THERMAL REMOTE SENSING
SOME FUNDAMENTALS

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Purpose of lecture

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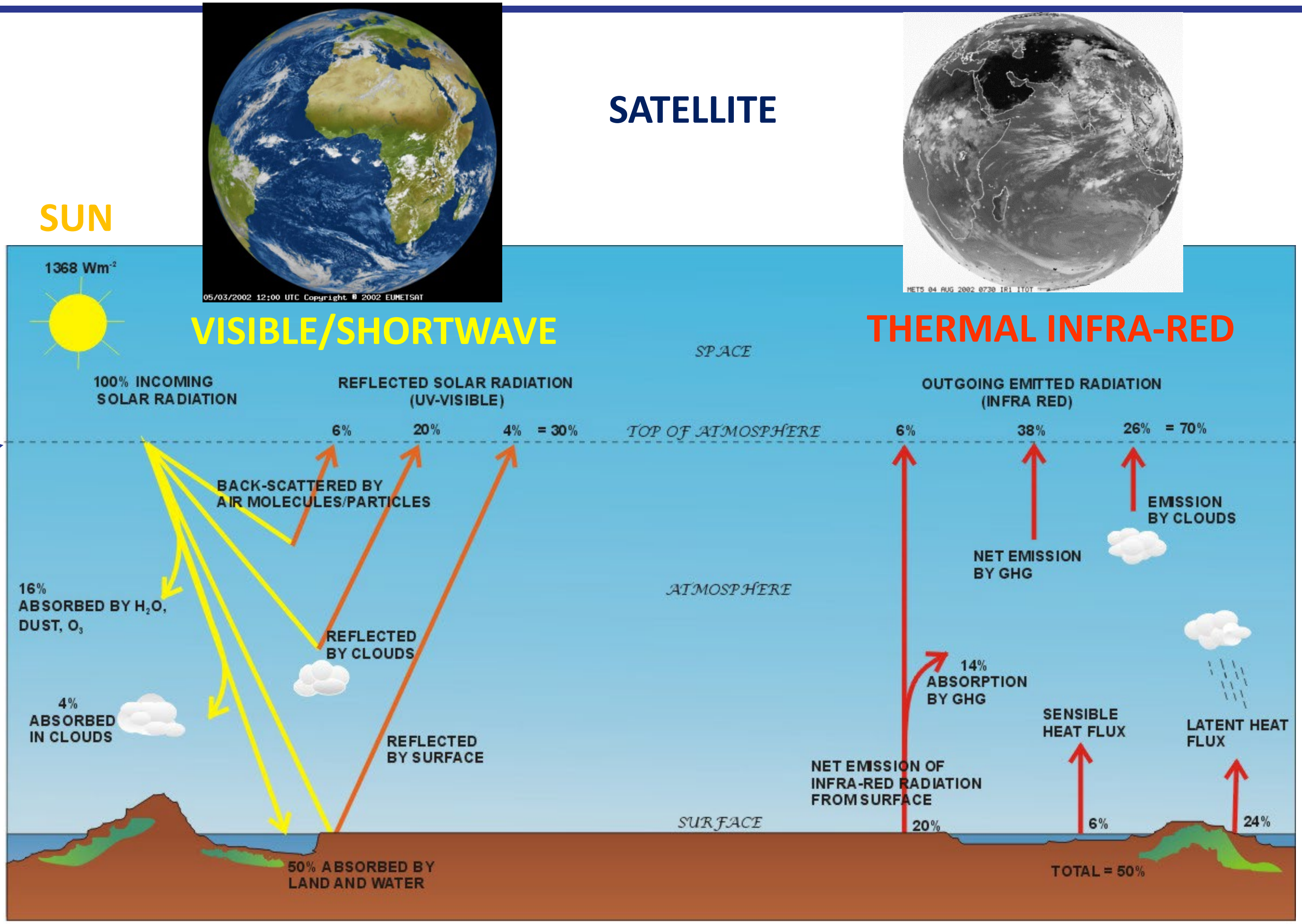
The objectives of this lecture are:

- To describe the basic principles of thermal remote sensing
- To give some insights into the physics of what is a familiar problem.
- To recall some of the key aspects that guide LST determination
- To consider the challenges for the next years

Radiation reaching space

TOA = TOP OF ATMOS PHERE



GHG - Greenhouse gases: CO_2, H_2O, CH_4, N_2O, O_3 and CFCs.

LATENT HEAT FLUX: Heat transfer mainly due to *evaporation* at the surface and later *condensation* in the atmosphere.
SENSIBLE HEAT FLUX: Heat transfer from the surface to the atmosphere through *condensation*, *convection* and *turbulent mixing*.

THE EARTH

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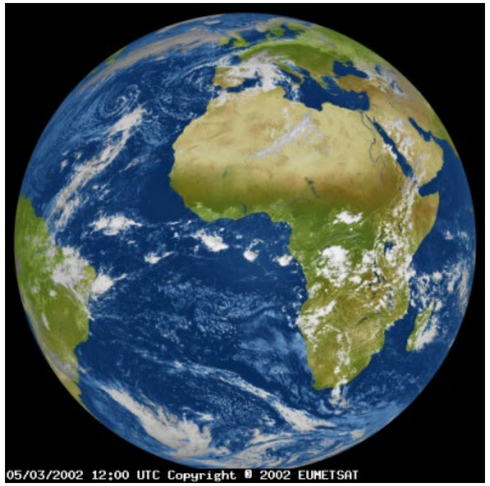
TOA radiance dependencies

The TOA signal (radiance) that we see depends on many factors

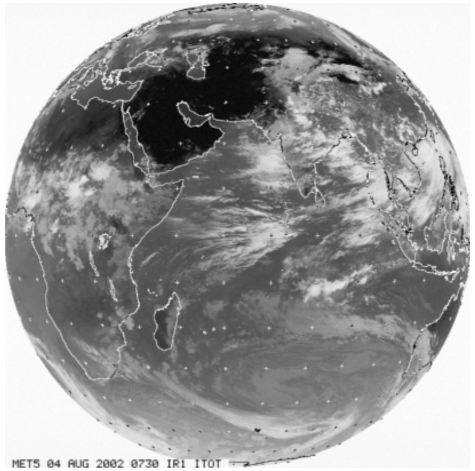
Visible/shortwave:

- Albedo (λ) of surface
- Aerosols
- Clouds
- Atmospheric gases



Infrared:

- Emissivity (λ) of surface
- Temperature of surface
- Atmosphere temperature and gases
- Clouds
- Aerosols



THE ATSR INSTRUMENTS

SOURCE = EARTH (I/R); SUN (VIS.)

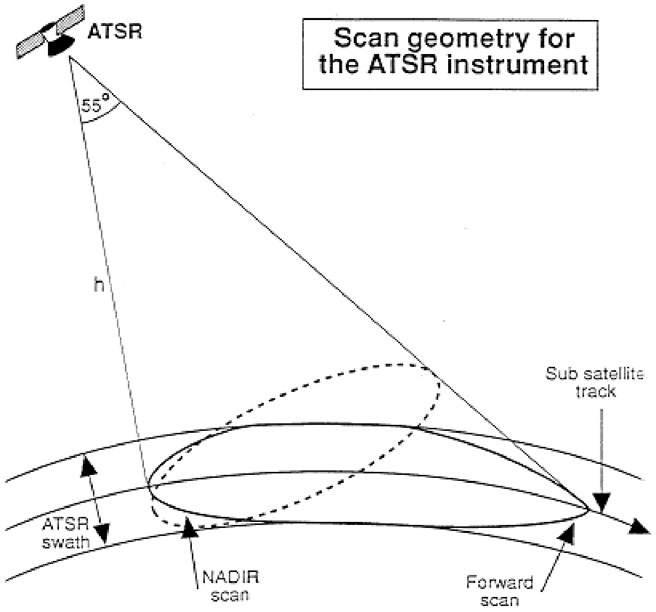
COLLECTOR = SCAN

DISCRIMINATION = SPECIFIC RADIOMETER CHANNELS

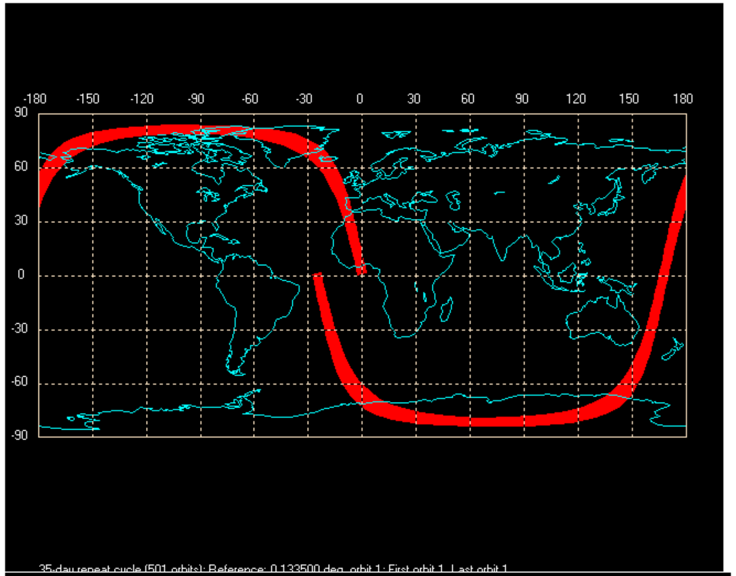
DETECTOR = COLD HgCdTe for MID-IR; Si for VIS

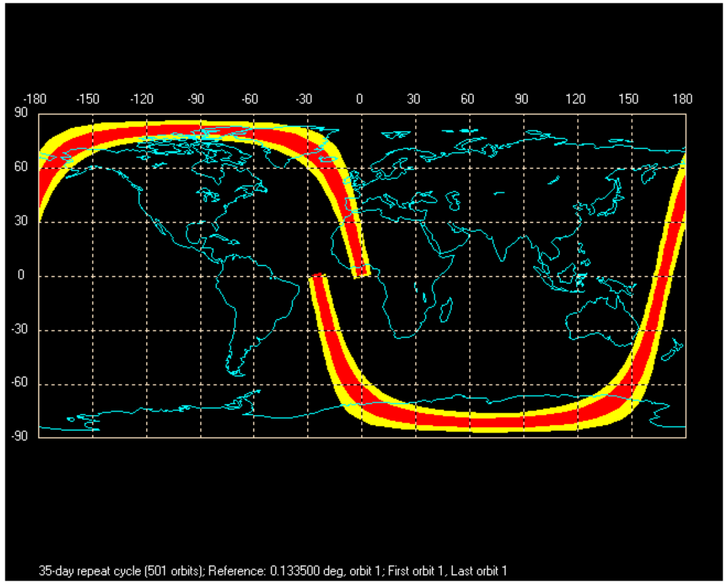
CAL=2 BLACKBODIES + VISCAL

THE ATSR INSTRUMENTS ARE DUAL VIEW RADIOMETERS



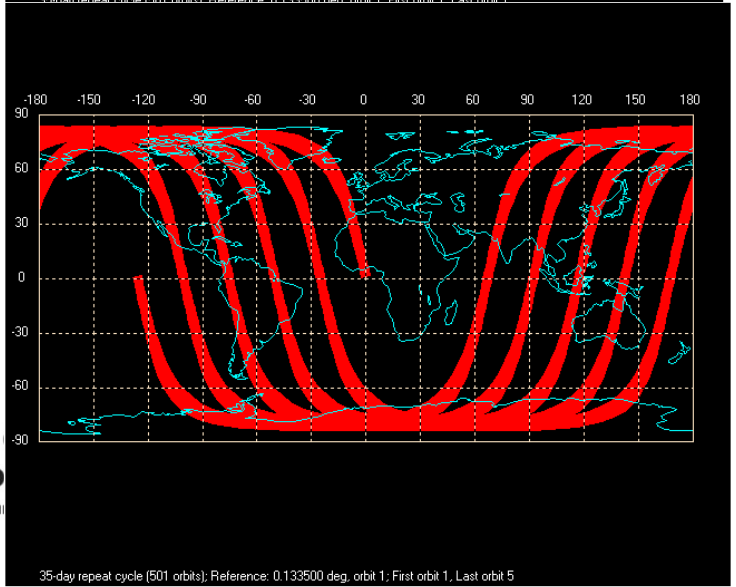
Envisat swath comparisons: AATSR vs MERIS

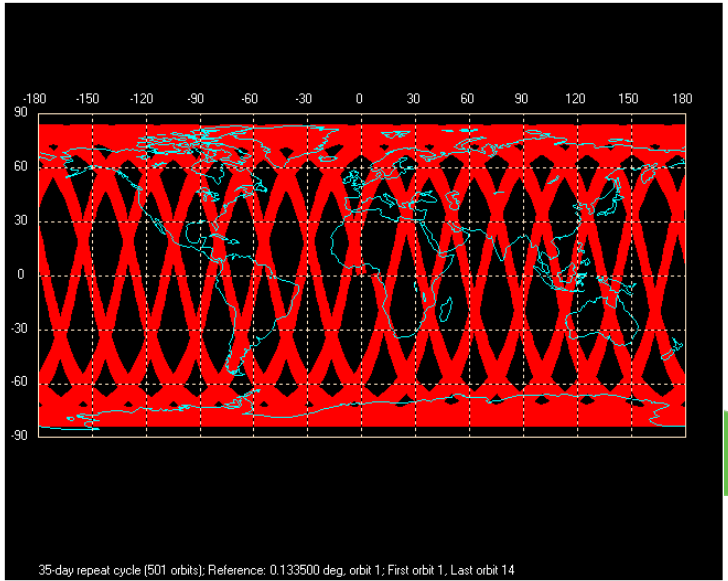




Single orbit for AATSR vs MERIS

SLSTR on Sentinel-3 much wider than AATSR





Five orbits for AATSR vs 14 orbits (1 day)

ATSR Infrared channel windows

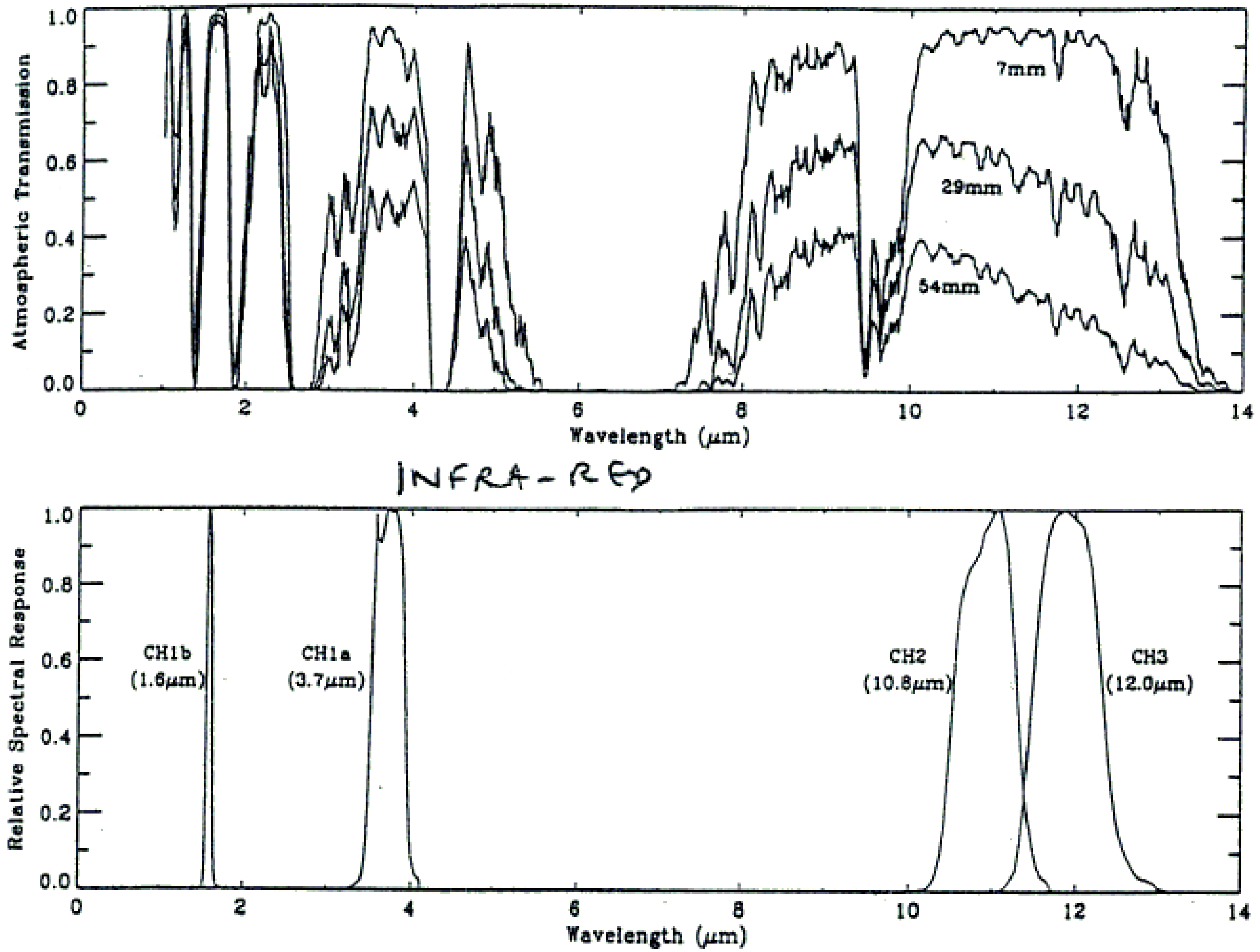


Figure 2.1: Atmospheric transmission for three different amounts of precipitable water (7mm — polar; 29mm — temperate; 54 mm — tropical), and the ATSR spectral channels matched to atmospheric 'window' regions.

Physics of passive thermal remote sensing

In clear-sky, we need to describe the:

- Source of radiation — Initial radiation
  - ➢ Wavelength
  - ➢ Temperature
  - ➢ Emissivity (and reflectivity of the surface)
- The attenuation of the atmosphere (chief gases, particularly water vapour):
  - Transmission (absorption) — Absorption removes radiation
  - Emission — Adds radiation (T body)
  - Scattering (not in clear sky) — Scattering removes/adds (direction)
  - [Atmospheric correction]

Black body and Planck fn.

The sources of signal in the thermal are the Earth (and the Sun)

Their emission is fundamentally determined by temperature T and essentially can be considered as blackbody radiation.

A black body is a body or gas volume that

- has constant temperature
- absorbs all incoming radiation completely
- has the maximum possible emission in all directions (isotropic) and at all wavelengths

Planck fn: Standard Wavelength (λ) form

$$B(\lambda,T) \quad d\lambda = \frac{2hc^2}{\lambda^5\{\exp(hc / k\lambda T) - 1\}} \quad d\lambda$$

Units of B are W m^{-2} sr^{-1} m^{-1}= W m^{-3} sr^{-1}

Planck fn and Stefan's Law

B(λ,T), is characterised by:

i. A unique dependence on wavelength, λ, for a given temperature T.

ii. A dependence on T only (at a given λ). For all wavelengths, B(λ,T) increases at all wavelengths with increasing T

iii. A well-defined maximum for a given T.

iv. The relationship λ_{max} T=constant (Wien's law)

Note:

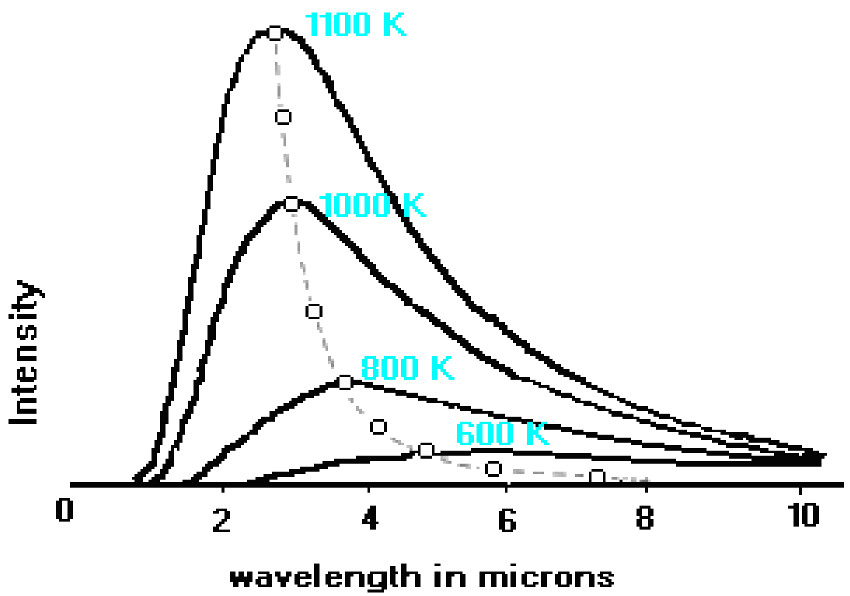
T(sun) ≈6000 K

(peaks at approx. 0.6 mm or 600 nm = visible)

T (Earth mean)≈ 255-245 K

(peaks at approx. 10 mm = infra-red)

[T(Earth surface mean) ≈288 K]



Adapted from Adkins "Thermal Physics" Dotted line shows Wien's Law i.e. the line joining the points of maximum emitted intensity.

Stefan's Law (integration of Planck's Law in absence of spectral absorption/scattering)

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

ε is the emissivity of a real body (i.e. a gray body). 0 < ε < 1 for a gray body

σ (Stefan's Constant) = 5.67 X 10^{-8} *W* m^{-2} *K* $^{-4}$

How we describe LST signals at satellite

Mean radiative temperature over pixel area

- L^{sat} is the radiance measured by the satellite sensor
- L^{ground} is the upwelling radiance emitted by the ground toward satellite and absorbed by the atmosphere in-between.
- L^{atm} is the upwelling radiance emitted by the atmosphere towards the satellite
- $L^{atm\_reflected}$ is the down-welling radiance emitted by the atmosphere and reflected by the ground

$$L^{sat} = L^{ground} + L^{atm} + L^{atm\_reflected}$$

For each channel (i):

$$L_{\lambda}{}^{\mathrm{TOA}}(i) = \tau_{a\lambda}\varepsilon_{s\lambda}B_{\lambda}(T_s) + L_{\lambda}{}^{atm} + \tau_{a\lambda}(1-\varepsilon_{s\lambda})L^{\ \ sky}$$

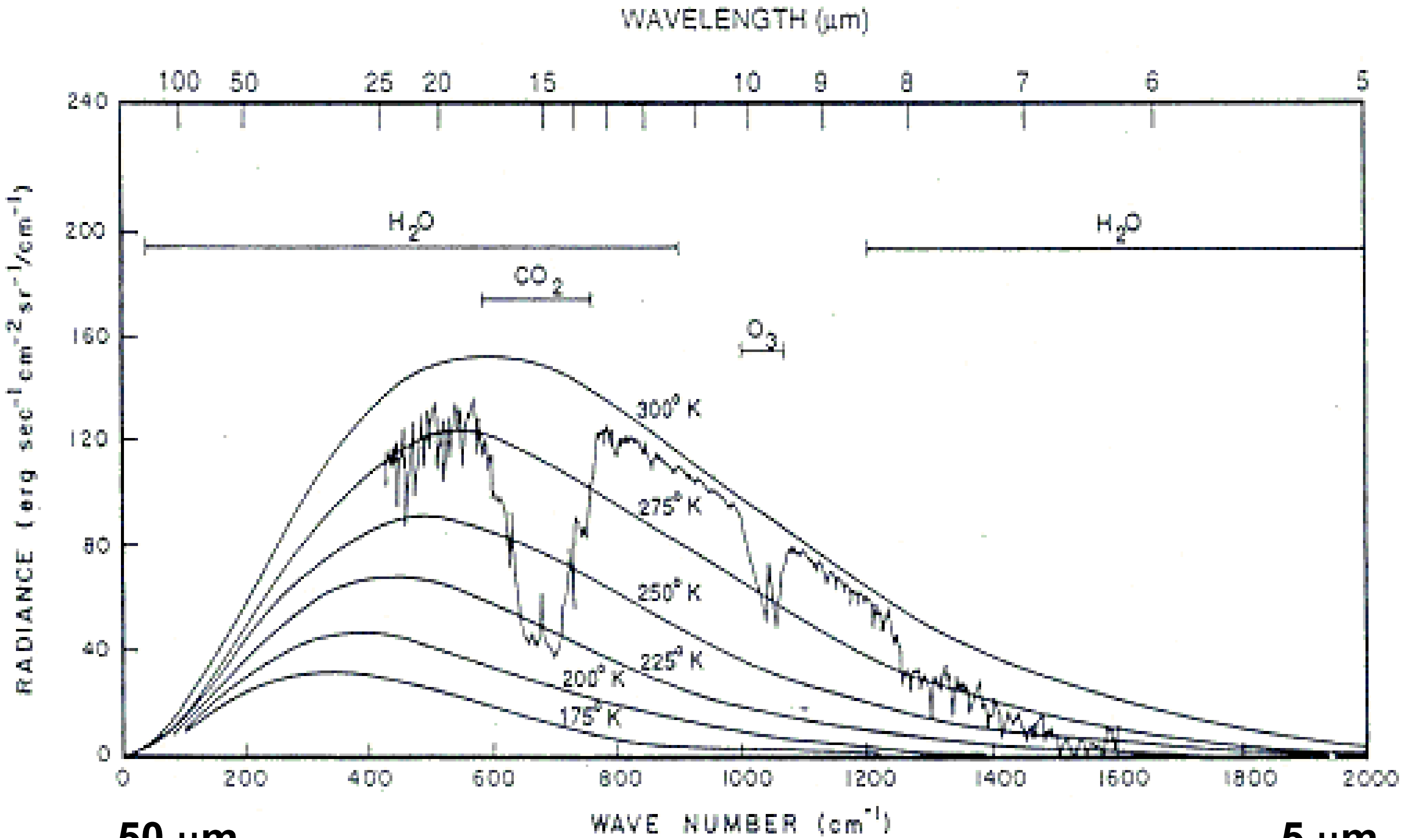
- Note $\varepsilon_{s\lambda}$ = $(1\text{-}R_{s\lambda})$
- Note $\varepsilon_{a\lambda}$ = absorption due to gas = $(1\text{-}\tau_{a\lambda})$

The thermal infra-red

- The thermal infra-red is also complicated.
- Clouds obscure the scene
- Some aerosols affect the signal but not in such a ubiquitous fashion.
- The real complication for clear sky signals is:
  - Emission from the surface (emissivity varies with wavelength)
  - The absorption from atmospheric gases
  - The re-emission of this signal according to the transmission of the gas and atmospheric temperature.
- So need to choose a spectral window (channel) avoiding the gas parts of the spectrum, remove clouds, and correct for gases (again water vapour).

ATMOSPHERIC GASES AND THE INFRA-RED SPECTRUM

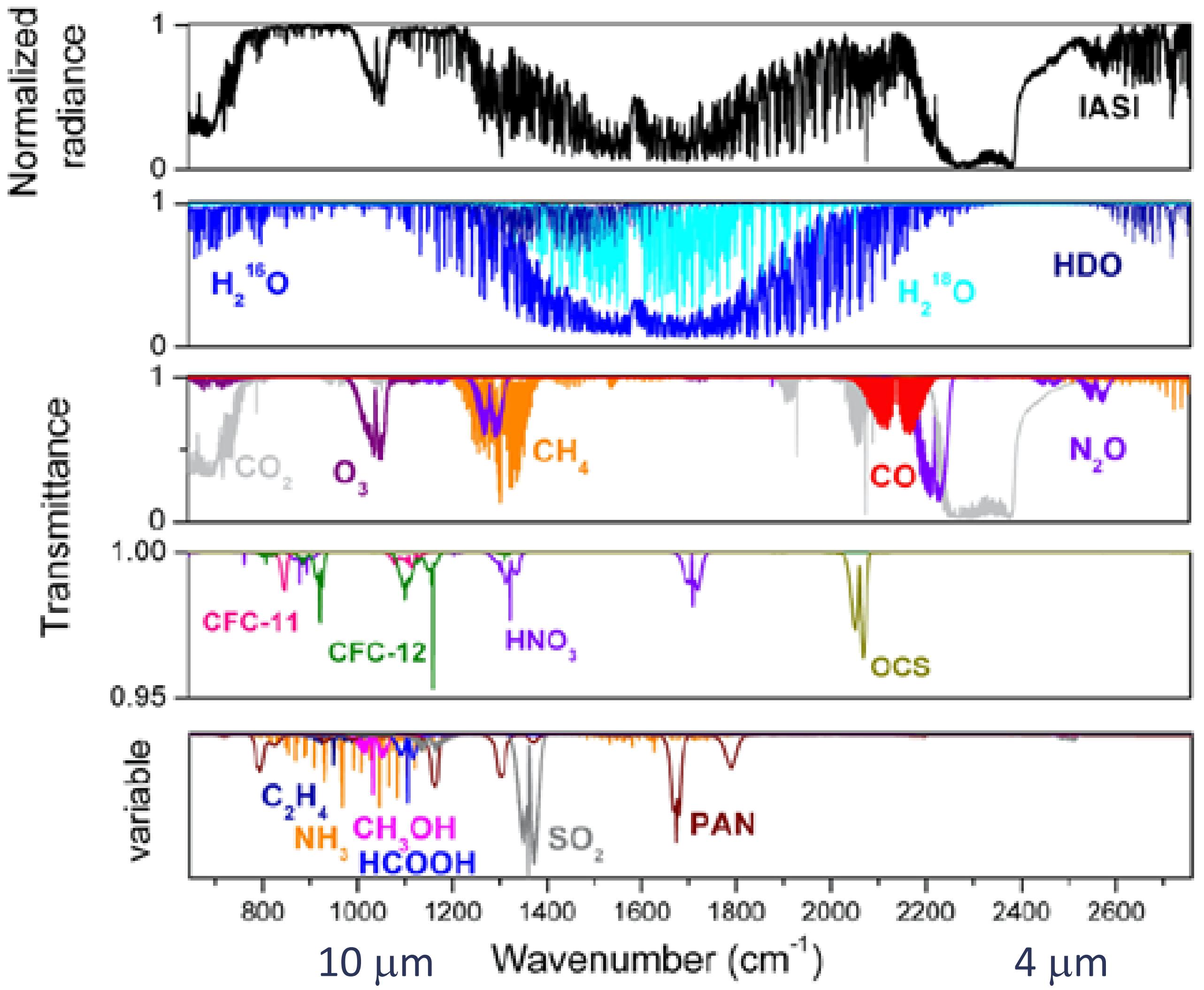
Main gases: CO_2, H_2O, O_3, [CH_4, N_2O, CFCs,…]



50 μm **5 μm**

Figure 8.5 Spectrum of outgoing LW radiation over (215° W, 15° N) observed by Nimbus-4 IRIS, as a function of wavenumber λ^{-1}. Blackbody spectra for different temperatures and individual absorbing species indicated. Adapted from Liou (1980).

Close up of thermal infra-red spectrum



Atmospheric transmission and absorption

- The atmosphere components are in general:

$$L^{atm} = \int B(\lambda,Tz)\ (d\tau(\lambda,\rho,Tz)\ /\ dz)\ dz$$

$$L^{atm\_reflected} = R_S(\lambda) I_{Down}(atm) \tau(\lambda,\infty)$$

- However, in practice the reflected term is small so we need to account for it in real calculations but not to detail it here.
- Much can be understood by considering the atmosphere as a single layer with transmission:

$$\tau(\lambda) = \exp\ [-\ k(\nu)\ u\ l\ ]$$

  - ➢ Spectroscopy: $k(\lambda)$
  - ➢ atmospheric composition/cross-sectional density: $u = \rho$ per unit length
  - ➢ photon (observation) pathlength: geometrical l

Single layer gas model

Single gas layer is conceptually **appropriate for sensing of the surface in window regions** where the atmosphere influence is small.

$\mathbf{L^{TOA}(\lambda) \approx \tau(\lambda)\, L_o(\lambda) + (1 - \tau(\lambda)) \times B(\lambda, Ta)}$, neglecting reflected atmosphere component. When the layer is transparent, the second term vanishes. When the layer is opaque, the first term vanishes.

$L_o(\lambda)\tau_a(\lambda)$

$\varepsilon_a(\lambda)\, B(\lambda, T_a) = (1-\tau_a(\lambda)) \times B(\lambda, T_a)$

GAS $\tau_a(\lambda)$, T_a

If $\tau(\lambda) = 0$ and $Ta > Ts$, then we have more signal than we started with!

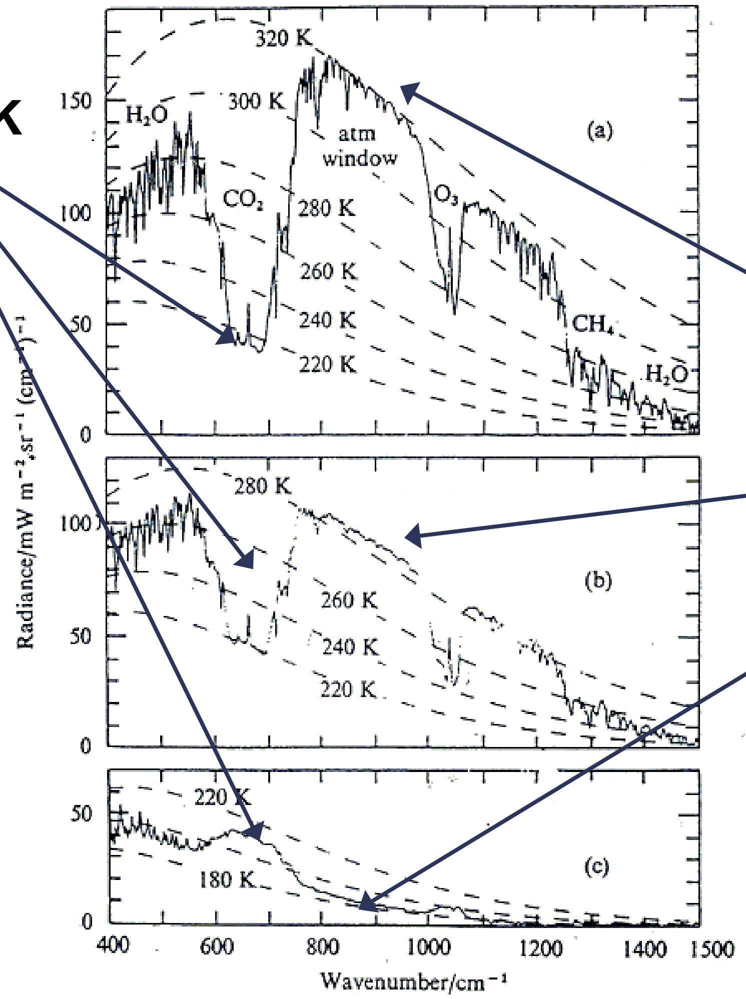
$L_o(\lambda) = \varepsilon_s(\lambda) B(\lambda, T_s)$

Interpreting observed I/R EMISSION SPECTRA

Fig. 12.6. Thermal emission from the earth plus atmosphere emitted vertically upwards and measured by the infrared interferometer spectrometer on Nimbus 4, (a) over Sahara, (b) over Mediterranean, (c) over Antarctica. The radiances of black bodies at various temperatures are superimposed. (From Hanel *et al.*, 1971)

Top of CO_2 layer: $\tau_g(\nu)$ ~0

Tatm(CO_2) ~ 220 K



Window: $\tau_g(\nu)$ ~1

a) Ts ~ 320 K

b) Ts ~ 285 K

c) Ts ~ 180 K

Top of O_3 layer: $\tau_g(\nu)$ ~0

Tatm(O_3) ~ 280-200 K

from (a) Sahara to (c) Antarctica

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Surface Emissivity

- Emissivity is the relative ability of the surface to emit radiation
- It is quantified as the ratio of energy radiated by the surface with respect to the energy radiated by a black body ($\varepsilon = 1$) at the same temperature
- Surface emissivities can be highly variable owing to the heterogeneity of the land. Factors influencing emissivity include:
  - Surface type
  - Fractional vegetation cover
  - Soil moisture
- Can range from less than 0.94 for some sandy soils to over 0.99 for some regions of inland water or snow and ice
- Variability of surface emissivities is amplified in regions of high topographic variance and for larger viewing angles.
- Need to accurately deal with uncertainties otherwise biases can occur in LST retrieval of several degrees (Schaadlich *et al., RSE, 2001).*

Surface emissivity in a GEO view

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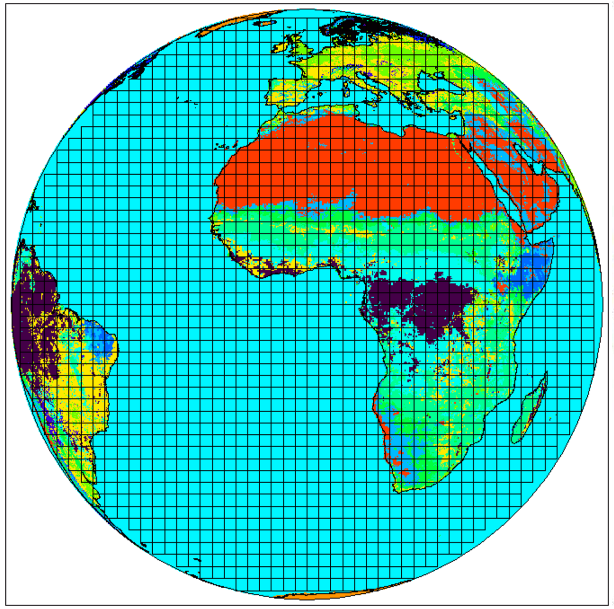
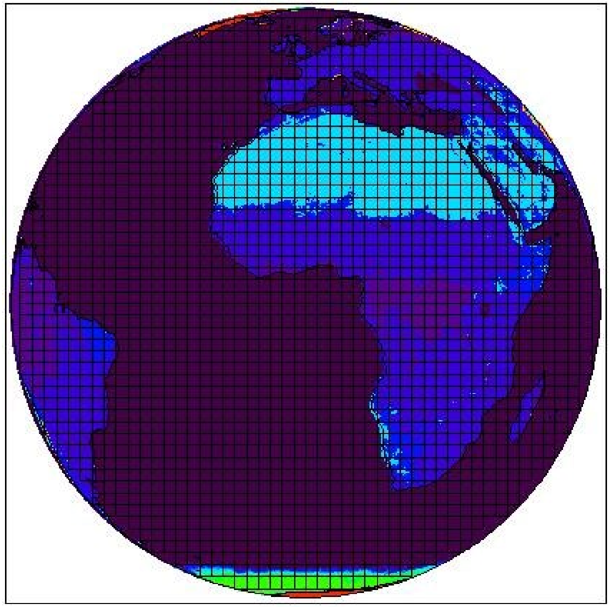
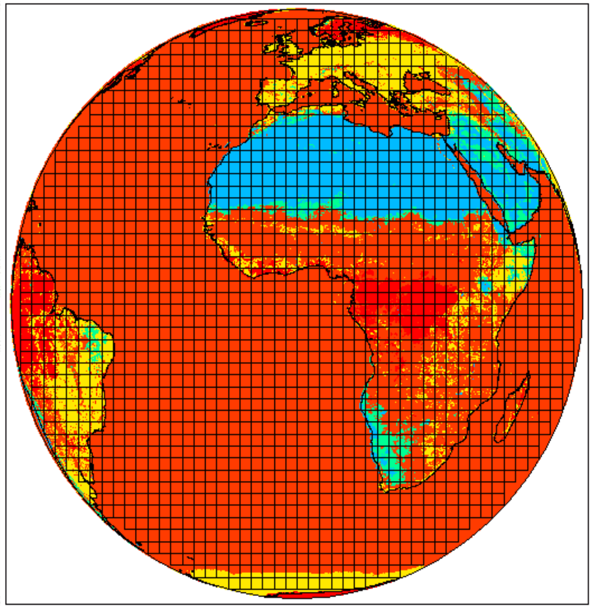
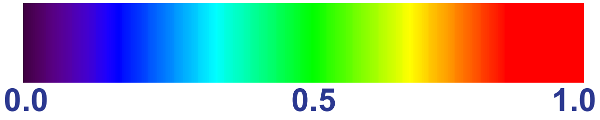
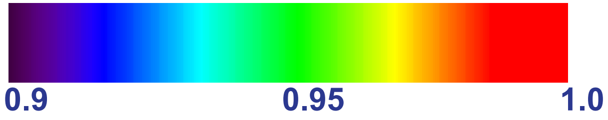
Surface types	Surface albedo	Surface emissivity
		

1. Evergreen n forest	7. Open scrubland	13. Urban
2. Evergreen b forest	8. Woody savannas	14. Cropland mosaic
3. Deciduous n forest	9. Savannas	15. Snow/Ice
4. Deciduous b forest	10.Grassland	16. Desert
5. Mixed forest	11.Permanent wetlands	17. Water
6. Closed scrublands	12. Croplands	





VISIBLE **INFRA-RED**

Surface albedo varies strongly between 0 and 1; does not include atmosphere

Surface emissivity varies between 0.9 and 1 (most averages).

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Surface emissivity of grass

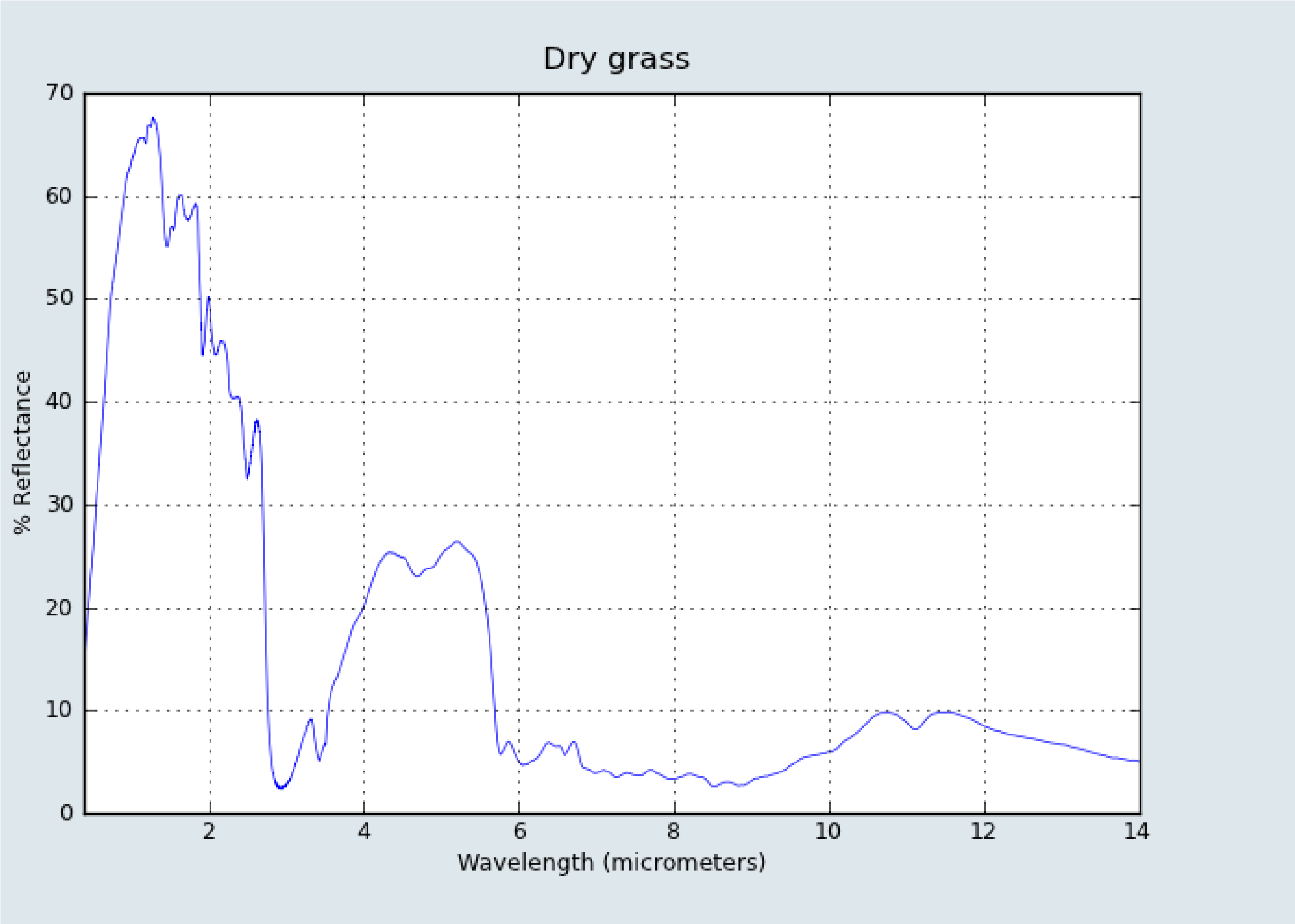
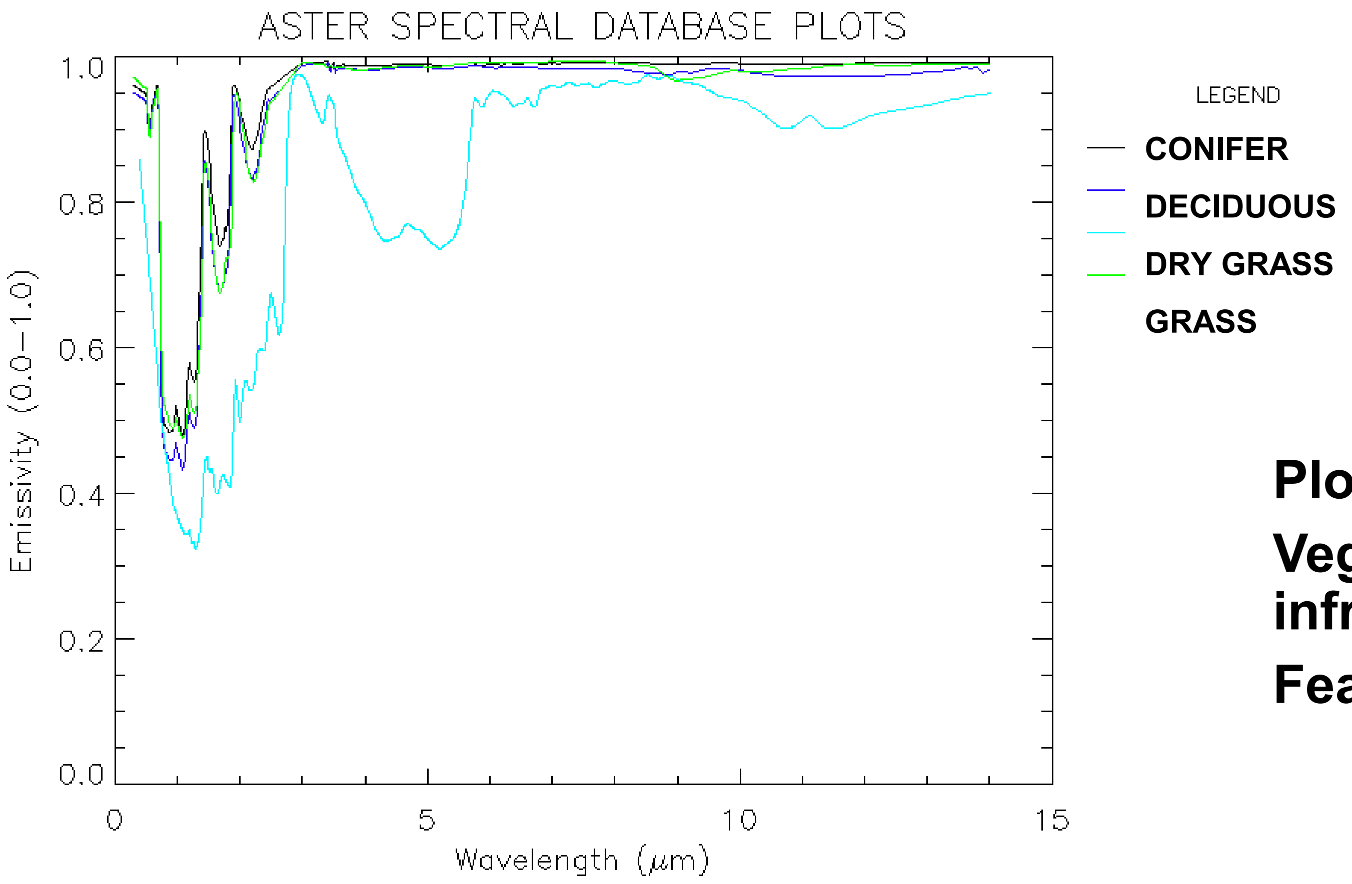


Image from ASTER spectral library V2

Surface emissivity of vegetation

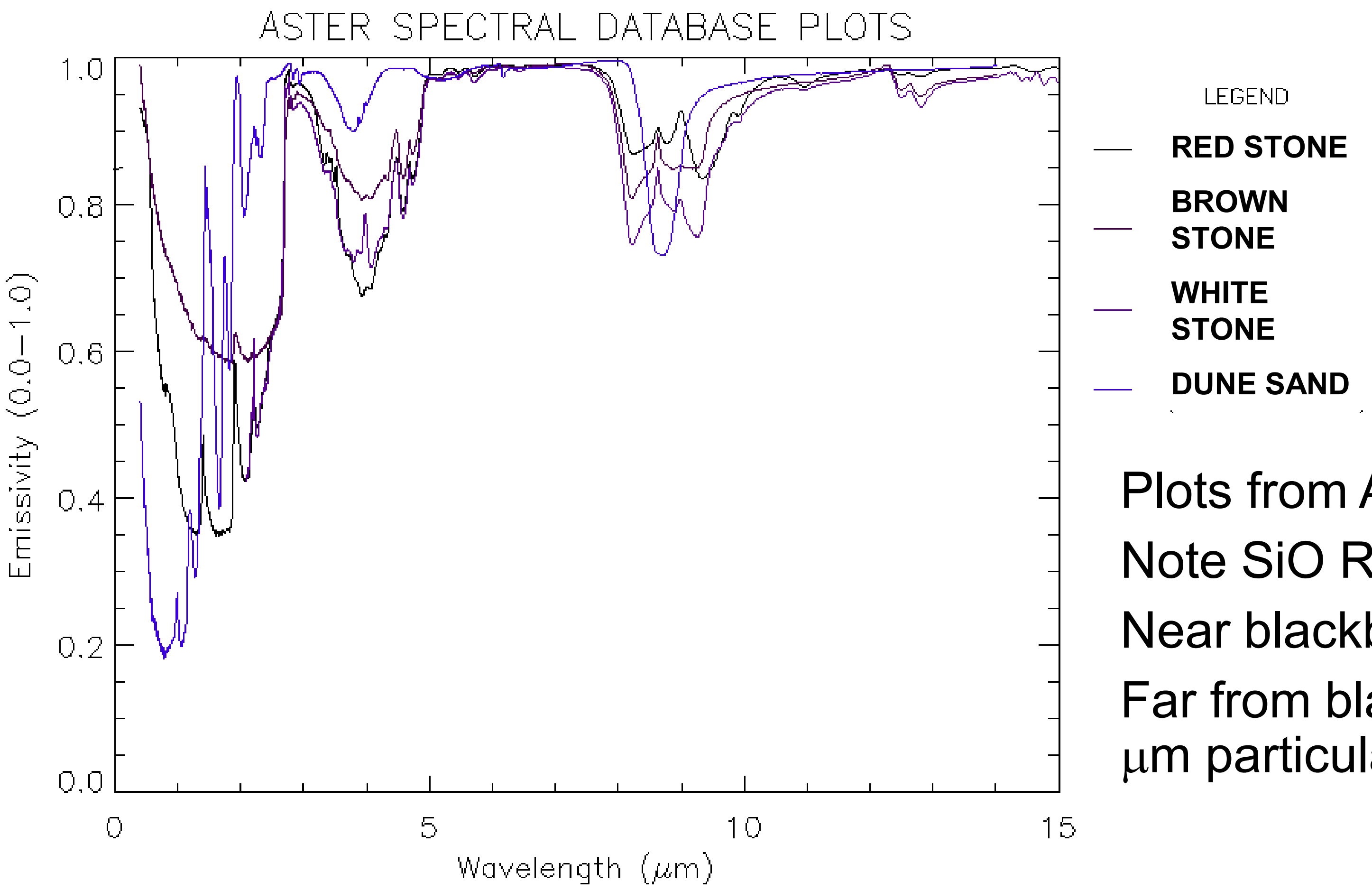


Plots from ASTER Spectral Database

Vegetation close to blackbody throughout infra-red.

Feature at 5 μm and in the near infra-red

Surface emissivity of stones/soils



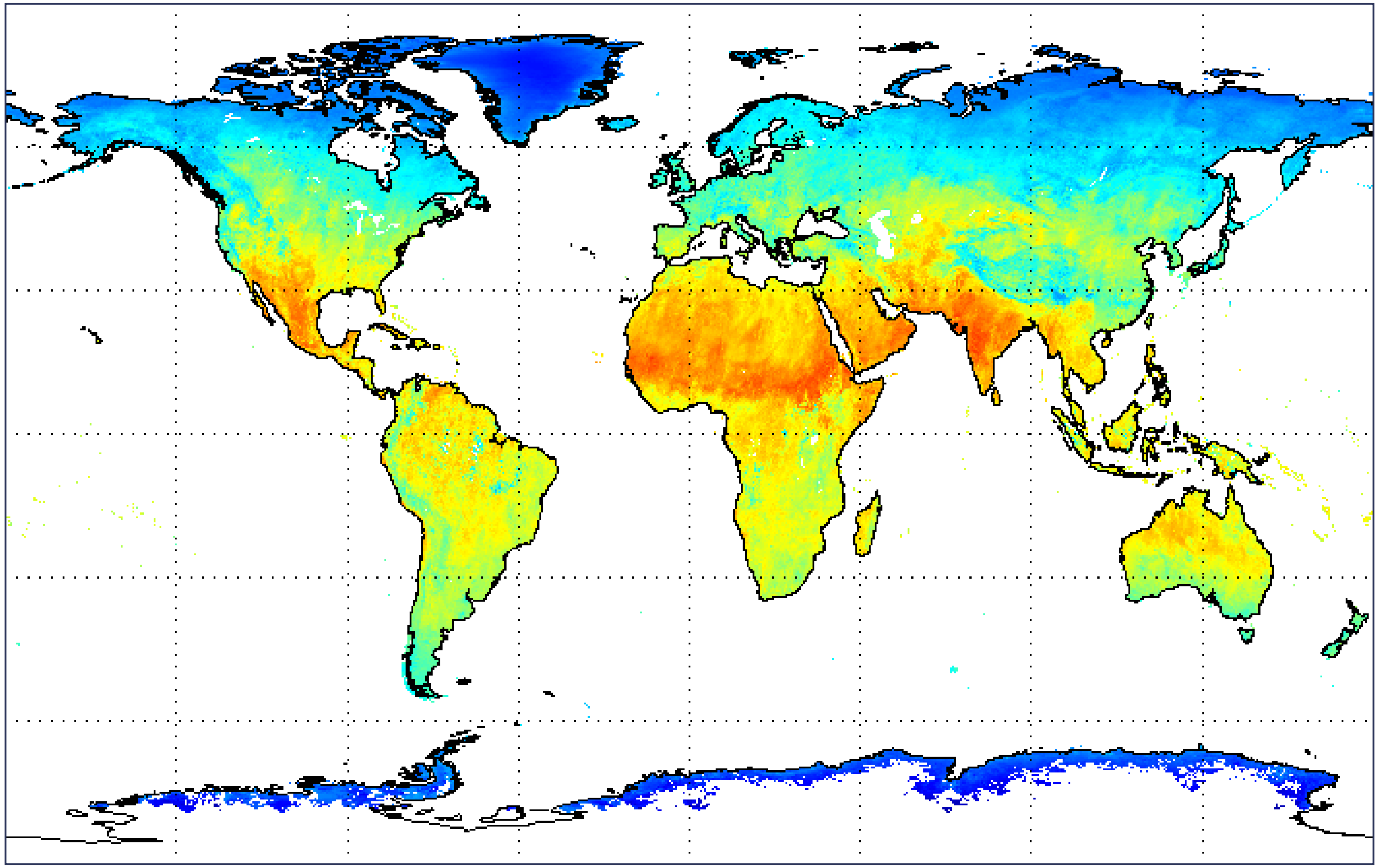
Plots from ASTER Spectral Database

Note SiO Restrauhlen bands near 8 to 9.5 μm

Near blackbody elsewhere in the i/r.

Far from black-body in the near infra-red (1 to 3 μm particularly).

Global LST: ATSRs



ASTER - Phoenix

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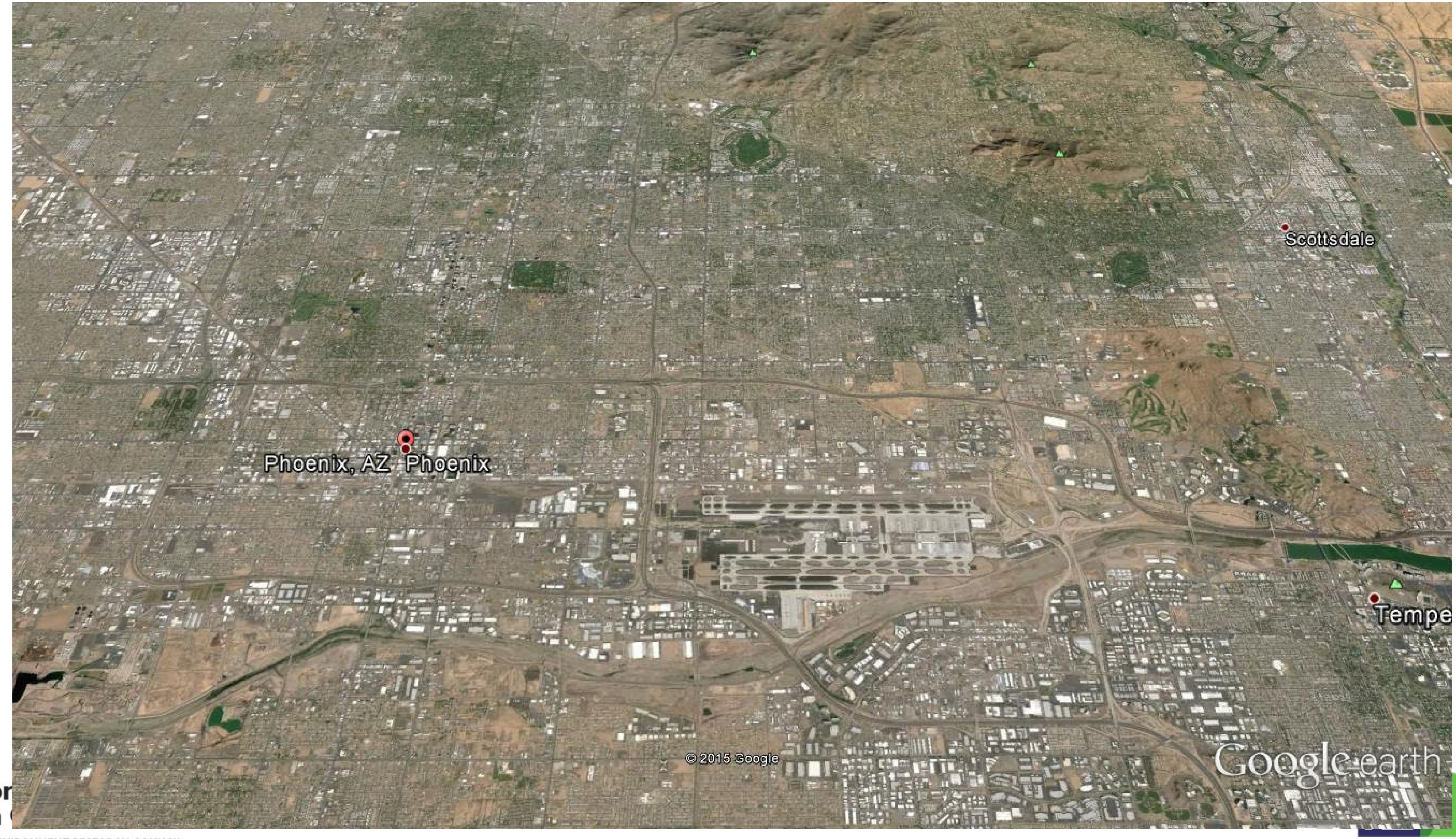
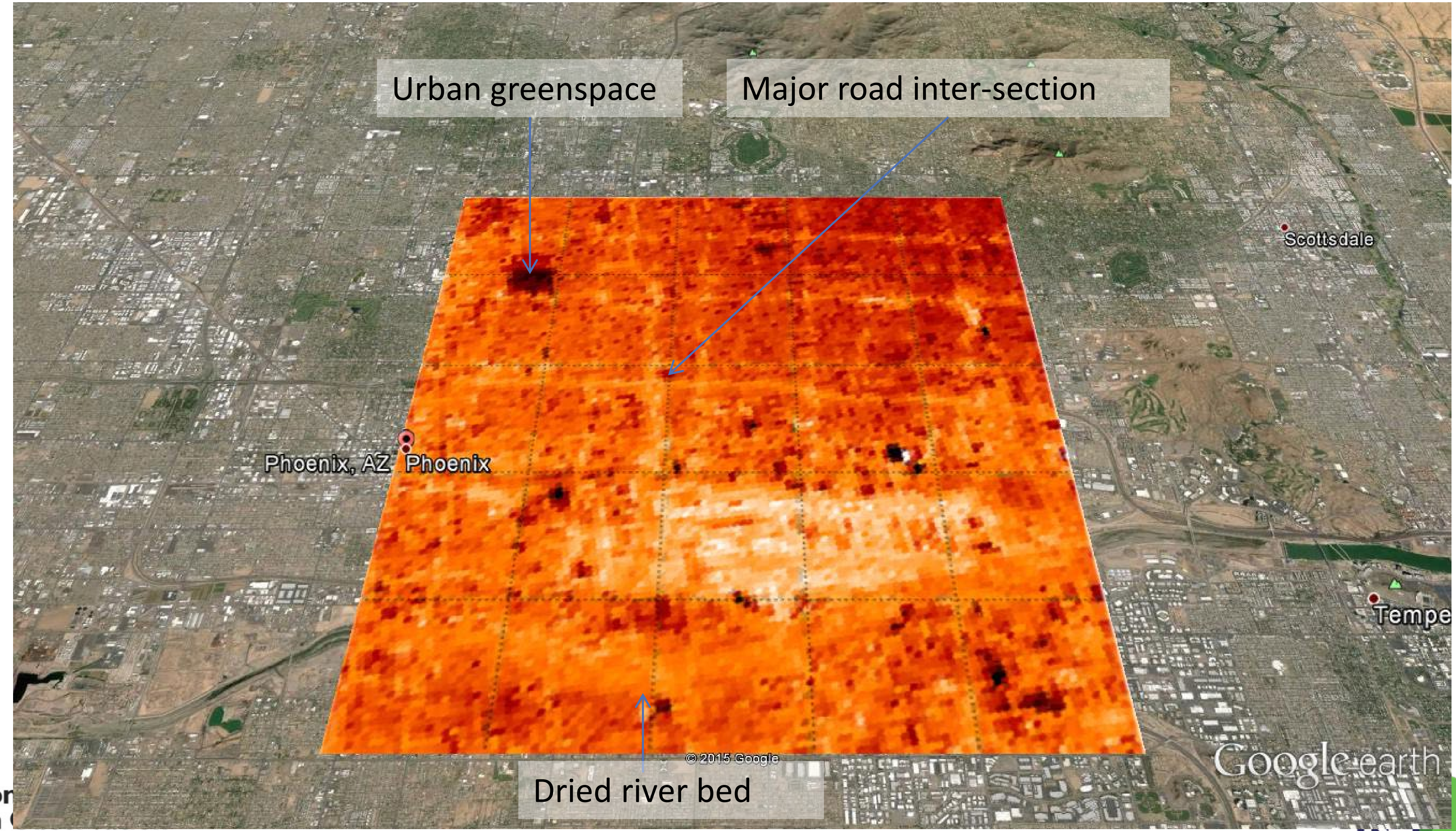
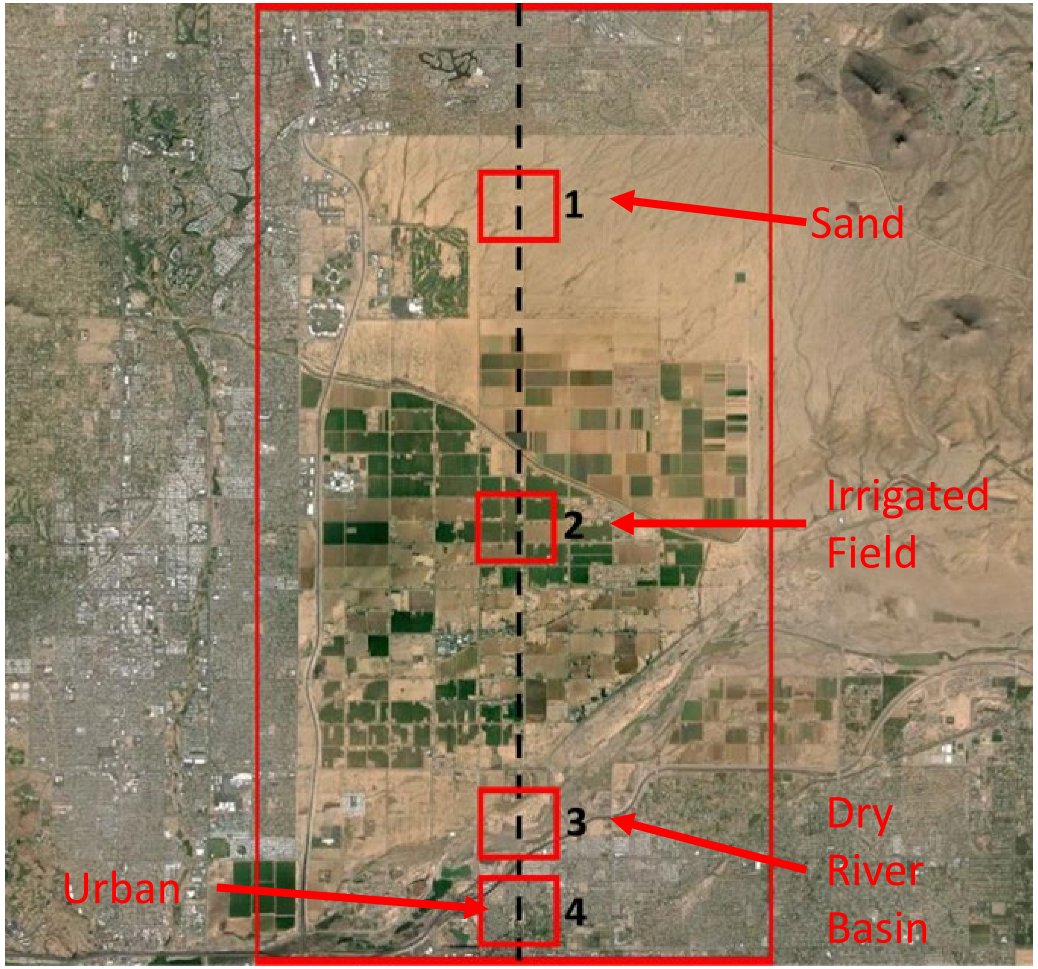


ASTER LST - Phoenix

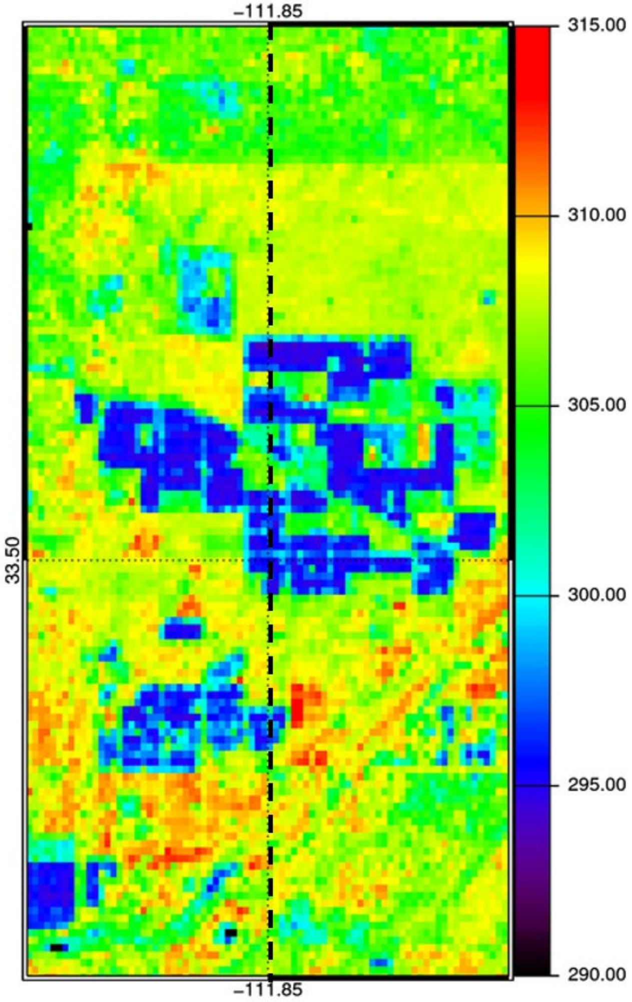


IRRIGATION: PHOENIX
LST and EMISSIVITY FROM ASTER

Visible Imagery (Landsat)



LST



Emissivity angular variations

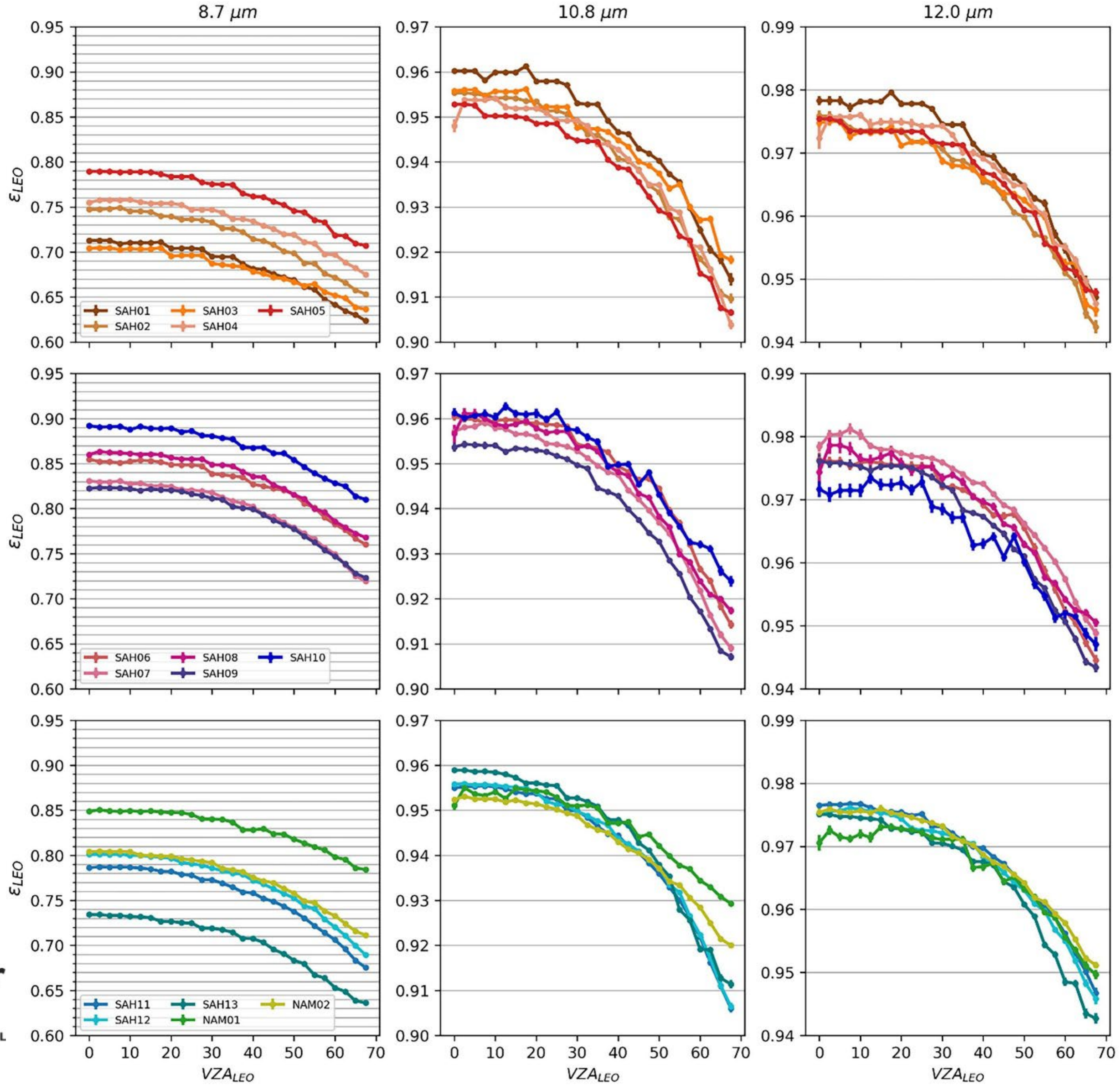


Fig. 4. Multi-sensor retrievals of angular dependence of LEO emissivity (εLEO) as function of LEO VZA (degrees) at the selected sites (represented by the colors). From left to right: emissivities for channels centered at 8.7 μm, 10.8 μm and 12.0 μm, respectively. The error bars indicate the 95% confidence intervals of the regressions. The y-axes have different ranges, but the grid lines correspond to the same intervals in all plots.

Ermida, et al.
Remote Sensing of Environment, 2024,
https://doi.org/10.1016/j.rse.2024.114280
.

There is also an anisotropy of LST itself particularly in the daytime

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Infrared and microwave skin depths (ocean)

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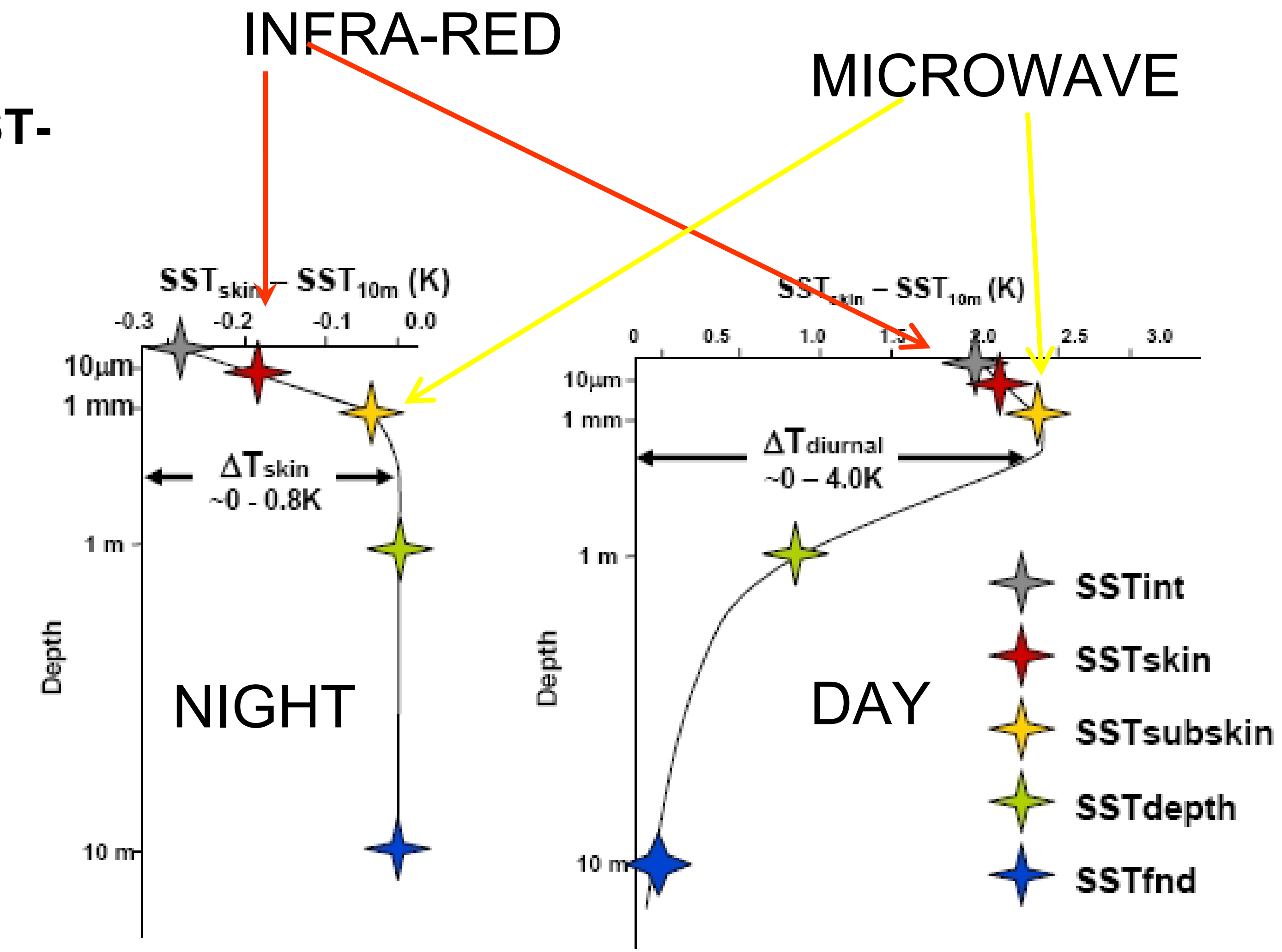
http://www.ghrsst.org/SST-Definitions.html



(a) Night time situation, light wind

(b) Day time situation, strong solar radiation and light winds

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Infrared vs microwave instruments

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ADVANTAGES OF INFRA-RED INSTRUMENTS:

- **Measure near the peak of the Planck fn. (≈ 10μm) so much greater T sensitivity!**
- **Larger, more uniform emissivity of sea water (but see below).**
- **Very small field-of-view (FOV) of instrument (typically 1 km diameter pixel for SST measurements).**
- **Microwave instruments: FOV ≈ 10 – 100 km "pixel" diameter, also side-lobes introduce far-away signals.**
- **Better end-to-end calibration of instrument.**

ADVANTAGES OF MICROWAVE INSTRUMENTS

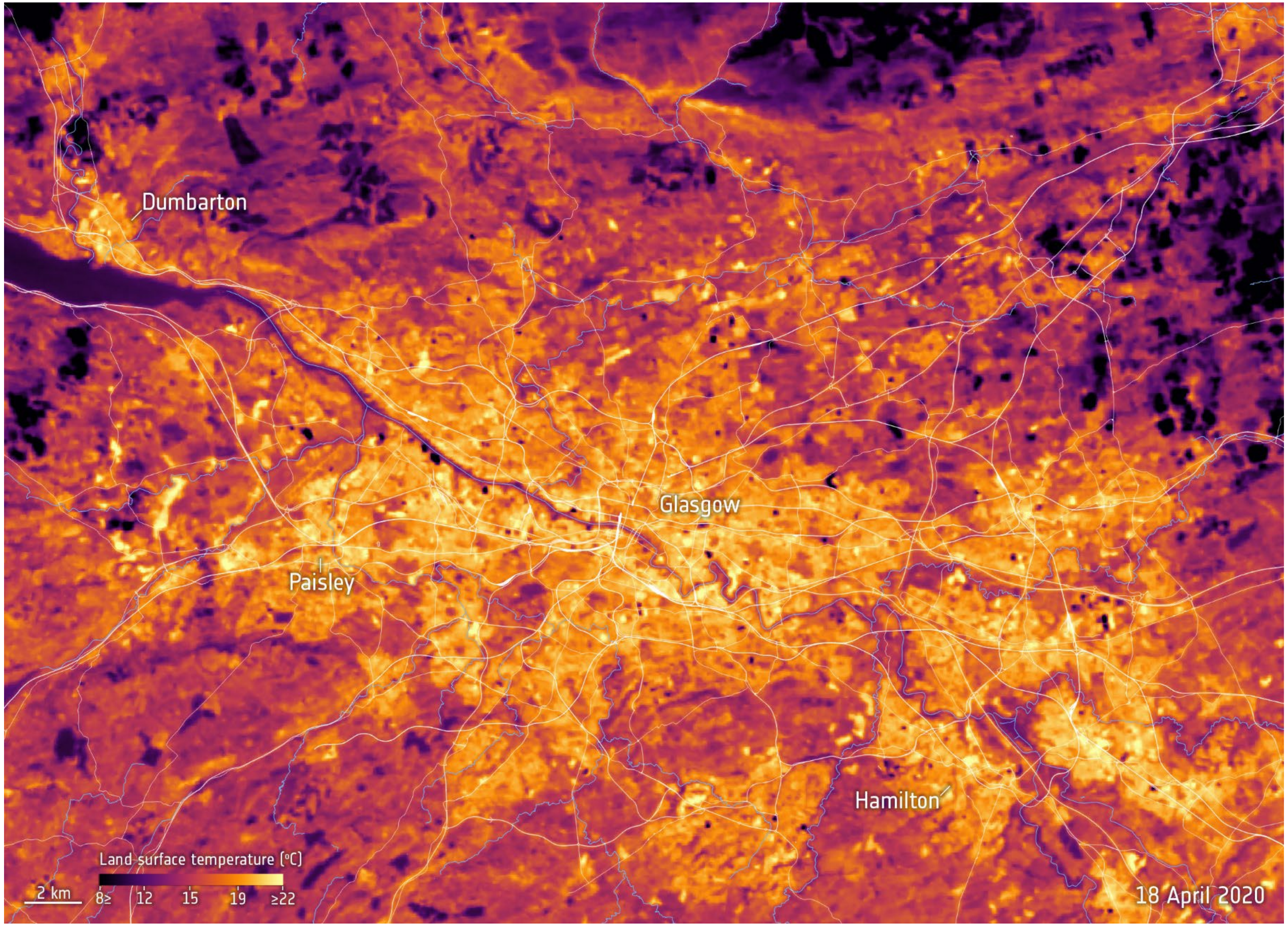
Very low noise instruments

Can see through many clouds unlike the infra-red.

Simpler atmospheric correction problem.

The infra-red measurements in atmospheric windows give the best sensitivity to Surface T

Urban imaging at high spatial resolution



- Leicester providing some newly improved data on urban temperatures.
- Data on cities being tested with government and industry users via an Ordnance Survey platform offering

Closing points

- Determination of LST has advanced considerably in recent decades
- In the thermal, the higher resolution instruments are channel-based, typically up to 5 bands.
- Emissivity remains a challenge to overcome for the highest accuracies and for inter-operability of data sets.
- Nonetheless, careful consideration of LST algorithms at least allows uncertainties to be calculated and "climate-quality" to be achieved.
- Anisotropy of LST itself, particularly in the daytime, also presents caveats
- There are very good prospects for improved data in urban and agricultural environments.
- International co-operation has proved very important in advancing the field
- With advent of multiple high spatial resolution sensors and high accuracy GEO thermal imagers, the prospects and demands for LST-related sensors are high.