Temperature Measuring Technologies

- Noncontact Methods

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References:
1. T.D. McGee, *Principles and Methods of Temperature Measurement*, John Wiley & Sons Inc., New York (1988).
2. *The Temperature Handbook,* Omega Engineering Inc., USA (1992).
3. J. Fraden, *Handbook of Modern Sensors*, Springer-Verlag, New York (1996).
4. W.L. Wolfe and G.J. Zissis, *The Infrared Handbook,* The Infrared Information and Analysis Center, ERIM (1978).
5. R.D. Hudson, *Infrared System Engineering, Ch.2*, John Wiley & Sons Inc., New York (1969).
6. AGEMA, *Thermovision 782 operation manual*, AGEMA (1984).
7. *The Infrared Observer,* 3(6) AGA Infrared Systems AB (1980).

Outline

The Early History of Temperature Sensing

Year	Events		
1592	The first instrument to measure temperature – The thermoscope	Galilei, Greek	Contact measurement
1611	Temperature scale was added (but uncalibrated).	Galen	
1613	Using a thermoscope to record "degrees of heat" of winter snow, summer heat…	Sagredo	
1624	"Thermometer" appeared in the literature.	Leurechon	
1654	The first sealed thermometer filled with spirits of wine – The Florentian thermometer.	Ferdinand II, Italy	
1661	The Florentian thermometer was exported to Rome, Paris, England.		
1663	Attempted to calibrate and standardize thermometers – using ice point.	Hooke	
1694	Suggested ice point and boiling point as two fixed points and scale 12.	Renaldini	
1701	Defined two fixed points: ice point and armpit temperature.	Newton, British	
1708	Modified Romer(a Danish astronomer) scale to a Fahrenheit scale, substitute mercury for spirits, used a mixture of sea salt, ice, and water to produce the zero point. Ice point = 32, boiling point = 212.	Fahrenheit, Netherland	
1742	Invented a scale with 0 at the steam point and 100 at the ice point.	Celsius, Sweden	
1743	Inverted Celsius scale and named "centigrade" to indicate a scale divided into 100 parts.	Christin, France	
1848	Define a thermodynamic (absolute) temperature scale with ideal gas (H_2).	Kelvin	

What is Temperature?

q Qualitative Definitions:

1. The degree of hotness or coldness of a body.
2. All bodies have the same temperature if they are in thermal equilibrium.
3. The level of thermal energy. (cf. Electrical energy; Mechanical potential energy.)

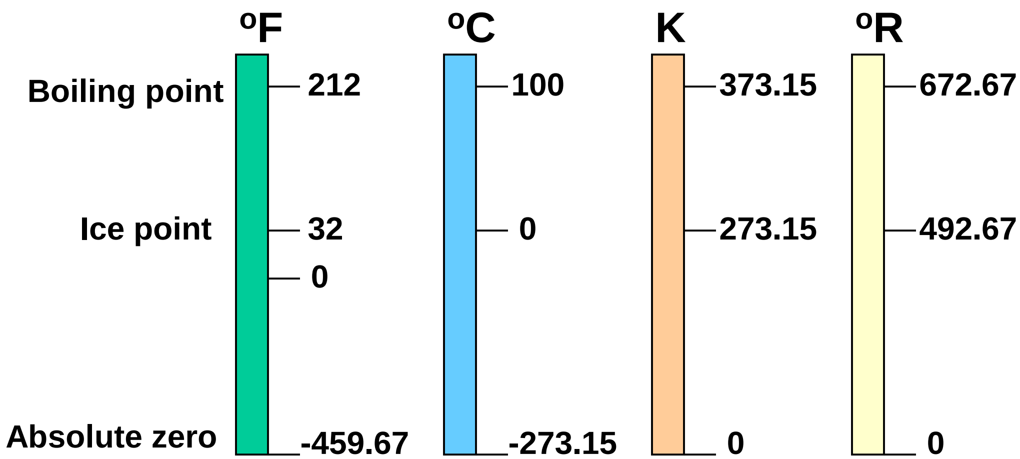
q Units of temperature (one of System International units, SI) :

Unit		Symbol	Quantity measured
Dimensioned	1. Meter	m	Length
	2. Kilogram	kg	Mass
	3. Second	s	Time
	4. Ampere	A	Electric current
	5. Kelvin	K	Temperature
	6. Mole	mol	Amount of substance
	7. Candela	cd	Luminous intensity
Dimensionless	8. Radian	rad	Plane angle
	9. Steradian	sr	Solid angle

How to Quantify It?

q Four common temperature scales:

Fahrenheit(1708), Celsius(1740), Kelvin(1848), Rankine(1730)



$$^{o}F = \frac{9}{5}(^{o}C) + 32$$

$$^{o}C = \frac{5}{9}(^{o}F - 32)$$

$$K = 273.15 + {}^{o}C$$

$$^{o}R = 459.67 + {}^{o}F$$

q Fundamental temperature scales:

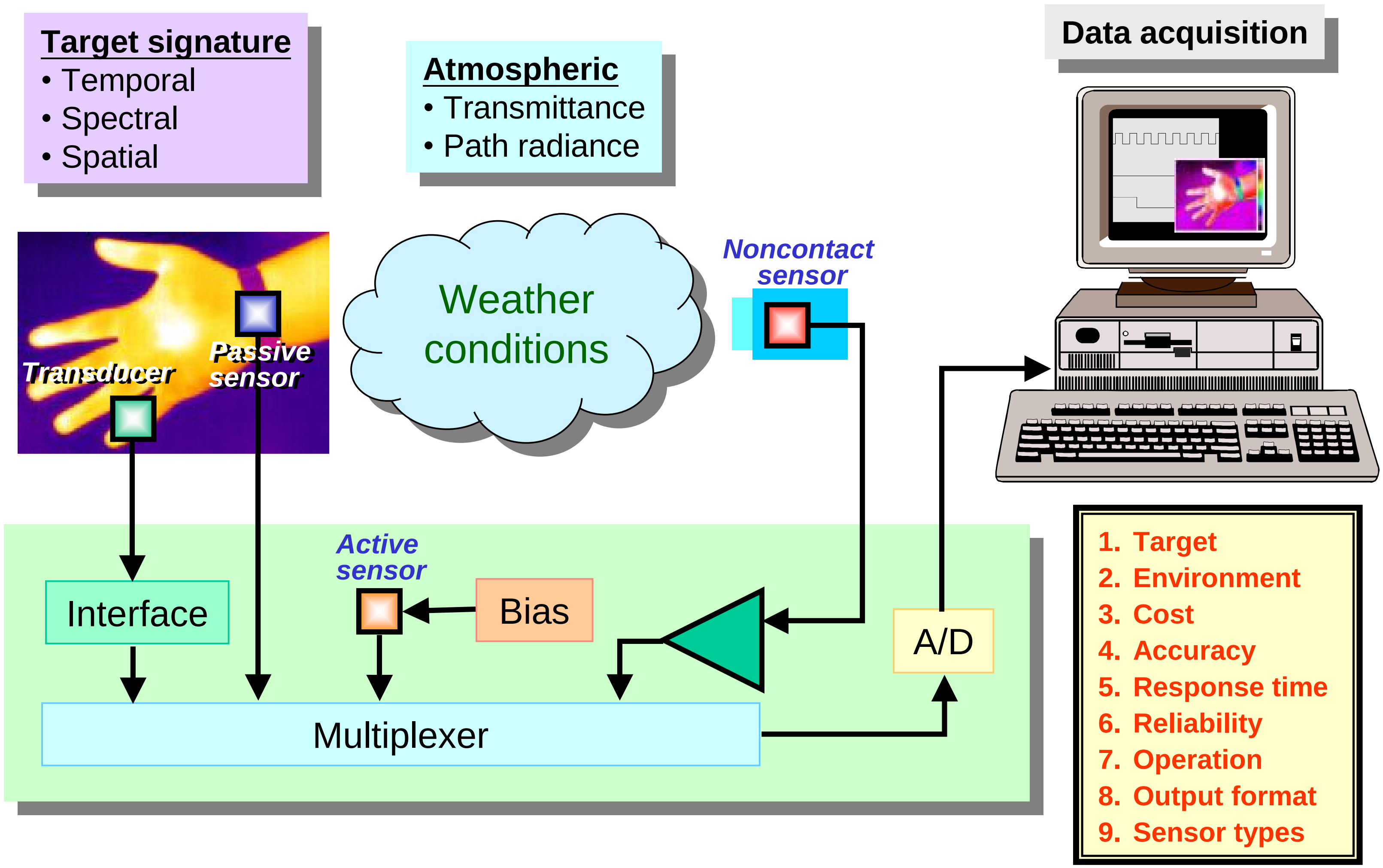
The relationship of measured variable to temperature depends only on fundamental physical constants, not on arbitrary calibrating constants.

Examples:

1.Thermodynamic, PV=PV(T, $\underline{N_A}$, $\underline{k}$)

2.Thermal radiance, W=W(T, $\underline{k}$, $\underline{c}$, $\underline{h}$)

What is Concerned?

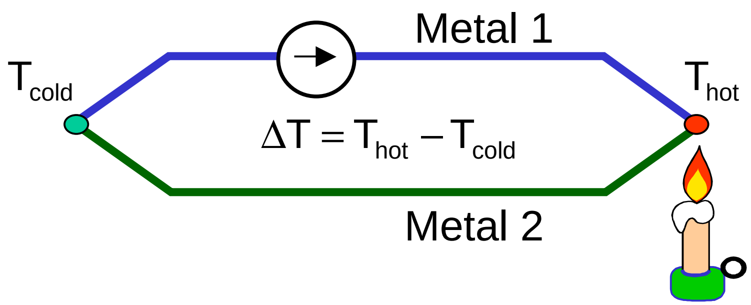


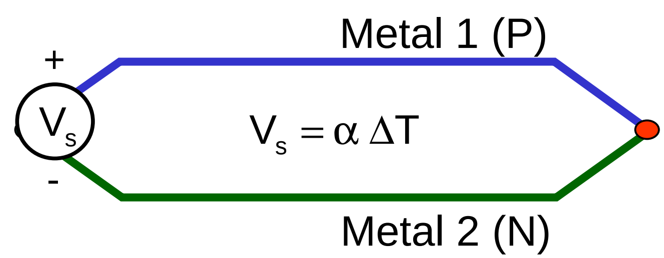
Temperature Sensor Classification

	Principle							
Sensor	**Thermo-electric**	**Electrical Resistance**	**Carrier Mobility**	**Thermal Radiation**	**Electrical Capacitance**	**Thermal Expansion**	**Resonant Frequency**	**Others**
Thermocouple								
Thermopile								
RTD(PTC, NTC)								
Thermistor								
P-N junction								
Optical pyrometer								
Pyro-electric								
Quantum								
Spectroradiometer								
Cooling IR imager								
Uncooled IR imager								
Gas								
Liquid								
Bi-metal								
Quartz								
Liquid Crystal								1
Others								2,3,4,5
[Remark]: 1.Reflectance, 2.Index of Refraction, 3.Ultrasonic, 4.Microwave, 5.Acoustic								

Thermocouple Sensor

- **Thermoelectric Effect (Thomas Seebeck, Germany, 1821):**
  Two wires composed of dissimilar metals are connected at both ends, to make a complete electrical circuit, an electrical current will flow in the circuit if one of the ends is heated. (Thermocouple - Nobili, 1829)



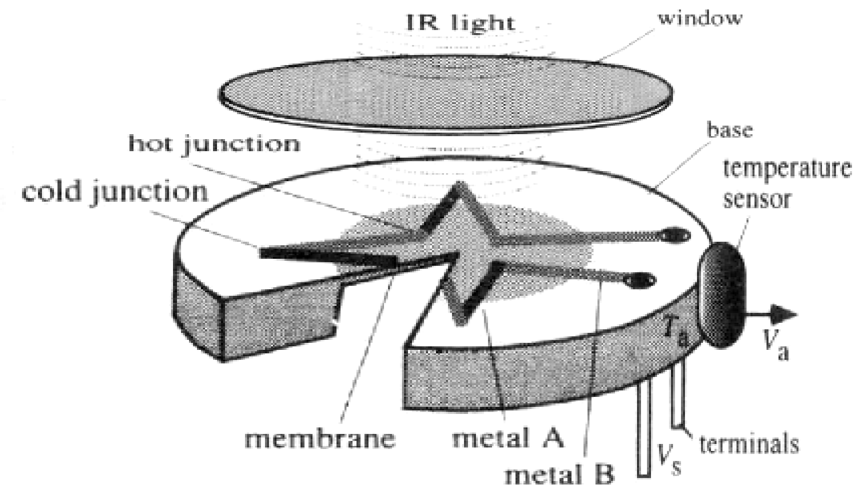


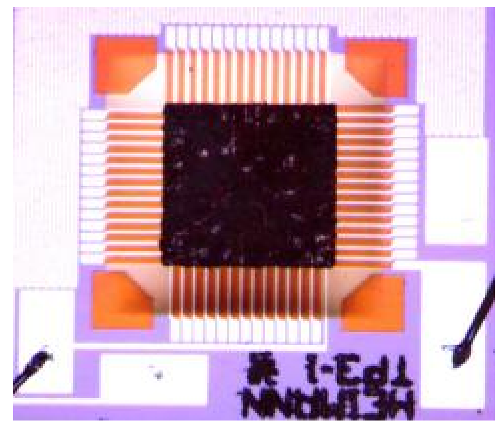
$$V_s = a_0 + a_1 T + a_2 T^2 + a_3 T^3 + a_4 T^4 + \ldots$$

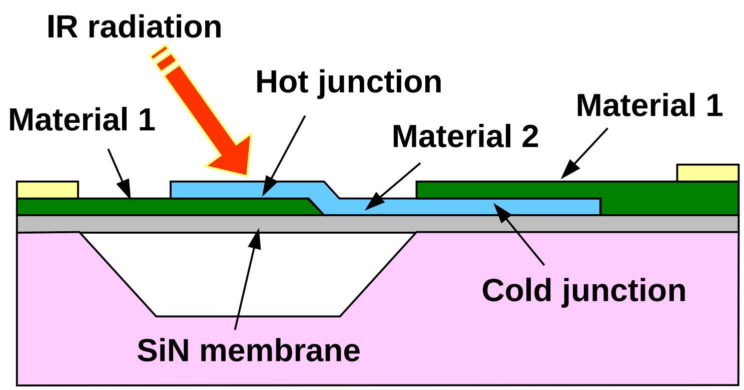
Letter	P wire	N wire	Range	Accuracy	Order
T	Cu	$Ni_{45}Cu_{55}$	-160~400℃	0.5℃	7th
J	Fe	$Ni_{45}Cu_{55}$	0~760℃	0.1℃	5th
E	$Ni_{90}Cr_{10}$	$Ni_{45}Cu_{55}$	-100~1000℃	0.5℃	9th
K	$Ni_{90}Cr_{10}$	$Ni_{95}Mn_2Al_2Si_1$	0~1370℃	0.7℃	8th
R	$Pt_{87}Rh_{13}$	Pt	0~1000℃	0.5℃	8th
S	$Pt_{90}Rh_{10}$	Pt	0~1750℃	1.0℃	9th
B	$Pt_{70}Rh_{30}$	$Pt_{94}Rh_6$	870~1700℃	-	-

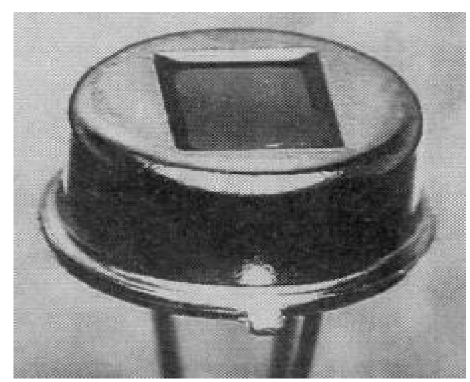
Thermopile Sensor

- **Thermopile (Melloni,1833):** A thermopile is serially connected thermocouples.

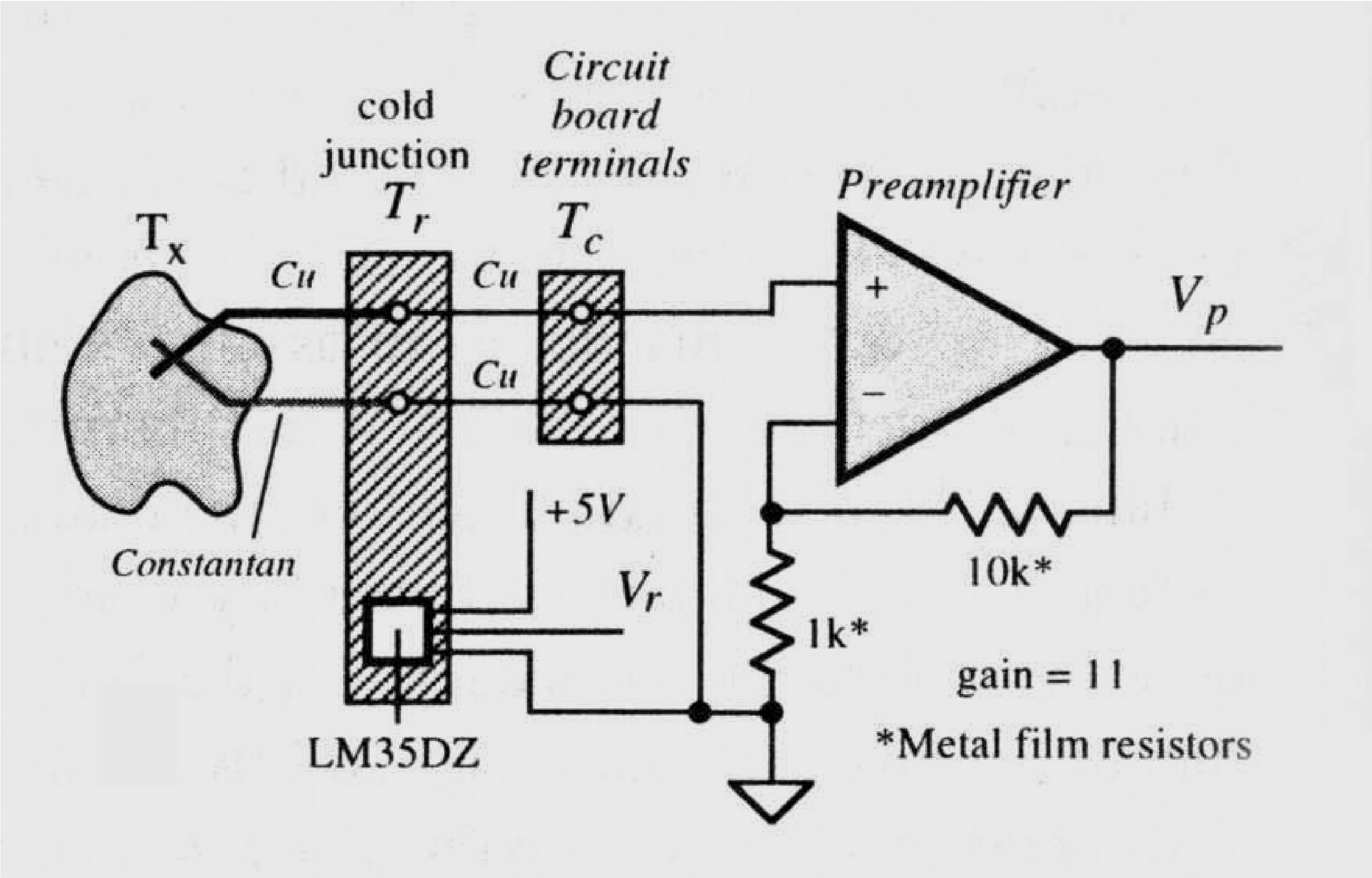








Practical Circuit of a Thermopile



RTD and Thermistor

q Resistance Temperature Detector (RTD)

For general metal,

PTCR : Positive Temperature Coefficient of Resistance

$$R(T) = R_0[1 + a_0(T - T_0) + a_1(T - T_0)^2 + \ldots]$$

$$a = \frac{1}{R}\frac{dR}{dT}\bigg|_{T=T_0}$$ Owing to a good linearity

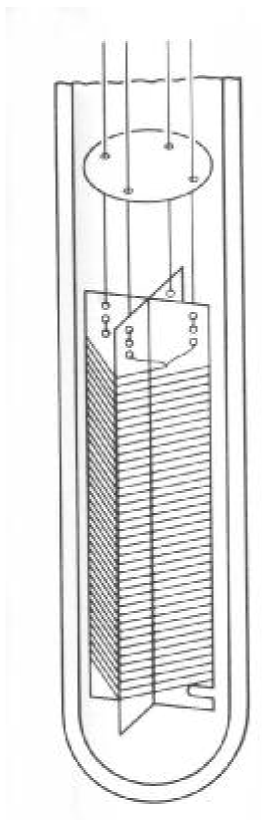
q Thermal Sensitive Detector (Thermistor)

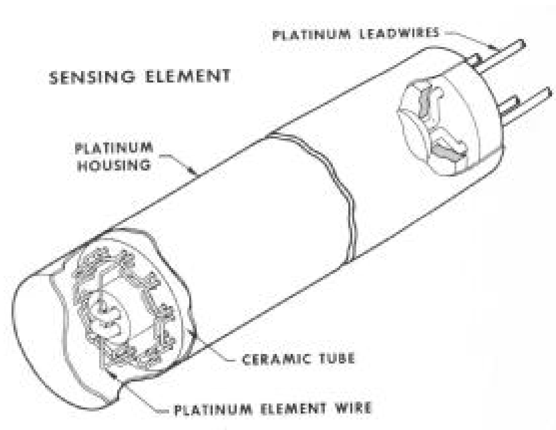
For Semiconductor,

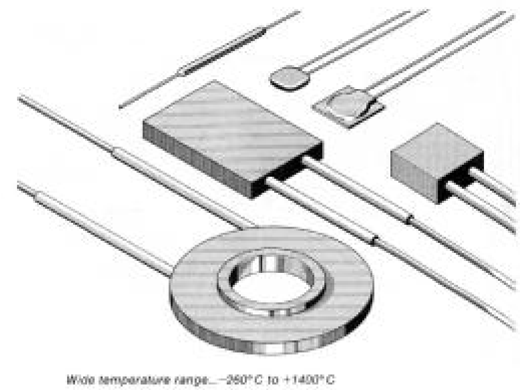
NTCR : Negative Temperature Coefficient of Resistance

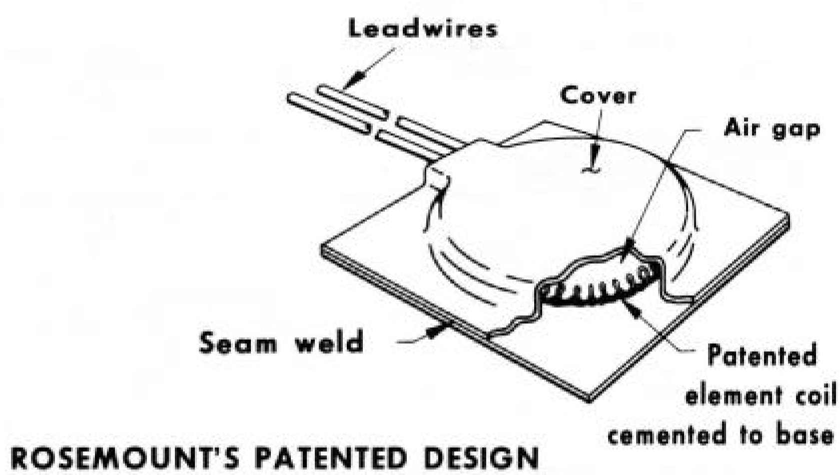
$$R(T) = R_0\, e^{B(\frac{1}{T} - \frac{1}{T_0})} \qquad a = \frac{1}{R}\frac{dR}{dT}\bigg|_{T=T_0} = -\frac{B}{T_0^2}$$

RTD Sensors

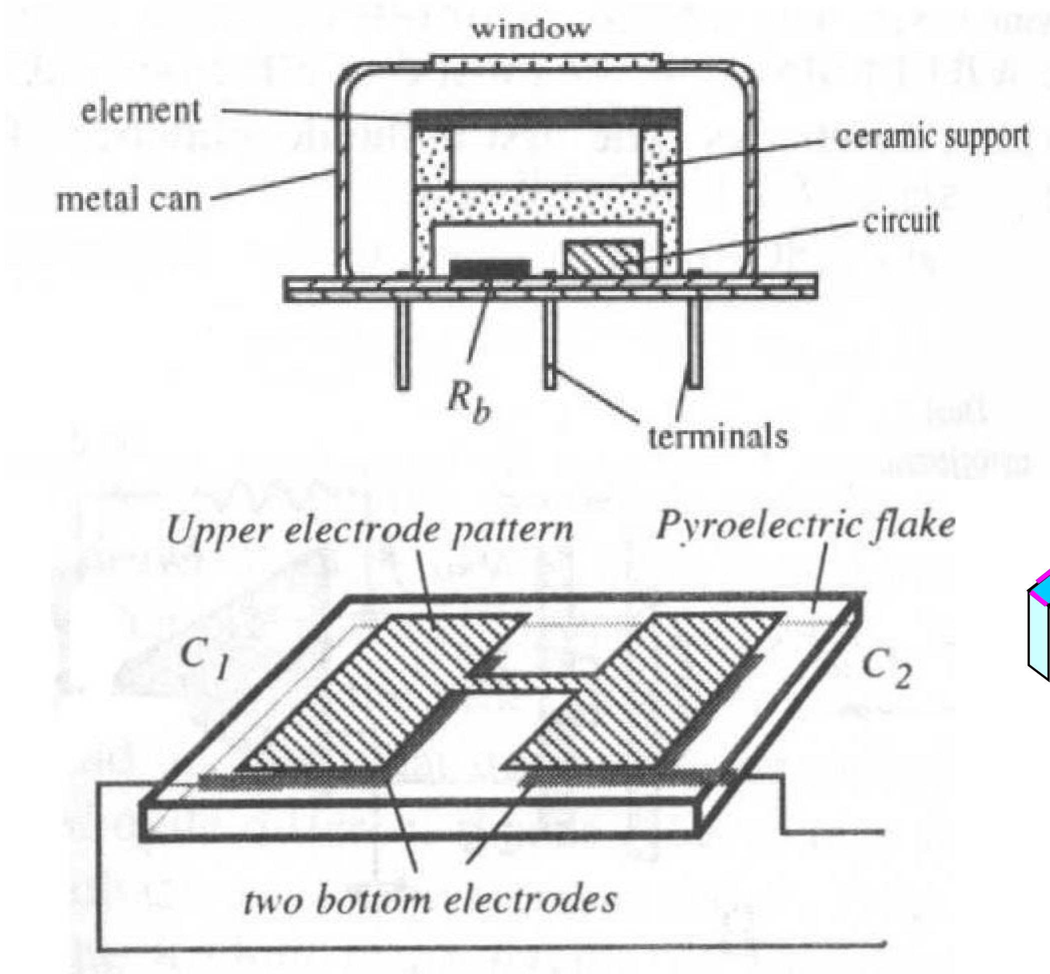


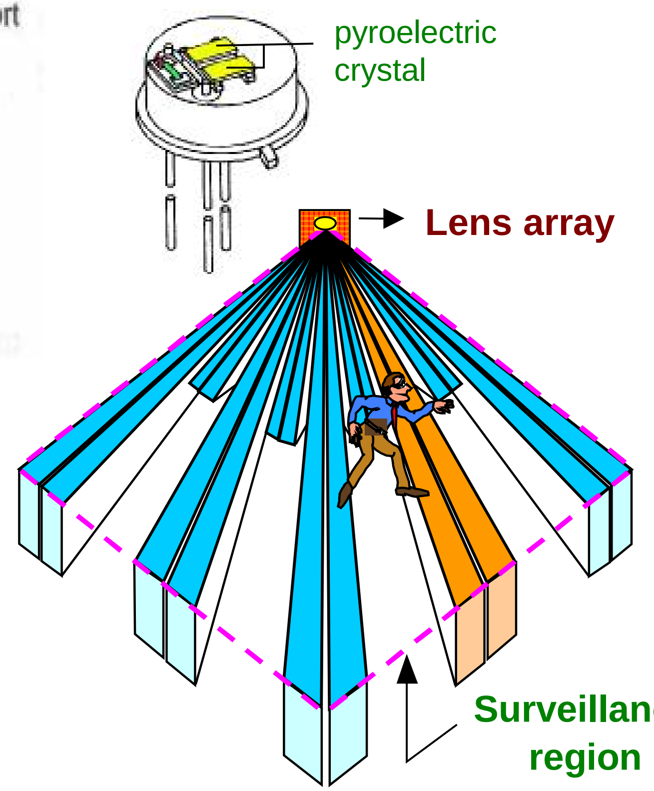

PLATINUM LEADWIRES
SENSING ELEMENT
PLATINUM HOUSING
CERAMIC TUBE
PLATINUM ELEMENT WIRE


Wide temperature range...−260°C to +1400°C


Leadwires
Cover
Air gap
Seam weld
Patented element coil cemented to base
ROSEMOUNT'S PATENTED DESIGN

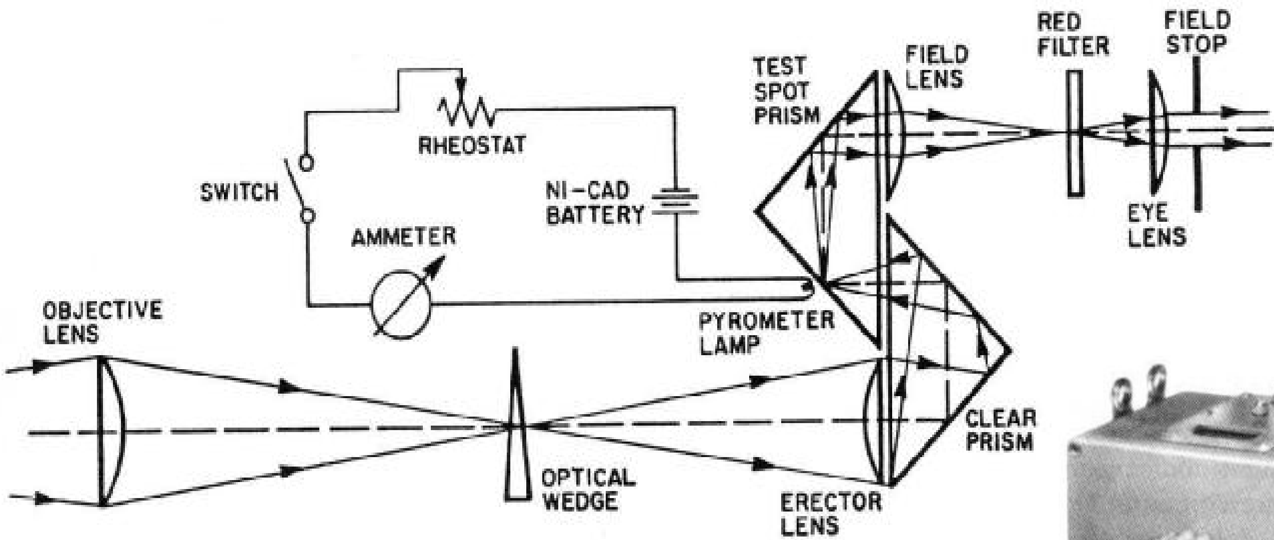
Pyro-electric Sensor

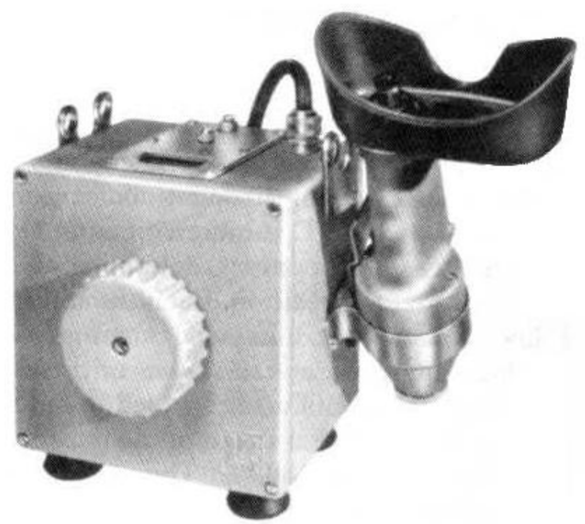




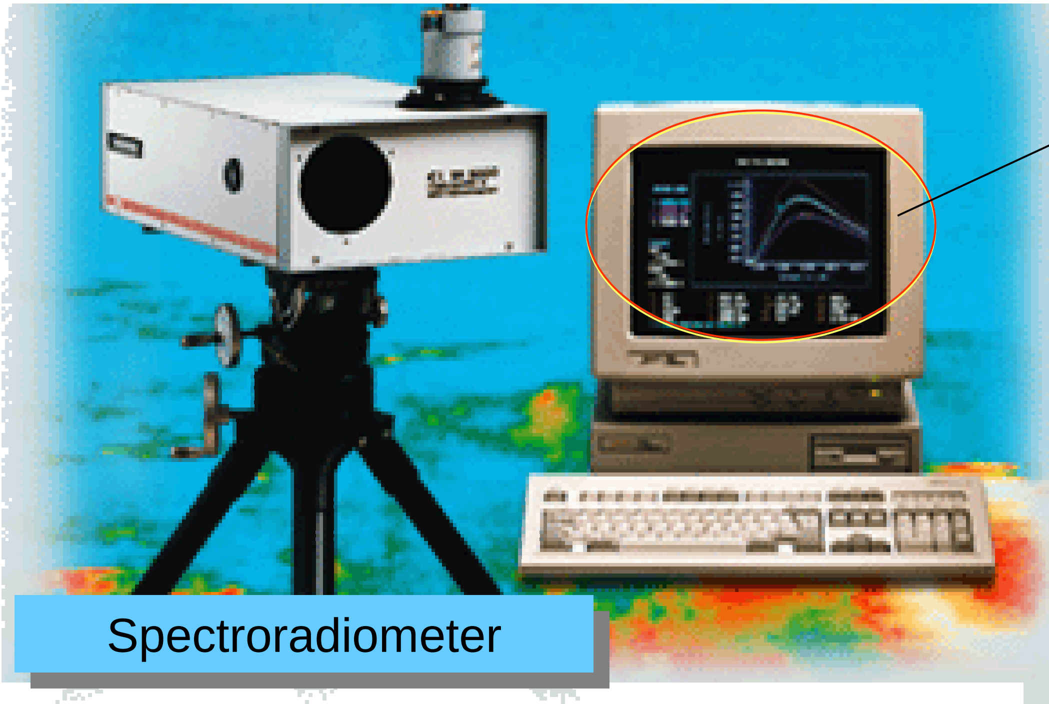
Optical Pyrometer

- **The disappearing filament optical pyrometer**





Spectroradiometer/Radiometer



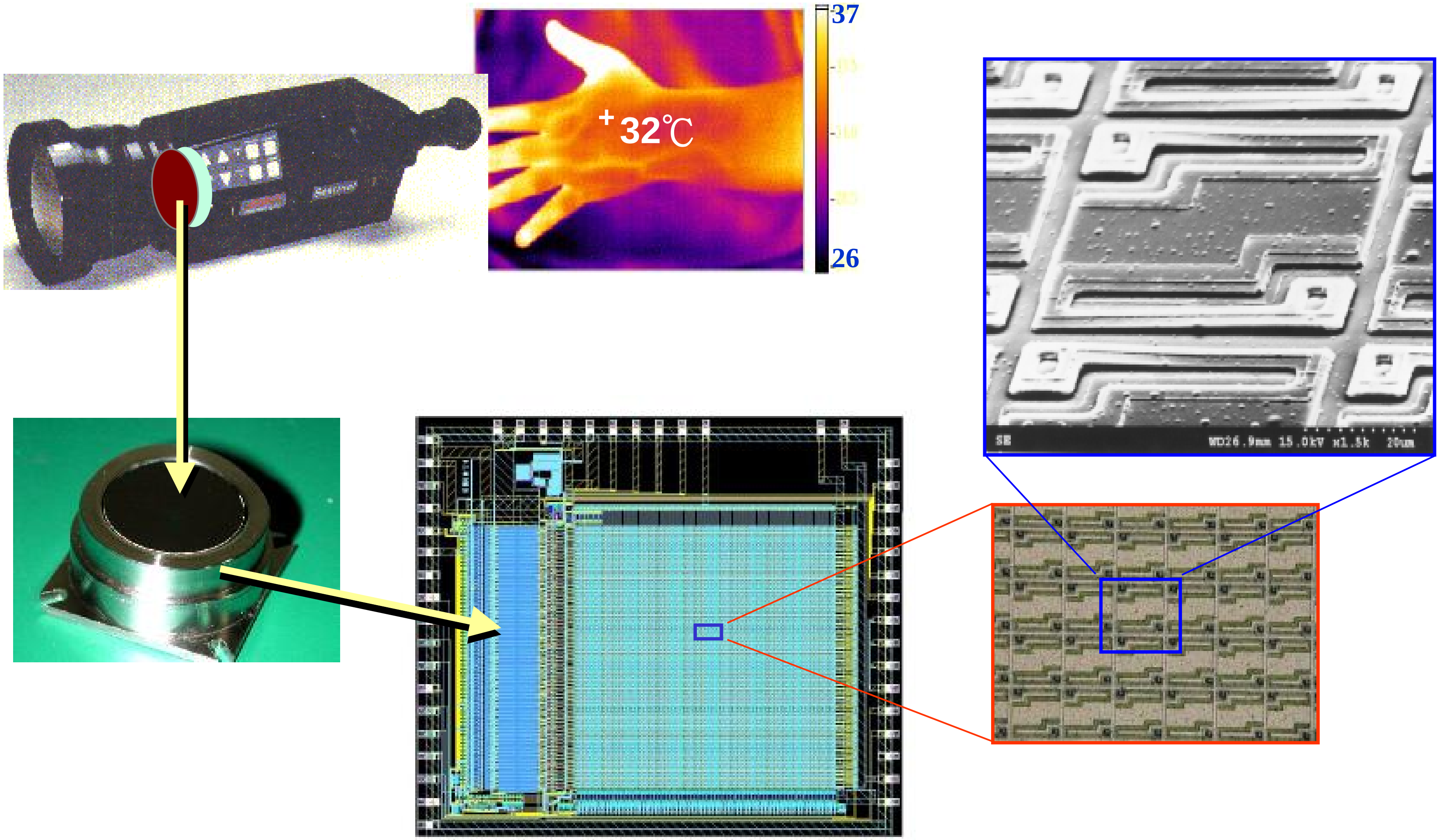
Spectroradiometer

Blackbody radiation spectrum fitting

Items	Specifications
Spectral range	0.2 to 25 microns
FOV	0.3 mrad - 100 mrad
Focusing range	2.5m to infinity
Scan rates	0.015 to 30 scans/sec
Chopping Frequency	100 to 1800 Hz.

Radiometer

Infrared Imager



Temperature Scales

q Requirements for establishing a temperature scale:

1. Set the fixed points and given the temperature value.
2. Choosing an appropriate instrument to interpolate scale.
3. Determine the relationship between the measurement variable and the temperature.

q The International Practical Temperature Scale:

The International Committee of Weights and Measures(1927,.. 1960,.. 1968,.. 1990)

Fixed points: 6(ITS-27), 13(IPTS-68), 17(ITS-90)

Defining fixed points of the ITS-27 ℃

Number	ºC	Substance	State
1	-182.97	O_2	Boiling Point
2	0.000	H_2O	Freezing Point
3	100.000	H_2O	Boiling Point
4	444.60	S	Boiling Point
5	960.5	Ag	Freezing Point
6	1063.0	Au	Freezing Point

Range	ºC	Interpolating Instrument
I	-182.97 ~ 0	Platinum resistance
II	0 ~ 660	Platinum resistance
III	660 ~ 1063.0	S-type thermocouple
IV	>1063.0	Optical pyrometer

ITS-90 (1)

q The International Temperature Scale of 1990 (ITS-90)

[Ref]:http://www.omega.com/techref/intltemp.html

1. Units of Temperature

The unit of the fundamental physical quantity known as thermodynamic temperature, symbol T, is the kelvin symbol K, defined as the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.
Because of the way earlier temperature scales were defined, it remains common practice to express a temperature in terms of its difference from 273.15 K, the ice point. A thermodynamic temperature, T, expressed in this way is known as a Celsius temperature, symbol t, defined by:

$t / ℃ = T / K - 273.15$

The unit of Celsius temperature is the degree Celsius, symbol ℃, which is by definition equal in magnitude to the kelvin. A difference of temperature may be expressed in kelvins or degrees Celsius.
The International Temperature Scale of 1990 (ITS-90) defines both International Kelvin Temperatures, symbol T90, and International Celsius Temperatures, symbol t90. The relation between T90 and t90 is the same as that between T and t, i.e.:

$t_{90} / ℃ = T_{90} / K - 273.15$

The unit of the physical quantity T90 is the kelvin, symbol K, and the unit of the physical quantity T90 is the degree Celsius, symbol ℃, as is the case for the thermodynamic temperature T and the Celsius temperature t.

ITS-90 (2)

2. Principles of the International Temperature Scale of 1990 (ITS-90)

The ITS-90 extends upwards from 0.65 K to the highest temperature practicably measurable in terms of the Planck radiation law using monochromatic radiation. The ITS-90 comprises a number of ranges and sub-ranges throughout each of which temperatures T90 are defined. Several of these ranges or sub-ranges overlap, and where such overlapping occurs, differing definitions of T90 exist: these differing definitions have equal status.

3. Definition of the International Temperature Scale of 1990

Between 0.65 K and 5.0 K T90 is defined in terms of **the vapour-pressure temperature relations 3He and 4He**.

Between 3.0 K and the triple point of neon (24.5561 K) T90 is defined by means of **a helium gas thermometer** calibrated at three experimentally realizable temperatures having assigned numerical values (defining fixed points) and using specified interpolation procedures.

Between the triple point of equilibrium hydrogen (13.8033 K) and the freezing point of silver (961.78℃) T90 is defined by means of **platinum resistance thermometers** calibrated at specified sets of defining fixed points and using specified interpolation procedures.

Above the freezing point of silver (961.78℃) T90 is defined in terms of a defining fixed point and **the Planck radiation law**.

Defining Fixed Points of the ITS-90

	Temperature			
Number	T_{90}/K	t_{90}/ºC	Substance	State
1	3 to 5	-270.15 to -268.15	He	V
2	13.8033	-259.3467	e-H_2	T
3	~17	~-256.15	e-H_2 (or He)	V (or G)
4	~20.3	~-252.85	e-H_2 (or He)	V (or G)
5	24.5561	-248.5939	Ne	T
6	54.3584	-218.7916	O_2	T
7	83.8058	-189.3442	Ar	T
8	234.3156	-38.8344	Hg	T
9	273.16	0.01	H_2O	T
10	302.9146	29.7646	Ga	M
11	429.7485	156.5985	In	F
12	505.078	231.928	Sn	F
13	692.677	419.527	Zn	F
14	933.473	660.323	Al	F
15	1234.93	961.78	Ag	F
16	1337.33	1064.18	Au	F
17	1357.77	1084.62	Cu	F

V: vapor pressure point; T: triple point; G: Gas thermometer point;
M: melting point; F: Freezing point

Evolution of IR Sensor Technologies

1800 ~ 1899	1900 ~ 1979	1980 ~ 1989	1990 ~ 1995	1996 ~ 2001...

IR discovery (Herschel, 1800)

Thermo-electric effect (Seebeck,1821)

Thermocouple (Nobili,1829)

Thermopile (Melloni,1833)

Bolometer (Langley,1880)

Radiation theory (1884)

Uncooled IRFPA electronic scan

Microbolometer
Micro-pyroelectric

Low cost Thermal Imager

Single detector

Single / Linear / Area array detector
LN_2, n_2/ argon gas cooling, mechanical scan

Thermal-type | **Quantum-type** | **Thermal-type**

Development of Uncooled IR Imagers

1970	1979	1980	1985 – 1986
Uncooled IR Detector	100x100 BST Array	Microbolometer Array	*SRTS*
NVEOD, Honeywell, Philip	TI	Honeywell	TI, Honeywell Magnavox (1x64 PbSe)

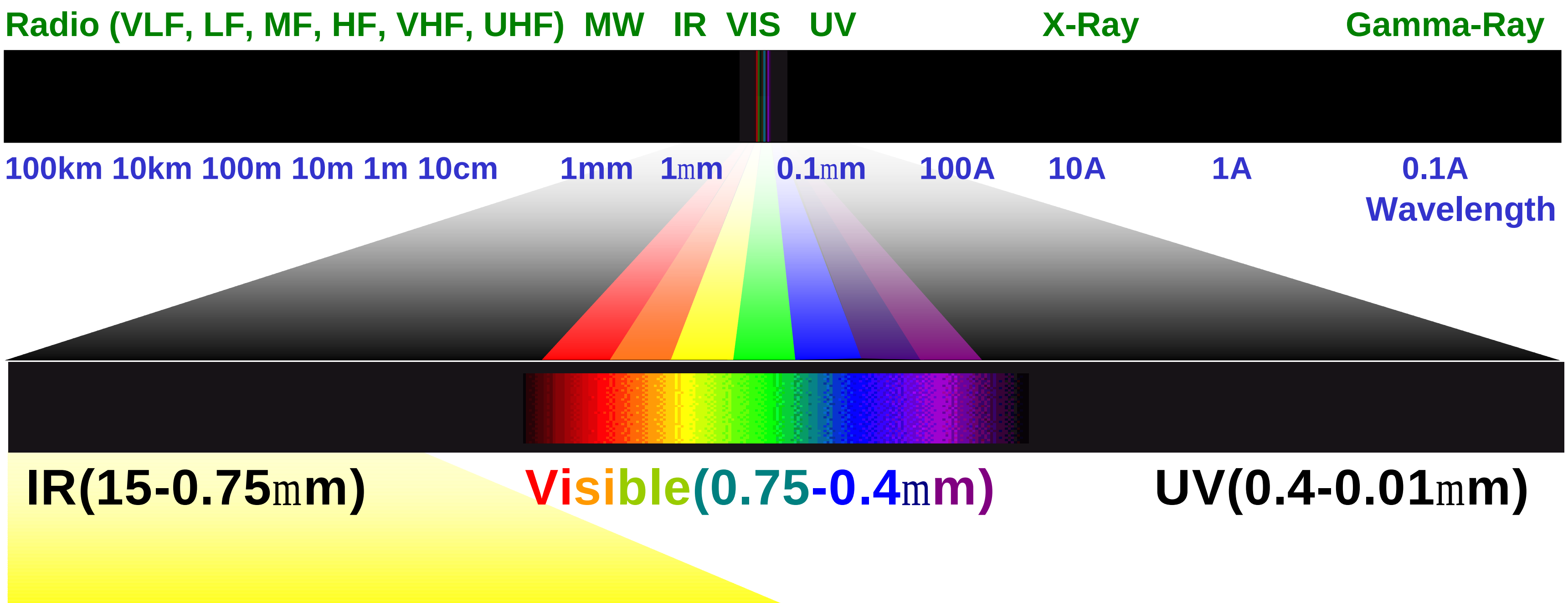
1987	1988	1989	1991	1995 – 2001
HIDAD	80000 pixels/ NETD < 1.0C		Microbolometer Imager/ NETD = 0.1C	Commercialized Uncooled IR Imager
Honeywell, TI Hughes Rockwell	TI (BST) 328x245	Honeywell (V_2O_5) 64x128	Honeywell 336x240	TI (Night Sight) Raytheon (TI, Hughes, Amber) Martin (Loral) Boeing (Rockwell) FLIR (AGEMA, Inframetric) NEC, INO, LETI...

1991 → 1. Loral 2. Rockwell 3. Hughes 4. Raytheon 5. Alliant Techsystems

Microbolometer IRFPA

NVEOD : *Night Vision & Electro-Optics Directorate*
BST : *Barium Strontium Titanate* pyroelectric detectors
SRTS : *Short-Range Thermal Sight* program / NVEOD & DARPA
-> uncooled rifle sights
HIDAD : *High-Density Array Development* program /NVEOD & DARPA
-> 80000 pixels, 2x2 mils, NETD<0.3C

The Electromagnetic Spectrum

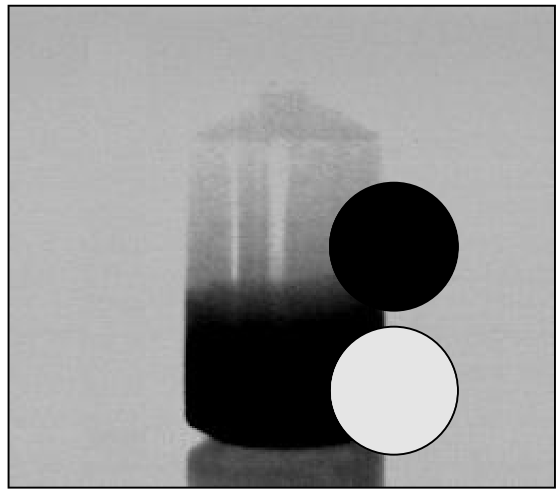


Near IR	(NIR)	:	0.75 - 3mm
Middle IR	(MIR)	:	3 - 6mm
Far IR	(FIR)	:	6 - 15mm
Extreme IR	(XIR)	:	15 - 1000mm

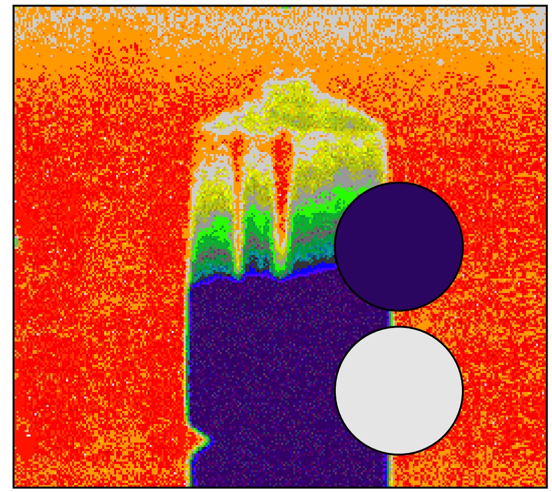
Visible cf. Thermal Radiation (1)

q Target signature (Spatial Distribution)

Visible(0.4-0.75μm)



FIR(8-12μm)

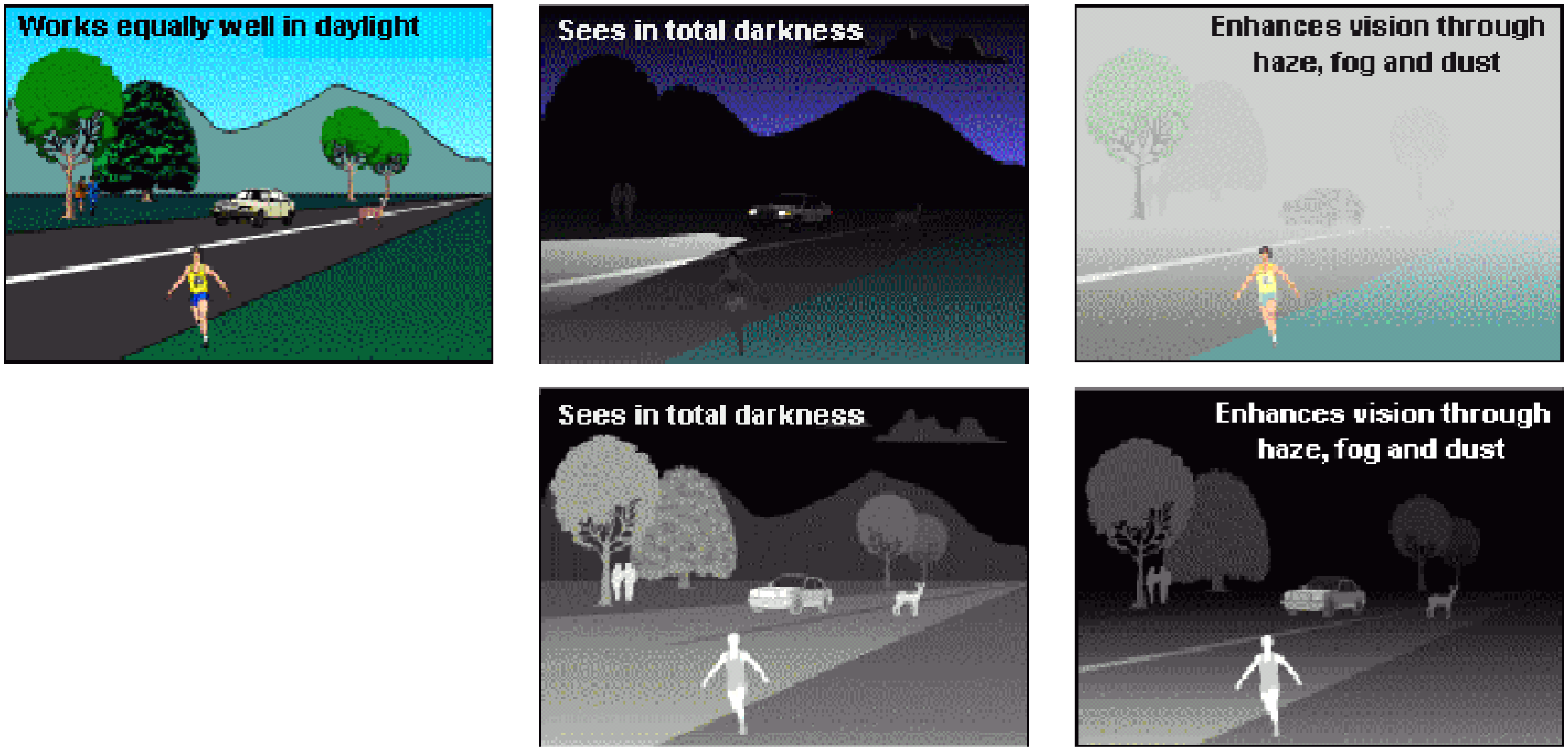


FIR(8-12μm)

- § Active sensing：Visible, NIR
- § Passive Sensing：Visible, NIR, MIR, FIR

Visible cf. Thermal Radiation (2)

- **Background signature (Spatial Distribution)**



Ref. "Thermal imaging solutions", TI NIGHTSIGHT interactive explorer.

Thermal Radiation Theory

q Thermal Radiation

All heated objects will emit EM radiant energy owing to the accelerated charges in the objects.

q Kirchhoff (1860)

- § Introduced the radiation transfer law, good absorbers are also good radiators.
- § Proposed the term ***blackbody*** to describe a body that absorbs all of the incident radiant energy. *- A standard radiator: can be used to compare any other source.*

q Key events of research for blackbody radiation

§ Stefan(1879), Boltzmann(1884)

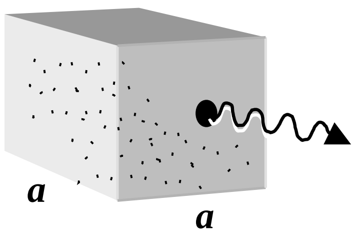
- the total amount radiation of a blackbody is proportional to the fourth power of its absolute temperature.

§ Wien (1894)

- attempted to give a general form for spectral distribution of the blackbody radiation.

§ Rayleigh, Jeans (1900)

- used a cavity model with the concepts of classical physics, derived an expression and attempted to fit the experimental data at long wavelengths.



Planck's Law

q Planck (1900)

§ The radiant energies of oscillators increases only in discrete step, differing by the quantity hn.

§ The spectral distribution of the radiation from a blackbody, spectral radiant emittance W_l is

$$W_l = p\,N_l = \frac{2p\,hc^2}{l^5}\,\frac{1}{e^{hc/lk_bT}-1} \qquad [\mathrm{W}\cdot\mathrm{cm}^{-2}\cdot\mu^{-1}]$$

k_b = 1.38×10^{-23} joule/K, Boltzmann's constant

h = 6.63x10^{-34} joule-sec, Planck's constant

Exitance or Emittance ?

Emissivity and Emittance ?

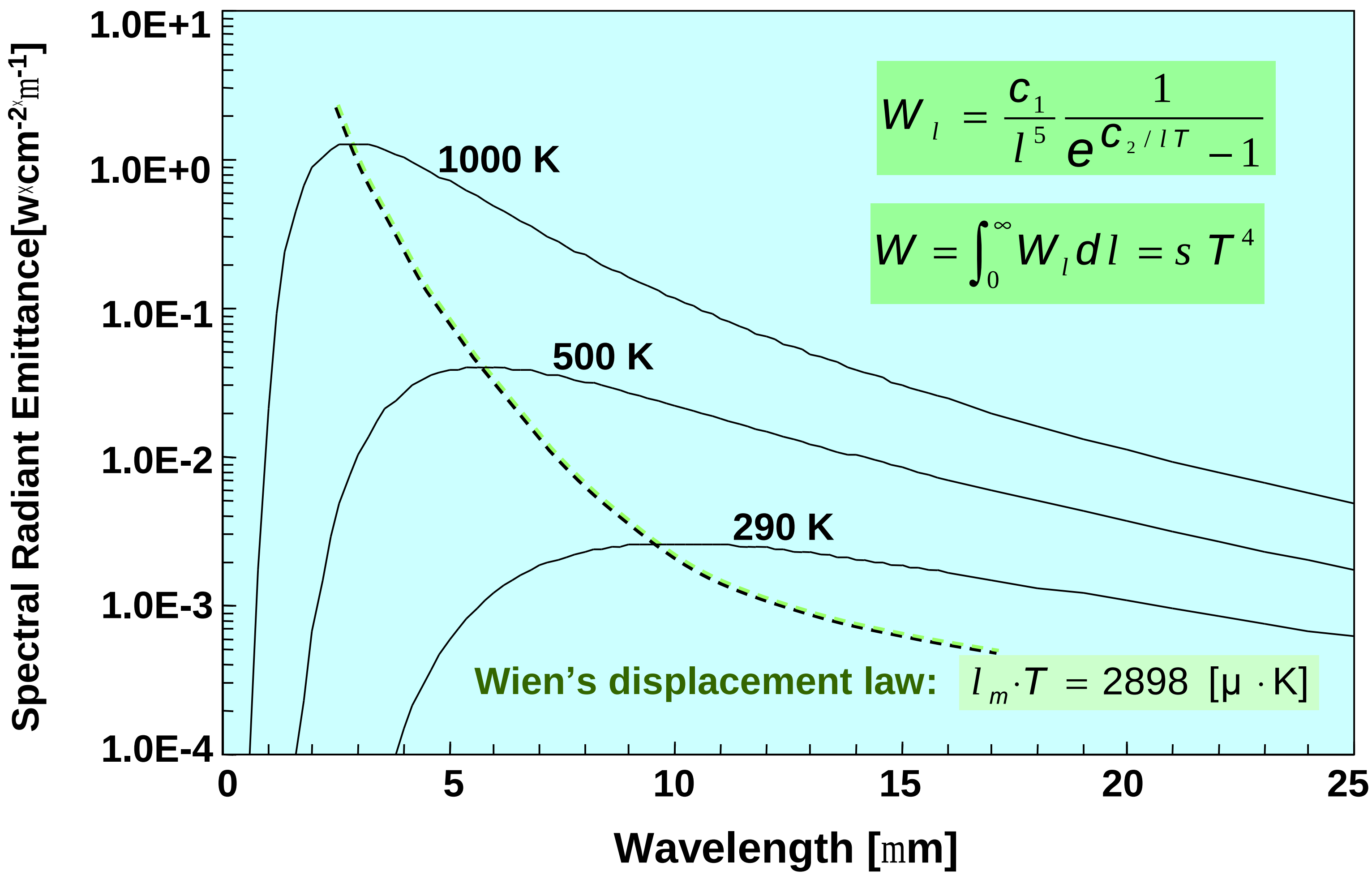
q Convenient form

$$W_l = \frac{c_1}{l^5}\,\frac{1}{e^{c_2/lT}-1}$$

$c_1 = 3.7415\times10^4$ $[\mathrm{W}\cdot\mathrm{cm}^{-2}\cdot\mu^4]$: 1st radiation constant

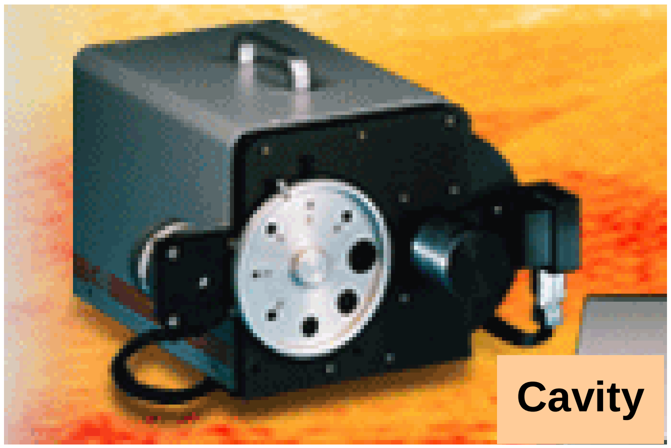
$c_2 = 1.4388\times10^4$ $[\mu\cdot\mathrm{K}]$: 2nd radiation constant

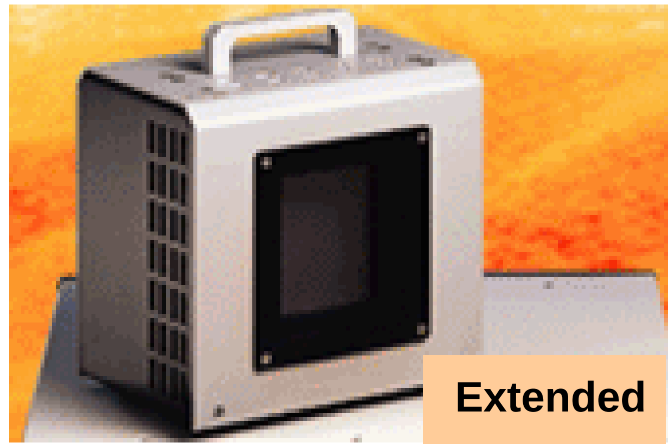
The Blackbody Radiation



The Standard Radiative Sources

q Blackbody types





q Standard types

1. Primary
2. Secondary
3. Working

Metal	Freeze Temp.[C]	Uncertainty
Copper	1084.62	0.50
Gold	1064.18	0.40
Silver	961.78	0.40
Aluminum	660.32	0.30
Zinc	419.53	0.30
Tin	231.93	0.20
Indium	156.60	0.20

Emissivity : 0.999 ± 0.0005

The Concepts of Emissivity

q **Definition:**

$$e \equiv W_t / W_{bb}$$

q **Kirchhoff's law:**

$$W_t / a = W_{bb}$$

§ $e_l = a_l$ (Only for a given temp. !)

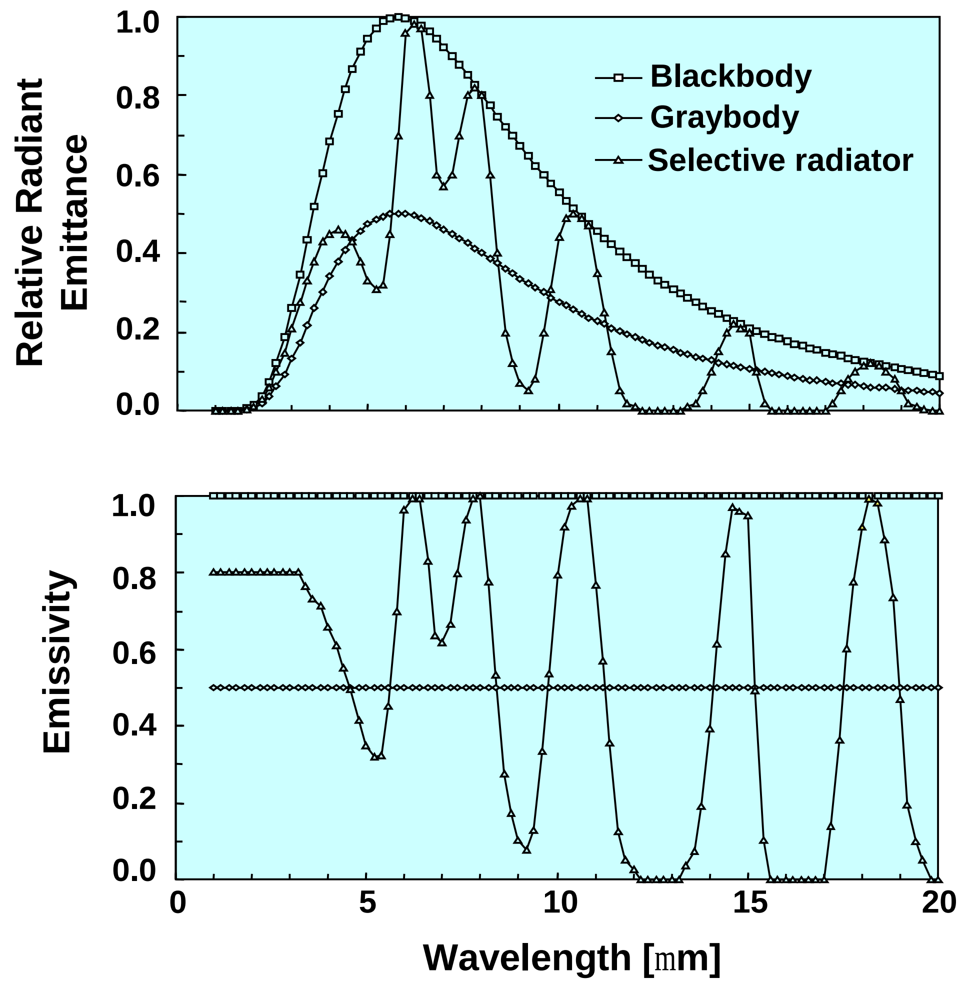
§ $a_l + r_l + t_l = 1$

§ **For semi-transparency object**

$$e_l = \frac{(1 - r_l)(1 - t_l)}{1 - r_l t_l}$$

q **General form**

$$e = \frac{\int_0^\infty e_l W_l dl}{\int_0^\infty W_l dl} = \frac{\int_0^\infty e_l W_l dl}{s T^4}$$



Emissivity of Common Materials

Metal		Temp[℃]	*e*	Metal		Temp[℃]	*e*
Al	polished anodized vacuum deposited	100 100 20	0.05 0.55 0.04	**Fe**	polished oxidized rusted	40 100 20	0.21 0.64 0.69
Stainless Steel	polished oxidized at 800℃	20 60	0.16 0.85	**Ni**	polished no polished oxidized	20 20 200	0.05 0.11 0.37
Steel	polished oxidized	100 200	0.07 0.79	**Cu**	polished oxidized	100 20	0.05 0.78
Au	polished	100	0.02	**Ag**	polished	100	0.03
Mg	polished	20	0.07	**Sn**	polished	100	0.07
Others		**Temp[℃]**	***e***	**Others**		**Temp[℃]**	***e***
Carbon	candle soot graphite	20 20	0.95 0.98	**Soil**	dry wet	20 20	0.92 0.95
Water	distilled ice	20 -10	0.96 0.96	**Water**	frost snow	-10 -10	0.98 0.85
Skin **Paper** **Glass**	human white polished	32 20 20	0.98 0.93 0.94	**Plaster** **Concrete** **Sand**	Rough coat - -	20 20 20	0.91 0.92 0.90

Temperature and Skin Materials

q Hot or cold skin?

in actual situations, a_l and e_l are not to be equal for a surface due to the temperature dependence of them and temperature differences between two sources. Using this fact, a hot or cold skin can be achieved by selecting materials with a high or low value of a_l / e_l .

§ The ratio of the absorptance a_s for solar radiation (6000K) and the emissivity e_a for low-temperature radiation (300K)

Material		a_s	e_a	a_s / e_a
Al	polished	0.387	0.027	14.35
	sandblasted	0.42	0.21	2.0
	anodized	0.15	0.77	0.19
Paints	Cu	0.782	0.49	1.60
	Al	0.54	0.45	1.2
	Mg	0.936	0.844	1.11
	TiO2(gray)	0.87	0.85	1.0
	TiO2(white)	0.19	0.94	0.2

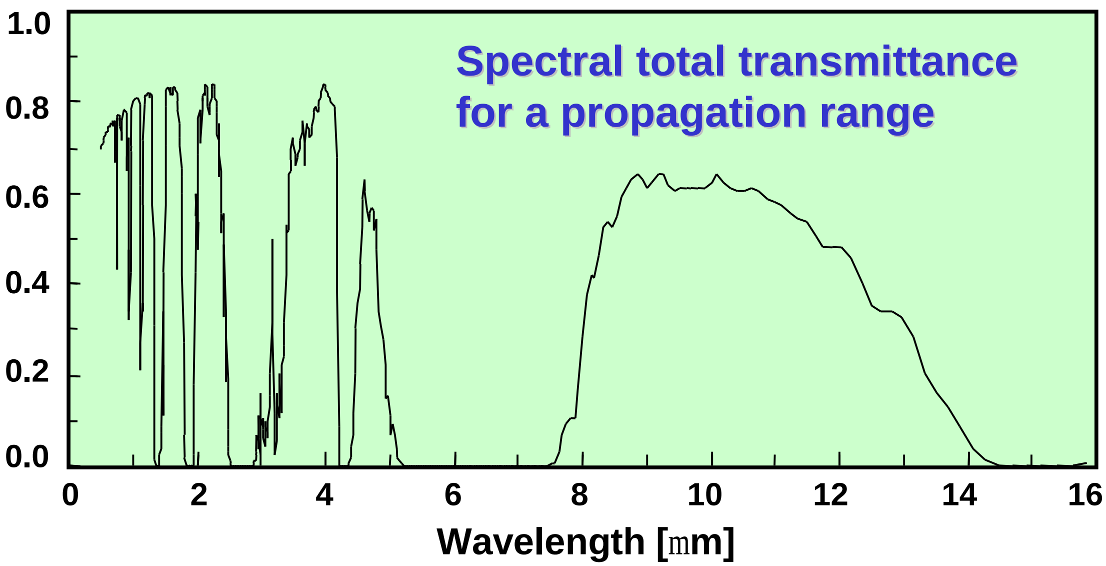
Atmospheric Transmittance

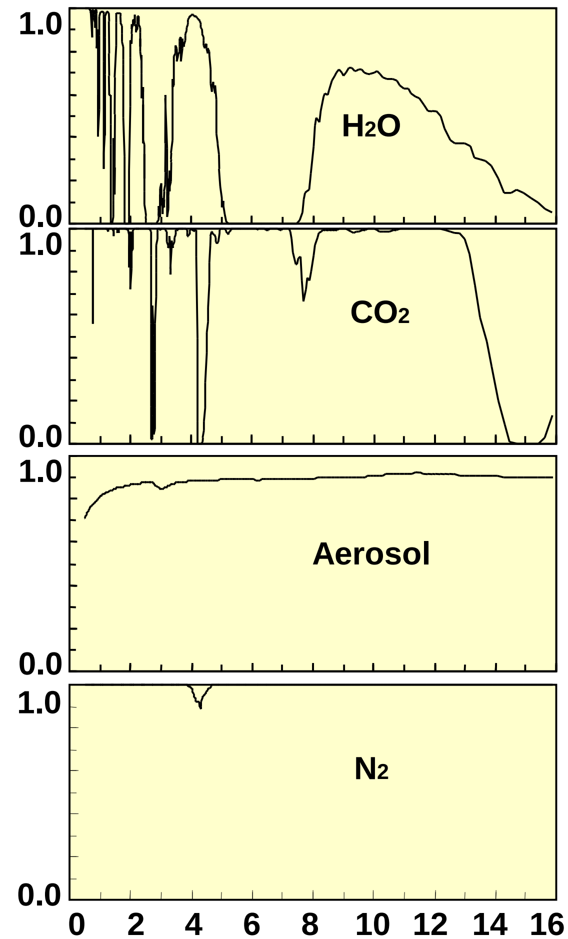
q Atmospheric transmittance

$$t\,(\,l\,, x) = e^{-s\,(\,l\,)\,x}$$

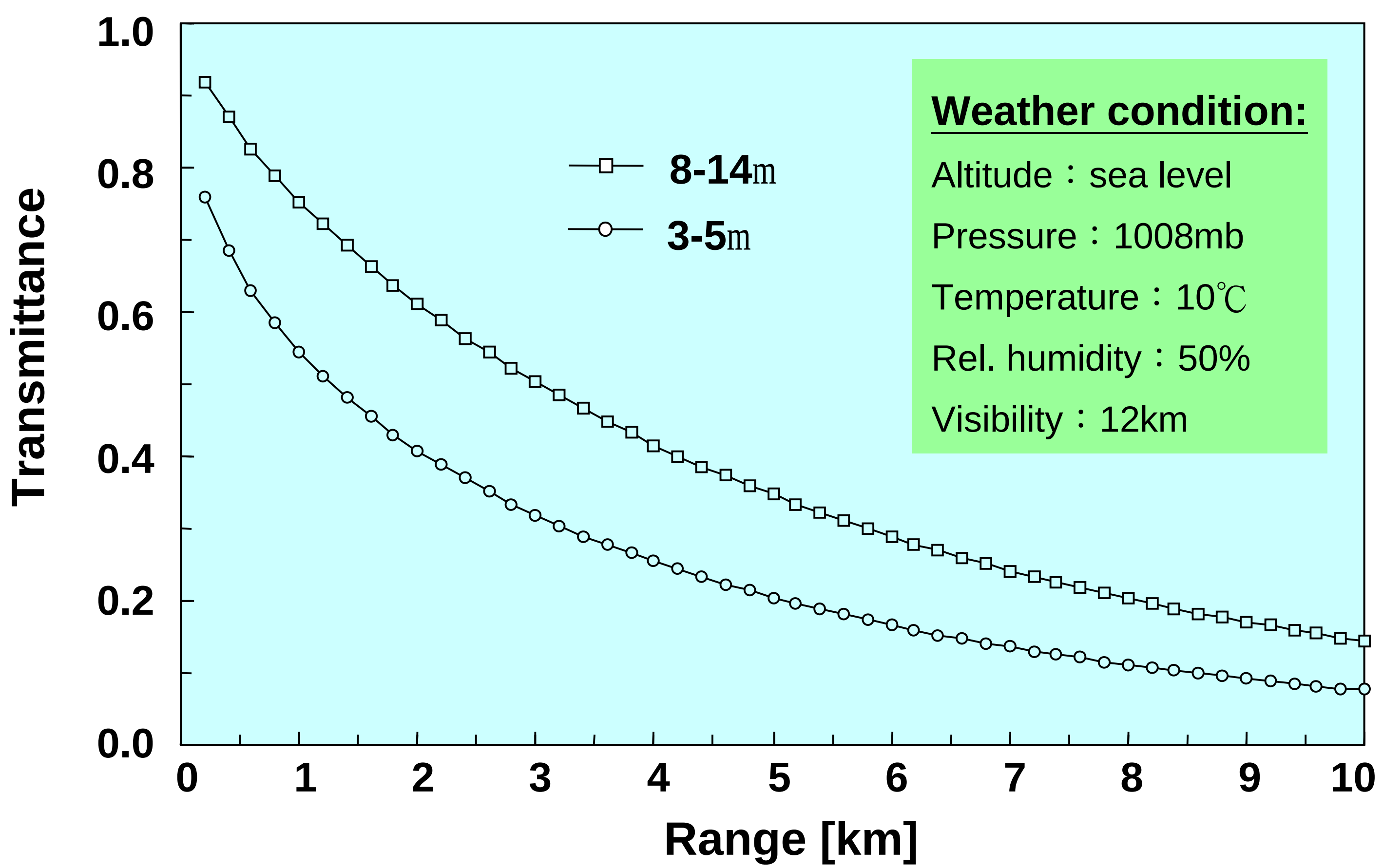
σ(l) : Spectral total coefficient of attenuation
(absorption, **scattering** s_s)

size << l,	$\sigma_s \propto l^{-4}$	(Rayleigh)
size ≥ 5 l,	σ_s = constant	(Mie)

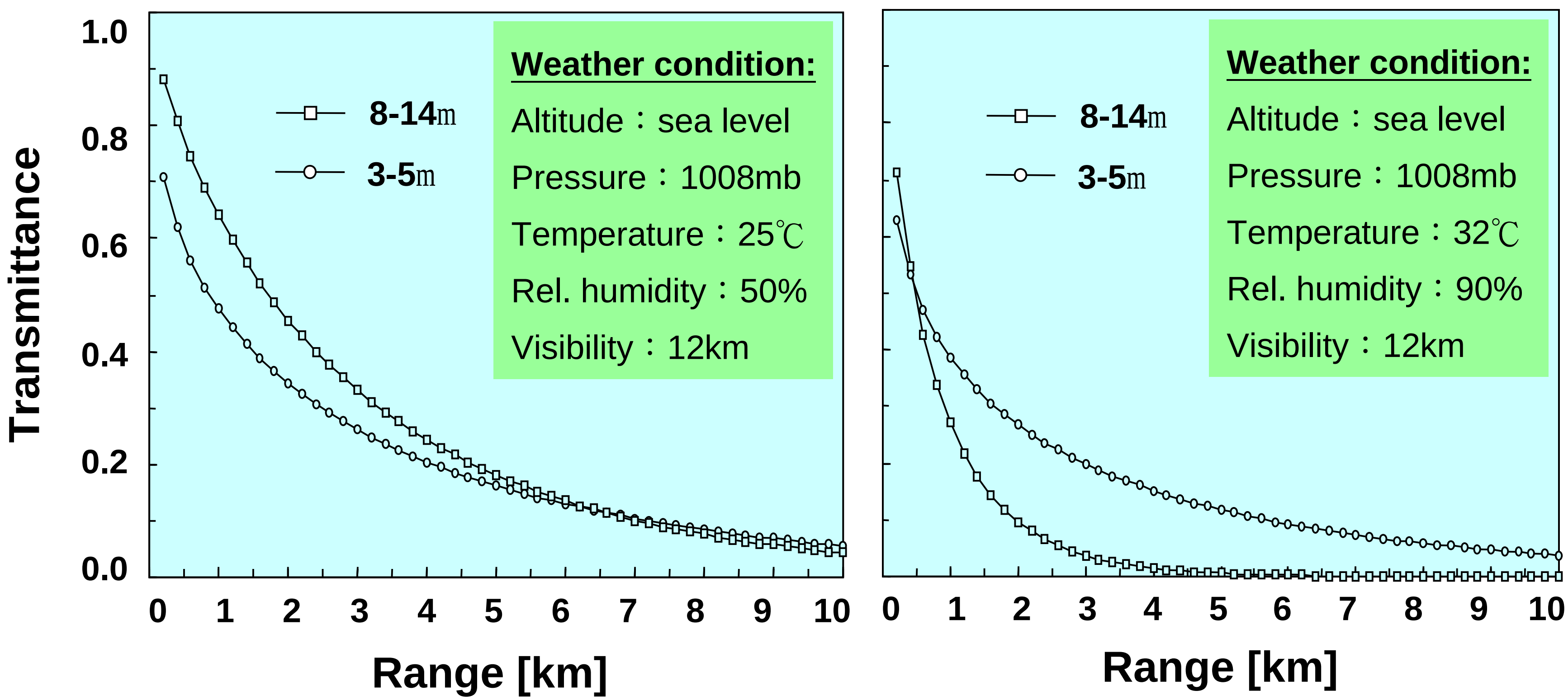




Atmospheric Trans. v.s. Range (1)



Atmospheric Trans. v.s. Range (2)



Radiometry Terminology

Terminology	Symbol	Unit
Radiant energy	*U*	Joule
Radiant power(flux)	*P*	Watt
Radiant emittance	*W*	W cm^{-2}
Radiance	*N (L)*	W cm^{-2} sr^{-1}
Radiant intensity	*J (I)*	W sr^{-1}
Irradiance	*H (E)*	W cm^{-2}
[Remarks]：Spectral + item = item per wavelength		

Point Radiator

q Point source

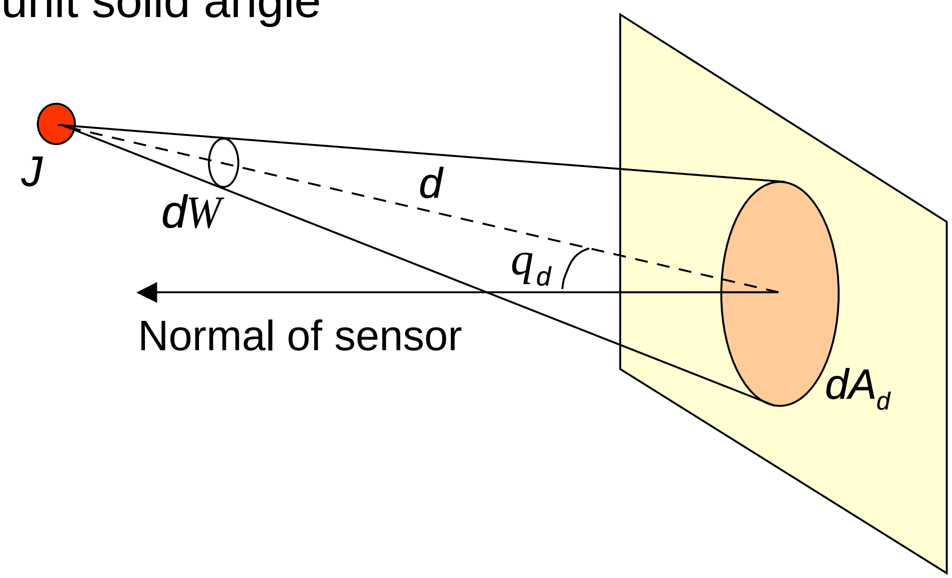
1. The physical size is not concerned but the subtend angle of the sensor.
2. If sensor has no optics, any source can be considered as a point source at a distance > 10 times the largest dimension of sensor.
3. If sensor has optics, the source size can not fill the FOV of the sensor.

q Radiant Intensity

The radiant flux emitted per unit solid angle

$$J = \frac{\partial P}{\partial \Omega}$$

$$H = \frac{dP}{dA_d} = \frac{J\,d\Omega}{dA_d} = \frac{J \cos q_d}{d^2}$$



Extended Radiator

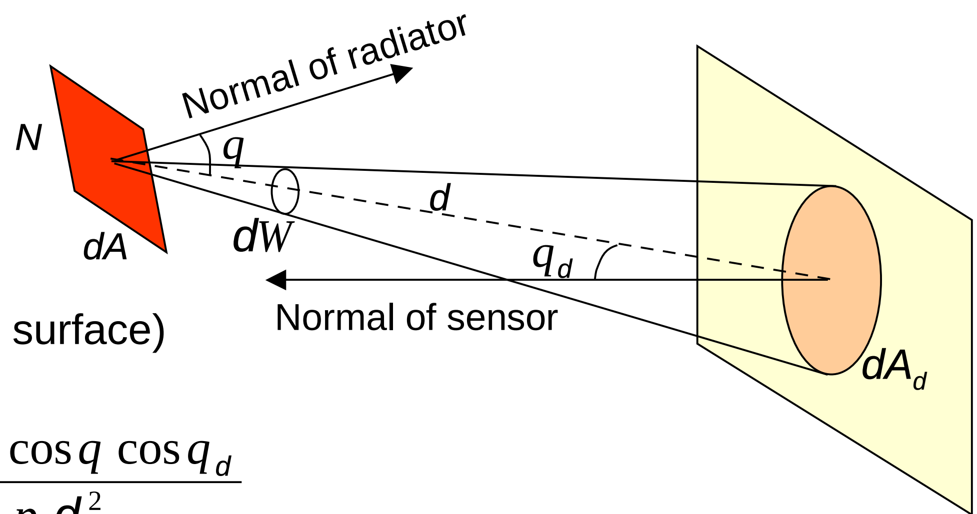
q Extended source

1. If sensor has no optics, the source at a distance < 10 times the largest dimension of sensor.
2. If sensor has optics, the source size can fill the FOV of the sensor.

q Radiance

The radiant flux emitted per unit solid angle per unit area

$$N = \frac{\partial^2 P}{\cos q \ \partial A \partial W}$$



$$W = \frac{dP}{dA} = \int N \cos q \ dW$$

$$= p \ N \quad \text{(for Lambertian surface)}$$

$$H = \frac{N \ dA \cos q \ \cos q_d}{d^2} = \frac{W \ dA \cos q \ \cos q_d}{p \ d^2}$$

Optical System Consideration

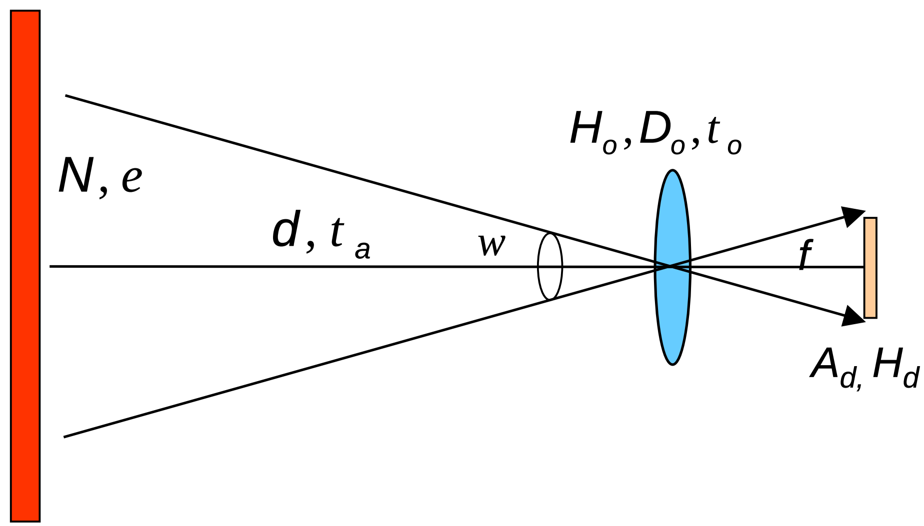
- **Spectral irradiance for an optical system in real world**
  (for target size fills FOV of the optical system)

  - **in front of optical system**

$$H_{o\lambda} = \tau_{a\lambda}\varepsilon_{\lambda}N_{\lambda}\omega = \tau_{a\lambda}\varepsilon_{\lambda}N_{\lambda}\frac{A_d}{f^2}$$

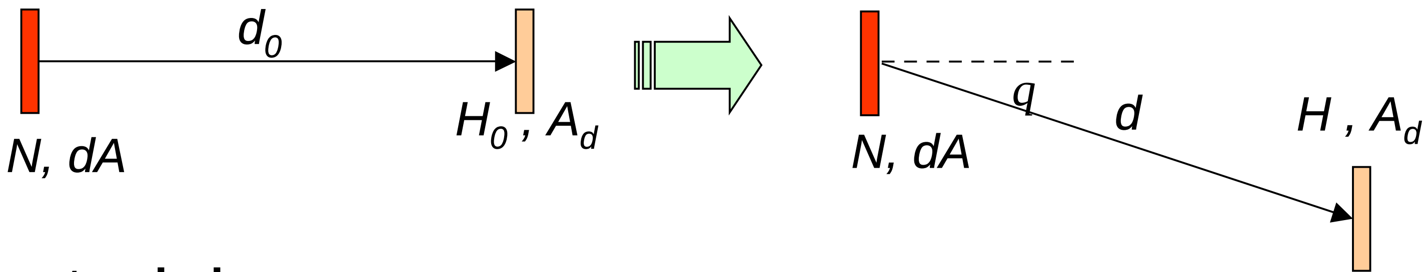
  - **on the detector**

$$H_{d\lambda} = H_{o\lambda}\tau_{o\lambda}\frac{\pi D_o^2}{4A_d} = \frac{\pi\varepsilon_{\lambda}N_{\lambda}\tau_{a\lambda}\tau_{o\lambda}}{4F_{no}^2} = \frac{\varepsilon_{\lambda}W_{\lambda}\tau_{a\lambda}\tau_{o\lambda}}{4F_{no}^2}$$



The Effect of Misalignment

q **The irradiance variation when misalignment occurs**

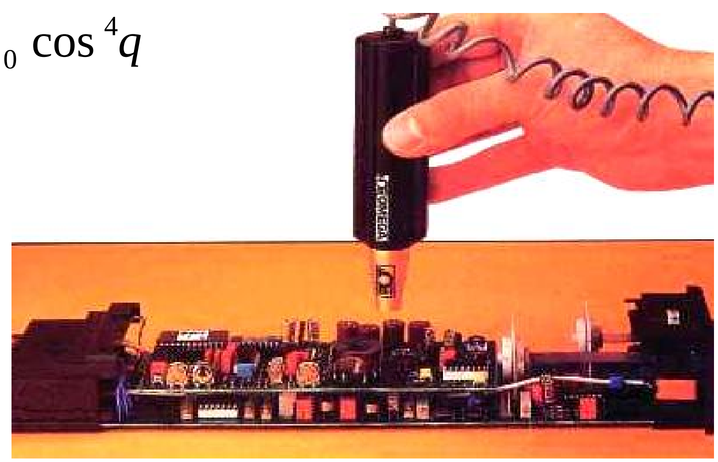


§ for extended source

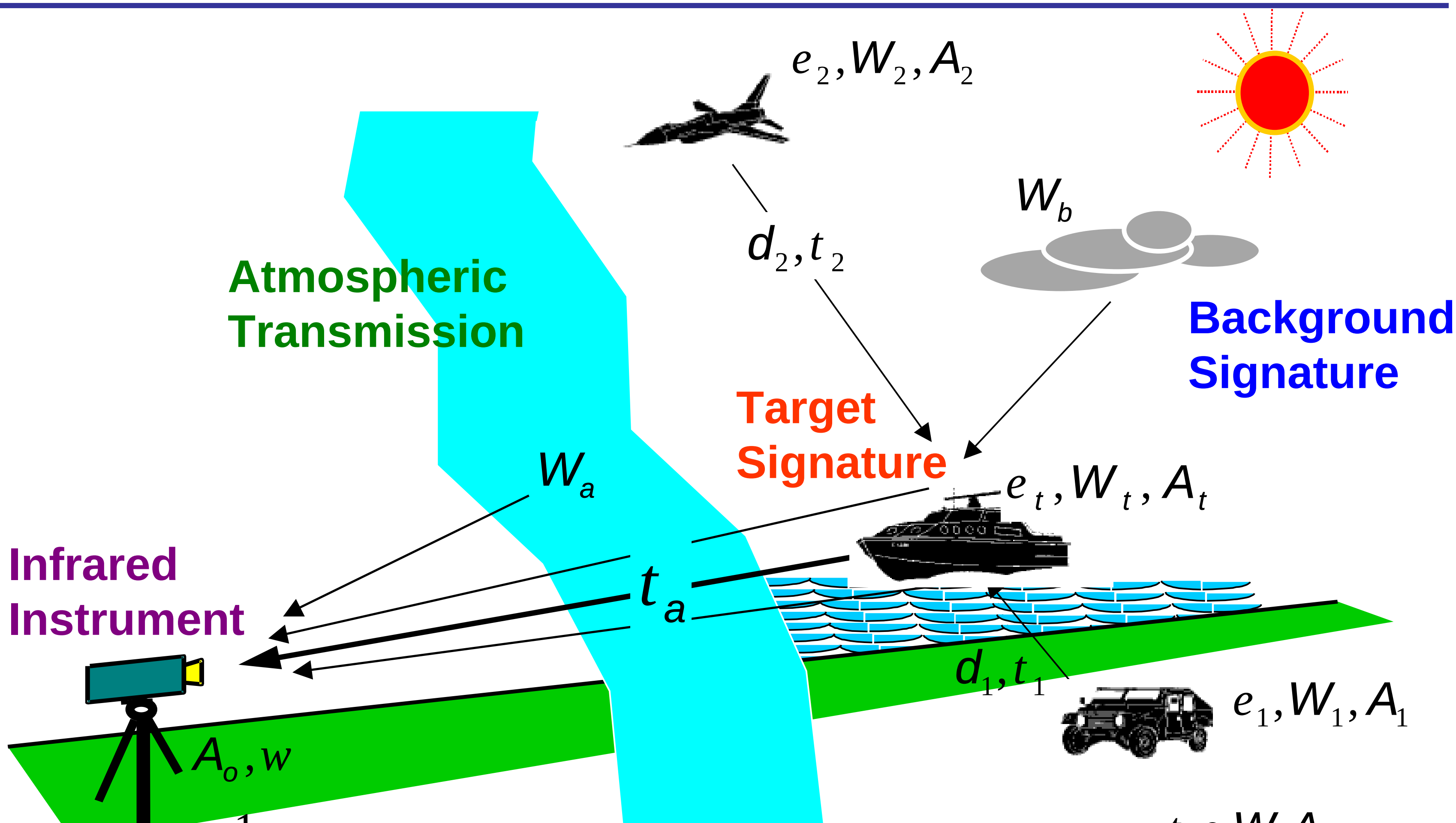
$$H = \frac{N\ dA \cos q\ \cos q}{(\frac{d}{\cos q})^2} = \frac{N\ dA}{d^2}\cos^4 q = H_0 \cos^4 q$$

§ for point source

$$H = \frac{J \cos q}{(\frac{d}{\cos q})^2} = \frac{J}{d^2}\cos^3 q = H_0 \cos^3 q$$



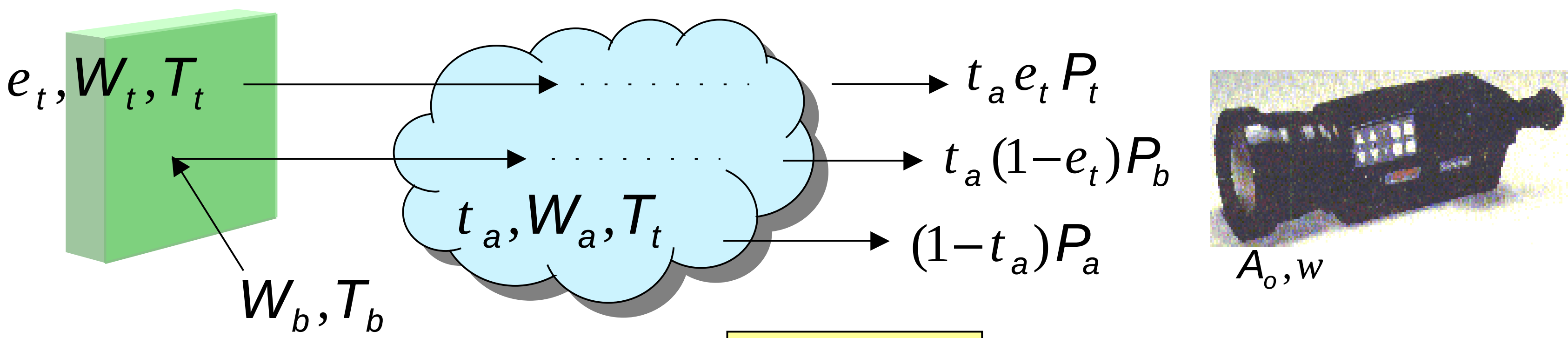
IR Measurement in the Nature



$$P_{tot} = A_o w \frac{1}{p} (t_a e_t W_t + (1 - t_a) W_a + t_a (1 - e_t) W_b + t_a (1 - e_t) \frac{t_1 e_1 W_1 A_1}{p\, d_1^2} + \ldots)$$

The Radiation Relationship

q The radiation relationship between target and sensor



§ **Detector responsivity**

$R = V / P$ [Volt/Watt]

$P_t = A_o w W_t / p$

$P_b = A_o w W_b / p$

$P_a = A_o w W_a / p$

Original blackbody radiant flux received by sensor from target, background and atmosphere.

§ **Sensor signal output**

$$V_{tot}^{t} = t_a e_t V_{bb}^{t} + t_a (1 - e_t) V_b + (1 - t_a) V_a$$

Temperature Measurement Process

- **The signal response of radiation from a blackbody target**

$$V_{bb}^{t} = \frac{V_{tot}^{t}}{t_a e_t} - (\frac{1}{e_t} - 1)V_b - \frac{1}{e_t}(\frac{1}{t_a} - 1)V_a$$

- **Treatment procedure**

1. Measure V_{tot}^{t}
2. Set e_t (by measurement or lookup table)
3. Set t_a (by measurement or theoretical calculation)
4. Set ambient temperature (by measurement) to obtain V_b and V_a by using the calibration curves
5. Substitute $V_{tot}^{t}, e_t, t_a, V_b$ and V_a into the above formula to calculate V_{bb}^{t}, then obtain target temperature by using the calibration curves

Calibration Model

- q **Transfer function for various system specs**

$$k = k(F_{no}, t_{ol}, t_{fl}, R_{l}, A_d)$$

Aperture, Lens, Filter, Detector

- q **System calibration by using a blackbody at various temperatures**

$$V_{out} = \int_{l_1}^{l_2} R_l H_{dl}(T) A_d \, dl$$

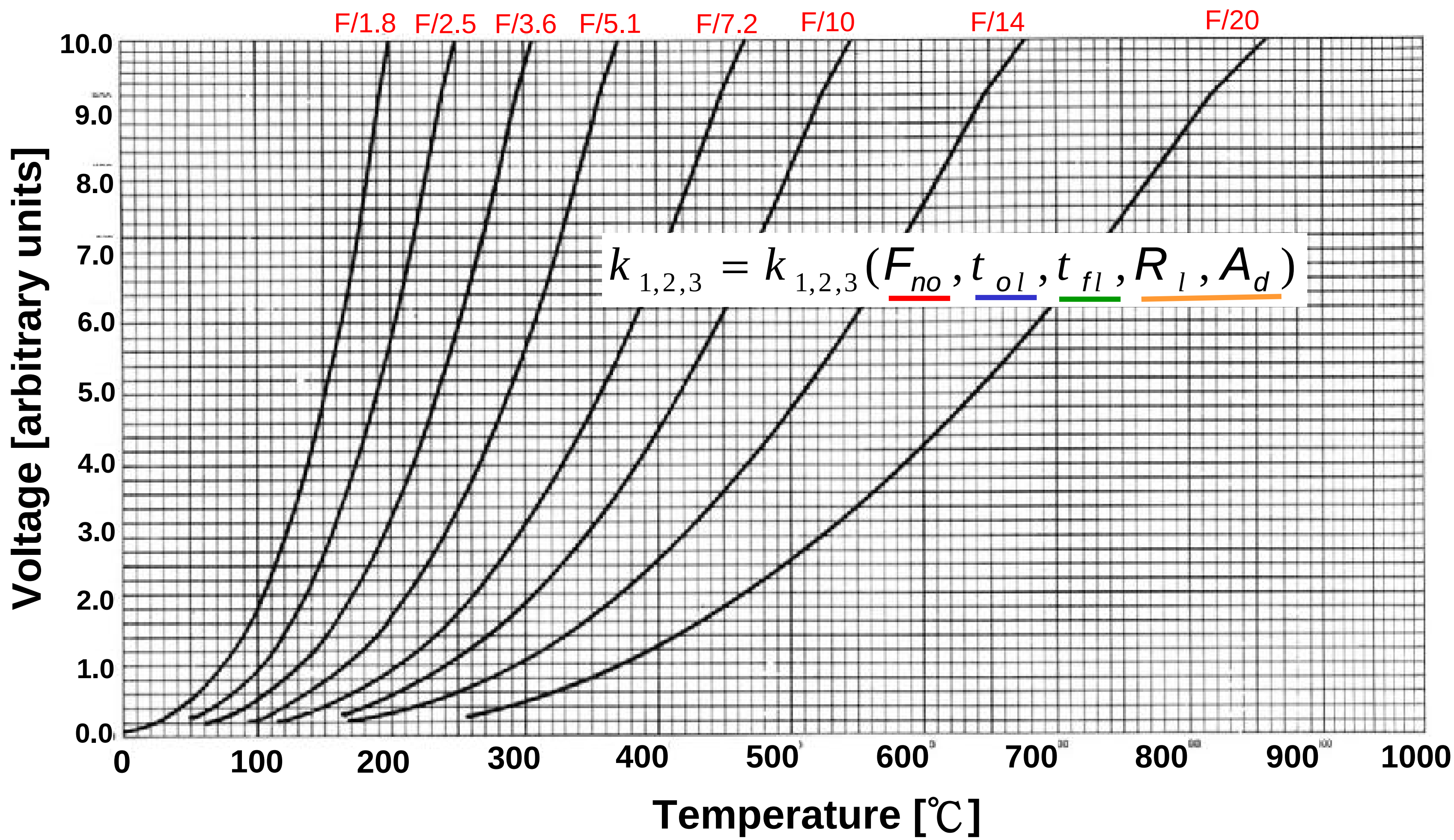
$$= \frac{1}{4F_{no}^2} \int_{l_1}^{l_2} R_l A_d t_{ol} t_{fol} W_l(T) \, dl$$

$$= \frac{k_1}{k_3 e^{k_2/T} - 1}$$

$$W_l(T) = \frac{c_1}{l^5} \frac{1}{e^{c_2/lT} - 1}$$

$$V_{out} = V_{out}(k_1, k_2, k_3, T)$$

Typical Calibration Curves



$$k_{1,2,3} = k_{1,2,3}(F_{no}, t_{ol}, t_{fl}, R_l, A_d)$$

Emissivity Measurement Model

q The general form of target emissivity measurement

$$e_t = \frac{V_{tot}^t - t_a V_b - (1 - t_a) V_a}{t_a (V_{bb}^t - V_b)}$$

q Eliminating the atmospheric radiance contribution

1. Using a reference source with known emissivity e_r close to the target

$$V_{tot}^r = t_a e_r V_{bb}^r + t_a (1 - e_r) V_b + (1 - t_a) V_a$$

2. Subtract V_{tot}^r from V_{tot}^t

$$V_{tot}^t - V_{tot}^r = t_a (e_t V_{bb}^t - e_r V_{bb}^r) + t_a (e_r - e_t) V_b$$

3. The new form

$$e_t = \frac{V_{tot}^t - V_{tot}^r + t_a e_r (V_{bb}^r - V_b)}{t_a (V_{bb}^t - V_b)}$$

Emissivity Measurement Methods (1)

q Case 1 (the commonest case)

1. Heat target to a known temperature or measure its temperature with any contact sensor
2. Obtain V_{bb}^{t} by using the calibration curves
3. Align the sensor with the normal of target and place it as close as possible, in order to neglect the effects of ambient conditions, i.e. $t_a = 1,\ V_b \approx 0$
4. Measure V_{tot}^{t} and calculate the emissivity with the formula, $e_t = V_{tot}^{t} / V_{bb}^{t}$

P.S. Using an available (calibrated) IR thermometer, you can adjust the emissivity value to force the indicator to display and to fit the correct known temperature.

$$V_{bb}^{t} = V_{tot}^{t} / e_t$$

display (↗ V_{bb}^{t}) **measure** (↑ V_{tot}^{t}) **adjust** (↖ e_t)

Emissivity Measurement Methods (2)

q Case 2 (the general case)

1. The same as case 1
2. The same as case 1
3. Obtain V_{bb}^{r} and V_b with the same method as V_{bb}^{t}
4. Calculate t_a with LOWTRAN model
5. Measure V_{tot}^{t} and V_{tot}^{r} calculate the emissivity with the formula,

$$e_t = \frac{V_{tot}^{t} - V_{tot}^{r} + t_a e_r (V_{bb}^{r} - V_b)}{t_a (V_{bb}^{t} - V_b)}$$

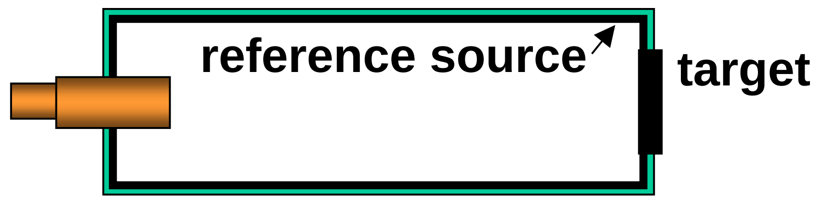
Emissivity Measurement Methods (3)

q Case 3

Using ambient (background) as the reference source

1. Obtain V_{bb}^{t} and V_{b} with the same method as case 2
2. Calculate t_{a} with LOWTRAN model
3. Measure V_{tot}^{t} and V_{tot}^{r} calculate the emissivity with the formula,

$$e_t = \frac{V_{tot}^{t} - V_{tot}^{r}}{t_a (V_{bb}^{t} - V_b)}$$



q Case 4

The portion of target is coated and as the reference source

1. The same as case 3
2. The same as case 3
3. The same as case 3 but with the formula, $e_t = \frac{V_{tot}^{t} - V_{tot}^{r}}{t_a (V_{bb}^{t} - V_b)} + e_r$

Emissivity Measurement Methods (4)

q **Case 5 (spectral emissivity)**

Using a spectroradiometer and a blackbody source as the reference source with known temperature equals to that of target

1. The same as case 1
2. The same as case 1
3. Obtain $V_{bb}^{r}(l)$ and $V_{b}(l)$ with the same method as $V_{bb}^{t}(l)$
4. Calculate t_{a} with LOWTRAN model
5. Measure V_{tot}^{t} and V_{tot}^{r} calculate the emissivity with the formula,

$$e_{t}(l) = \frac{V_{tot}^{t}(l) - V_{tot}^{r}(l)}{t_{a}(l)(V_{bb}^{t}(l) - V_{b}(l))} + e_{r}(l)$$

Note: in this case,

$$e_{r}(l) \approx 1, \quad V_{bb}^{r}(l) \approx V_{bb}^{t}(l)$$

Classification of IR Thermometer

- **Wideband**

  Most IR thermometer use a wideband and choose 8-14μm range for adequate target radiation and atmospheric transmittance.

  Ex. Radiometer, Thermal Imager

- **Narrowband**

  The IR thermometers use a narrowband are costlier because they need a special filter and usually to be constructed by a complicated optomechanical system.

  Ex. Optical pyrometer, Thermal Imager for high temperature or special purpose measurement

- **Ratio (Two-color)**

  Measuring the ratio of radiations at two selected narrow bands (near 0.9 μm for high temperature measurement).

  Ex. Two-color IR thermometer

Narrowband Measurement

q Wien's law and Planck's law

$$W_l(T)_{Wien} = \frac{c_1}{l^5}\frac{1}{e^{c_2/lT}} \longleftrightarrow W_l(T)_{Planck} = \frac{c_1}{l^5}\frac{1}{e^{c_2/lT}-1}$$

$$Error = \frac{W_l(T)_{Planck} - W_l(T)_{Wien}}{W_l(T)_{Planck}} = e^{-c_2/lT}$$

Ex. T=1000K

Error = 23.7% (10µ)

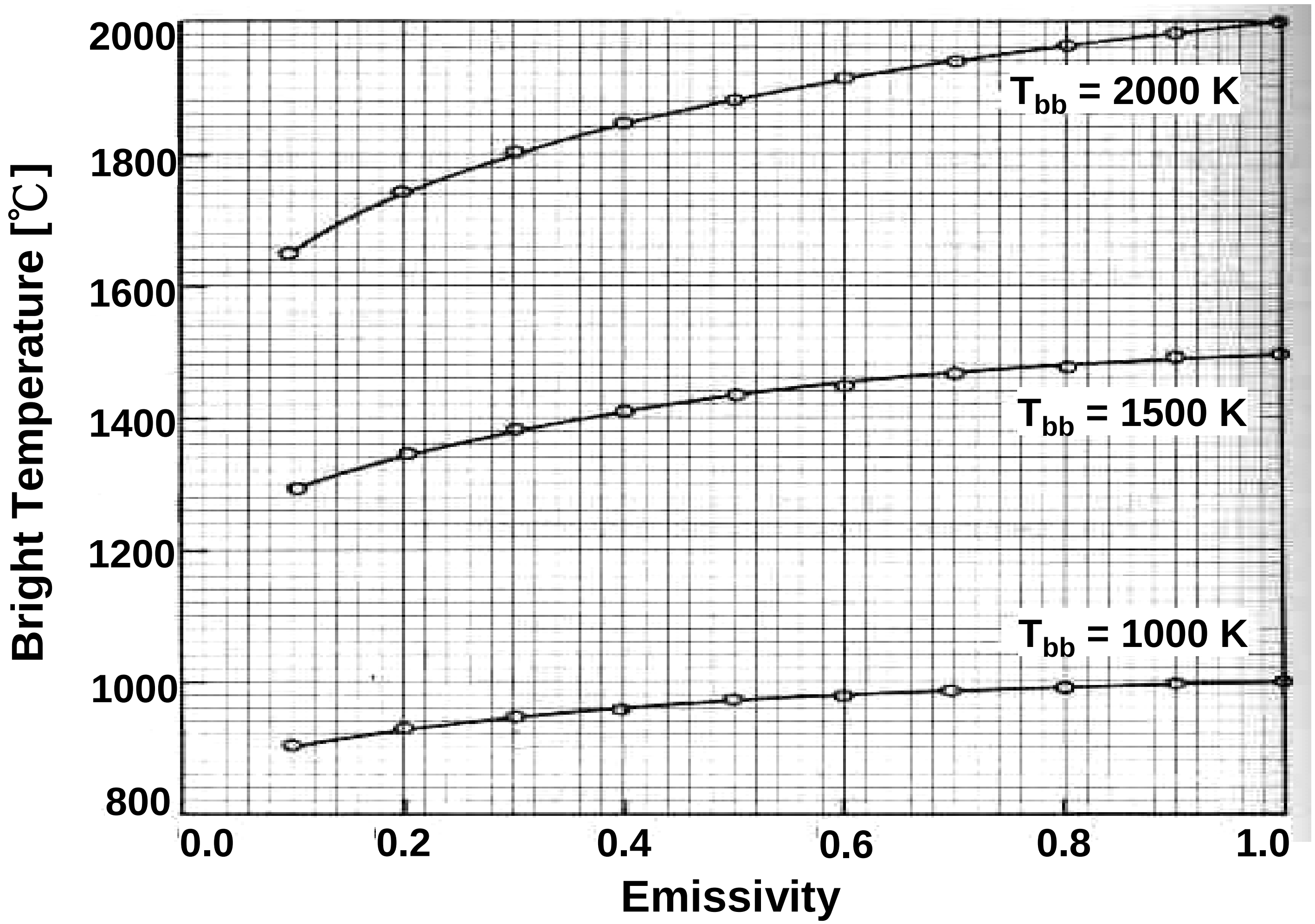
Error = 2x10^{-8}% (0.655µ)

q The brightness temperature

$$e = \frac{c_1 l^{-5} e^{-c_2/lT_B}}{c_1 l^{-5} e^{-c_2/lT_{bb}}} \qquad \frac{1}{T_B} = \frac{1}{T_{bb}} - 4.552\times 10^{-5}\ln e$$

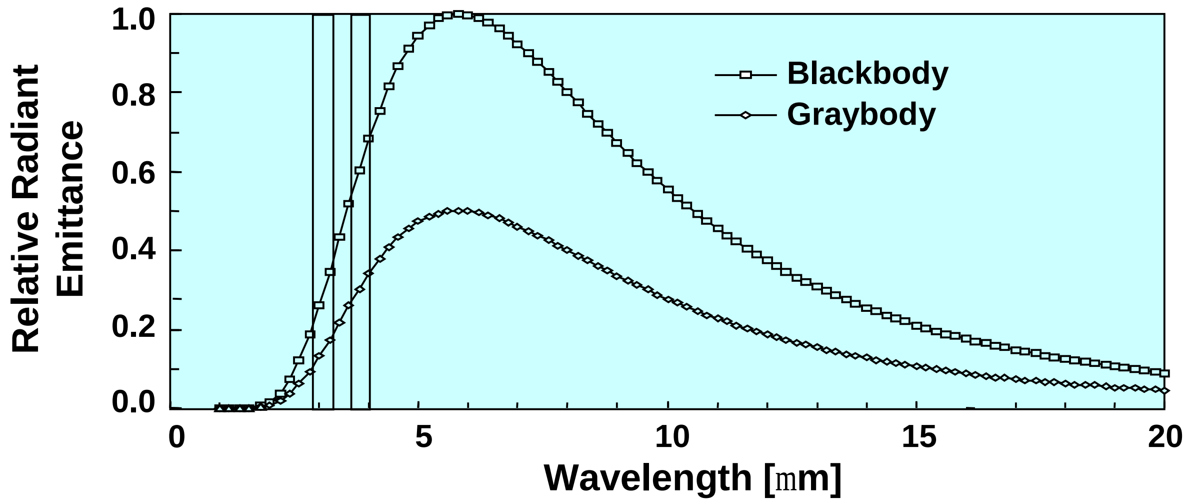
for $l = 0.655\,m$m

The Effect of Emissivity Errors



Two-color Measurement

q Why two color?



q Advantages and Disadvantages

- § If the change in emissivity at the two selected wavelength is the same, the effect of emissivity is eliminated.
- § The target need not fill the FOV of the thermometer. The effects of dust, smoke, and distance can be neglected as long as the ratio dose not vary.
- § The accuracy will be less than 1-color thermometer if the ratio highly varies.

Two-color Temperature

q Derivation of two-color temperature

The received radiation ratio *R* of two selected wavelength

$$R = \frac{k(l_1)e(l_1)W_{l_1}(T)dl_1}{k(l_2)e(l_2)W_{l_2}(T)dl_2} = \frac{k(l_1)e(l_1)c_1 l_1^{-5} e^{-c_2/l_1T} dl_1}{k(l_2)e(l_2)c_1 l_2^{-5} e^{-c_2/l_2T} dl_2}$$

$$T = \left(\frac{1}{l_2} - \frac{1}{l_1}\right)\frac{c_2}{\ln R + 5\ln(l_1/l_2) - \ln[k(l_1)/k(l_2)] - \ln[e(l_1)/e(l_2)]}$$

If the transmission factor and emissivity are the same at both wavelength,

$$T_c = \left(\frac{1}{l_2} - \frac{1}{l_1}\right)\frac{c_2}{\ln R + 5\ln(l_1/l_2)}$$

Analysis of Two-color Methods

q The error occurs between actual temperature and T_c

$$Error = \frac{1}{T} - \frac{1}{T_c} = \frac{\ln[k(l_1)/k(l_2)] + \ln[e(l_1)/e(l_2)]}{c_2\left(\frac{1}{l_1} - \frac{1}{l_2}\right)}$$

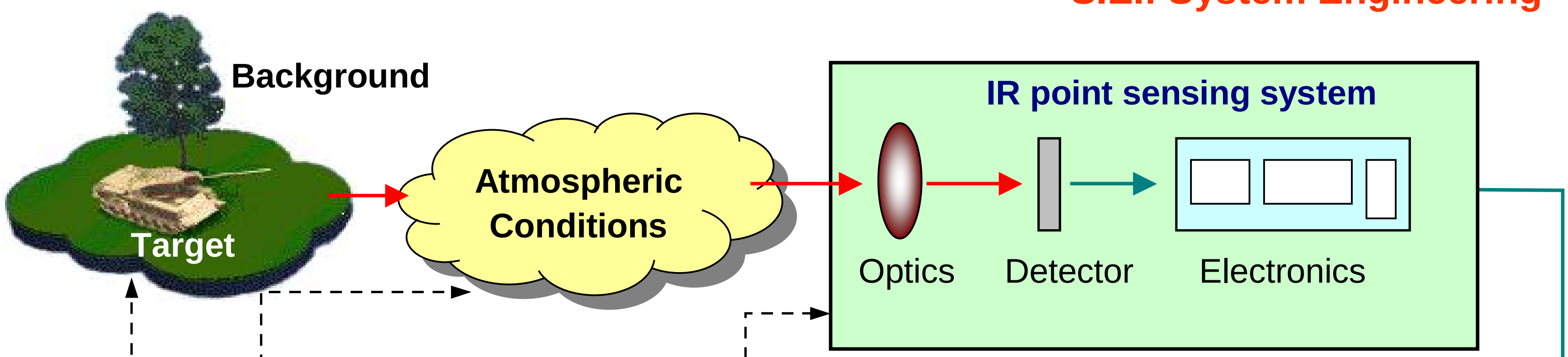
§ The measured temperature T_c can be equal, lower, or higher than actual temperature, it is different from the result of other IR thermometers which always get a lower one.

q The better measurement conditions

§ Higher target temperature
§ Shorter wavelength used
§ The bandwidth for each color must be very narrow
§ To obtain the ratio of emissivity and transmission factor at both wavelength if they are not equal

IR S.E. for Point Sensing

S.E.: System Engineering



Signature
- Spectral
- Temporal

Noise
- **Detector**
  - 1/f
  - Johnson
- **System**
  - NEI

Evaluation model
- Range

$$R = \left[\frac{J\,\tau_a}{NEI \cdot SNR}\right]^{1/2}$$

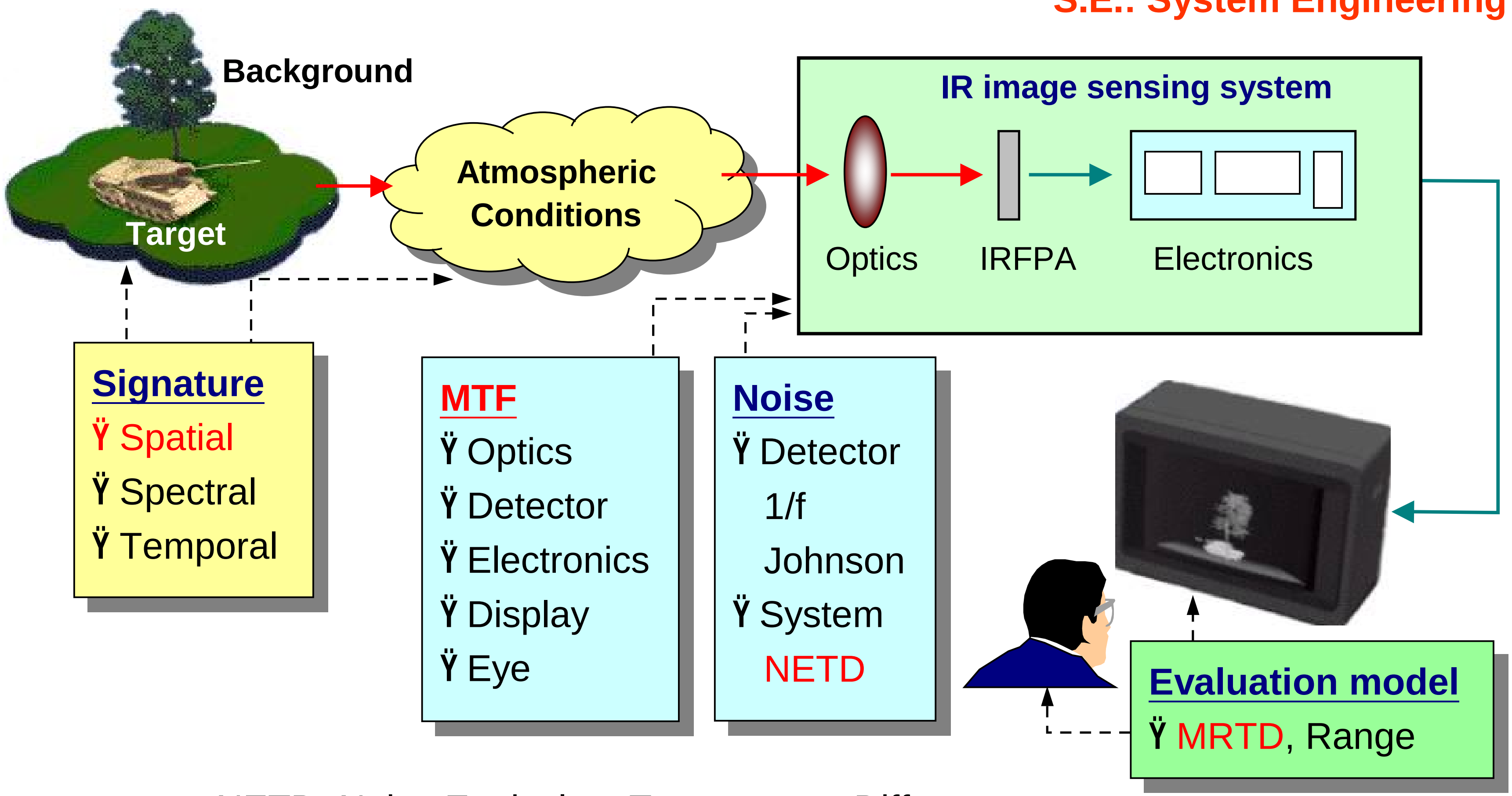
$$R = \left[\frac{\int_{\Delta\lambda} \varepsilon_\lambda J_\lambda \tau_{a\lambda} A_o \tau_{o\lambda}\, d\lambda}{NEP \cdot SNR}\right]^{1/2}$$

NEI: Noise Equivalent Irradiance
NEP: Noise Equivalent Power

$$NEP = \frac{V_n}{R_v} = \frac{V_n}{V_s / P_d} \qquad NEI = \frac{NEP}{A_o \tau_o}$$

IR S.E. for Image Sensing (1)

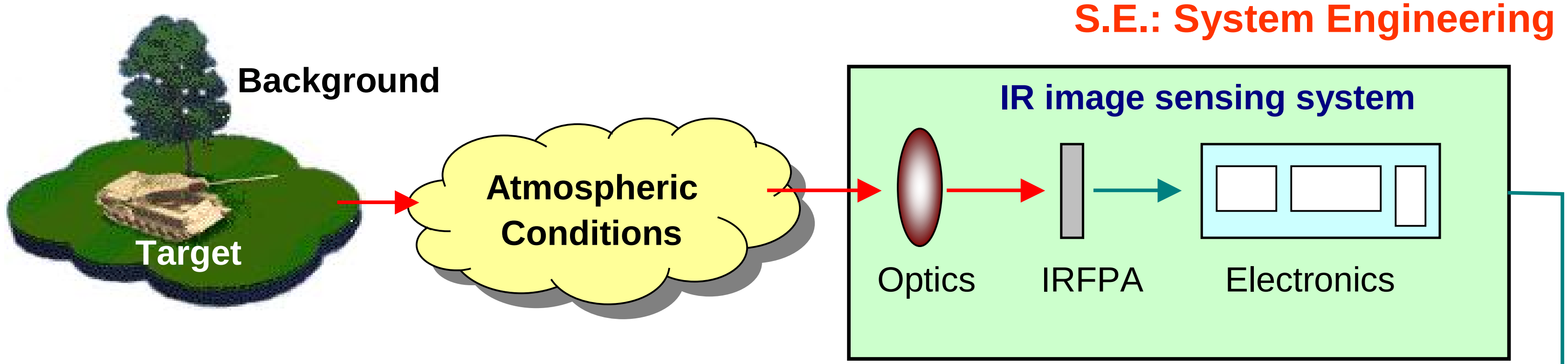
S.E.: System Engineering



NETD: Noise Equivalent Temperature Difference
MRTD: Minimum Resolvable Temperature Difference

IR S.E. for Image Sensing (2)

S.E.: System Engineering



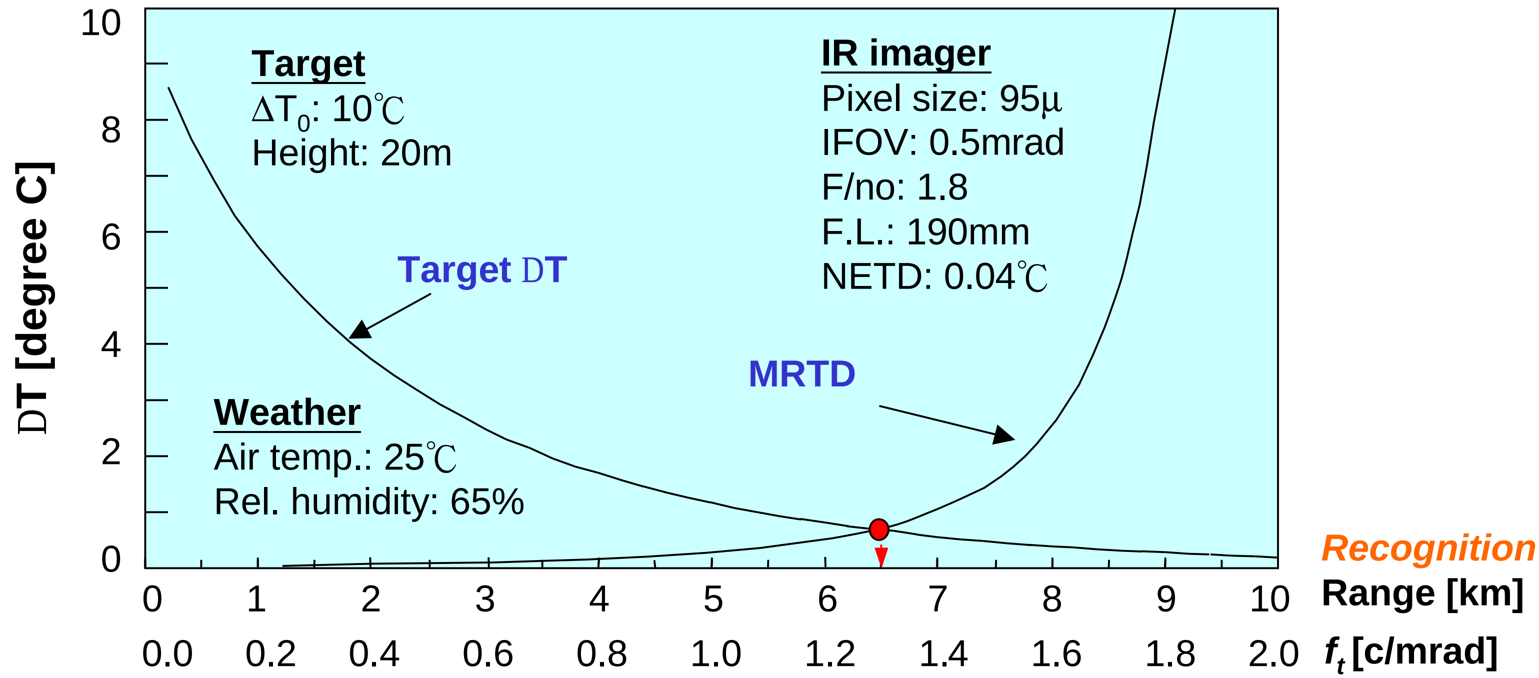
Evaluation model

- MRTD, Range

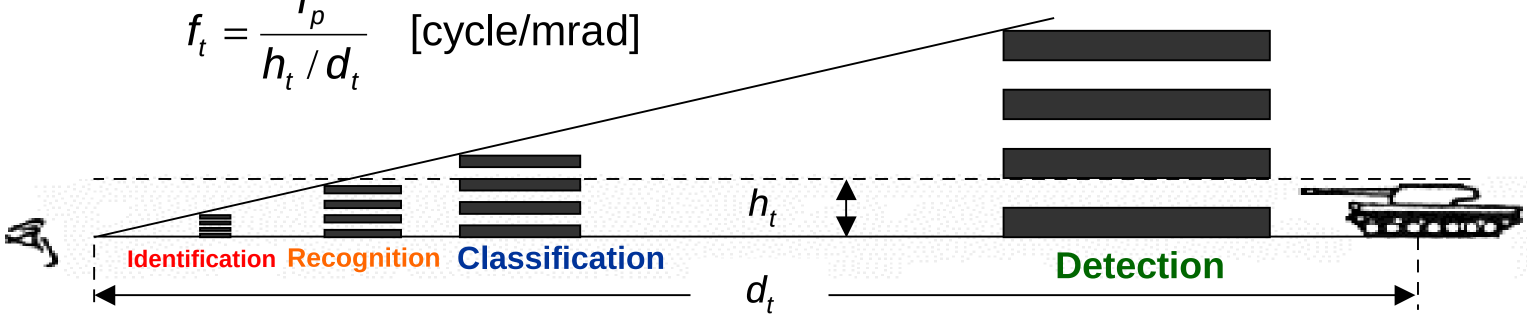
$$MRTD = 3\left(\frac{W}{\Delta f\, t_d\, t_e\, \rho}\right)^{1/2}\left[\frac{NETD}{(MTF)_{system}}\right]f_t = k\left[\frac{NETD}{(MTF)_{system}}\right]f_t$$

$$NETD = \frac{4F_{no}^2}{D^*\int_{Dl} t_{al}\, t_{ol}\left(\frac{\partial W}{\partial T}\right)\Big|_{T=T_B} dl}\sqrt{\frac{\Delta f}{A_d}} \qquad (MTF)_{system} = \prod_i (MTF)_i$$

Evaluation of System Performance



$$f_t = \frac{l_p}{h_t / d_t} \quad \text{[cycle/mrad]}$$

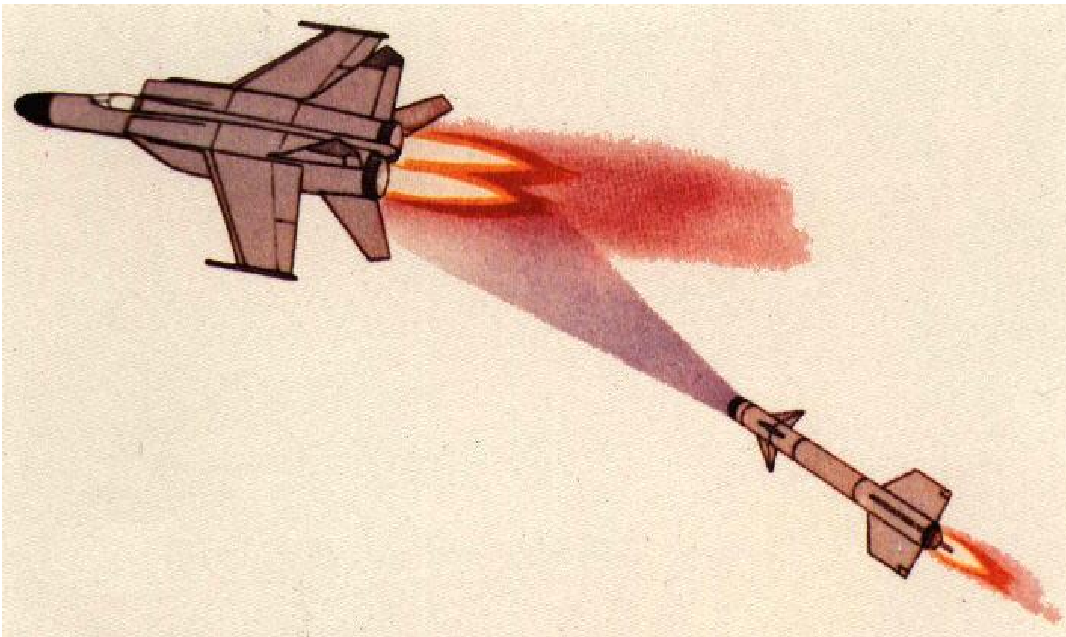


Military Applications of IR sensing (1)

目標檢知	戰略	戰術	後勤支援
存在 方位 運動	• 戰略警告 • 洲際飛彈預警 • 軍事行動確認	• 飛彈導引 • 近發引信 • 碰撞警告 • 入侵偵測	• 入侵偵測 • 碰撞警告 • 坦克偵測
時間變化	• 目標確認	• 目標確認	• 監視傷患治療 • 生化感應器
光譜分佈	• 目標背景信號 • 大氣溫度	• 毒氣偵測 • 氣流偵測 • 目標背景信號	• 污染偵測
空間分佈	• 戰略搜索 地球資源、農業 天候、冰山 • 軍事行動確認	• 戰場搜索監視 • 潛艇偵測 • 損害鑑定	• 傷患鑑定監視 • 防寒衣物效能

Military Applications of IR sensing (2)

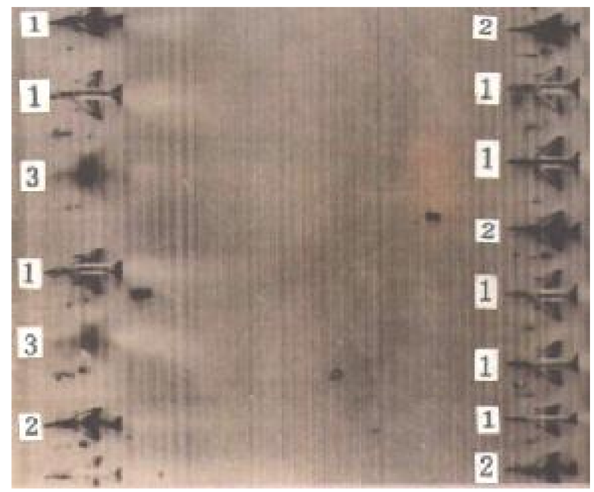
q IR reticle seeker



Military Applications of IIR (1)

IIR: Imaging IR Sensing

- **FLIR system**



Military Applications of IIR (2)

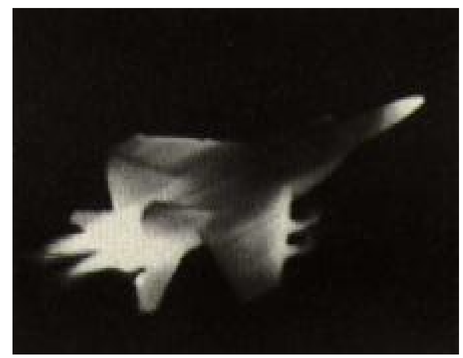
- Military Surveillance/ Search and track









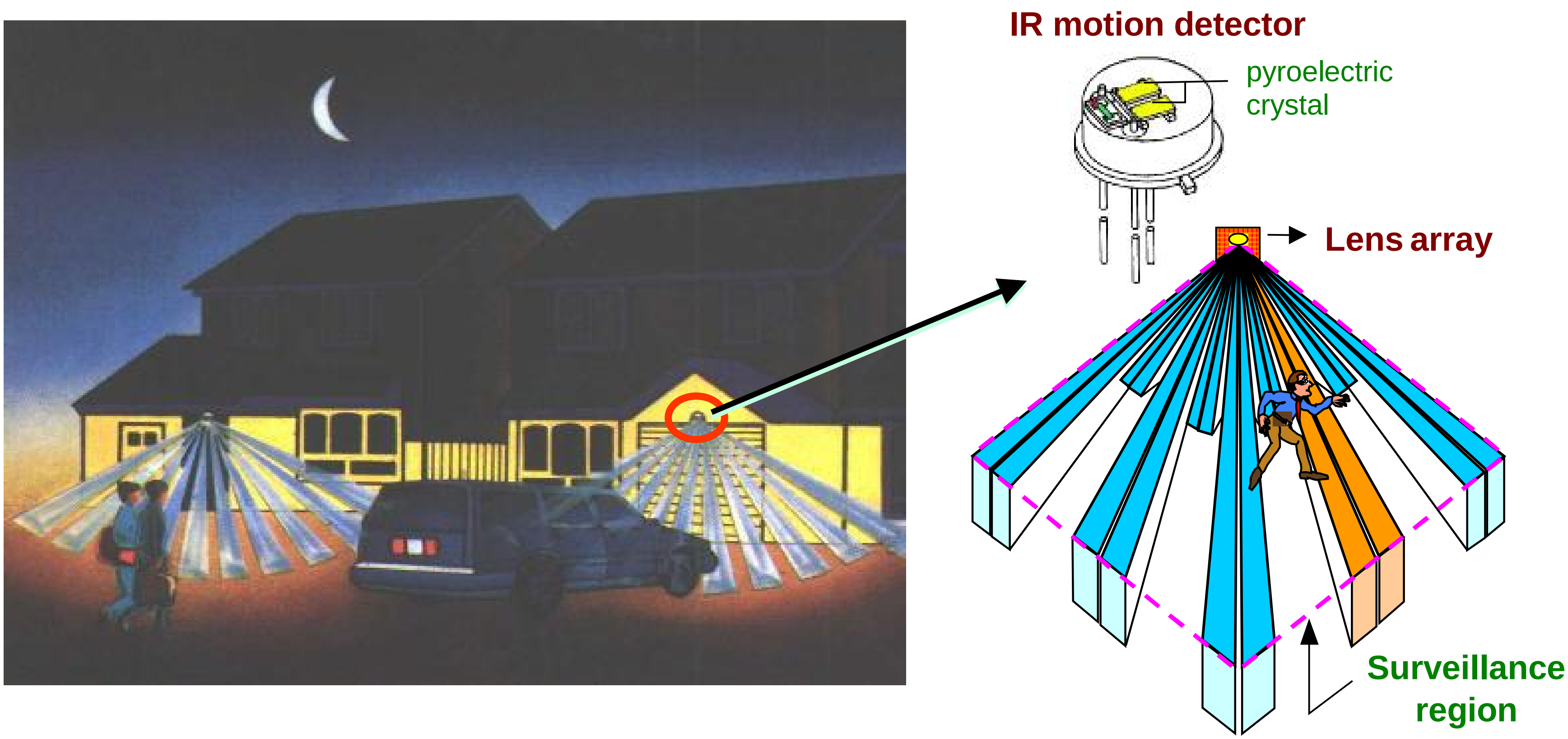


Commercial Applications of IR sensing

環保	·工廠廢氣監控　·核能廠排水監控 ·森林防火　·大氣汙染偵測
製程監控	·電力系統檢測　·熱流管線安全檢查 ·設備自動監控　·各種非破壞性檢測
治安保全	·海上緝私與海岸偵查　·警察夜間勤務 ·各種災難搜索救援　·一般保全系統
交通	·汽車輔助駕駛　·飛機輔助起降 ·船艦夜視導航
醫療診斷	·癌症腫瘤診斷　·血管與皮膚異常檢查 ·運動傷害檢查
其他	·地球資源遙測　·衛星氣象偵測 ·材料性質研究　·各種熱分佈科學研究

Consuming Applications of IR sensing (1)

- PIR system for lighting switch



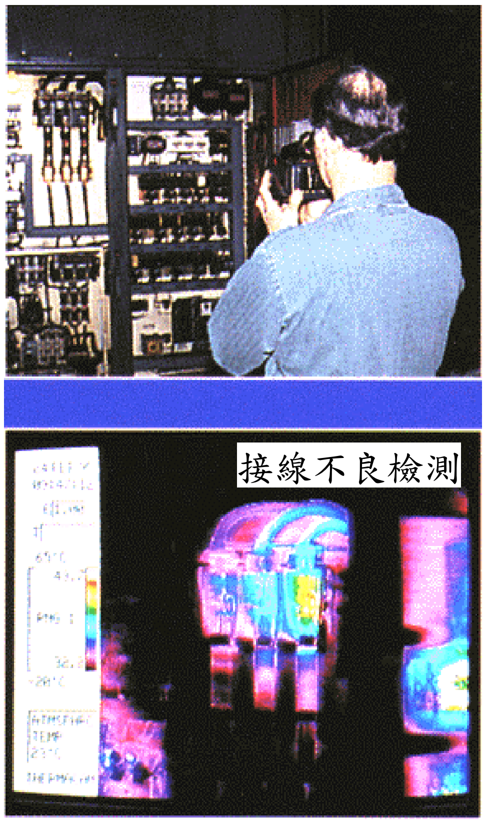
Consuming Applications of IR sensing (2)

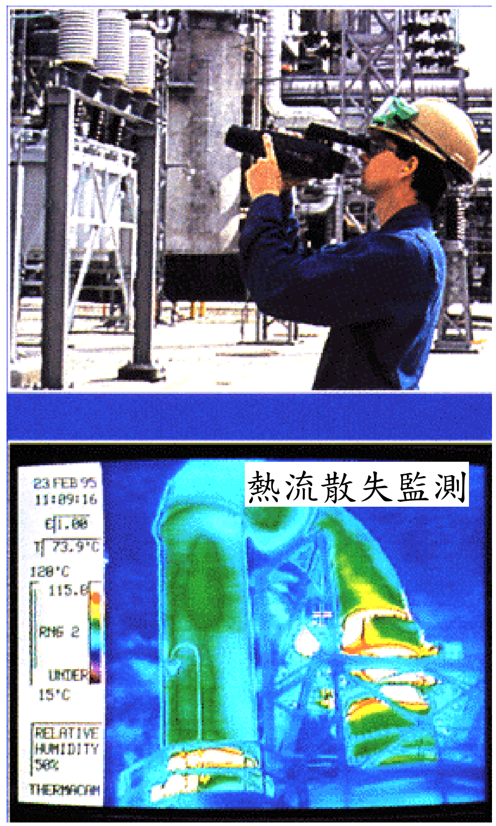
Radiometer

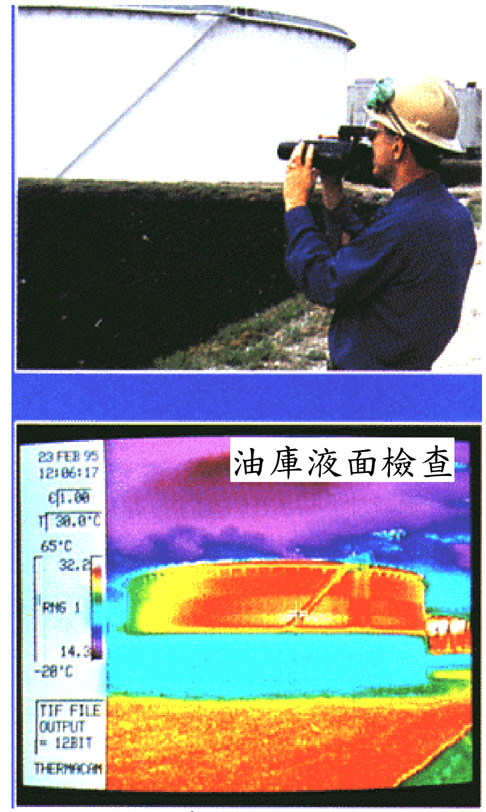
Ear thermometer

Industrial Applications of IIR (1)

- **General nondestructive testing**

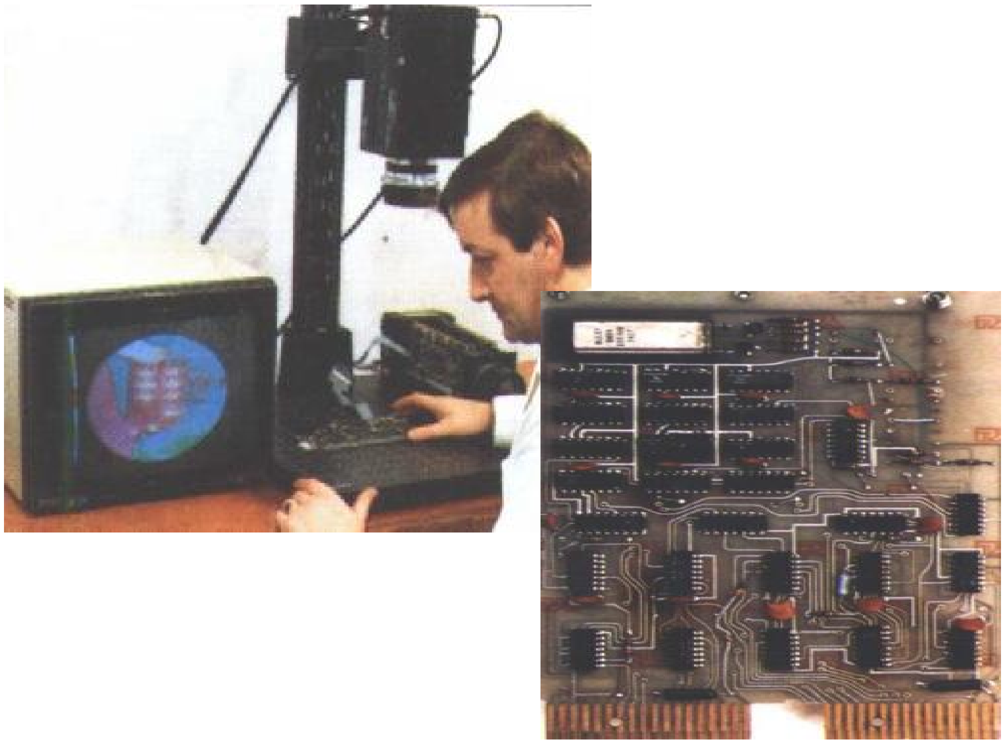


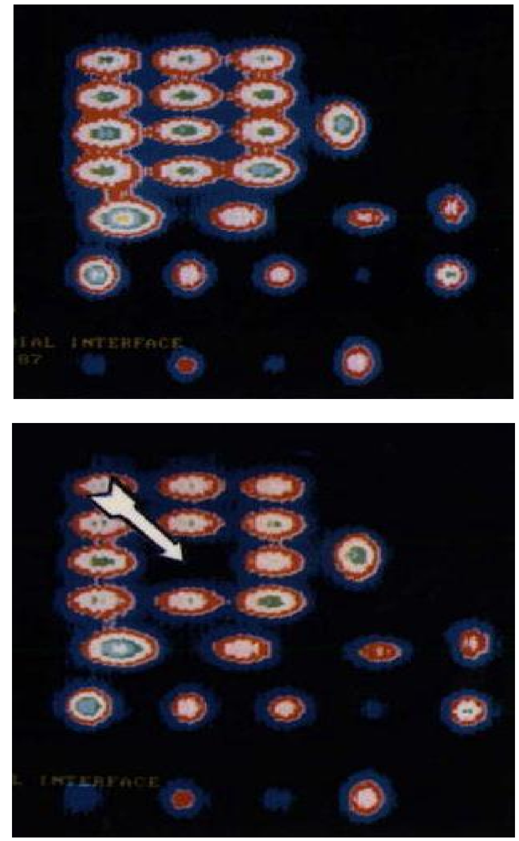




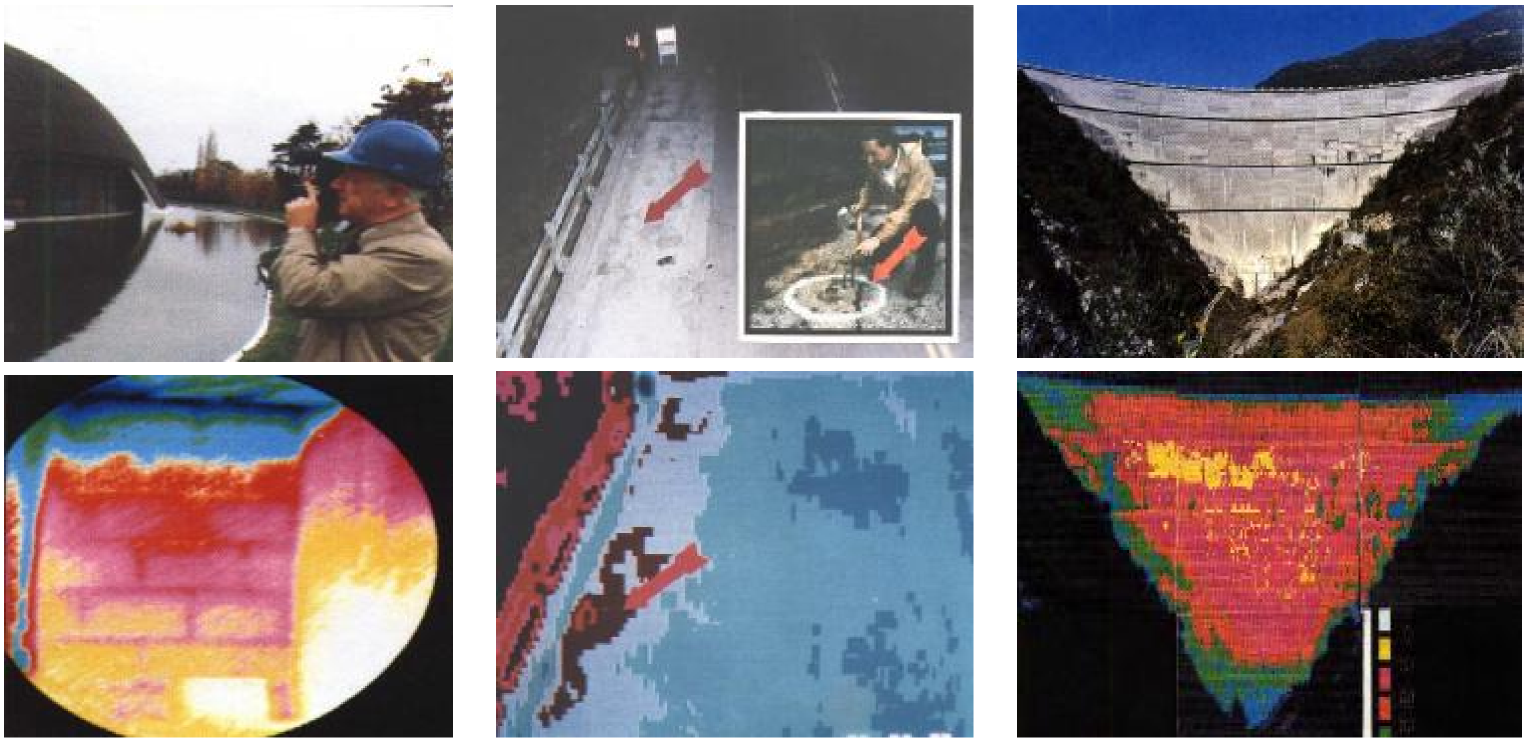
Industrial Applications of IIR (2)

- PCB nondestructive testing

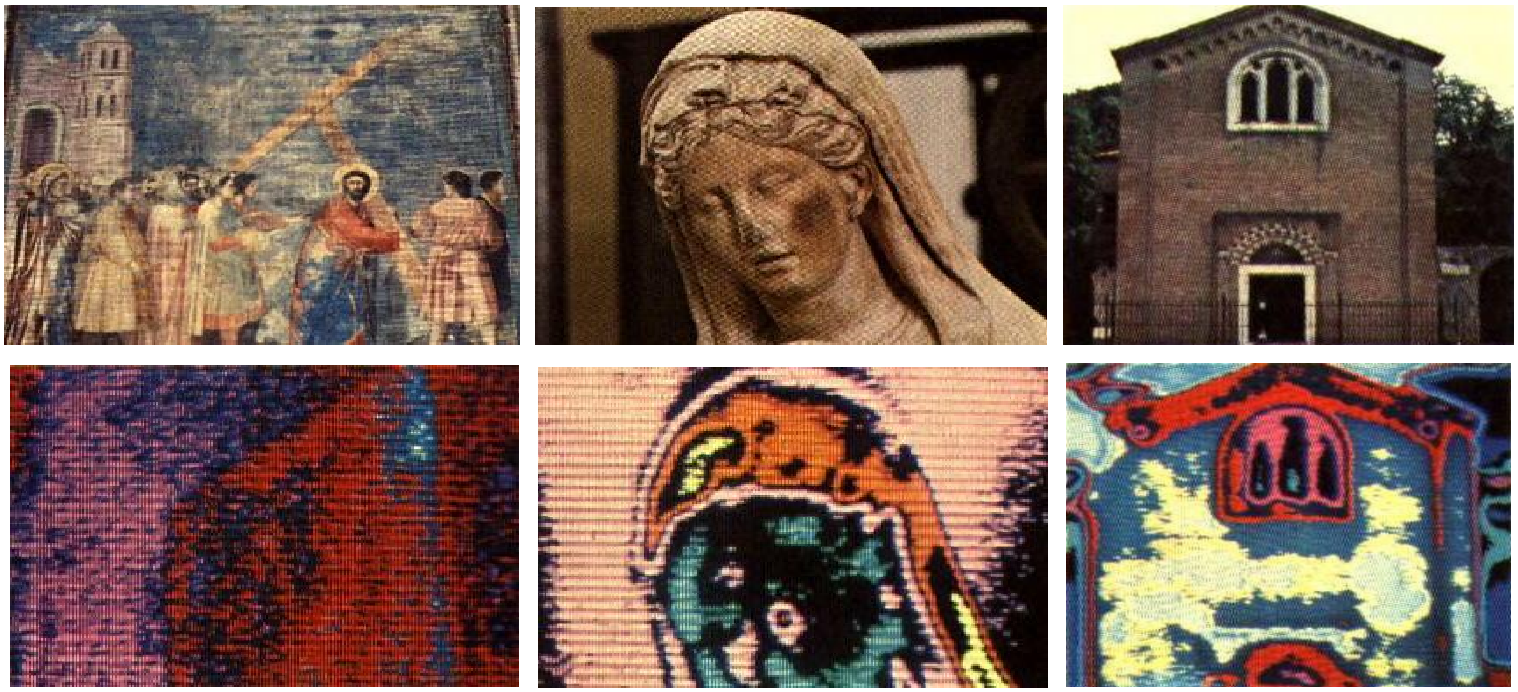




Industrial Applications of IIR (3)

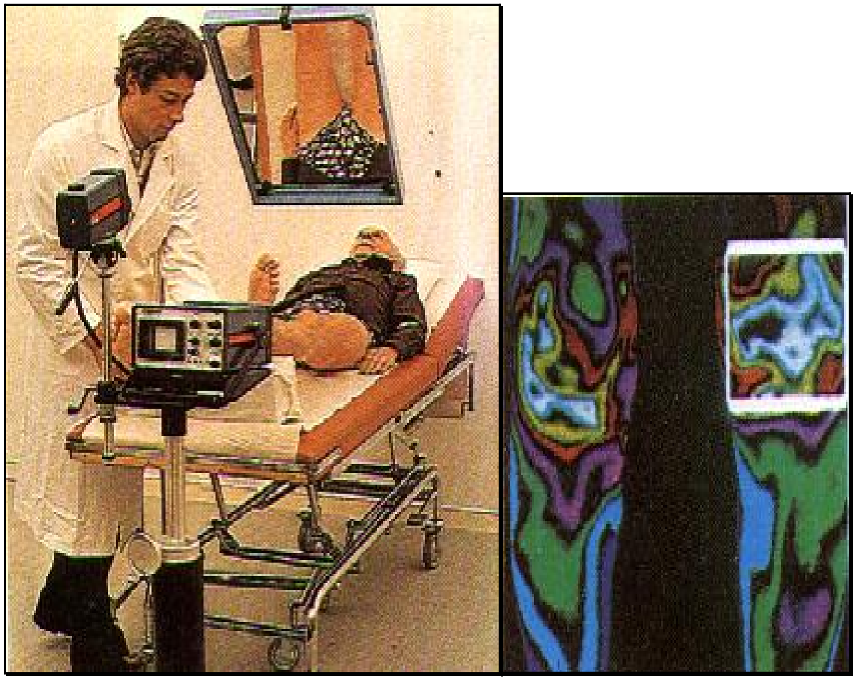


Industrial Applications of IIR (4)



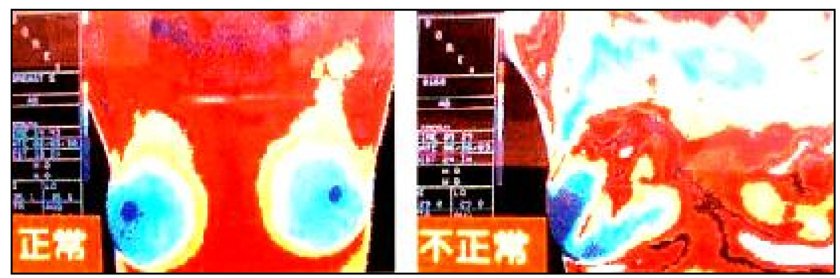
Ref. The IR Observer, AGA infrared systems AB.

Medical Applications of IIR (1)



利用熱像儀檢查關節發炎的部位
與嚴重程度

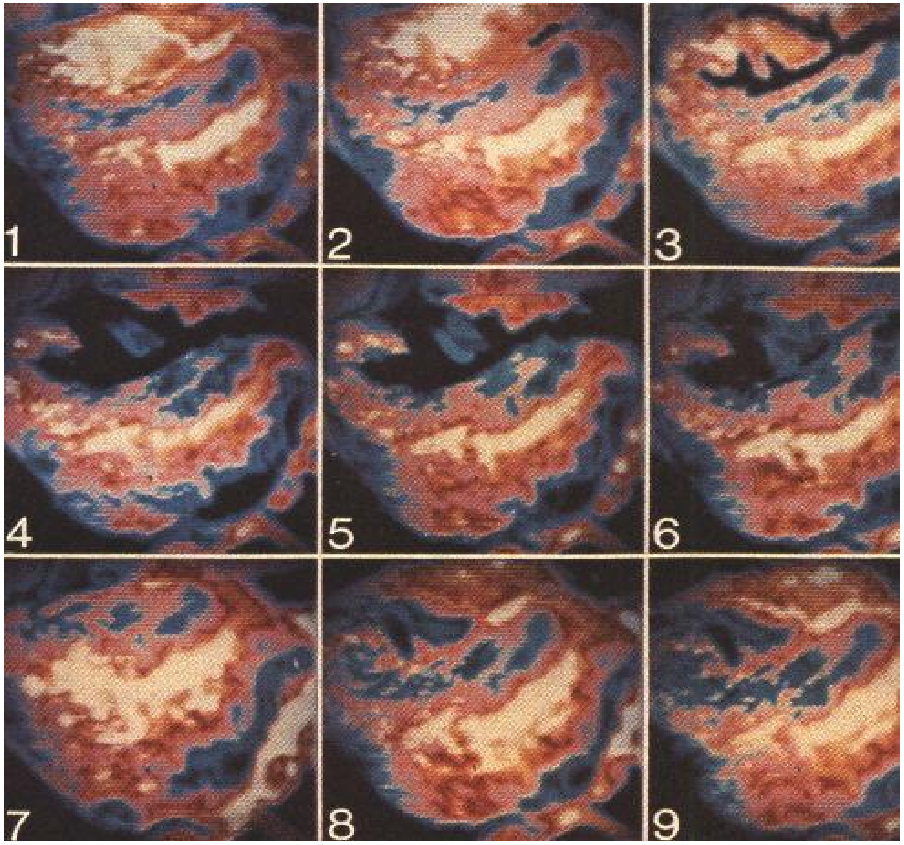
利用熱像儀診斷手部因運動傷害，所造成的
血液循環不良狀況



乳癌診斷

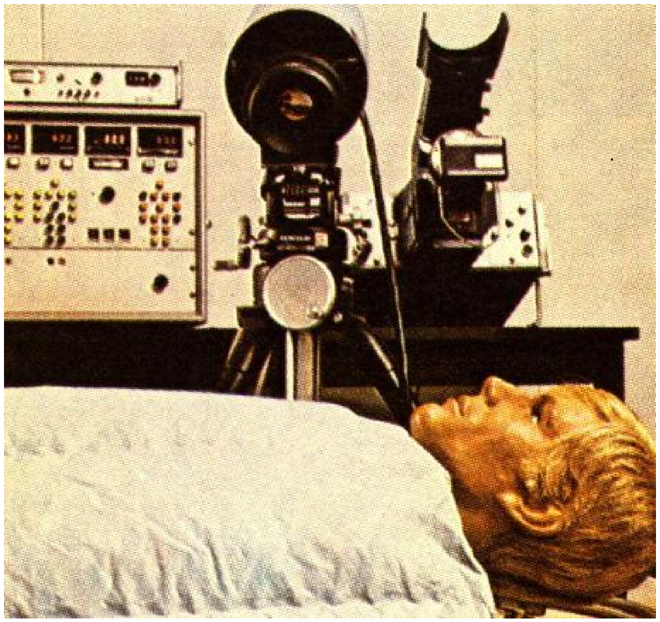
Medical Applications of IIR (2)

- Surgical operation

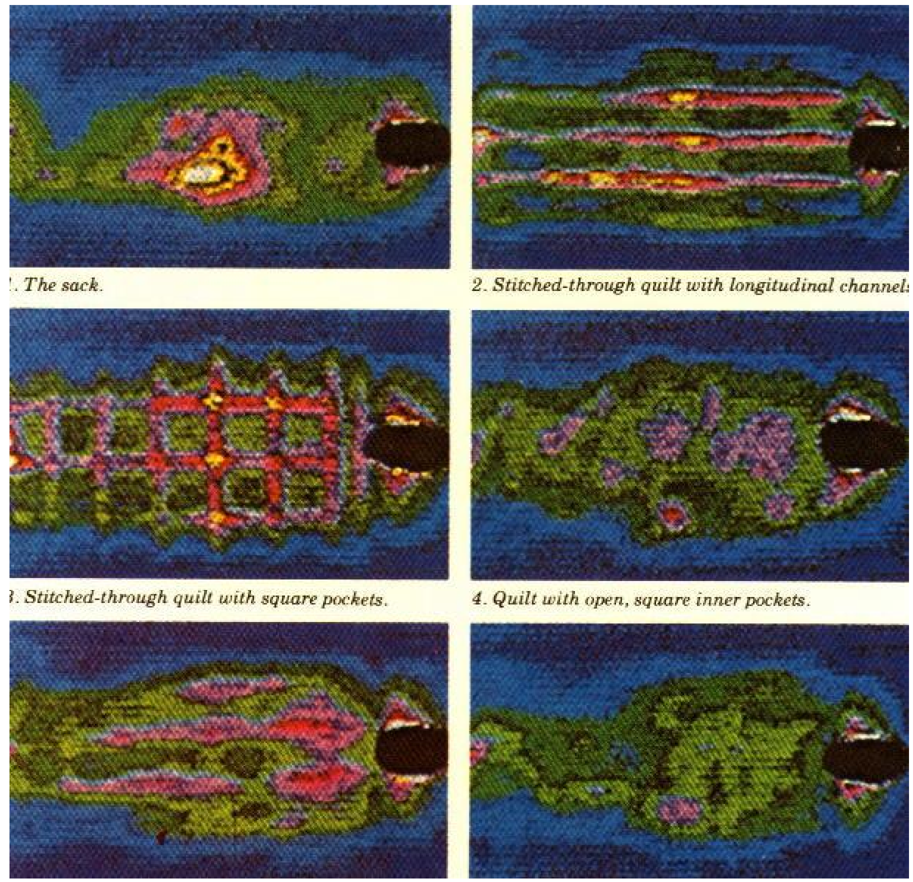


Ref. The IR Observer, AGA infrared systems AB.

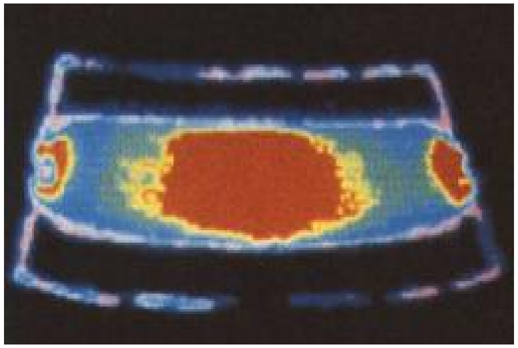
Applications of IIR (1)

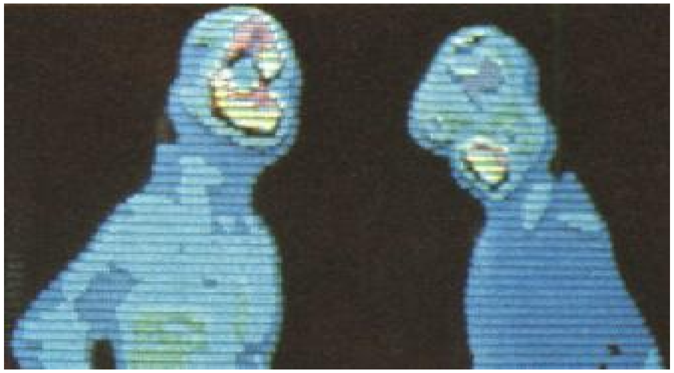


Ref. The IR Observer, AGA infrared systems AB.



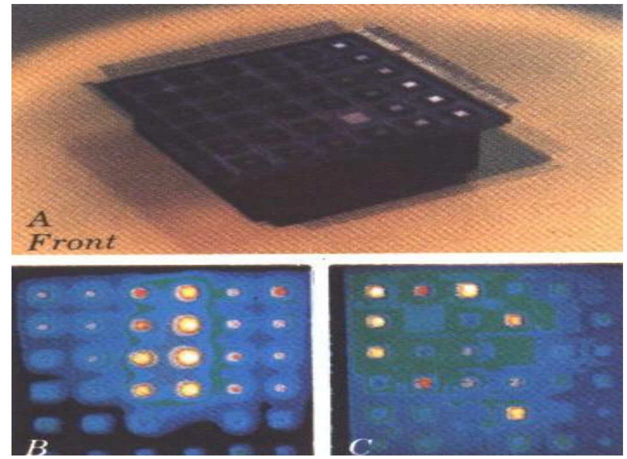
Applications of IIR (2)

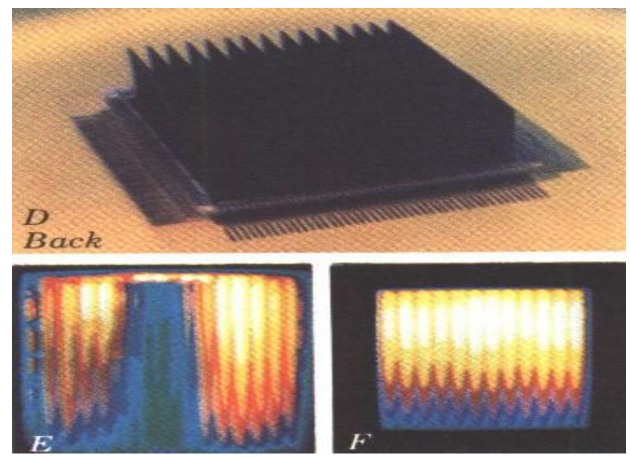




Ref. The IR Observer, AGA infrared systems AB.

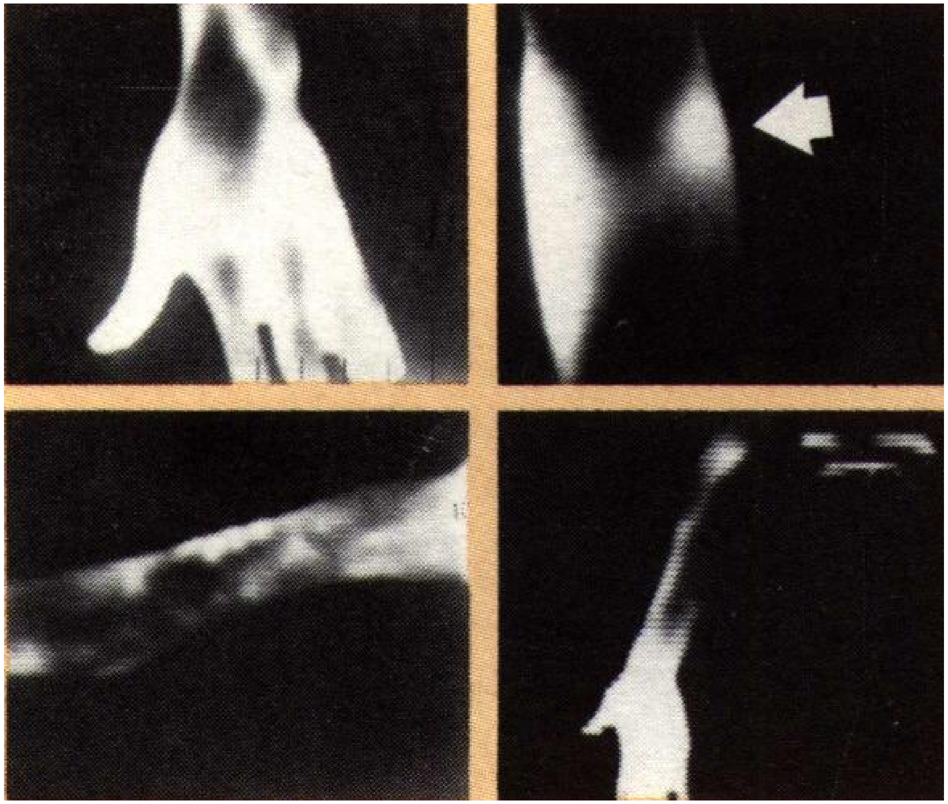
Applications of IIR (3)

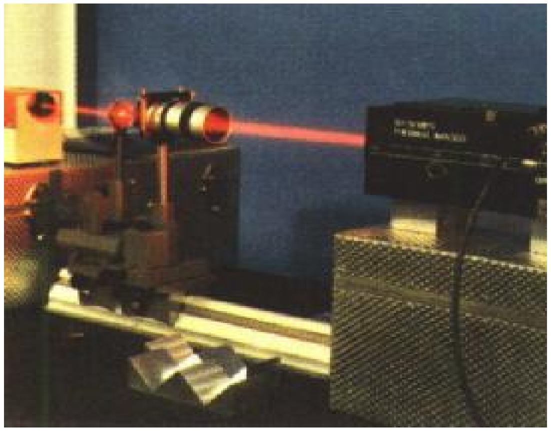


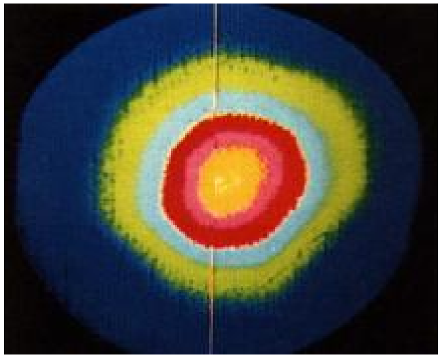


Ref. The IR Observer, AGA infrared systems AB.

Applications of IIR (4)





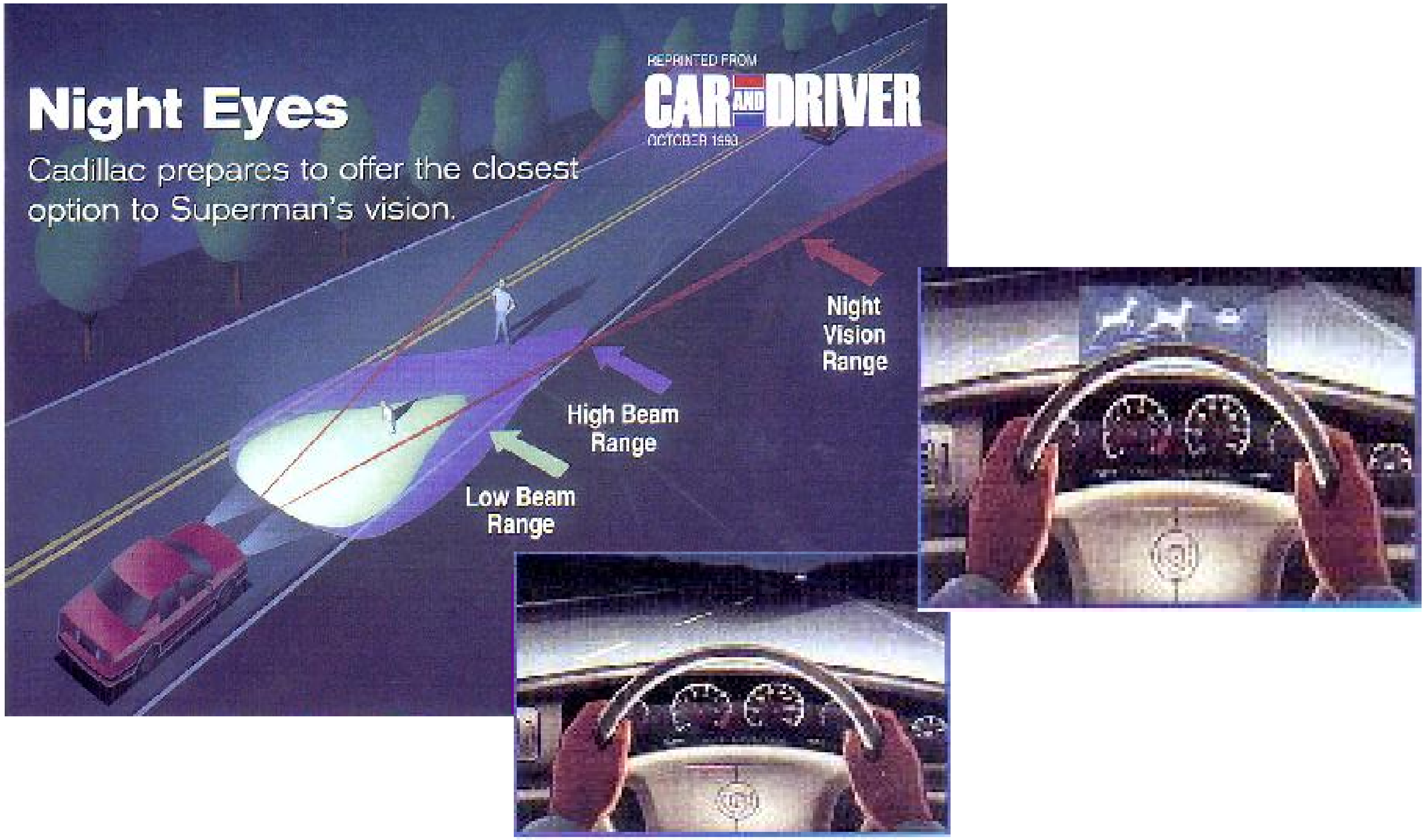


Ref. The IR Observer, AGA infrared systems AB.

Applications of Uncooled IIR (1)

Source: TI NIGHTSIGHT interactive explorer.

Applications of Uncooled IIR (2)



Applications of Uncooled IIR (3)