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# Robust Satellite Techniques (RST) for Natural and Environmental Hazards Monitoring: theoretical issues

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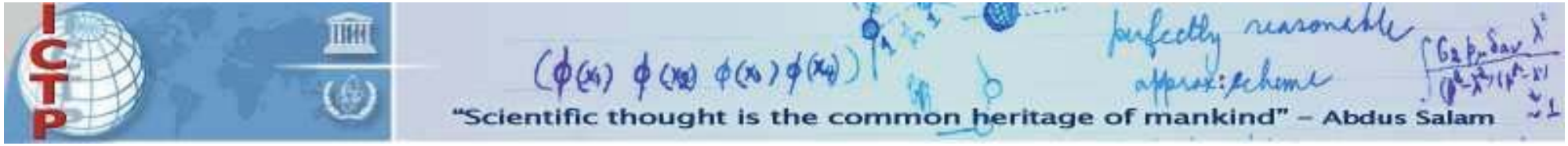


**WINTER COLLEGE ON OPTICS IN ENVIRONMENTAL SCIENCE**
**Trieste 2 – 13 February 2009**

# Robust Satellite Techniques (RST) for Natural and Environmental Hazards Monitoring: theoretical issues

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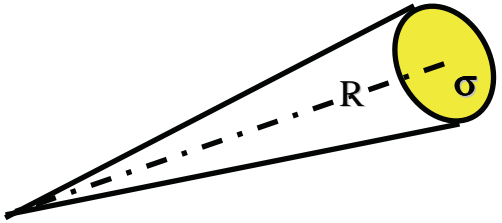
# THEORETICAL TOOLS:
# Basic Definitions and Physical Laws

# SOLID ANGLE $\Omega$

$$\Omega = \frac{\sigma}{R^2}$$

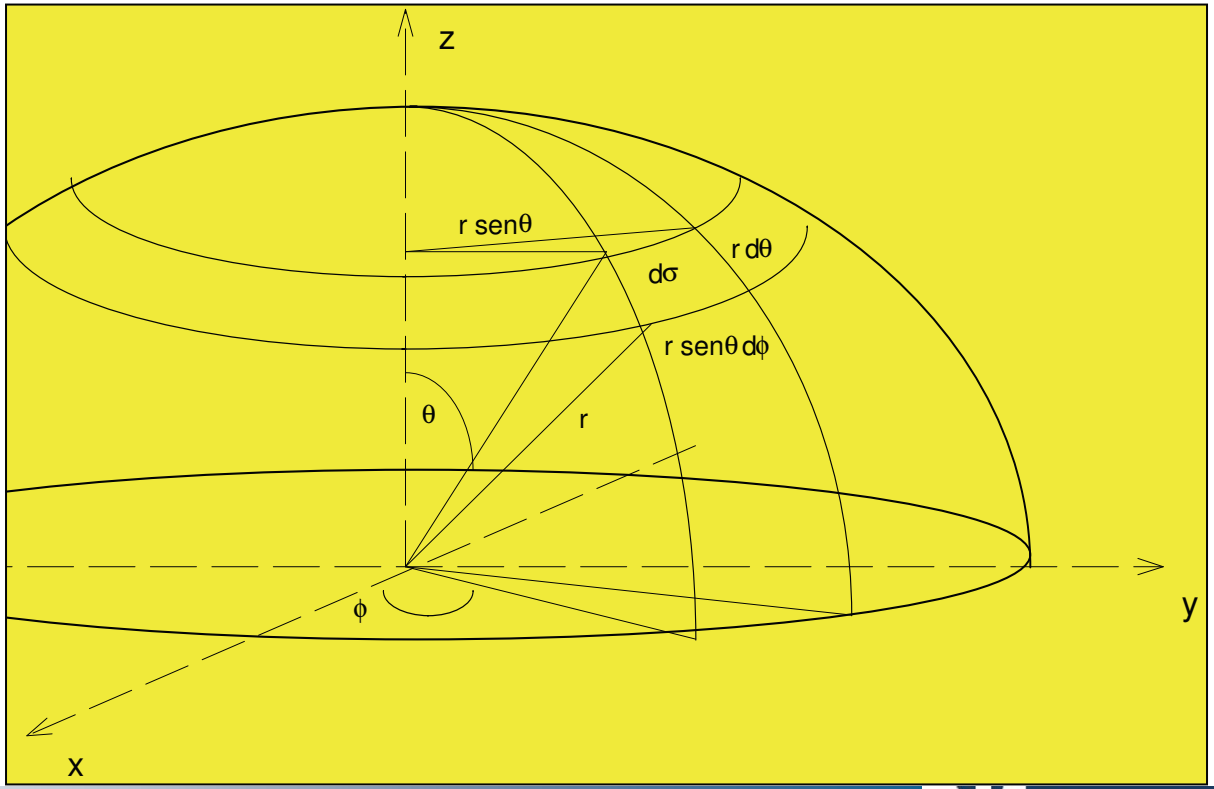



e.g. for the sphere $\Omega = \frac{4\pi R^2}{R^2} = 4\pi [ster]$

## infinitesimal

$$d\sigma = (r\, d\theta)\,(r\, sen\theta\, d\phi)$$

$$d\Omega = \frac{d\sigma}{r^2} = sen\theta d\theta d\phi$$

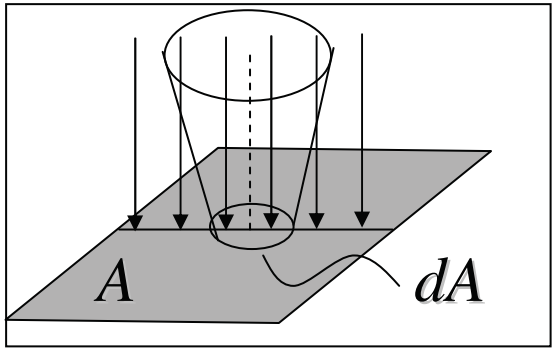


# Monocromatic Radiance

## Normally Incident Radiation

$$I_\lambda = \frac{dE_\lambda}{dt \cdot dA \cdot d\lambda \cdot d\Omega}$$

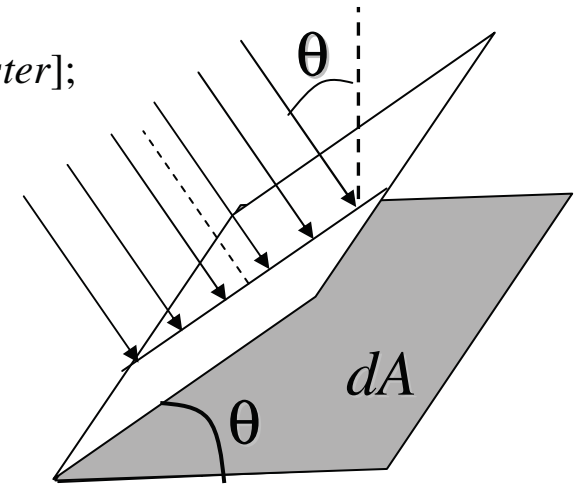
$$[I_\lambda] = [Watt \cdot m^{-2} \mu m^{-1} sr^{-1}]$$




$dE_\lambda$=energy, [J]; $dt$=time $[s]$; $dA$=collecting area $[m^2]$;
$d\lambda$= wavelength interval [$\mu m$]; $d\Omega$=collecting solid angle [$ster$];

## General $\theta \neq 0$

$$I_\lambda = \frac{dE_\lambda}{dt \cdot dA \cdot \cos\theta \cdot d\lambda \cdot d\Omega}$$



# Blackbody Radiation

## Planck's function

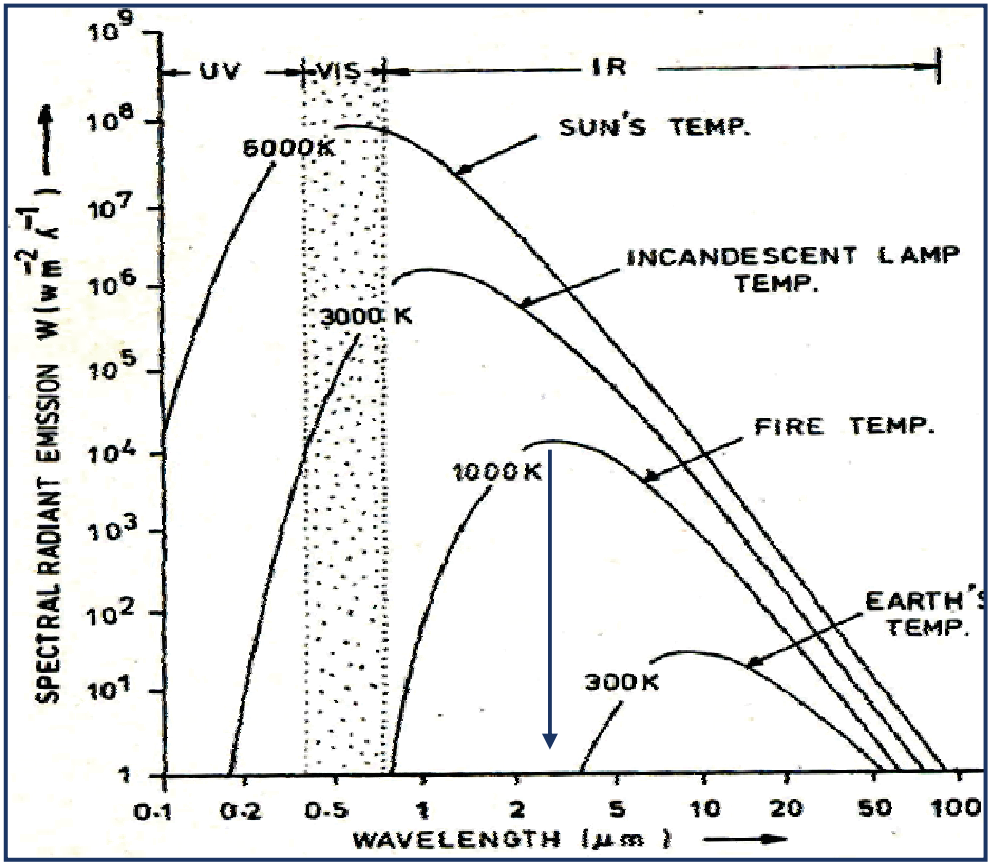
$$B_\lambda(T) = \frac{2hc^2}{\lambda^5\left(e^{\frac{hc}{\lambda k T}} - 1\right)}$$

$B_\lambda(T)$=monochromatic radiance emitted at the wavelength λ by a blackbody at the absolute temperature $T$ [W/m$^3$]

$c$=2,998·10$^8$ m/s speed of light in the vacuum

$h$=6,626 ·10$^{-34}$ Js Planck's constant

$k$= 1,380·10$^{-23}$ J/K Boltzman constant



# Reyleigh-Jeans approximation

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5\left(e^{\frac{hc}{\lambda k T}} - 1\right)}$$

**Planck**

if $\lambda > 0.001\text{m}$ T ~ 300K

$$x = \frac{hc}{\lambda k T} \to 0$$

$$e^x = 1 + x + \ldots. \qquad \textit{Taylor}$$

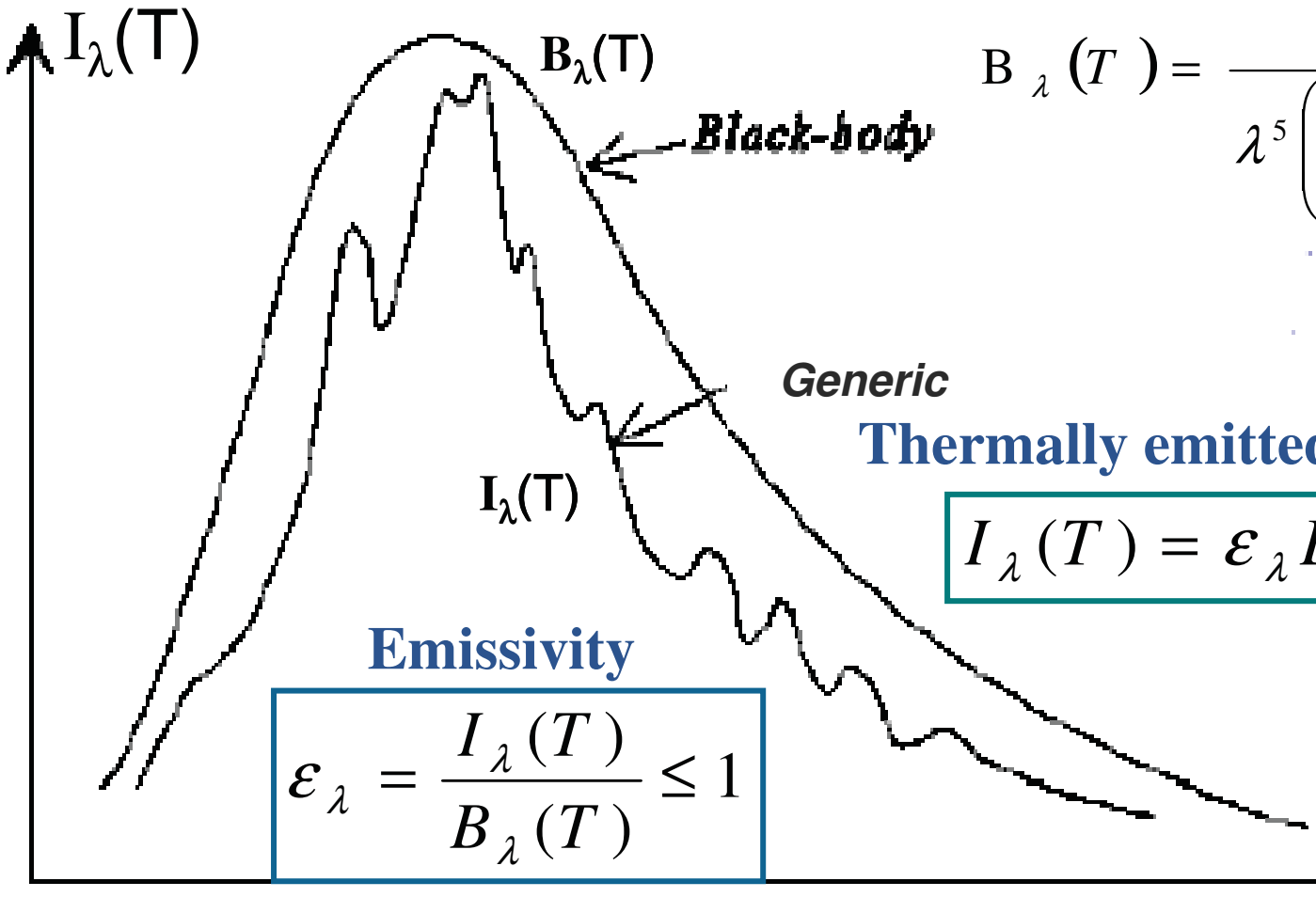
$$e^{\frac{hc}{\lambda k T}} \approx 1 + \frac{hc}{\lambda k T}$$

$$B_\lambda(T) \approx \frac{2hc^2}{\lambda^5\left(1 + \frac{hc}{\lambda k T} - 1\right)}$$

$$B_\lambda(T) \approx \frac{2kcT}{\lambda^4} \propto T$$

Radiation law of **Reyleigh-Jeans**

# Emissivity




$$B_\lambda(T) = \frac{2hc^2}{\lambda^5\left(e^{\frac{hc}{\lambda kT}} - 1\right)}$$

**Thermally emitted radiation**

$$I_\lambda(T) = \varepsilon_\lambda B_\lambda(T)$$

**Emissivity**

$$\varepsilon_\lambda = \frac{I_\lambda(T)}{B_\lambda(T)} \leq 1$$

# Brightness Temperature

## Planck's function

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5\left(e^{\frac{hc}{\lambda k T}} - 1\right)}$$

## Blackbody Temperature

$$T = \frac{hc}{\lambda k}\frac{1}{\ln\left[1 + \frac{2hc^2}{\lambda^5 B_\lambda(T)}\right]}$$

Inversion

## Brightness Temperature

$$T_B = \frac{hc}{\lambda k}\frac{1}{\ln\left[1 + \frac{2hc^2}{\lambda^5 I_\lambda(T)}\right]}$$

$$T_B \leq T$$

# Exercise: Moon surface temperature

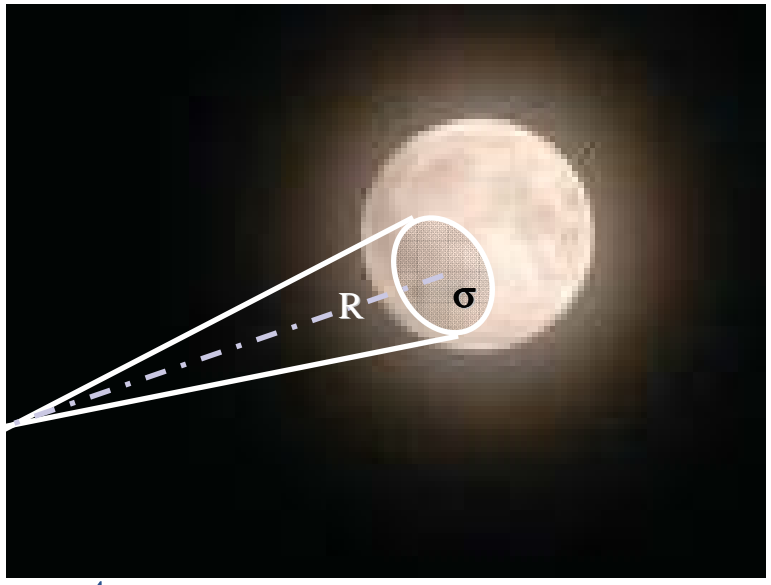
$$I_{\lambda=10\mu} = 3\cdot 10^{4}\, erg\cdot s^{-1}\cdot cm^{-2}\mu m^{-1} sr^{-1}$$

monochromatic radiance emitted at the wavelength $\lambda=10\mu$ by he Moon surface

$c \sim 3\cdot 10^{10}$ cm/s speed of light in the vacuum

$h \sim 6{,}6\cdot 10^{-27}$ erg•s Planck's constant

$k \sim 1{,}4\cdot 10^{-16}$ erg/K Boltzman constant




## Brightness Temperature

$$T_B = \frac{hc}{\lambda k}\frac{1}{\ln\left[1+\frac{2hc^2}{\lambda^5 I_\lambda(T)}\right]} = \frac{6{,}6\cdot 10^{-27}\, erg\cdot s\cdot 3\cdot 10^{10}\, cm/s}{10\cdot 10^{-4}\, cm\cdot 1{,}4\cdot 10^{-16}\, erg/K}\frac{1}{\ln\left[1+\frac{2\cdot 6{,}6\cdot 10^{-27}\, erg\cdot s\cdot (3\cdot 10^{10})^2\, cm^2/s^2}{10\,\mu m\cdot (10\cdot 10^{-4}\, cm)^4\cdot 3\cdot 10^{4}\, erg\cdot s^{-1}\cdot cm^{-2}\mu m^{-1} sr^{-1}}\right]} =$$

$$= \frac{6{,}6\cdot 3\cdot 10^{2}}{1{,}4}\frac{1}{\ln\left[1+\frac{2\cdot 6{,}6\cdot 9}{3}sr\right]}K = \frac{6{,}6\cdot 3\cdot 10^{2}}{1{,}4}\frac{1}{3{,}7}K \approx 382\ K$$

$$T \geq T_B$$

## Brightness Temperature

# Exercise: Earth's surface temperature

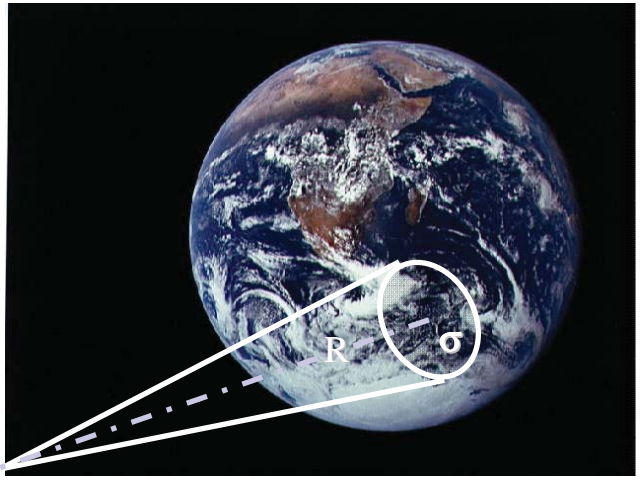
$$I_{\lambda=10\mu} = 1 \cdot 10^{4} erg \cdot s^{-1} \cdot cm^{-2} \mu m^{-1} sr^{-1}$$

monochromatic radiance emitted at the wavelength $\lambda=10\mu$ by he Moon surface

$c \sim 3 \cdot 10^{10}$ cm/s speed of light in the vacuum

$h \sim 6{,}6 \cdot 10^{-27}$ erg•s Planck's constant

$k \sim 1{,}4 \cdot 10^{-16}$ erg/K Boltzman constant




## Brightness Temperature

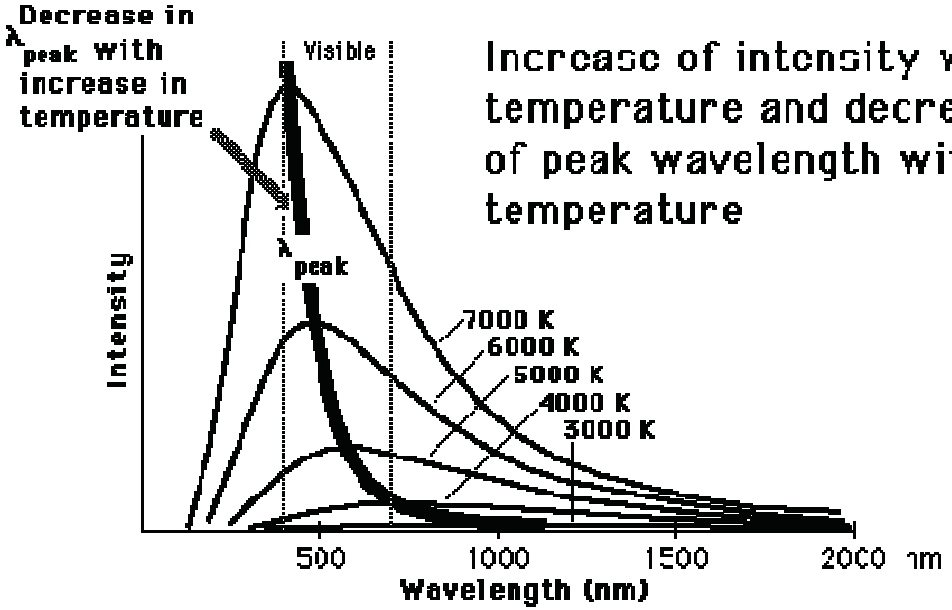
$$T_B = \frac{hc}{\lambda k} \frac{1}{\ln\left[1 + \frac{2hc^2}{\lambda^5 I_\lambda(T)}\right]} = \frac{6{,}6 \cdot 10^{-27}\ erg \cdot s \cdot 3 \cdot 10^{10}\ cm/s}{10 \cdot 10^{-4}\ cm \cdot 1{,}4 \cdot 10^{-16}\ erg/K} \frac{1}{\ln\left[1 + \frac{2 \cdot 6{,}6 \cdot 10^{-27}\ erg \cdot s \cdot (3 \cdot 10^{10})^2\ cm^2/s^2}{10\ \mu m \cdot (10 \cdot 10^{-4}\ cm)^4 \cdot 1 \cdot 10^{4}\ erg \cdot s^{-1} \cdot cm^{-2} \mu m^{-1} sr^{-1}}\right]} =$$

$$= \frac{6{,}6 \cdot 3 \cdot 10^{2}}{1{,}4} \frac{1}{\ln\left[1 + \frac{2 \cdot 6{,}6 \cdot 9}{1} sr\right]} K = \frac{6{,}6 \cdot 3 \cdot 10^{2}}{1{,}4} \frac{1}{4{,}8} K \approx 296\ K$$

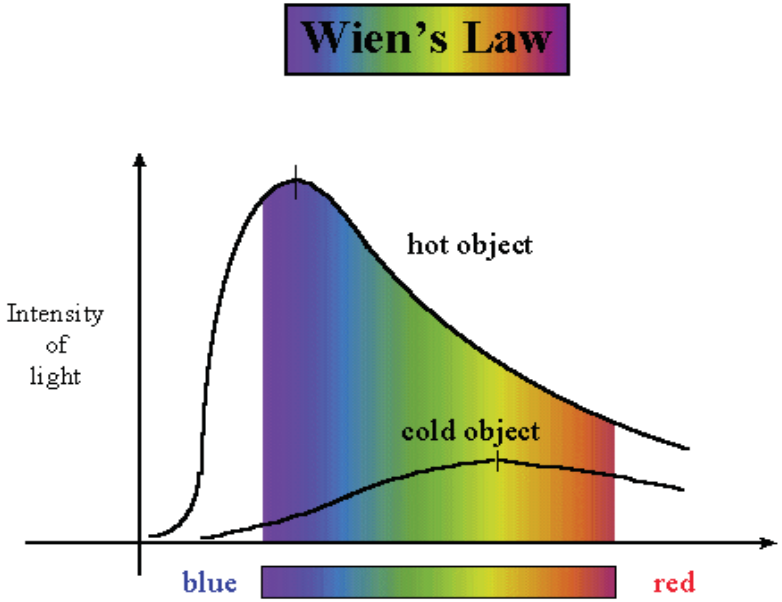
$$T \geq T_B$$

# Wien's Displacement Law

$$\lambda_{MAX}\,(\mu m) = \frac{2898}{T(K)}$$




Increase of intensity with temperature and decrease of peak wavelength with temperature



## Wien's Displacement Law

# Exercise: choosing the best spectral range

$$\lambda_{MAX}(\mu m) = \frac{2898}{T(K)}$$

Earth surface T=**300 K**

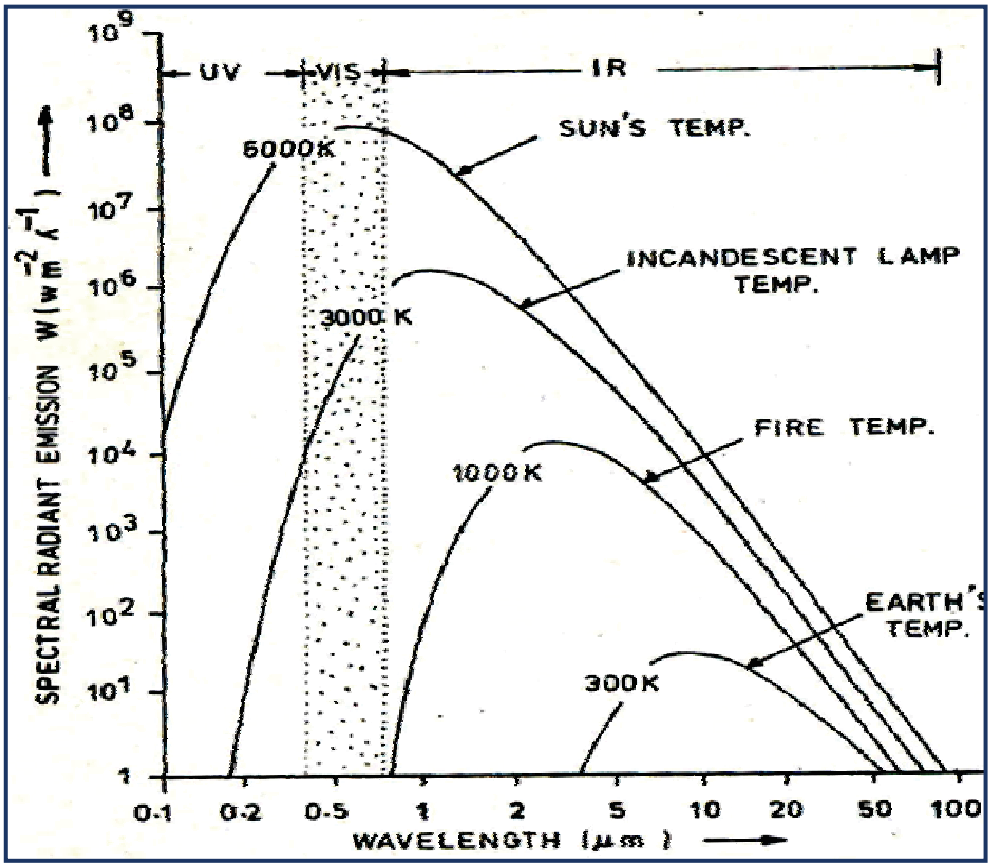
$\lambda_{MAX}$=10μm = TIR

fires, lava flows T=**800 -1000** K

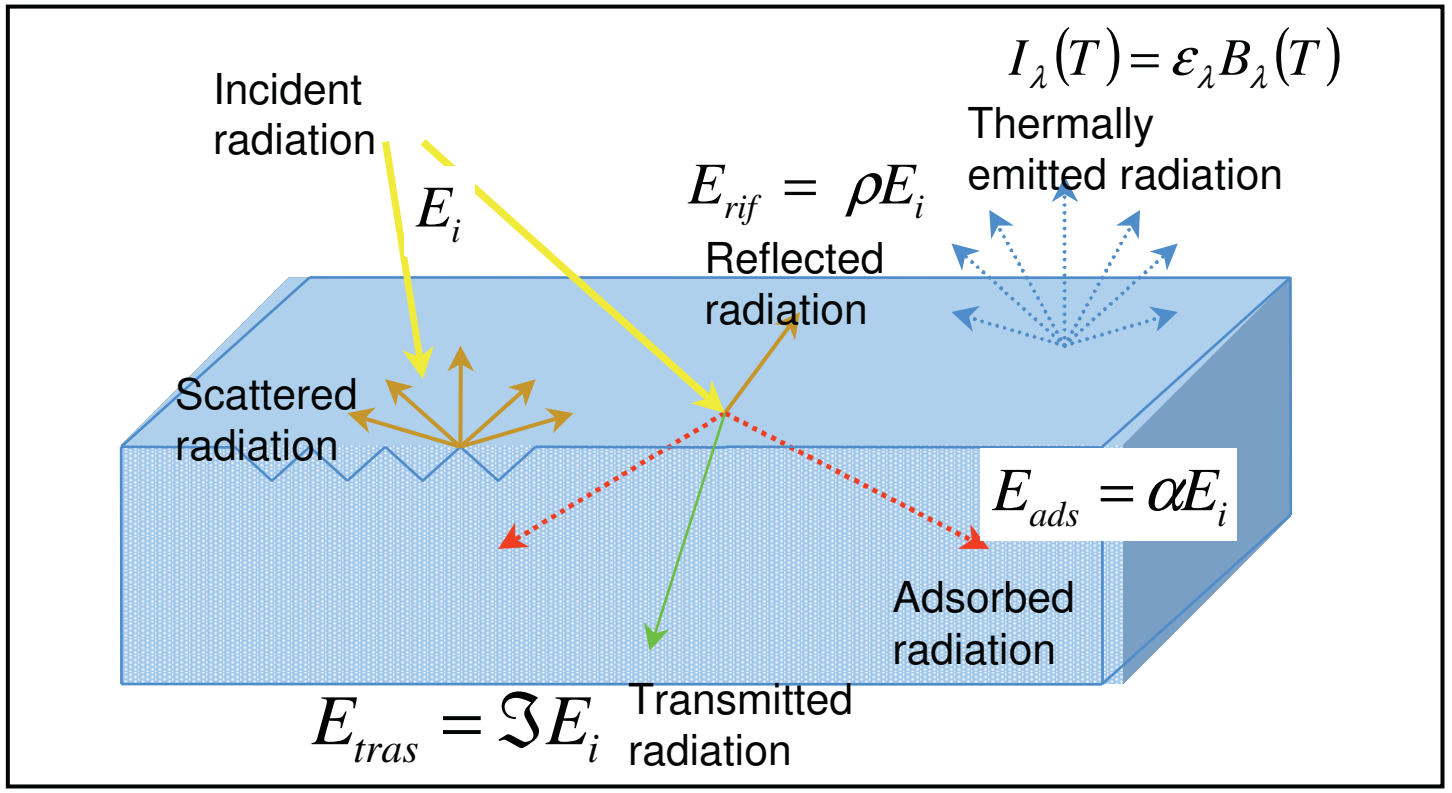
$\lambda_{MAX}$=3-4μm = MIR

Sun photosphere T=**6000** K

$\lambda_{MAX}$ = 0,5μm = VIS



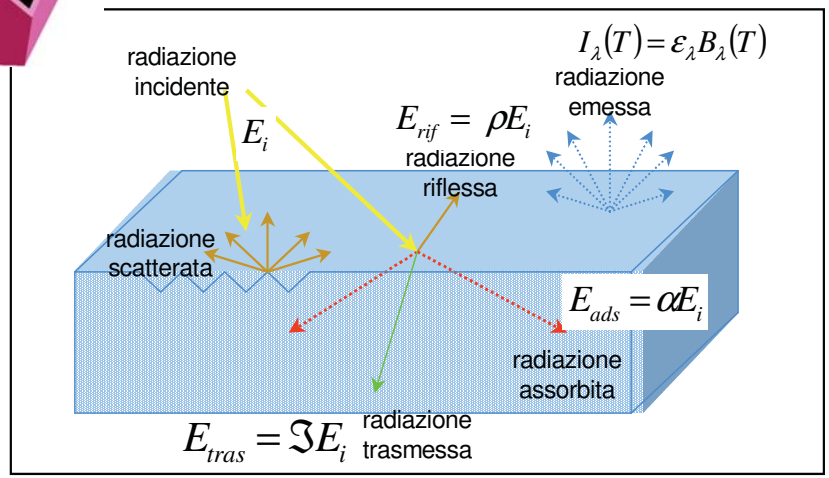
# Matter/Radiation Interaction




**Conservation of Energy**

$$E_i = E_{rif} + E_{ads} + E_{tras}$$

# Matter/Radiation Interaction




**Conservation of energy**

$$E_{rif} + E_{ads} + E_{tras} = E_i$$

**In terms of radiances:**

$$I_\lambda^R + I_\lambda^A + I_\lambda^T = I_\lambda^I$$

$$\rho_\lambda = \frac{I_\lambda^R}{I_\lambda^I}$$

$$\alpha_\lambda = \frac{I_\lambda^A}{I_\lambda^I}$$

$$\Im_\lambda = \frac{I_\lambda^T}{I_\lambda^I}$$

Reflectance

Adsorbance

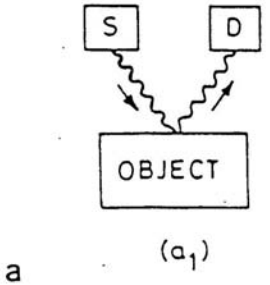
Transmittance

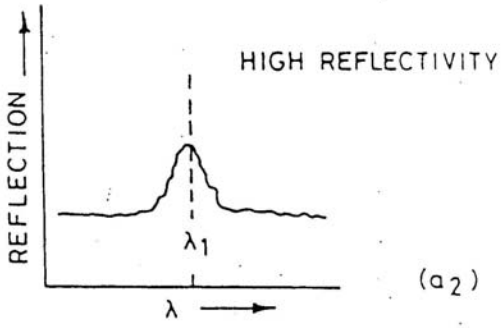
$$\frac{I_\lambda^R}{I_\lambda^I} + \frac{I_\lambda^A}{I_\lambda^I} + \frac{I_\lambda^T}{I_\lambda^I} = \frac{I_\lambda^I}{I_\lambda^I} = 1$$

monochromatic

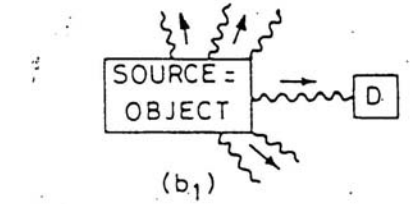
$$\rho_\lambda + \alpha_\lambda + \Im_\lambda = 1$$

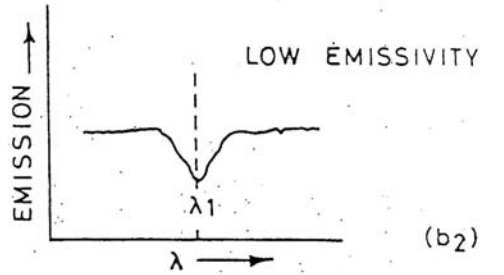
# Spectral Signatures in the laboratory



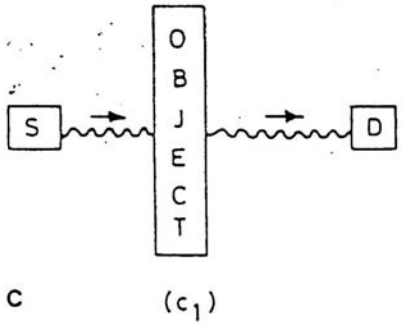



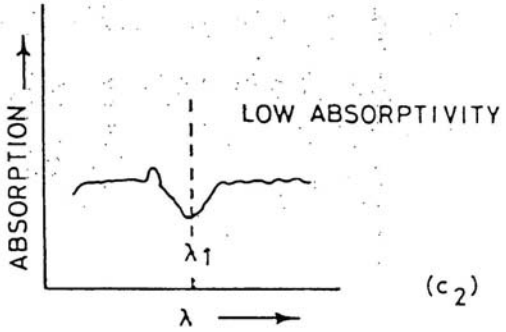

$$\rho_\lambda = \frac{I_\lambda^D}{I_\lambda^S}$$



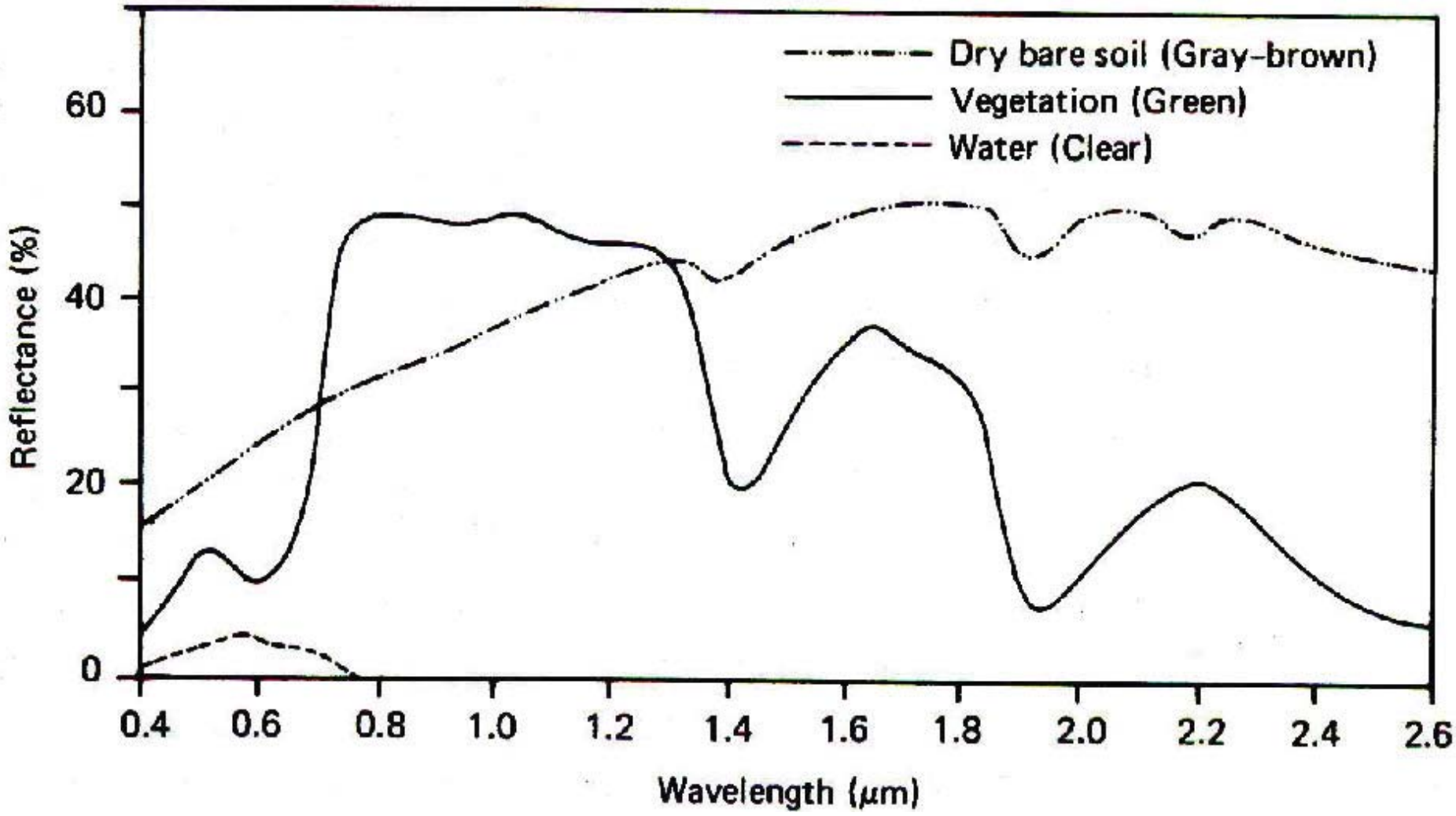

$$\varepsilon_\lambda = \frac{I_\lambda^D}{B_\lambda(T)}$$




$$\Im_\lambda = \frac{I_\lambda^D}{I_\lambda^S}$$

# Spectral Signatures in the laboratory

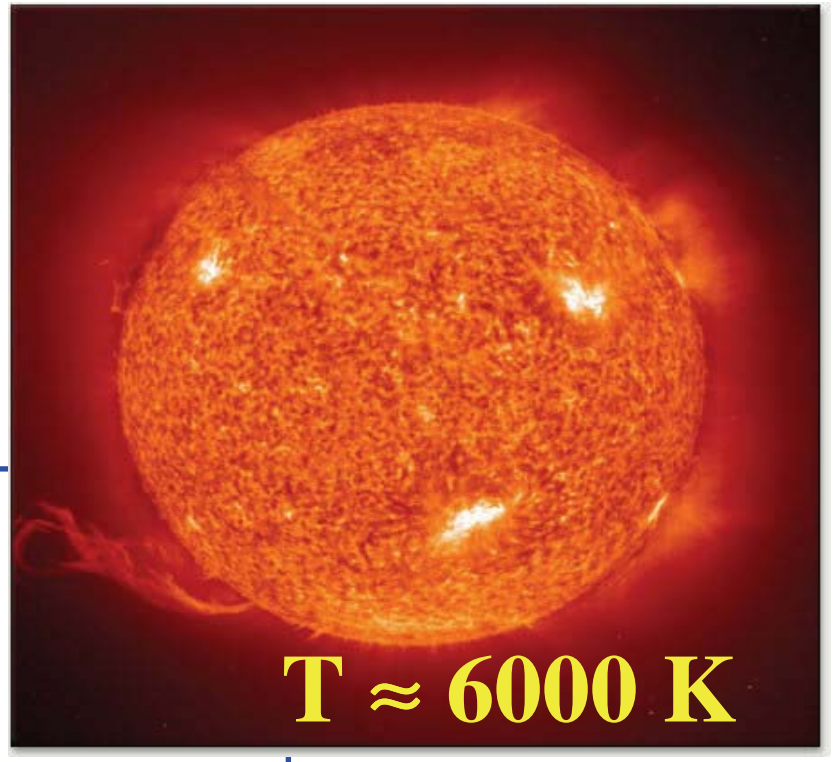


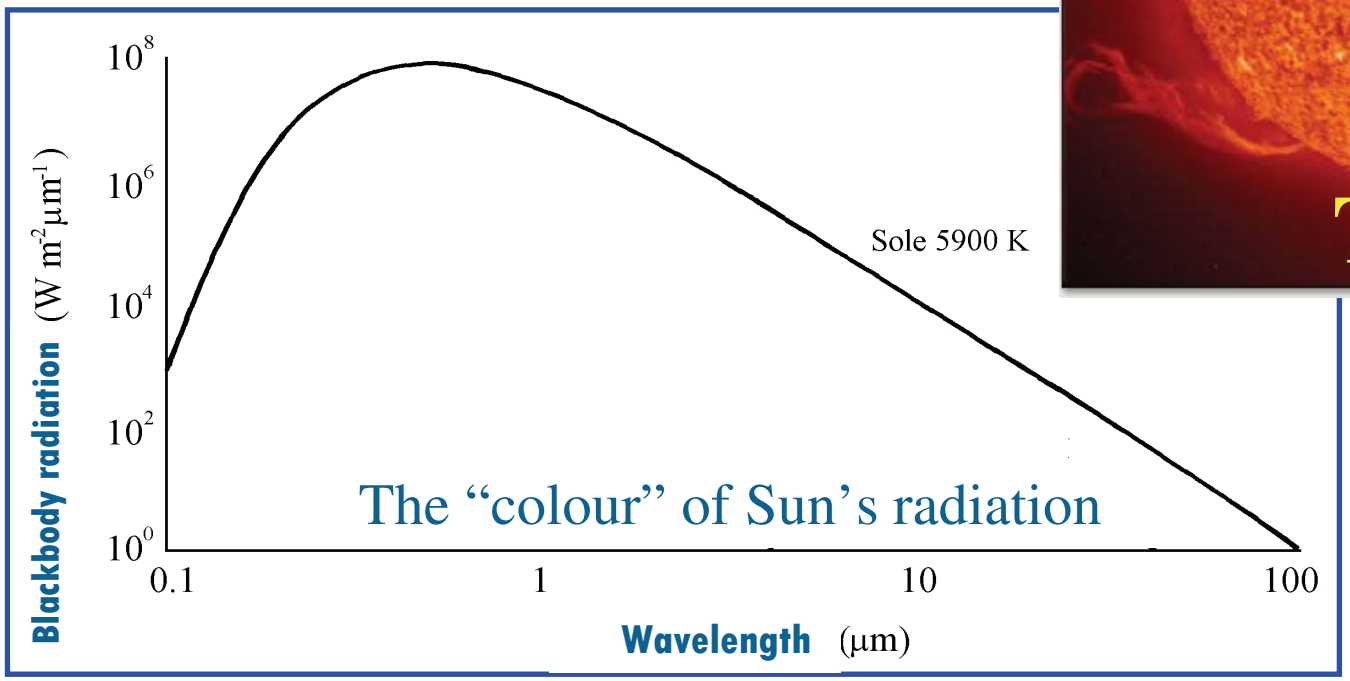
# Natural sources of radiation for Earth Observation

## The Sun (only daytime !)

### Wien

$$\lambda_{MAX} = \frac{2898}{T(K)} \approx \frac{3000}{6000} = 0{,}5\mu m$$



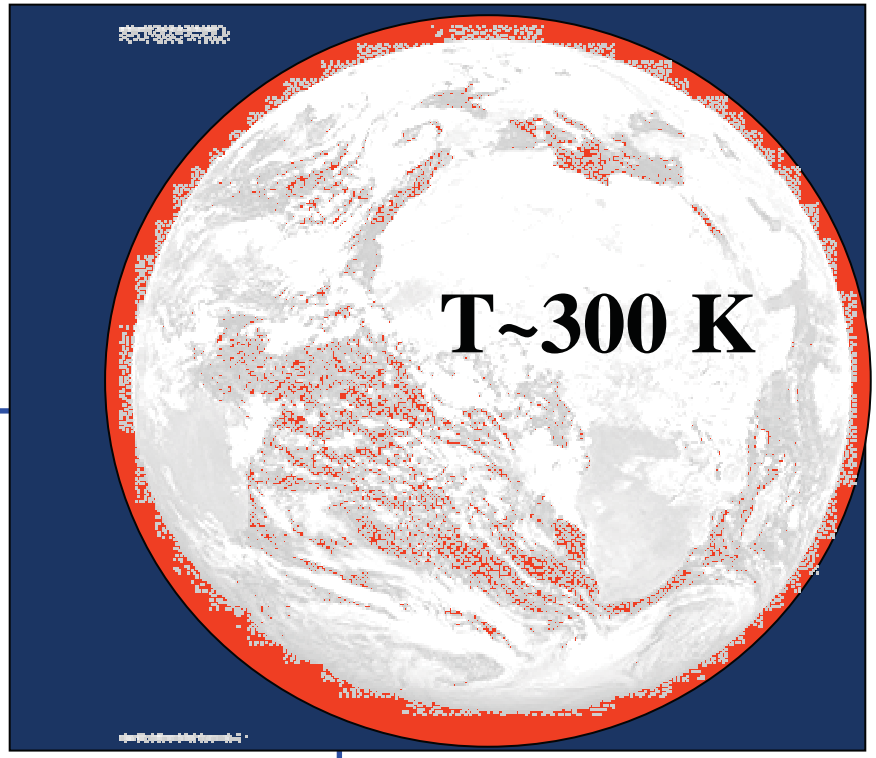



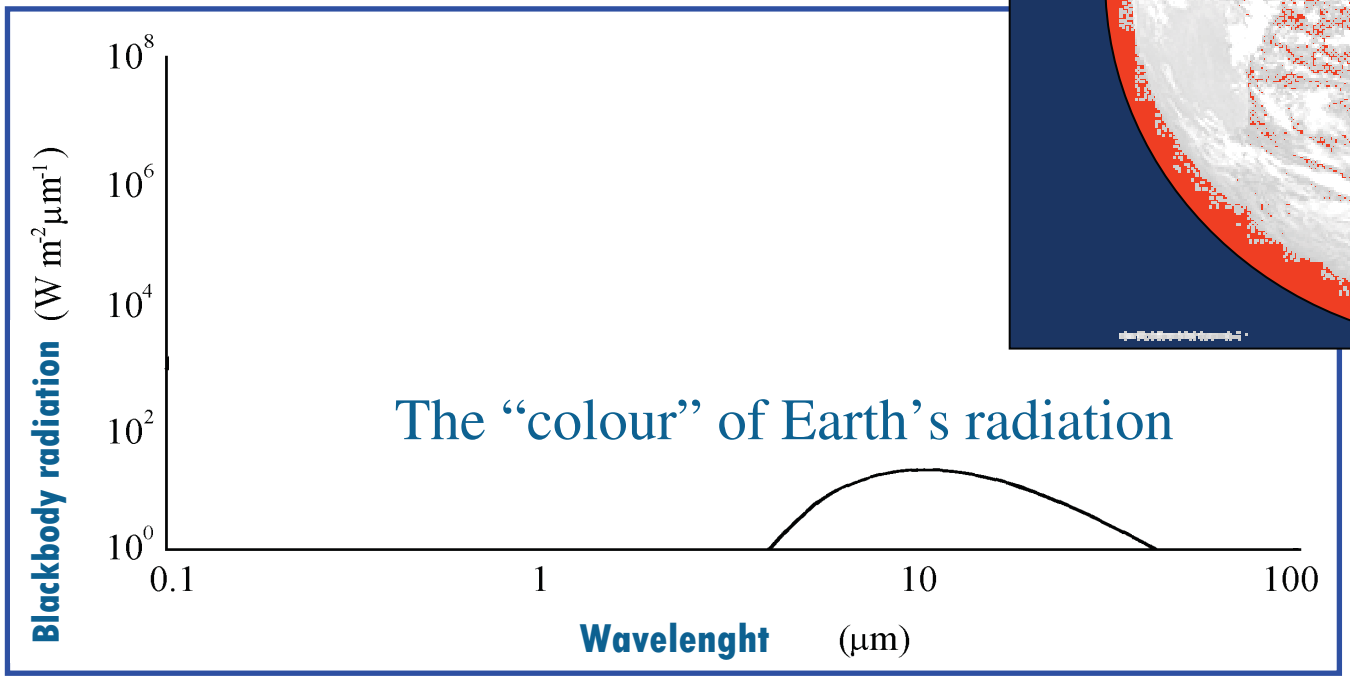
# Natural sources of radiation for Earth Observation

## The Earth itself (day and night !)

### Wien

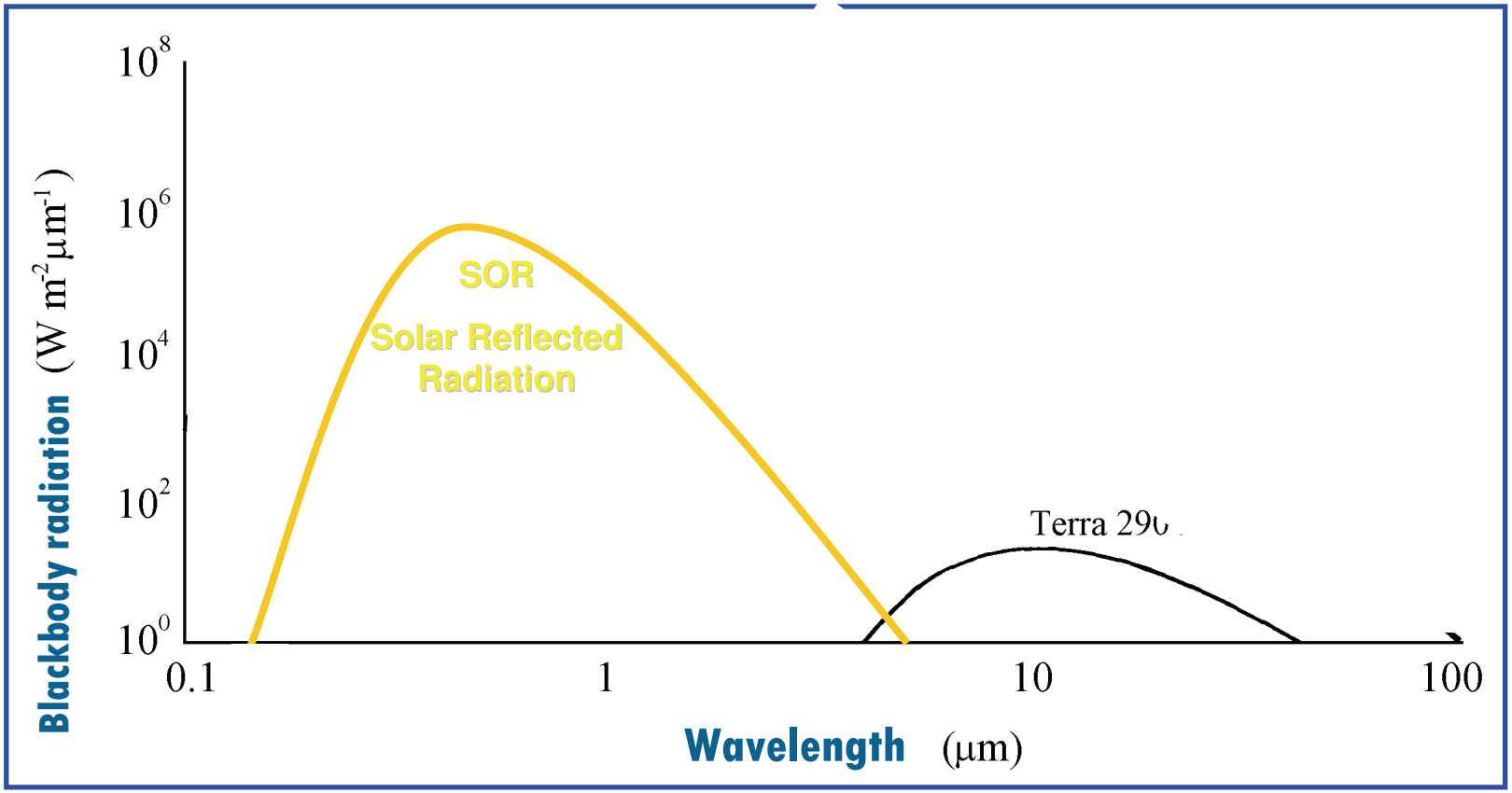
$$\lambda_{MAX} = \frac{2898}{T(K)} \approx \frac{3000}{300} = 10\mu m$$



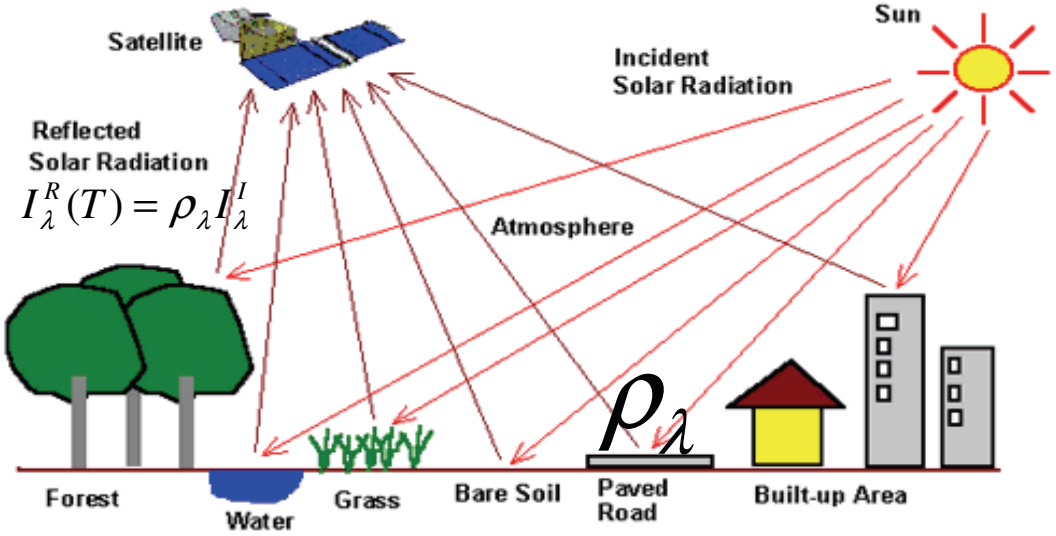
## Natural sources of radiation

# Actually available for Earth Observation




| | Peak Wavelength | Max. Intensity |
|---|---|---|
| Sun | 0.5 micrometers | 7.35 X $10^7$ W/m$^2$ |
| Earth | 10 micrometers | 390 W/m$^2$ |

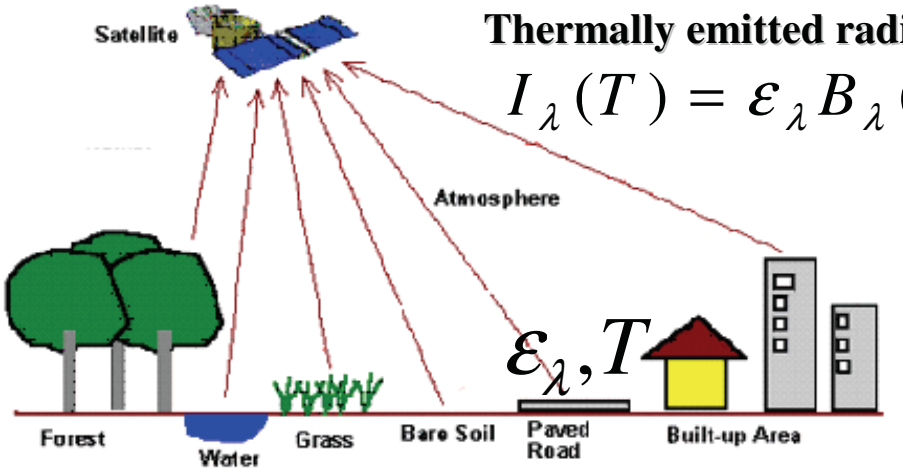
# Passive Earth Observing Techniques




**Natural source of radiation (Sun) different from the target**

**Diagnostic parameter:**

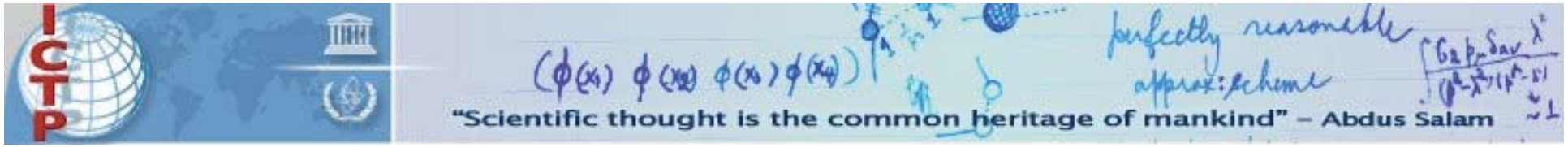
$\rho_\lambda$




**Natural source of radiation (Earth) coincident with the target**

**Diagnostic parameters:**

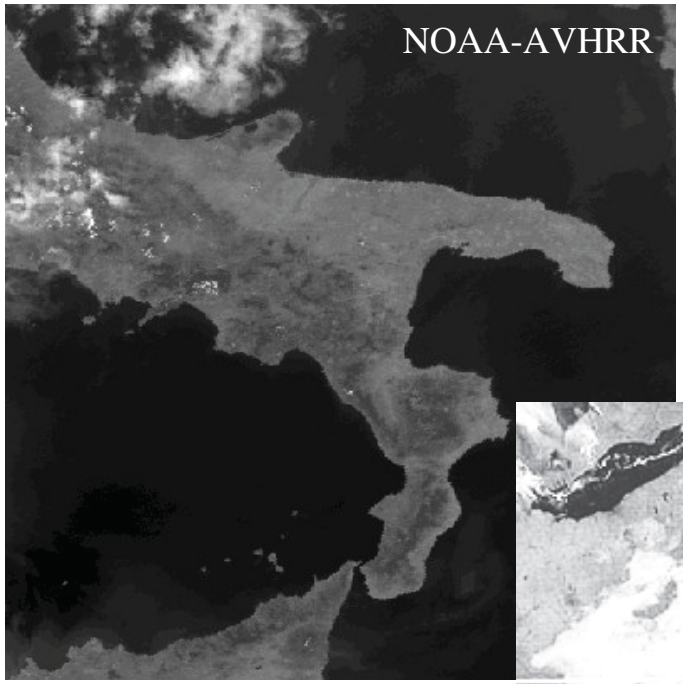
$\varepsilon_\lambda, T$

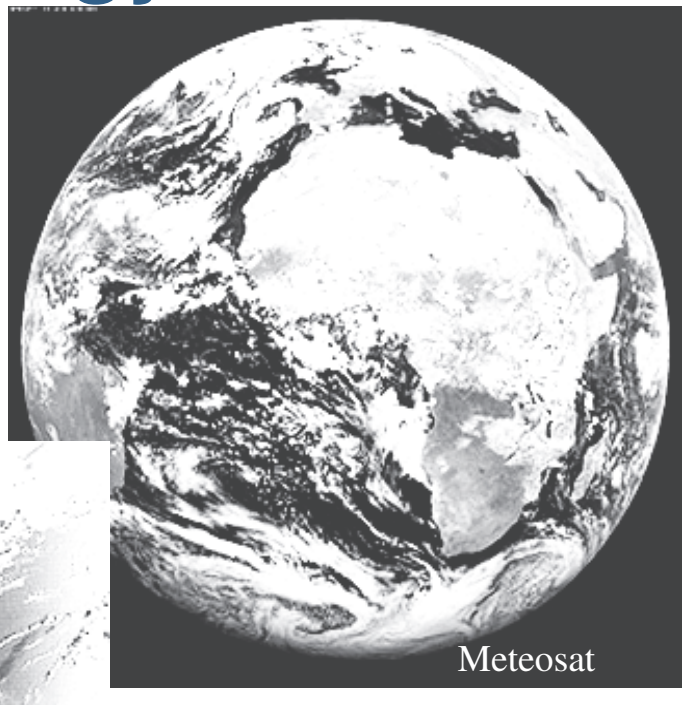


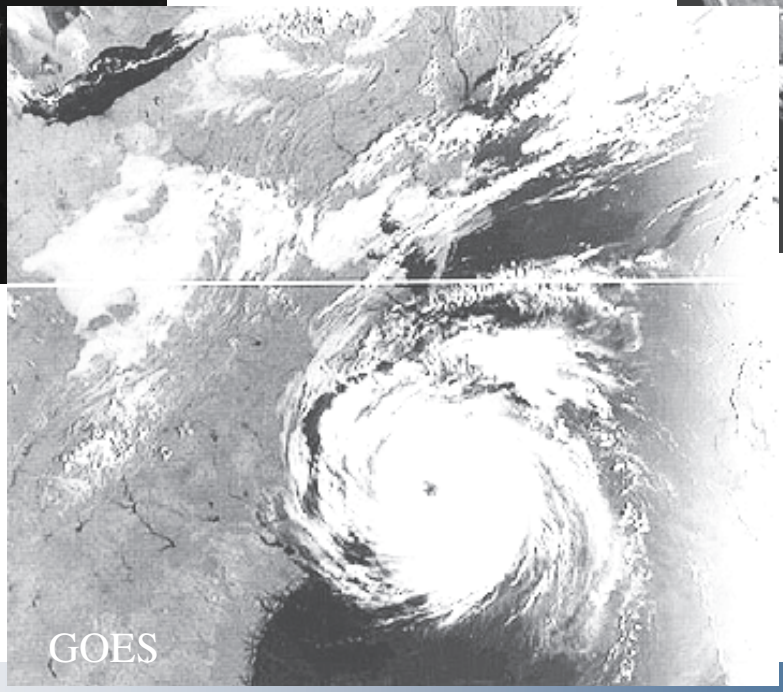



# THEORETICAL ISSUES:
## False Ideas

# Meteorological satellites systems: only for meteorology ?



# The trade-off between spatial and temporal resolution.

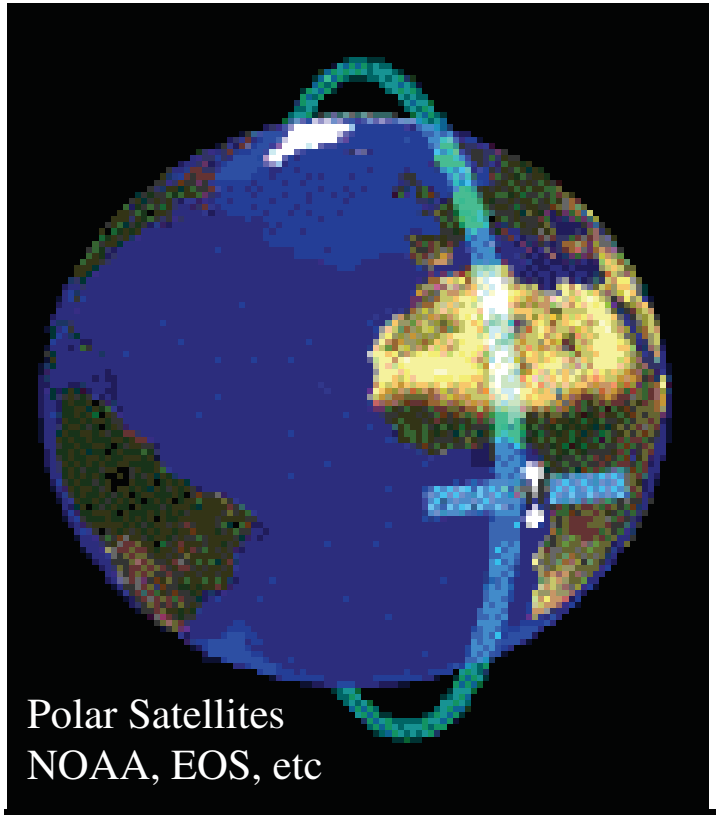
| Satellite platform | Sensor | Spectral Range | Spatial Resolution (max-min nadir view) | Temporal Resolution (the worst) |
|---|---|---|---|---|
| EOS (since 1999) | MODIS AMSR-E | Optical Microwave | 250 mt -1km ≅ 5 km | 12 hours |
| NOAA (since 1979) | AVHRR AMSU | Optical, Microwave | 1km ≅ 25 km | 6 hours |
| Meteosat (since 1977) | MVIRI | Optical | 2,5 – 5 km | 30 min |
| MSG (since 2003) | SEVIRI | Optical | 1 – 4 km | 15 min |

for timely detection of signal variations



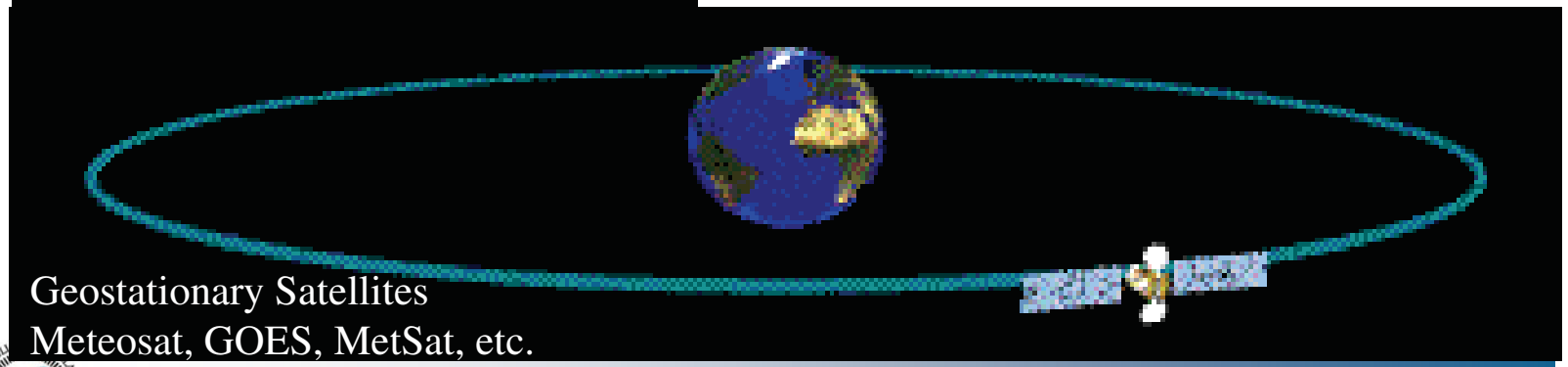
Dipartimento di Ingegneria e Fisica dell'Ambiente

# Satellite systems for early warning



Polar Satellites
NOAA, EOS, etc

- **The shortest revisitation time** (<6 hours, up to 15 minutes)
- **Global coverage** (by polar satellites or geostationary constallations)
- **Long term missions** (past & future)
- **Low, sustainable costs**



Geostationary Satellites
Meteosat, GOES, MetSat, etc.

# Main meteorological satellites systems

## spatial resolution

- **VIS-PAN 0,25 km→ 1 km** (nadir view)
- **IR 0,5→ 4km** (nadir view)

**to low ?**

**it depends …**

# Example 1
# Forest fire monitoring

## on the relation between:

**sensor spatial resolution**
**(i.e. minimum ground resolution cell)**

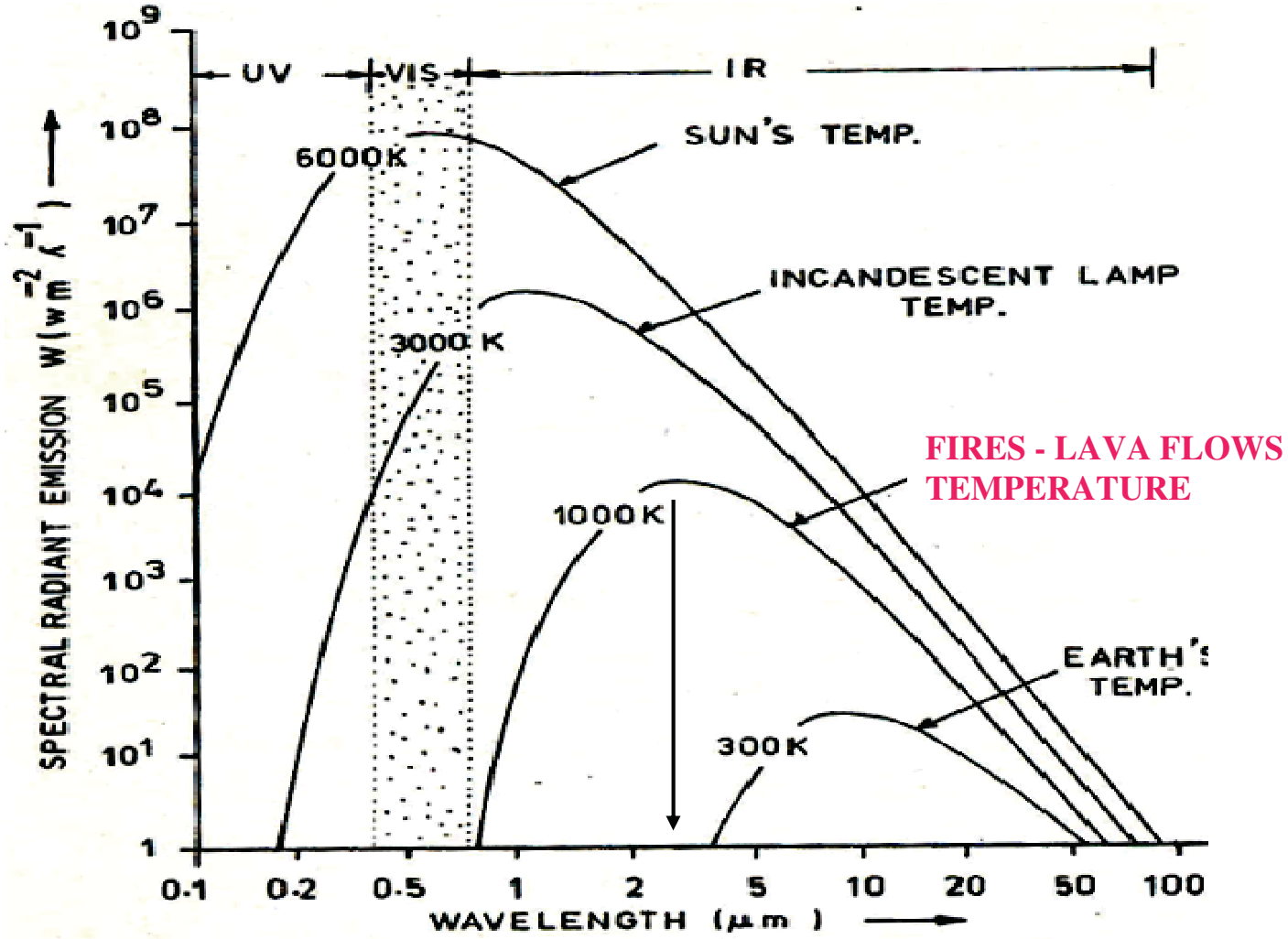
**and**

**minimum detectable fire extension within it**

**?**

# Looking for fires in the MIR region

**Black body radiation**



# Sensitivity (α) to temperature change

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5\left(e^{\frac{hc}{\lambda k T}} - 1\right)}$$

**Planck**

$$\frac{dB}{dT} = -\frac{2hc^2}{\lambda^5\left(e^{\frac{hc}{\lambda k T}} - 1\right)^2} \bullet e^{\frac{hc}{\lambda k T}} \bullet \left(-\frac{hc}{\lambda k T^2}\right) =$$

$$= \frac{2hc^2}{\lambda^5\left(e^{\frac{hc}{\lambda k T}} - 1\right)} \bullet \frac{e^{\frac{hc}{\lambda k T}}}{\left(e^{\frac{hc}{\lambda k T}} - 1\right)} \bullet \left(\frac{hc}{\lambda k T}\right) \bullet \frac{1}{T} = \alpha \cdot \frac{B}{T}$$

B

α

$$\alpha = \frac{hc}{\lambda k T\left(1 - \frac{1}{e^{\frac{hc}{\lambda k T}}}\right)}$$

# Sensitivity (α) to temperature change

$$\frac{dB}{dT} = \alpha \frac{B}{T}$$

$$\frac{dB}{B} = \alpha \frac{dT}{T}$$

$$d \ln B = \alpha \cdot d \ln T$$

$$d \ln B \approx d \ln T^{\alpha}$$

$$\ln B \approx \ln T^{\alpha} + \ln \text{cost}$$

$$B \approx \text{cost} \cdot T^{\alpha}$$

$$B \propto T^{\alpha}$$

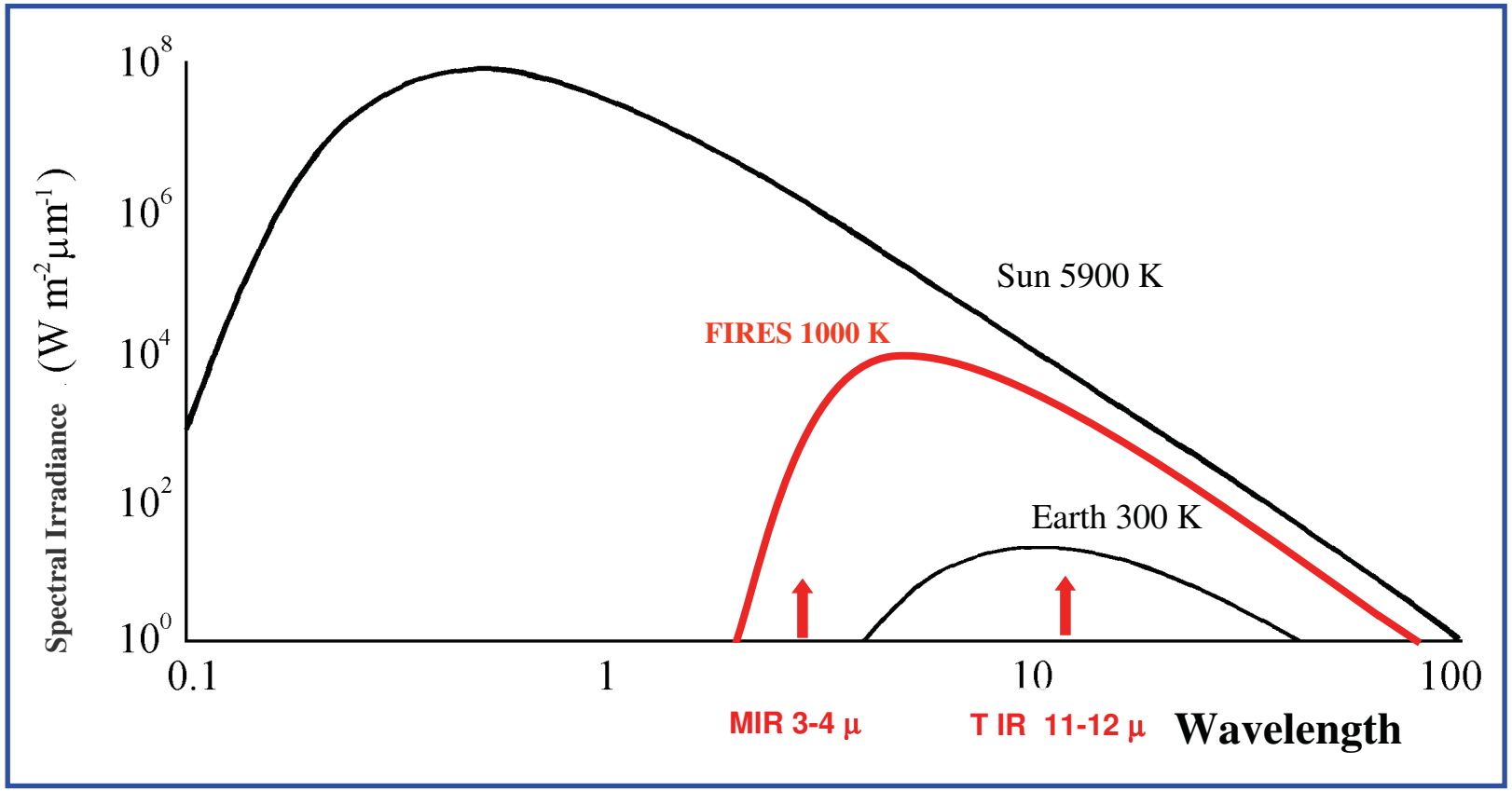
$$B_{\lambda}(T) = \frac{2 h c^2}{\lambda^5 \left( e^{\frac{h c}{\lambda k T}} - 1 \right)}$$

**Planck**

$$\alpha = \frac{hc}{\lambda k T \left( 1 - \frac{1}{e^{\frac{hc}{\lambda k T}}} \right)}$$

$$\alpha = \frac{\beta}{\left(1 - e^{-\beta}\right)} \quad \text{with} \quad \beta = \frac{hc}{\lambda k T}$$

# Dependence of $\alpha$ on spectral regions of observation



# Dependence of α on spectral regions of observation

$$\alpha = \frac{hc}{\lambda k T \left(1 - \frac{1}{e^{\frac{hc}{\lambda k T}}}\right)}$$

$$B \propto T^{\alpha}$$

| $T$=220 K (e.g. clouds) | | $T$=300 K | $T$=1000 K (e.g. fires) |
|---|---|---|---|
| λ (μ) | α | α | α |
| 11 | 5.96 | 4.4 | 1.8 |
| 4 | 16.4 | 12 | 3.7 |

# Dependence of α on spectral regions of observation

$$\alpha = \frac{hc}{\lambda k T \left(1 - \frac{1}{e^{\frac{hc}{\lambda k T}}}\right)}$$

$$B \propto T^{\alpha}$$

| *Es. T*=300 K | | |
|---|---|---|
| λ (μ) | α | $B_\lambda(T)$ |
| 11 | 4.4 | $B_{11} \propto T^{4.4}$ |
| 4 | 12 | $B_4 \propto T^{12}$ |

At the shorter wavelengths the warmer portion of the pixel gives a relatively higher contribution to the radiance

# Sensitivity ($\alpha$) to temperature change
## sub-pixel response and sensor saturation

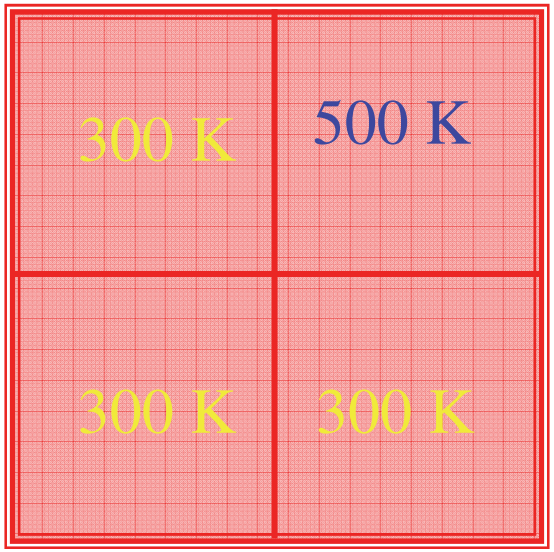
**example 1 (25%)**
**Fire (500 K) affecting a quarter of pixel area**

**MIR 4μm**
**$B = T^{12}$**

$B=(B1+B2+B3+B4)/4$
$=(3x300^{12}+500^{12})/4$

$T \sim B^{1/12}$

**T = 446 K**
**AVHRR saturation**
**SEVIRI saturation**




$T_{4\mu} - T_{12\mu} > 58$ K

**TIR11 μm**
**$B = T^{4.4}$**

$B=(B1+B2+B3+B4)/4$
$=(3x300^{4.4}+500^{4,4})/4$

$T \sim B^{1/4.4}$

**T = 388 K**
**AVHRR saturation**
**SEVIRI saturation**

# Sensitivity ($\alpha$) to temperature change
## sub-pixel response and sensor saturation

**example 2 (1%)**
**Fire (500 K) affecting 1/100 of pixel area**

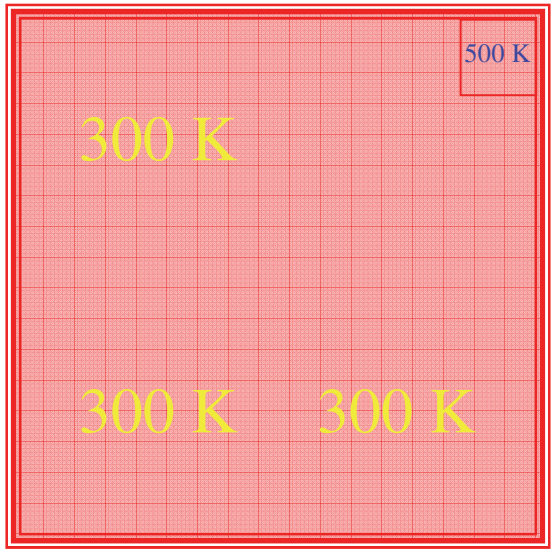
**MIR 4μm**
**$B = T^{12}$**

$B=(B1+..+B100)/100$
$=(99x300^{12}+500^{12})/100$

$T=B^{1/12}$

**T = 346 K**

**AVHRR saturation**
**SEVIRI saturation**




$T_{4\mu} - T_{12\mu} > 40$ K

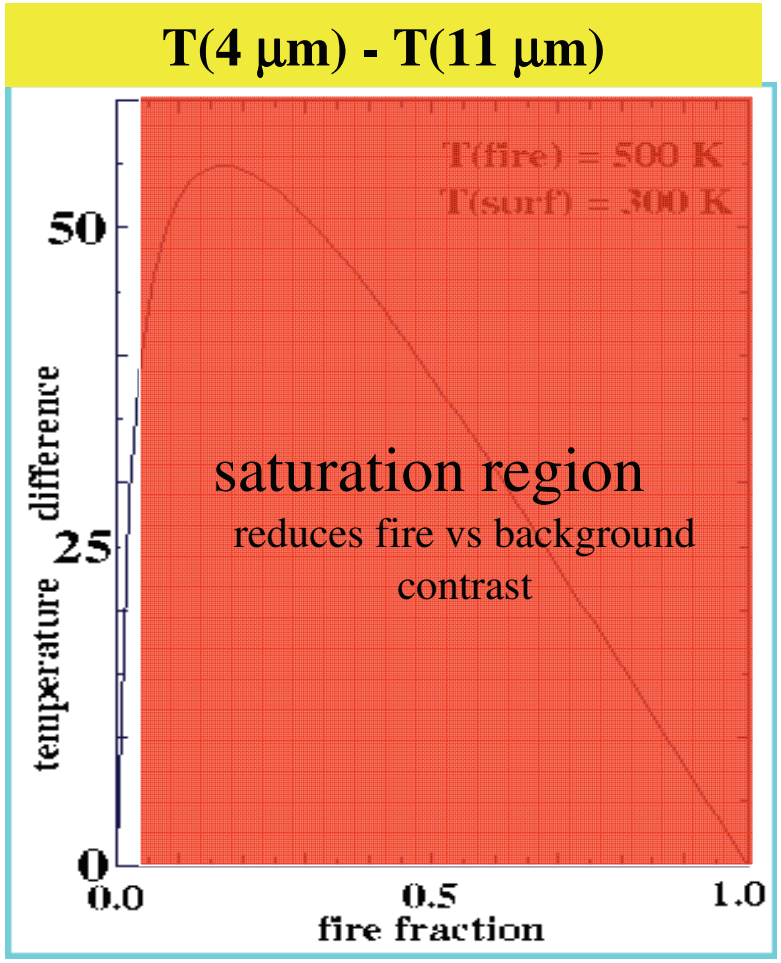
**TIR11 μm**
**$B = T^{4.4}$**

$B=(B1+..+B100)/100$
$=(99x300^{4.4}+500^{4.4})/100$

$T = B^{1/4.4}$

**T = 306 K**

# Sensitivity (α) to temperature change
## sub-pixel response and sensor saturation




but
sensor saturation easily occurs for fire affected pixel fractions > 0,001 depending on fire temperature

# Sensitivity ($\alpha$) to temperature change
## sub-pixel response and sensor saturation

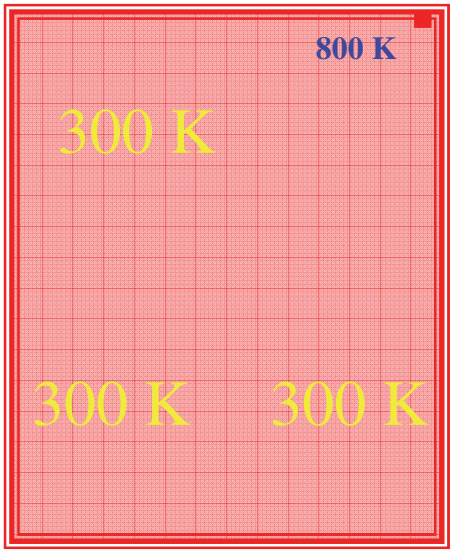
**example 3 (1/100.000)**
**Fire (800 K) affecting 1/100.000 of pixel area**

**MIR 4μm**
**$B = T^{12}$**

$B=(B1+..+B100000)/100000$
$=(9999x300^{12}+800^{12})/100.000$

$T=B^{1/12}$

**T = 321 K**




**$T_{4\mu} - T_{12\mu} > 20$ K**

**TIR11 μm**
**$B = T^{4.4}$**

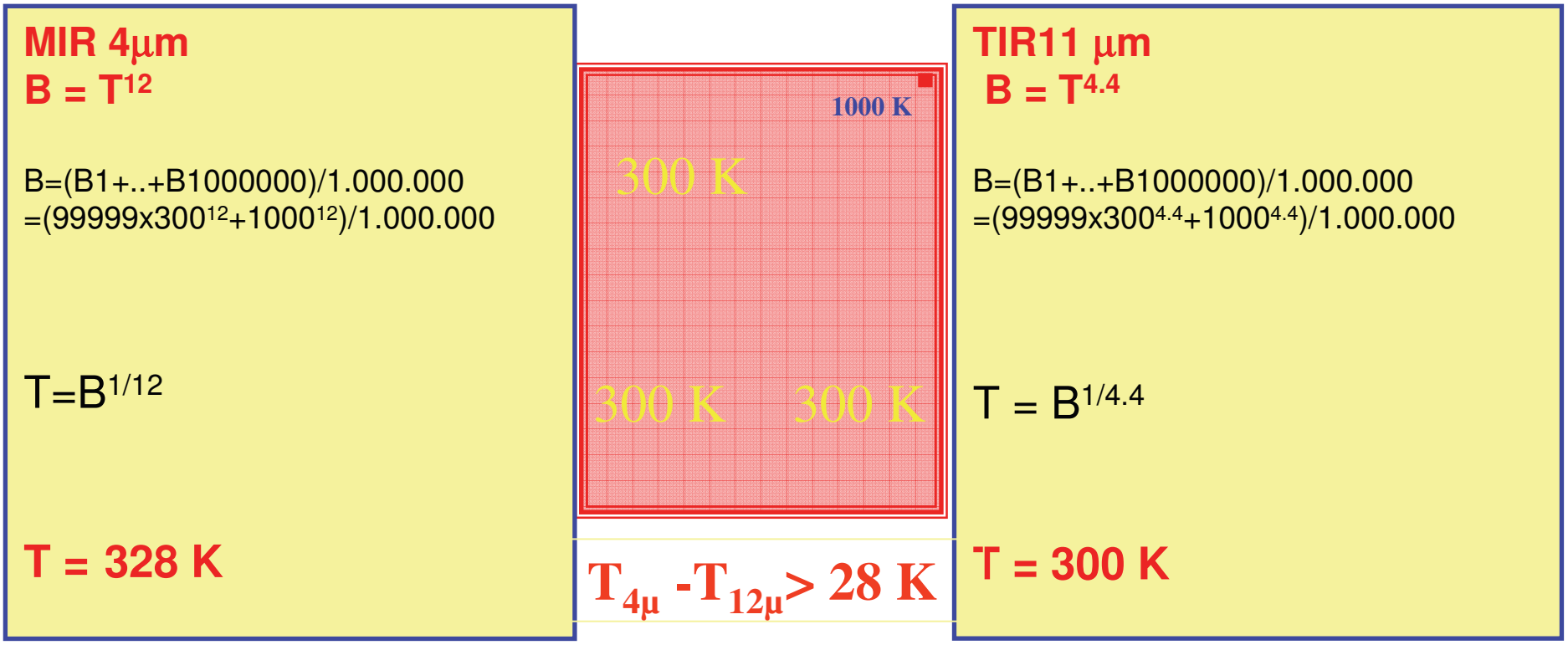
$B=(B1+..+B100000)/100000$
$=(9999x300^{4.4}+800^{4.4})/100.000$

$T = B^{1/4.4}$

**T = 300 K**

# Sensitivity ($\alpha$) to temperature change
## sub-pixel response and sensor saturation

**example 4 (1/1.000.000)**
**Fire (1000 K) affecting 1/1.000.000 of pixel area**

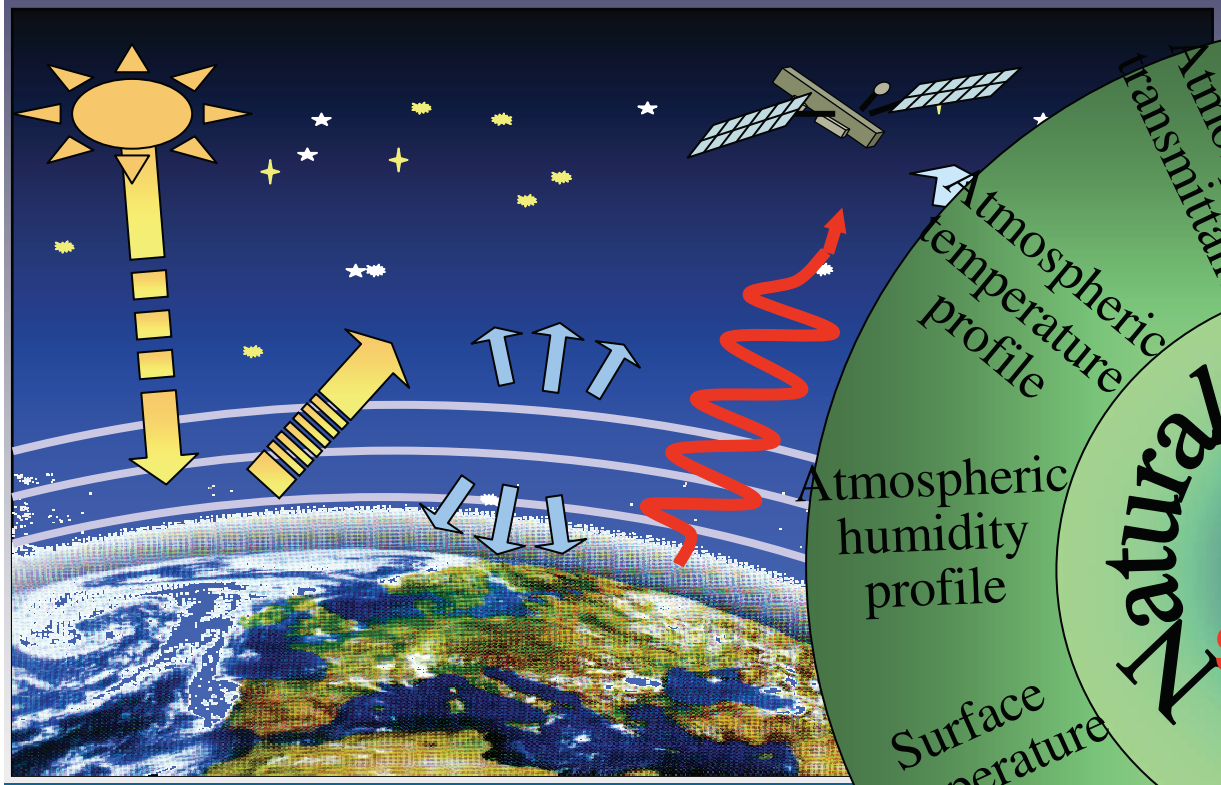


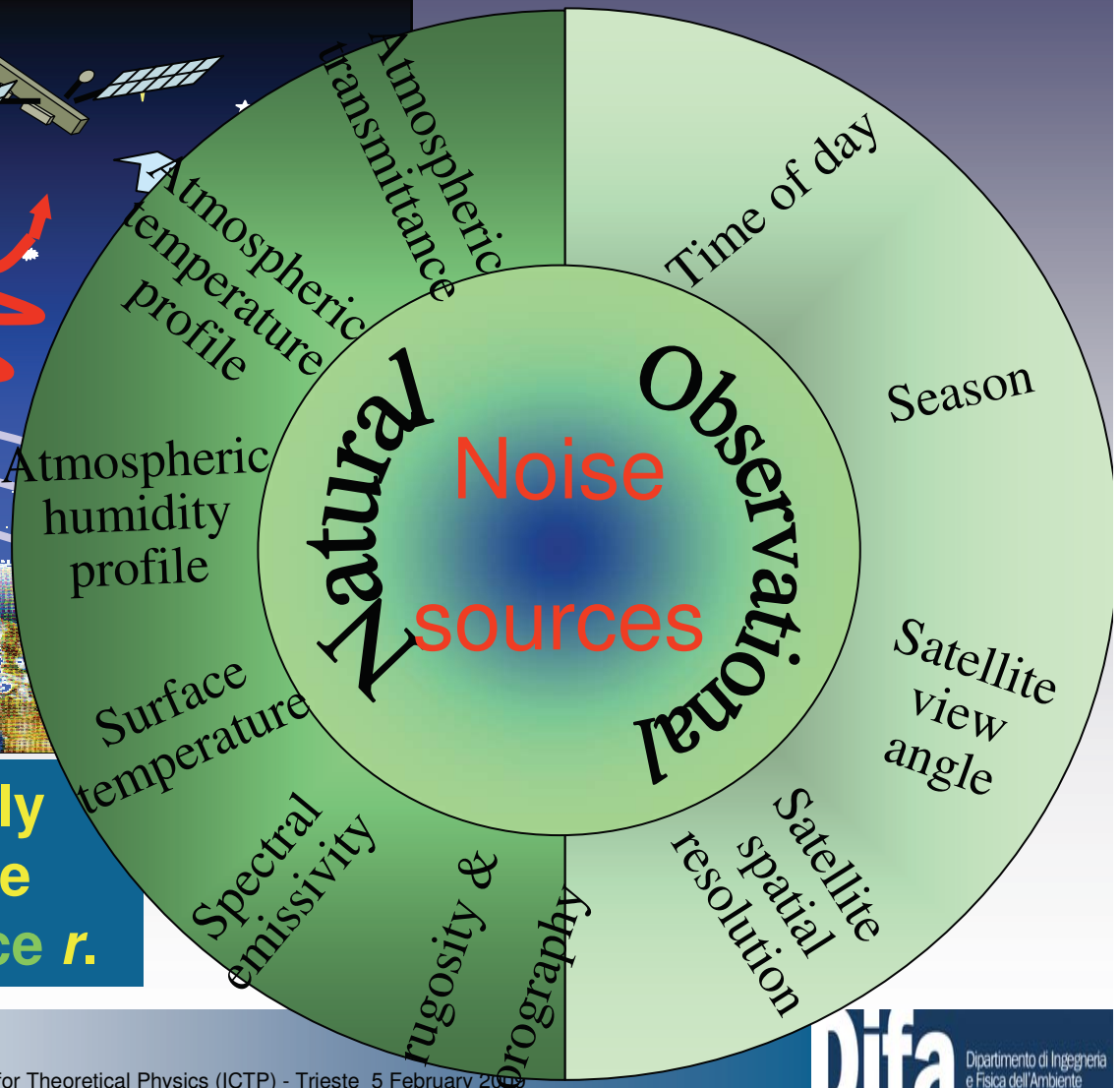
**WINTER COLLEGE ON OPTICS IN ENVIRONMENTAL SCIENCE**
**Trieste 2 – 13 February 2009**

# THEORETICAL ISSUES
# Satellite Change Detection Techniques:

## Why (sometimes, in some place) don't work?

# Earth observation by satellite:
# the signal and the noise






**Measured signal is strongly variable depending on the observation time *t* and place *r*.**



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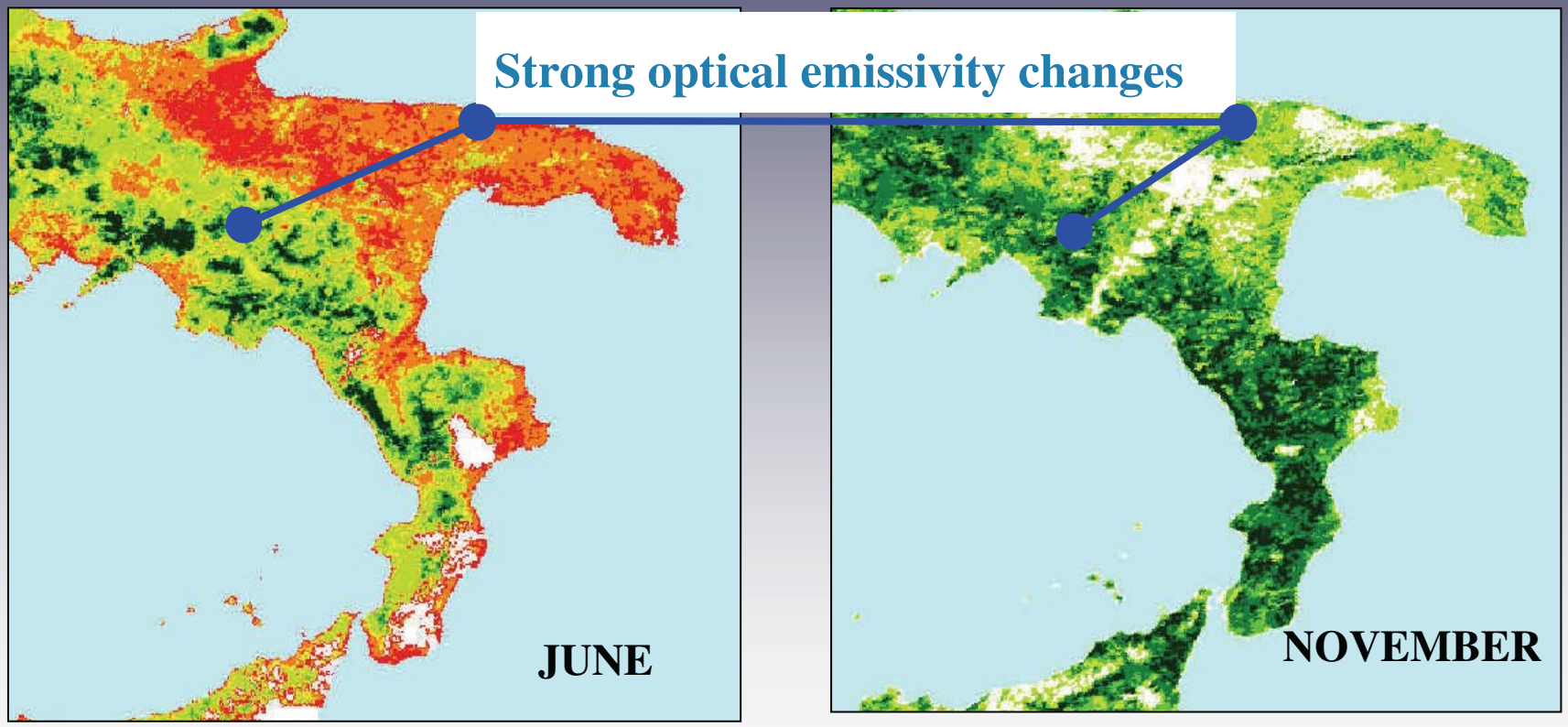
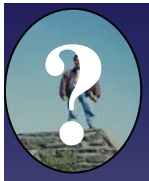
# NATURAL NOISE: SEASONAL CHANGE IN LAND COVER AND RELATED EMISSIVITY





# NATURAL NOISE: SURFACE TEMPERATURE SPACE-TIME CHANGES

**SPATIALLY DEPENDENT ON ALTITUDE, SOIL COVER etc.**

**TIME DEPENDENT ON SEASONS, DAYTIME etc.**

time

space

More than 10°C of difference

More than 10°C of difference

SUMMER

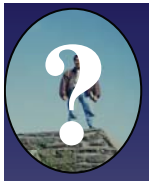
*15 June 1996*

WINTER

*3 November 1996*

(AVHRR-Land Surface Temperature)

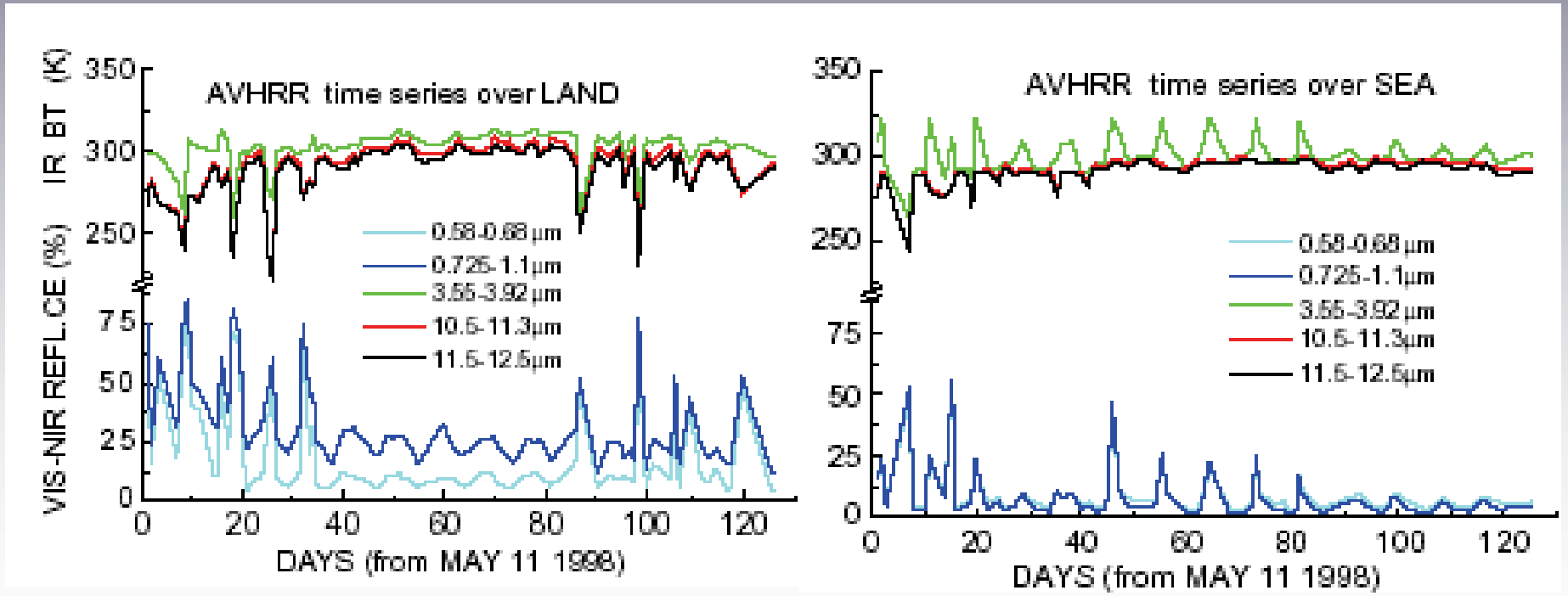
NUBI 12 15 18 21 24 27 32 °C



# Earth observation by satellite:

# the natural/observational noise

**Measured signal is strongly variable depending on the observation spectral range $\Delta\lambda$, time *t* and place *r***



# Why don't work?

## Example 1
## Detecting fires

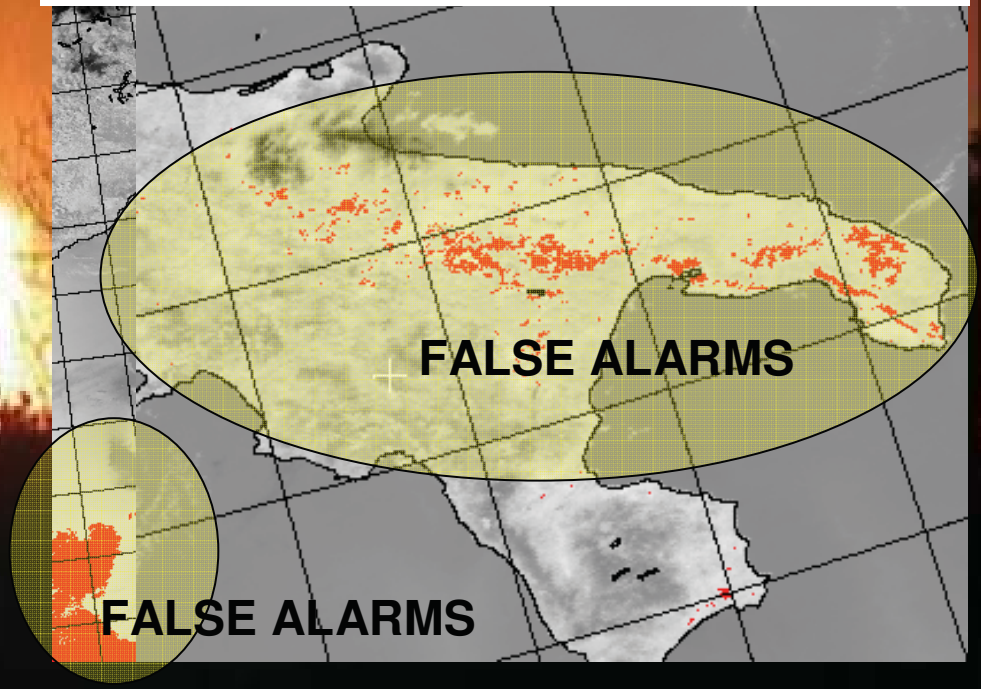
Polar Satellites
NOAA/AVHRR

# Single image – fixed threshold algorithms

- Fixed threshold on single bands ***(Muirhead and Cracknell 1985; Malingreau and Tucker 1988; Setzer and Pereira 1991b, 1992; etc.)***

- Fixed threshold on band combinations ***(Kaufman et al., 1990; Arino et al., 1993; Kennedy et al., 1993; Li et al., 2000; etc.)***

**NOAA-AVHRR** (Kaufman et al. 1990)
**South Italy - SUMMER**

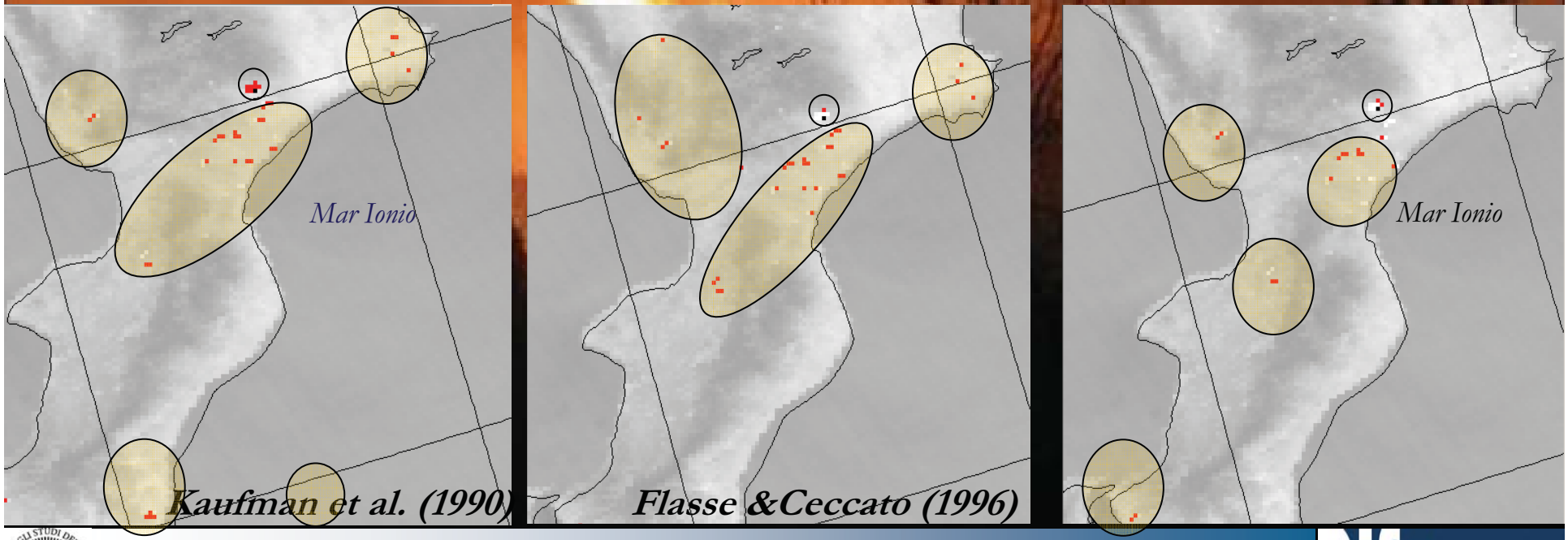


# Single image – fixed threshold algorithms

- Fixed thresholds – multi-bands ***(Kaufman et al., 1990; Arino et al., 1993; Kennedy et al., 1993; Li et al., 2000; etc.)***
- Contextuals ***(Justice et al., 1996; Flasse e Ceccato, 1996, Lee et al., 2000, Elvidge et al., 1997, Giglio et al., 1999; etc.)***

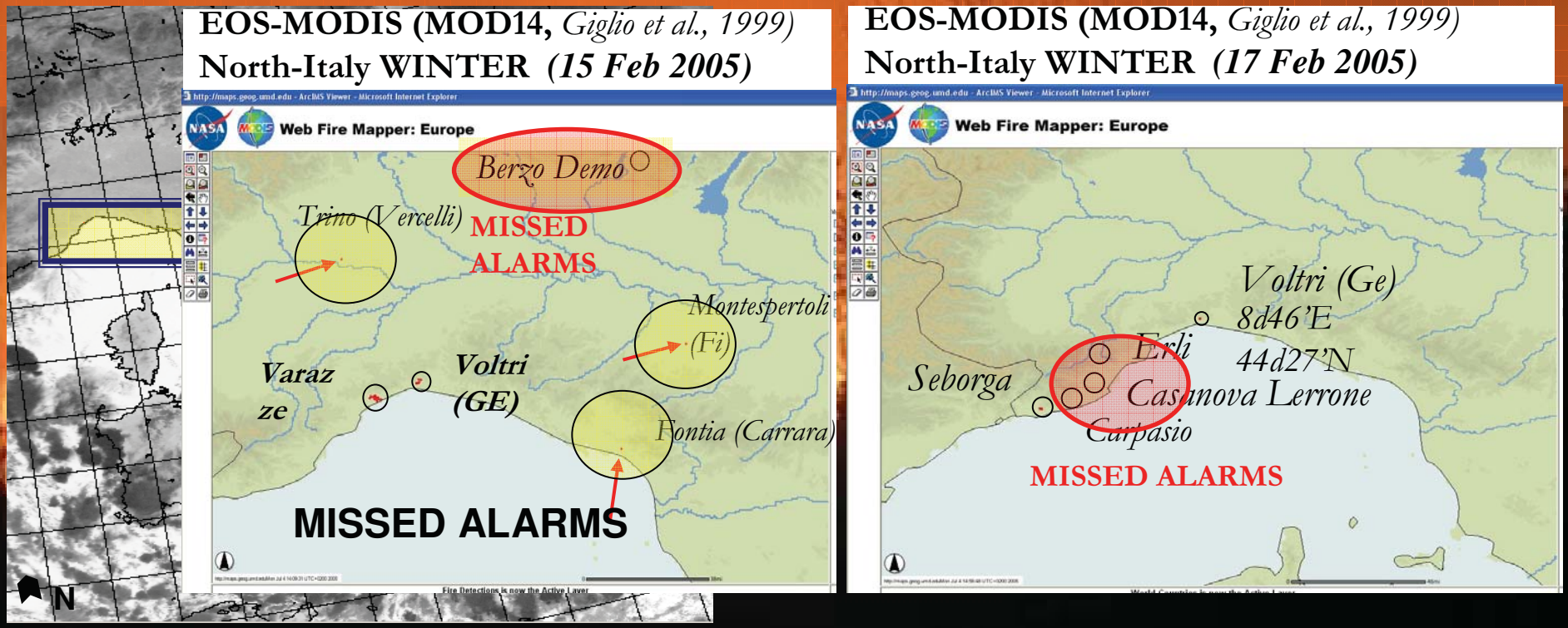
**AVHRR – 5th july 2000 15:00 GMT**

**FALSE ALARMS** **Actually occurred** **Detected**



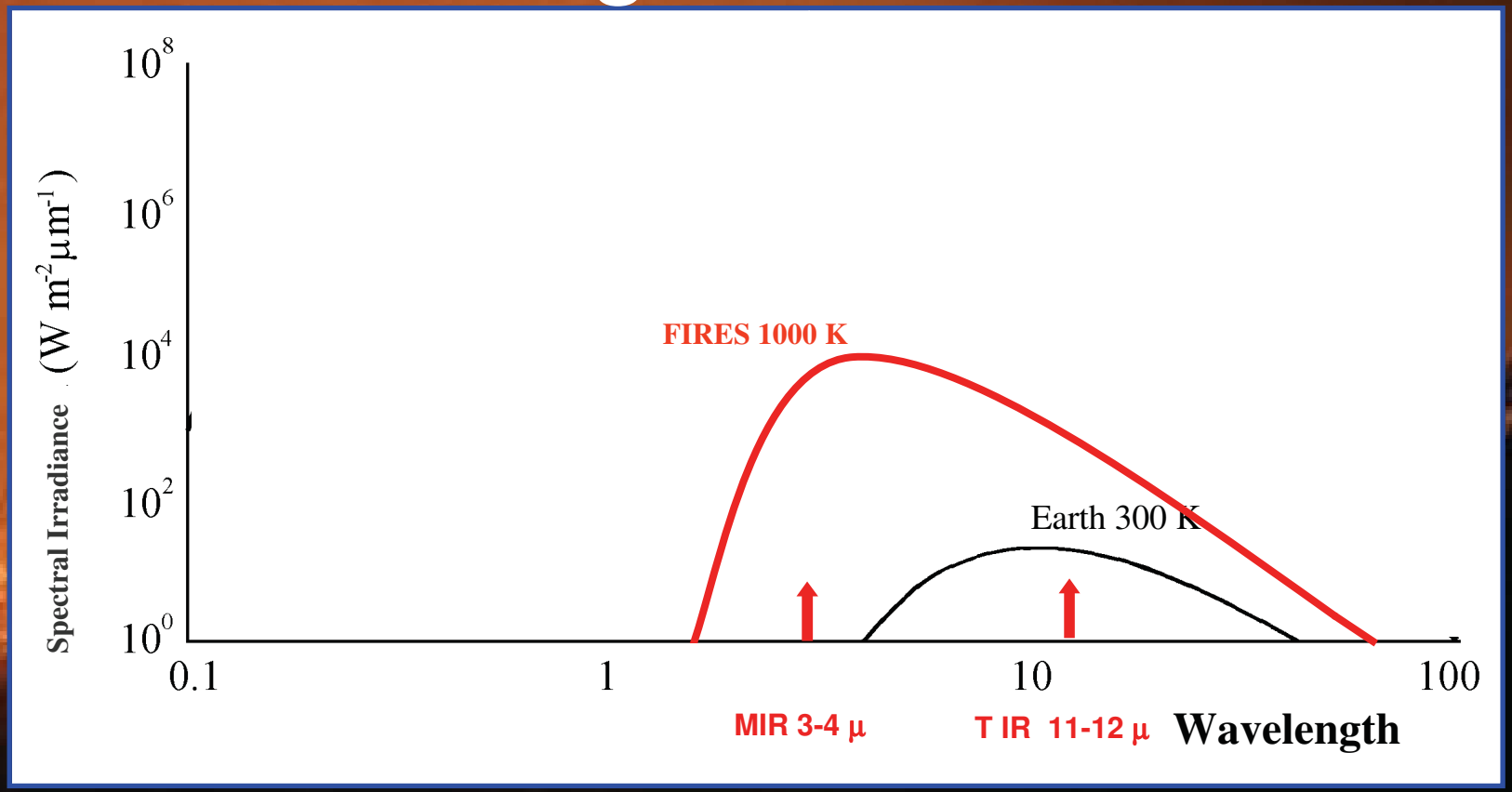
# Single image – fixed threshold

- Contesxtual : ***(Justice et al., 1996; Flasse e Ceccato, 1996, Lee et al., 2000, Elvidge et al., 1997, Giglio et al., 1999; etc.)***



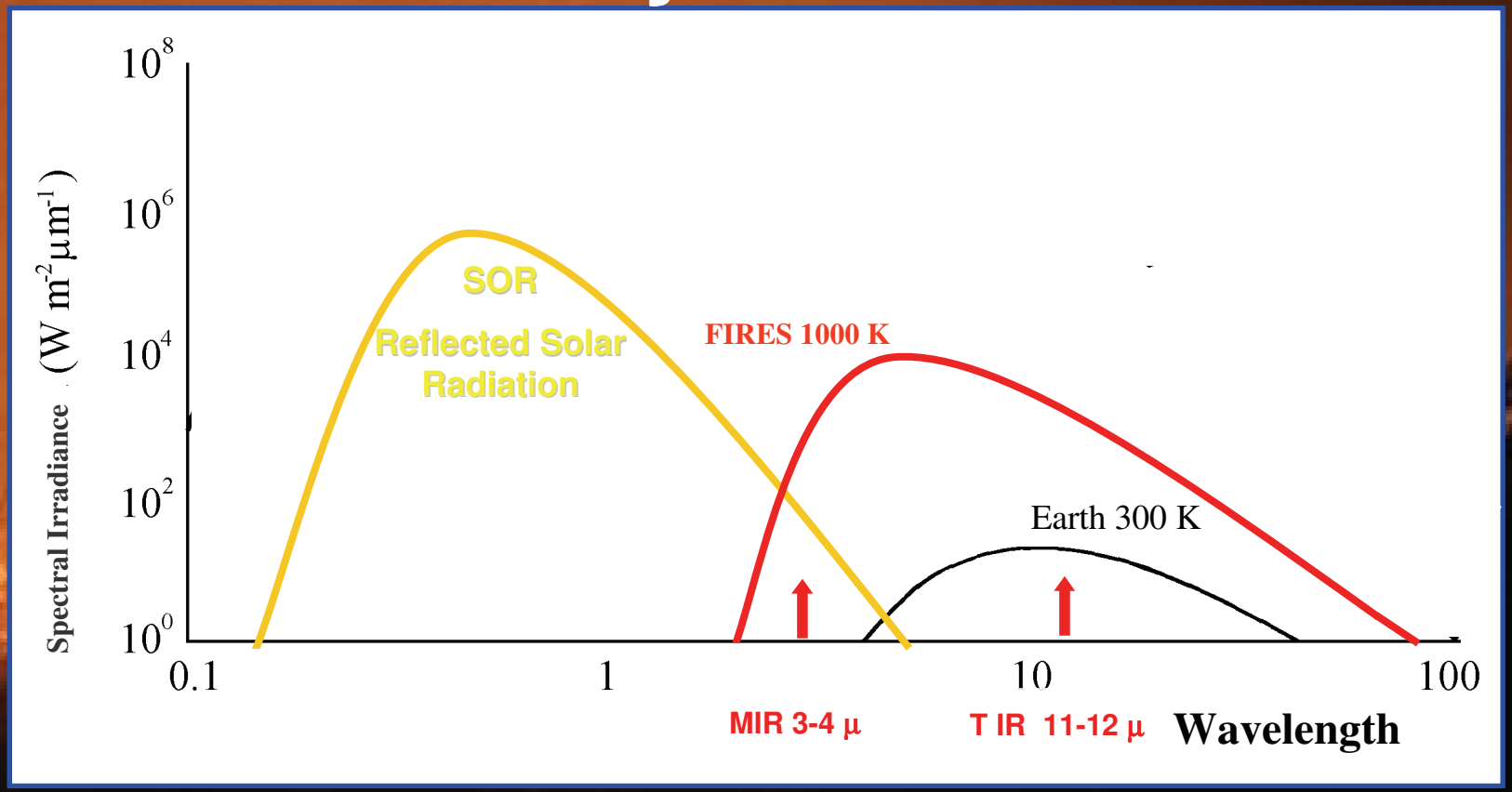
# Main natural radiation sources for Earth Observation from satellite

## night-time

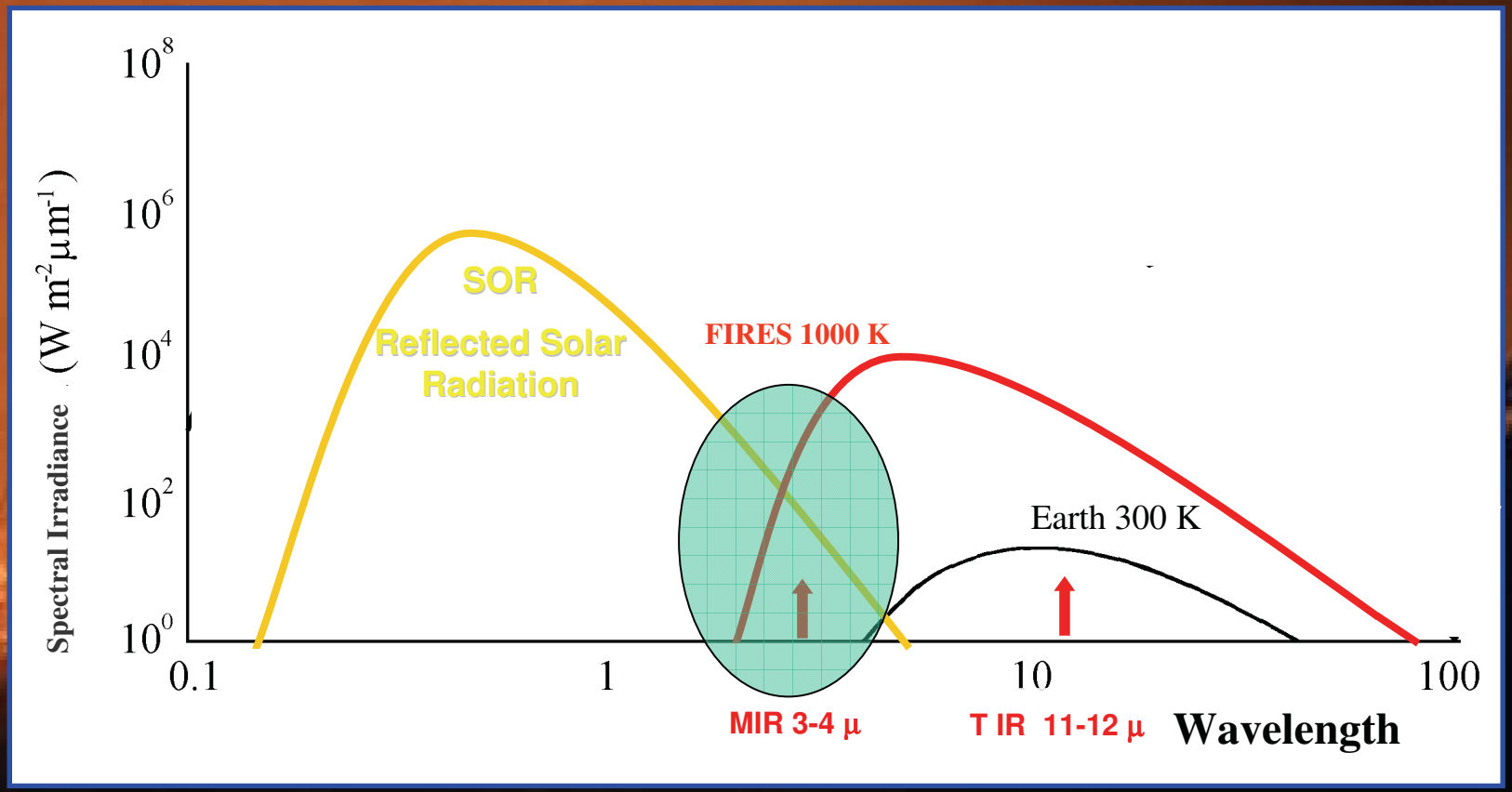


# Main natural radiation sources for Earth Observation from satellite

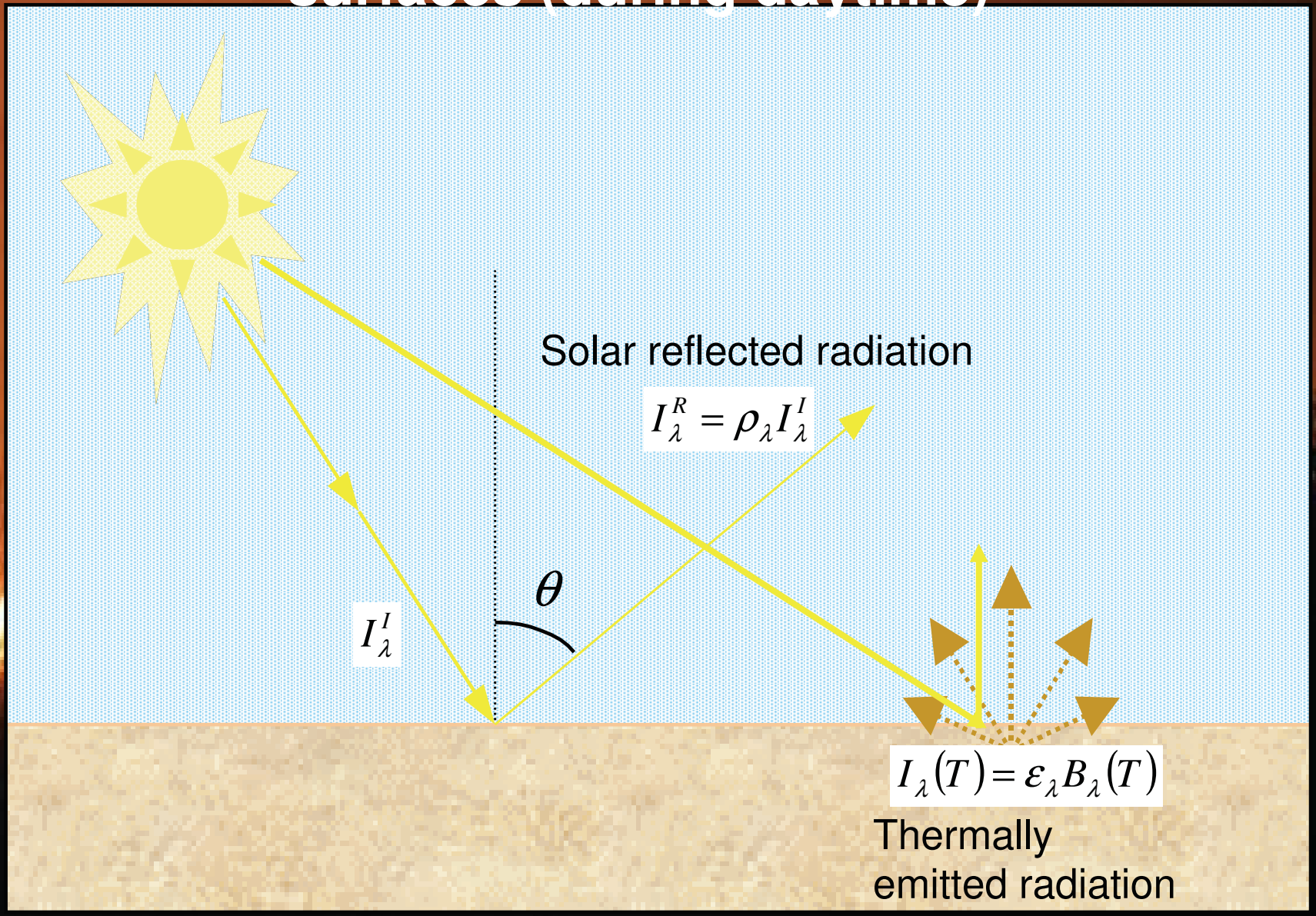
## day-time

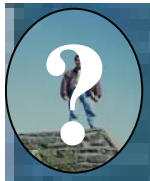


# False fire alarms generated by highly reflecting surfaces (during daytime)



# False alarms generated by highly reflecting surfaces (during daytime)





# Why don't work?

# Example 2
# Detecting oil spills

# Example 2: Oil Spill Detection

## Single image processing – Fixed threshold (Cross, 1991)

**23 - 30 January 1991 (Gulf War): release of crude oil on Kuwait and Saudi Arabia coasts**

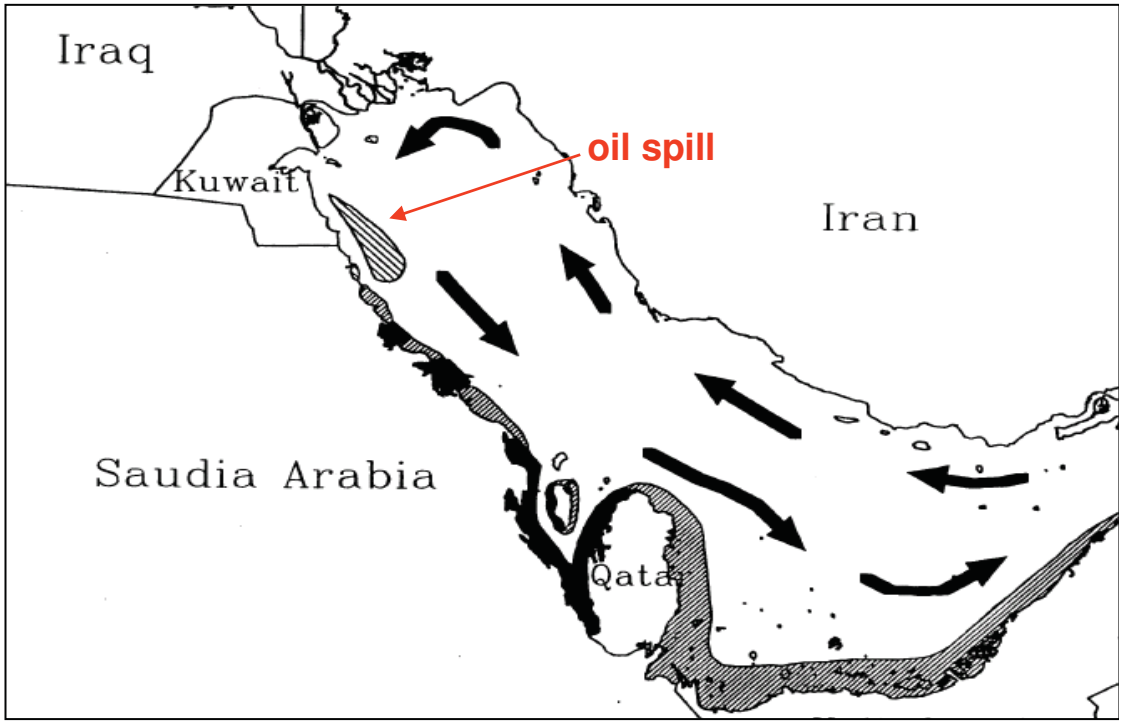
land

(Kuwait)

sea

land

(Saudi Arabia)

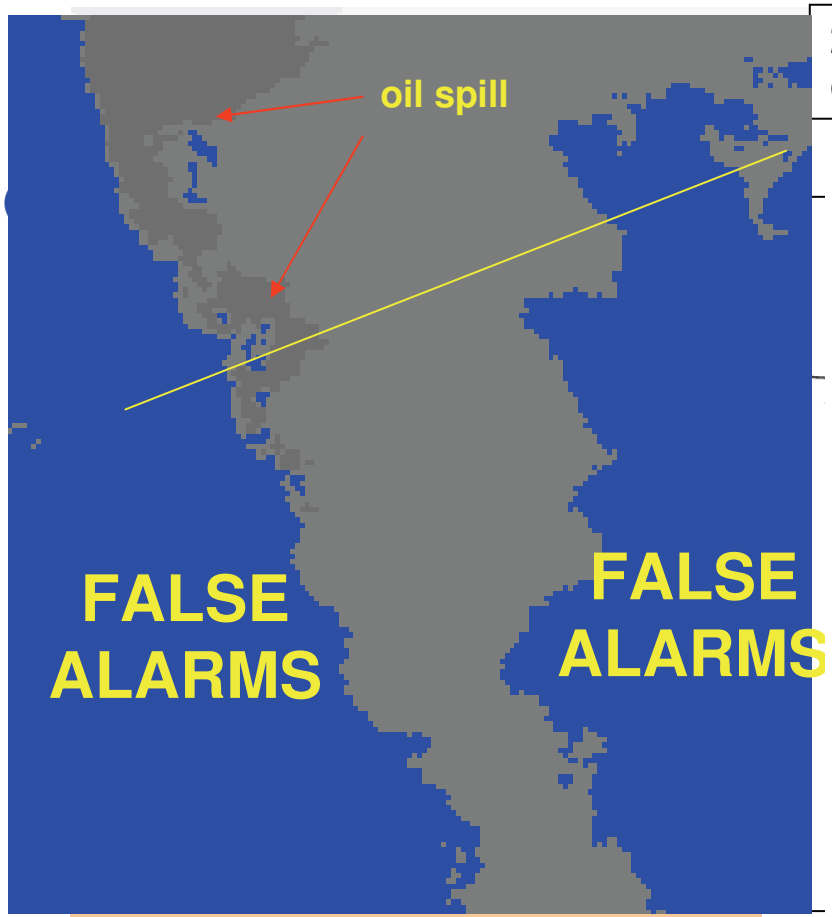



**24th January 1991**
**(NOAA/AVHRR TIR channel 4 – 10:38 GMT)**

# Example 2: Oil Spill Detection

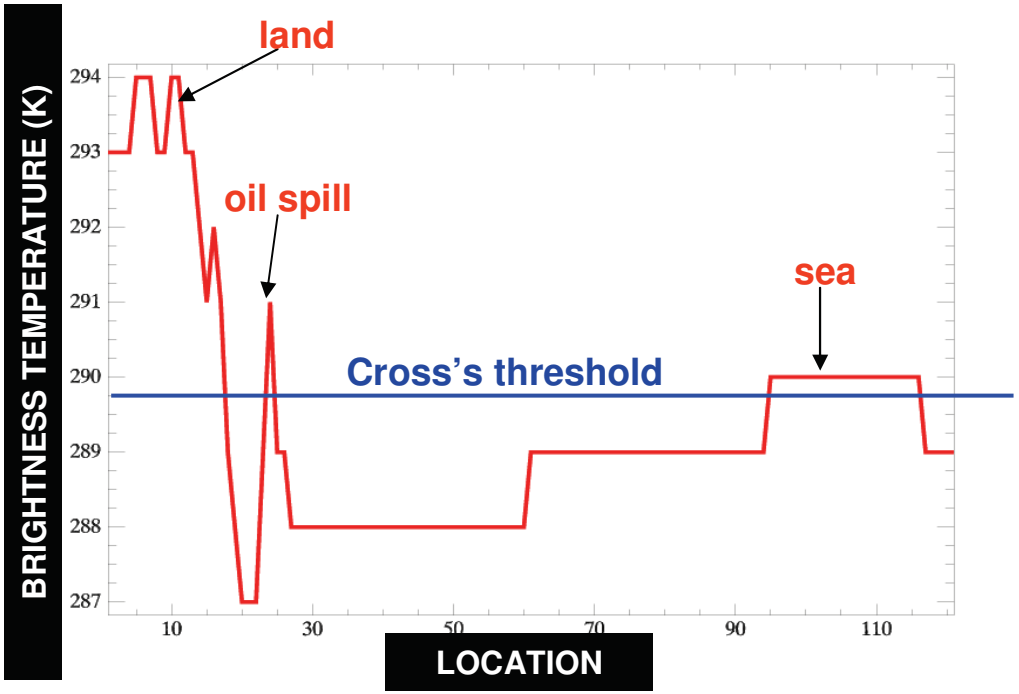
## Single image processing – Fixed threshold (Cross, 1991)

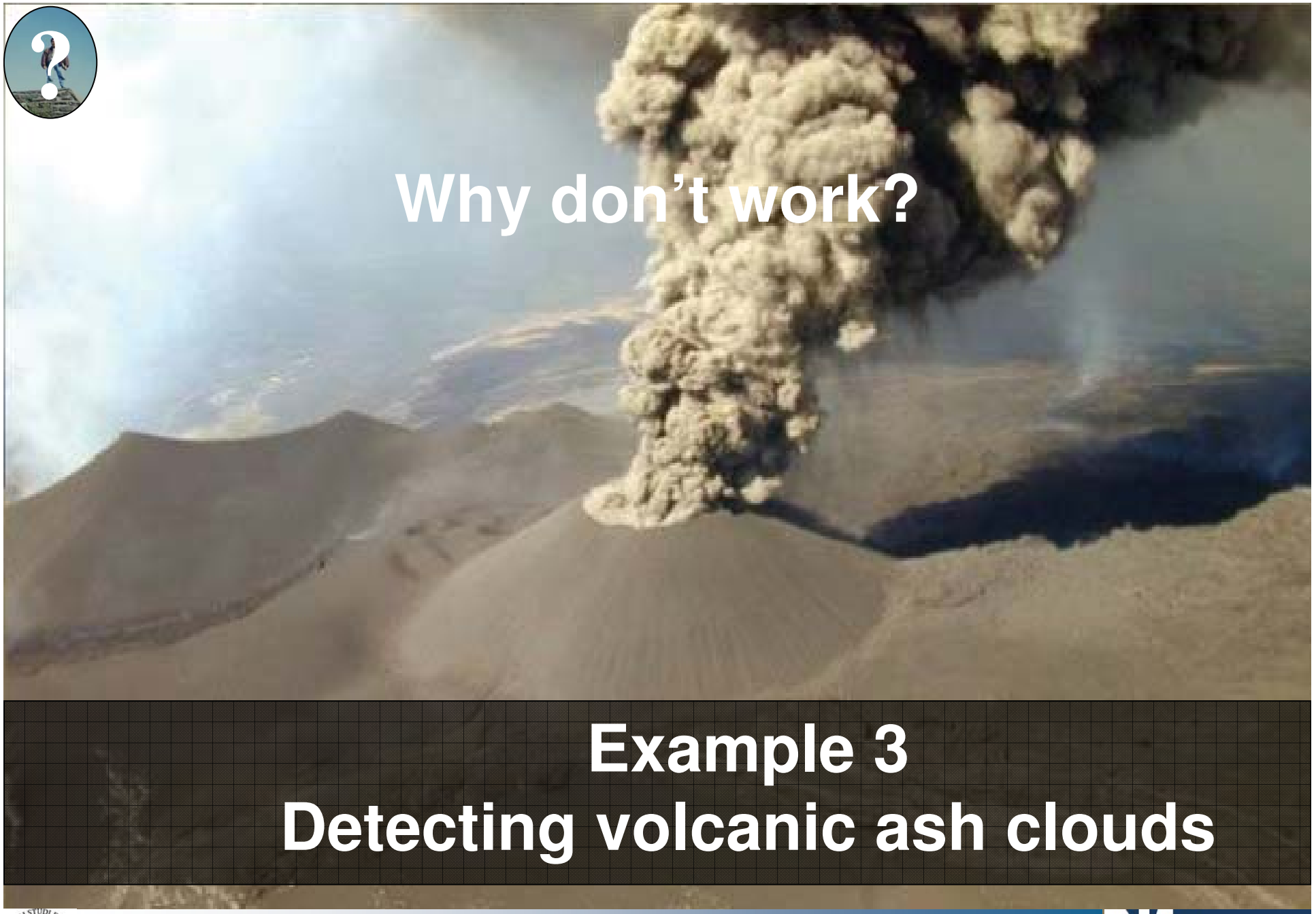
oil spill if $T_4 > 289.8$ K




24th January 1991
(NOAA/AVHRR TIR channel 4 – 10:38 GMT)

**23 - 30 January 1991 (Gulf War): release of crude oil on Kuwait and Saudi Arabia coasts**

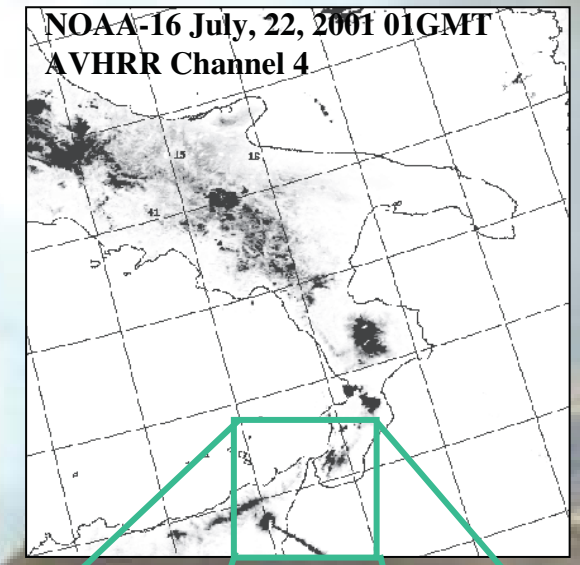


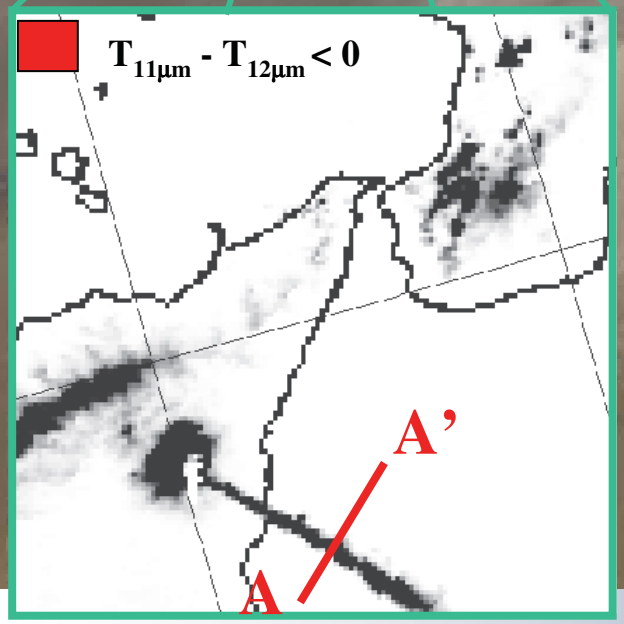


# Why don't work?

# Example 3
# Detecting volcanic ash clouds

# Example 3: Volcanic Ash cloud detection
## (Single image – Fixed threshold )
## e.g. Prata, 1989



NO DETECTIONS!!



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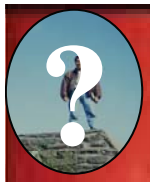
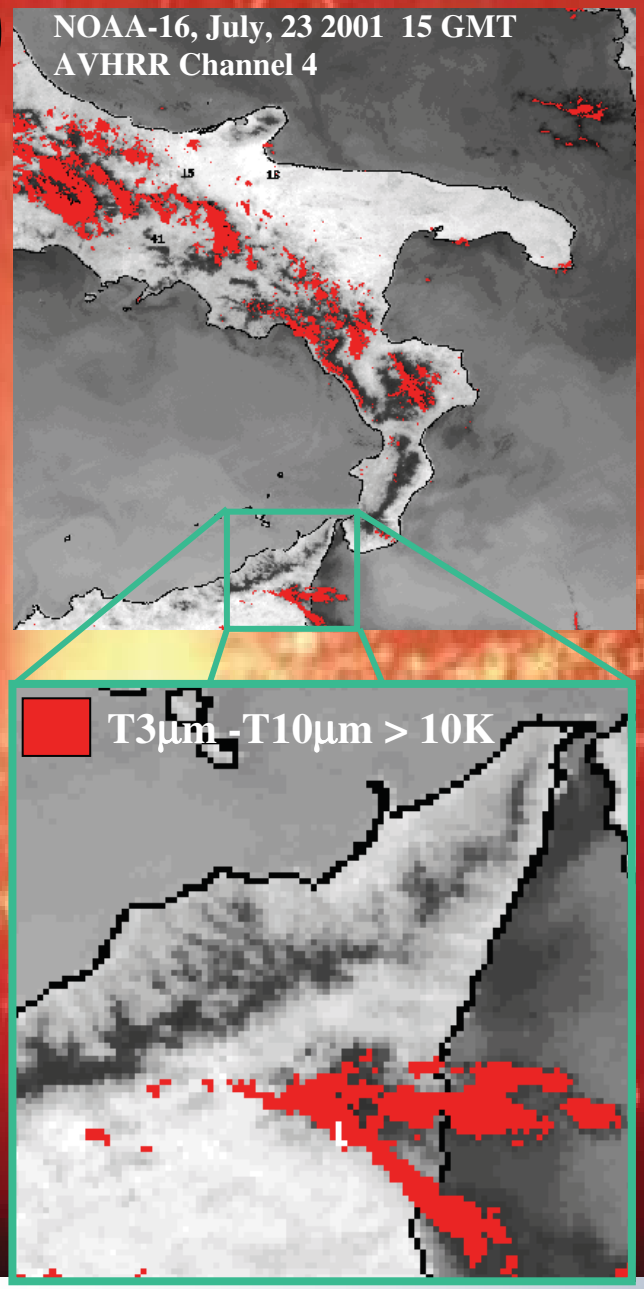


# Why don't work?

# Example 4
# Monitoring lava flows

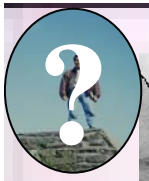
# Example 4:
# Volcanic Lava flow Detection
## (Single image – Fixed threshold )
## e.g. Harris et al. 1995

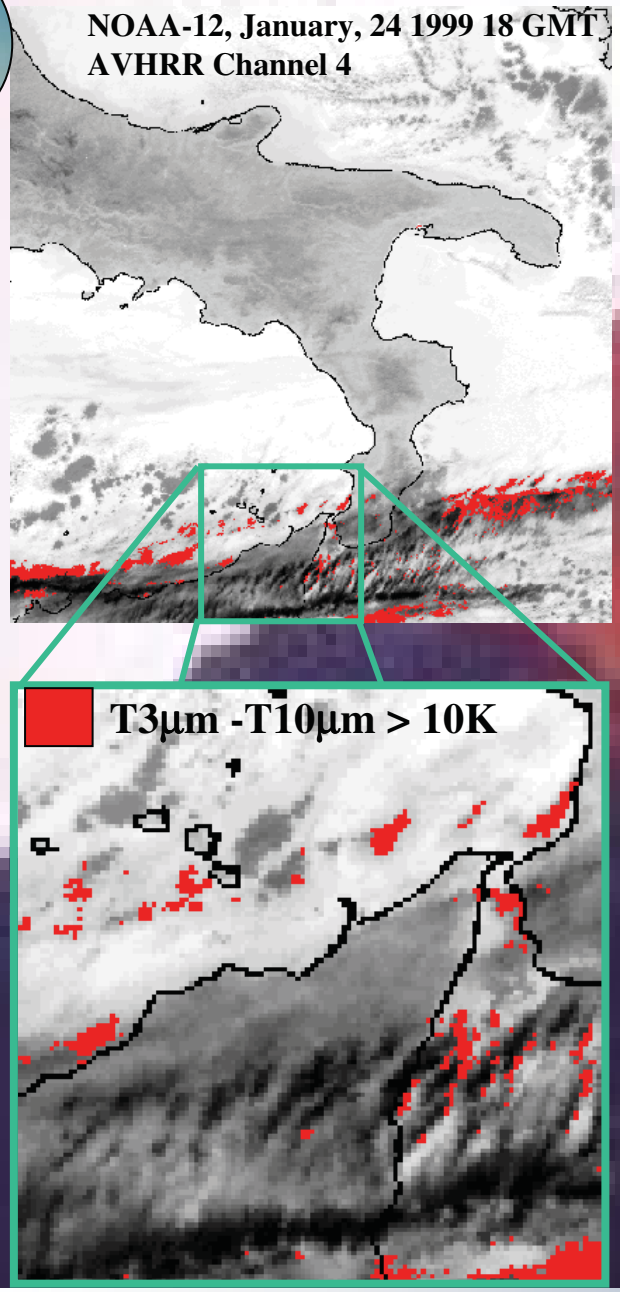



## Summer

A "clouds problem":
- High reflectivity of clouds in MIR band (during daytime)
- Low BTs values of clouds in the TIR (during both day and night)

FALSE DETECTIONS!!



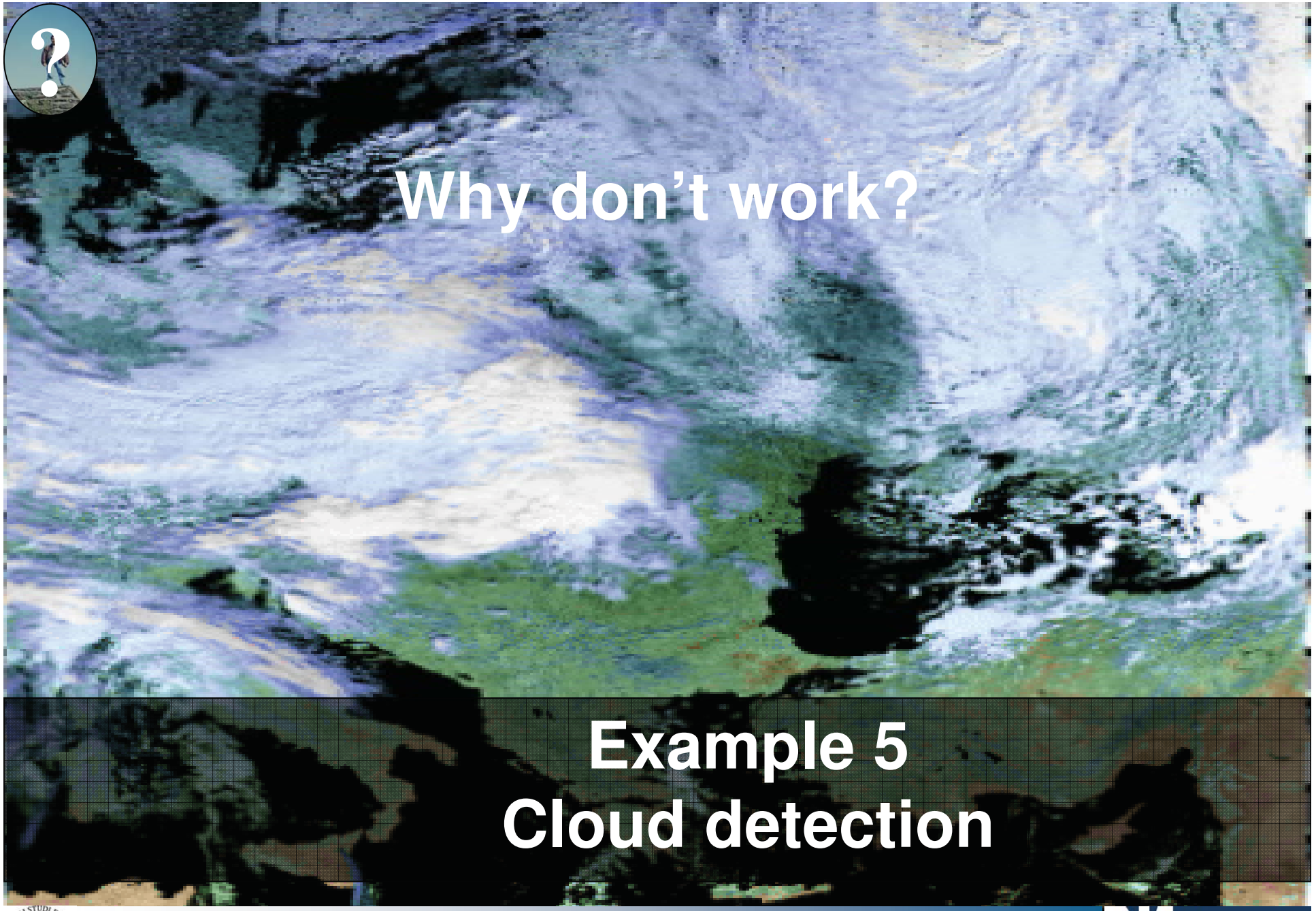



# Example 4:
# Volcanic Lava flow Detection
## (Single image – Fixed threshold )
## e.g. Harris et al. 1995

## Winter

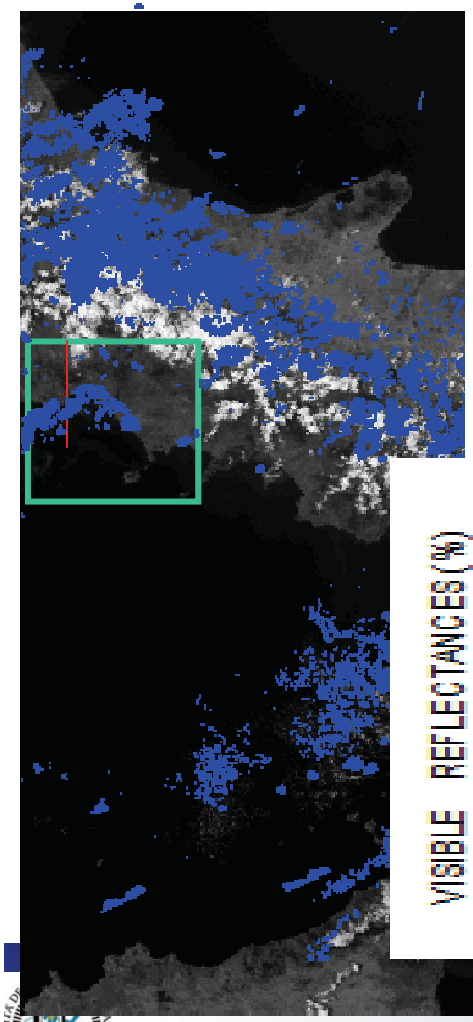
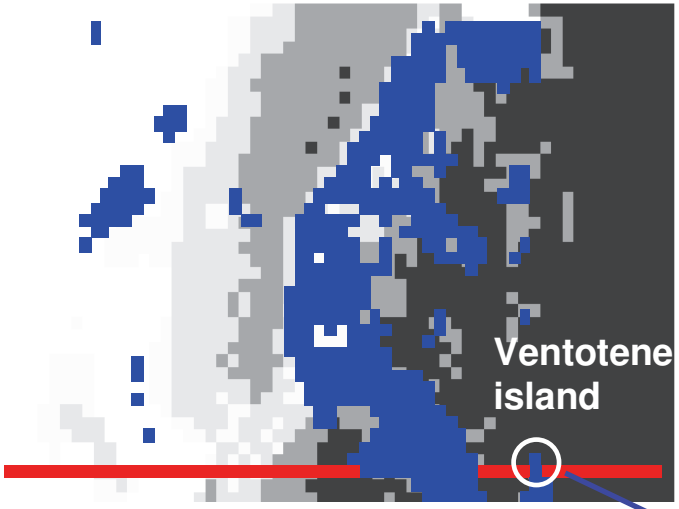
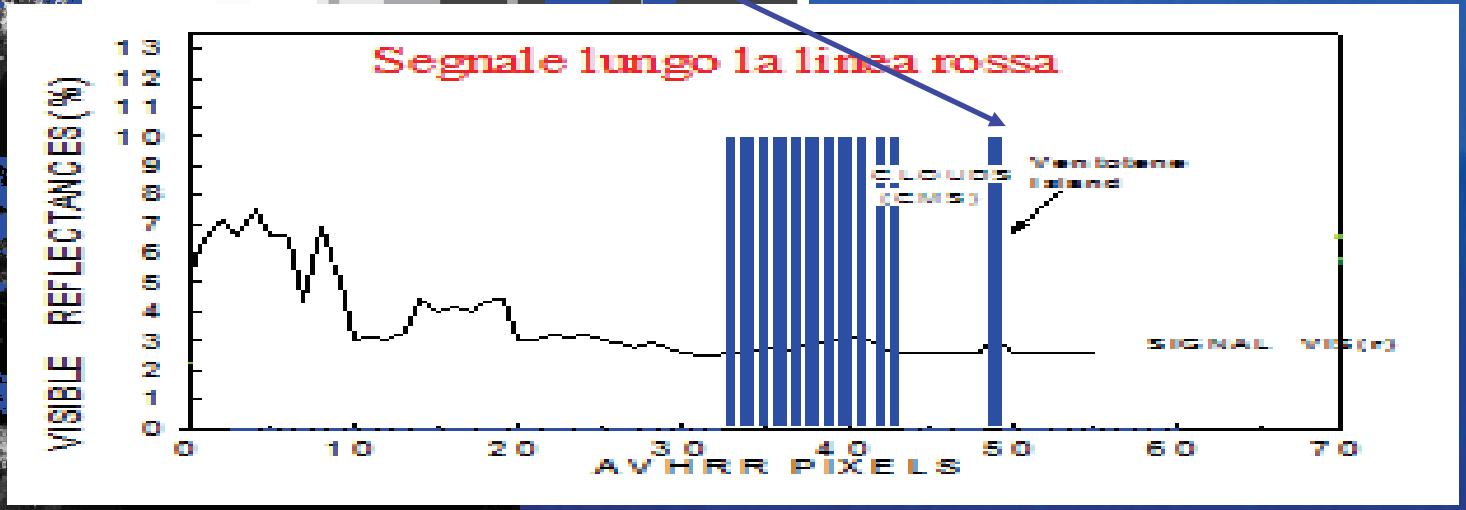
(…again a "clouds problem" )

FALSE DETECTIONS!!



# Why don't work?

# Example 5
# Cloud detection

# Example 5: Cloud Detection

# (Single image processing – Fixed threshold ) e.g. CMS-algorithm