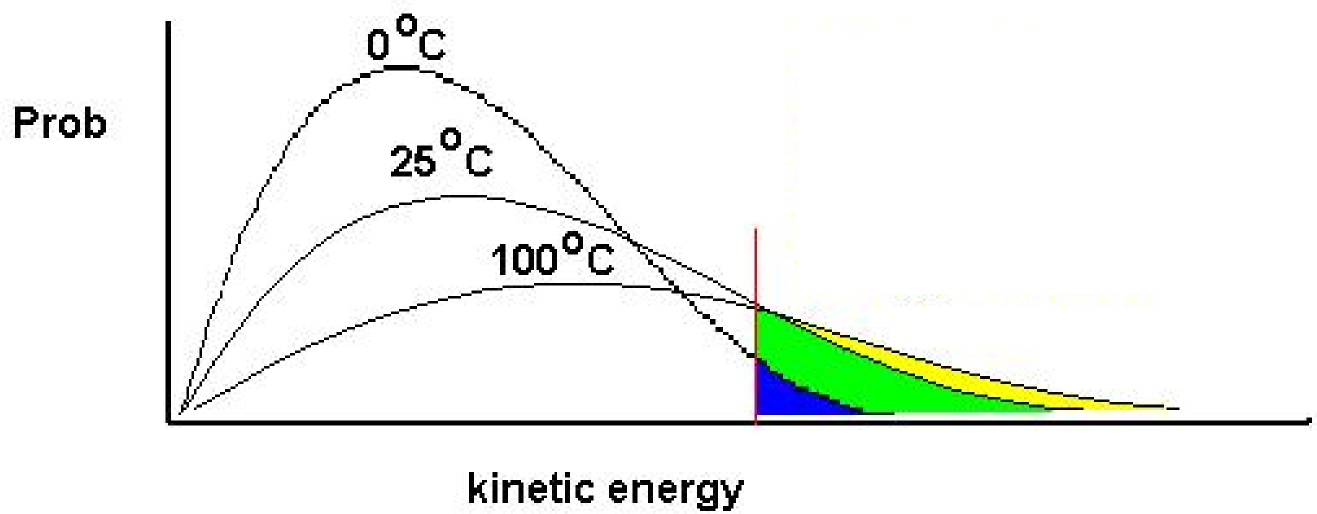


The Infamous SAR Fighter: Ear Cavity Thermometer

- a clinically reliable indicator of body core temperature
- Pyro-Electric Transducer

Electron Thermal Energy: Why IR Detectors Must be Cooled!

- $$KE_{avg} = \left[\overline{\frac{1}{2}mv^2}\right] = \frac{3}{2}kT$$



NEP Concept

- If we use the entire spectrum, then to detect 38ºC (vs. 37 ºC), the difference is $[(38 + 273)/(37 + 273)]^4 = 1.013\%$

So to resolve 1ºC the “system” must be able to resolve 1.3% difference

=>Noise Equivalent Power or NEP

How good is my System Stacking Against the Others?

D*

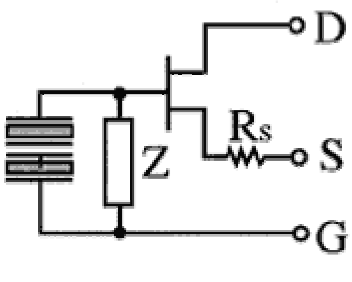
Pyro-electric Detectors

- Pyro: Gk “Fire”
- Pyro-electric: electrical output caused by heat
- Sometimes used for “fiery sparks” display for stage effects
- Low sensitivity, low cost
- Usually for intrusion detection only

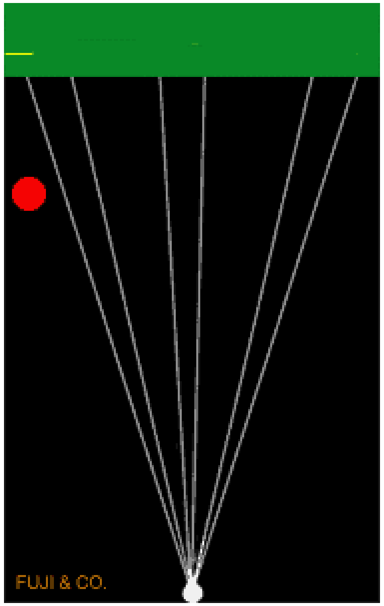
Pyro-electric Detector

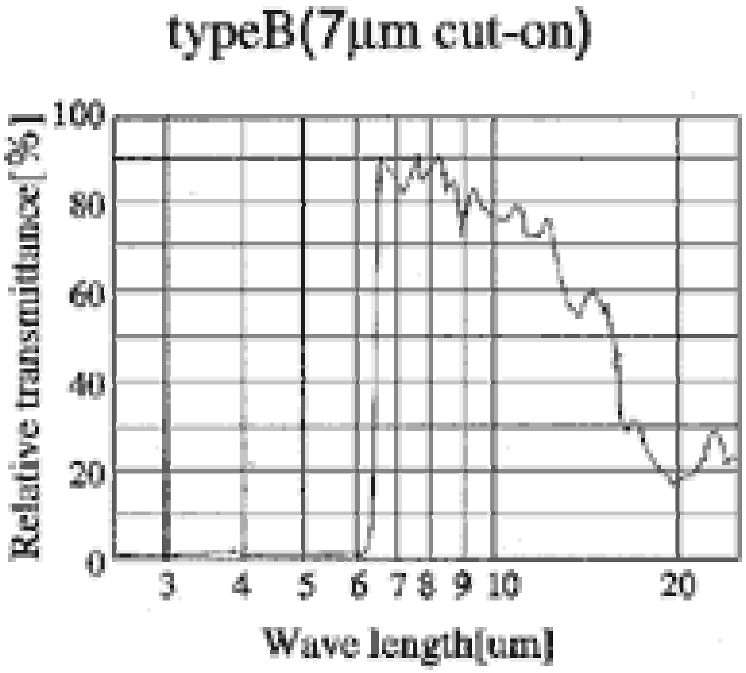
polyethylene Fresnel lens are typically used for their low costs

TGS (Tri-glicine-sulfate)



dual-1





http://www.fuji-piezo.com/TechGen.htm

PV $Hg_xC_{1-x}Te$

- Short for “photo-voltaic Mer-Cad-Telluride”,,or, “Mer-Cad”
- Chemical compound of HgTe and CaTe
- Response ranging from 1μm to 5.5μm, and 8μm up to 13μm, depending on the Hg to Cd ratio
- Most versatile IR detector

PC HgCTe

- Response to 18 microns
- Need “chopping”
- Response varying with temperature
- Operative in higher temperature than PV

Thermal Transducer is “Export Control” Items

- InSb, HgCdTe, and room-temperature Thermal-pile Focal Plane Arrays (FPA) are all “Strategically sensitive” items