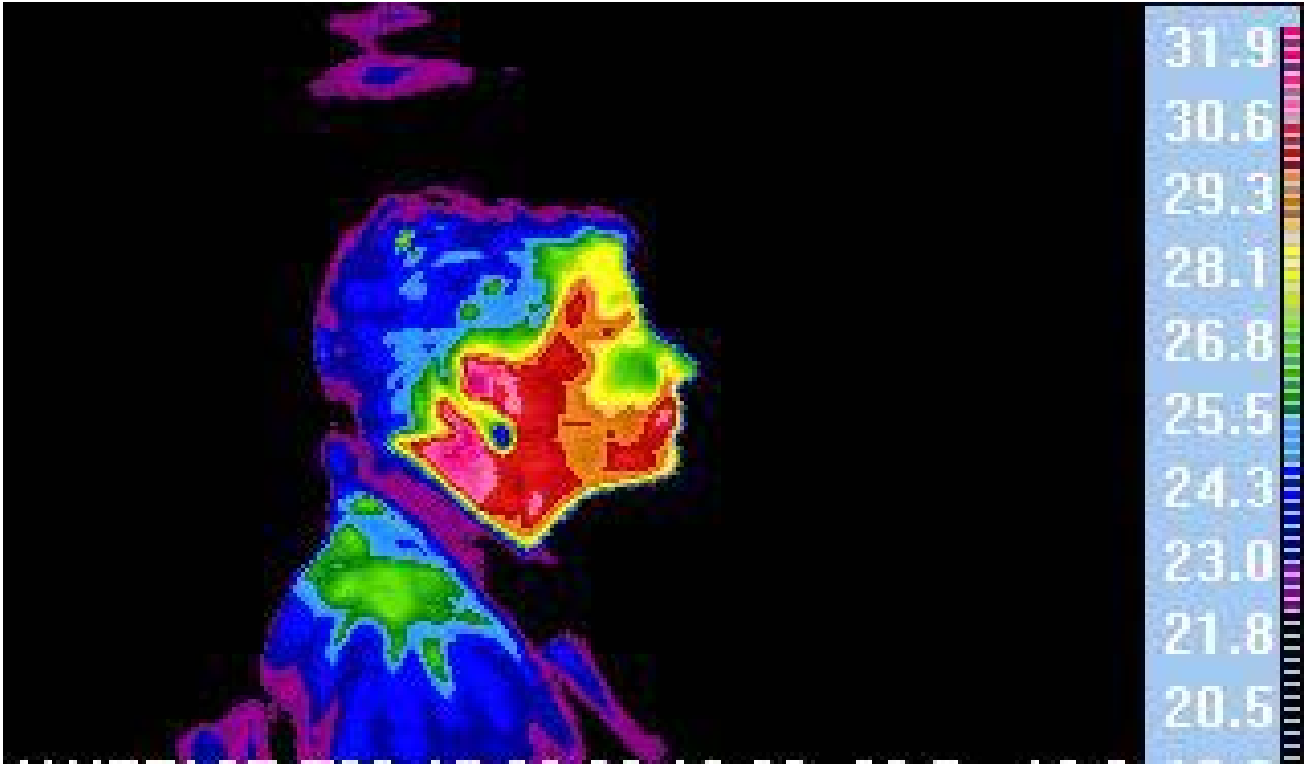
Thermal Infrared Systems

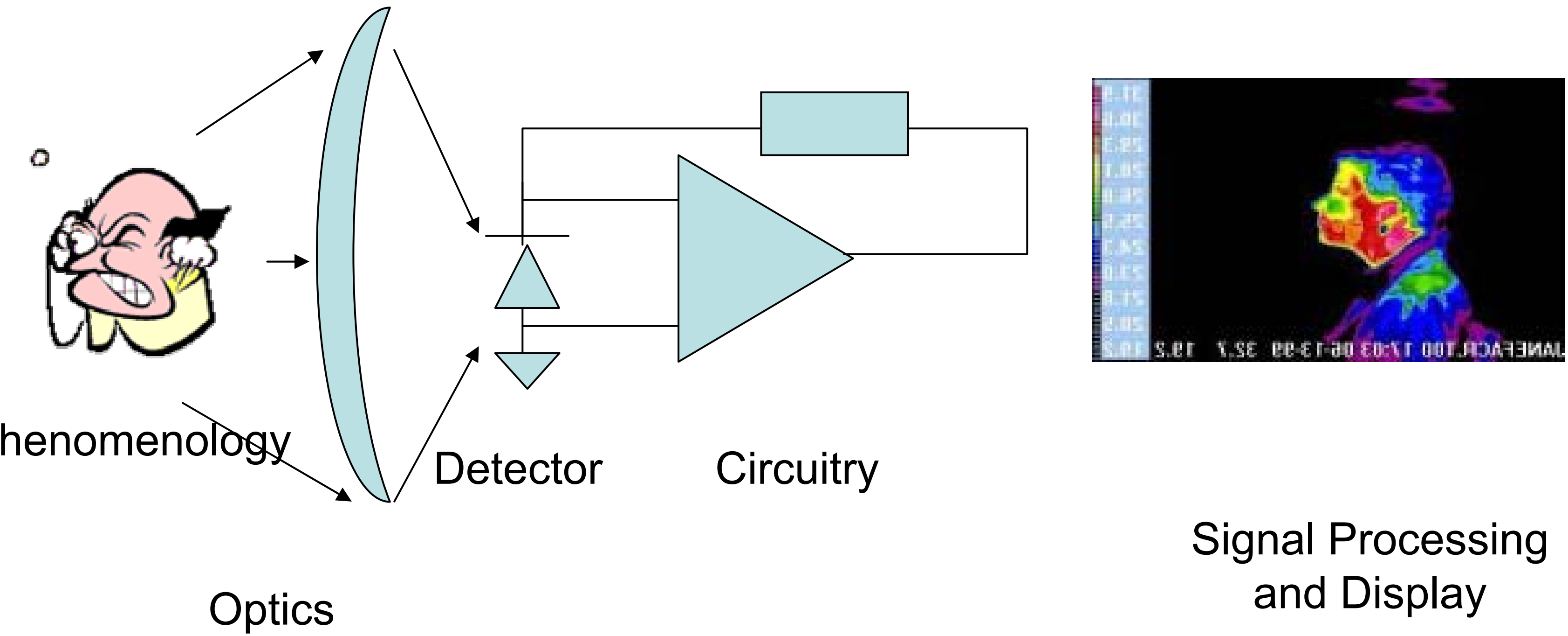
Lecturer: B T Yang 楊丙郁 March 2005 NTU



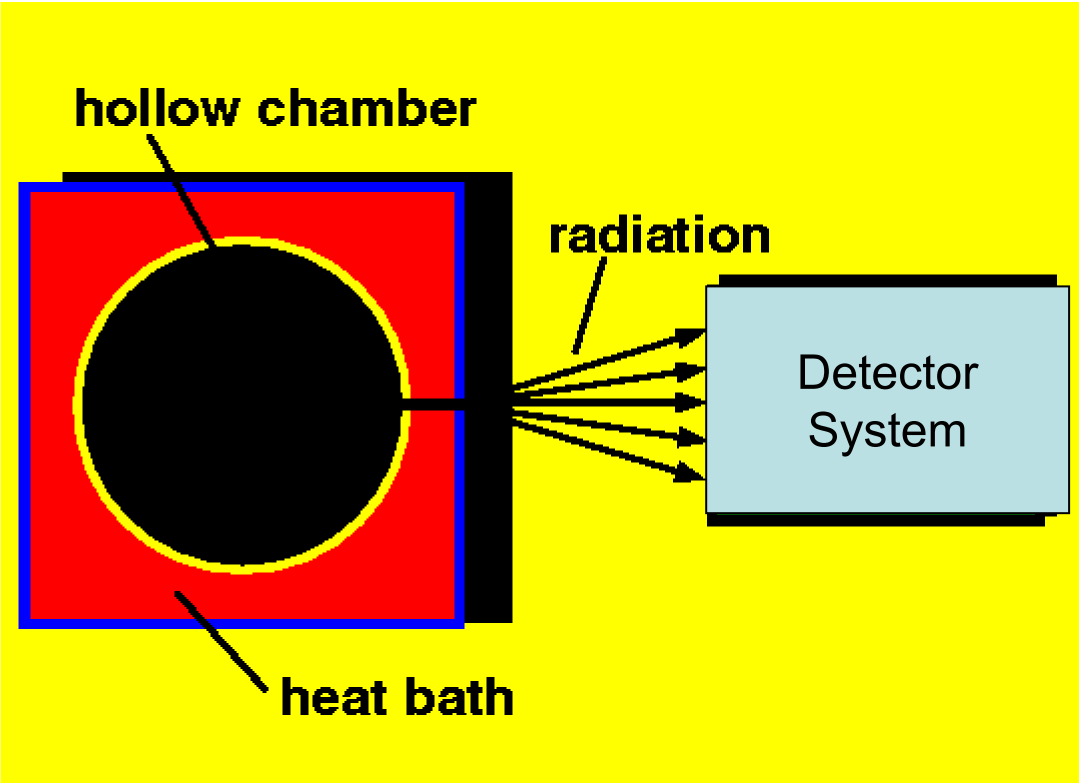
Lecture Outline

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



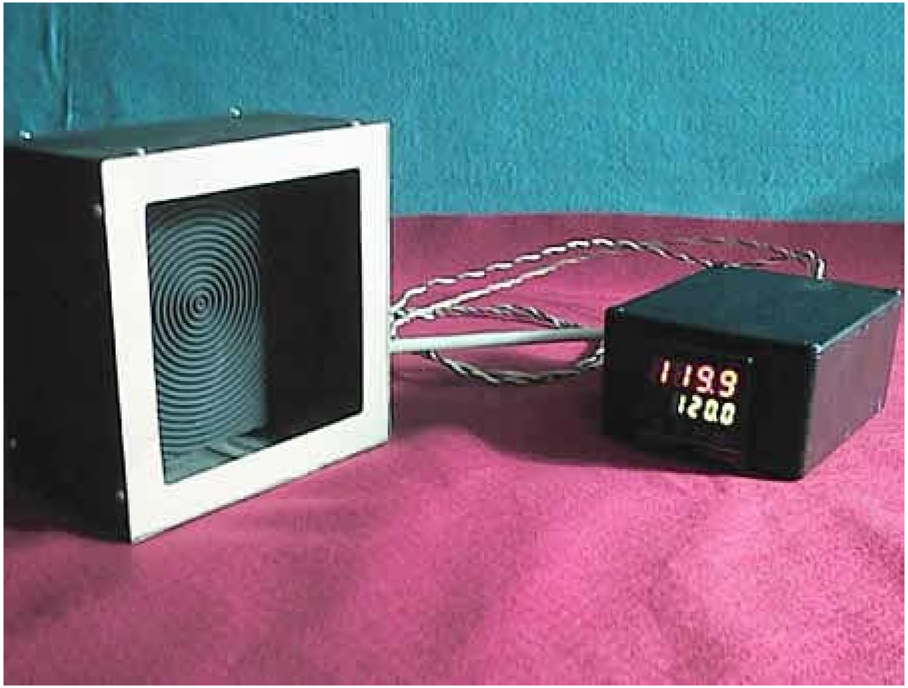
IR is Never Complete without Introducing the “Blackbody”



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

Grooved Planar Black Body Source

- “Grooved surface enhancing the emissivity



Absolute Blackbody Radiance Calibration Standard: Metal Freeze Temperature

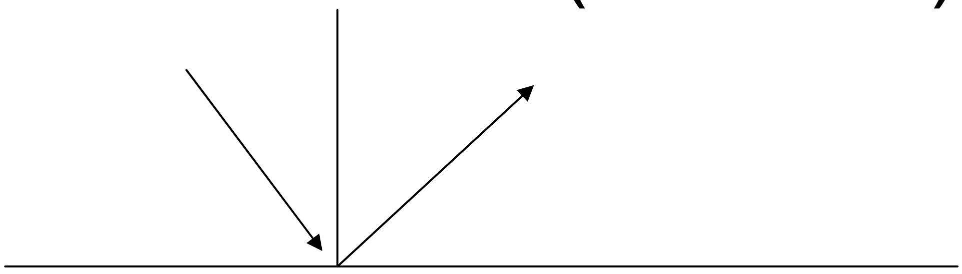
Pure Metal	Freeze Temp* (°C)	Pure Metal	Freeze Temp* (°C)
Gallium	29.7646**	**Aluminum**	660.323
Indium	156.5985	**Silver**	961.78
Tin	231.928	**Gold**	1064.18
Zinc	419.527	**Copper**	1084.62

Definition of a Black Body

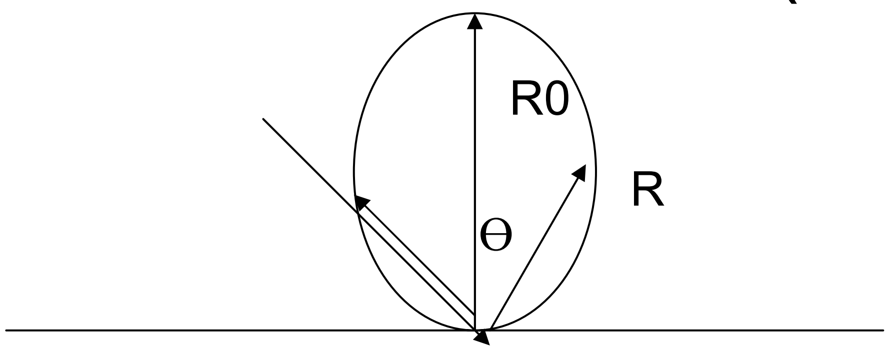
- **A blackbody absorbs all incident radiation; r=0**
- **At a given temperature, no surface can emit more energy than a blackbody**
- **A blackbody is a “diffuse” emitter that follows the “Lambertian Laws”**

Lambertian Law

- Specular Surface (reflective)



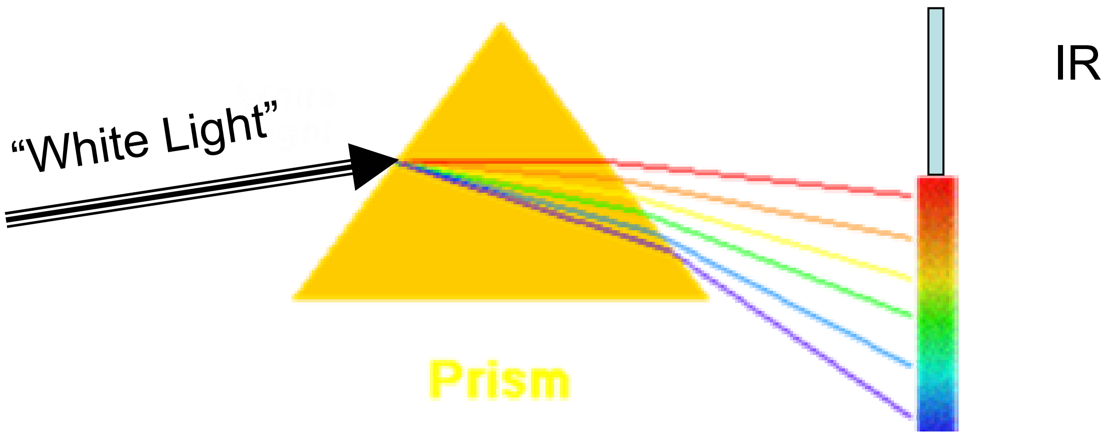
- Lambertian Surface (diffuse surface)



$R=R_0 \cos\Theta$

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?

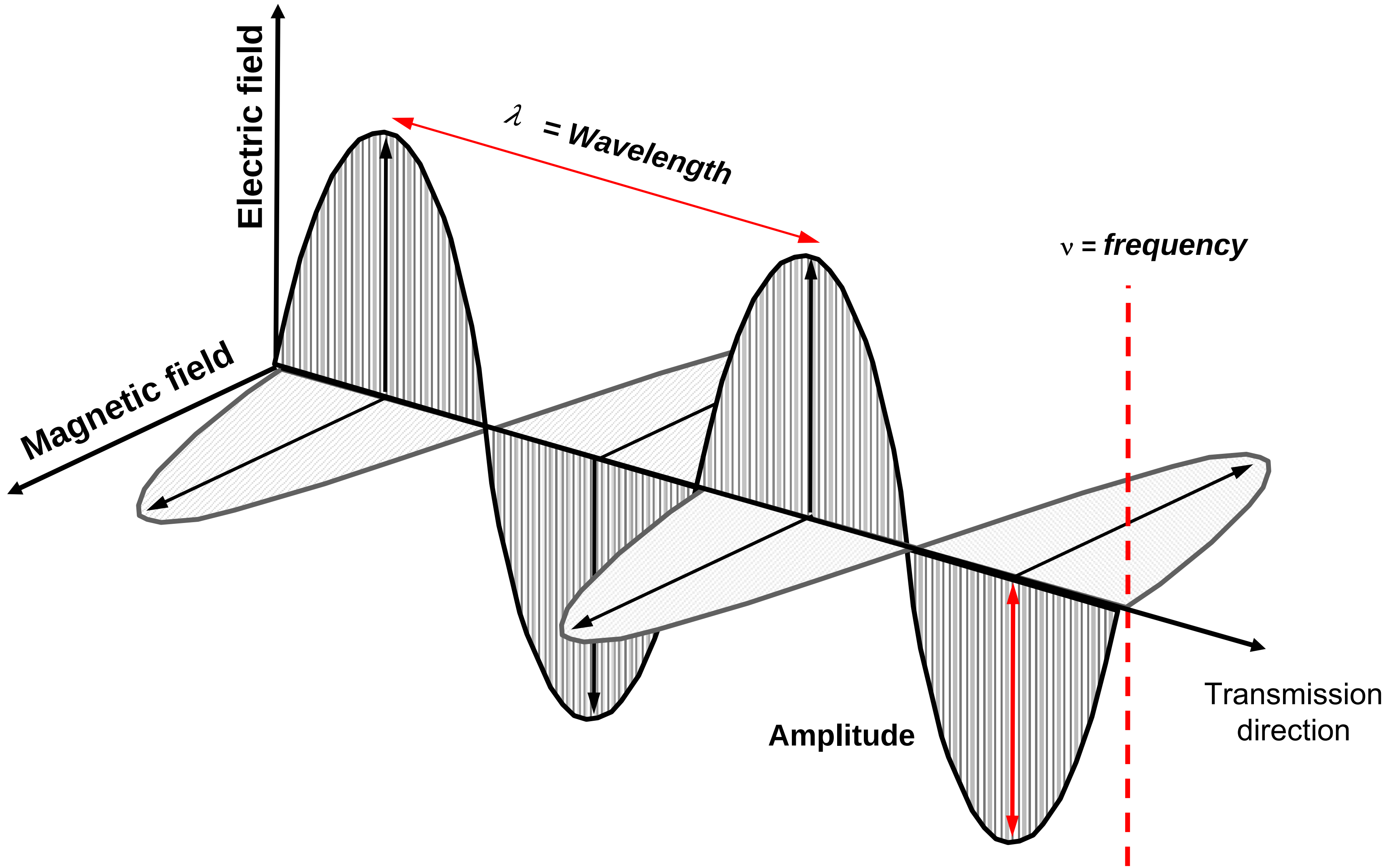
- A known effect of infrared light on skin is dilation of blood vessels that transport blood to and from the skin for cooling=> sensation of heat!

- According to Kirchhoff Law, if r=0

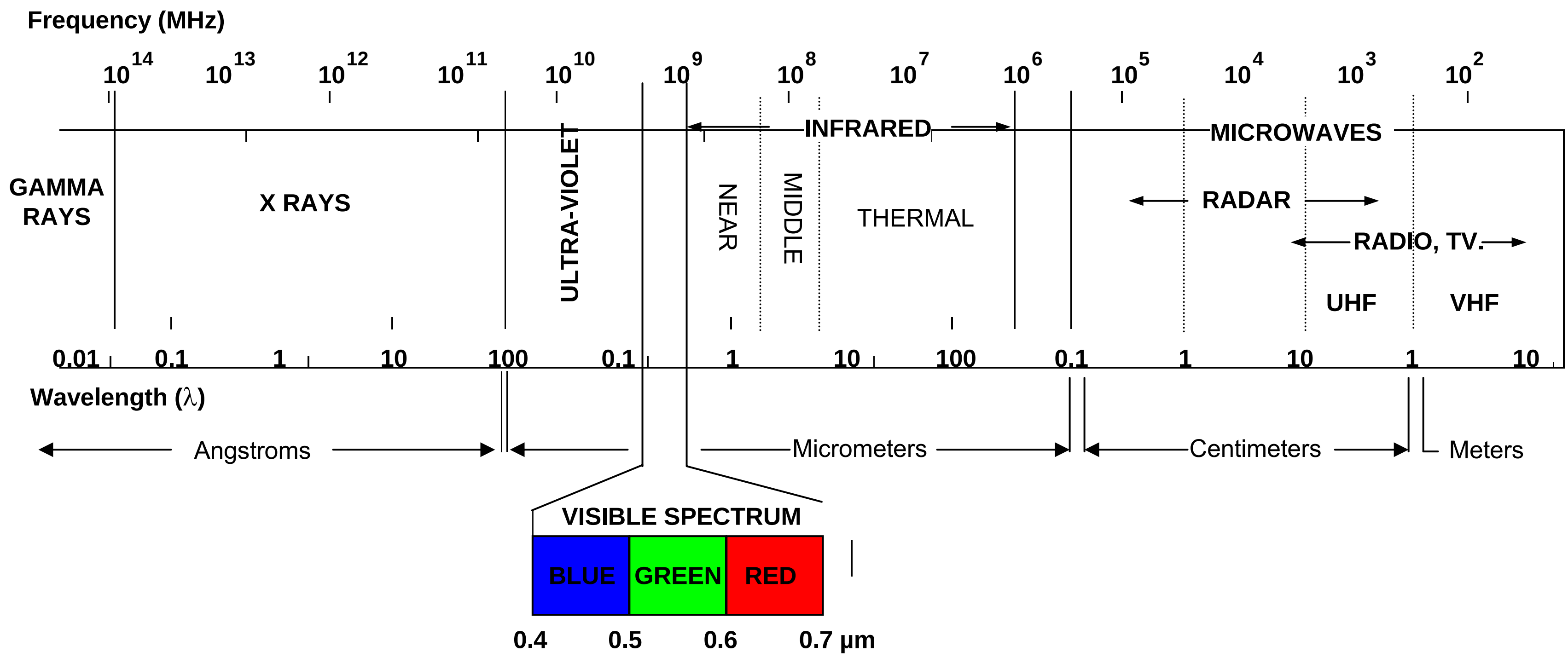
$$\varepsilon(\text{absorptivity}) = \sigma(\text{emissivity})$$

- 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 4.3×10^{14} Hz
- Wavelengths: 1 mm – 0.7 μm
- Quantum energies: 0.0012 - 1.16 eV

ΔE [eV]=1.24 / λ [μm]

For Si, ΔE =1.13eV; λ_{cutoff}=1.1 μm

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}

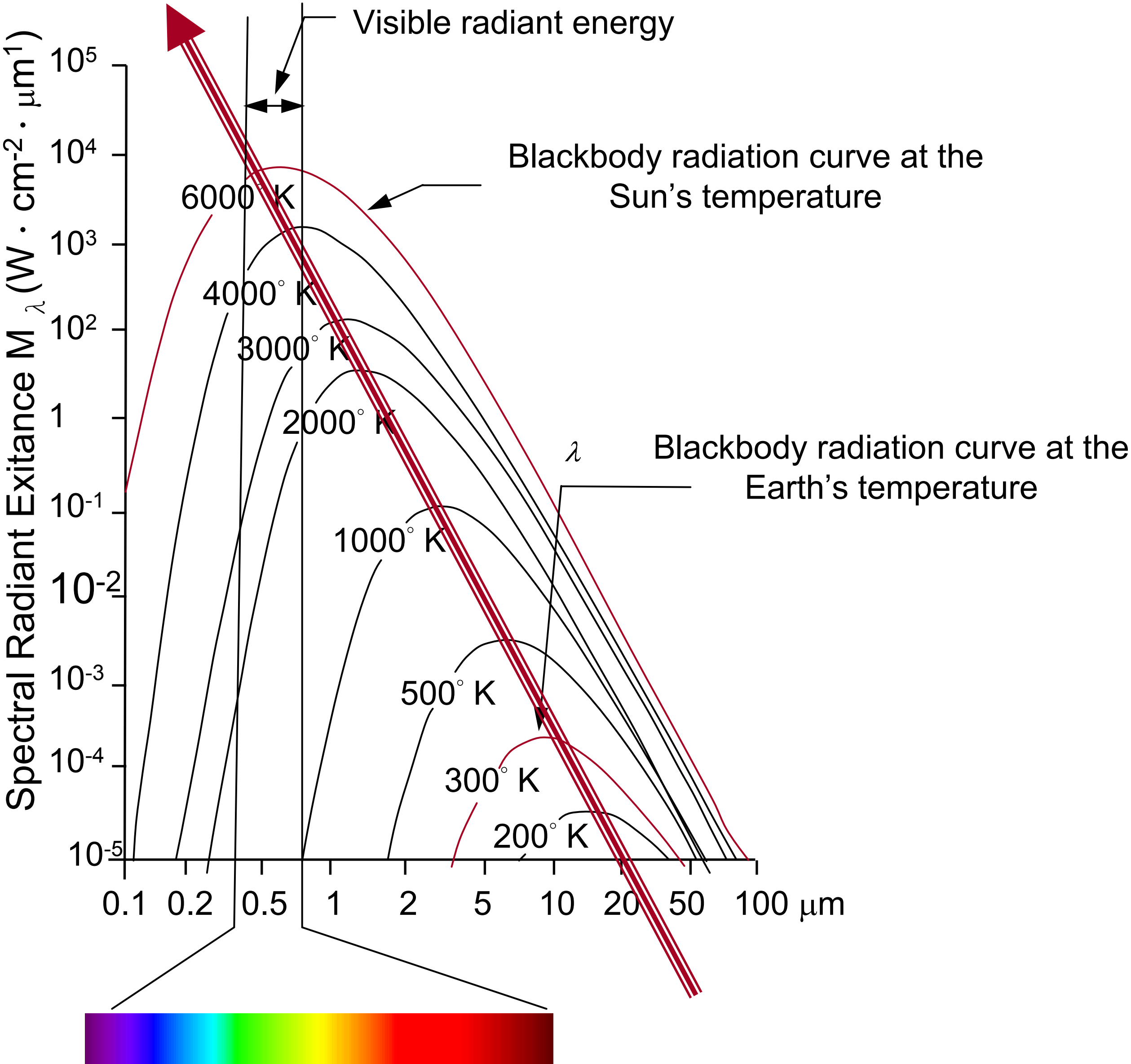
C= 3x10^{14} μm /sec

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

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

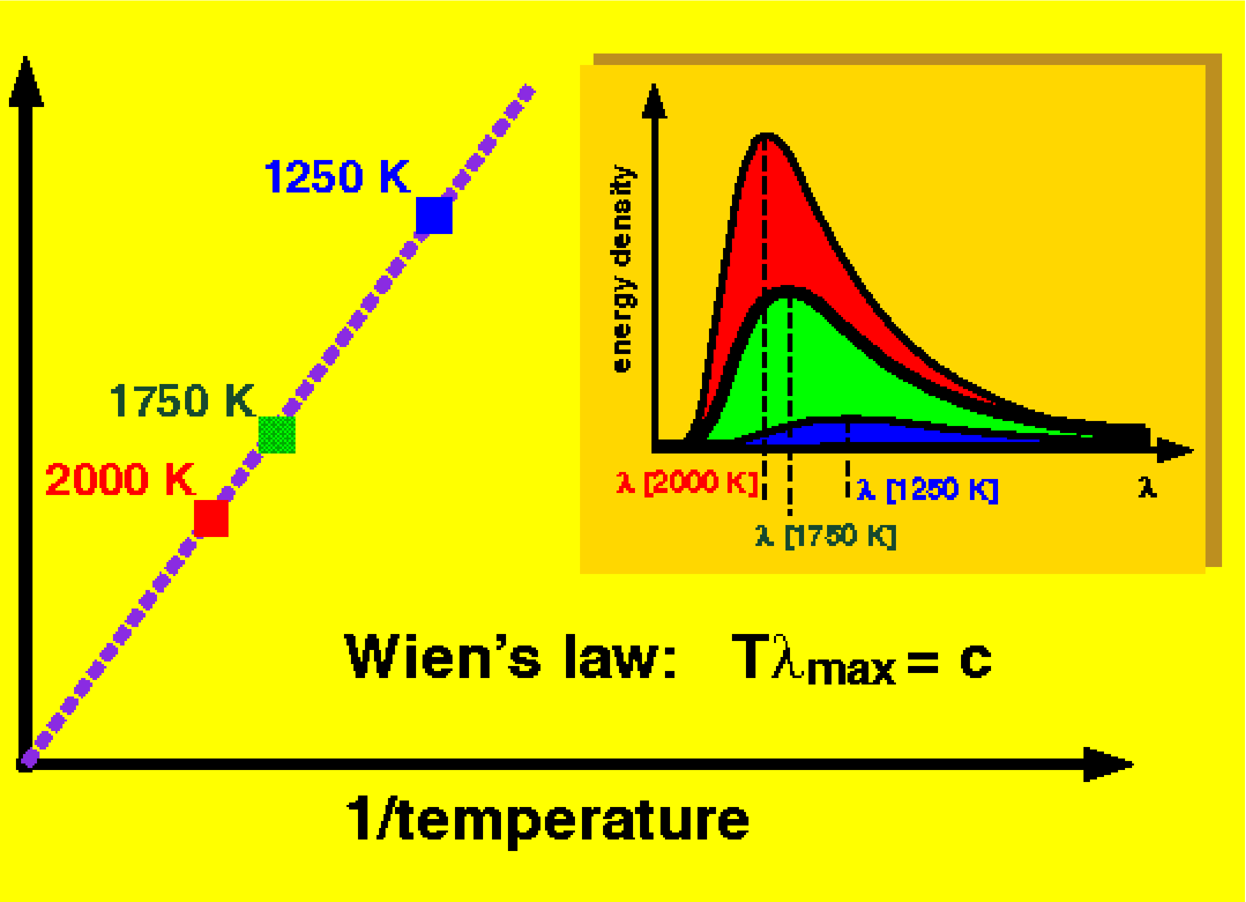
$$= \frac{3.74 x 10^4}{\lambda^5 [e^{1.44 x 10^4 / \lambda T} - 1]}$$

Spectral exitance of a blackbody



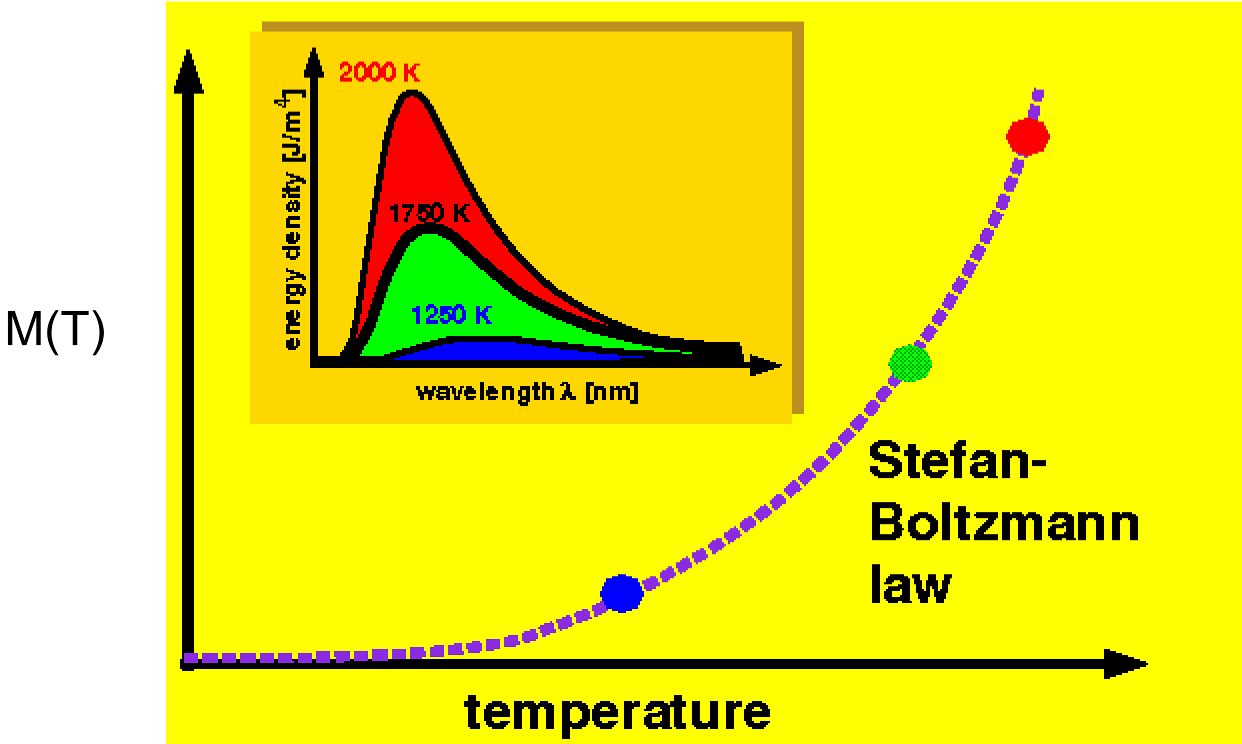
Wien's Law

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



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 5.67×10^{-12} $W \cdot cm^{-2} \cdot K^{-4}$**



Grey Body?

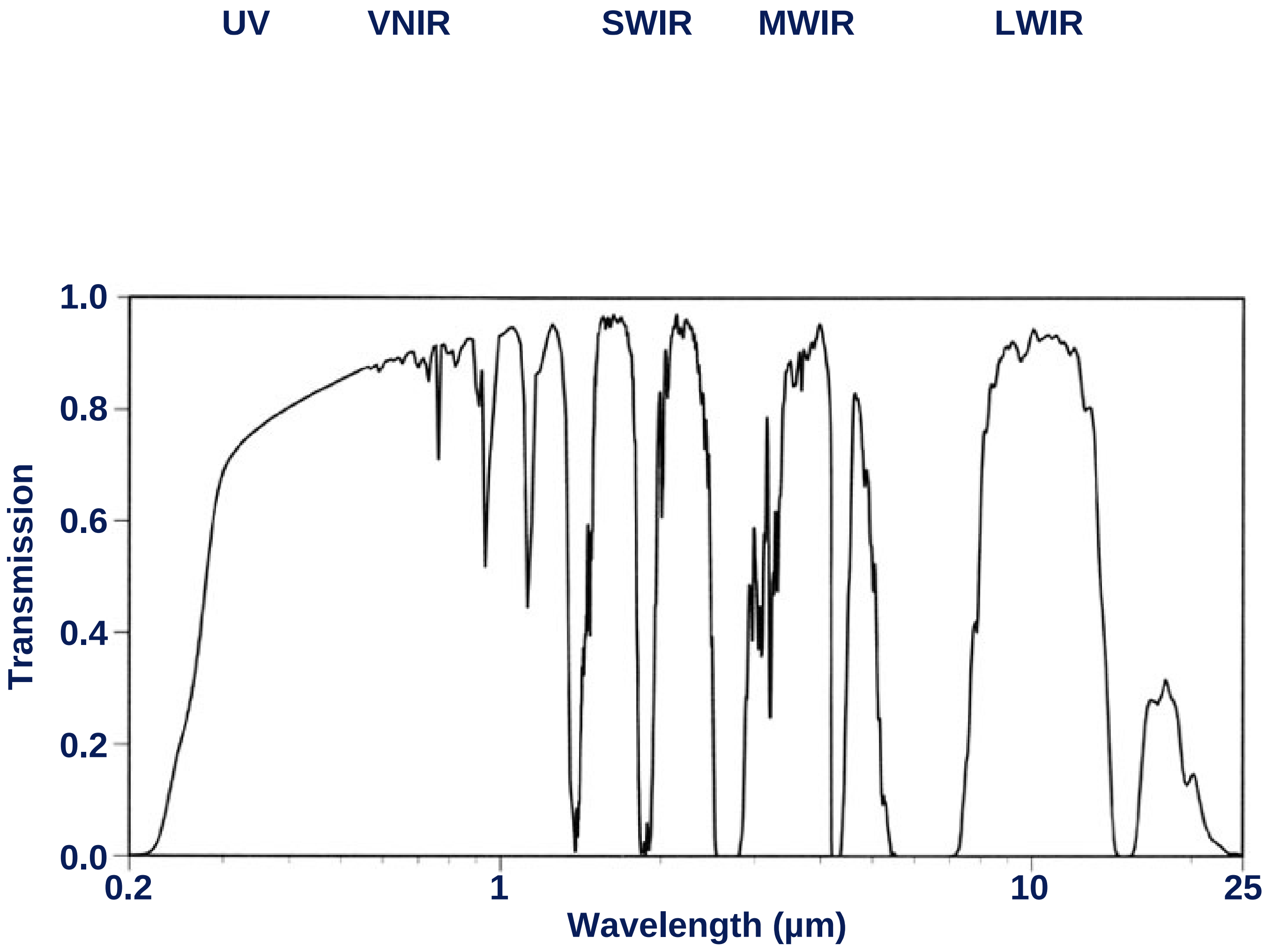
- When emissivity ε is not unity
- Most physical surfaces are grey bodies

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

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

$M = \varepsilon \ \sigma \ T^4$

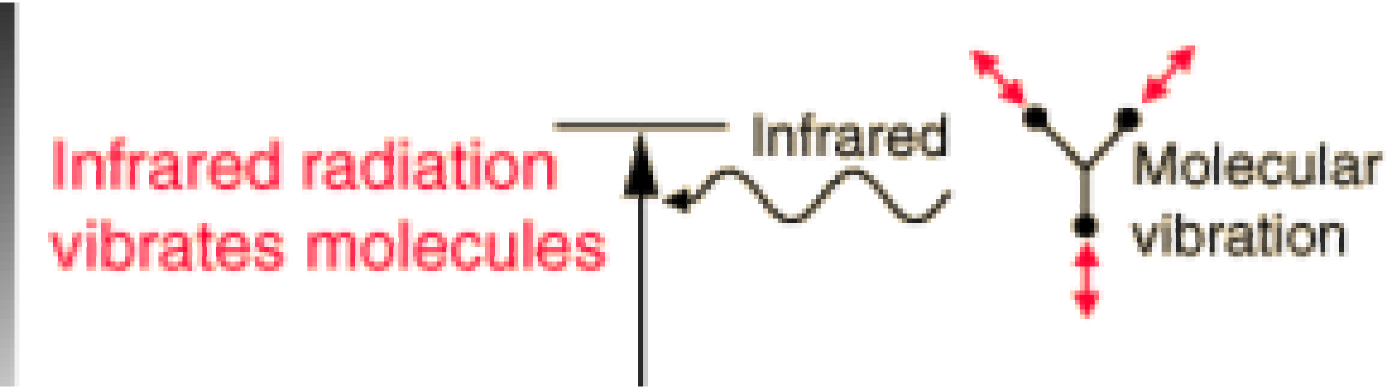
Atmospheric Transmission Spectra



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" $\Delta E = h\nu$

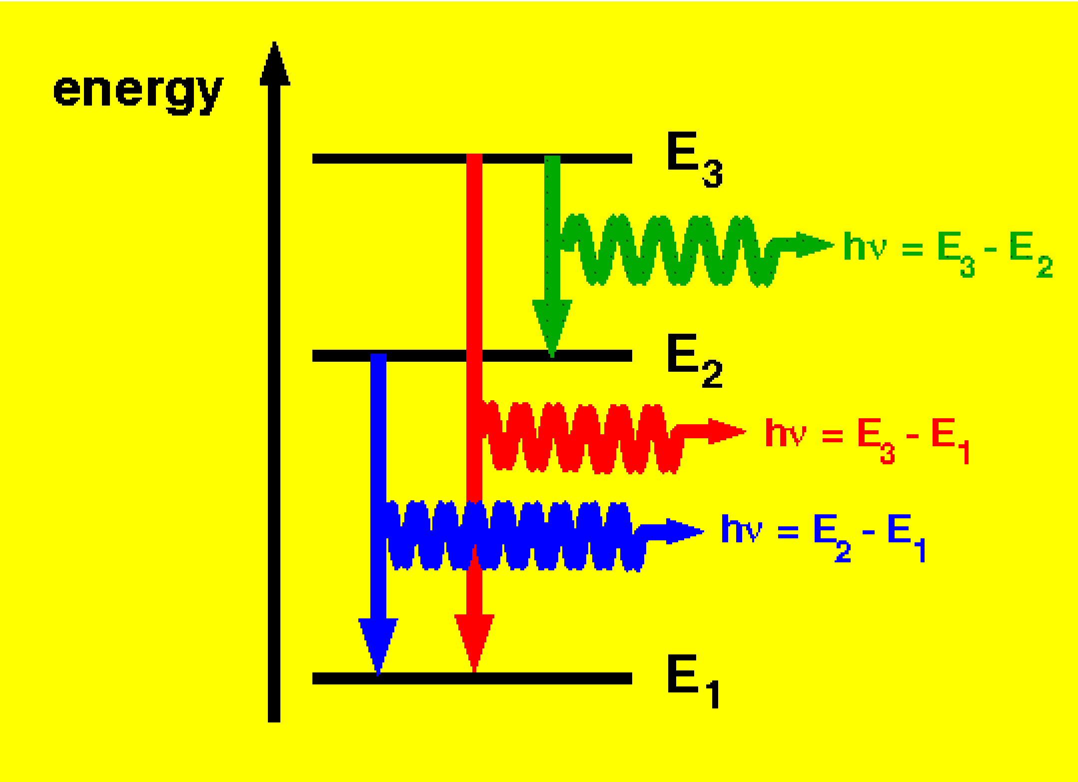
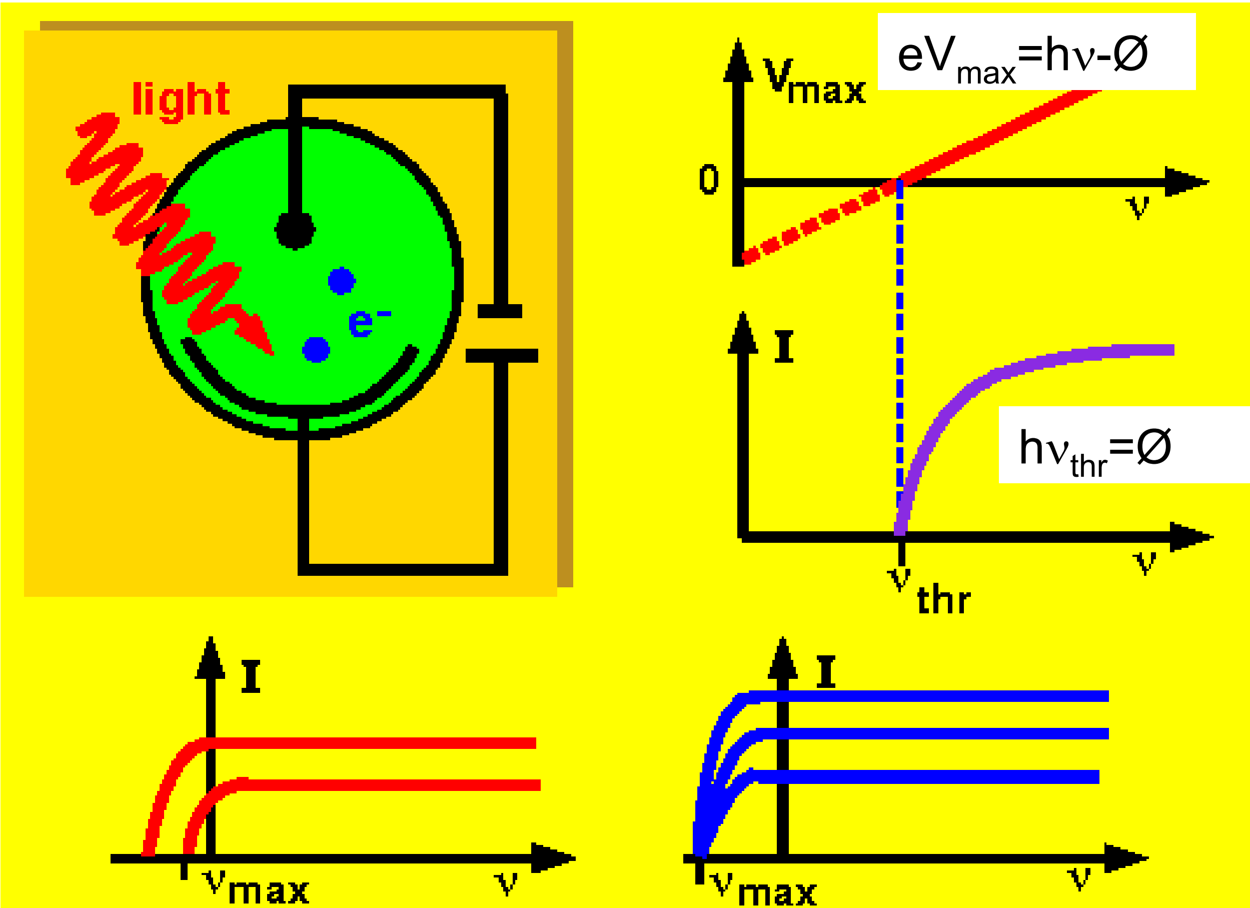


Photo-Electric Effect

- Eienstein 1905's Paper Confirming the Discret Energy

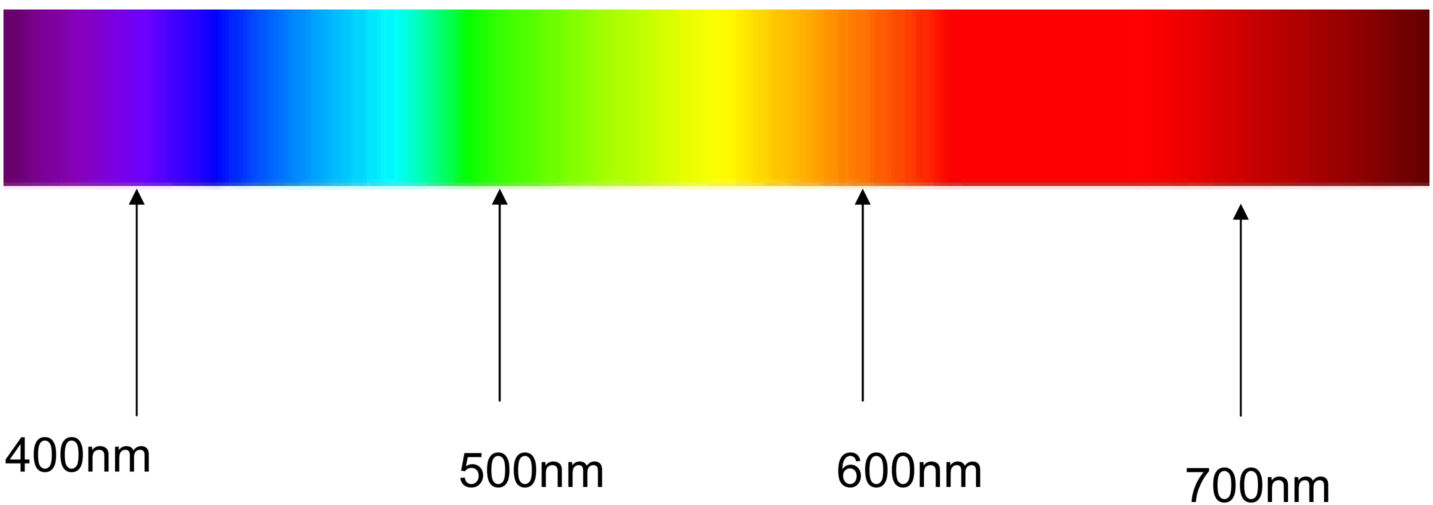


Varying ν

Same ν, varying

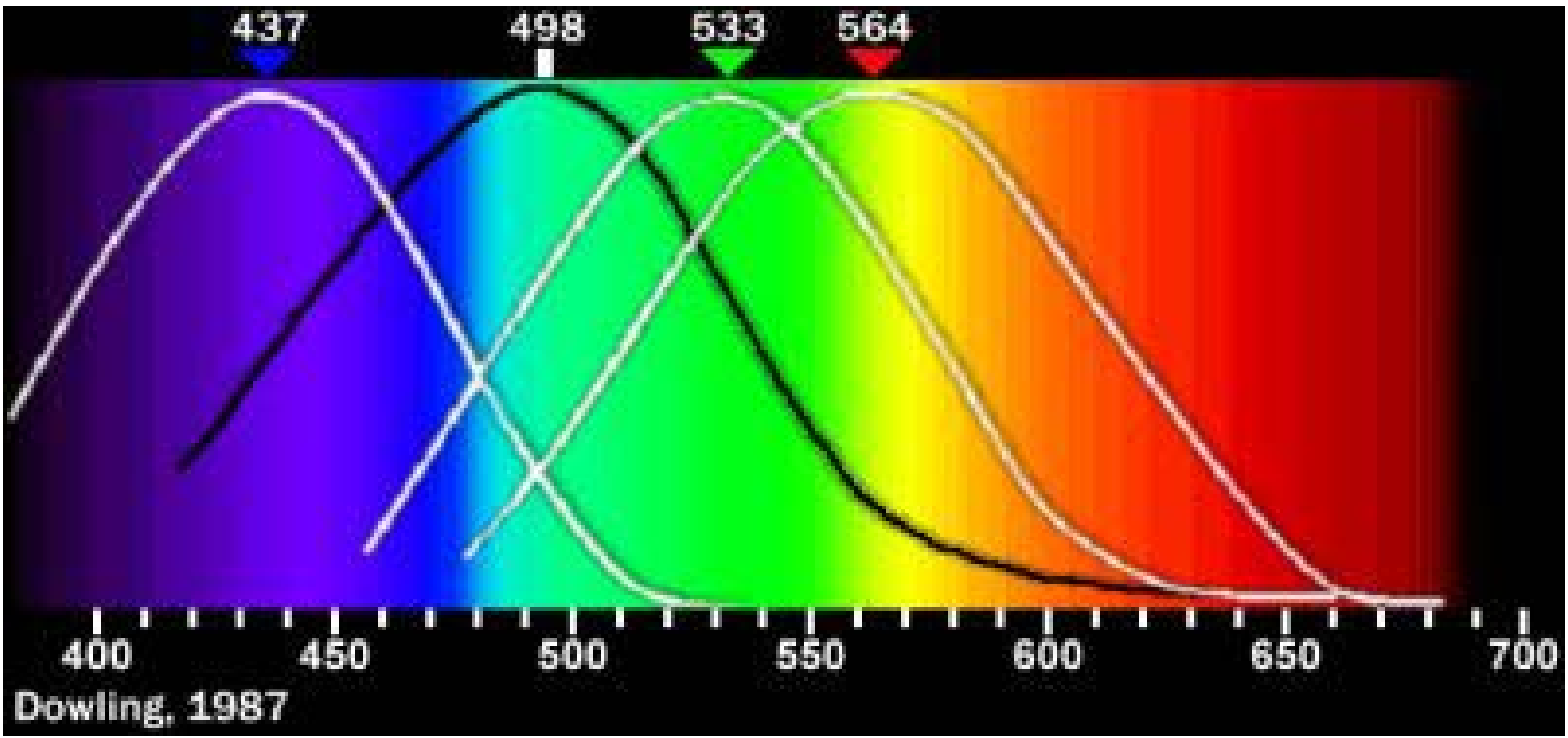
Visible Spectral Range

- Visible Band: 400nm to 700nm



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

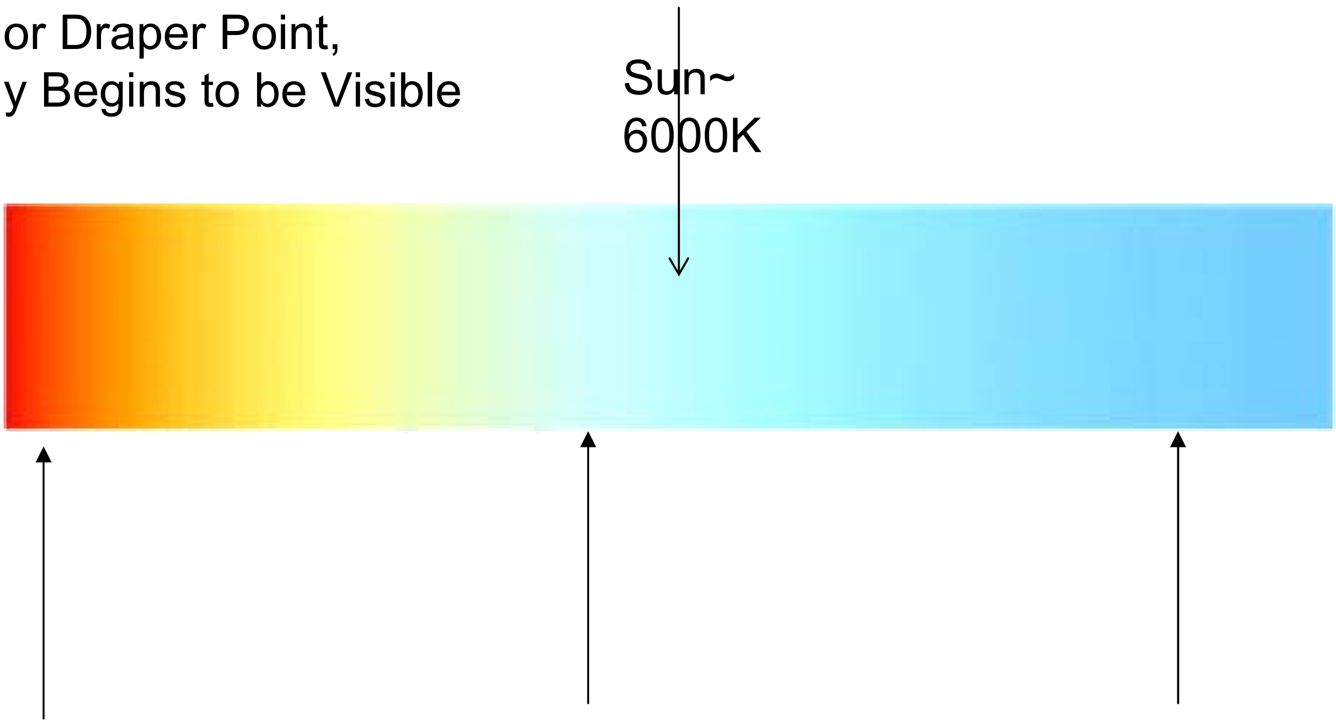
- Rods for night vision (more sensitive)
- Cones for color day vision



"Color" Temperature

An Apparent Visible Color of a Blackbody at T

At 800K, or Draper Point,
Blackbody Begins to be Visible



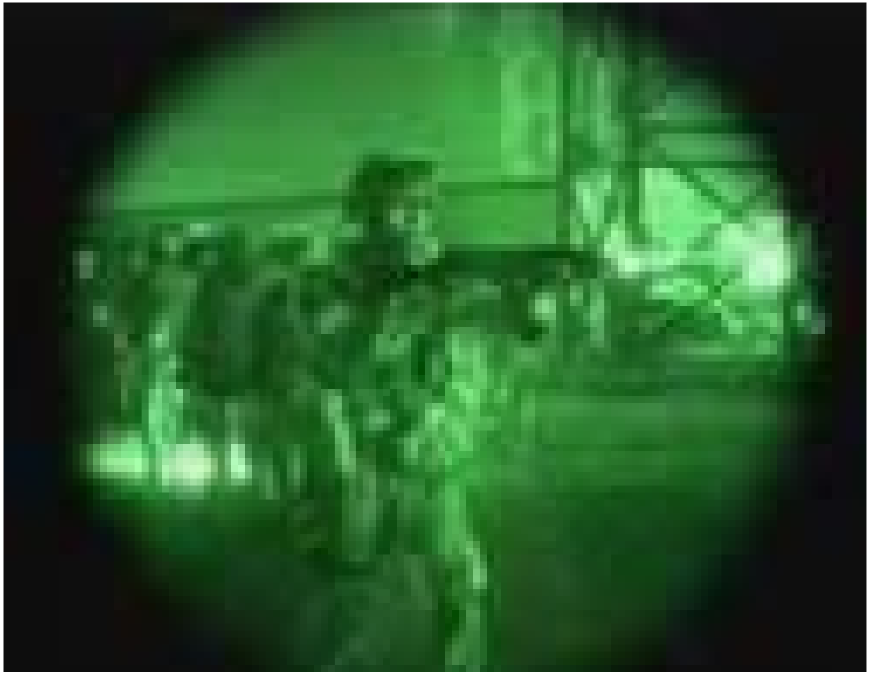
1,000K

5,000K

10,000K

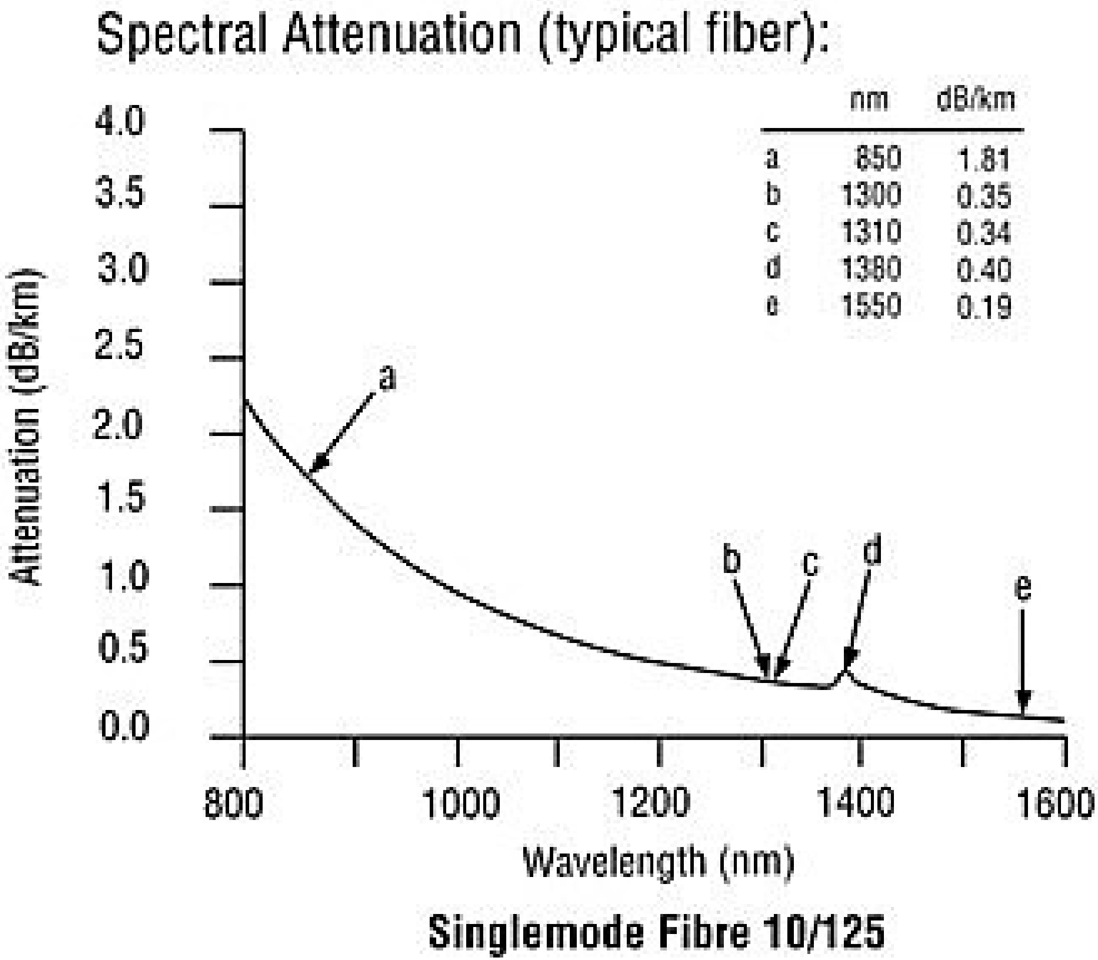
Night Goggles are "not" true Thermal Images

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

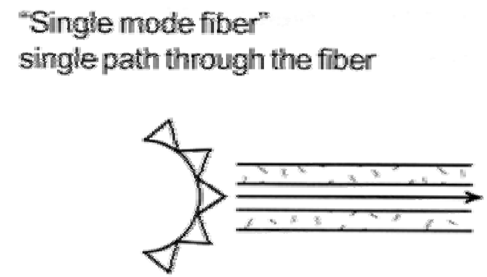


Many Low-Cost Low-Light Detection Systems are NIR Systems

“Near IR Wavelength Used for Optical Communications

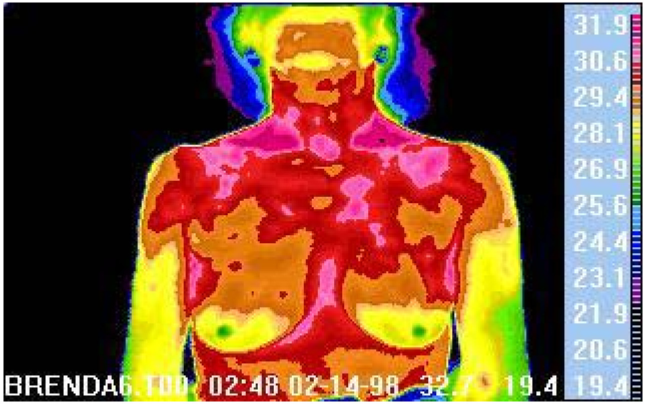


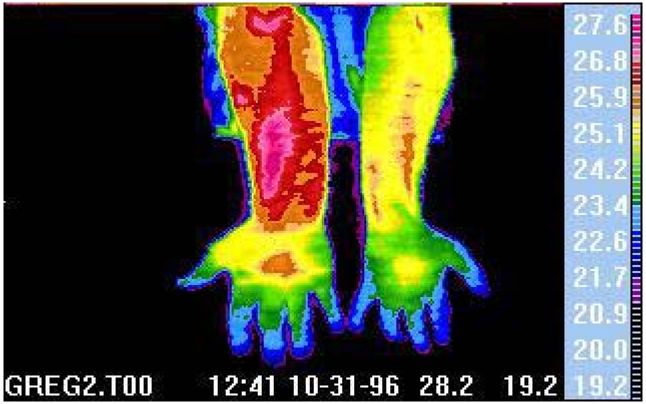
	nm	dB/km
a	850	1.81
b	1300	0.35
c	1310	0.34
d	1380	0.40
e	1550	0.19



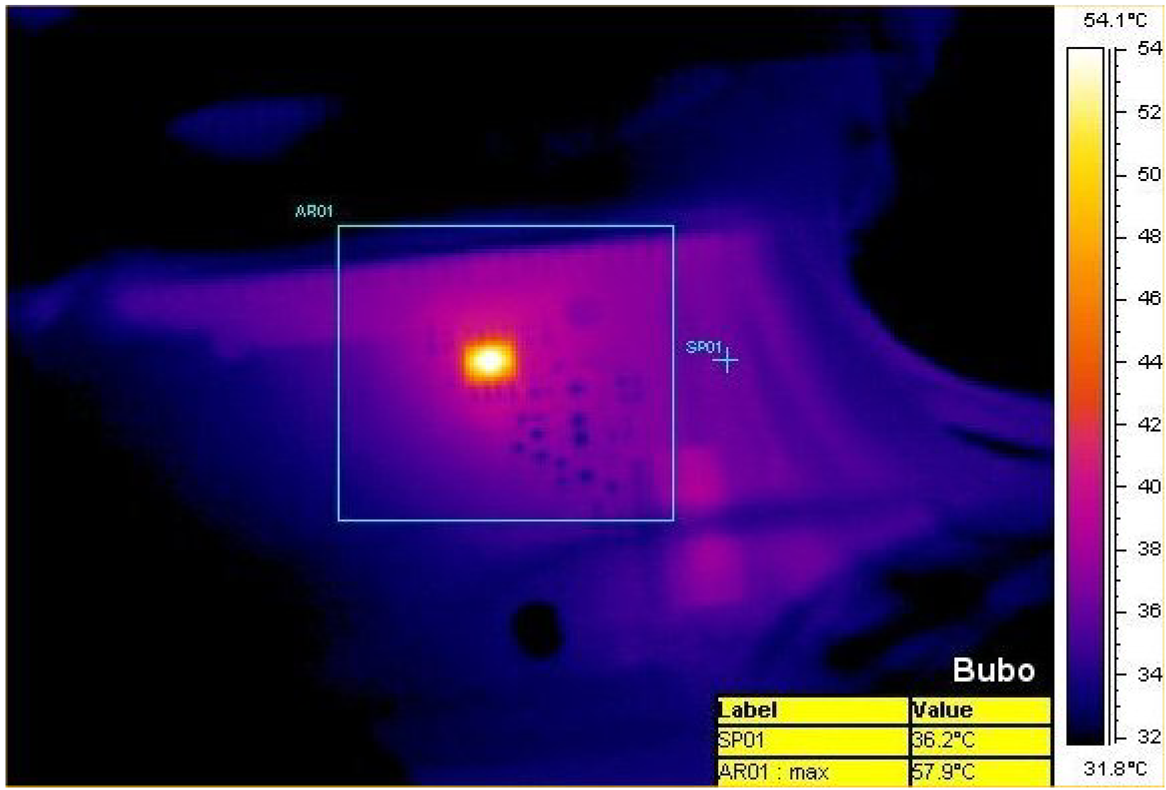
Human Thermal Images

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

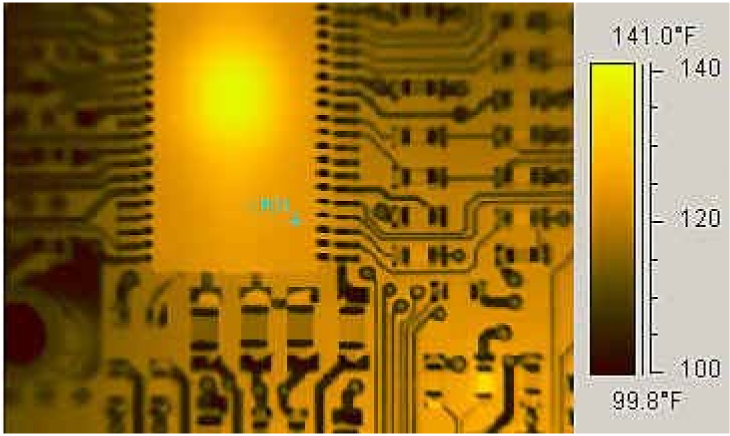


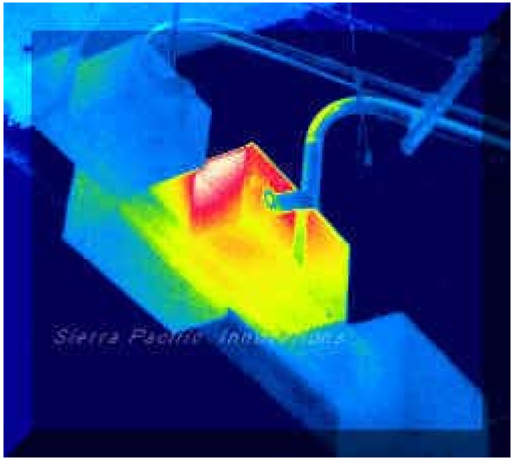


PC Board Localized Heating



Localized IC Chip Detection





Burglar Detection

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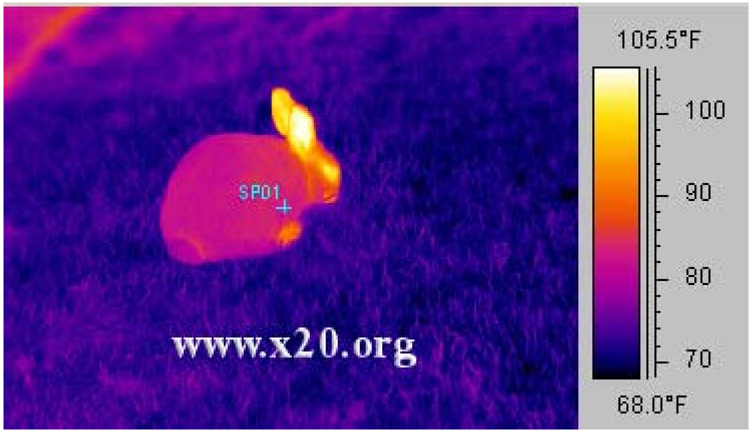

Underside Celeron Chip

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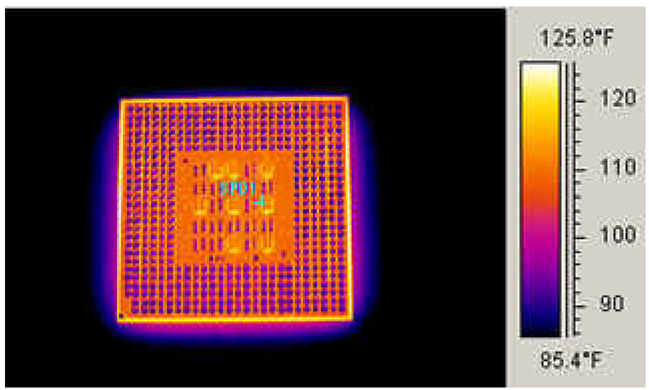

SARS Temperature Screening

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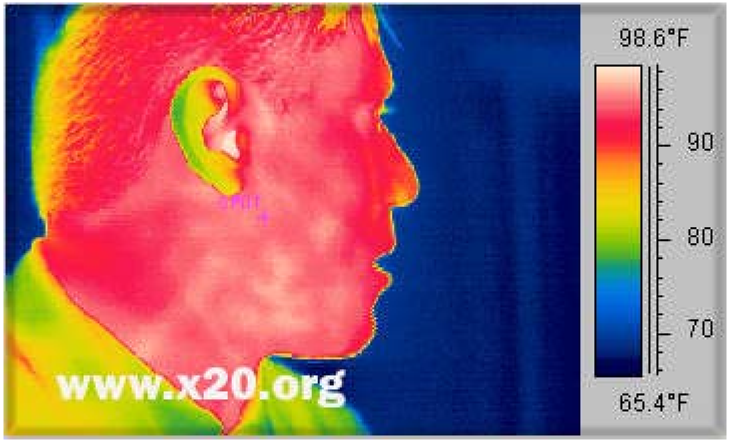
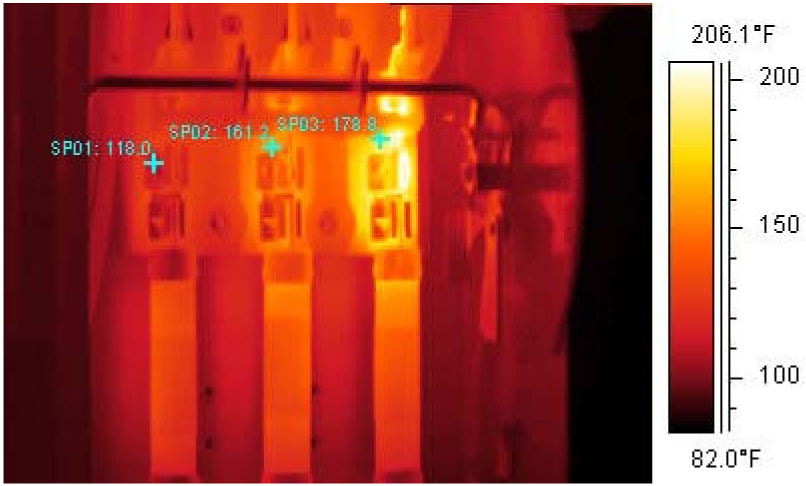


Preventive Maintenance

- Electrical Fuse Thermal Image



Thermal Management

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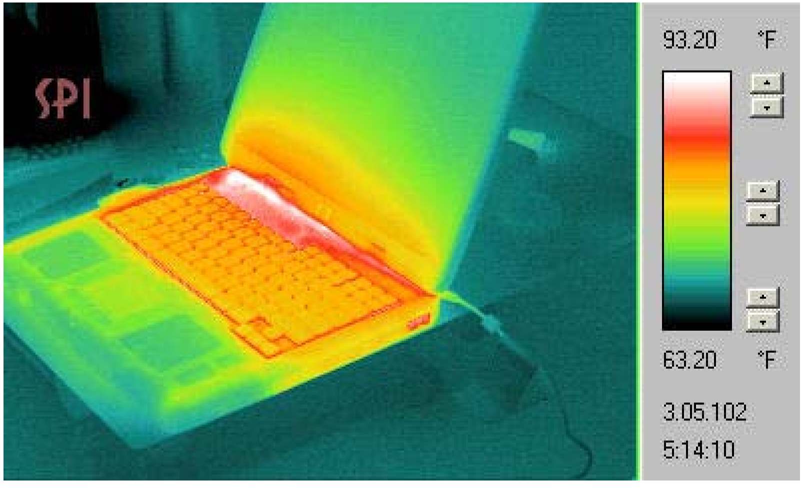
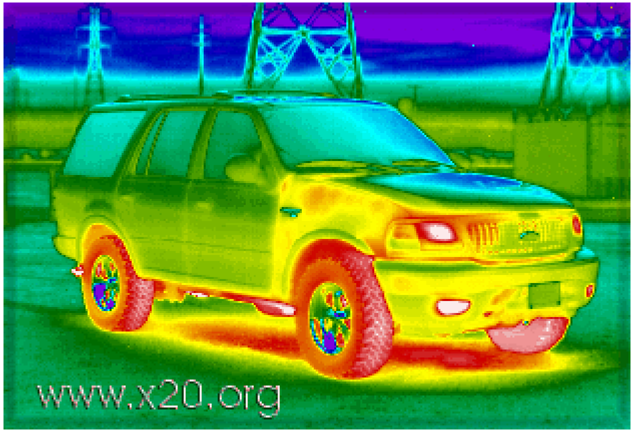
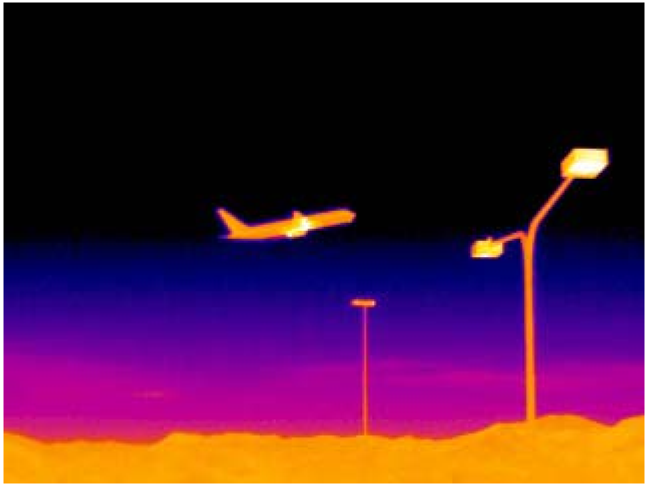


Defense Applications



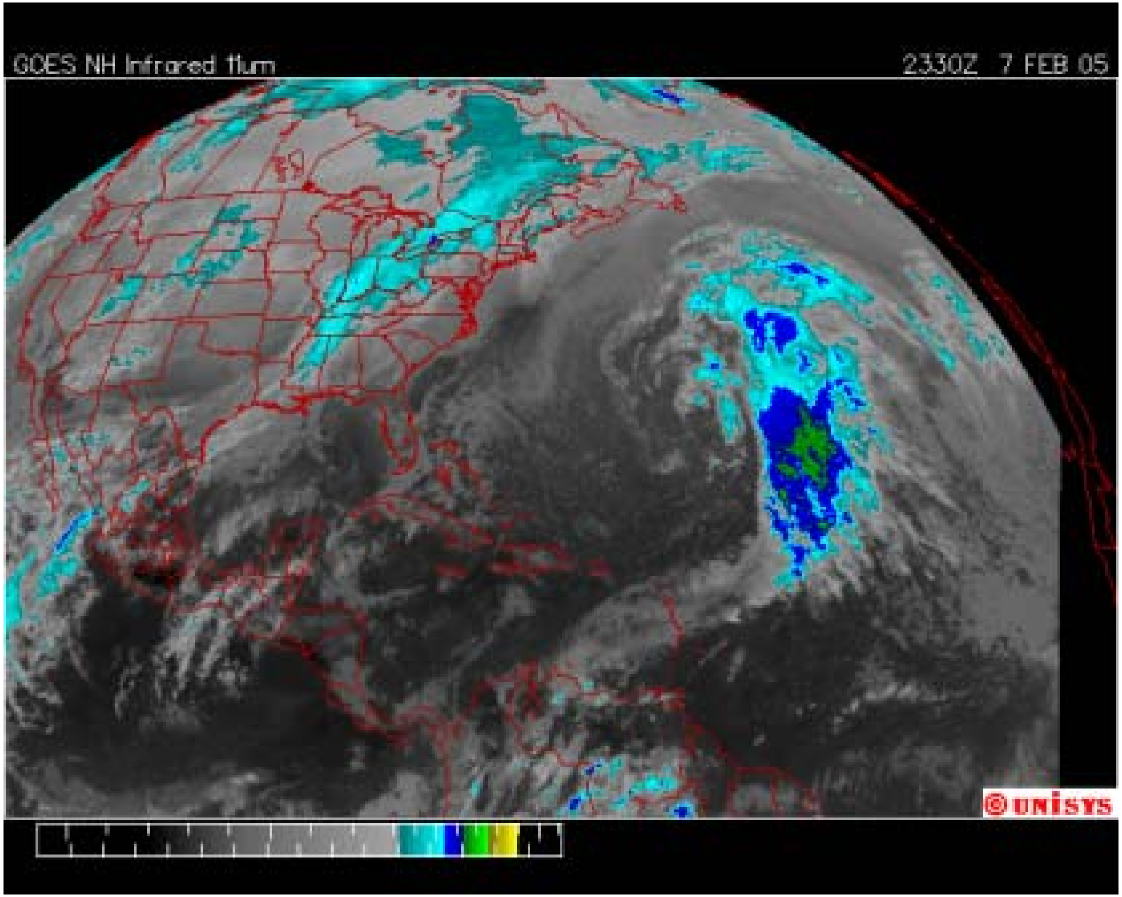
Sky Surveillance

- Collision Prevention



Weather Monitoring

- Geosynchronous Weather Satellite Application



What "Limits" Your Measurements?

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

   Optics

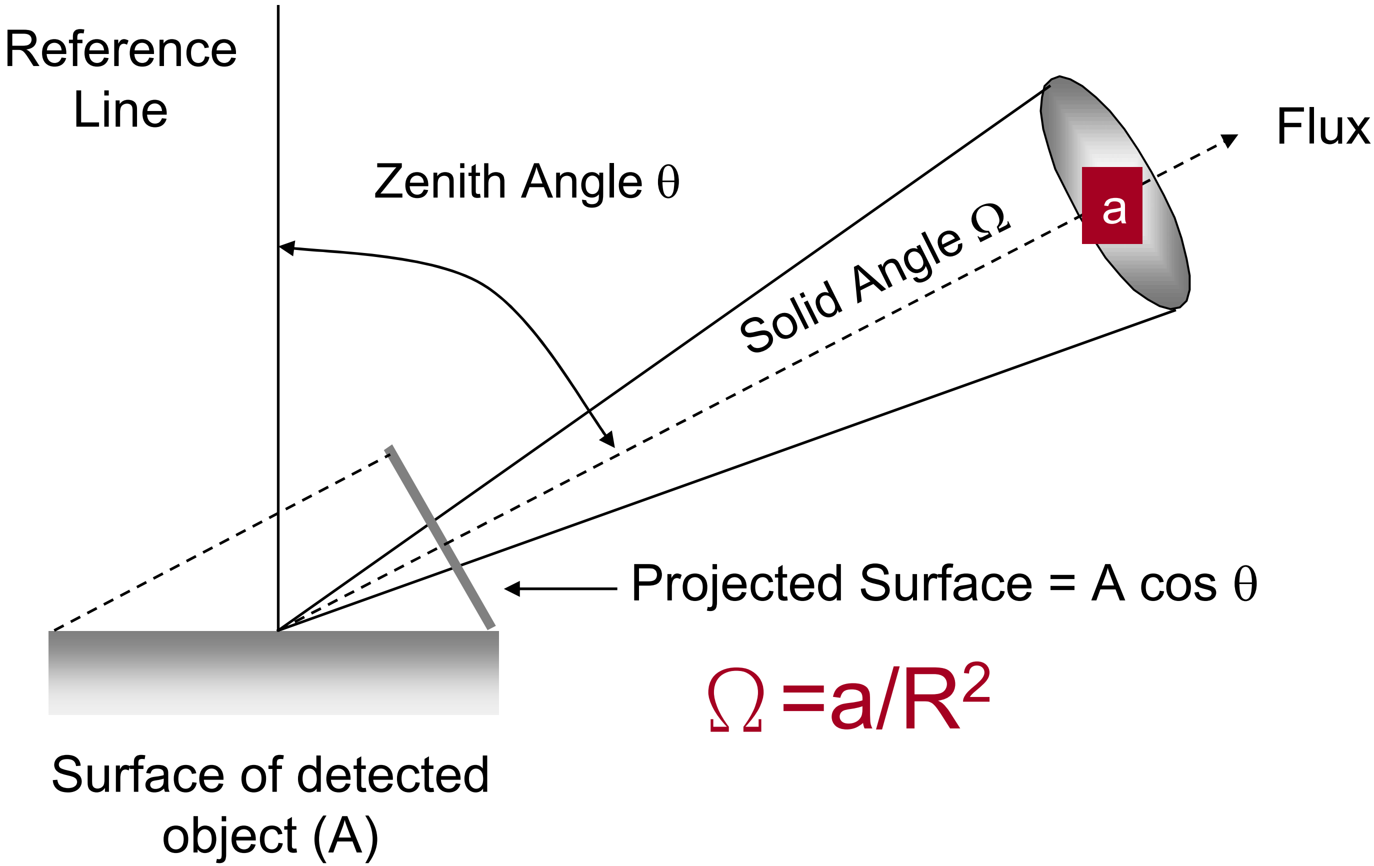
2. Temporal (How Fast Can the System Do?):

   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:
- $\sigma T_{plate}^4 = K_{solar}$
- $T_{plate} = (1500/\sigma)^{1/4} \sim 403K = 130^oC$

$= \sqrt[4]{\frac{\ \ solar}{\varepsilon\sigma}}$

How to Manipulate the Equilibrium Temperature T_{equi}

- By varying Surfaces Solar Absorption Coefficient α and ε
- For α of 0.2 and ε 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 Surface so Warm in the Sun?

Polished Metal Surfaces have low α and ε

Assume $\alpha = \varepsilon = 0.2$

$$T_{equi} = \sqrt[4]{\frac{\alpha K_{solar}}{\varepsilon\sigma}} = \sqrt[4]{\frac{0.2 X 1500}{0.2 X 5.67 X 10^{-8}}} = 403K!$$

- 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

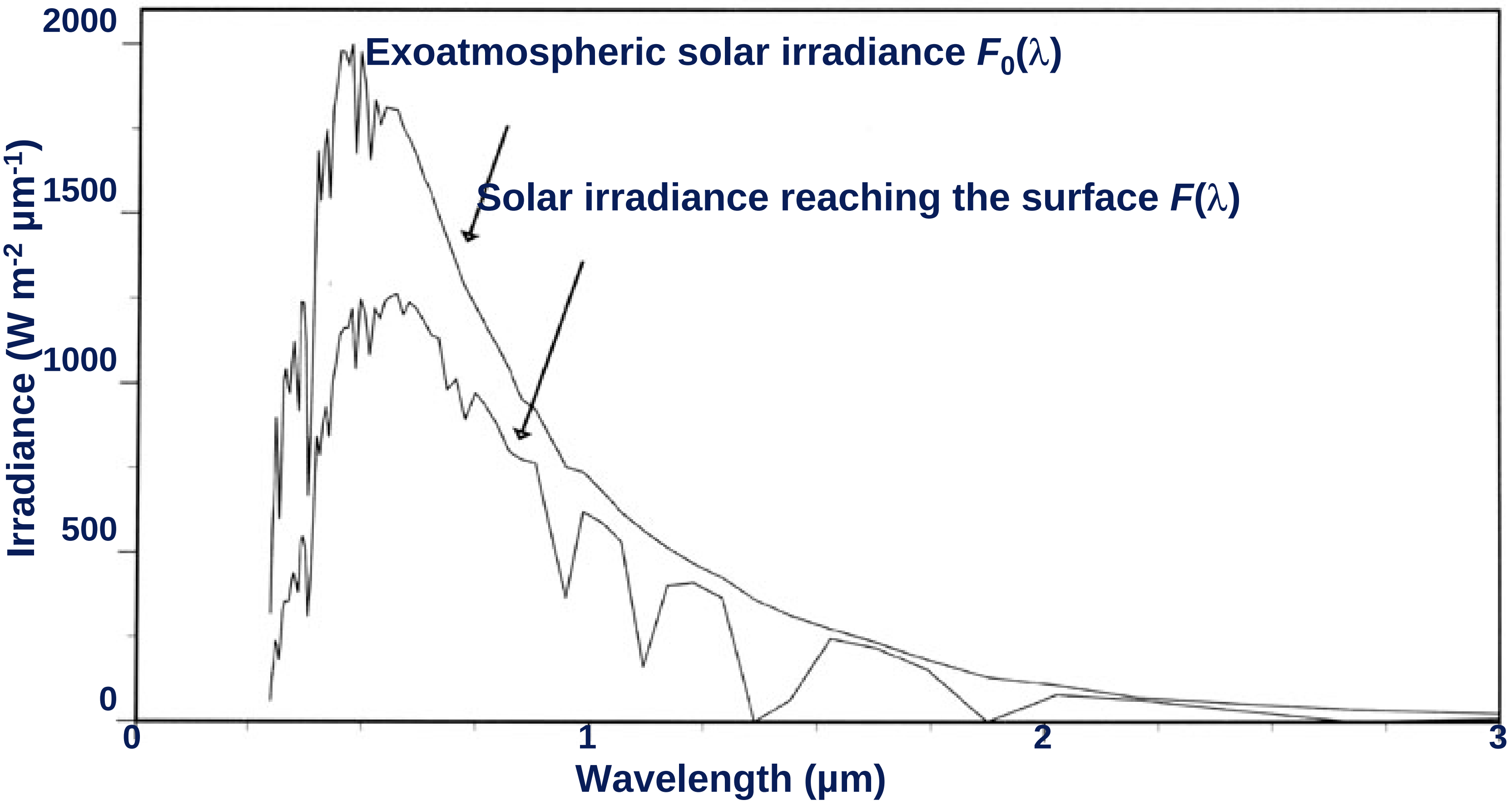
$\Delta Q \sim \Delta T^{n};\ n \neq 1$

- Radiation

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

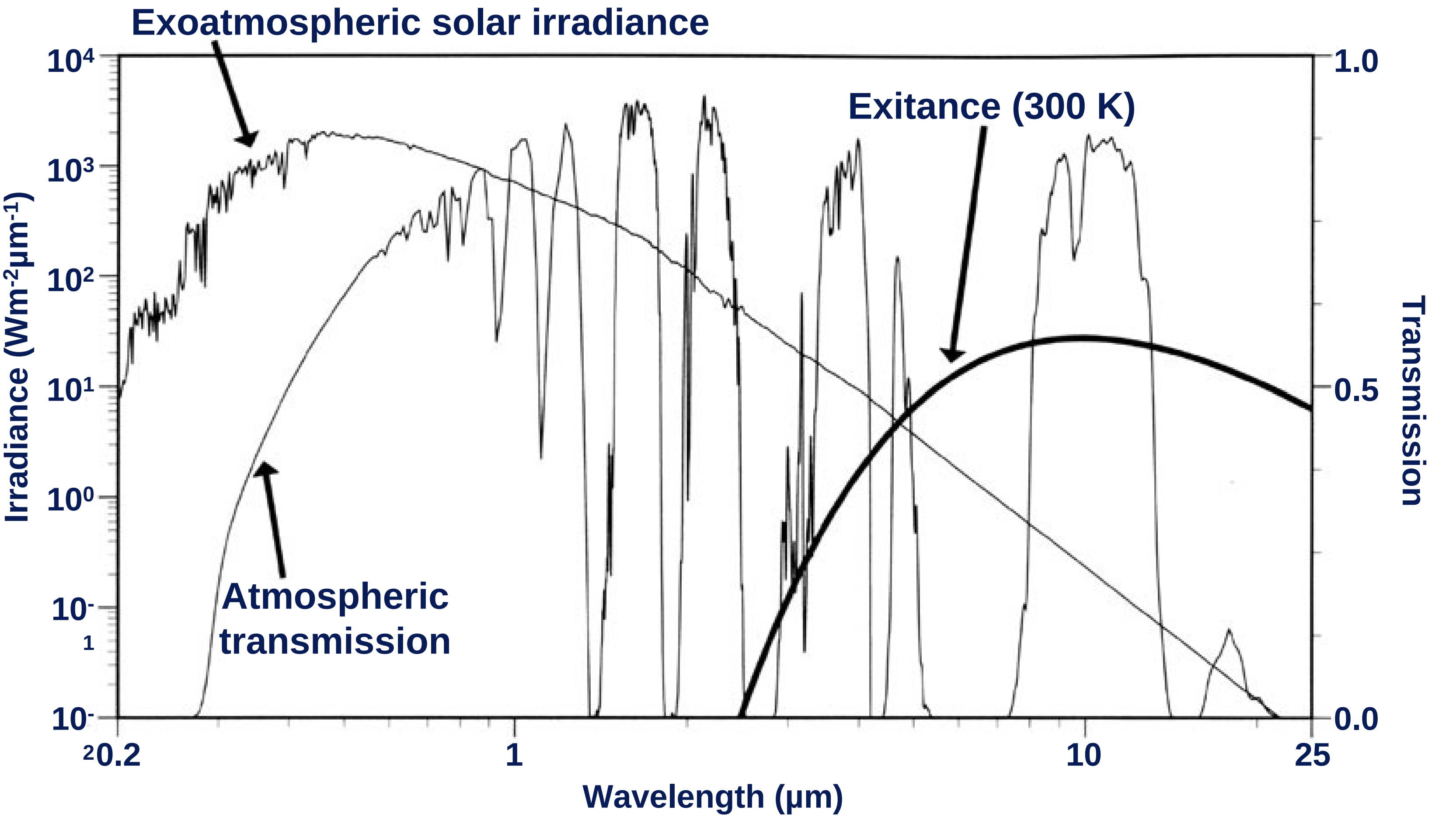
Radiative Heat Transfer is the Only Form of Heat Transfer that requires Absolute Temperature instead of Temperature Difference

Scattering of Sunlight by the Earth-Atmosphere-Surface System



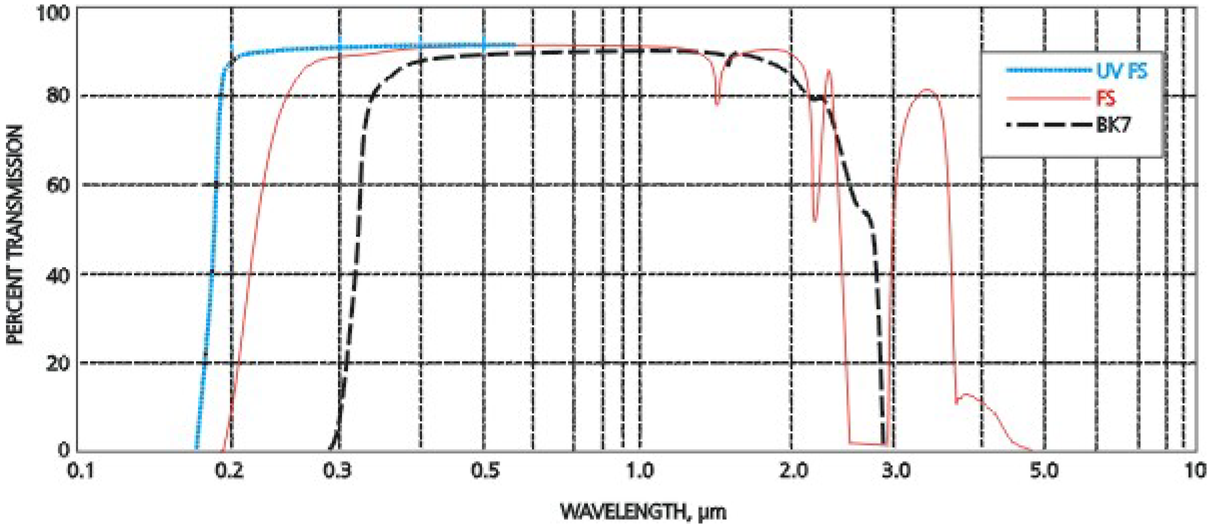
Atmospheric Transmission and Greenhouse Effects

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



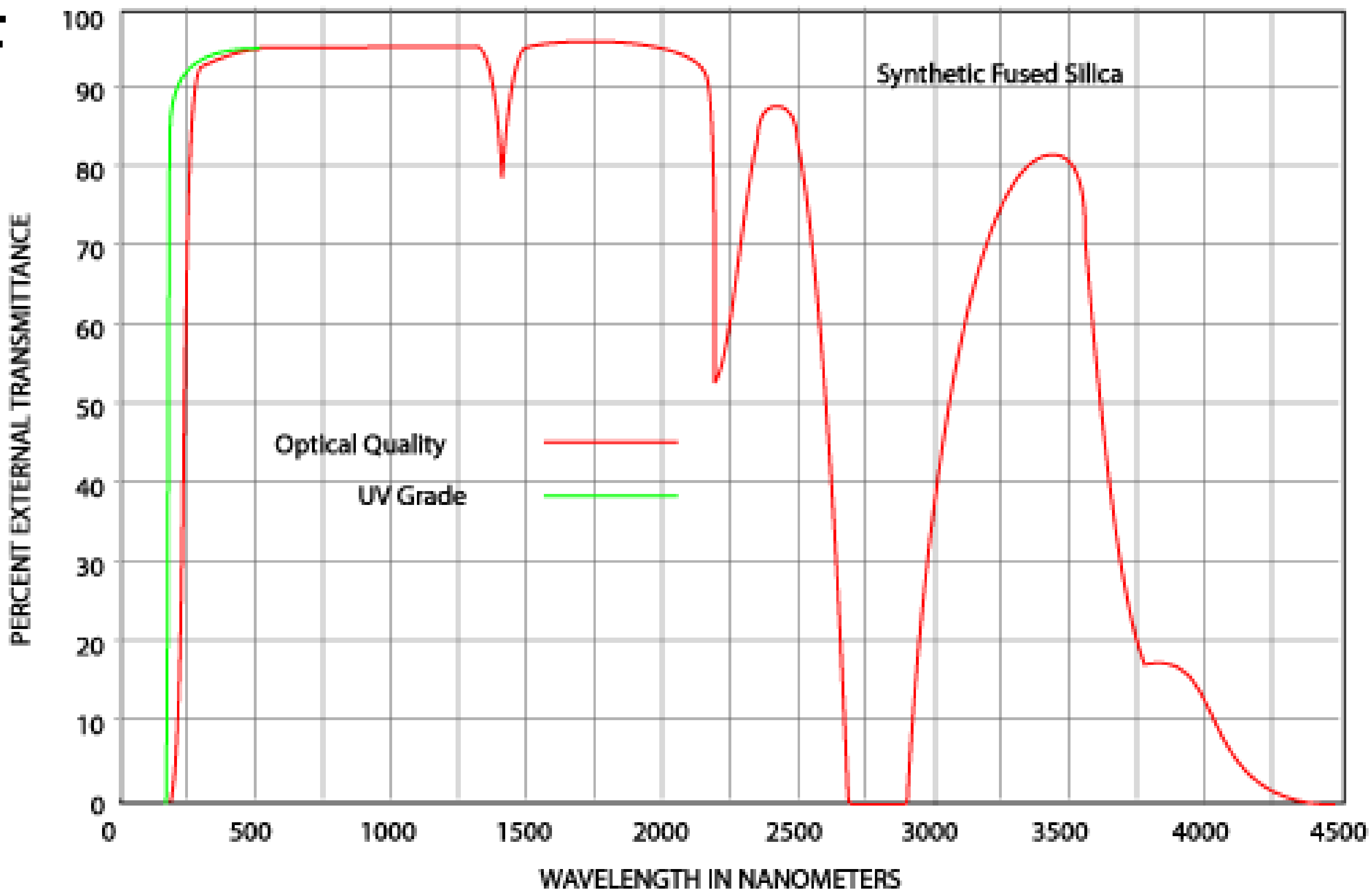
BK-7 Transmission Curve

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



Fuse Silica (quartz)Transmission

- F



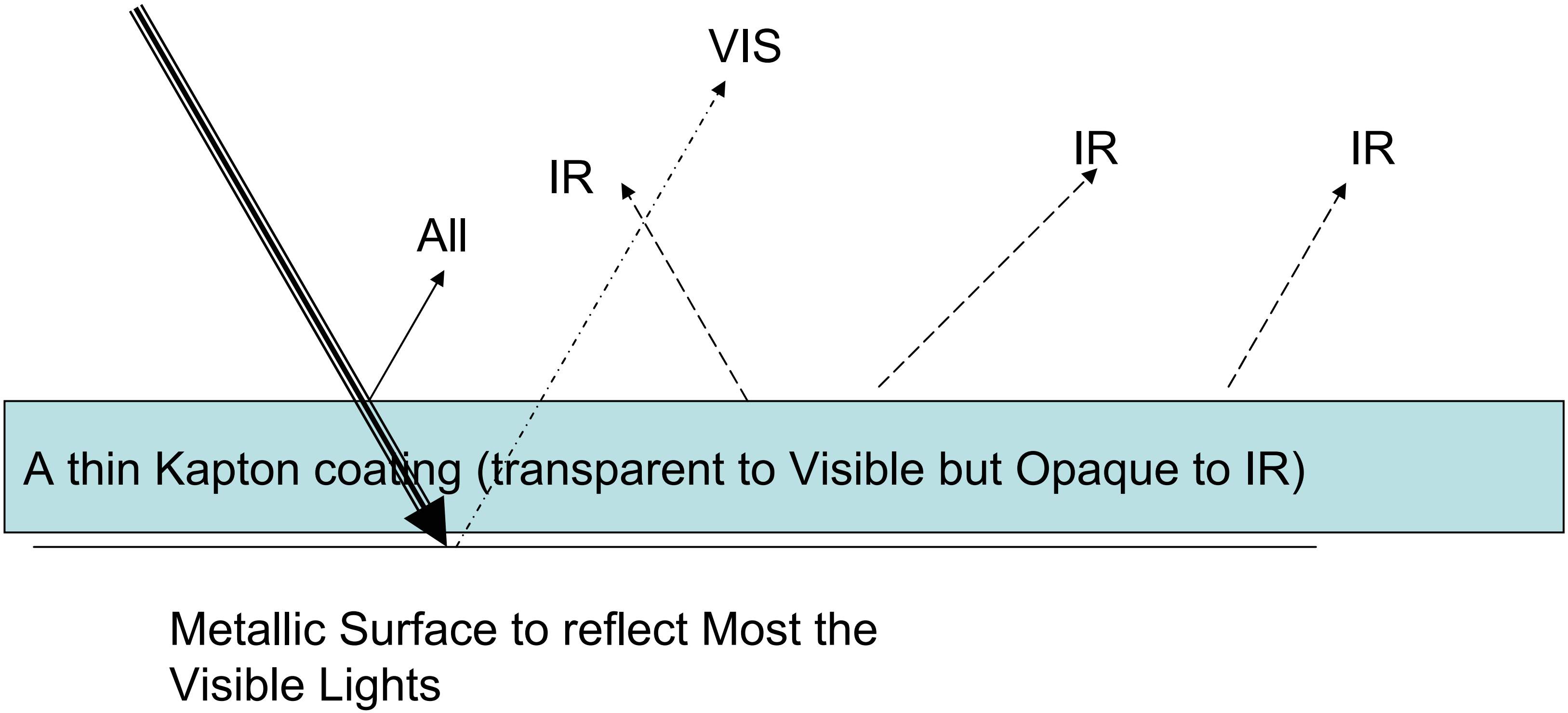
http://www.mellesgriot.com/products/optics/mp_3_2.htm

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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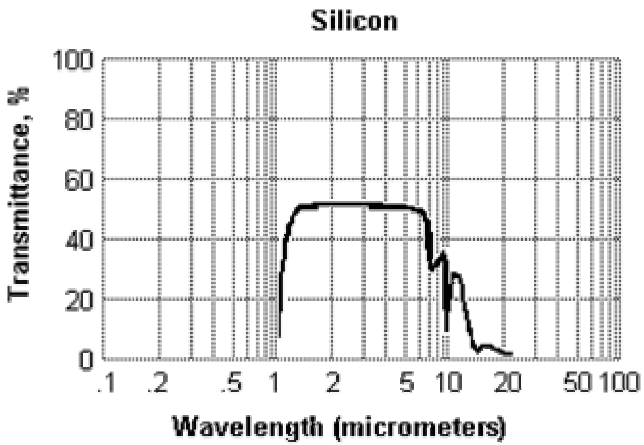
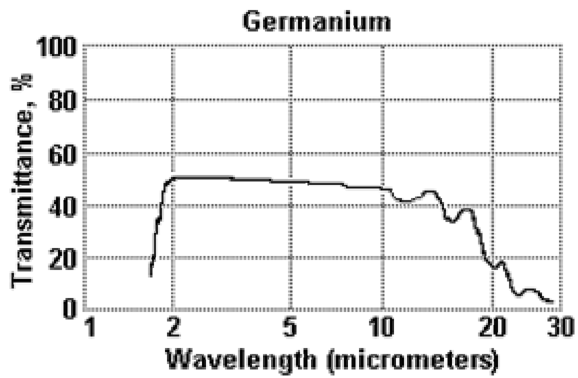
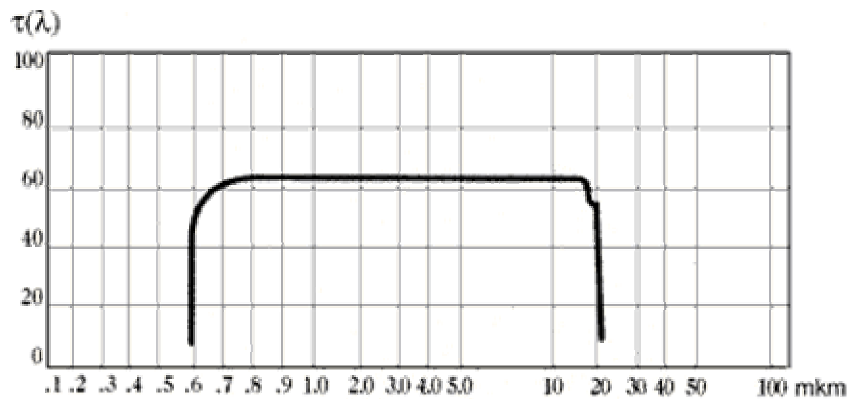




ZnSe Transmission

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



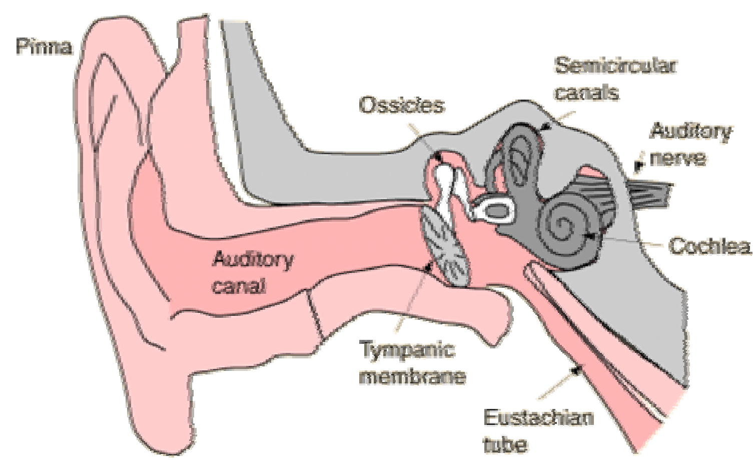
Regardless the “skin tone” difference, all men are equal in Infrared

- 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!!

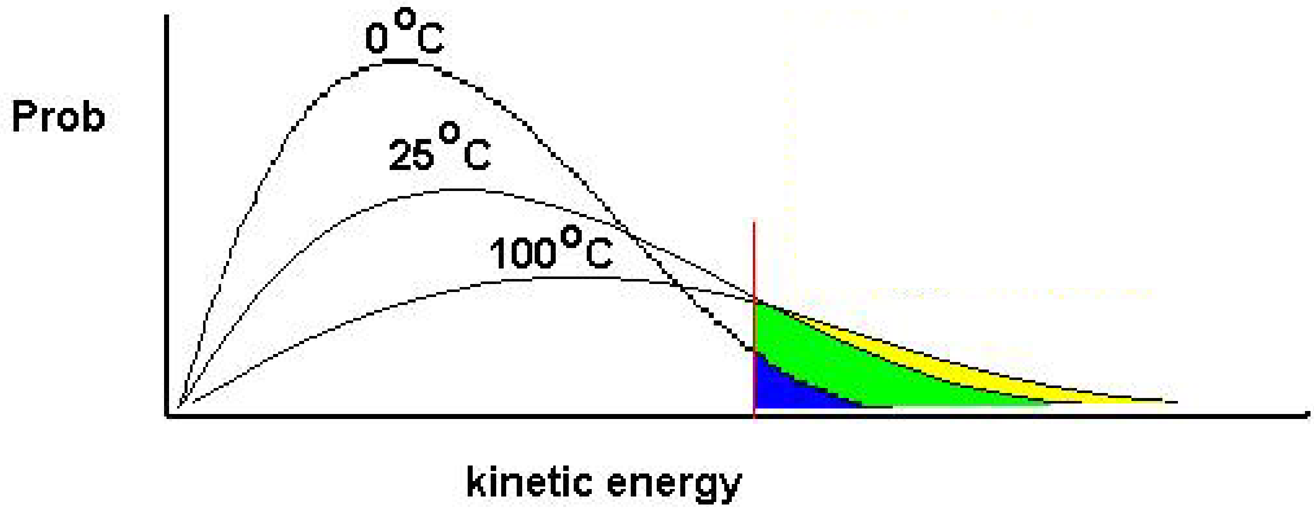


The Infamous SAR Fighter: Ear Cavity Thermometer

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

Electron Thermal Energy: Why IR Detectors Must be Cooled!

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



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?

$$D^*=(A_{det}\,\Delta f)^{1/2}/NEP$$

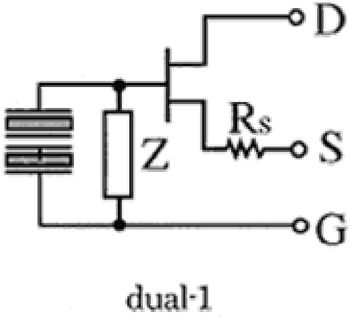
Pyro-electric Detectors

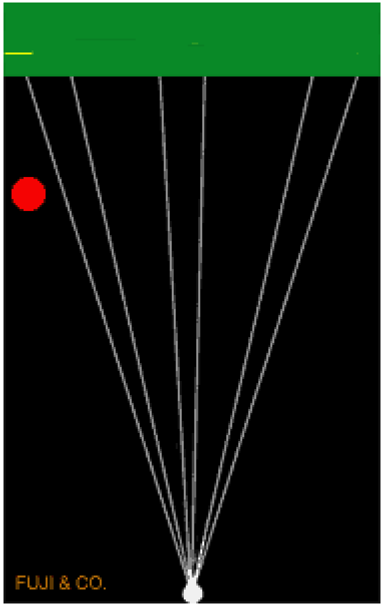
- Pyro: Gk “Fire”
- Pyro-electric: electrical output caused by heat
- Sometimes used for “fiery sparks” display for stage effects
- Low sensitivity, low cost
- Usually for intrusion detection only

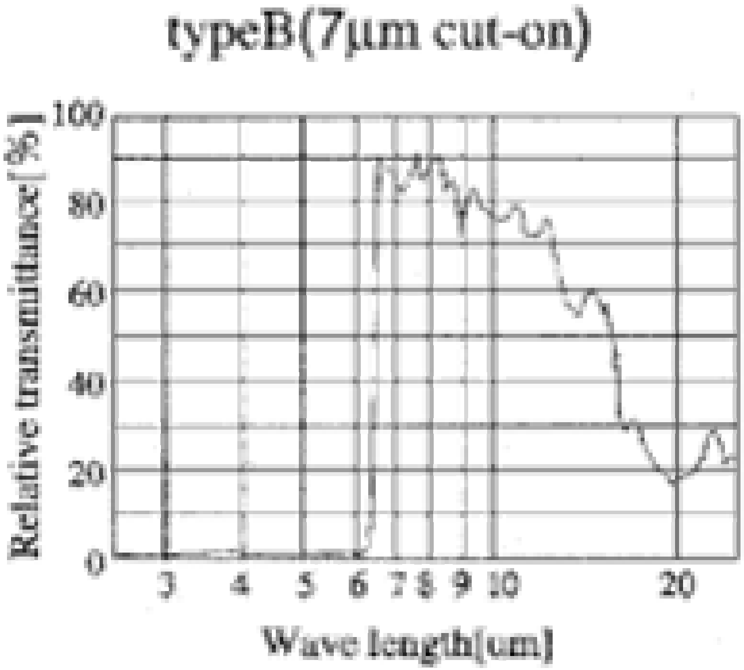
Pyro-electric Detector

polyethylene Fresnel lens are typically used for their low costs

TGS (Tri-glicine-sulfate)







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
- Intrinsic Detectors
- Need “chopping”
- Response varying with temperature
- Operative in higher temperature than PV

Thermal Transducer is “Export Control” Items

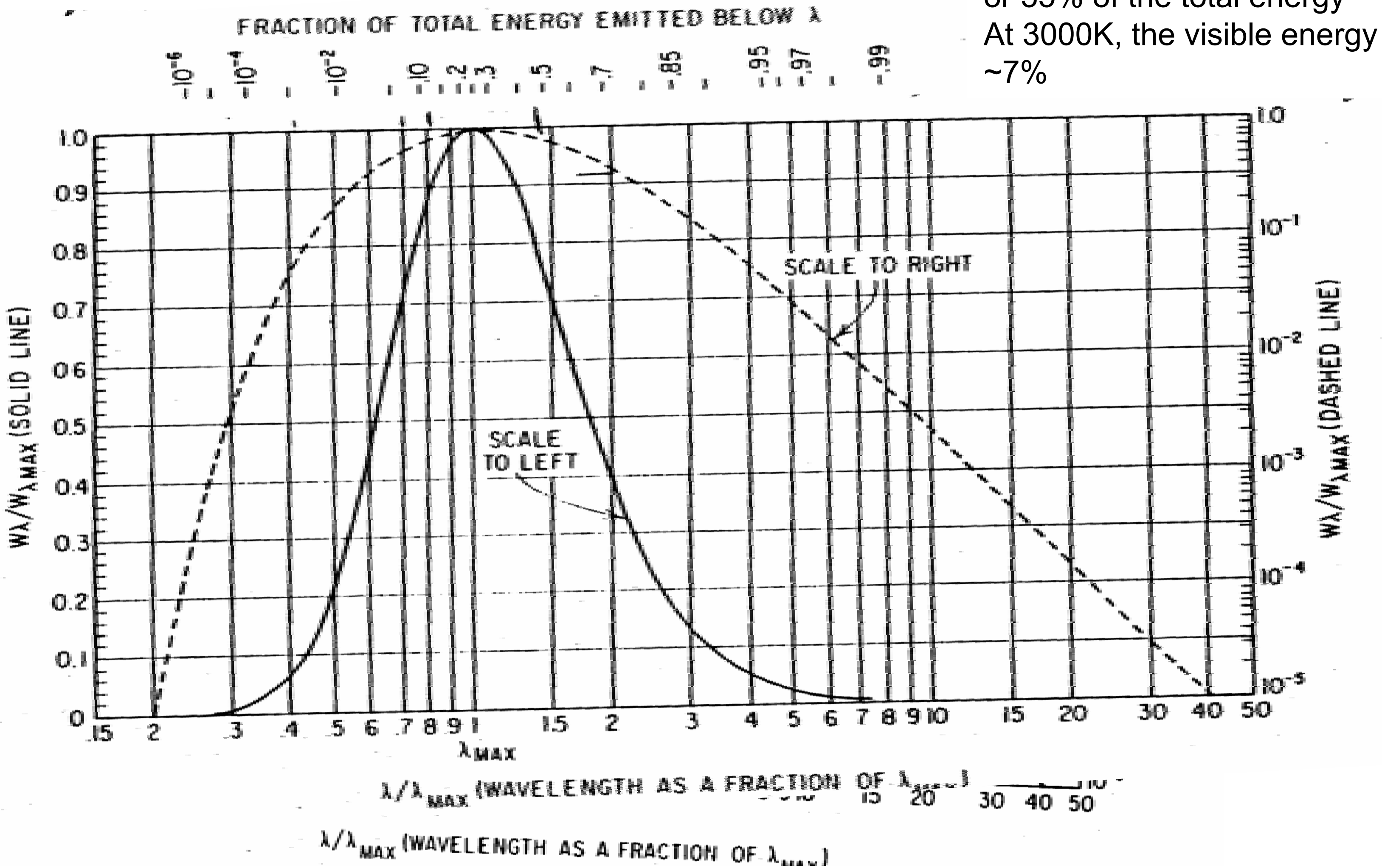
- InSb, HgCdTe, and room-temperature Thermal-pile Focal Plane Arrays (FPA) are all “Strategically sensitive” items

References

- *Electro-Optics* by Lewis J Pinson, John Wiley & Sons, Inc., (1985)
- *Modern Physics* by Serway, Moses, and Moyer, Saunders College Publishing, 1997
- *Optical Radiation Detectors* by Dereniak and Crowe, John Wiley and Sons
- *Infrared Handbook* by Wolfe etc., Environmental Research Institute of Michigan

Normalized Blackbody Equation

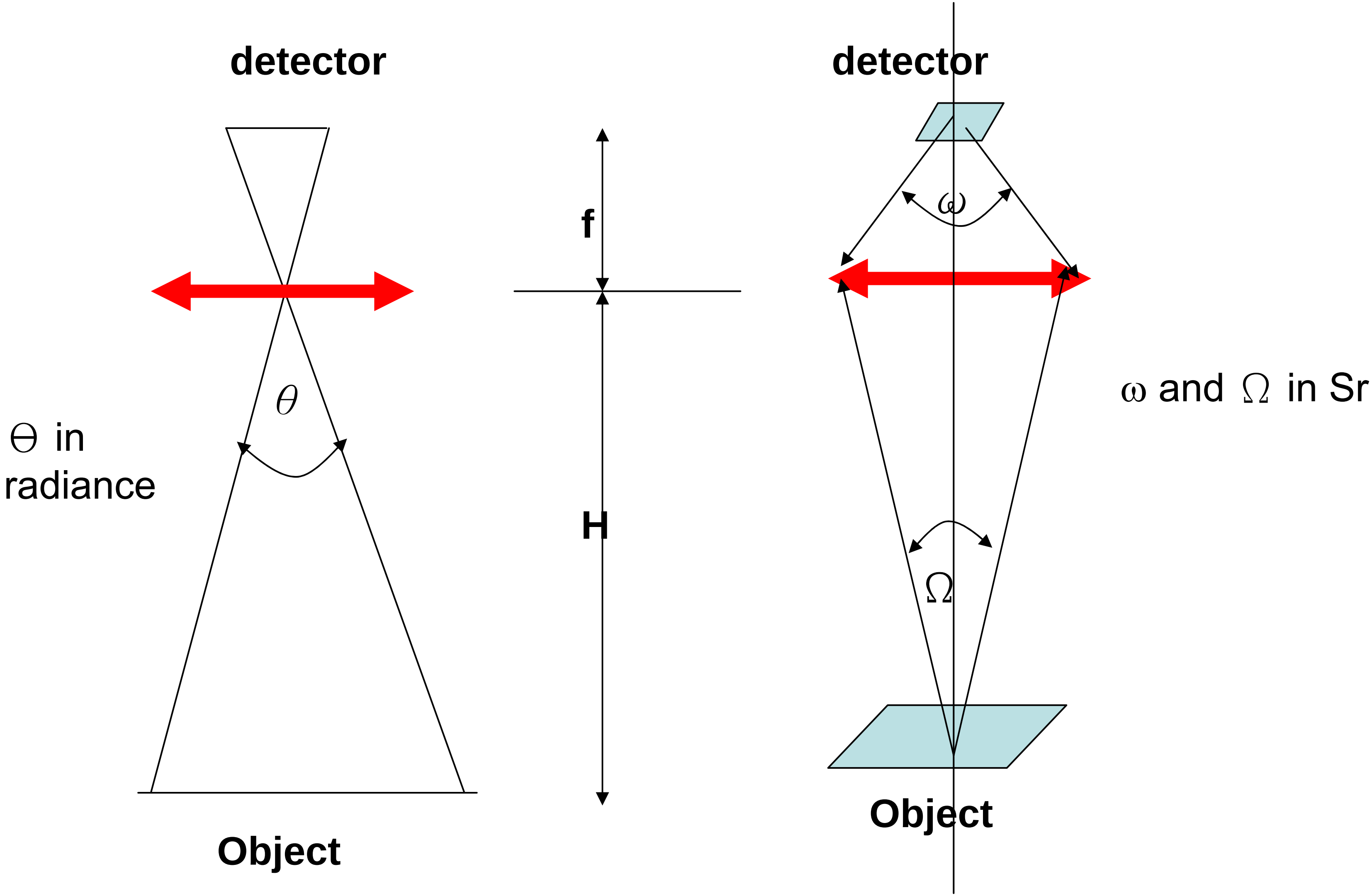
At T=6000K, λmax=0.5 μm
Since o.4<$\lambda_{vis(}\mu$m<0.7 or
0.8 < $\lambda / \lambda_{max} < 1.4$
So % visible energy is
0.45-0.1=0.35
or 35% of the total energy
At 3000K, the visible energy ~7%



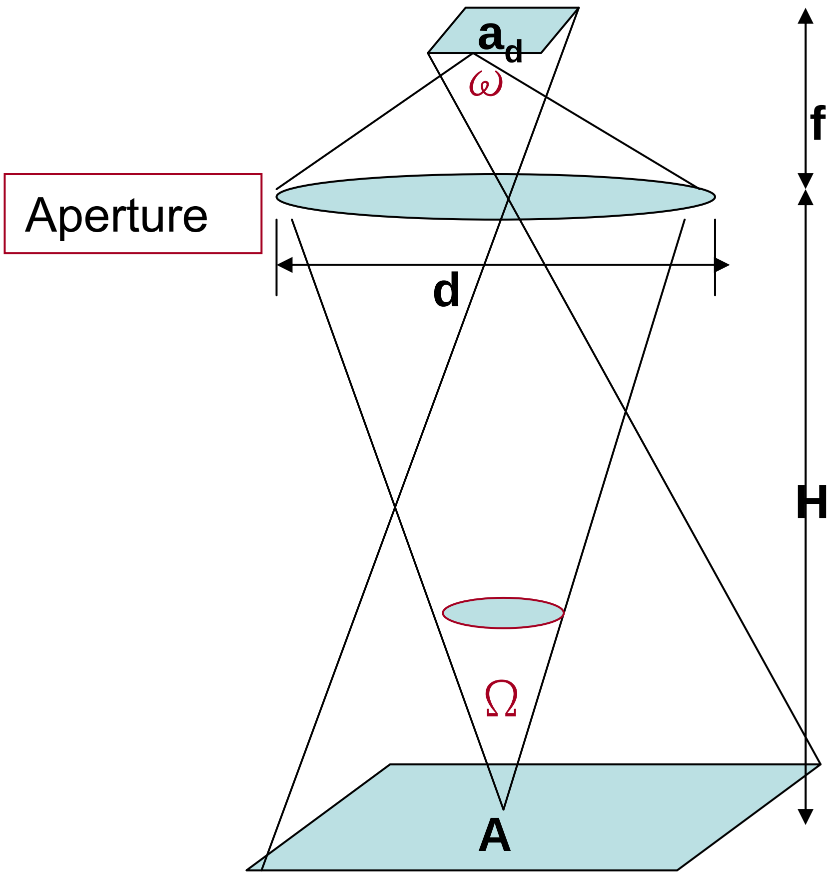
Homework(1)

- At the Daper point (800K), a blackbody begins to be visible, computer the visible exitance
- A 1-cm thick,1m square plate has one side perpendicular to the sun and a conductivity of 0.01 W/m/K. If the emissivities of both surfaces are all 1/5.67, and the shodow side of the surface temperature is 300K, compute the solar absorptivity of the surface facing the Sun
- Prove the blackbody equation can be normalized as $M_{\lambda} / M_{\lambda, max}$ vs. λ / λ_{max}
- Compute the percentage increase in visible energy for a 3000K blackbody to 3400K (incandescent tungsten to halogen)

IFOV and Solid Angles



Radiometry Identity $a_d \omega = A \Omega$



$$\frac{a_d}{f^2} = \frac{A}{H^2}$$

Multiplying both sides by $\pi d^2/4$ yields

$$\frac{\pi d^2}{4}\frac{a_d}{f^2} = \frac{\pi d^2}{4}\frac{A}{H^2}$$

Since $\omega = \pi d^2/4f^2$ and $\Omega = \mathrm{p} d^2/4f^2$

Thus

$$a_d \omega = A \Omega$$

Optical Power on a Detector

- The Optical Power Falling on a Detector is:

P[W]

$= T_{opt} \cdot L[W\ Sr^{-1}\ m^{2}\ \mu m] \cdot \Omega A \cdot \Delta\lambda$

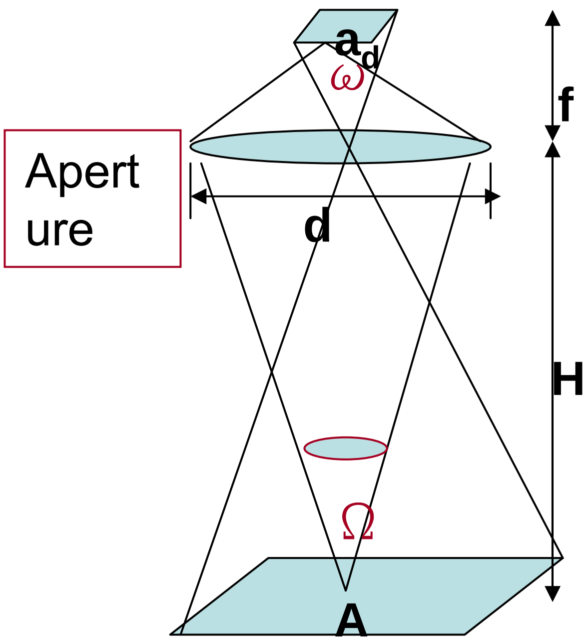
Substituting the Radiometry Identity yields:

$= T_{opt} \cdot L \cdot \omega a_{det} \cdot \Delta\lambda$

$$= T_{opt} \cdot L \cdot \frac{\pi}{4 \bullet (F/\#)^2} a_{det} \cdot \Delta\lambda$$

Since

$$\varpi = \frac{\pi d^2}{4 f^2} = \frac{\pi}{4(f/d)^2} = \frac{\pi}{4 \bullet (F/\#)^2}$$



Detector Responsivity

- An Ideal Detector Generates one e- for every Photon absorbed:

$$R_{ideal} = \frac{q}{h\nu} = \frac{q\lambda}{hc} \approx 0.8 \bullet \lambda [A/W]$$

An Actual Detector Responsivity is:

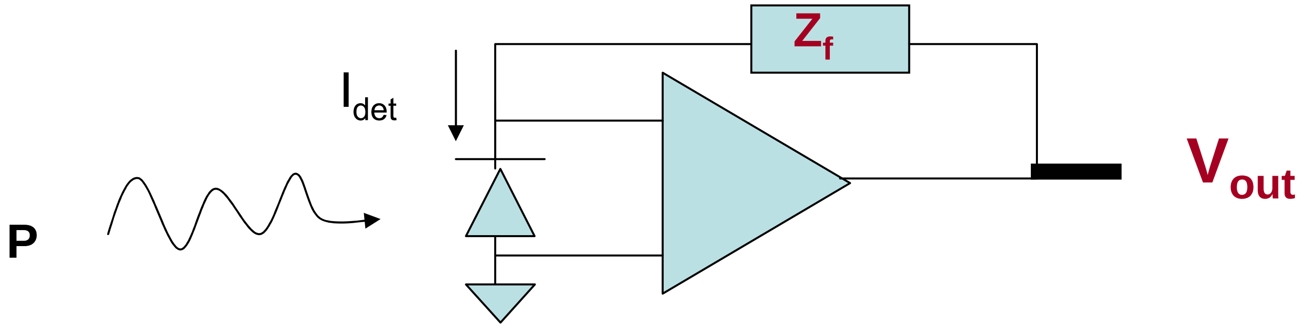
R[A/W]= η R_{ideal}= 0.8 η λ

q=1.6x10^{-19} Amp-sec

Note: λ in μm

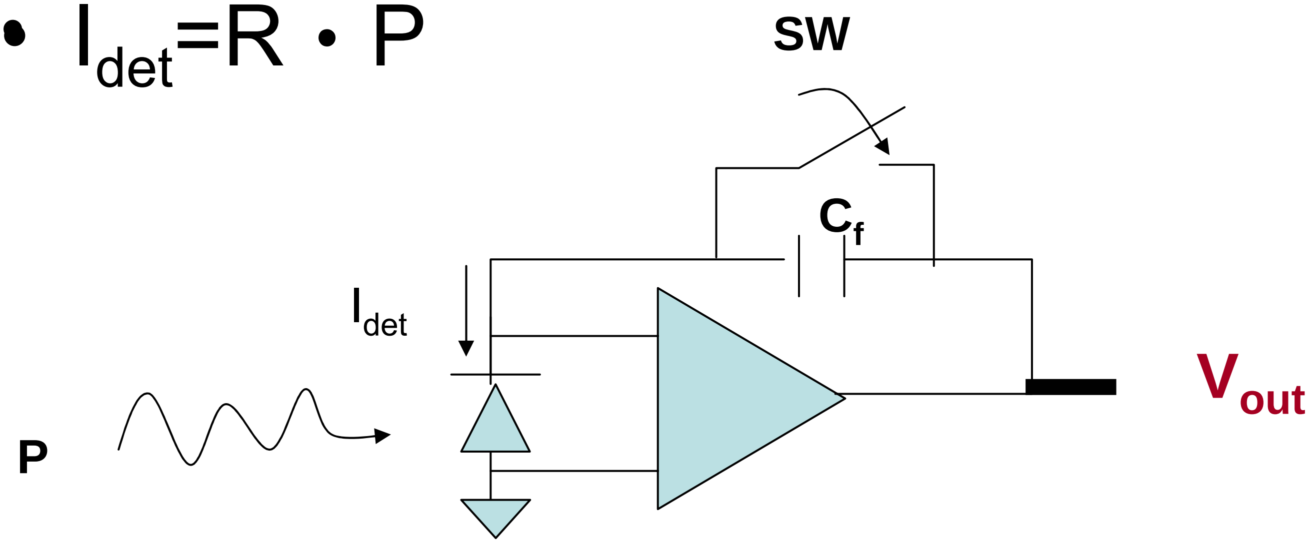
Theoretical Detector Output (TIA)

- $I_{det}=R \cdot P$
- $V_{out}= I_{det} \cdot Z_f$



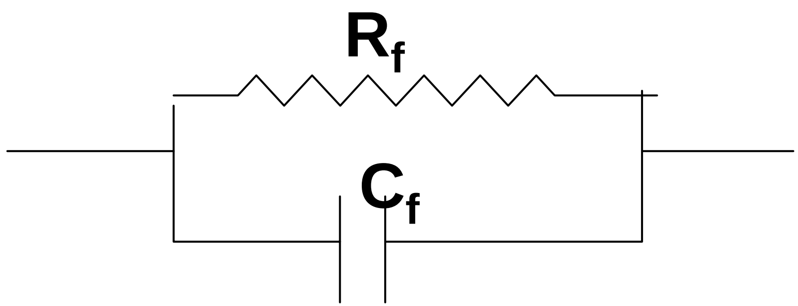
Theoretical Detector Output (CTIA)

- $I_{det}=R \cdot P$



$$V_{out} = \frac{I_{det} \bullet \tau_{int}}{C_f}$$

TIA Impedance Transfer Function



$$\frac{1}{Z_f} = \frac{1}{R_f} + \frac{1}{1/(j\varpi C_f)}$$

The Complex Impedance is

$$Z_f = \frac{R_f - j\varpi R_f^{\,2} C_f}{1 + \varpi^2 R_f^{\,2} C_f^{\,2}}$$

The Transfer Function is:

$$\left[\mathbf{Z_f}\right] = \frac{R_f}{\sqrt{1 + \varpi^2 R_f^{\,2} C_f}}$$

When ω=1/RC

$|Z_f|$=Rf/$\sqrt{2}$

l

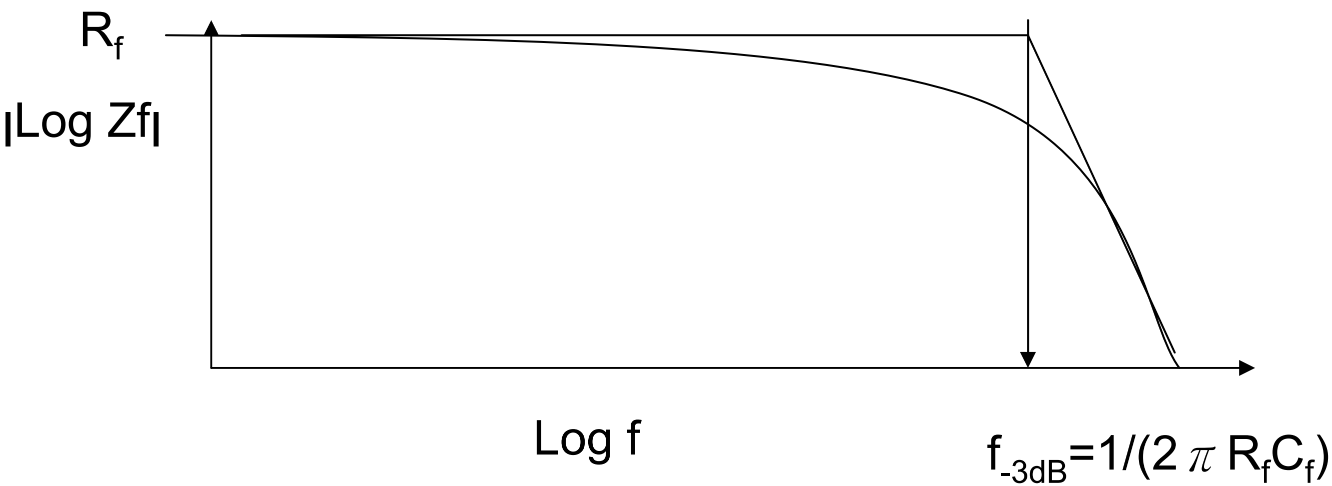
Frequency Response of Z_f

Since ω=2 π f, and $f_{3db}=1/(2\pi R_f C_f)$

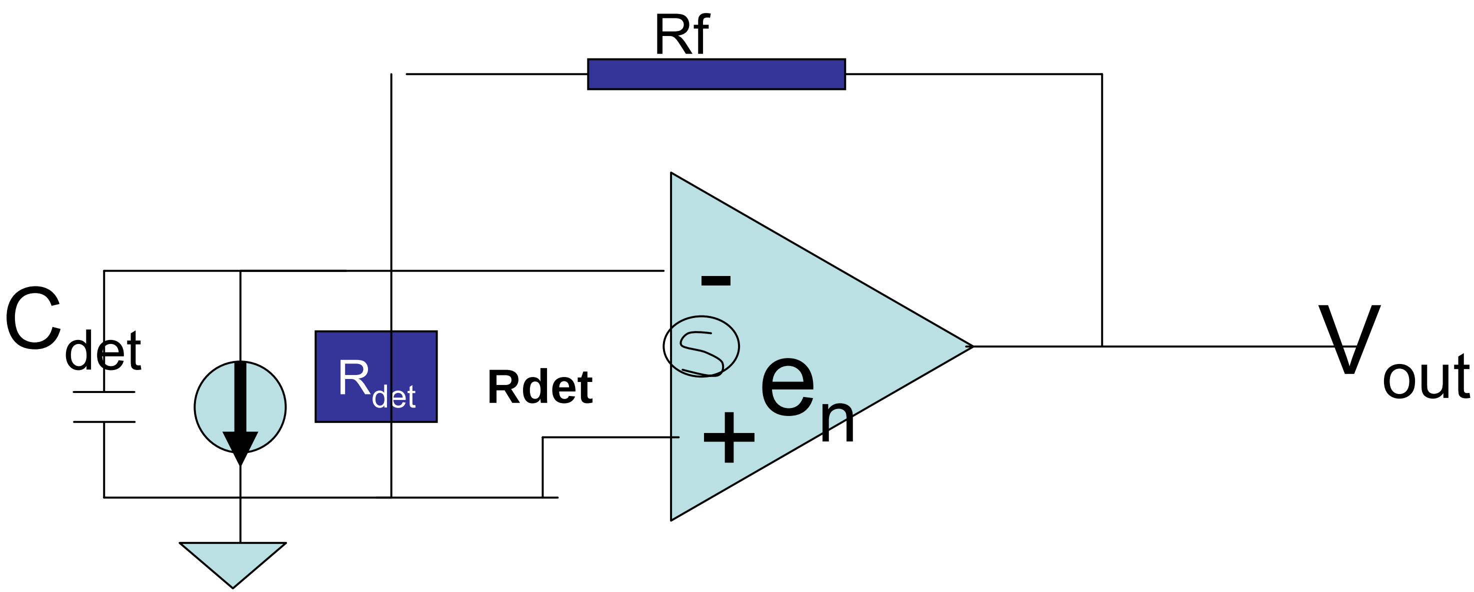
$|Z_f|=Rf/\sqrt{2}=0.707\ R_f$ @ $f_{-3dB}=1/(2\pi R_f C_f)$

dB=20 log (0.707)= -3 dB

$$[\mathbf{Z_f}]=\frac{R_f}{\sqrt{1+\varpi^2 R_f{}^2 C_f}}$$



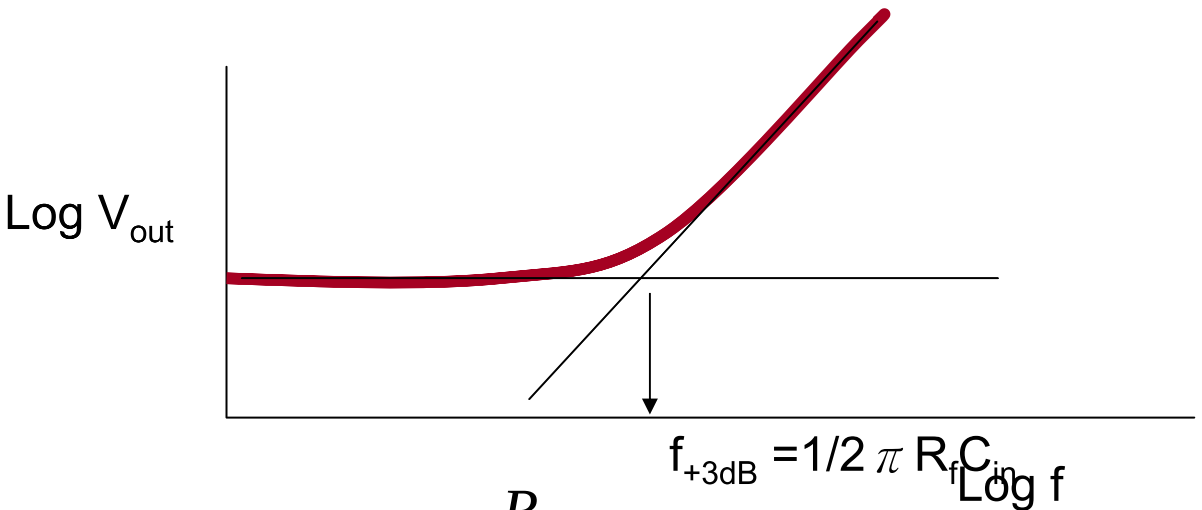
Why is that Detector Impedance needs to be High



If $R_{det} >> R_f$

$$V_{out} = e_n\left(1 + \frac{R_f}{R_{det}}\right) \approx e_n$$

"Boosted Input Noise from C_{in}"



$$V_{out} = e_n\left(1 + \frac{R_f}{1/j\varpi C_{in}}\right) = e_n(1 - j\varpi C_{in})$$

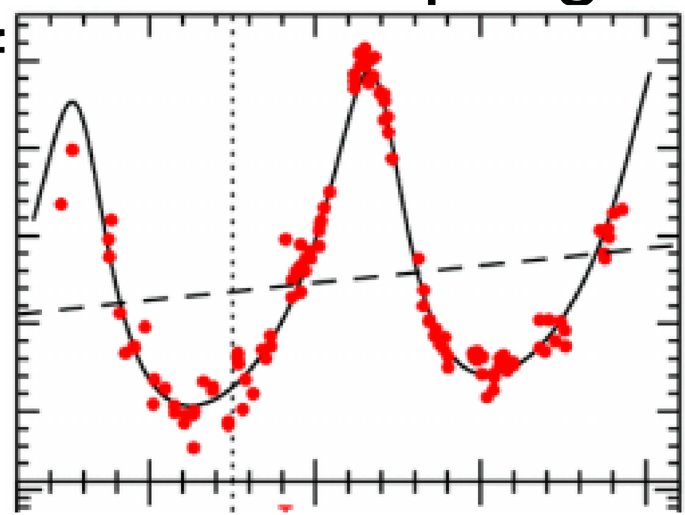
$$|V_{out}| = e_n\sqrt{(1+\omega^2 R_f^2 C_{in}^2)}$$

When $\omega = 1/RC$

$|V_{out}| = \sqrt{2}$ en

Chopping is Essential for "Drifting Signal"

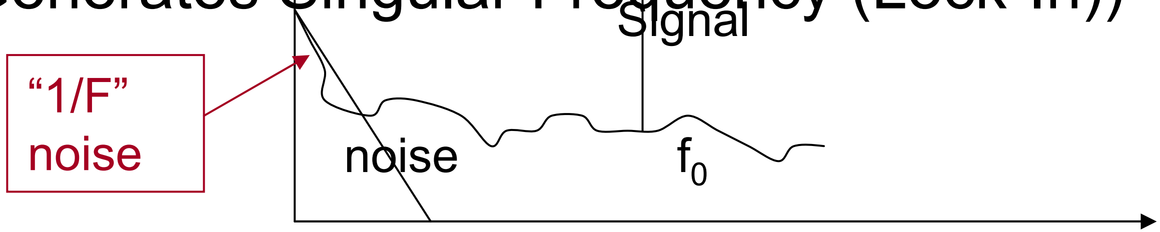
- Chopping Effectively "De-couples" the Slow Drifting "1/f" Noise (including D.C. Level)
- In CCD, A "Correlated Double Sampling" is Used to Eliminate Drif

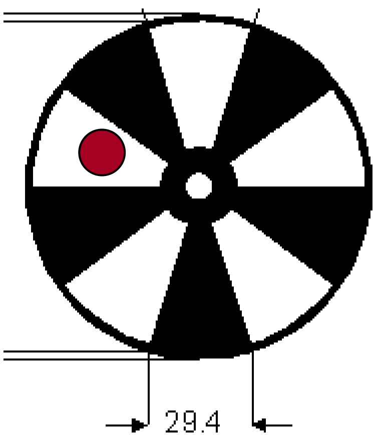


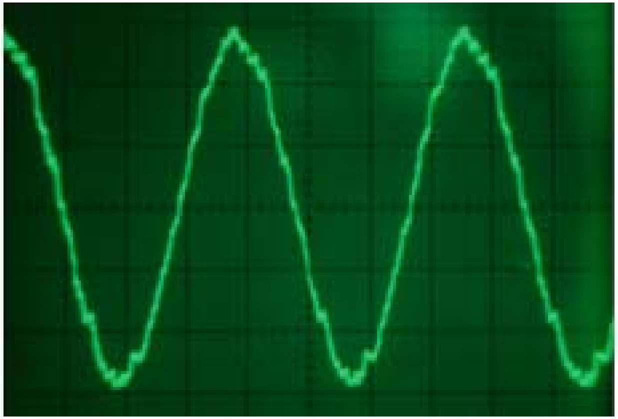
The Concept of Signal Chopping

- An Ideal way to “decouple” the 1/F noise is the use of a Sine Wave Chopper

That Generates Singular Frequency (Lock-In))

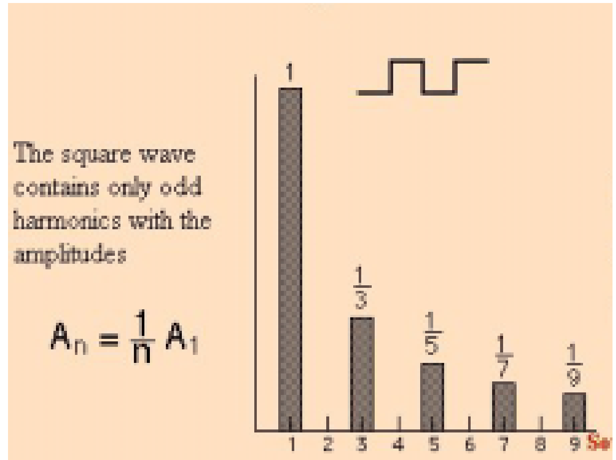


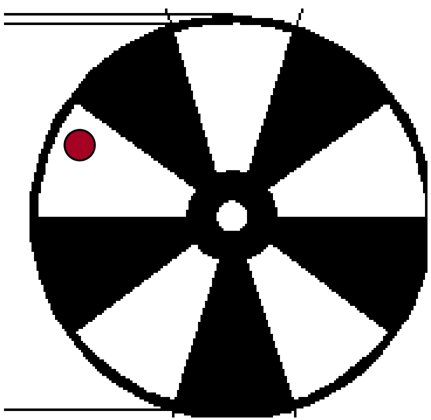


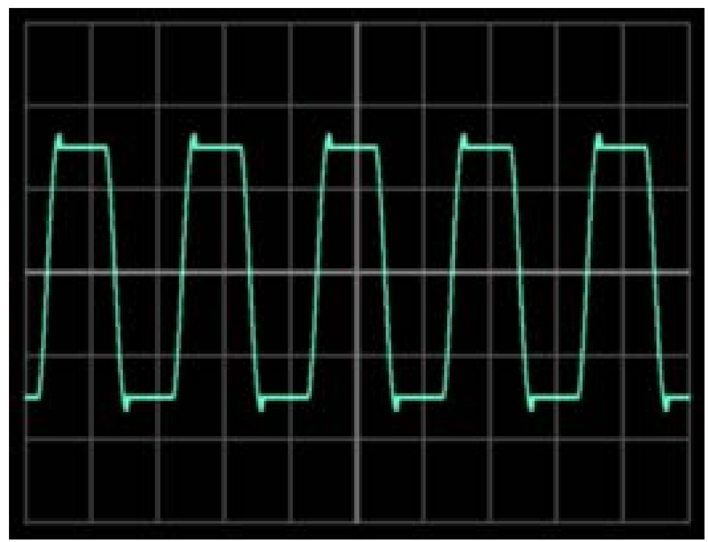


If the Aperture >> Beam Size You Have Square Waves

- So we May Still Utilize the "Fundamental Frequency" for Signal Comparison

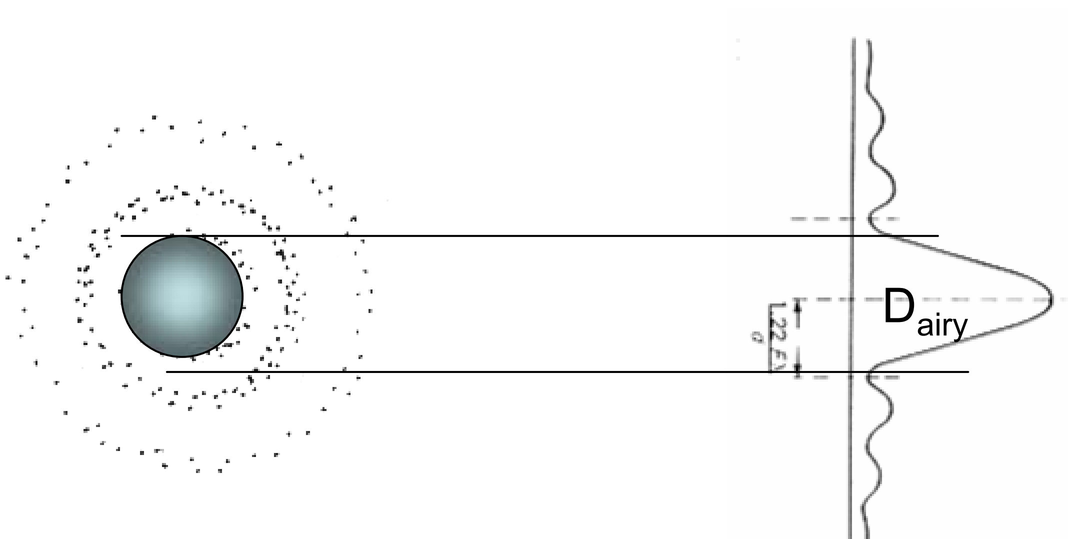






Airy Disc: Diffraction Limited Spot

D_{airy}=2.44 λ (F/#)
F/*: F-Stop of an Optical System=f.l./$D_{aperture}$
Since Numerical Aperture NA=$D_{aperture}$/(2 • f.l.)=1/(2F/#)
So D_{airy} =1.22 • λ • NA



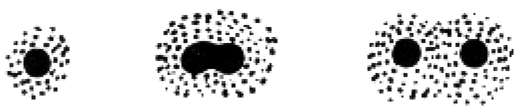
How Many Pixels Do we need on a Digital Cameral? The More the Better?

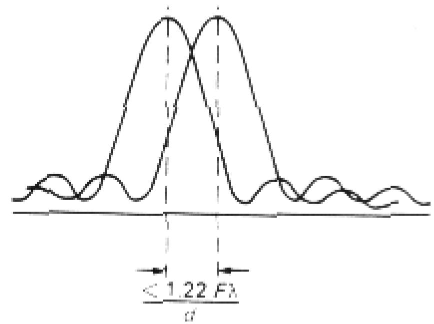
- Suppose a CCD Chip is 1000x1000, with each pixel dimensions of 7μm x 7μm
- The F/*=3.0;
- at 0.7 μm, the Airy disc is
- 2.44x 0.7x 3=5μm

- When λ =10μm, then the Airy disc=73 μm!
- In IR cameras, the pixels are “coarser”.

Rayleigh's Spatial Resolution

- The Resolution is Half of the Spot





Optical MTF

An Optical MTF is the Fourier Transform of its “Optical Spot” .If the system is Diffraction limited then its Optical MTF

Can be approximated by:

$MTF_{optical}=(2/\pi)\ (\phi\text{-}Cos\phi\ \sin\phi)$

Where $\phi=Cos^{-1}(\lambda f/2NA)$ because the “blur circle is wavelength dependent

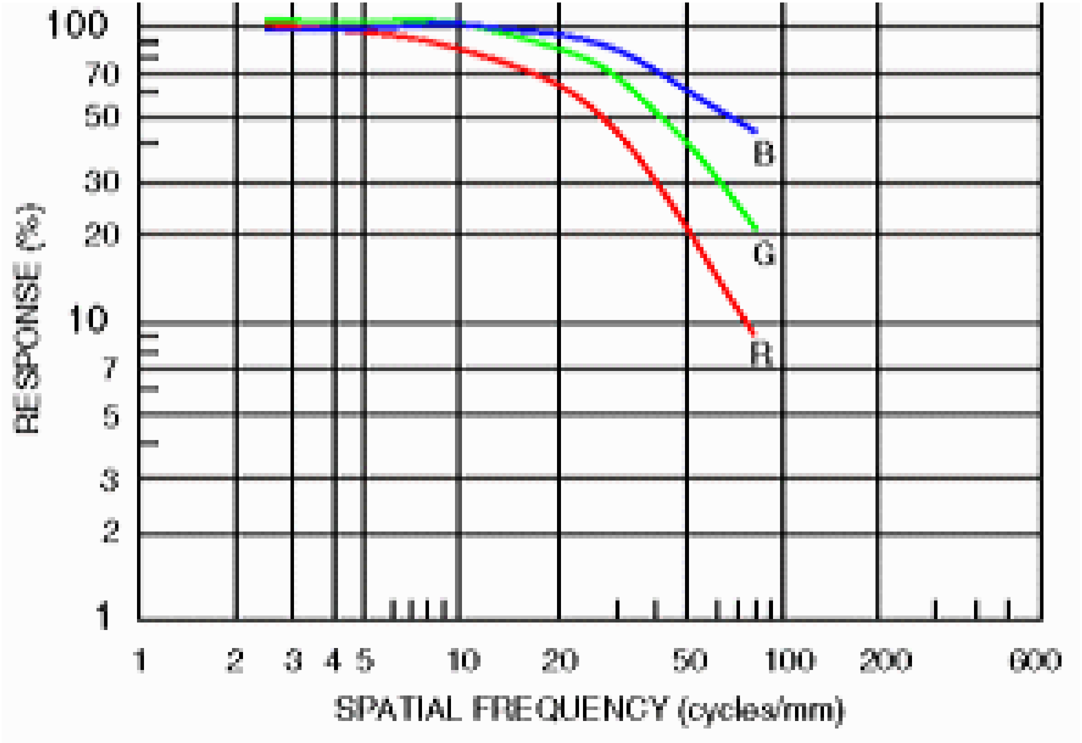
f: spatial frequency in “line pairs/ mm”

Practical Optical MTF Approximation

Most film MTF curves can be closely approximated by a Lorentzian function

MTF (f) = $1/(1+(f/f_{50})2)$

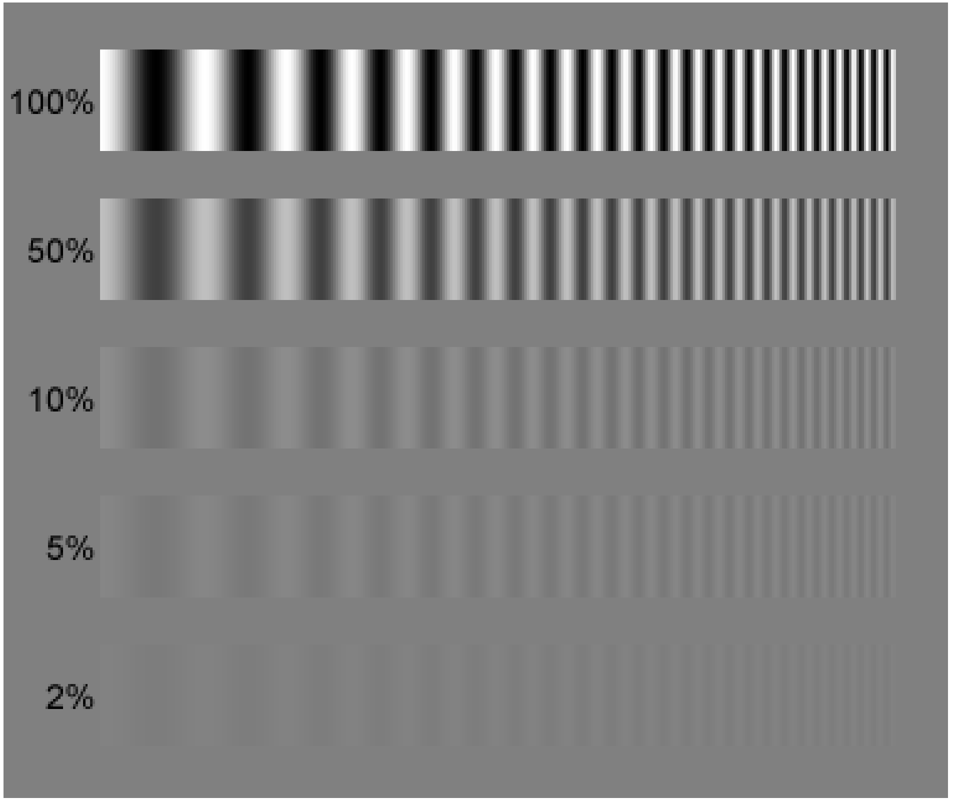
Where the "Nyquist MTF" f_{50} is wavelength dependent



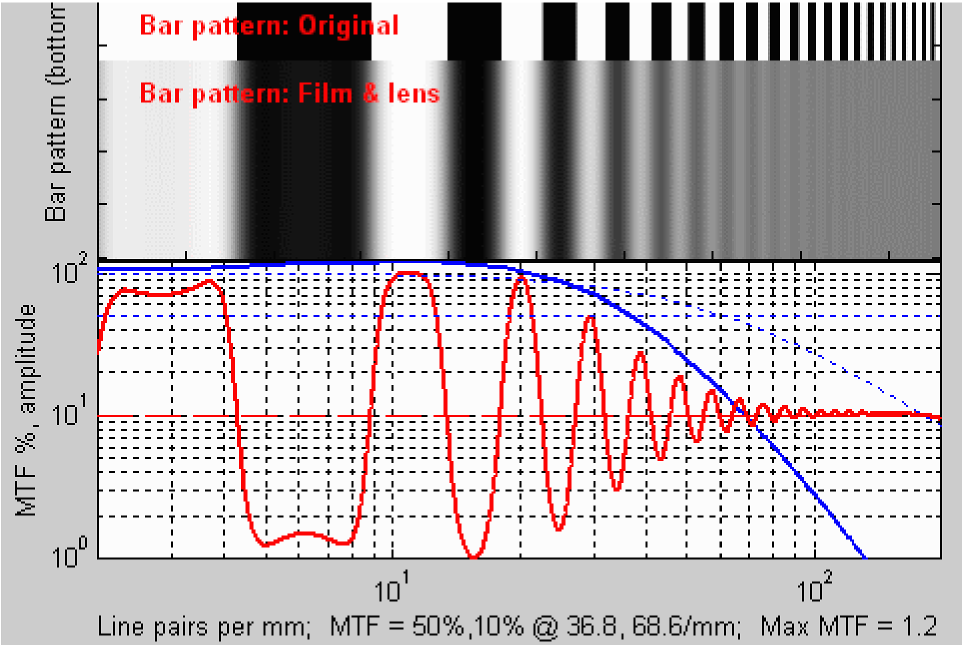
http://www.normankoren.com/Tutorials/MTF1A.html

MTF Examples-1

- MTF for a “Pure Tone”: sine function

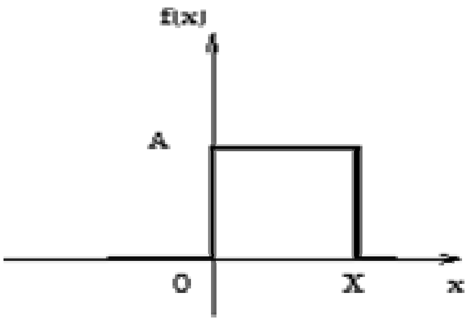


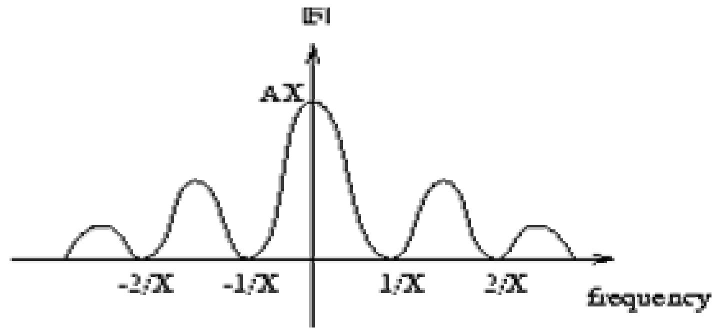
MTF Example-2



Detector MTF:Sinc Function

- Convolution of A Square Detector’s and a Sine Scene is Detector’s MTF



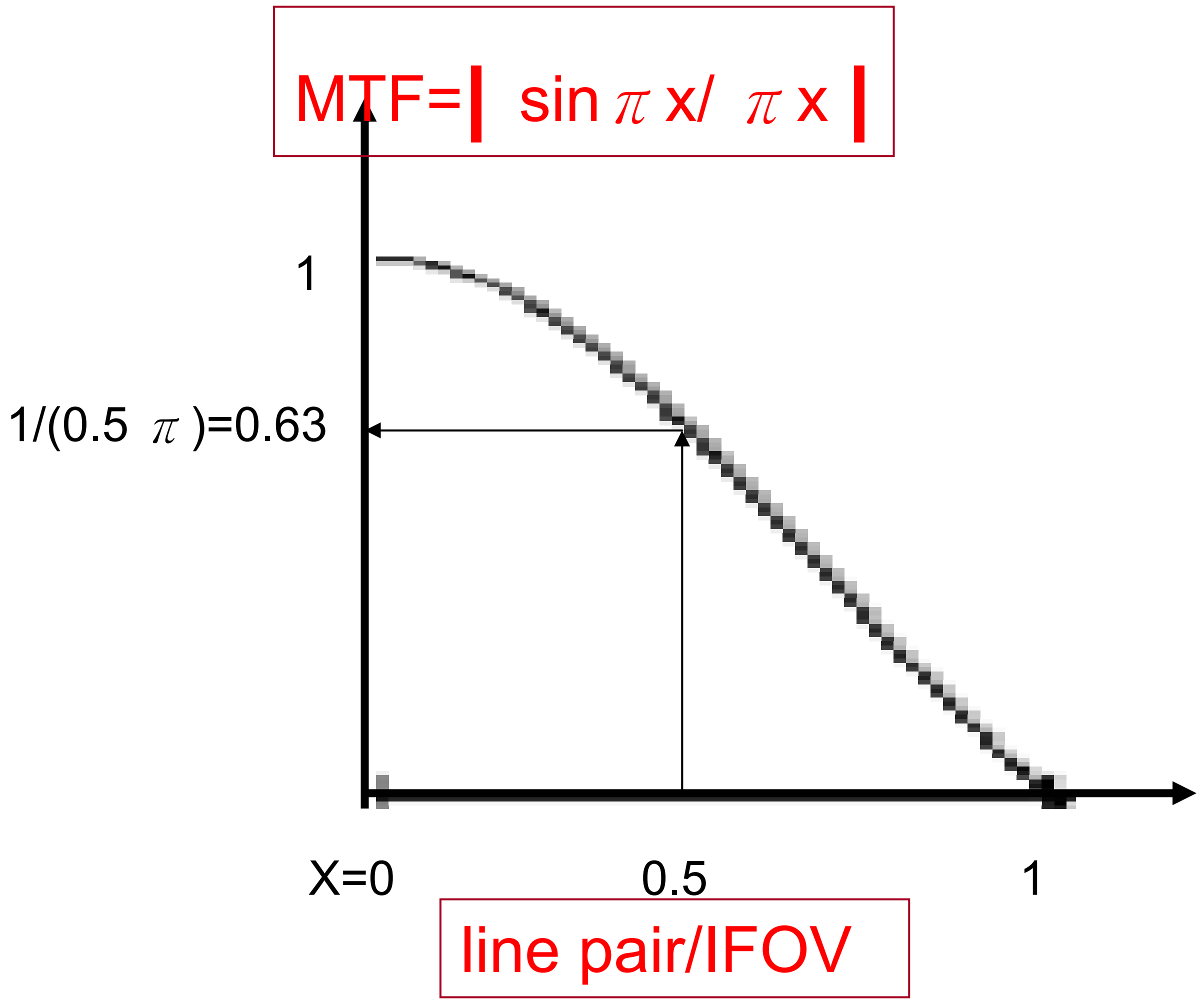


f=ωX

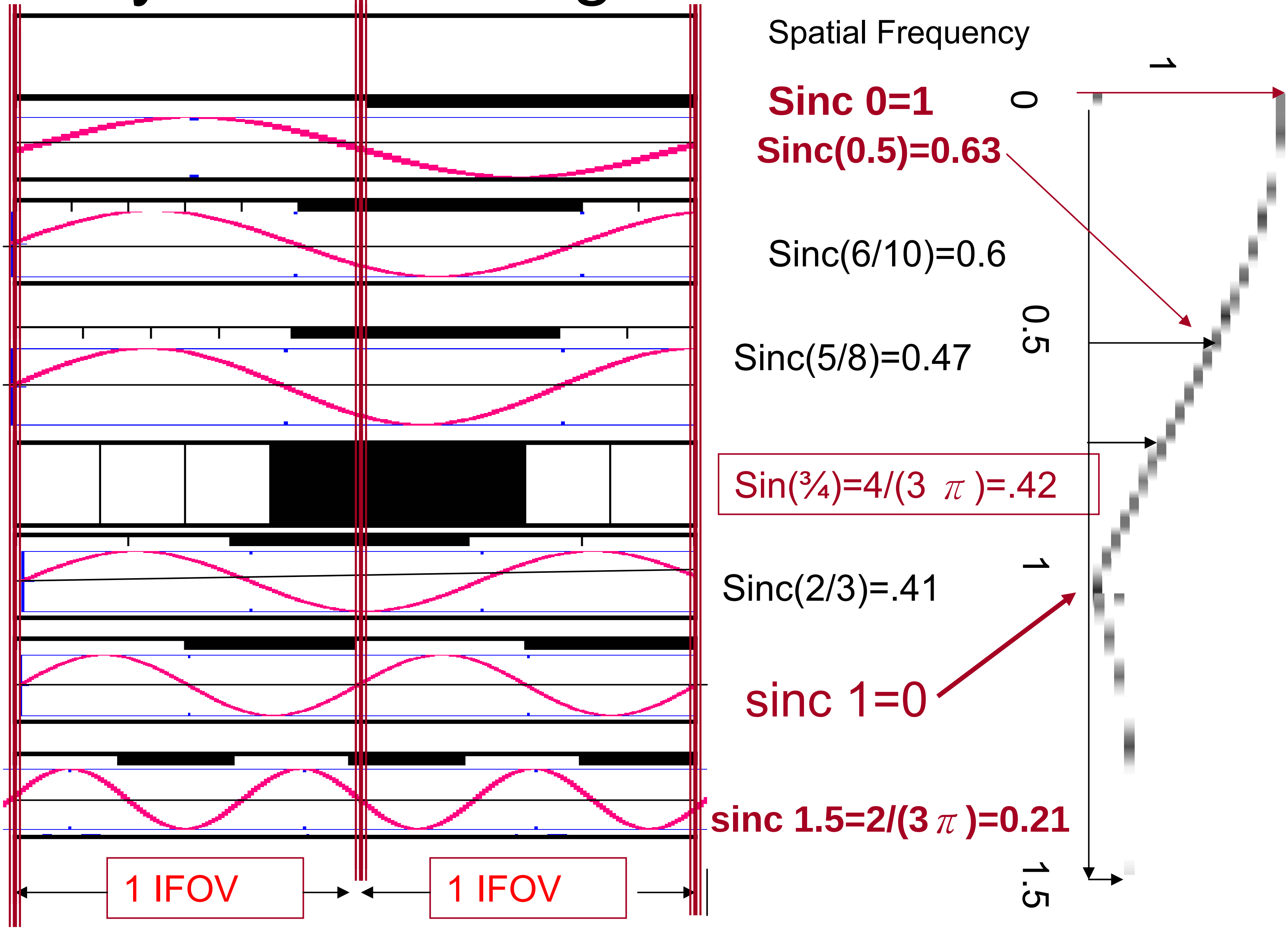
$$MTF = AX\frac{\sin(\pi\varpi X)}{\pi\varpi X}$$

X: I “IFOV”

Sinc Function: sinc x=(sin π x)/ π x



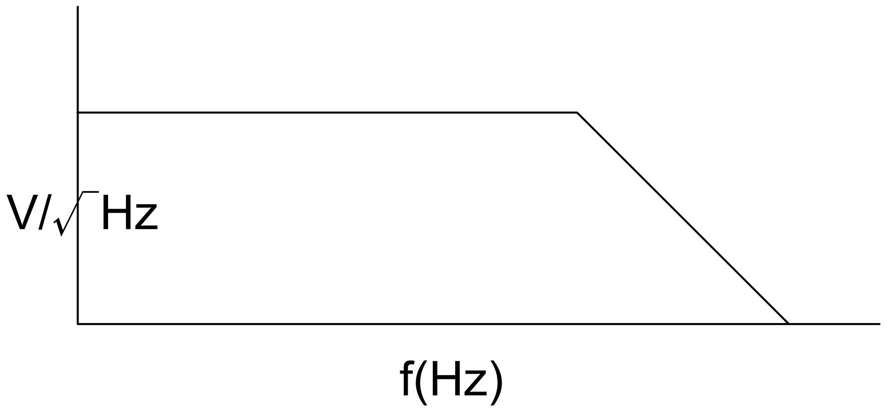
Physical Meaning of a Detector MTF



Total MTF

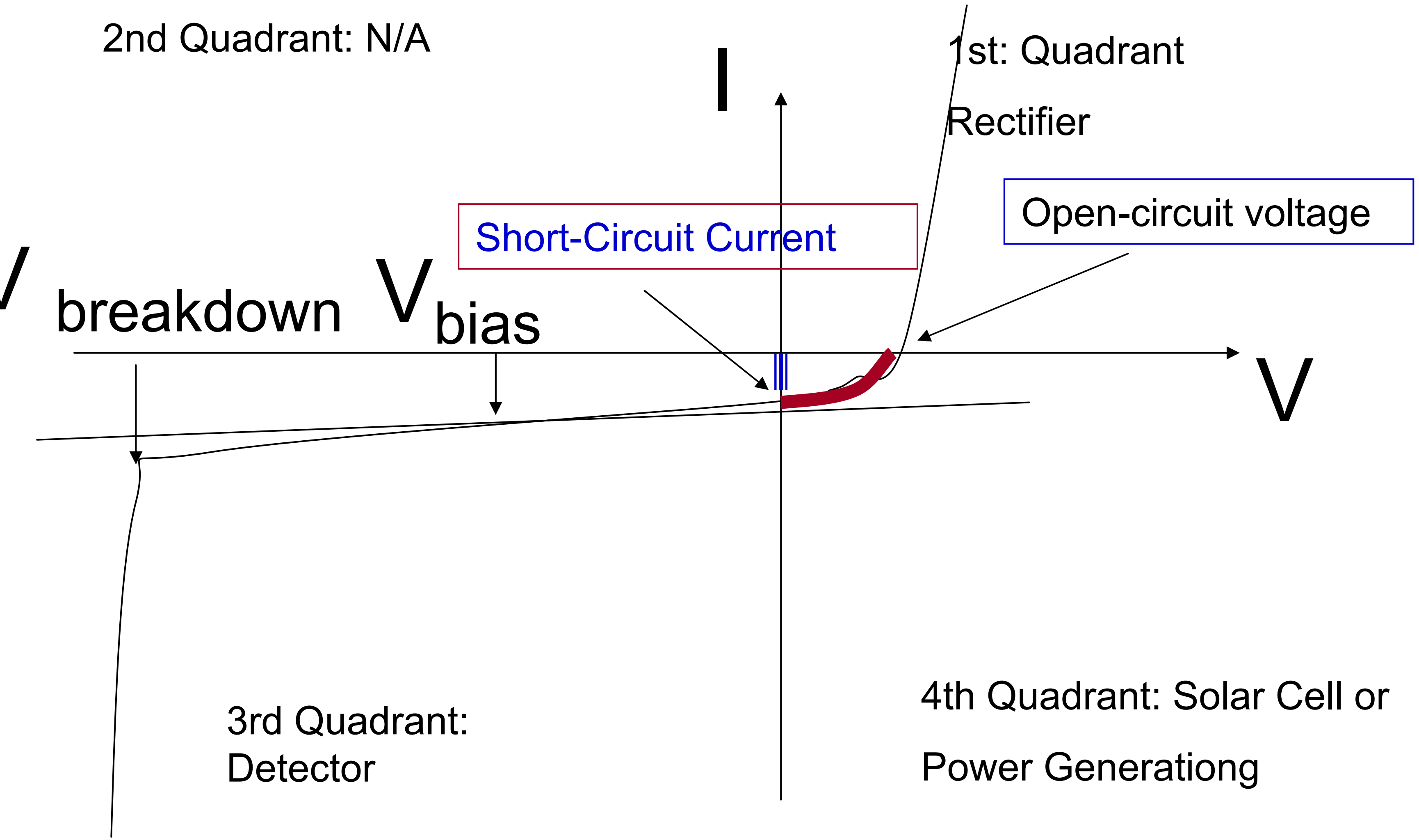
- The Total MTF is the Product of:
- $MTF_{total} = MTF_{optical} \cdot MTF_{det}$
- (If scanning is involved, another MTF electronics would be included as well)
- In the Actual Imaging Space, it means
- "Convolution" of both Optical Blur and the Detector with a Pure Tone Sine wave

Noise Density

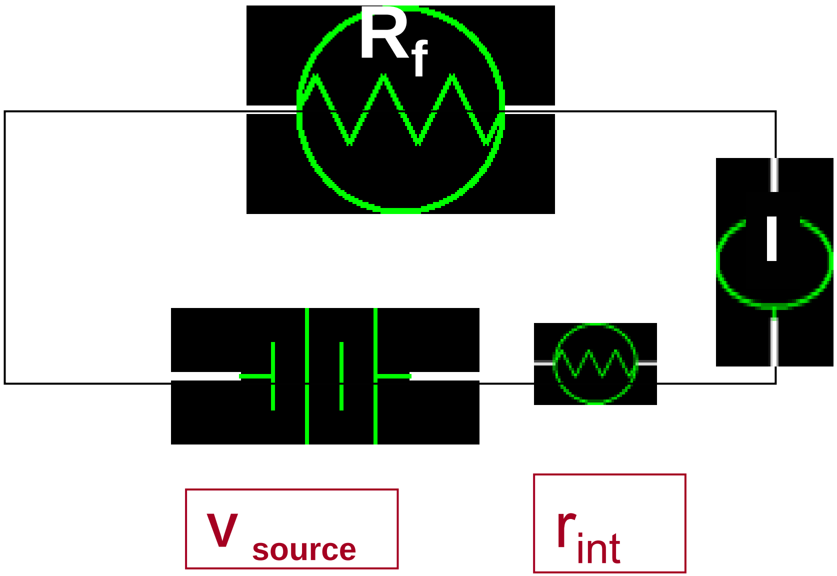


$$r.m.s.noise = \sqrt{\frac{\int_{\Delta f} v^2 df}{\Delta f}}$$

An Ideal Diode Curve



An Ideal Current Source has “Infinite Output Impedance”



$$I=V_{source}/(R_f+r_{int})$$

When $r_{int}>>R_f$

Then

$$I=V_{source}/r_{int}$$

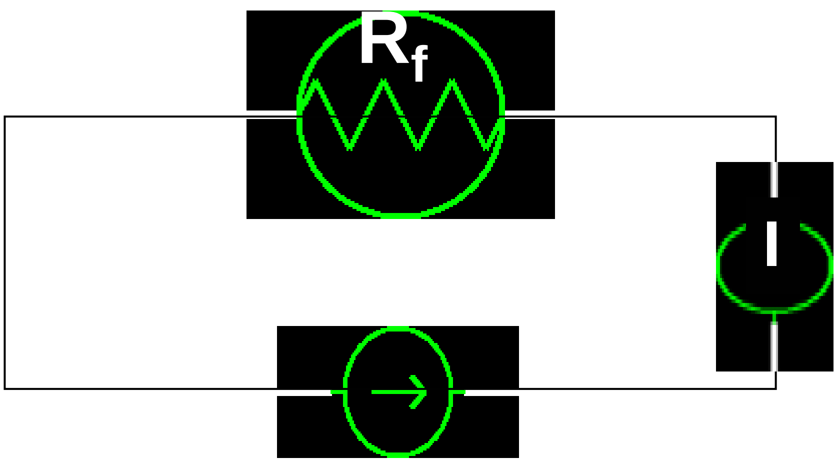
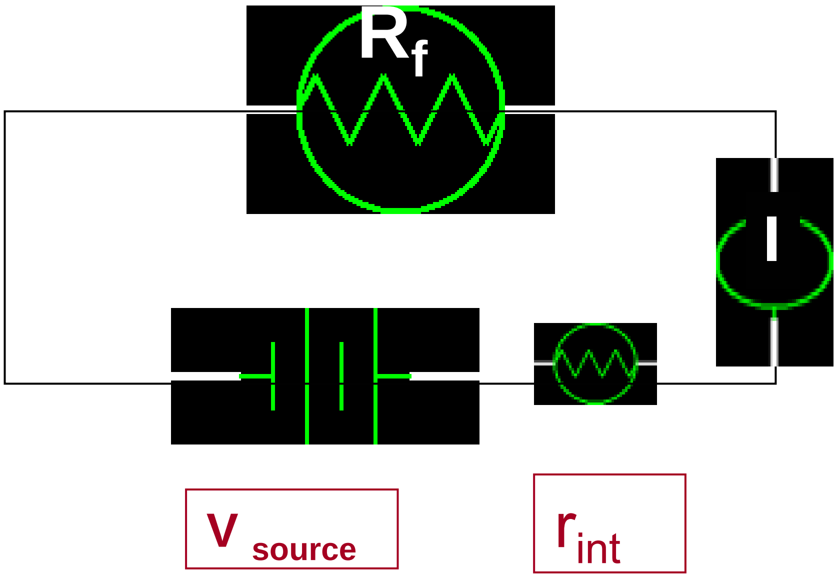


Photo-Diodes are a good Current Sources

An Ideal Voltage Source has “Infinitesimal Output Impedance”

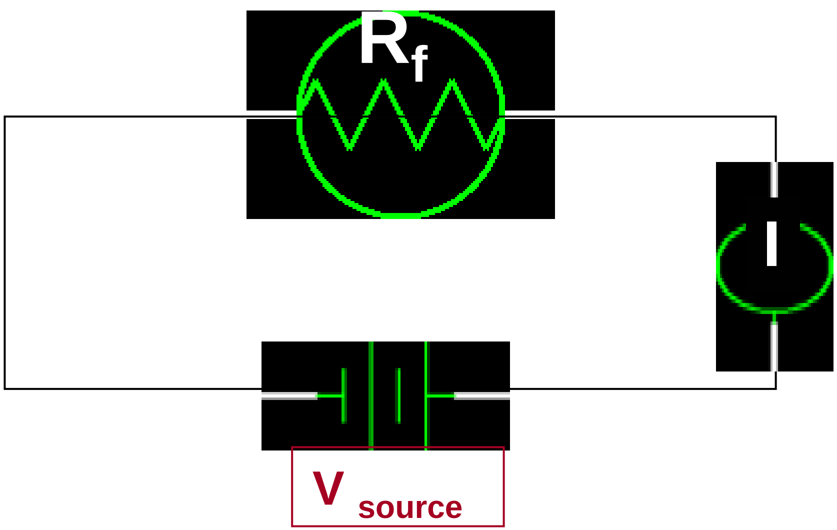


$I=V_{source}/(R_f+r_{int})$

When $r_{int} << R_f$

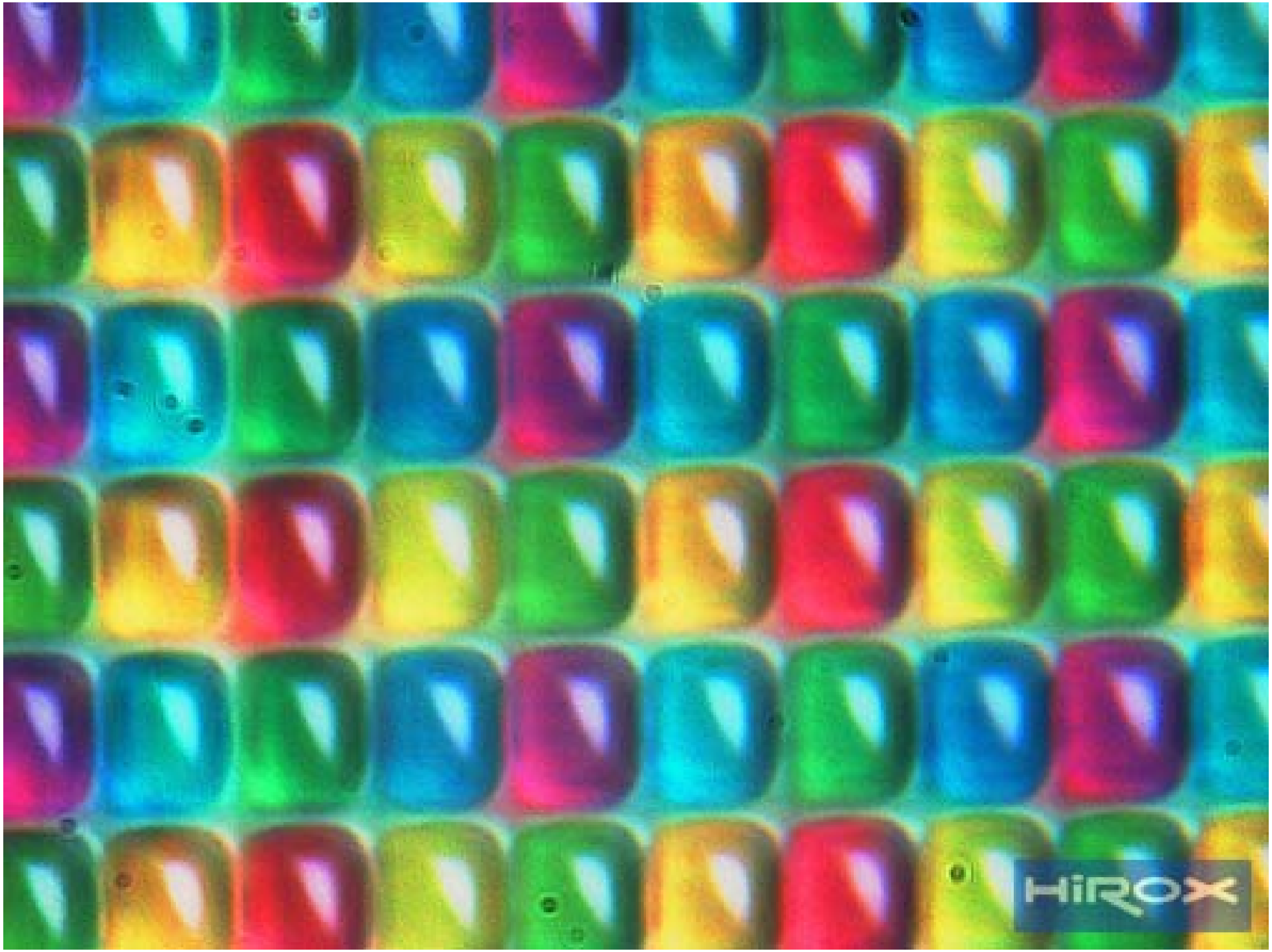
Then

$$I=V_{source}/R_f$$



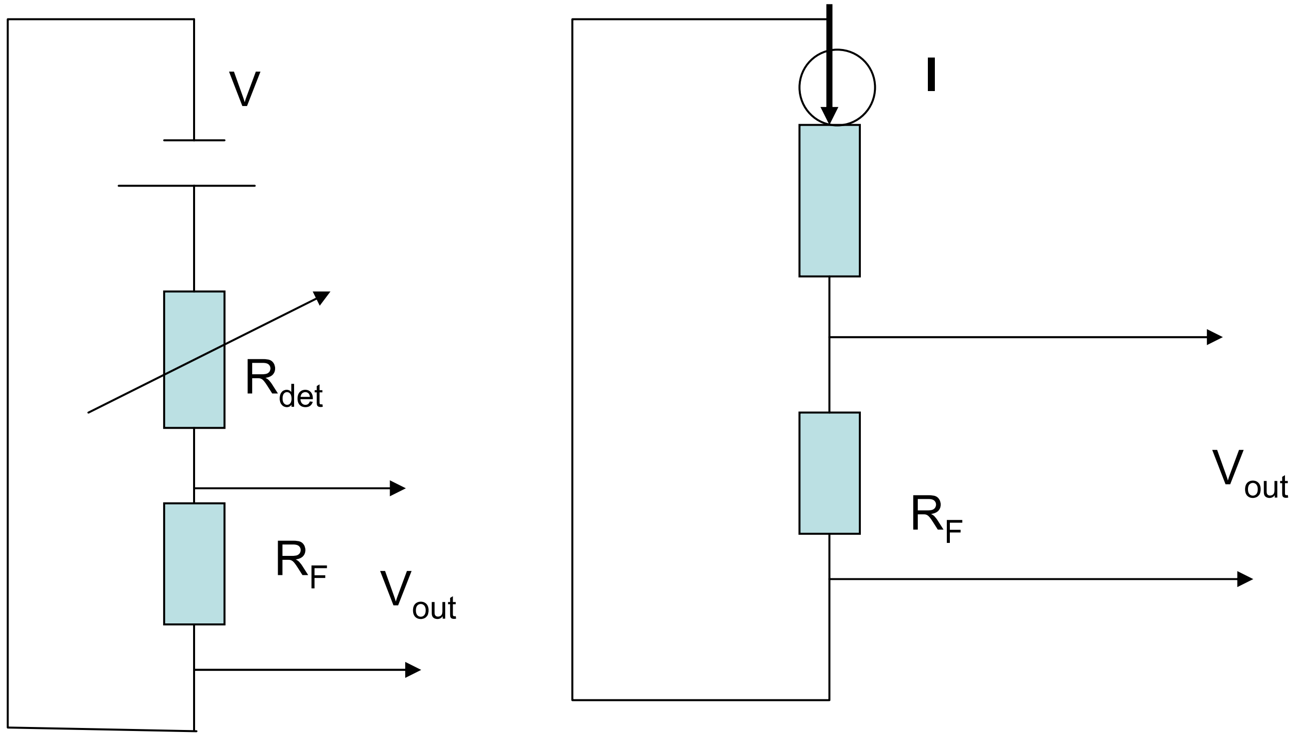
Power Supplies and Voltage Buffers are good Current Source

Video CCD Close-up

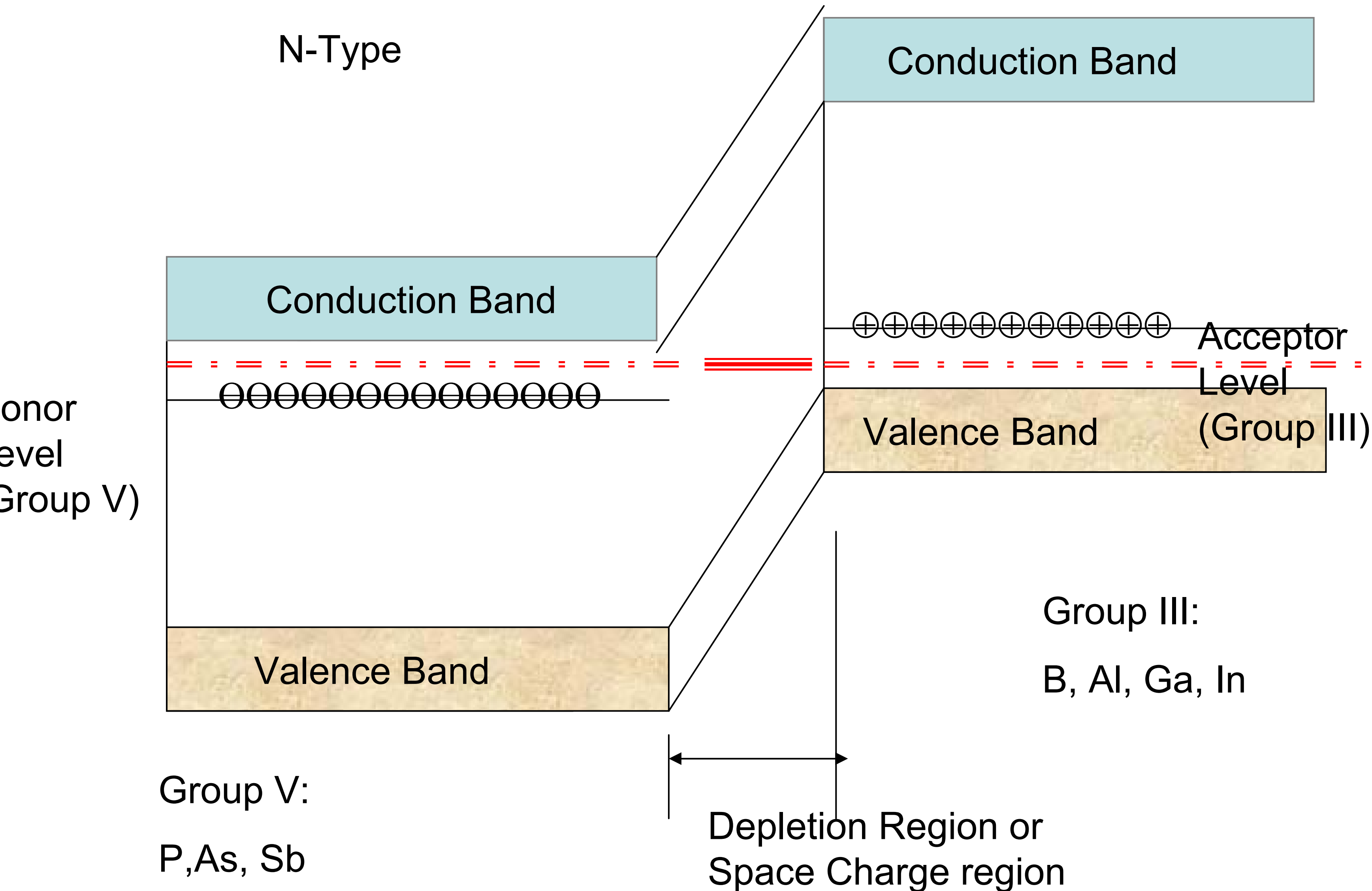


Simple PC Detector Biasing

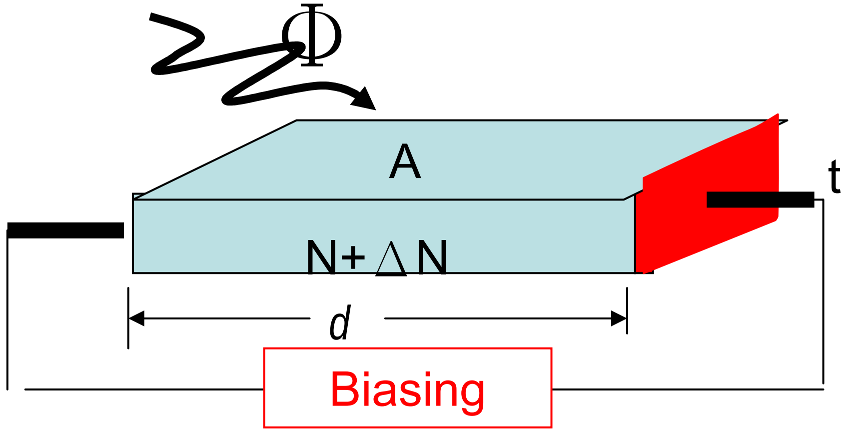
Voltage Biasing



Semi-Conductor P and N types



PC Detector Principle



τ_L=carrier life

Photon-induced Charges $\Delta N = \eta \cdot \Phi \tau_L / (A \cdot t)$

Conductivity $\Delta \sigma = q \cdot \Delta N \cdot (\mu_e + \mu_h) \sim \Delta N \sim \Phi$

$R_{det} = 1/(\sigma \cdot A)$

$\Delta R_{det} = -1/(\sigma^2 \cdot A) \cdot \Delta\sigma = -(R_{det}/\sigma) \cdot \Delta\sigma \sim \sim \Phi$

$R_{PC}(A/W_{)} = \eta \, (q/h\nu) G$

PC Detector Responsibility

RPC(A/W)= η (q/h ν)G=0.8 η • λ • G

G: photo-conductive gain =τ • μ • E/d

Where μ= (μ_e + μ_h)

d=inter-electrode spacing

G can be greater than unity; a blessing and a curse!

PV Detector Principle

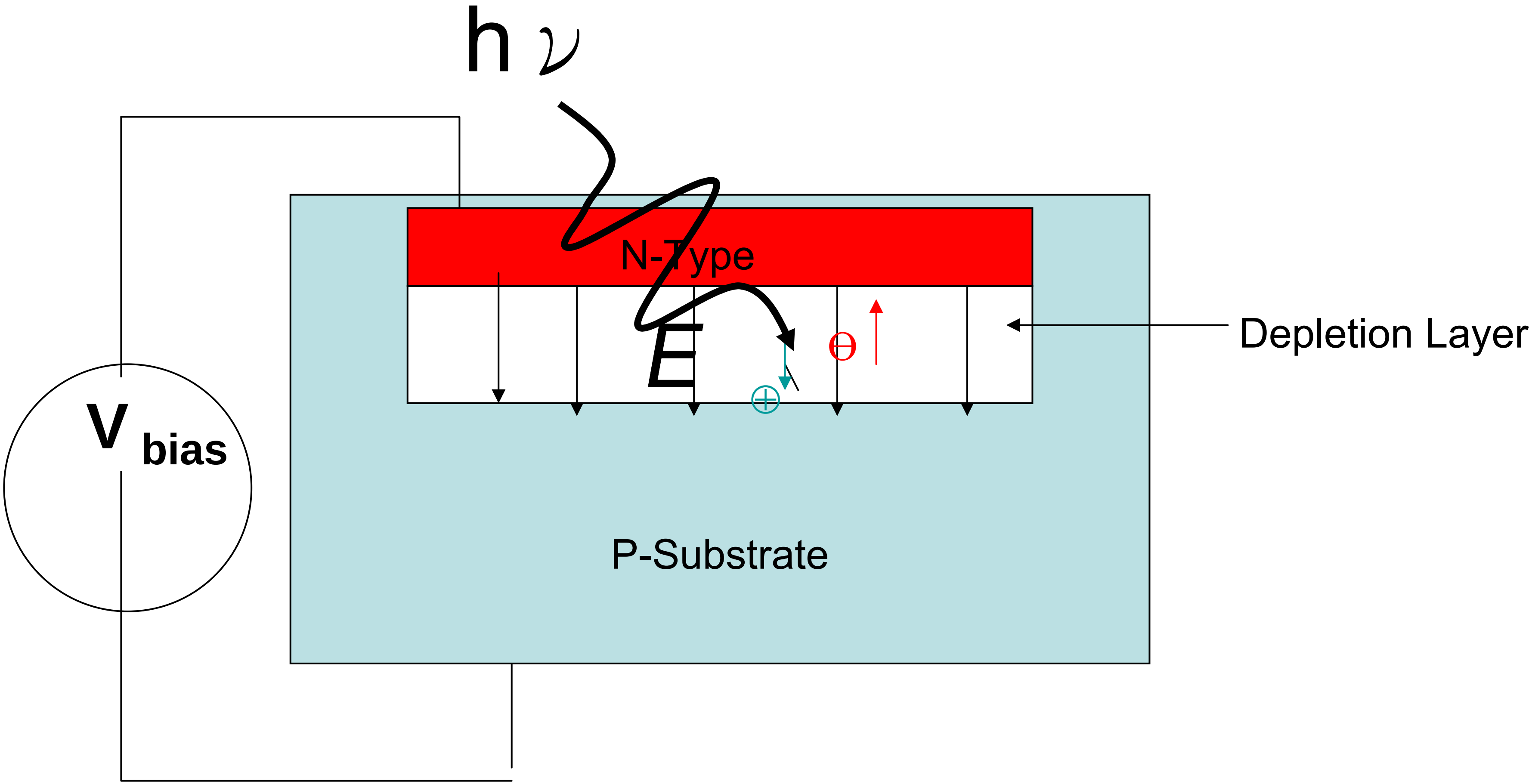
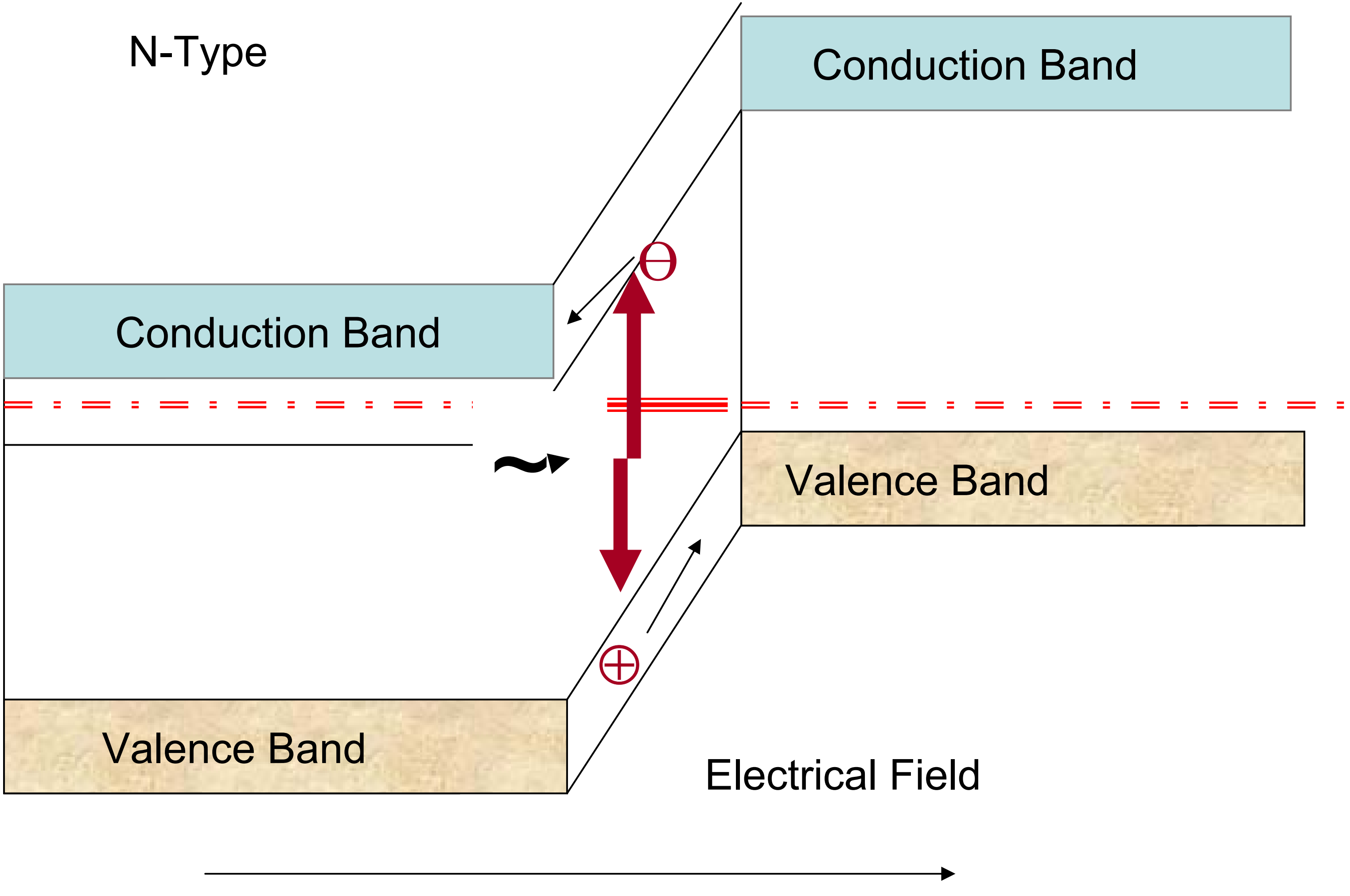


Photo-Voltaic Operation



Diode Schematics