Thermal remote sensing of active volcanoes

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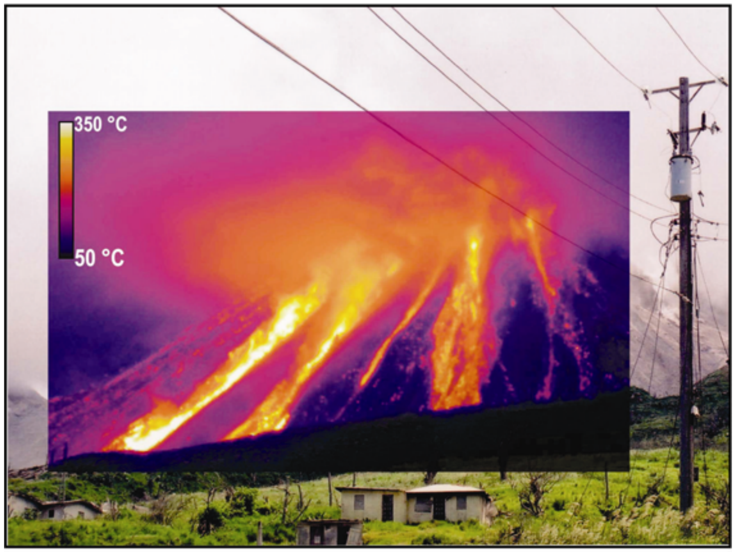
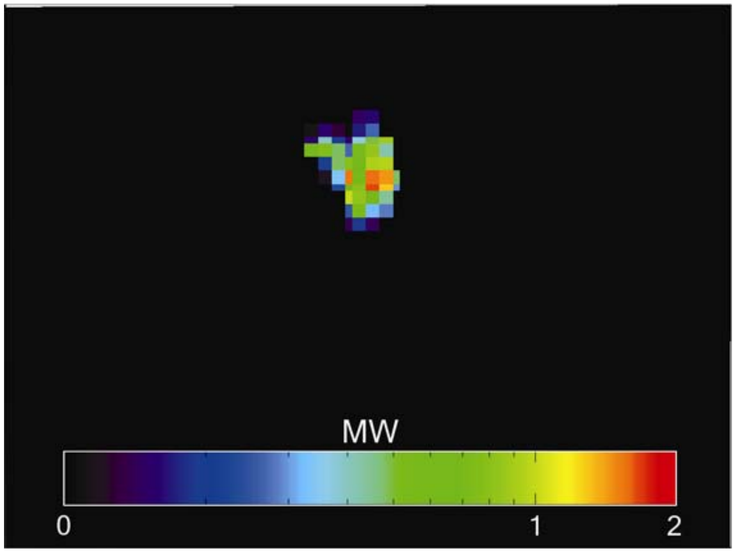
Topics

- The contribution that thermal infrared remote sensing can make to studying active volcanism
- The physical measurement that satellite sensors make and how they make it
- Extracting information from the data
    - Determining lava temperatures from space
    - Monitoring global volcanism from space
- Examples of some ways in which the data and information have been applied

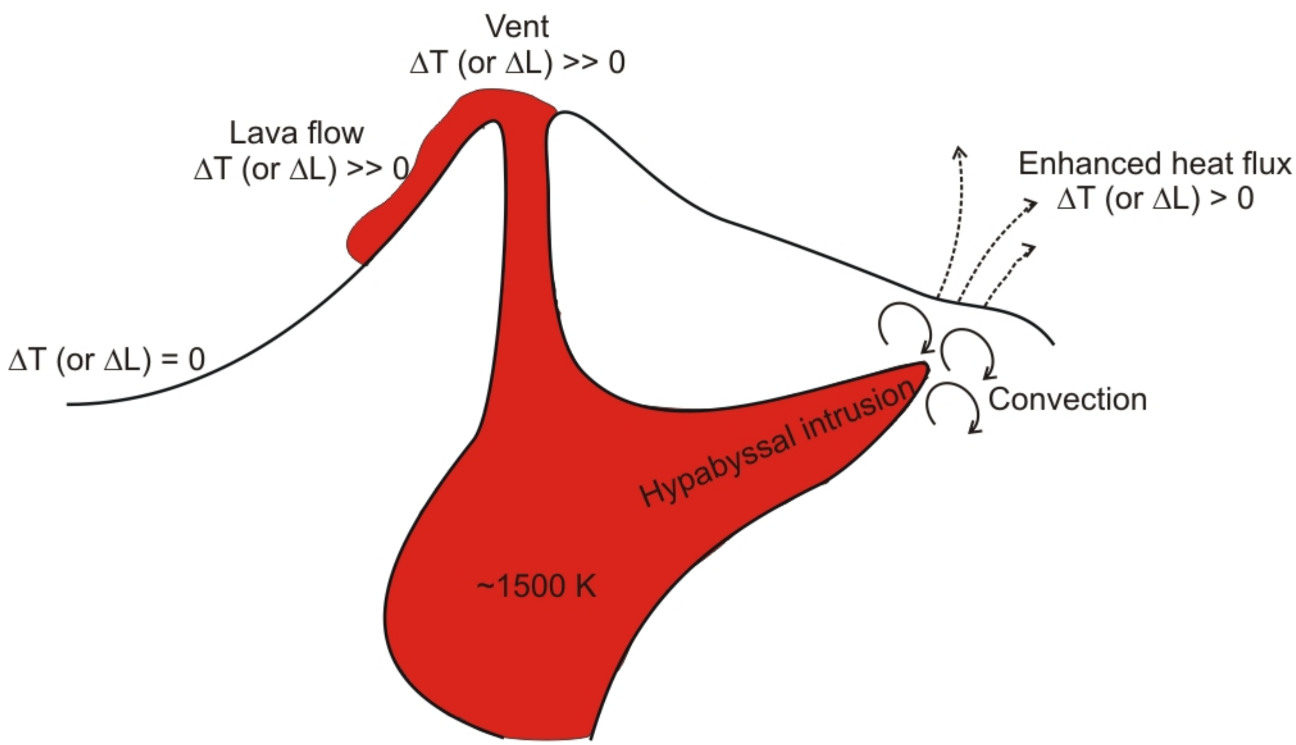




The role of thermal remote sensing in studying active volcanism

$\Delta T = T_{target} - T_{ambient}$

$\Delta L = L_{target} - L_{ambient}$



- Volcanism raises the local geothermal heat flux, both geographically and temporally
- Instruments onboard Earth orbiting spacecraft allow us to quantify these variations

Rothery et al., 1995

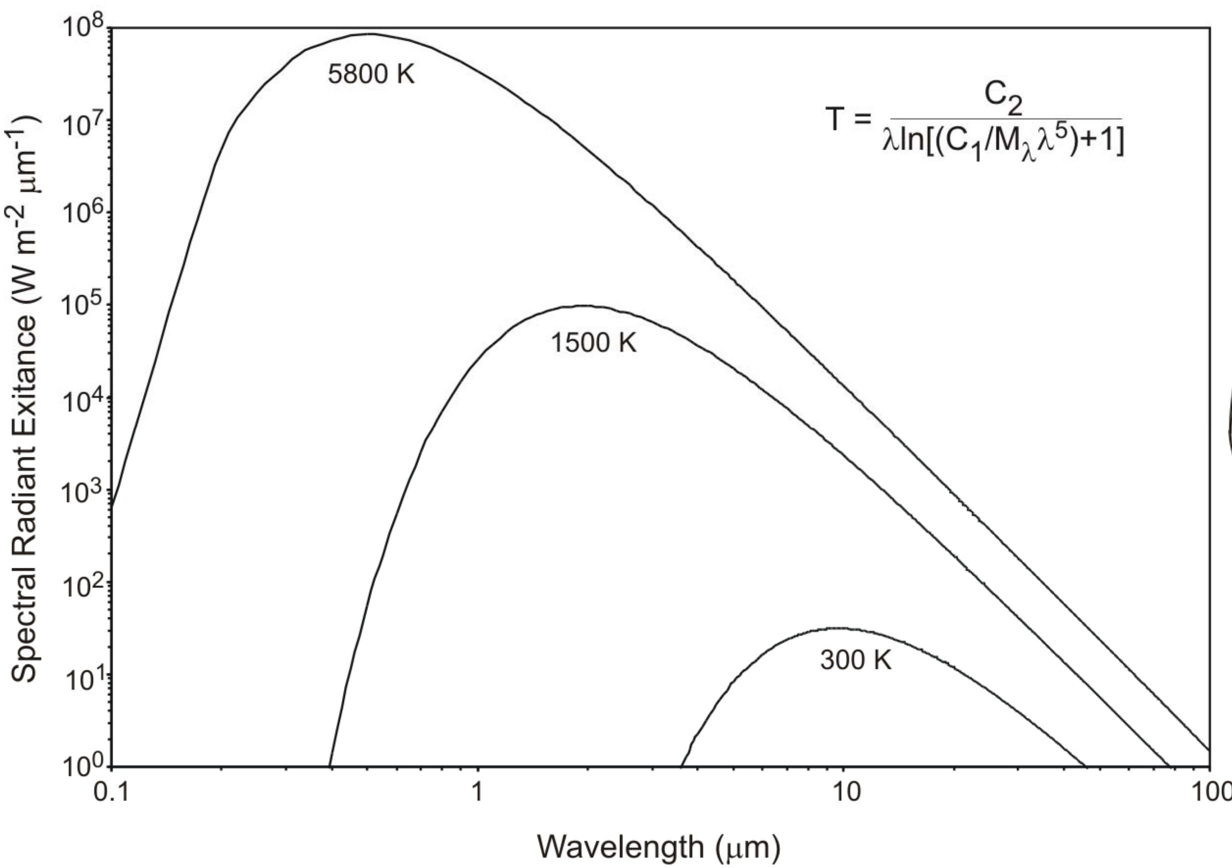
Planck's blackbody radiation law

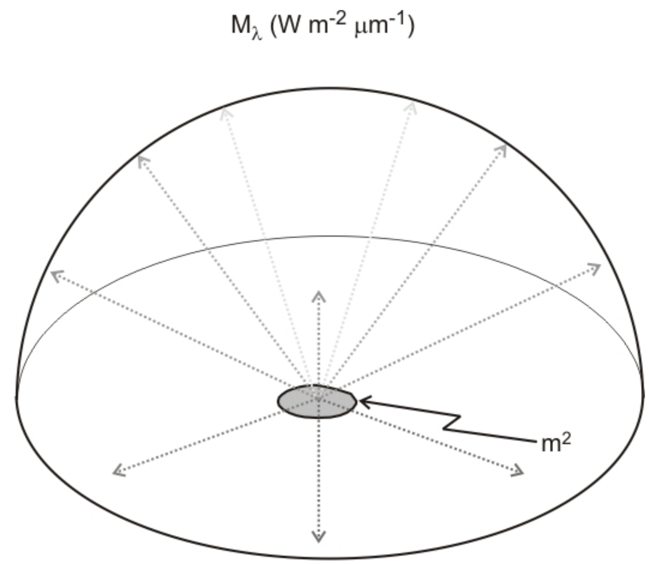
$$M_\lambda = \frac{2\pi hc^2}{\lambda^5}\left(e^{hc/\lambda kT} - 1\right)^{-1}$$

M_λ = spectral radiant exitance (W m^{-2} m^{-1})
h = Planck's constant (6.6256 × 10^{34} J s^{-1})
c = speed of light (2.9979246 × 10^8 m s^{-1})
k = Boltzmann's constant (1.380662 × 10^{-23} J K^{-1})
λ = wavelength (m)
T = temperature (K)

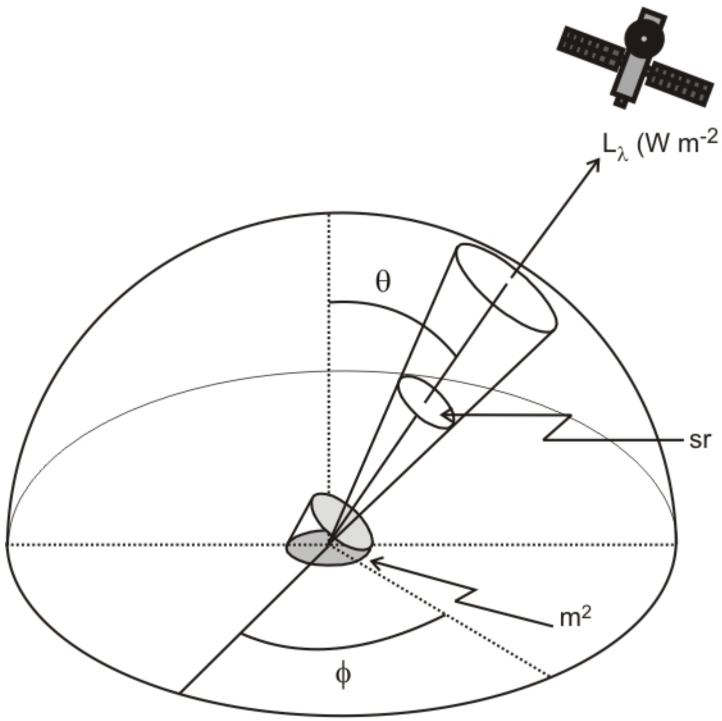
$$M_\lambda = \frac{C_1}{\lambda^5}\left(e^{C_2/\lambda T} - 1\right)^{-1}$$

M_λ = spectral radiant exitance (W m^{-2} μm^{-1})
λ = wavelength (μm)
T = temperature (K)
C_1 = 3.74151 × 10^8 W m^{-2} μm^4
C_2 = 1.43879 × 10^4 μm K





What quantity does a remote sensing instrument measure?



For a Lambertian surface $L = \frac{M}{\pi}$

If light is a stream of photons each carrying a quantity of energy (q):

$$q = hc/\lambda \text{ (joules/photon)}$$

and $L_\lambda = \text{W m}^{-2}\text{ sr}^{-1}\ \mu\text{m}^{-1}$

then: $\frac{L_\lambda}{\text{Optical system throughput}}$ = Spectral irradiance arriving at the detector (E_λ; W m^{-2} μm^{-1})

and if the detector intercepts a % of this in accordance with its area (A_d) then:

$$\phi_\lambda = E_\lambda A_d = \text{the spectral flux landing on the detector (W } \mu\text{m}^{-1})$$

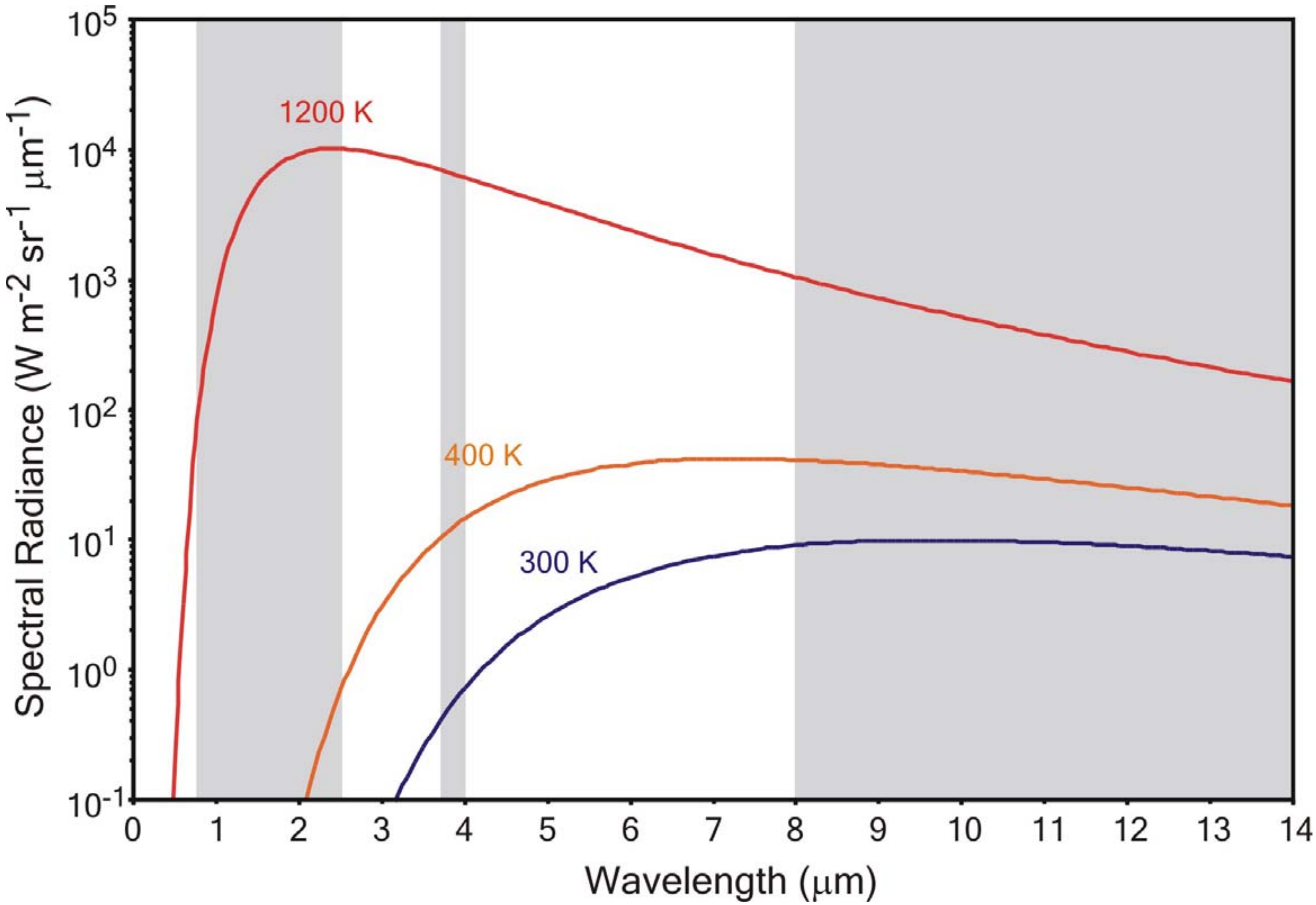
and the flux over a narrow spectral band is:

$$\phi = \phi_\lambda \Delta_\lambda \text{ (W)}$$

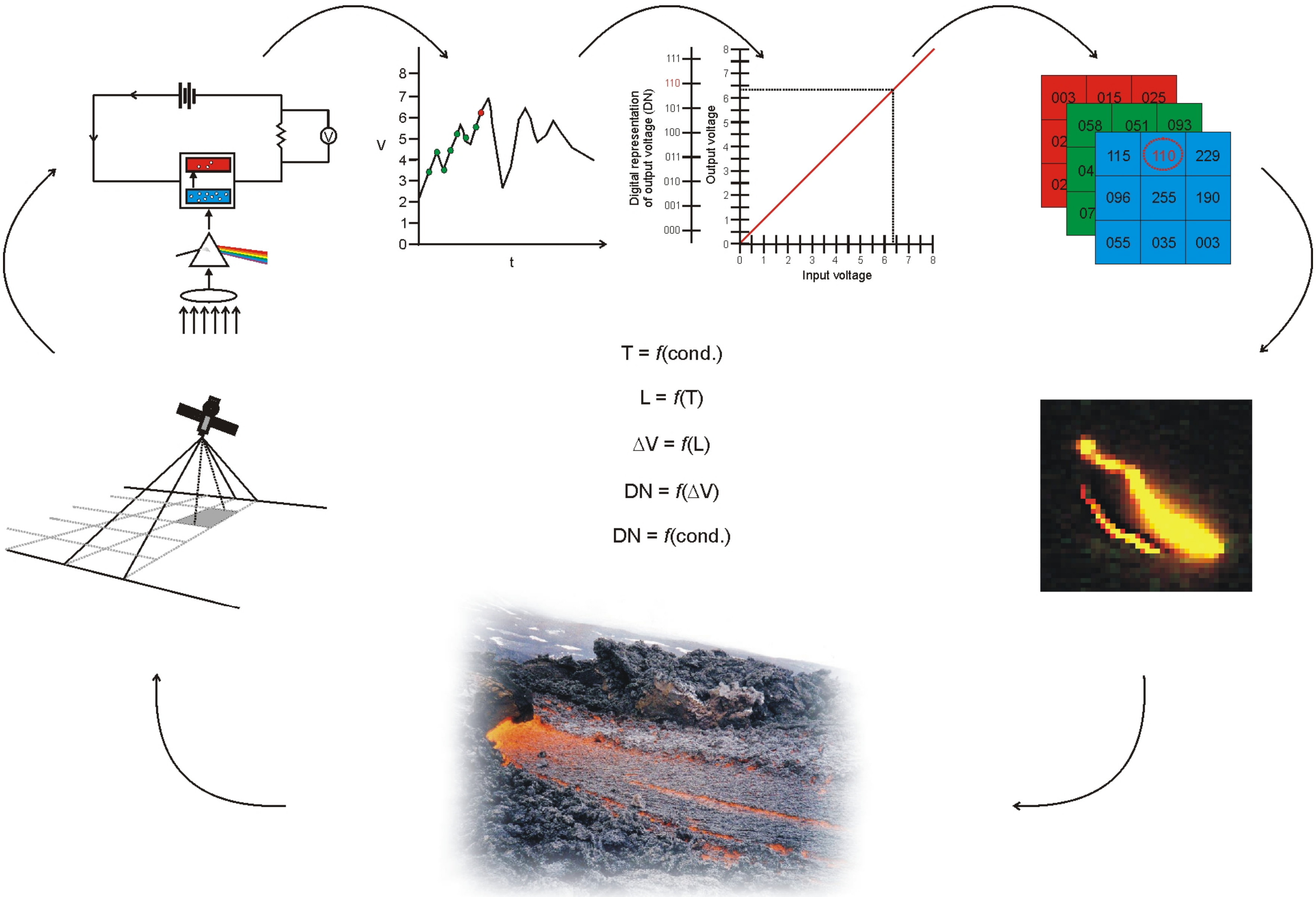
and the flux of photons in this spectral band landing on the detector is

$$\phi_p = \frac{\phi}{hc/\lambda} \text{ (photons/sec)}$$

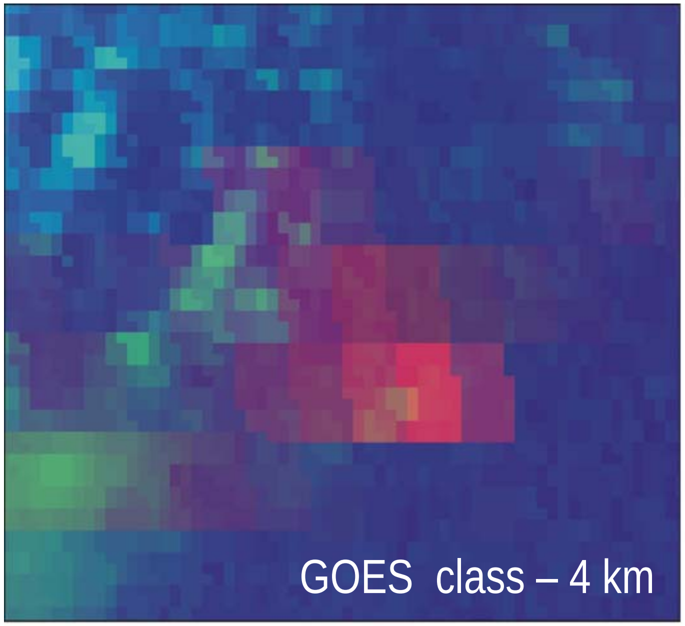
Active volcanic phenomena emit prodigious amounts of radiance

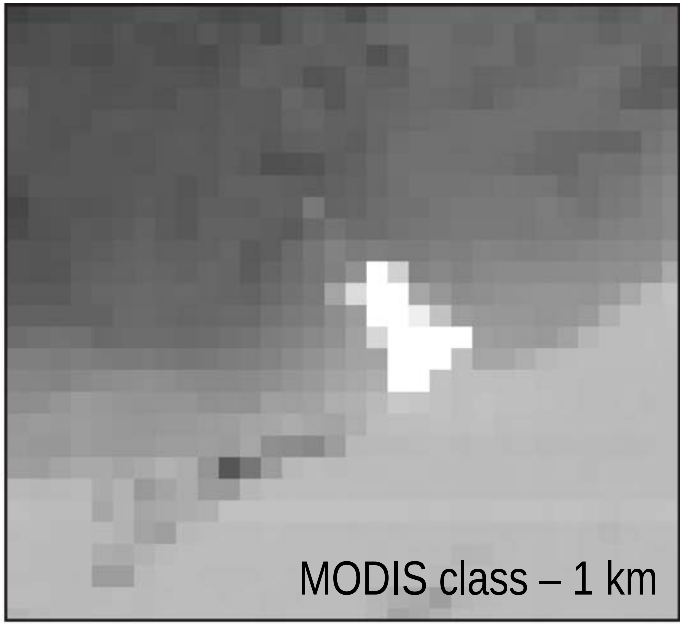


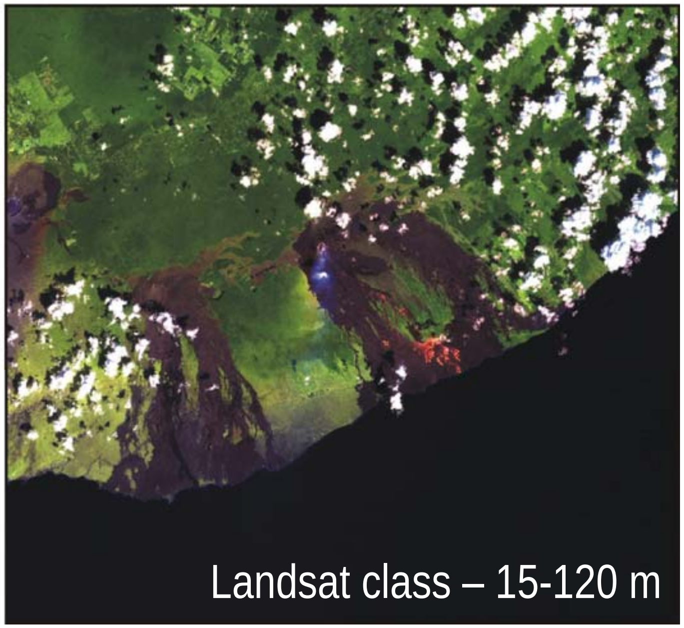
How do remote sensing instruments make the measurement?



Thermal volcano remote sensing: what kinds of data are available?

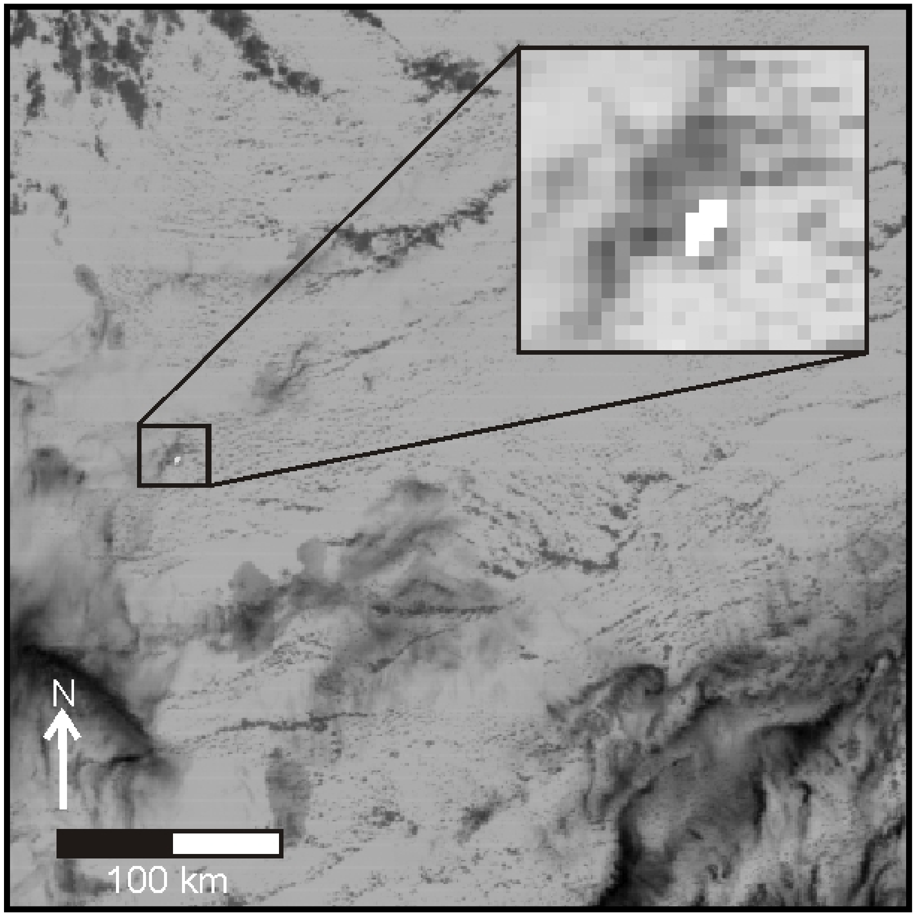


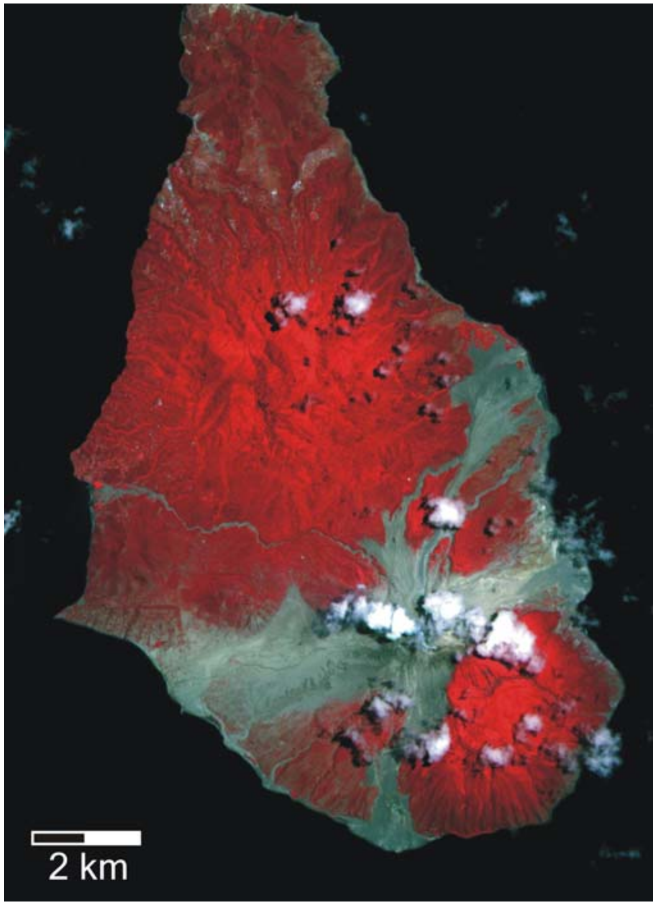




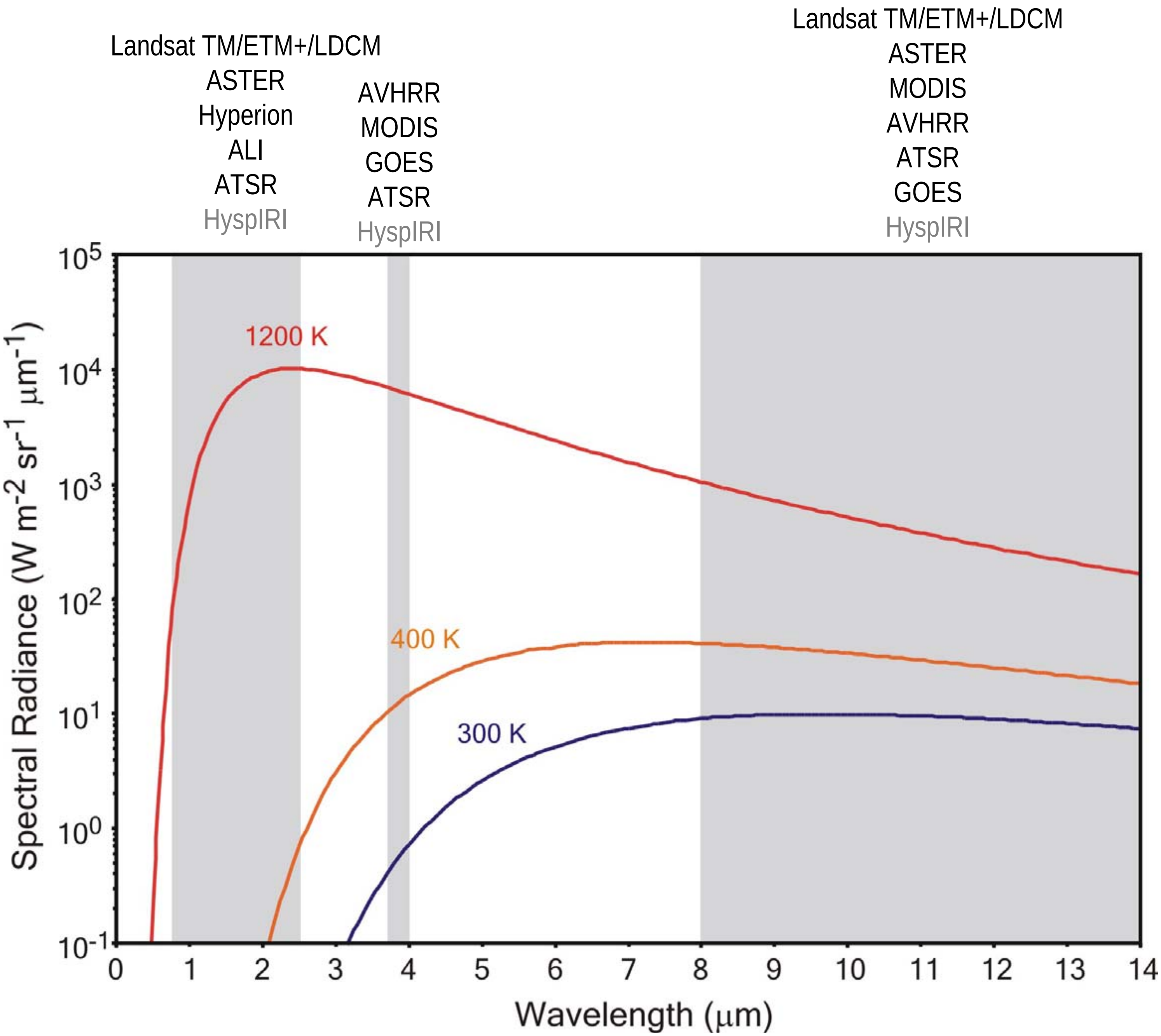
- All vary with respect to the fidelity with which the system records the spatial, temporal, and spectro-radiometric properties of the phenomena

Spatial information is resolved differently by different sensors





Spectral information is resolved differently by different sensors

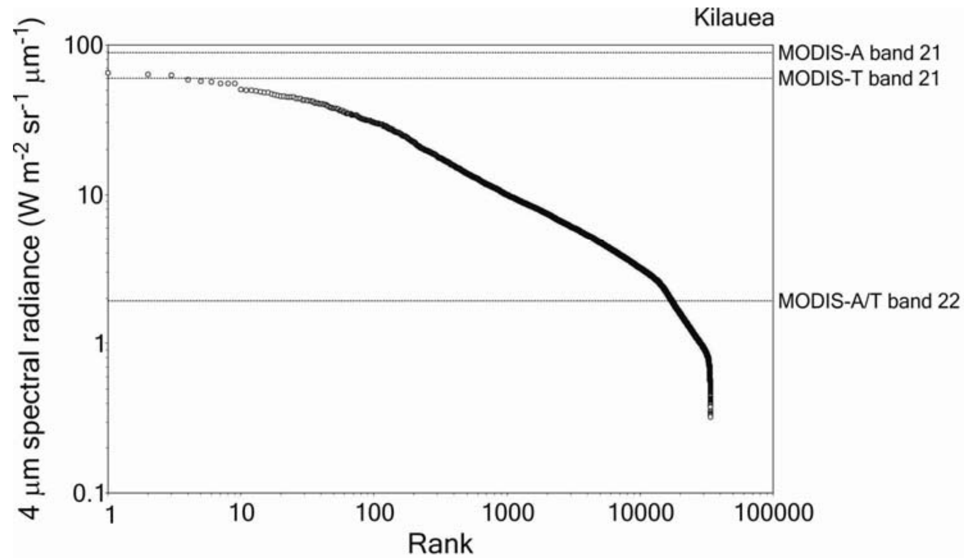


Spectral radiance is resolved differently by different sensors

Kilauea 2000-2009

- 33763 “hot” MODIS pixels
- 0 (0%) were saturated in Band 21
- 16543 (49%) were saturated in Band 22

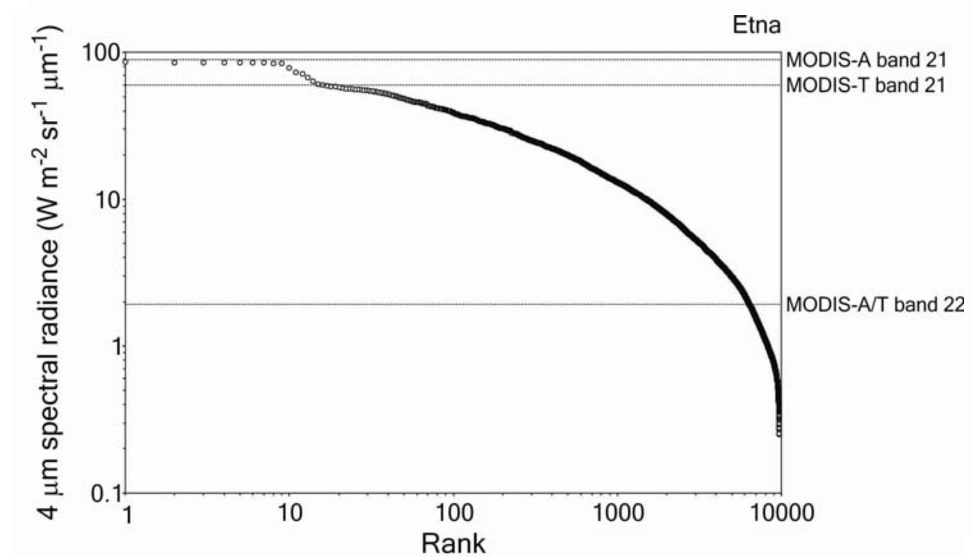
- Total 4 micron radiance is 101,369 W m^{-2} sr^{-1} μm^{-1}
- Of this, Band 22 recorded 21,644 W m^{-2} sr^{-1} μm^{1}
- 79% of the actual spectral radiance contained within pixels that saturated Band 22

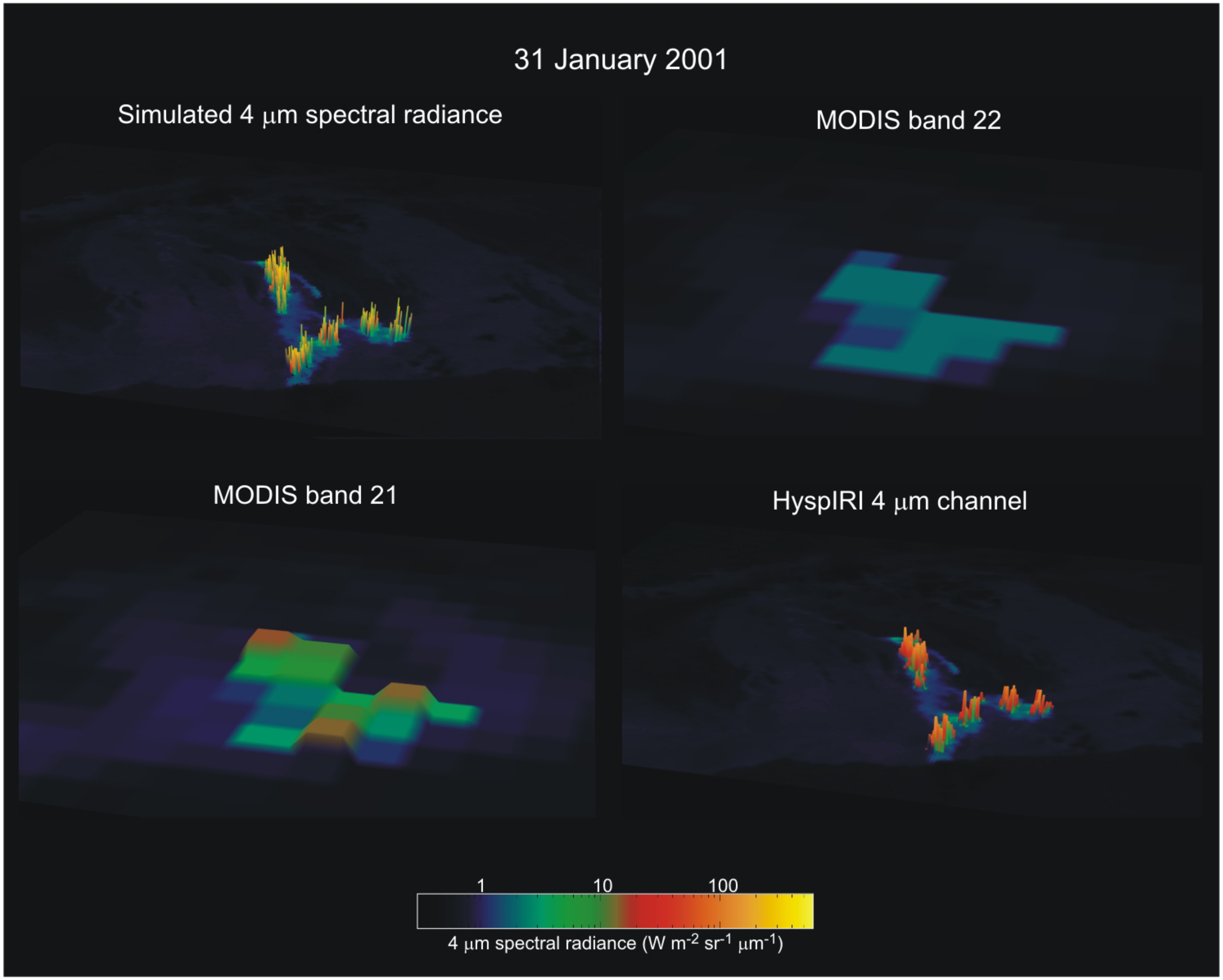


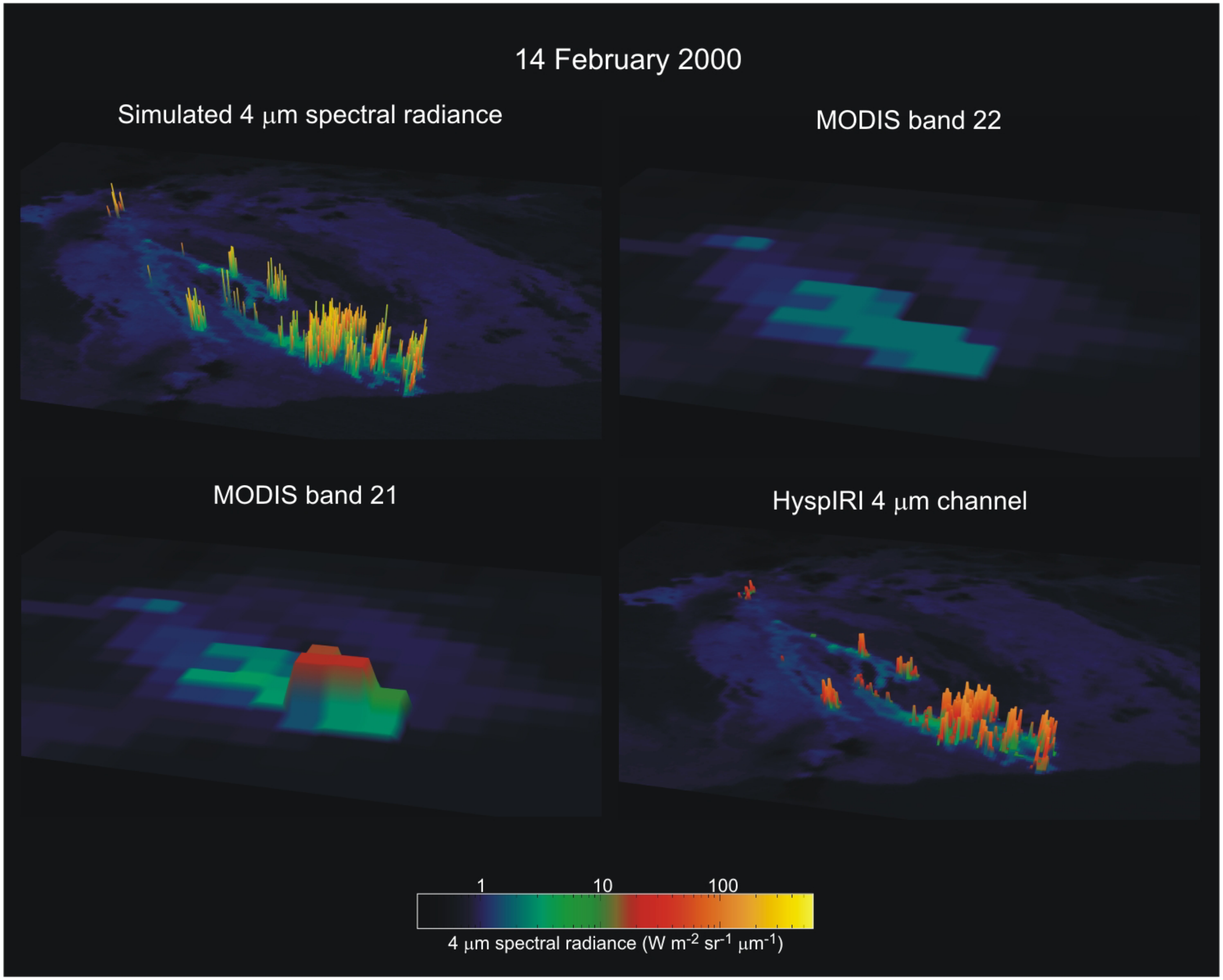
Etna 2000-2009

- 9699 “hot” MODIS pixels
- 2 (0.02%) were saturated in Band 21
- 6198 (64%) were saturated in Band 22

- Total 4 micron radiance is 55,535 W m^{-2} sr^{-1} μm^{-1}
- Of this, Band 22 recorded 4108 W m^{-2} sr^{-1} μm^{1}
- 93% of the actual spectral radiance contained within pixels that saturated Band 22




31 January 2001
Simulated 4 μm spectral radiance
MODIS band 22
MODIS band 21
HyspIRI 4 μm channel
1
10
100
4 μm spectral radiance (W m-2 sr-1 μm-1)


14 February 2000
Simulated 4 μm spectral radiance
MODIS band 22
MODIS band 21
HyspIRI 4 μm channel
1
10
100
4 μm spectral radiance (W m-2 sr-1 μm-1)

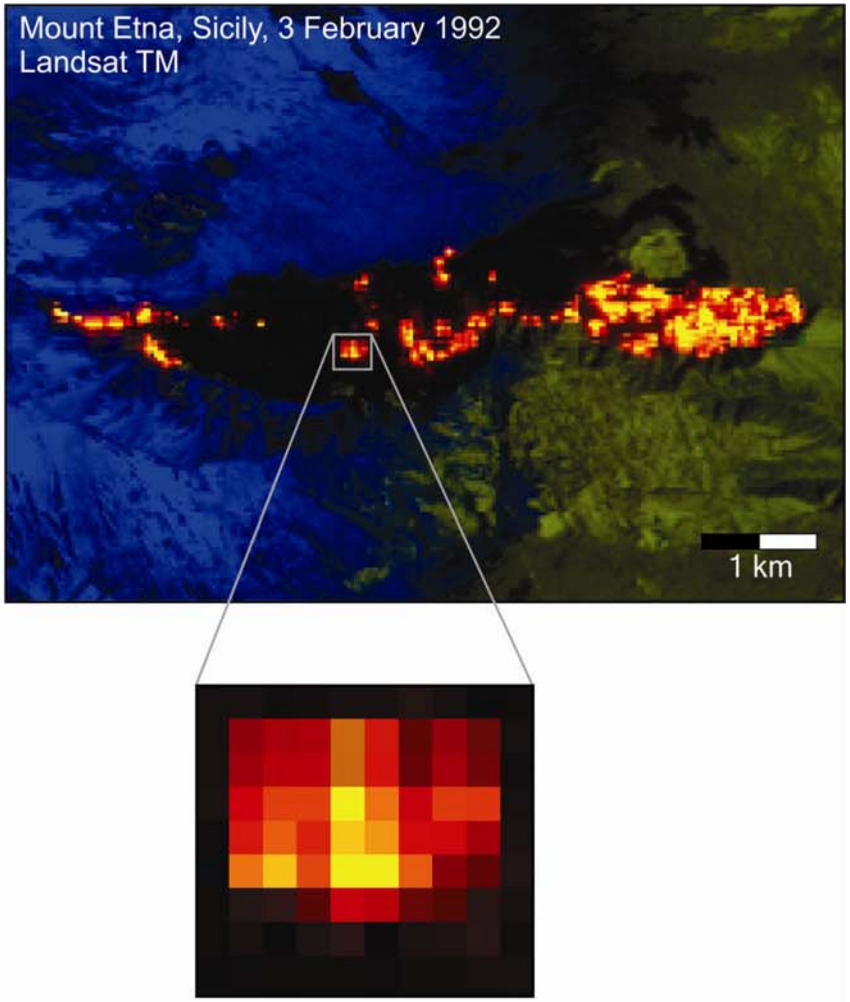
Extracting information from the data

- Temperature analyses
- Volcano monitoring

Measuring the temperature of active volcanic targets remotely

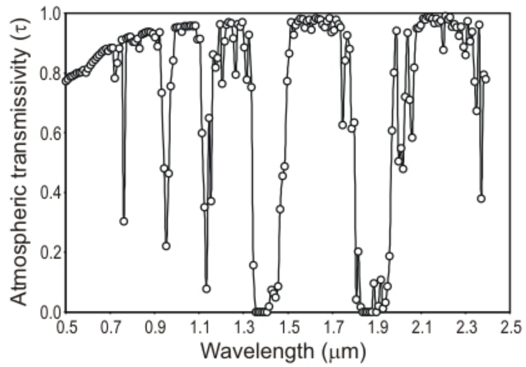
Pre-processing the data

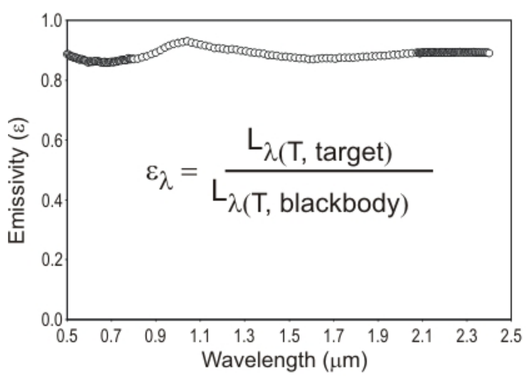
Inverting at-satellite radiance to obtain lava surface temperature

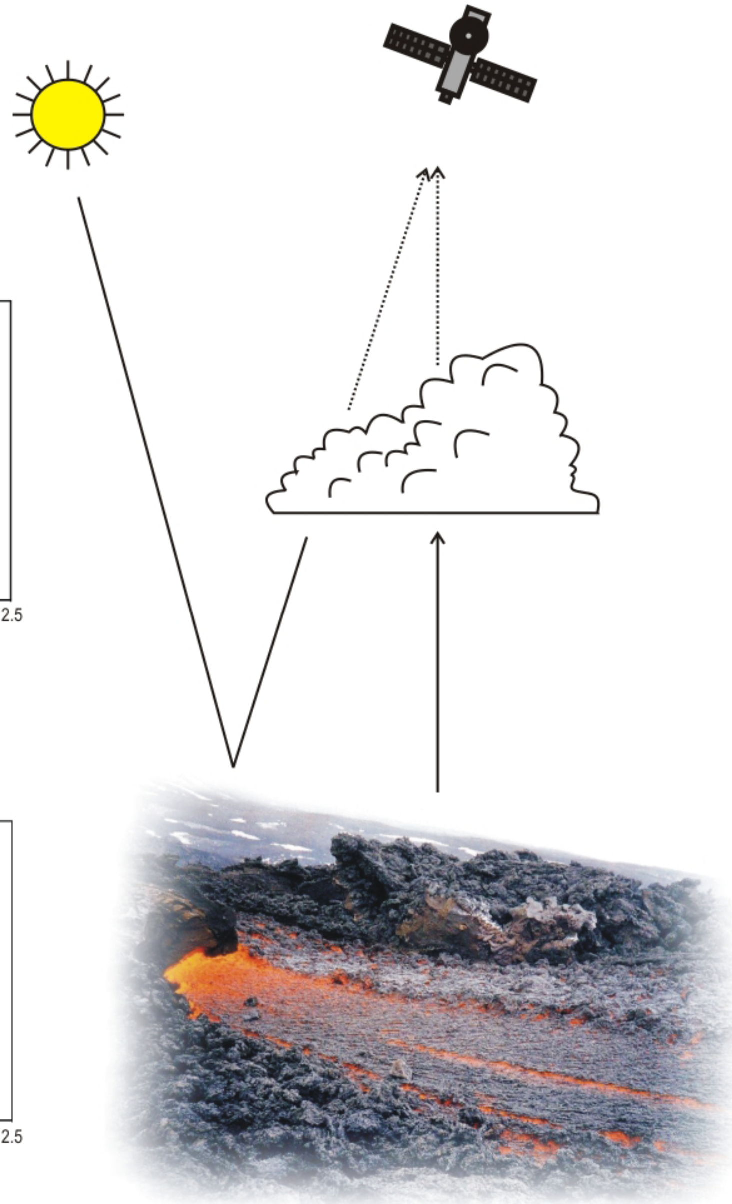


What's going on inside these pixels?

Pre-processing the data: isolating the volcanogenic signal







$L_{\lambda,\text{at-satellite}}$

τ_λ

$$T = \frac{C_2}{\lambda \ln[(C_1/L_{\lambda,corr}\lambda^5)+1]}$$

where $L_{\lambda,corr} = \frac{L_{\lambda,\text{at-satellite}}}{(\tau_\lambda \times \varepsilon_\lambda)}$

ε_λ

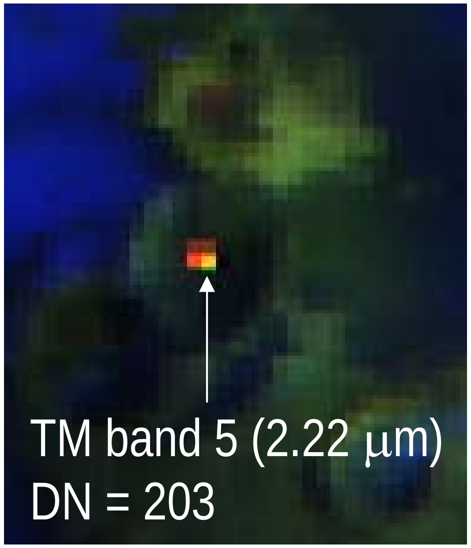
$T_a = 1000$ K

Calibrating the data: convert DC to L_λ

- *e.g.* Landsat Thematic Mapper (TM)

$$L_\lambda = DC_\lambda[(L_{max\lambda} - L_{min\lambda})/255] + L_{min\lambda}$$

($mW\ cm^{-2}\ sr^{-1}\ \mu m^{-1}$)



where $L_{min\lambda}$ and $L_{max\lambda}$ are given by….

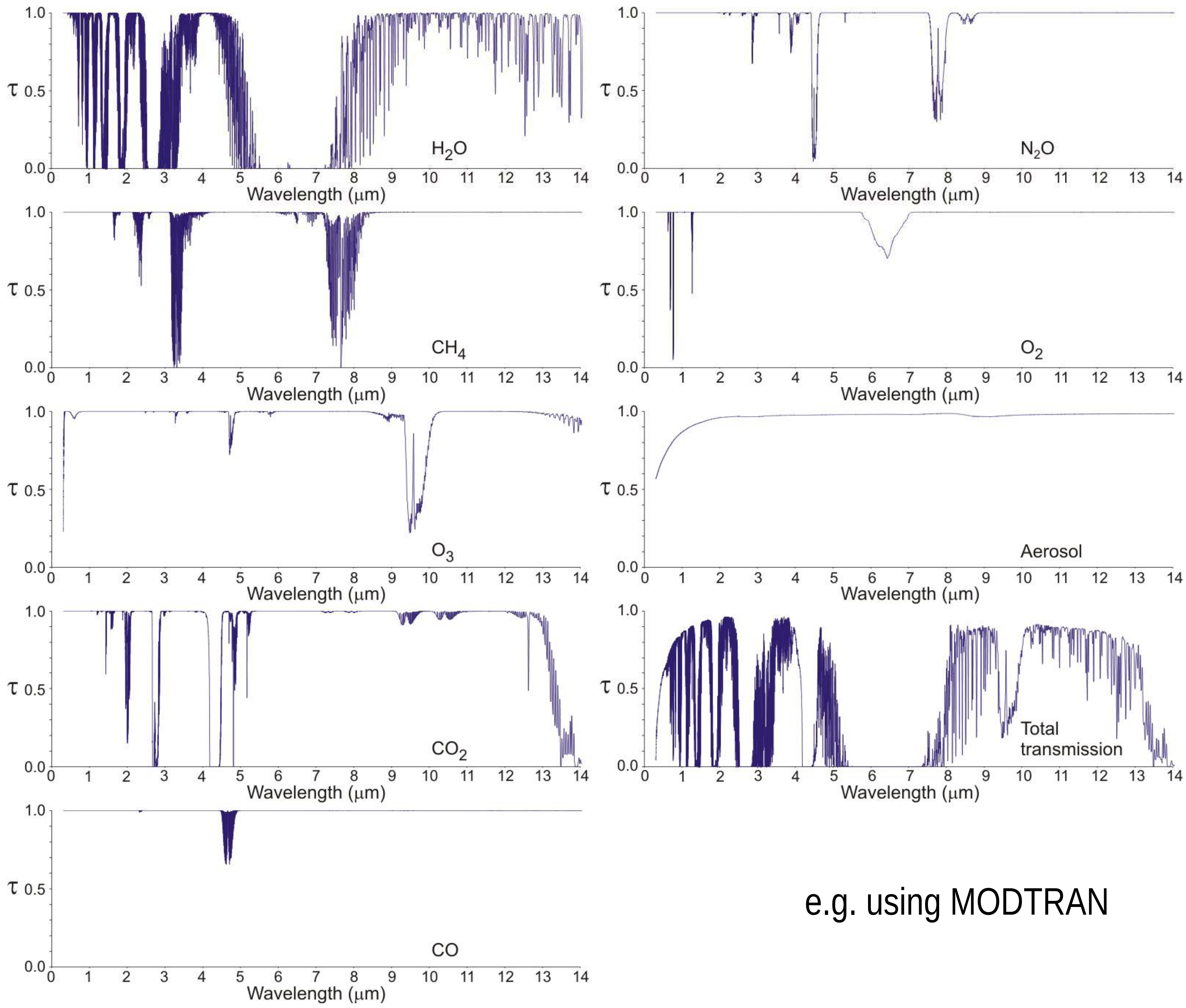
Band	$L_{min\lambda}$	$L_{max\lambda}$
1	-0.15	15.21
2	-0.28	29.86
3	-0.12	20.43
4	-0.15	20.62
5	-0.037	2.719
7	-0.015	1.438

$$L_5 = 203[(2.719 - (-0.037))/255] + (-0.037)$$

$$L_5 = 2.16\ mW\ cm^{-2}\ sr^{-1}\ \mu m^{-1}$$

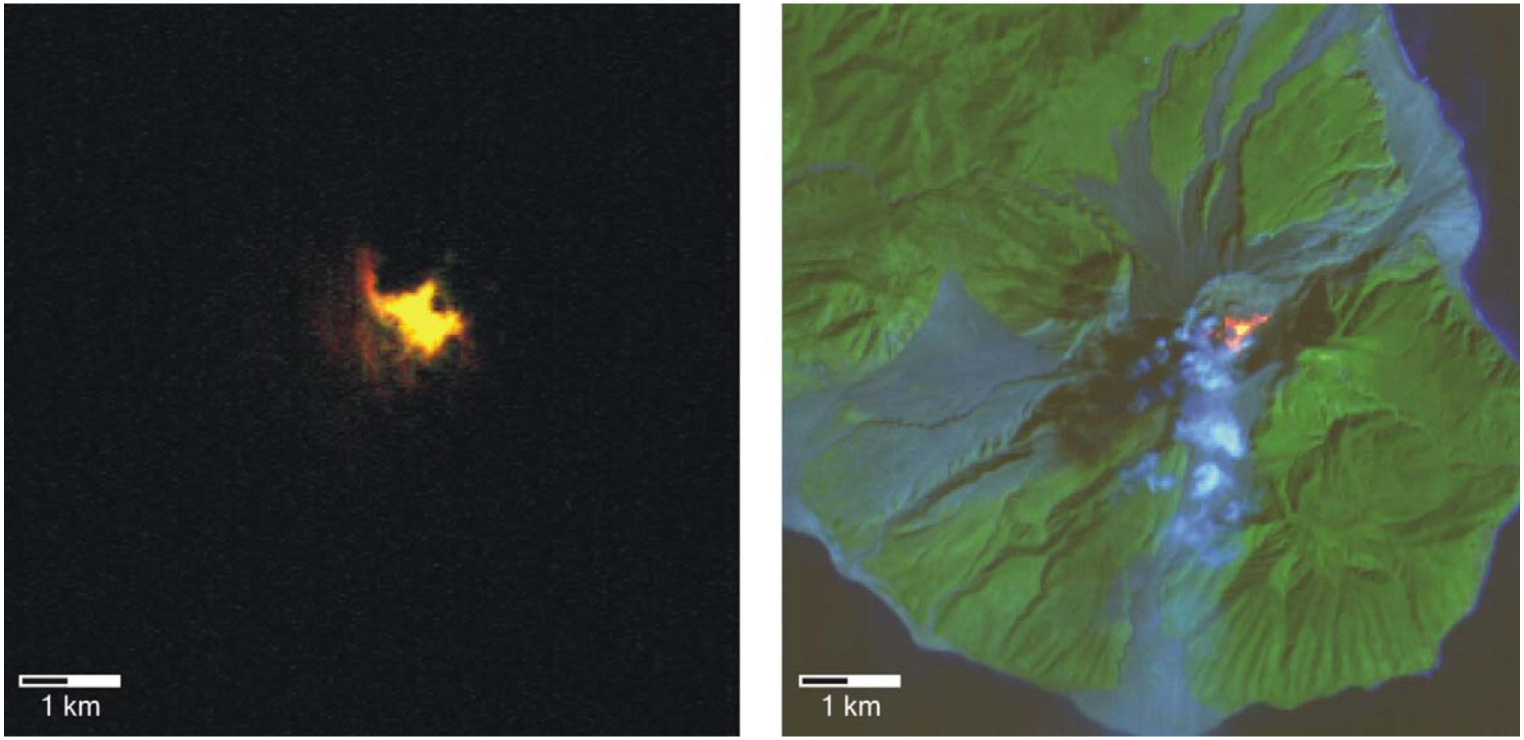
$$L_5 = 21.6\ W\ m^{-2}\ sr^{-1}\ \mu m^{-1}$$

Compensating for absorption of surface leaving radiance by the atmosphere



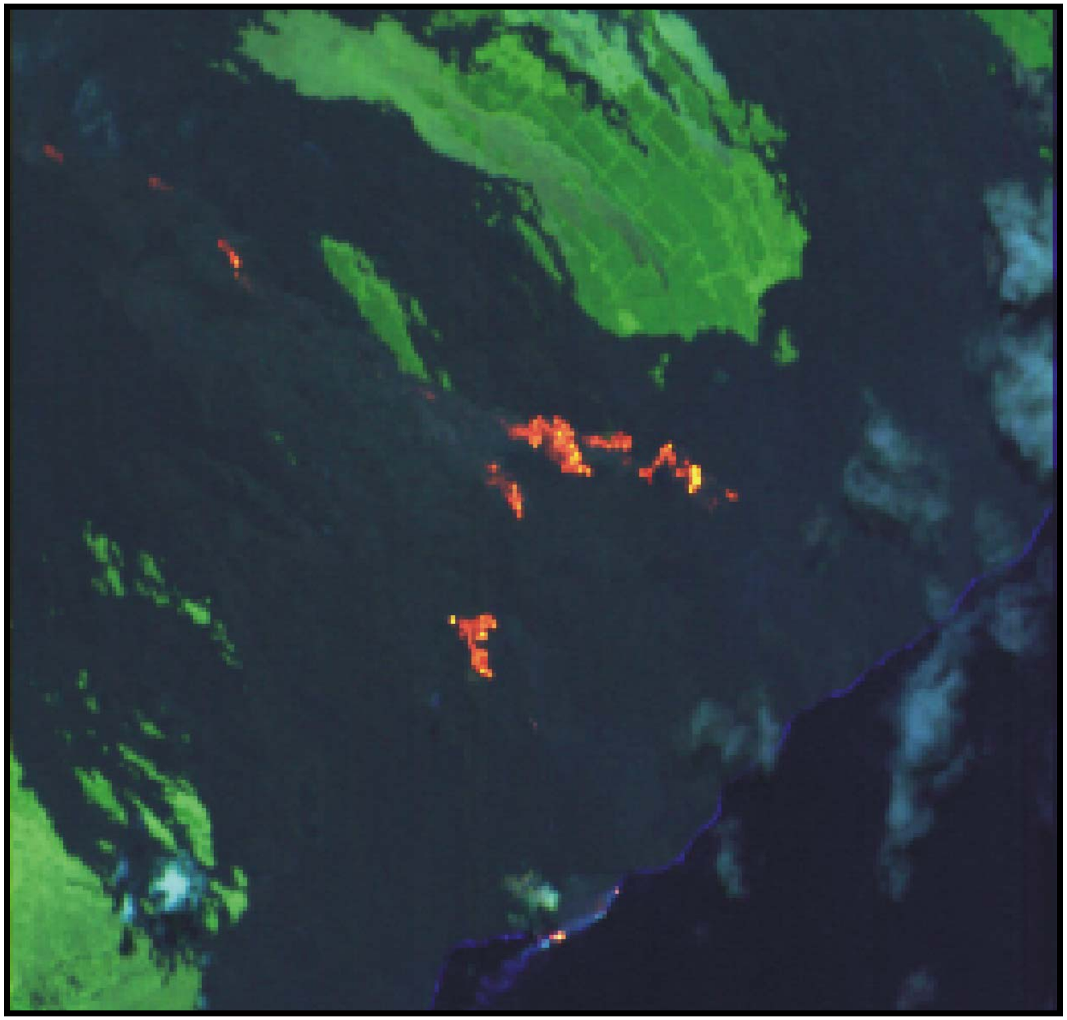
e.g. using MODTRAN

Compensating for the contamination of the signal by reflected sunlight



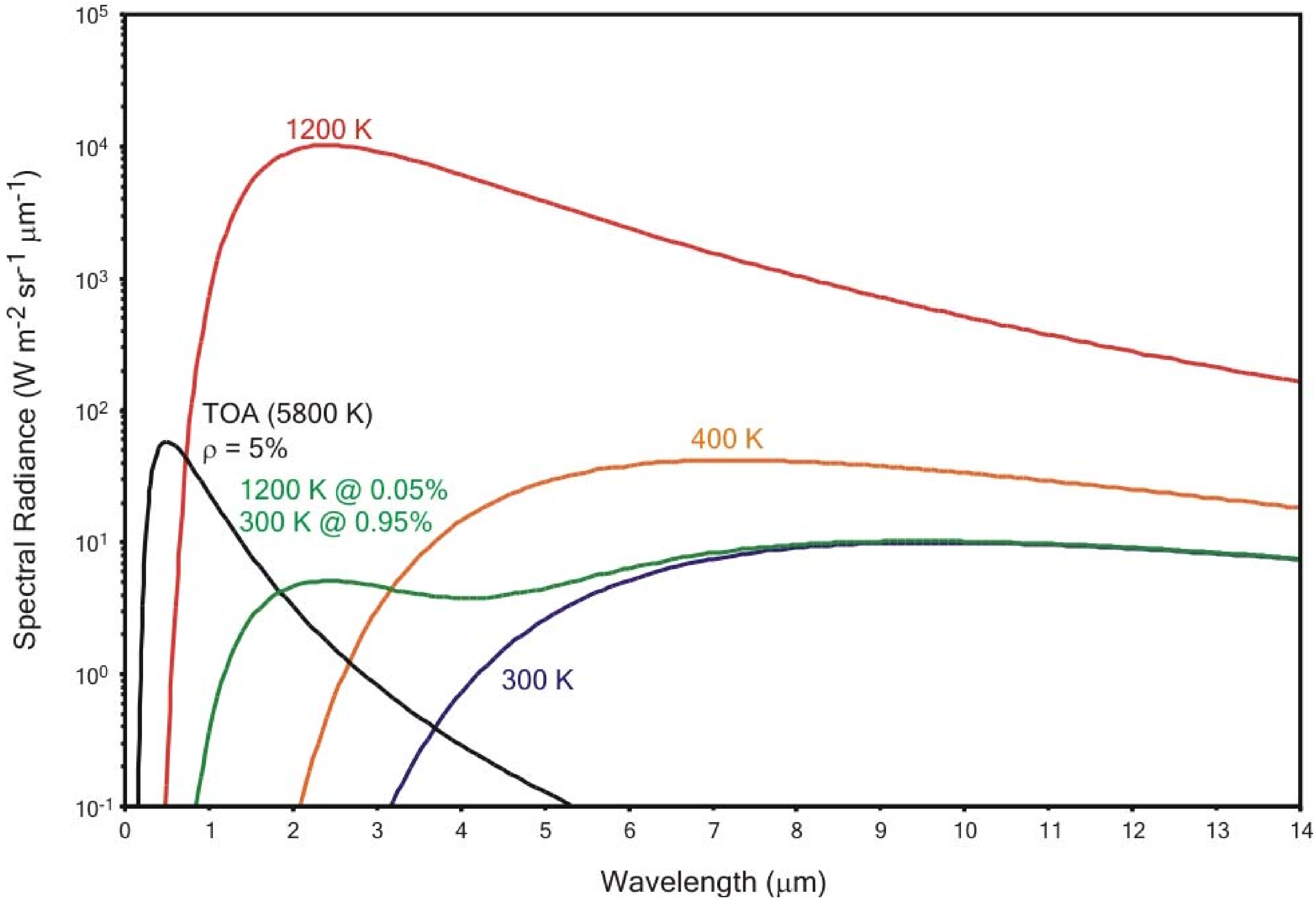
• Use nighttime data

Compensating for the contamination of the signal by reflected sunlight



• Correct on a per-pixel basis using the reflectance of adjacent “cold” lava pixels

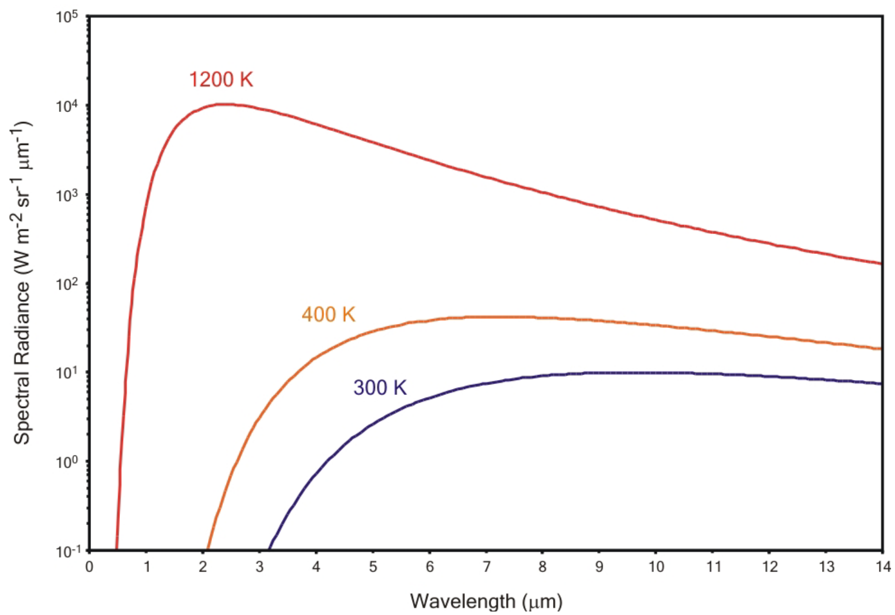
The ability to isolate the volcanogenic signal depends on wavelength, time of day, and temperature and size of the target

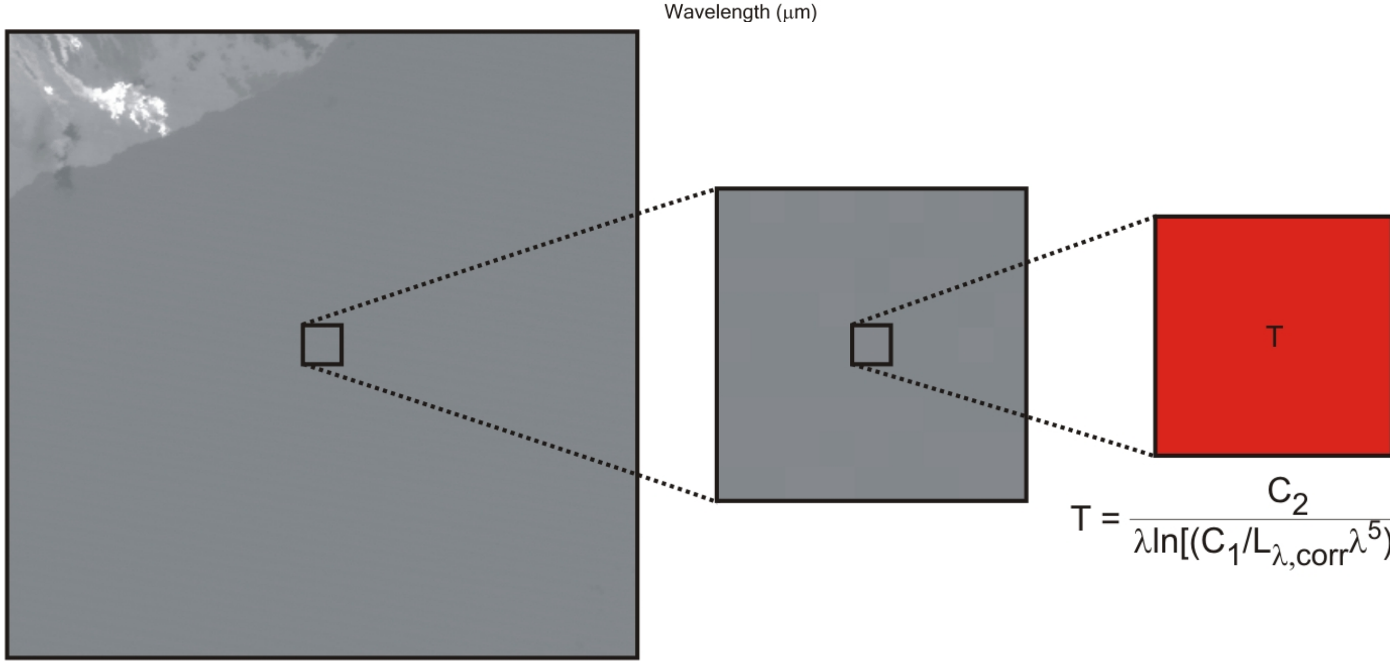


Measuring the temperature of active volcanic targets remotely

Converting at-satellite spectral radiance to temperature

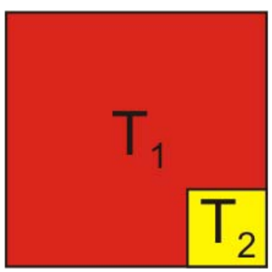
Temperature retrievals for thermally homogenous surfaces using single band data





$$T = \frac{C_2}{\lambda \ln[(C_1/L_{\lambda,corr}\lambda^5)+1]}$$

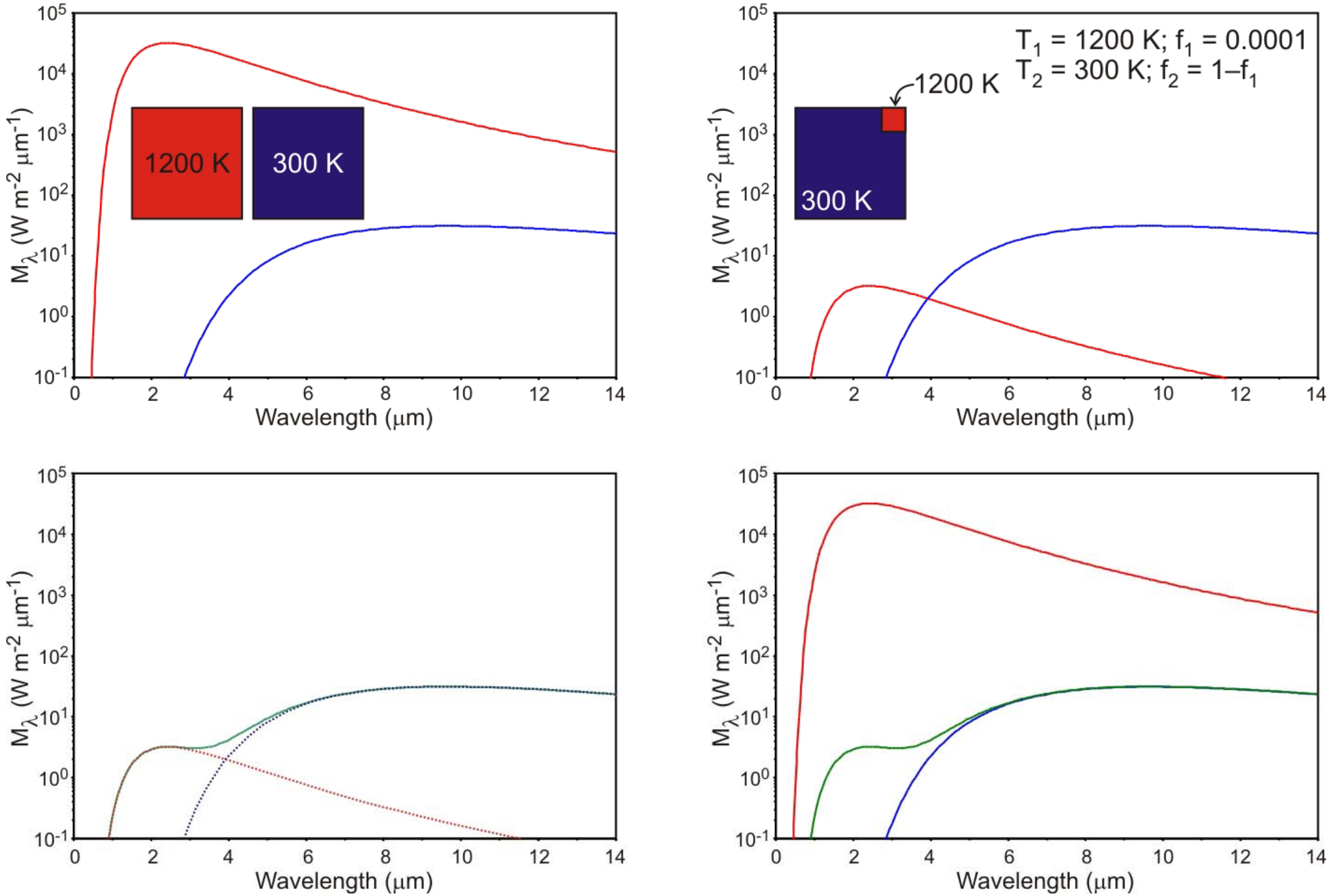
Temperature retrievals for thermally complex surfaces using multi-spectral data: the Dozier (dual-band) approach



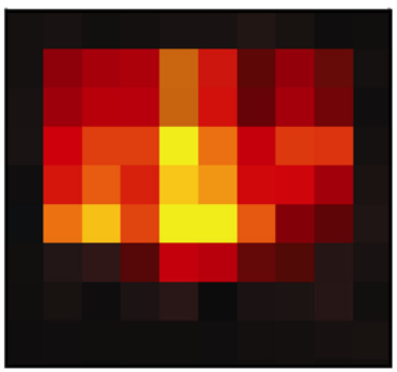
$$L_a = f_1 L(\lambda_a, T_1) + (1-f_1)L(\lambda_b, T_2)$$

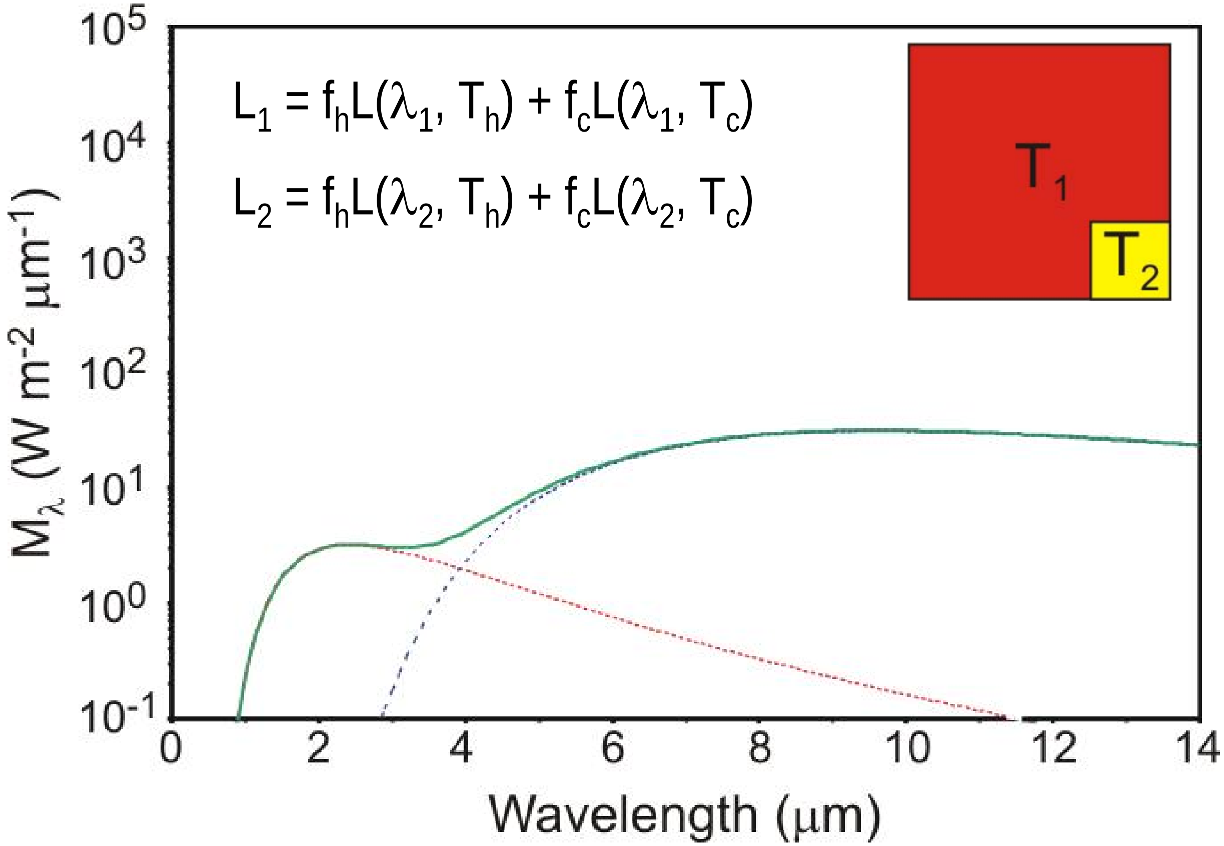
$$L_b = f_1 L(\lambda_b, T_1) + (1-f_1)L(\lambda_b, T_2)$$

Sub-pixel temperature retrievals using simple mixture models



Volcano radiometry using the dual-band method

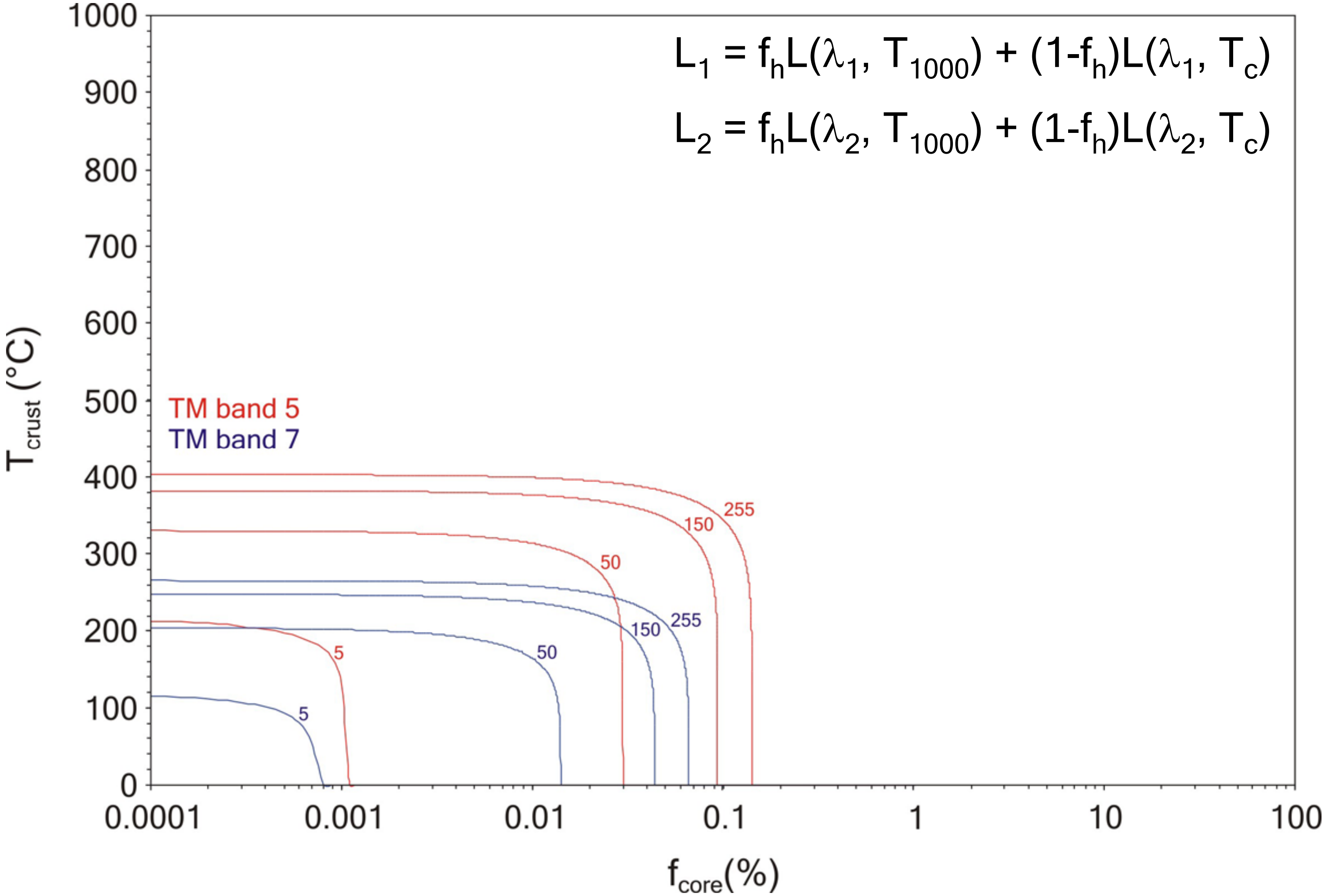


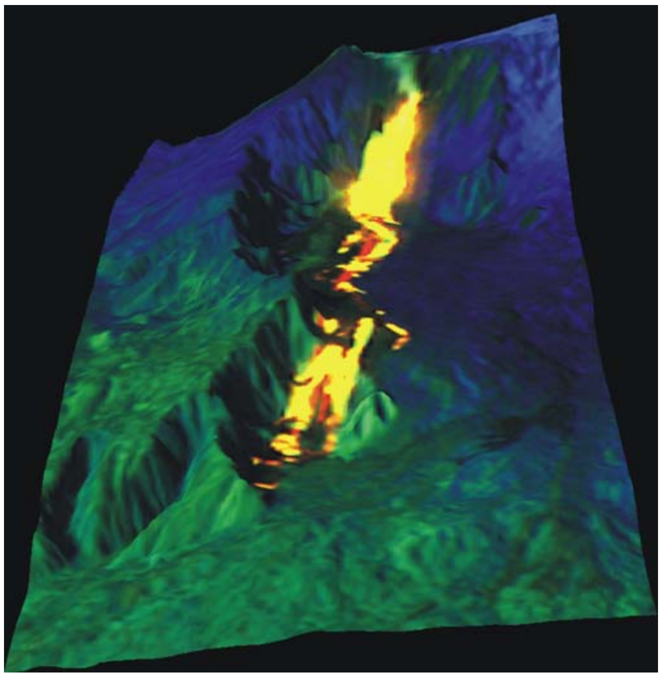


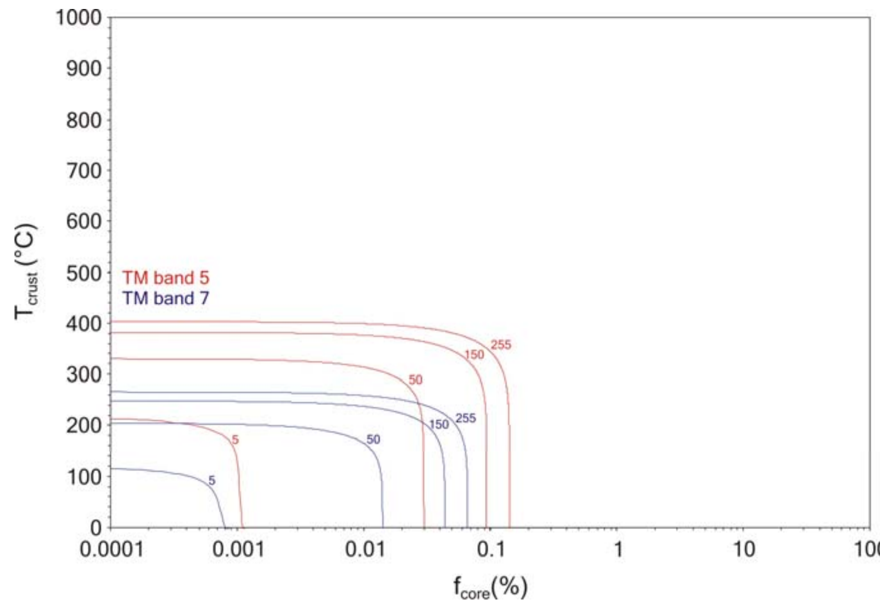
- Can you apply it?
- Is it realistic?

Francis and Rothery, 1987; Rothery et al., 1988; Oppenheimer, 1990

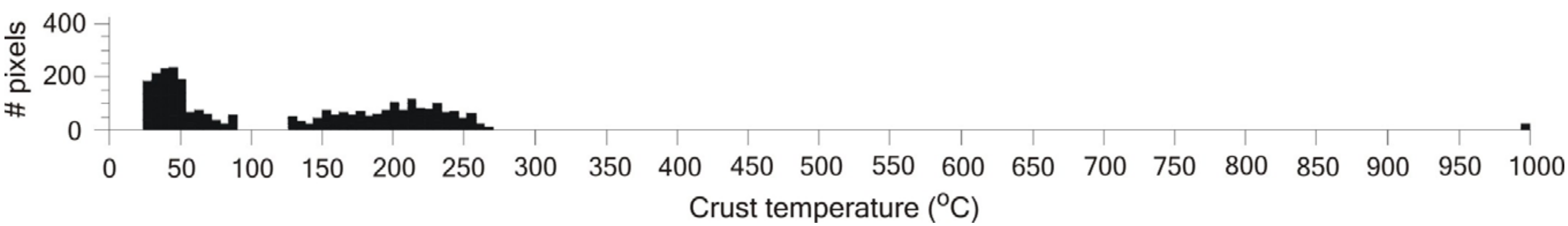
Multi-spectral data: the problem of sensor dynamic range



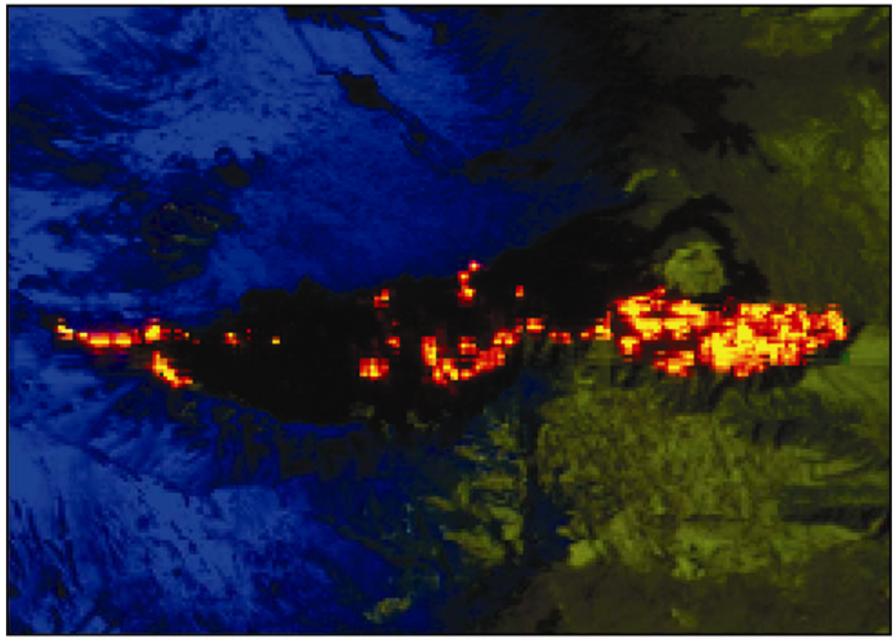


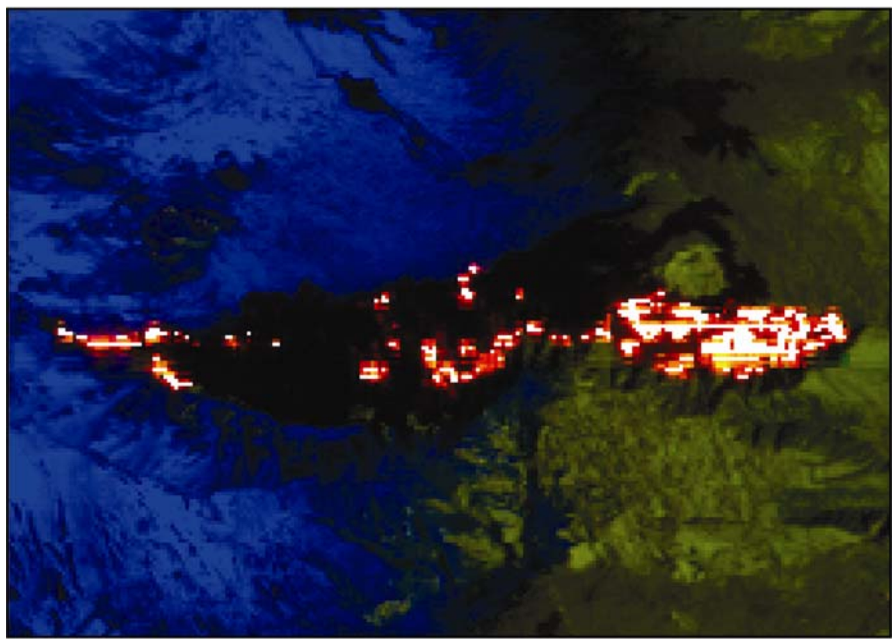


T_crust (°C)
f_core(%)
TM band 5
TM band 7
0
100
200
300
400
500
600
700
800
900
1000
0.0001
0.001
0.01
0.1
1
10
100
255
150
50
5

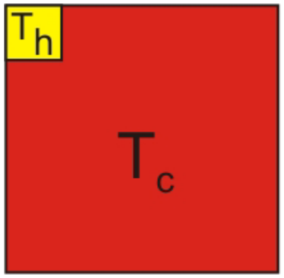


pixels
400
200
0
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
Crust temperature (°C)





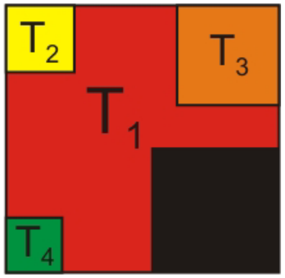
Is the Dozier method an oversimplification?



$$L_1 = f_h L(\lambda_1, T_h) + (1-f_h) L(\lambda_1, T_c)$$

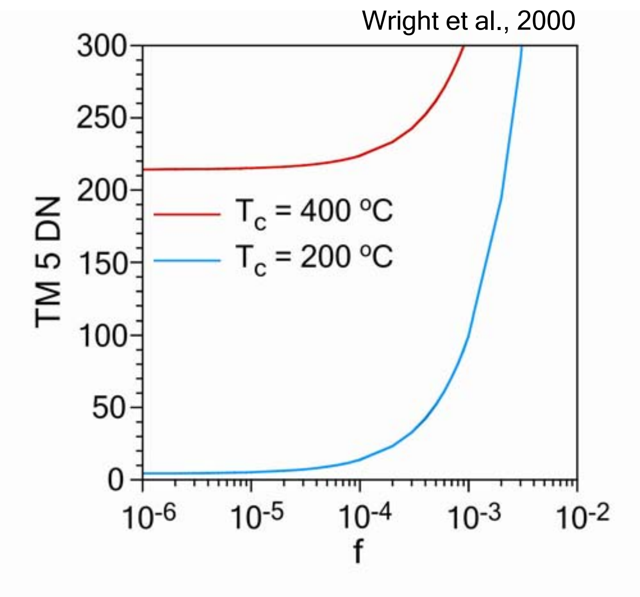
$$L_2 = f_h L(\lambda_2, T_h) + (1-f_h) L(\lambda_2, T_c)$$

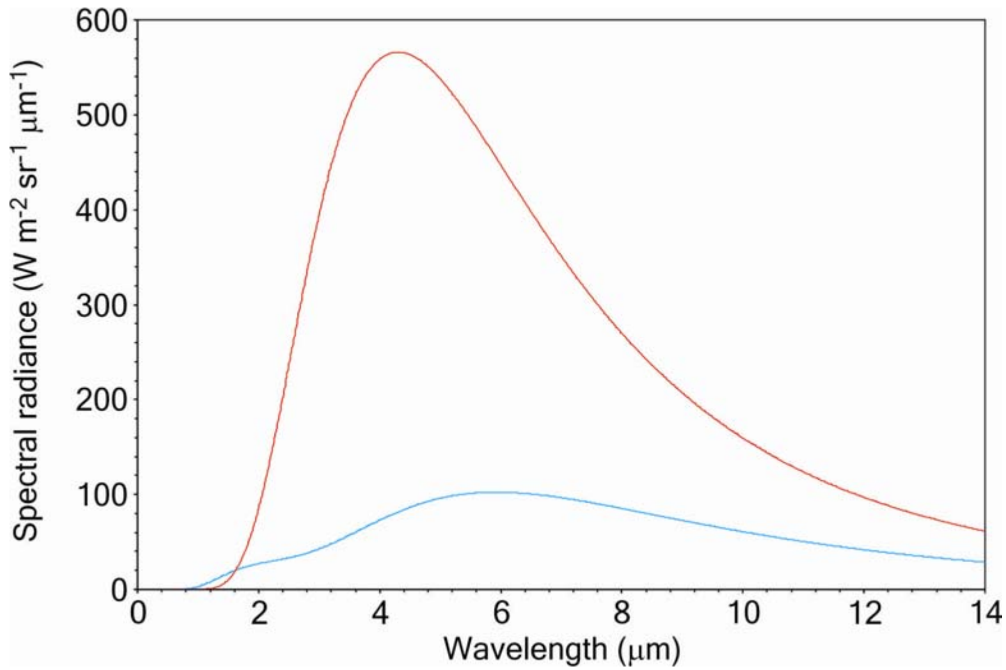
$$L(\lambda) = \sum_{i=1}^{n} f_i (L, T_i)$$

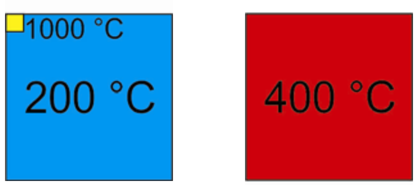


- How large should *n* be?
- What is the physical meaning of *n*?

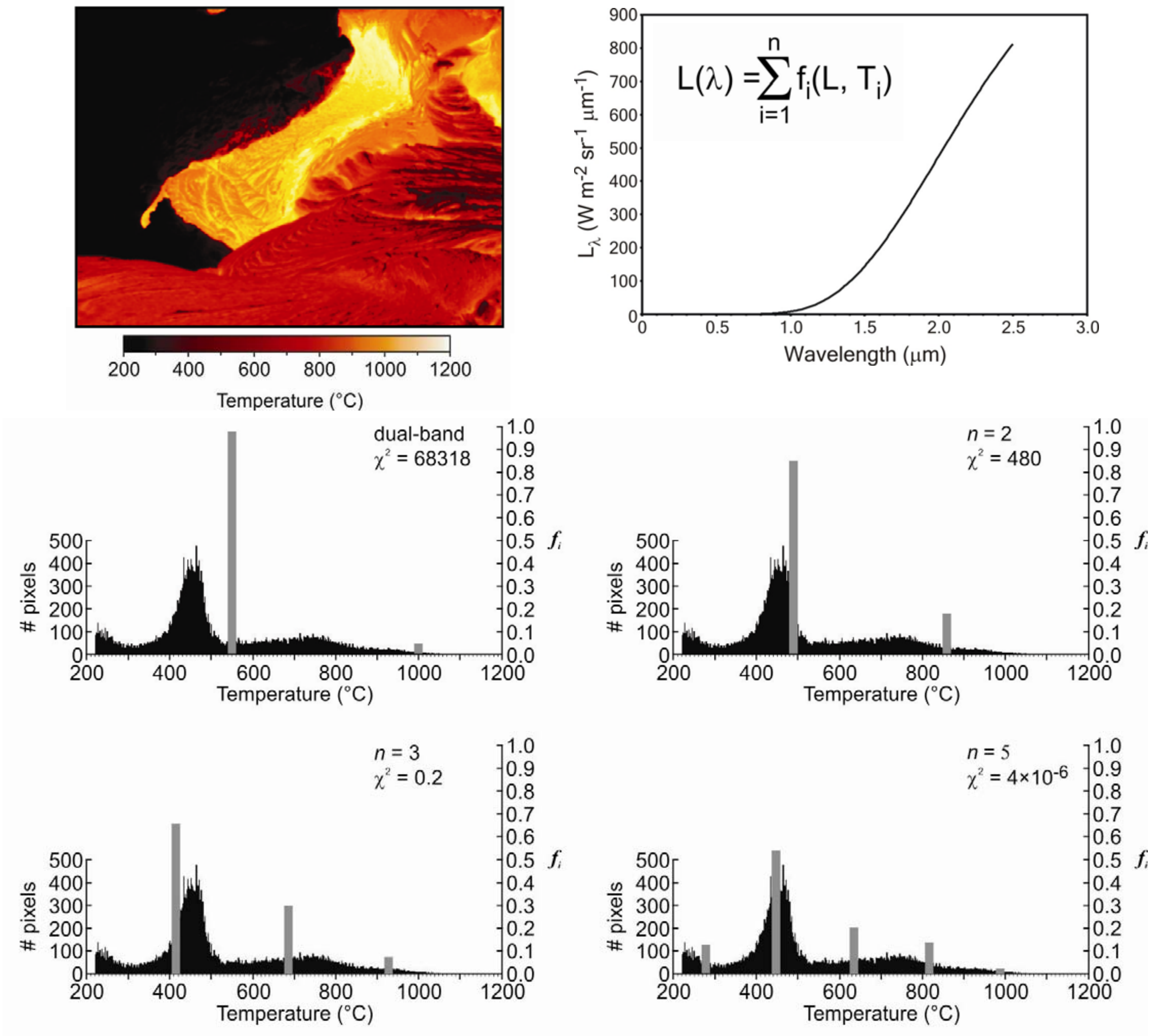
It’s important to get the temperatures right





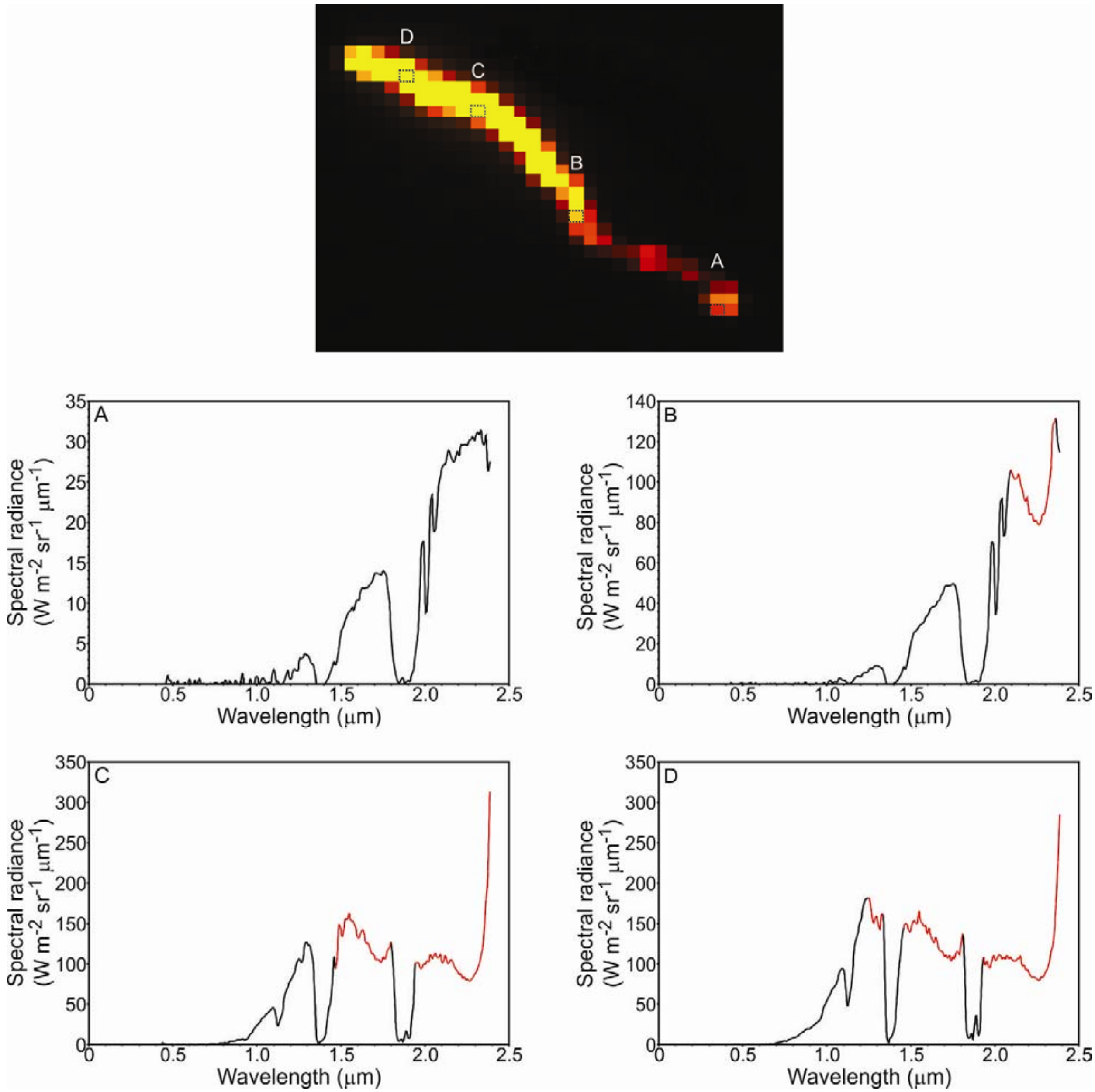


Multi-component mixture modeling of lava surface temperatures

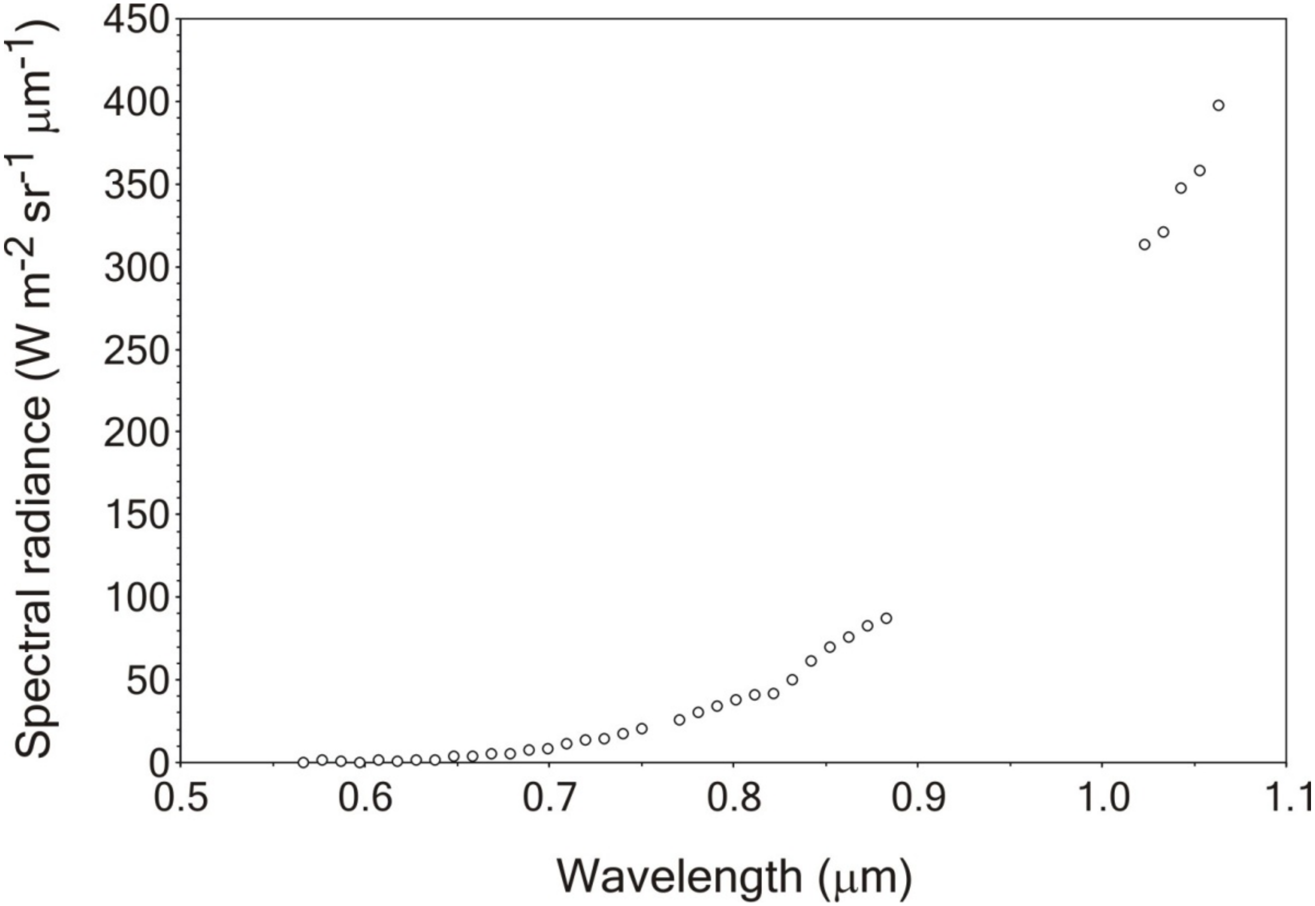


Wright and Flynn, 2003

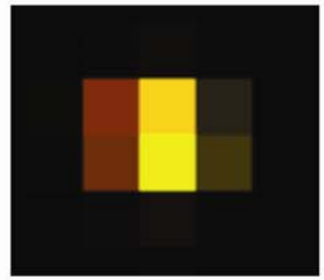
Imaging spectrometers always provide some unsaturated data…..

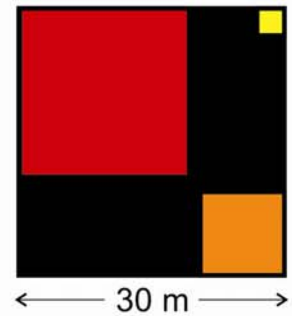


Even for the most radiant lava bodies

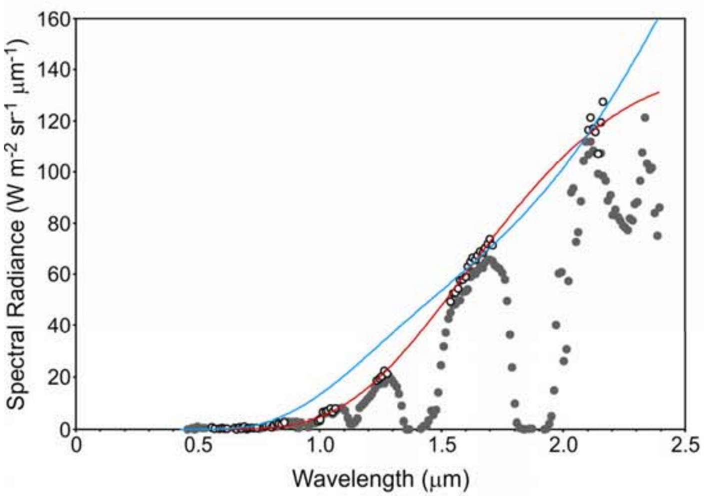


Calibration and validation of the non-linear unmixing algorithm





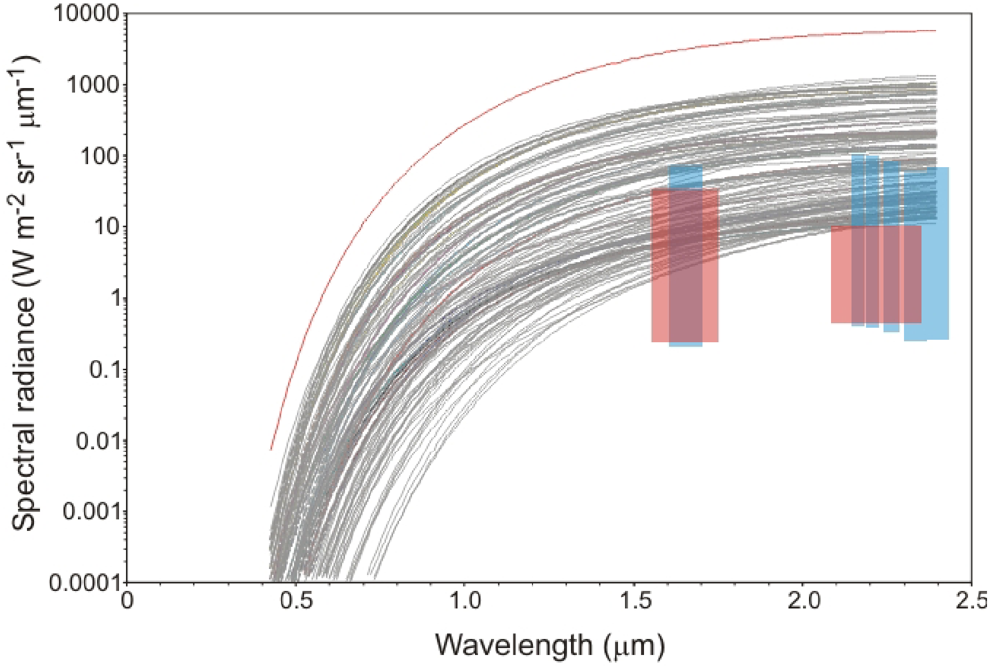
$$L(\lambda) = \sum_{i=1}^{n} f_i(L, T_i)$$

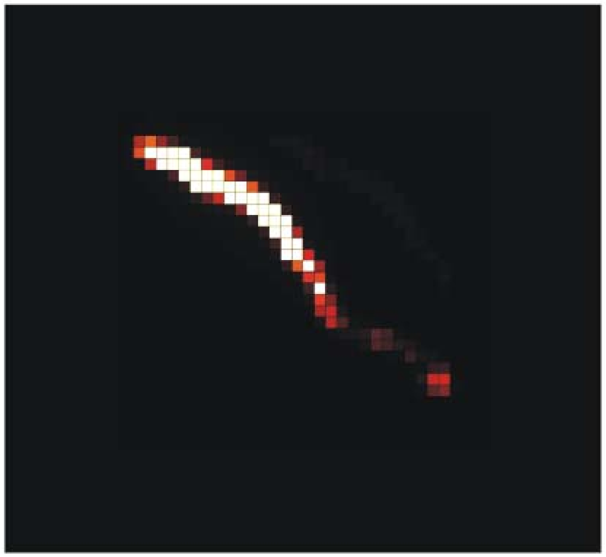


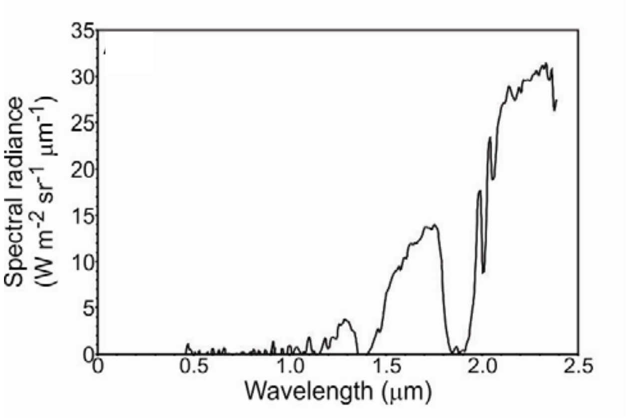
	In-situ	Hyperion
Lake area (m^2)	910	1000
Radiant flux (MW)	5-30	10
Max. T (°C)	1174	1138
Mean T (°C)	350-450	60% in this range

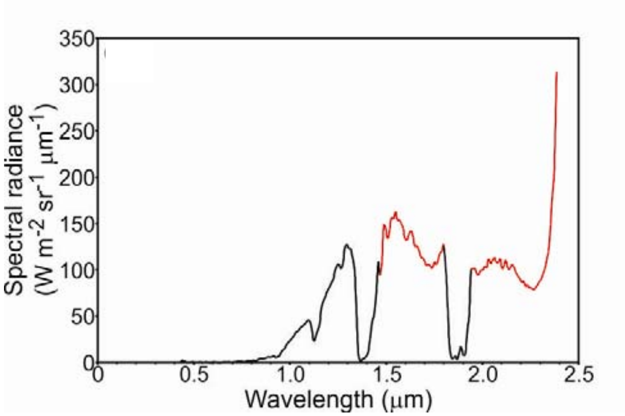
Wright et al., 2010

Volcano radiometry will rely on the availability of imaging spectrometer data



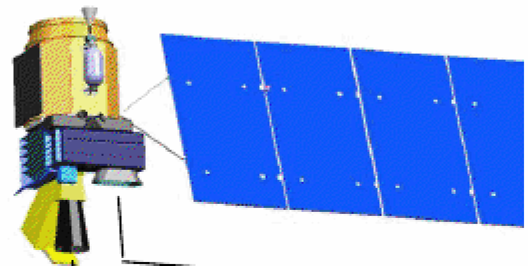






NRC Decadal Survey HyspIRI

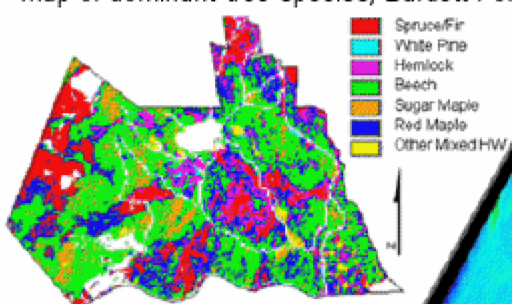
Visible ShortWave InfraRed (VSWIR) Imaging Spectrometer
+
Multispectral Thermal InfraRed (TIR) Scanner

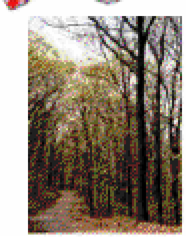


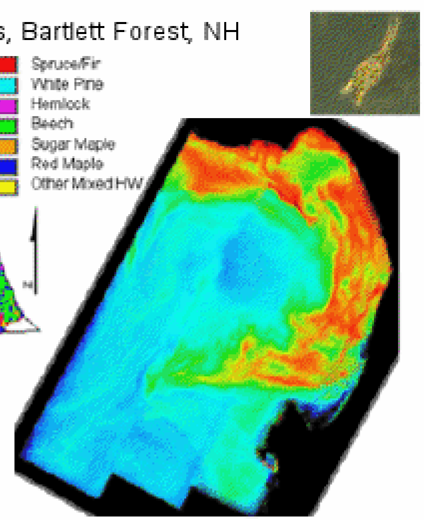
VSWIR: Plant Physiology and Function Types (PPFT)

Multispectral TIR Scanner

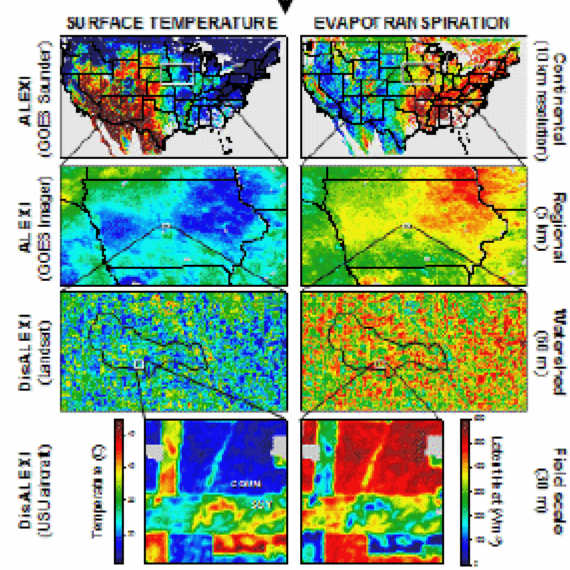
Map of dominant tree species, Bartlett Forest, NH







Red tide algal bloom in Monterey Bay, CA



Volcano monitoring techniques and algorithms

Some requirements for a space-based thermal volcano monitoring system

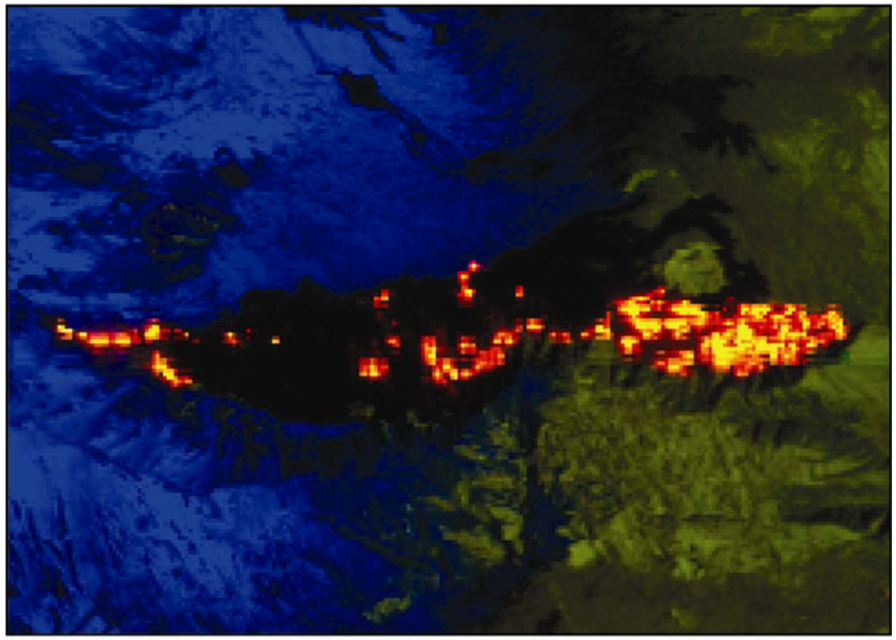


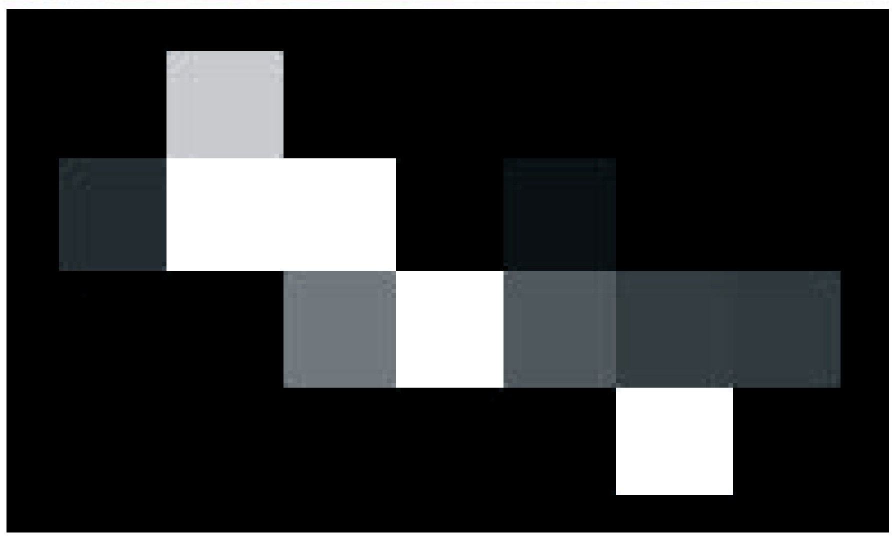


- Physical requirements
  - Should be able to detect active volcanism at the hectametre scale
  - Make repetitive, frequent observations (eruption intensity fluctuates on < hourly time scales)

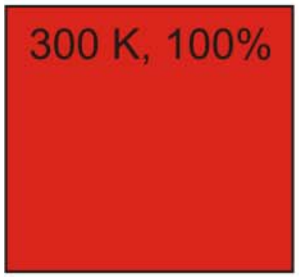
- Practicalities
  - Minimise “false” positives (erode trust in the “real” positives)
  - Depend on cost-free data
  - Objectivity
  - Minimise communication overhead (band-width a problem, and a potential failure point)
  - Allow results to be communicated ‘rapidly’
  - Any others you can think of……..?

The need for timely information drives us to use low spatial resolution sensors

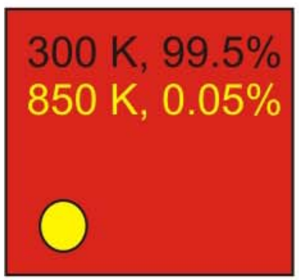




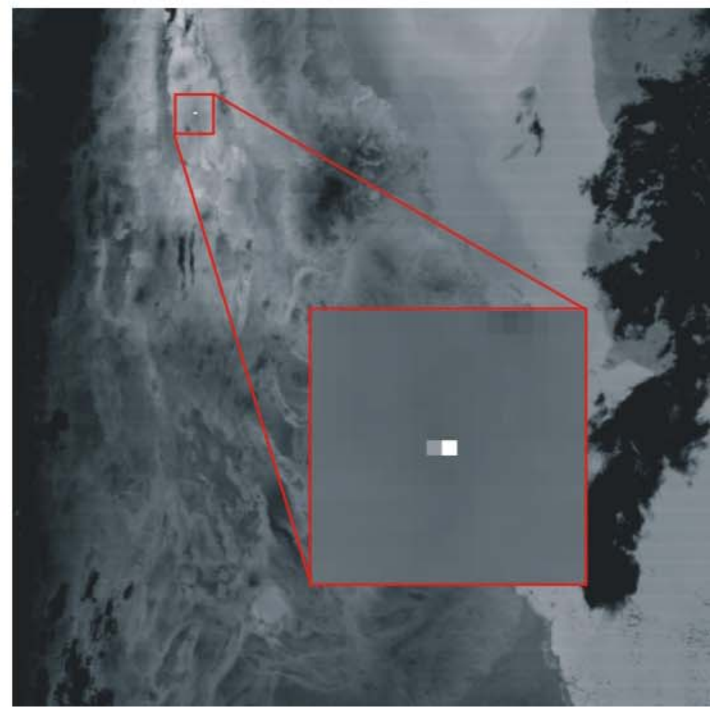
Coarse spatial resolution is no barrier to detection of lava

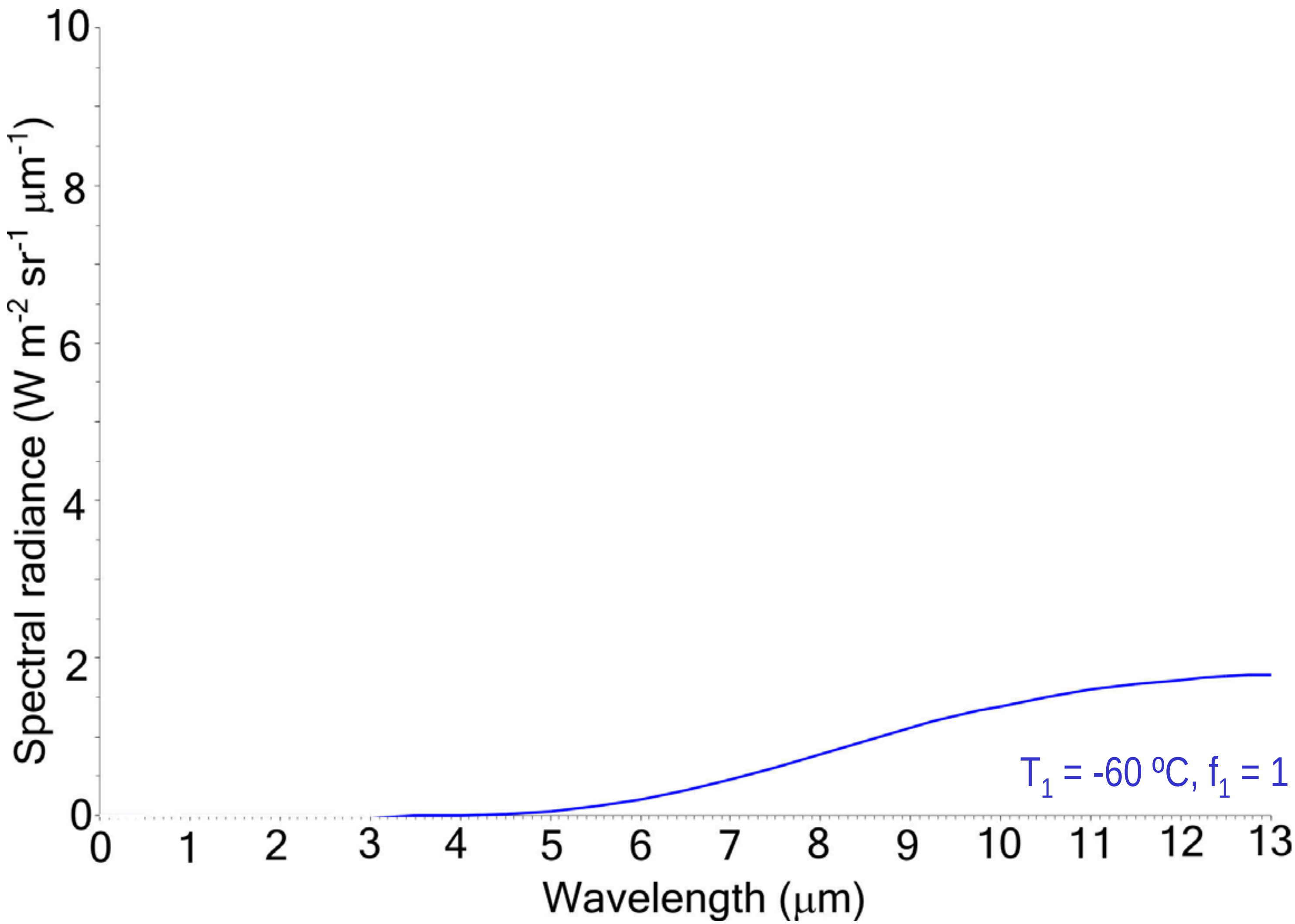


At 11 μm, L_λ = 9.5 W m^{-2} sr^{-1} μm^{-1}
At 4 μm, L_λ = 0.4 W m^{-2} sr^{-1} μm^{-1}

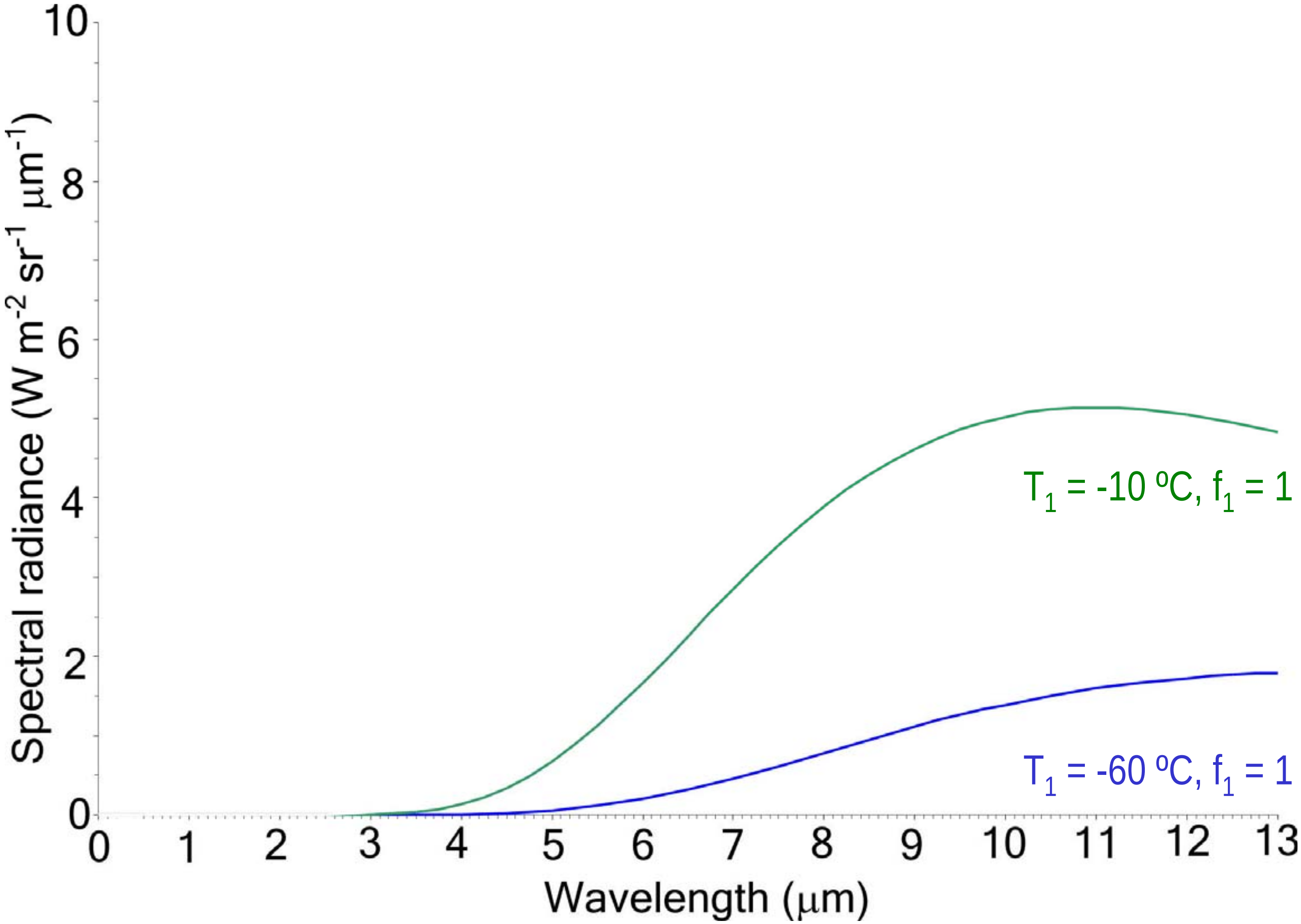


At 11 μm, L_λ = 9.6 W m^{-2} sr^{-1} μm^{-1}
At 4 μm, L_λ = 1.3 W m^{-2} sr^{-1} μm^{-1}

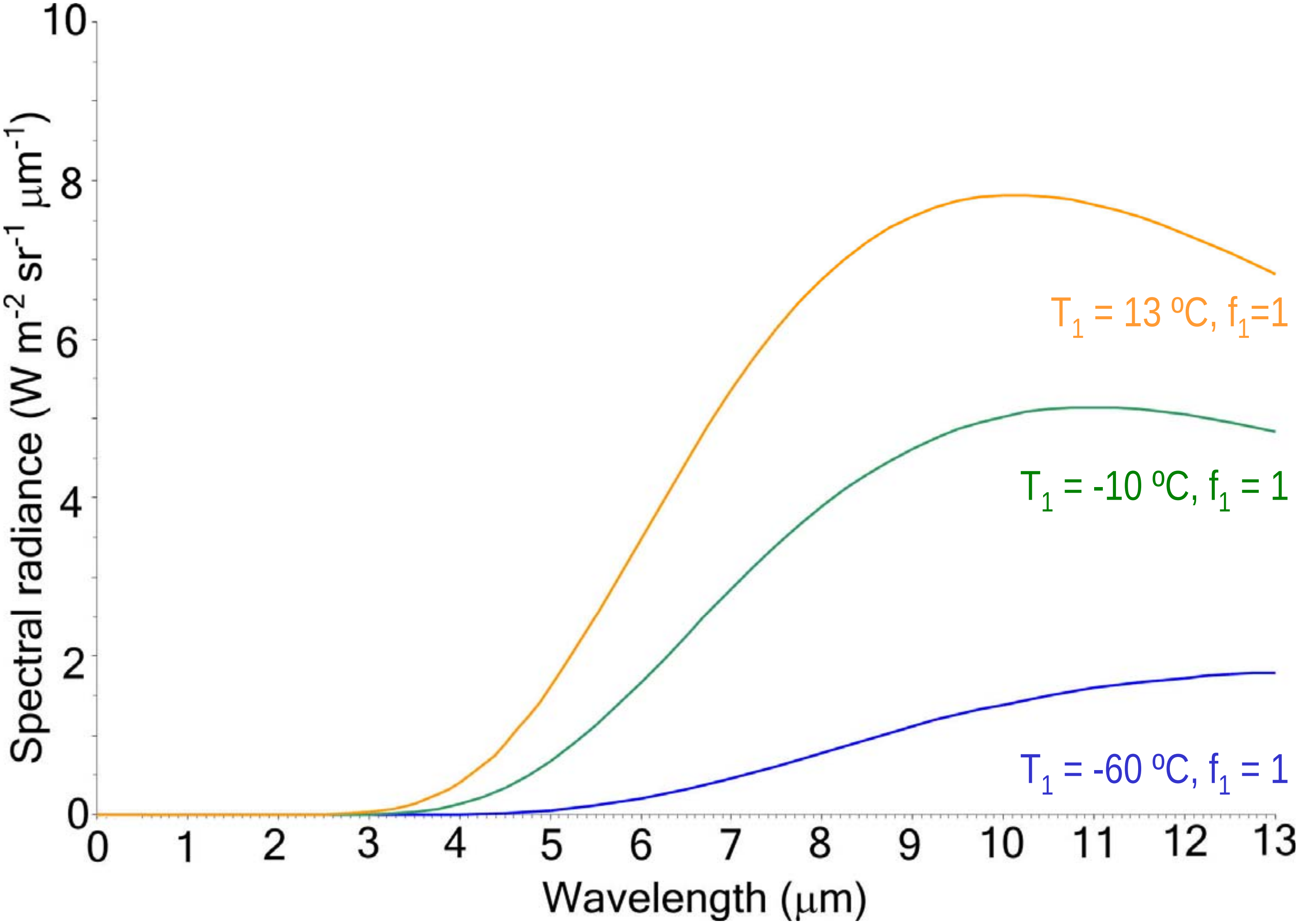




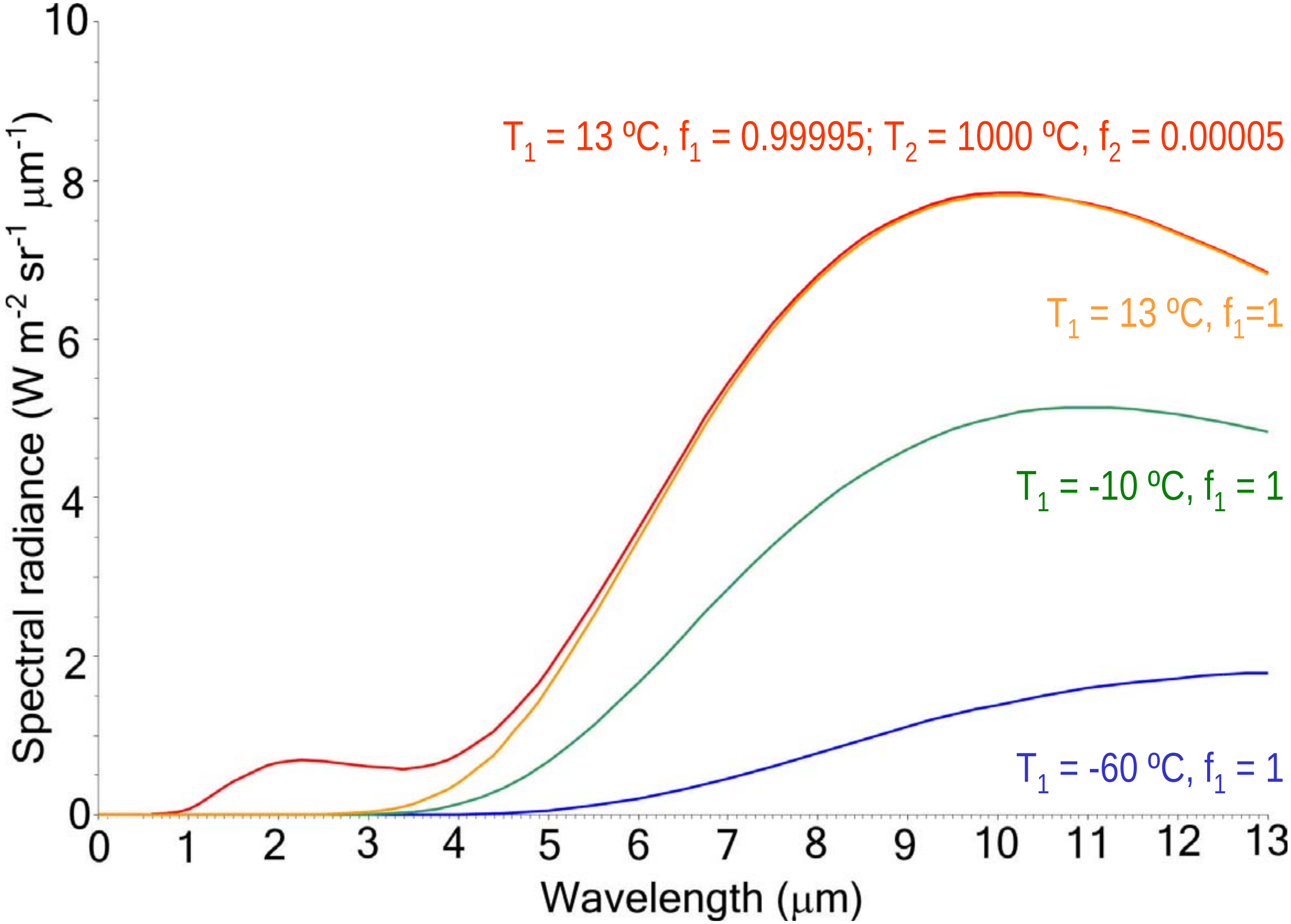
Spectral radiance (W m-2 sr-1 μm-1)
Wavelength (μm)
T1 = -60 ºC, f1 = 1



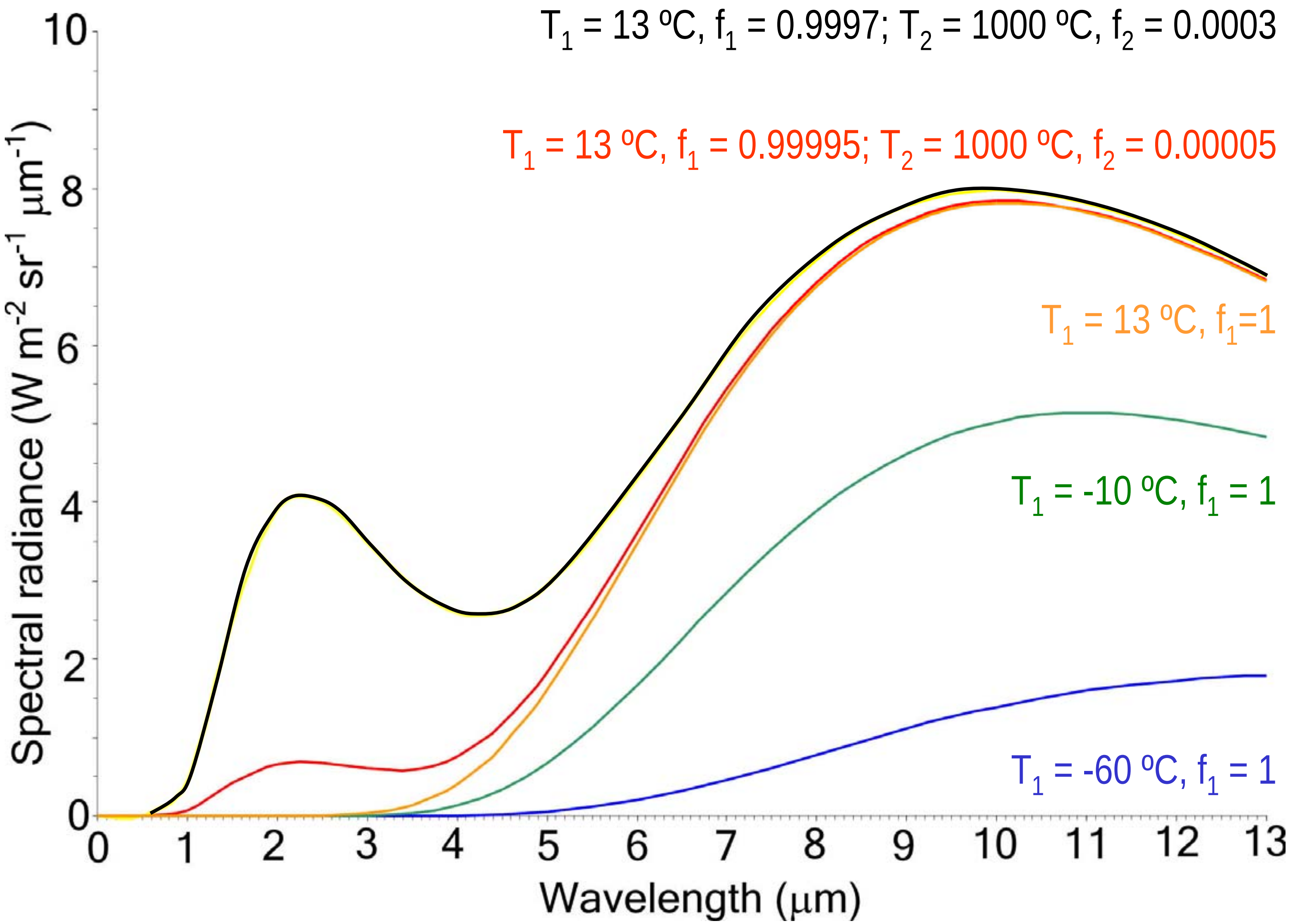
Spectral radiance (W m-2 sr-1 μm-1)
10
8
6
4
2
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
Wavelength (μm)
T1 = -10 ºC, f1 = 1
T1 = -60 ºC, f1 = 1



Spectral radiance (W m-2 sr-1 μm-1)
Wavelength (μm)
T1 = 13 ºC, f1=1
T1 = -10 ºC, f1 = 1
T1 = -60 ºC, f1 = 1
0
2
4
6
8
10
0
1
2
3
4
5
6
7
8
9
10
11
12
13



10
8
6
4
2
0
Spectral radiance (W m-2 sr-1 μm-1)
0 1 2 3 4 5 6 7 8 9 10 11 12 13
Wavelength (μm)
T1 = 13 ºC, f1 = 0.99995; T2 = 1000 ºC, f2 = 0.00005
T1 = 13 ºC, f1=1
T1 = -10 ºC, f1 = 1
T1 = -60 ºC, f1 = 1



T1 = 13 ºC, f1 = 0.9997; T2 = 1000 ºC, f2 = 0.0003
T1 = 13 ºC, f1 = 0.99995; T2 = 1000 ºC, f2 = 0.00005
T1 = 13 ºC, f1=1
T1 = -10 ºC, f1 = 1
T1 = -60 ºC, f1 = 1
Spectral radiance (W m-2 sr-1 μm-1)
Wavelength (μm)
0
2
4
6
8
10
0 1 2 3 4 5 6 7 8 9 10 11 12 13

How easy is it to detect different kinds of volcanic unrest?

- Ability to detect the thermal emission associated with volcanic activity depends on:
  - The temperature of the lava/process
  - The area it covers
  - Its longevity

Easier ⟷ *Harder*

Basic lava flows

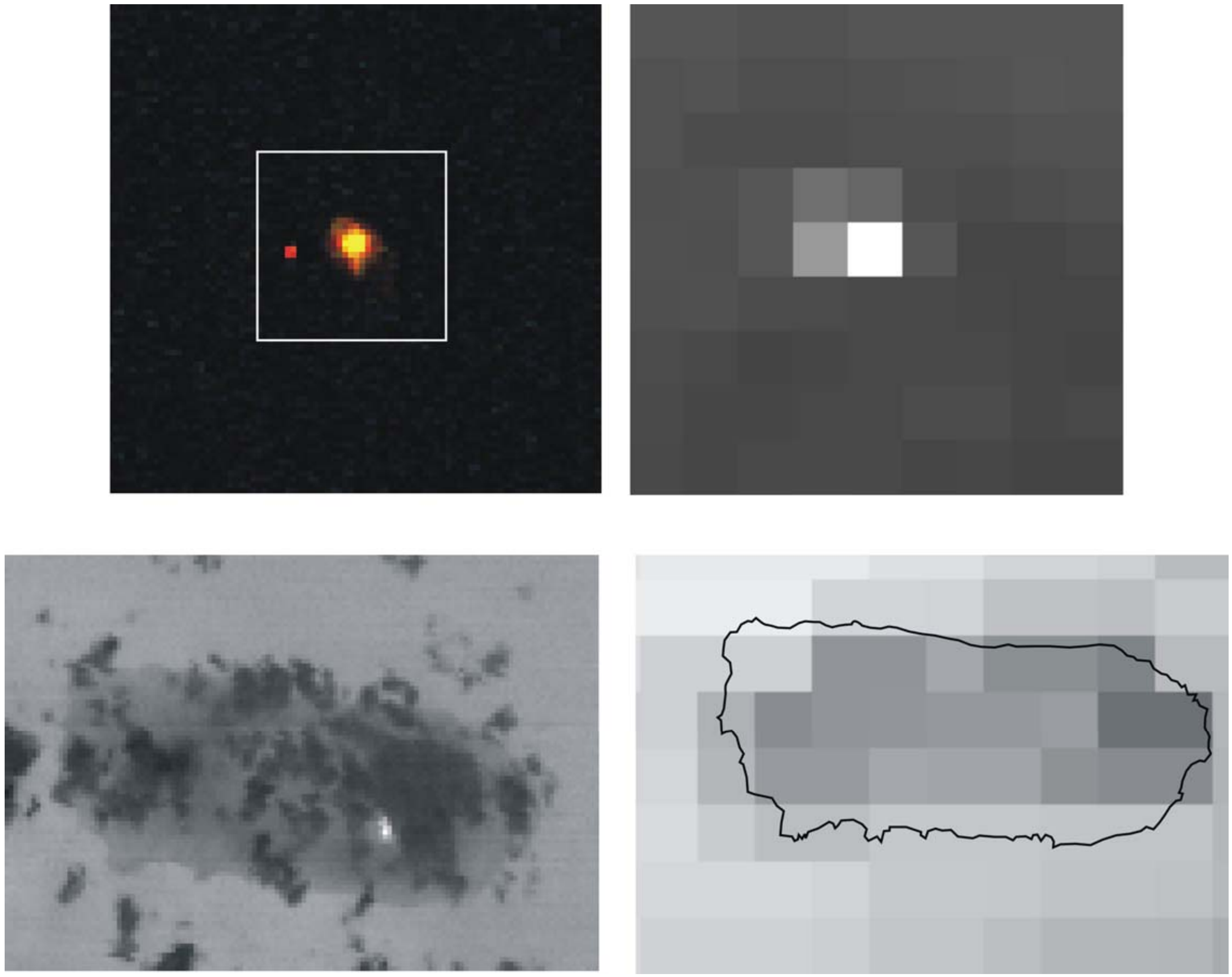
Basic lava lakes

Acidic lava domes

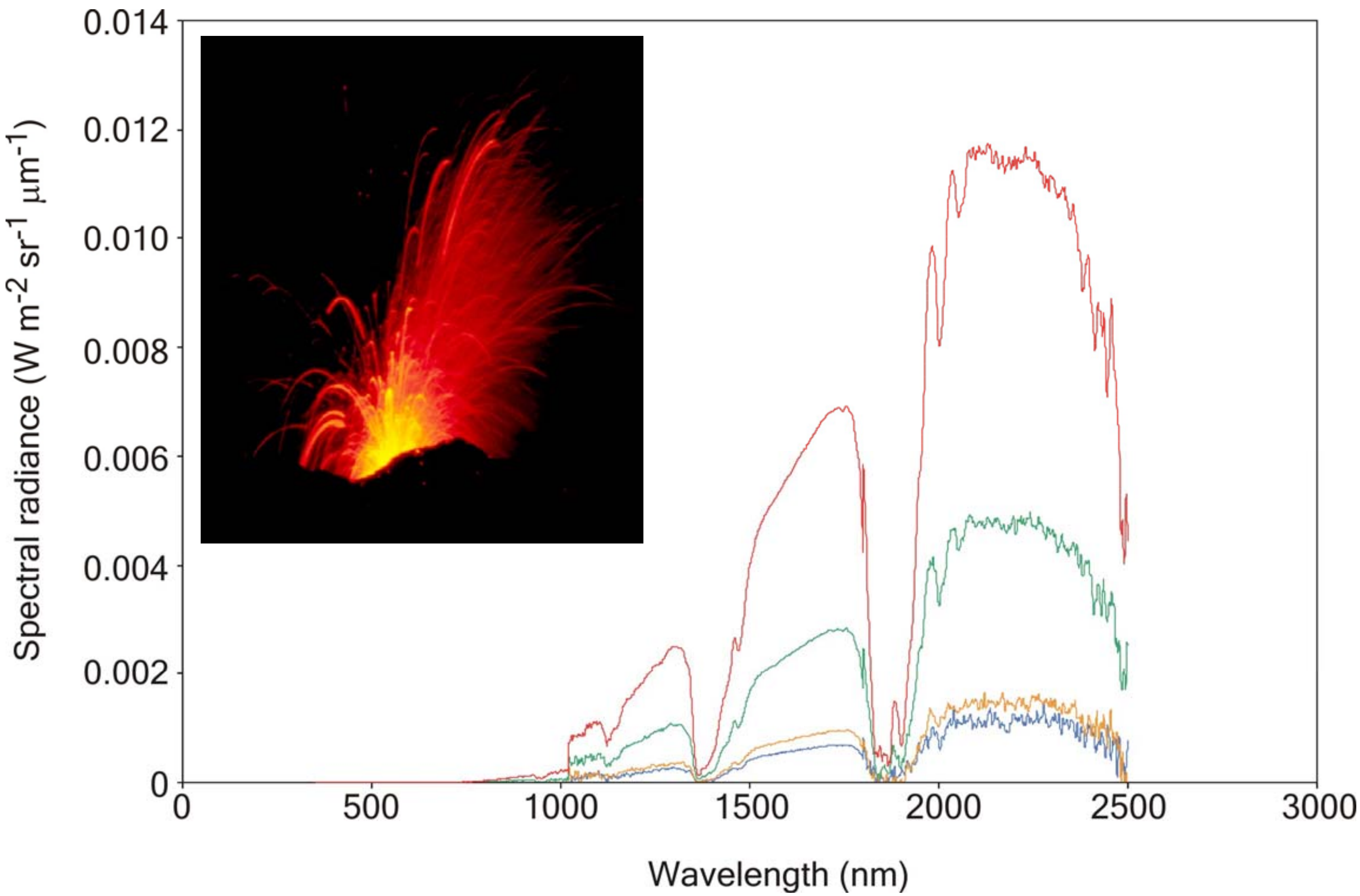
Acidic lava flows

Strombolian activity
Fumarolic activity
Hydrothermal activity
etc.

Lava = “easier”; hydrothermal = “harder”

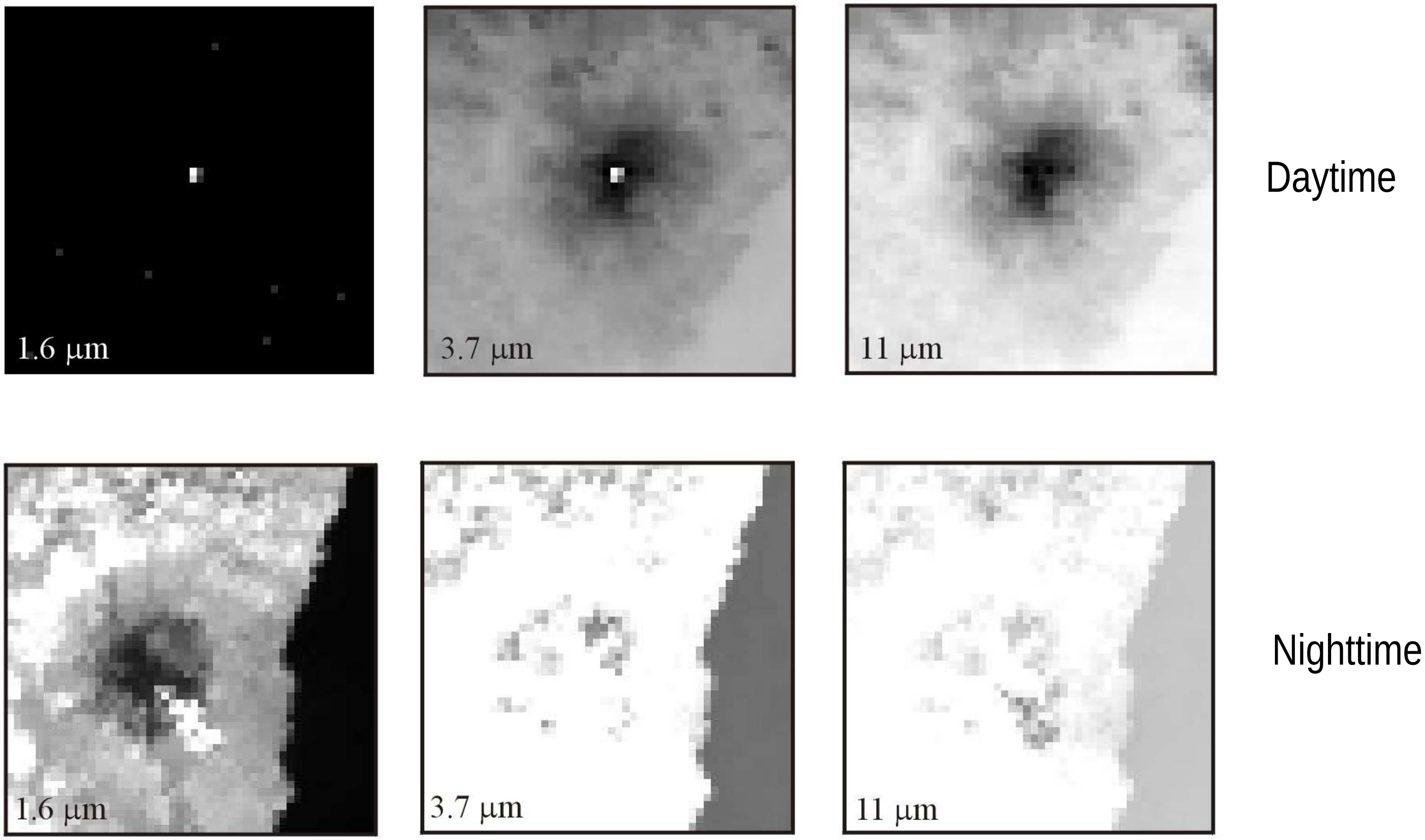


Persistent = “easier”; transient = “harder”



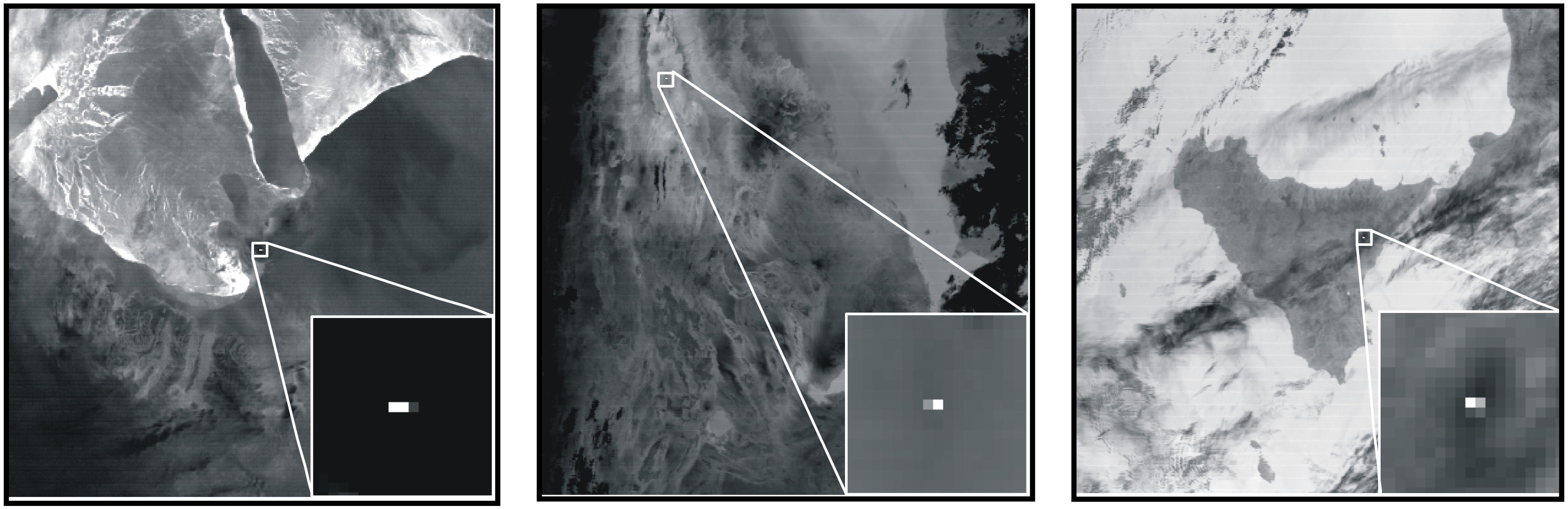
ASD derived spectra of Mount Etna’s South East Crater, October 1998

4 μm data are the workhorse of low resolution volcano monitoring

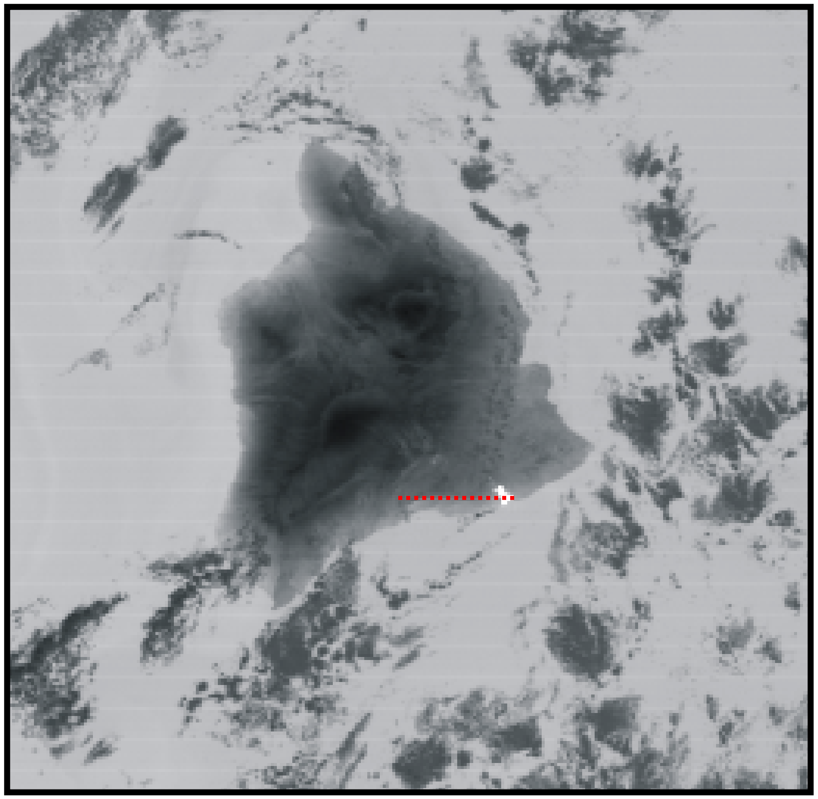


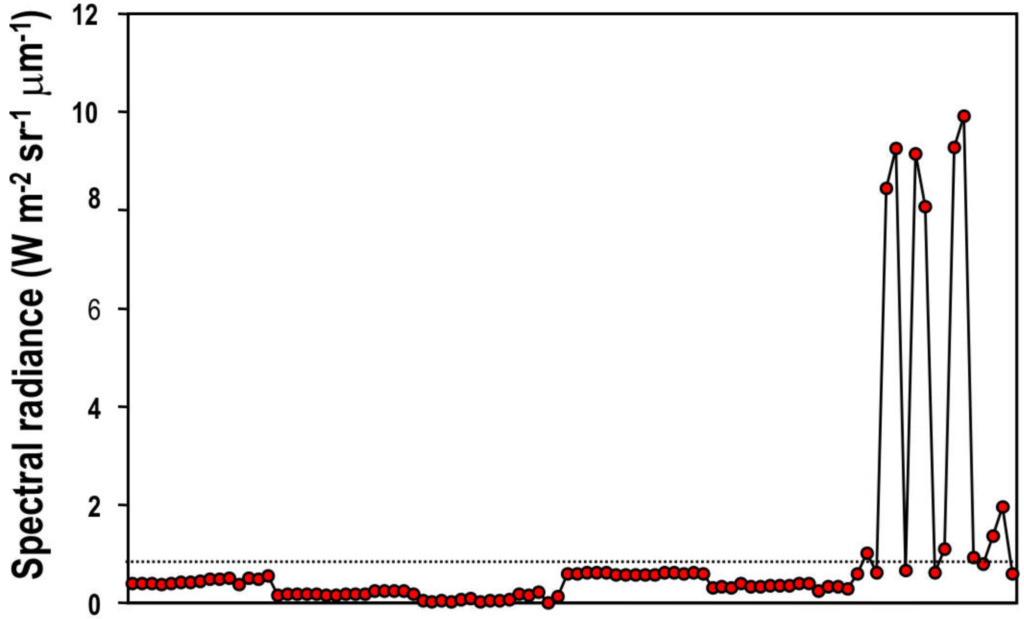
- How can the data be used to automatically detect thermal unrest at Earth's volcanoes?

Brute force

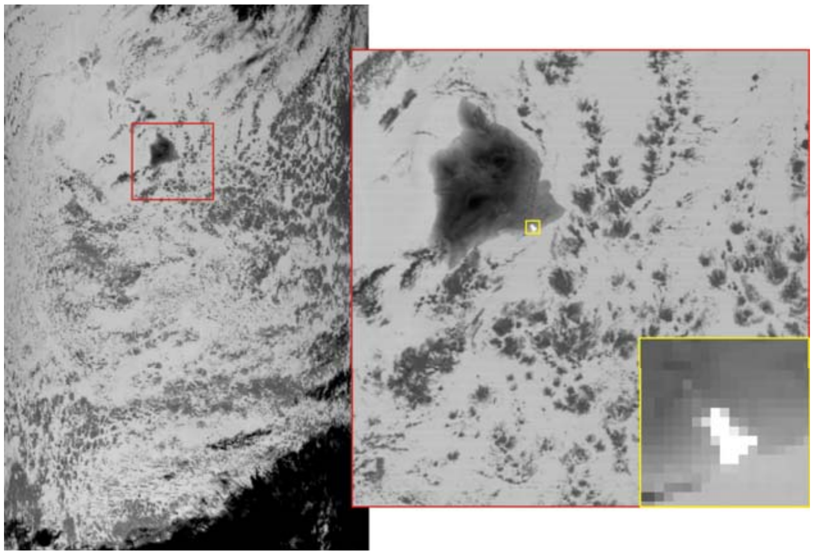


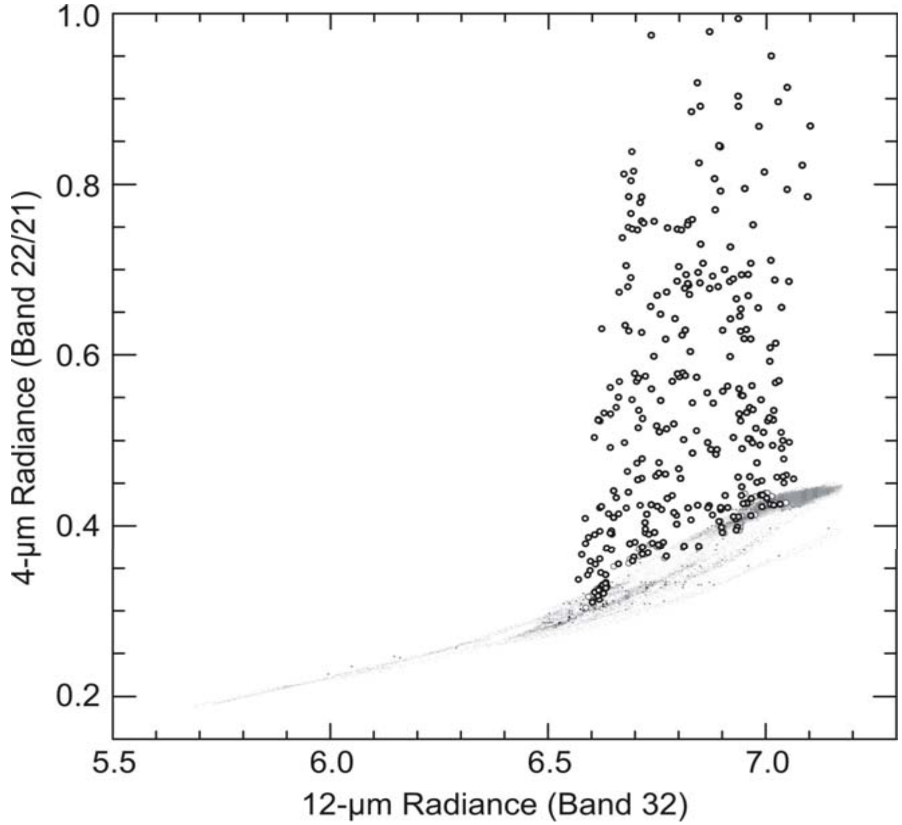
Single wavelength thresholds



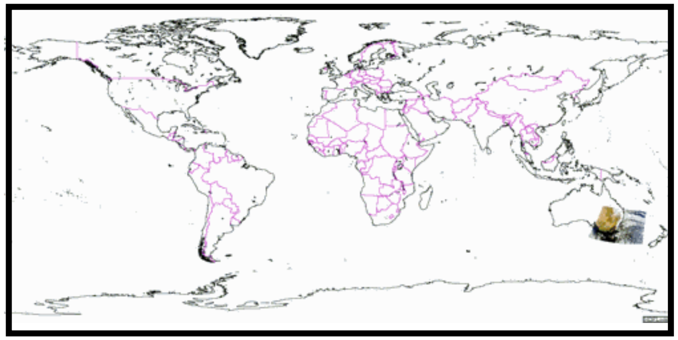


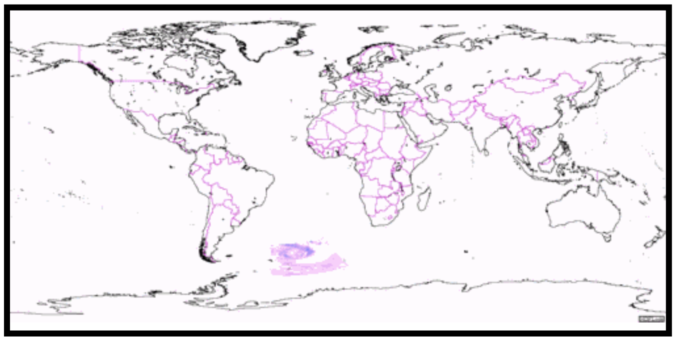
4 μm vs. 12 μm allow volcanogenic radiance sources to be distinguished

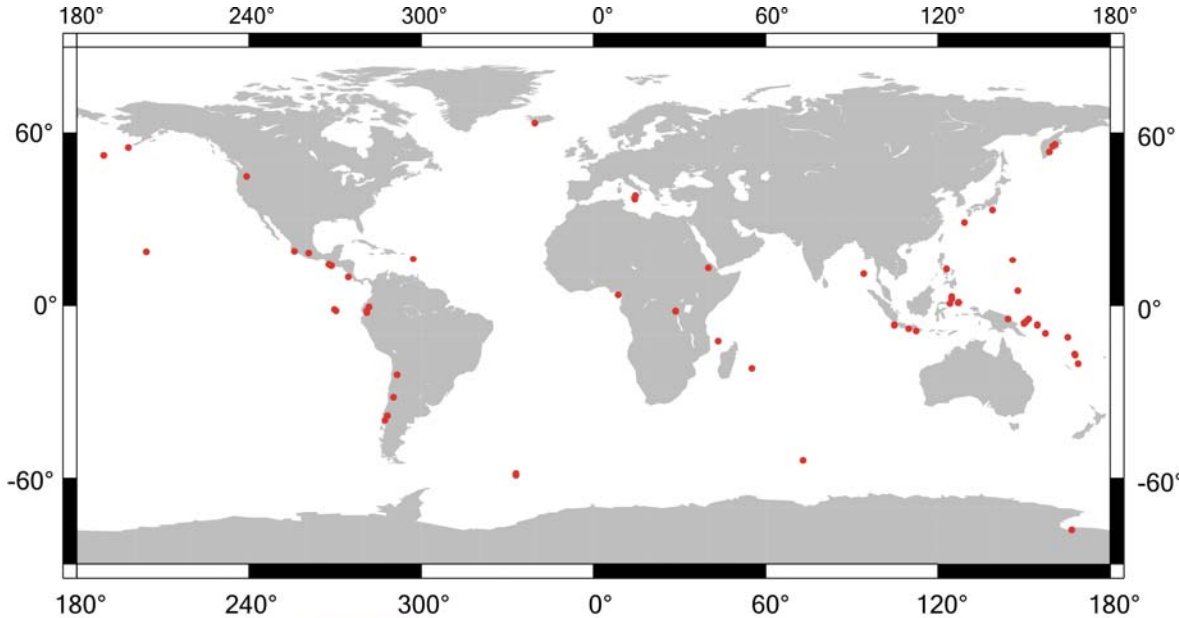




MODVOLC: an operational algorithm for global volcano monitoring

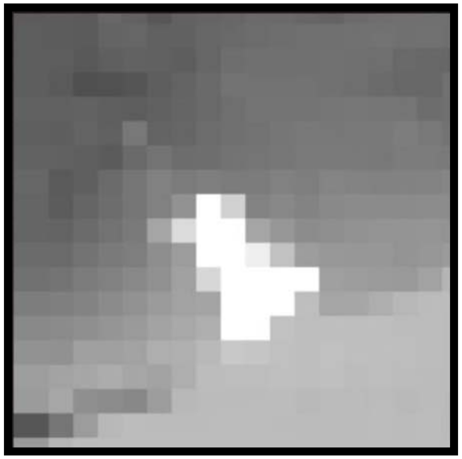


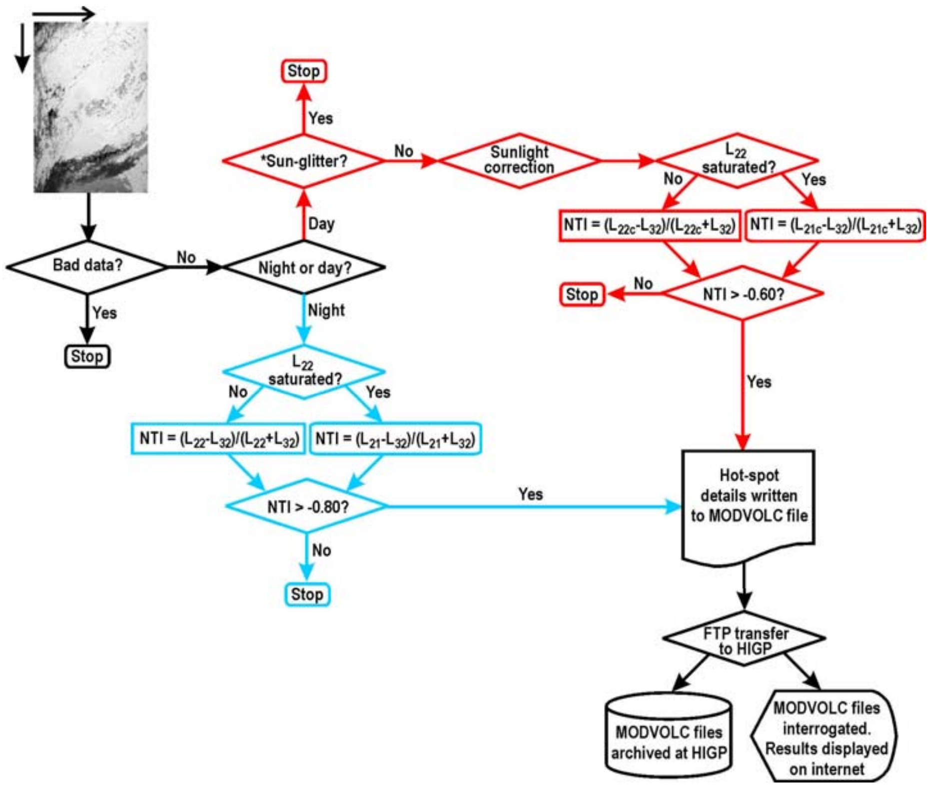


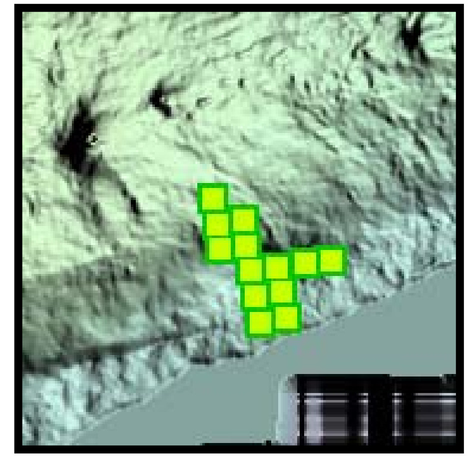


- Operational system for the timely detection and cataloguing of volcanic eruptions around the world
- Requirements: 1) Detect elevated levels of thermal emission at the pixel/sub-pixel scale
  2) Return accurate location information for hot-spots
  3) Operate in near-real-time
- Constraints: 1) Point operation
  2) No more than 5 mathematical operations
  3) No external data dependencies

MODVOLC: algorithm and output

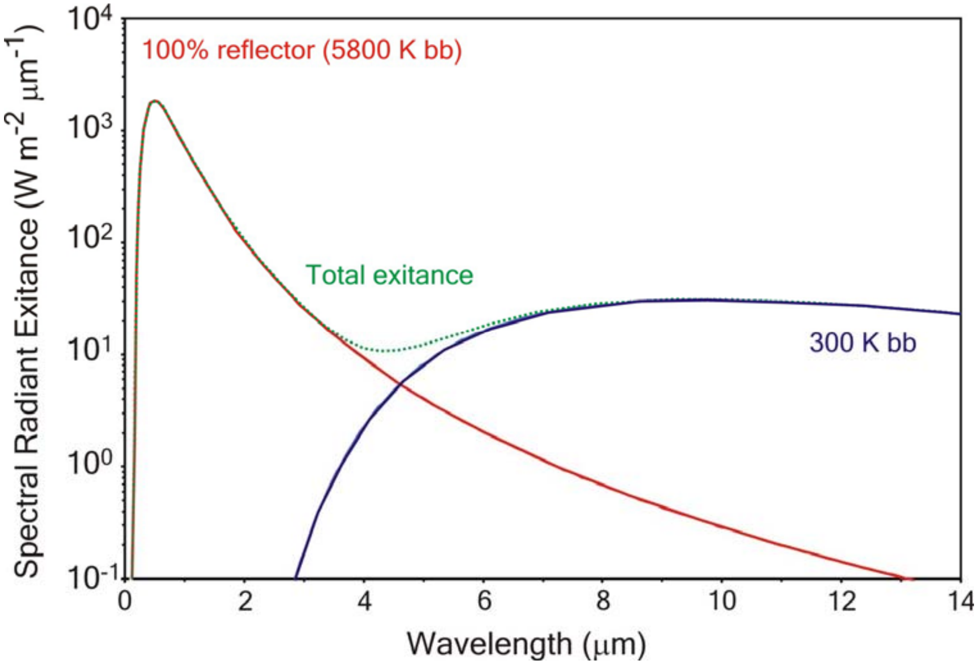






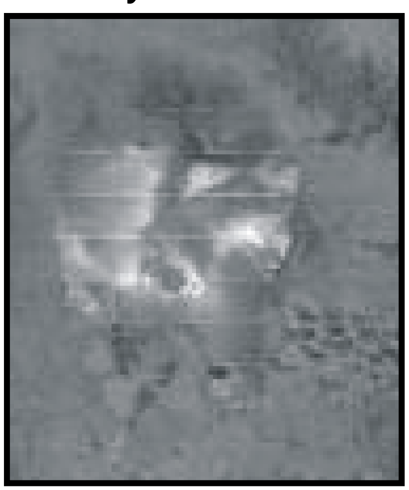
Unix time	Satellite	Year	Month	Day	Hour	Minute	Longitude	Latitude	L_{21}	L_{22}	L_6	L_{31}	L_{32}	Satellite zenith	Satellite azimuth	Sunzenith	Sun azimuth	Line	Sample	NTI	Glint vector
									W m^{-2} sr^{-1} μm^{-1}												
1089853500	A	2004	07	14	15	05	159.424927	54.047855	0.775	0.802	177.015	7.087	6.790	42.97	96.49	101.53	22.91	329	210	-0.789	109.602
1089838800	T	2004	07	14	11	00	159.439728	54.049419	2.228	-10.000	166.546	8.392	7.967	5.88	75.11	98.09	325.58	793	743	-0.563	95.933
1089853500	A	2004	07	14	15	05	159.448288	54.052444	1.440	1.453	177.015	7.786	7.453	42.97	97.57	101.53	22.93	331	211	-0.674	108.869
1089853500	A	2004	07	14	15	05	159.453903	54.045853	1.218	1.235	177.015	7.558	7.156	42.97	96.49	101.53	22.93	329	211	-0.706	109.617

Dealing with daytime 4 μm data



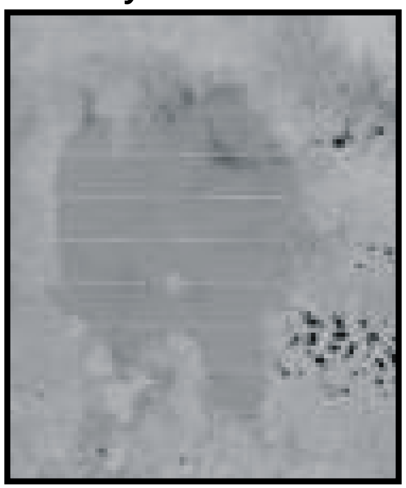
- 'Cold' but 'reflective' surfaces can generate false positives (e.g. snow, sand)
- Need to isolate emitted portion of pixel radiance

'Raw' 4 μm daytime data

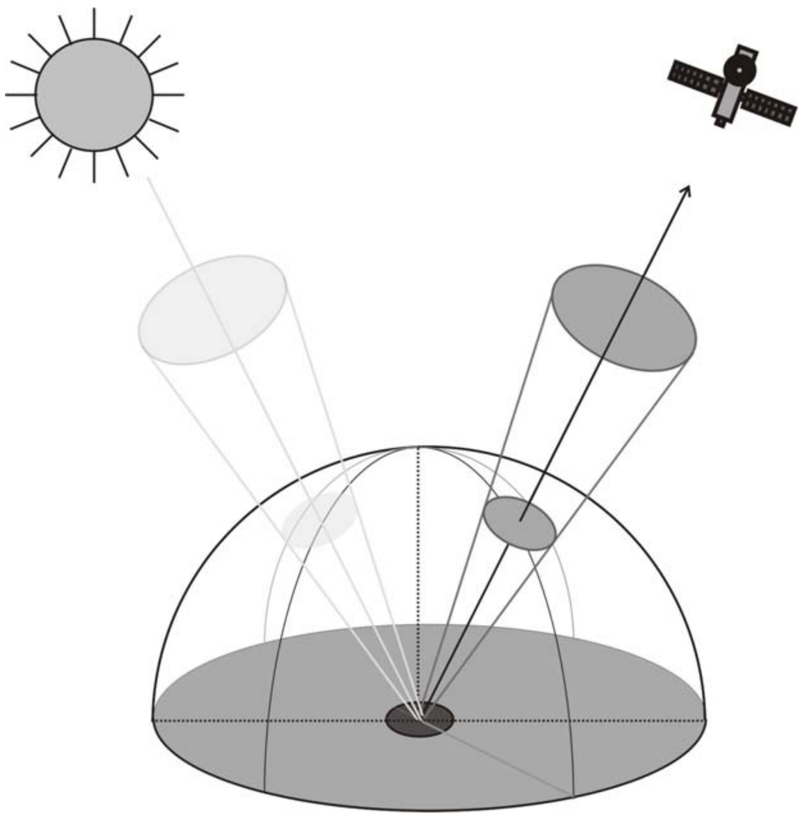


$$L_{4corr} = L_4 - 0.0426 \times L_{1.6}$$

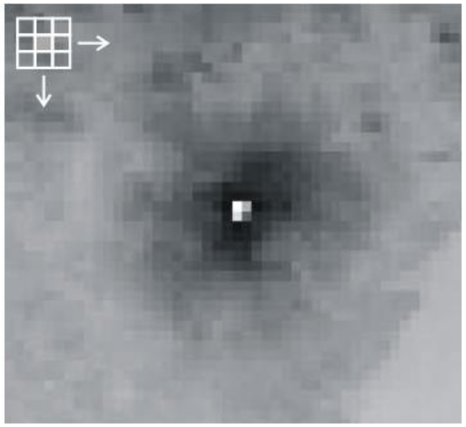
Corrected 4 μm daytime data

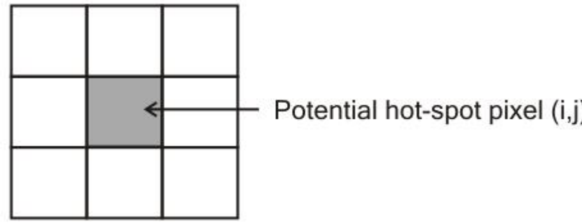


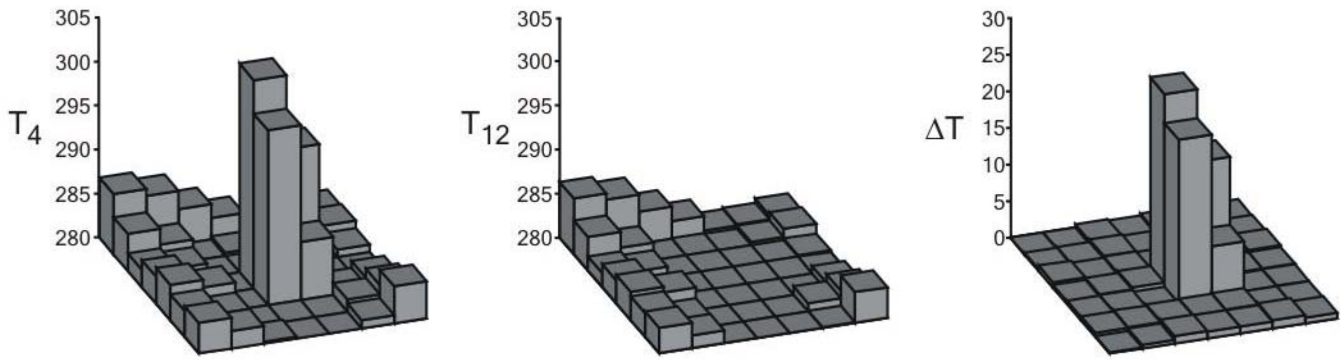
Must also account for sunglint in daytime data



A generic contextual hot-spot detection algorithm







$T_{4,b}$	$T_{4,b}$	$T_{4,b}$
$T_{4,b}$	$T_{4,(i,j)}$	$T_{4,b}$
$T_{4,b}$	$T_{4,b}$	$T_{4,b}$

ΔT_b	ΔT_b	ΔT_b
ΔT_b	$\Delta T_{(i,j)}$	ΔT_b
ΔT_b	ΔT_b	ΔT_b

Potential hot-spot pixel reclassified as an actual hot-spot pixel when:

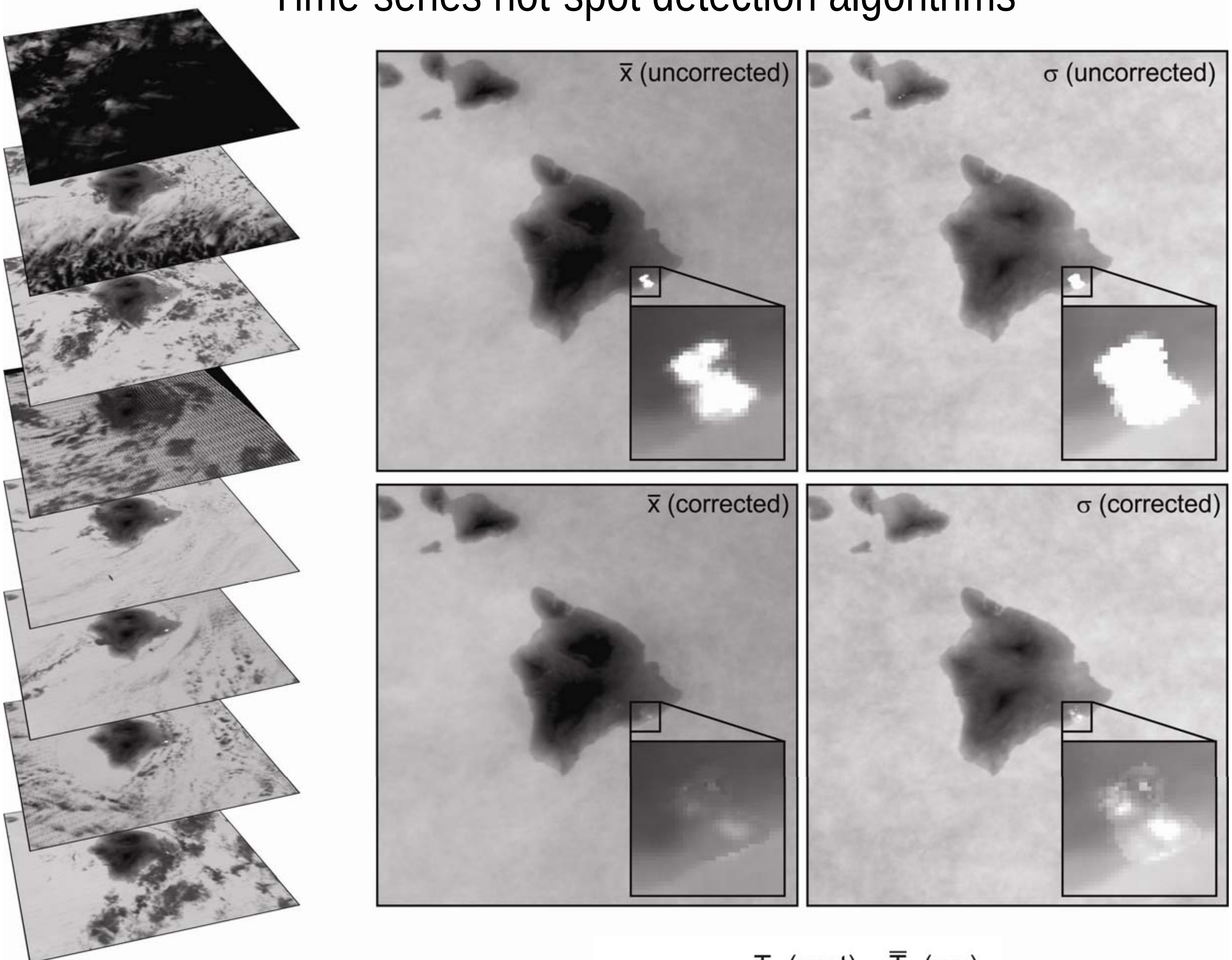
$$T_{4,(i,j)} > \bar{T}_{4,b} + n\sigma\bar{T}_{4,b}$$

and

$$\Delta T_{(i,j)} > \Delta\bar{T}_b + n\sigma\Delta\bar{T}_b$$

Giglio et al., 2003

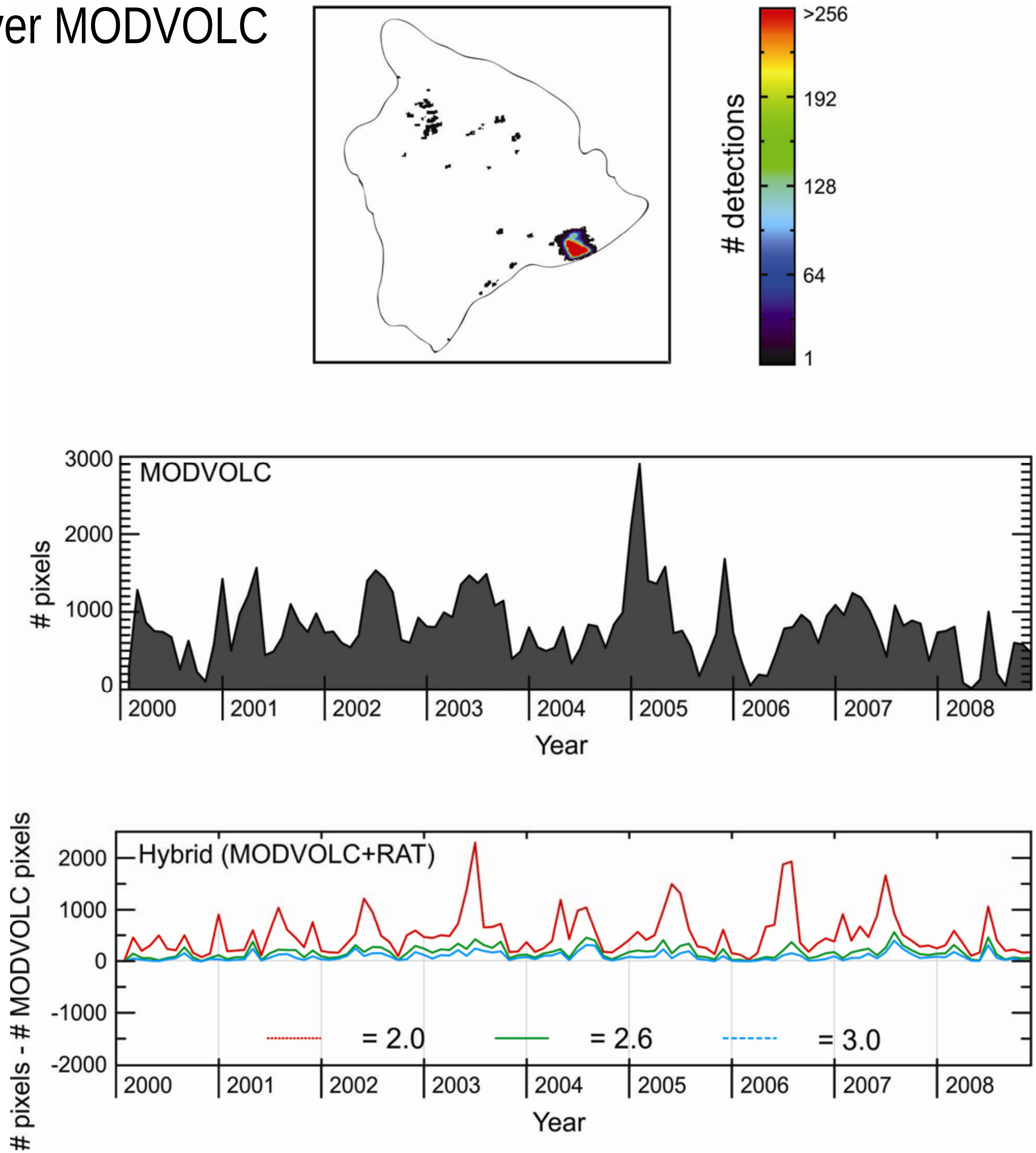
Time-series hot-spot detection algorithms



$$\otimes T_4(x,y,t) = \frac{T_4(x,y,t) - \overline{T}_4(x,y)}{\sigma_4(x,y)}$$

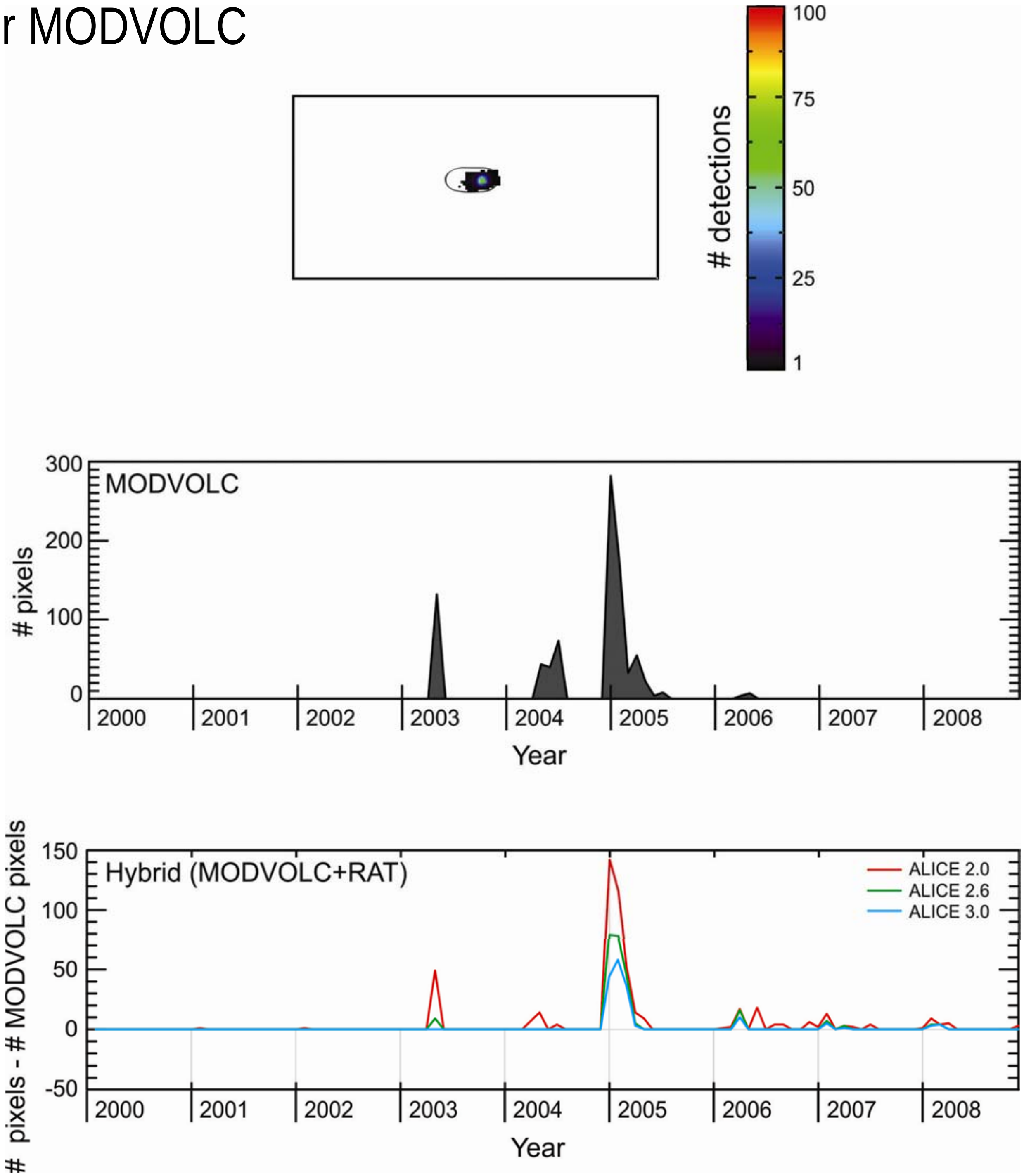
Koeppen et al., 2010, after Pergola et al., 2004

Improved performance over MODVOLC



Koeppen et al., 2010

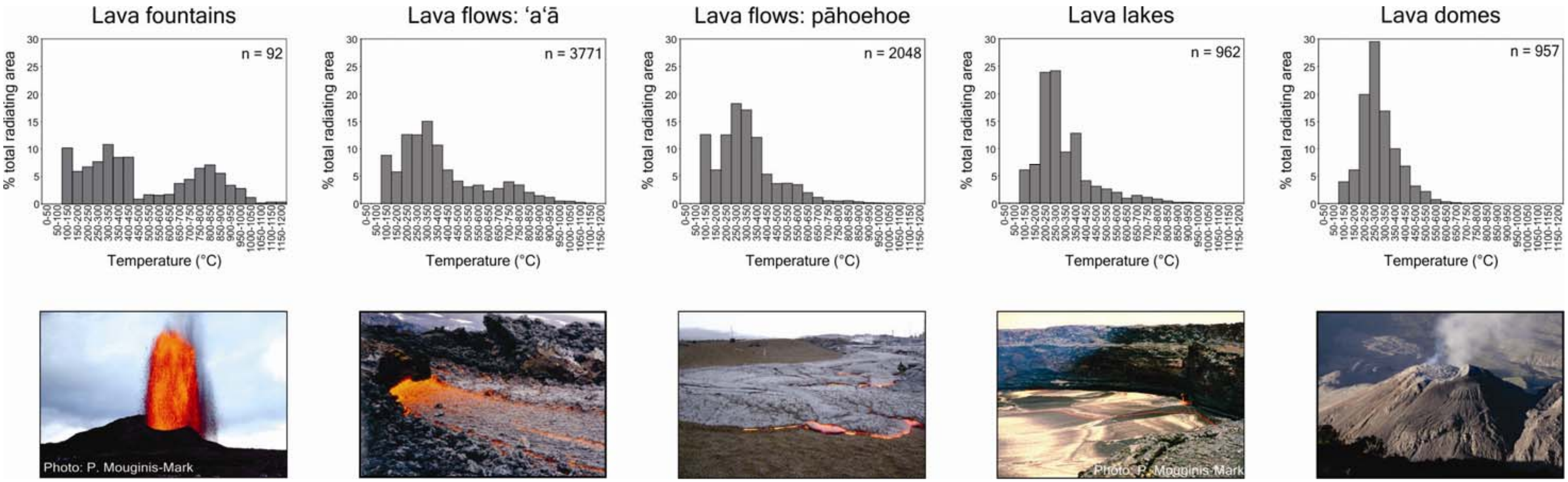
Improved performance over MODVOLC



Koeppen et al., 2010

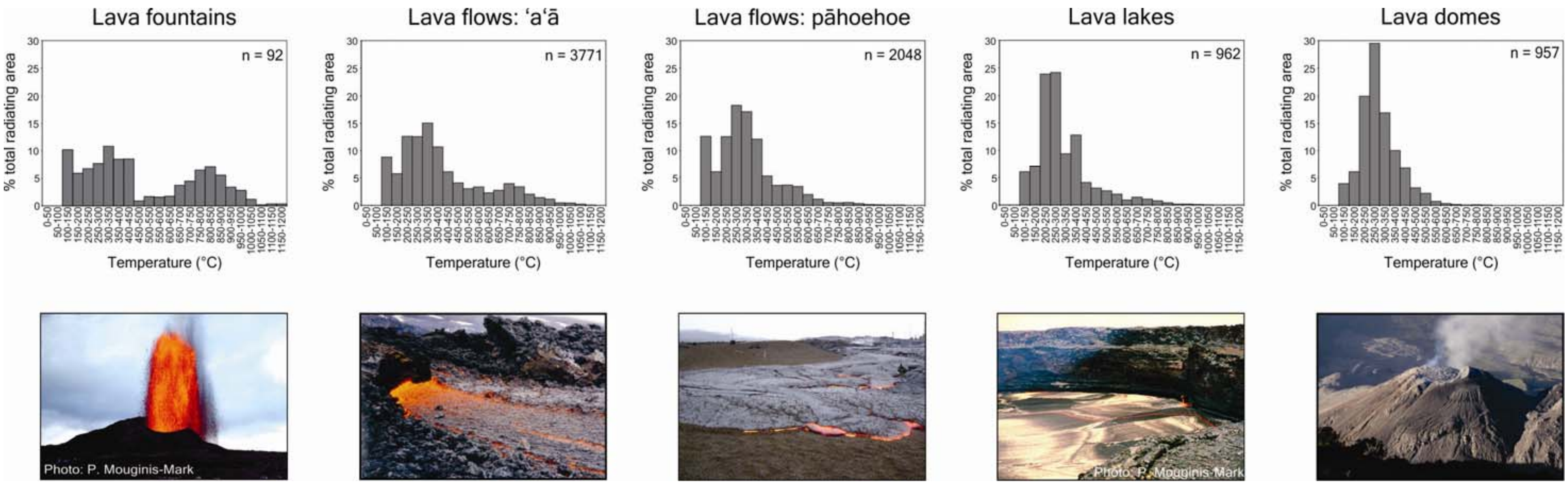
Application of the data

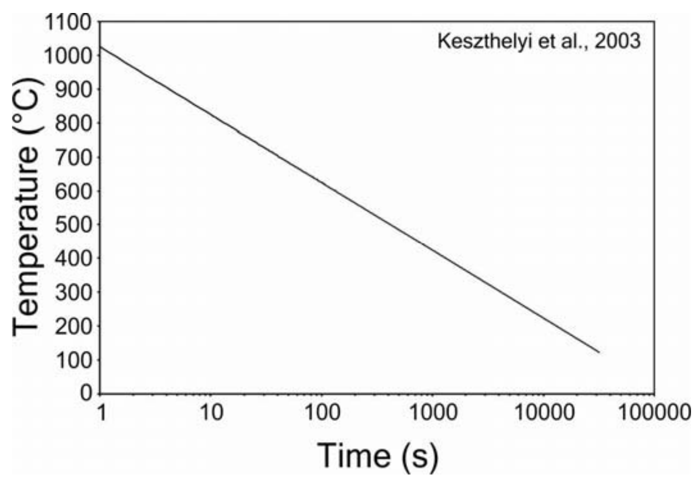
Lava composition and eruption style can be determined remotely from temperature data alone



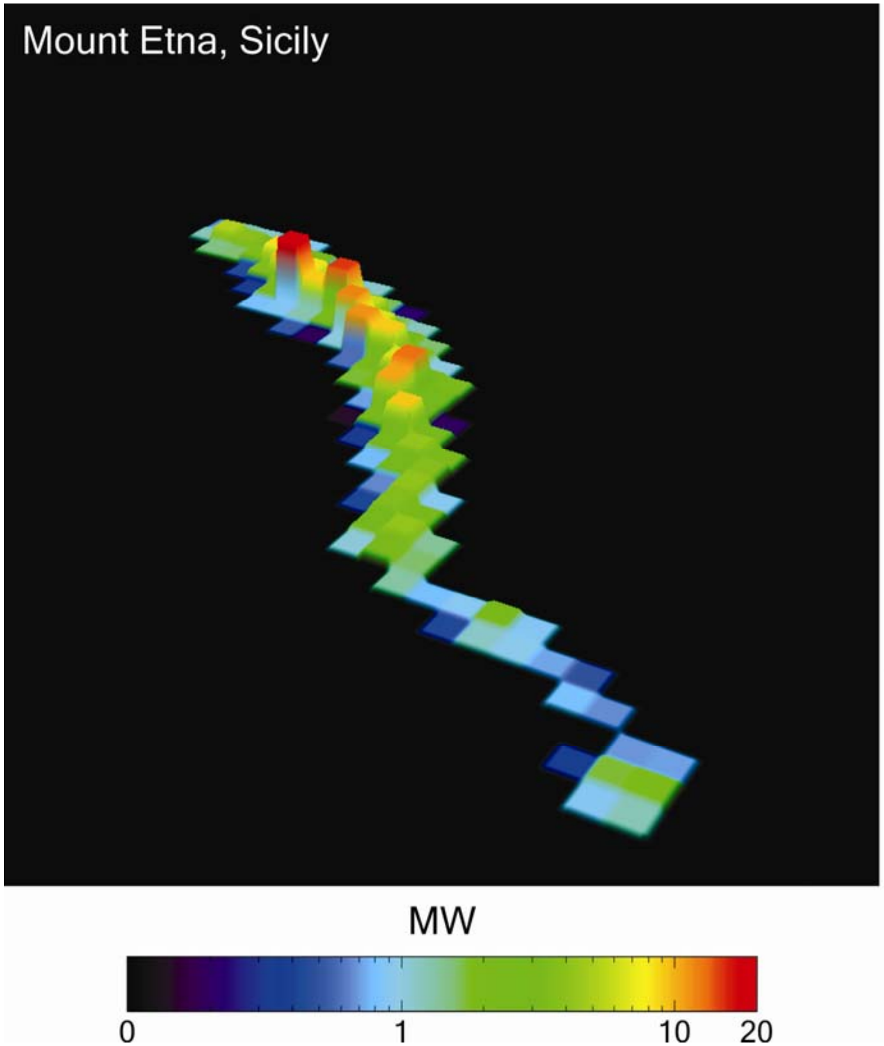
Wright, in prep.

Lava composition and eruption style can be determined remotely from temperature data alone

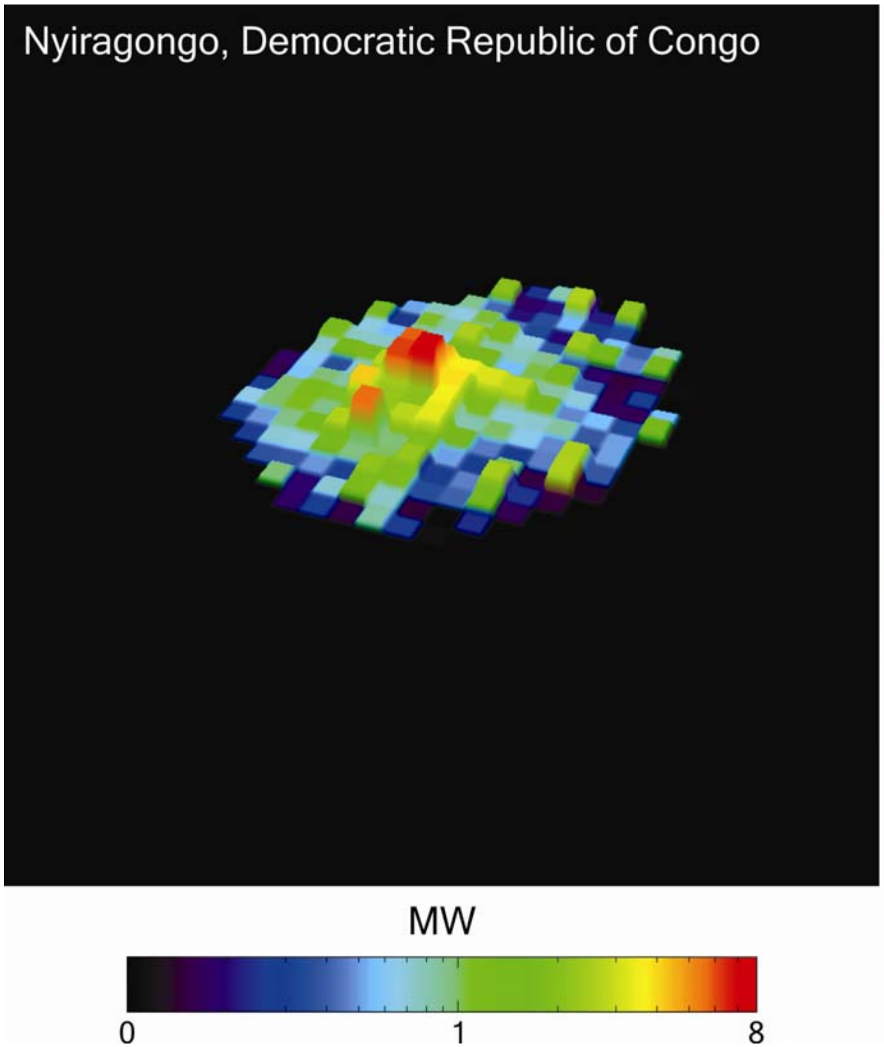




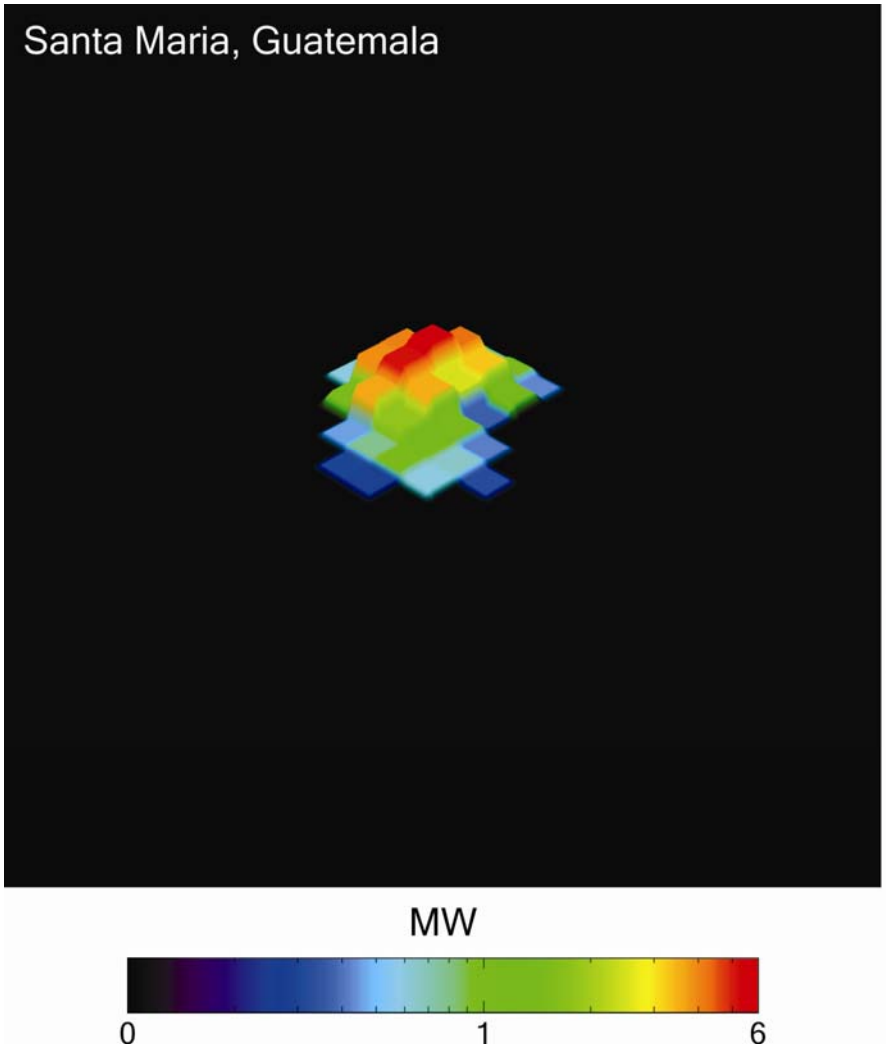
Lava cooling rates determined using Hyperion



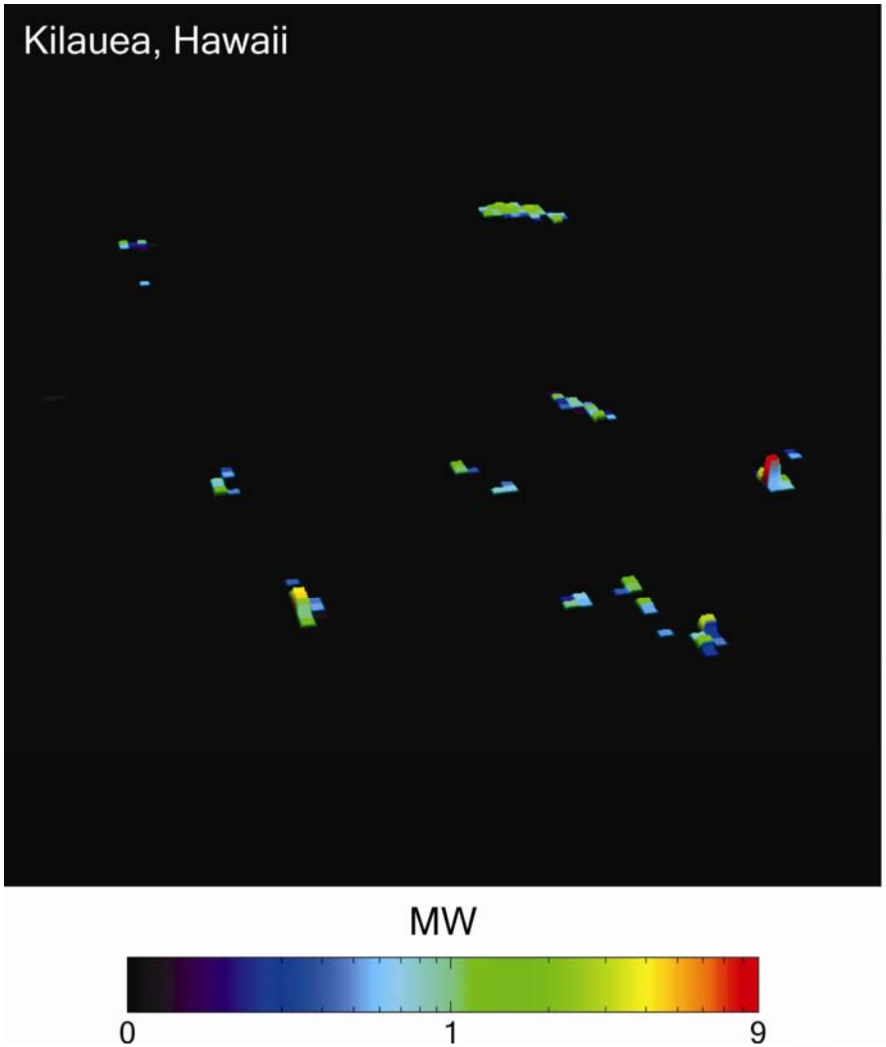
Lava cooling rates determined using Hyperion



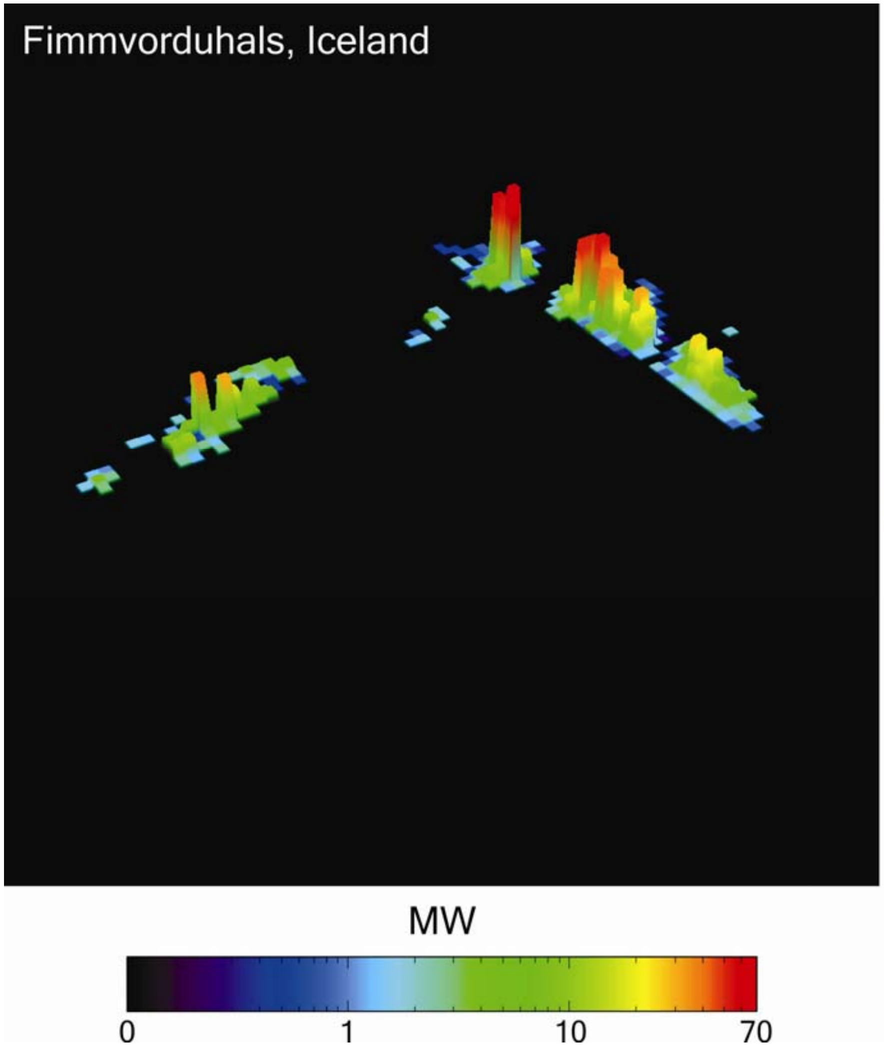
Lava cooling rates determined using Hyperion



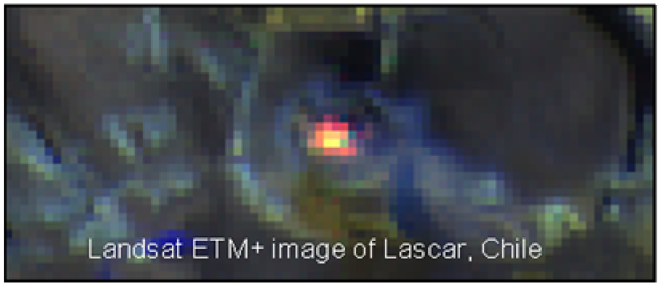
Lava cooling rates determined using Hyperion

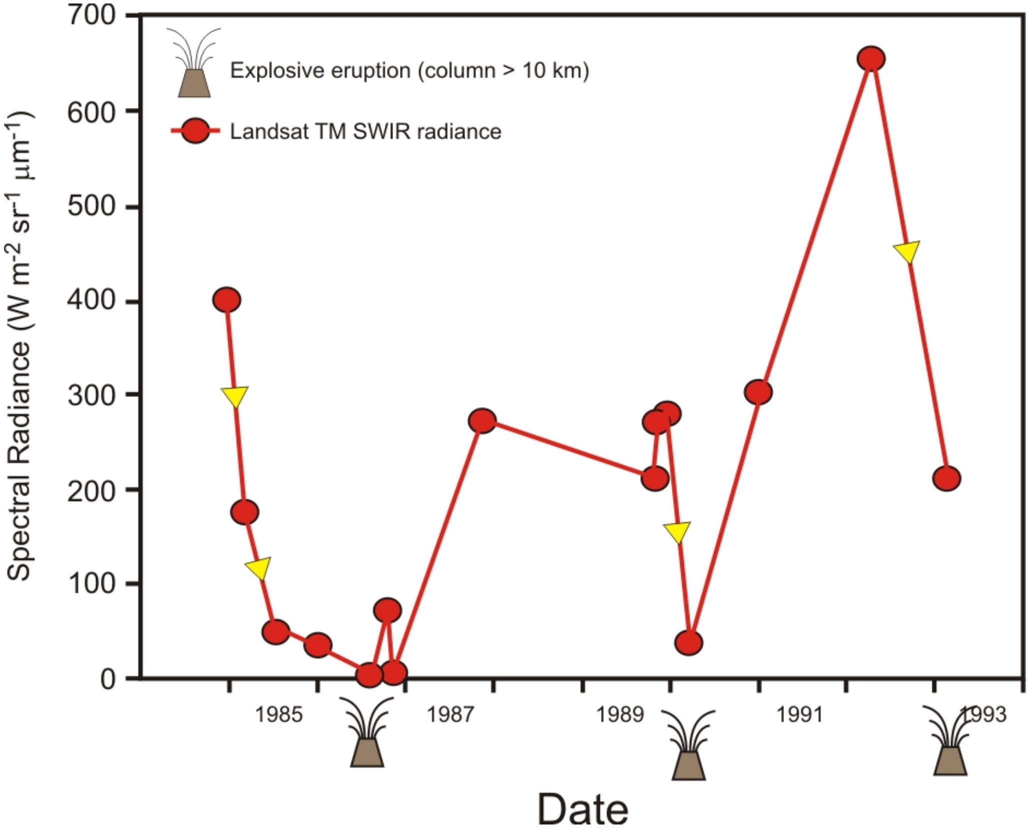


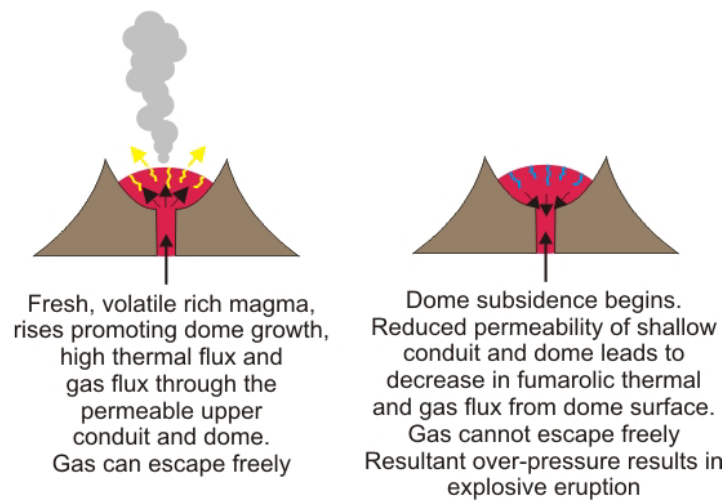
Lava cooling rates determined using Hyperion



Monitoring pressurization of acidic domes

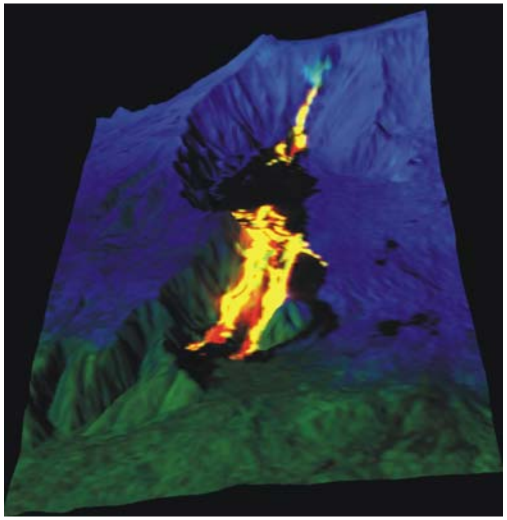






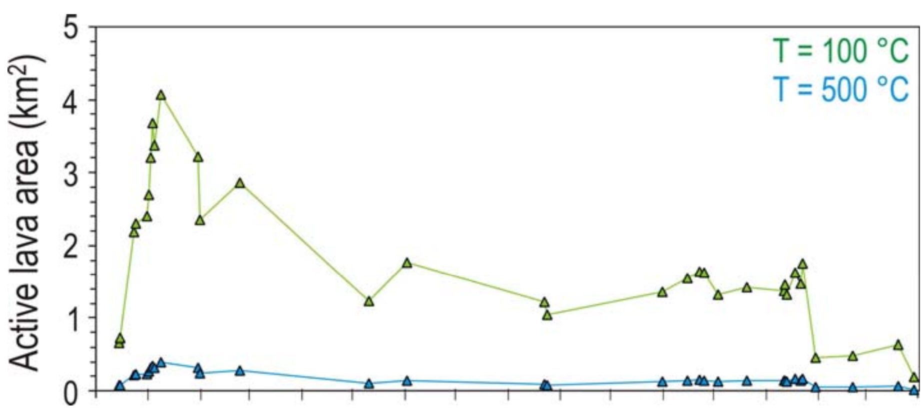
Oppenheimer et al., (1993); Wooster and Rothery, (1997).

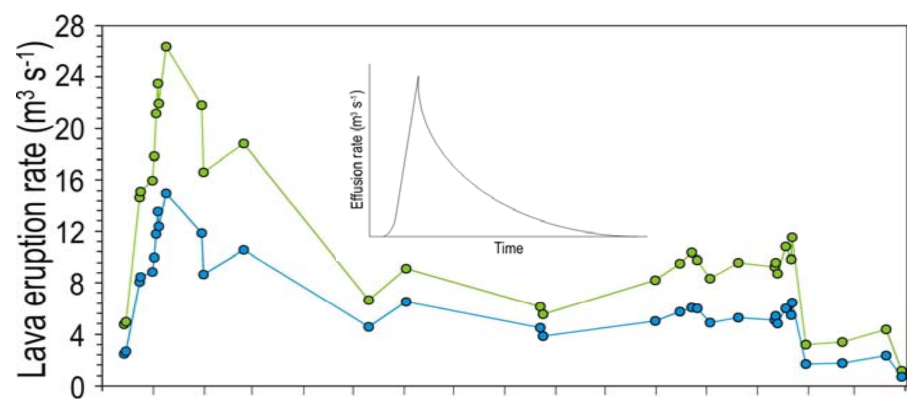
Estimating lava eruption rates from space



$$A_{lava(T)} = \frac{L_{(sat)12} - L_{12}(T_b)}{L_{12}(T) - L_{12}(T_b)}$$

Area a lava flow attains ∝ the rate at which the lava comes out of the ground

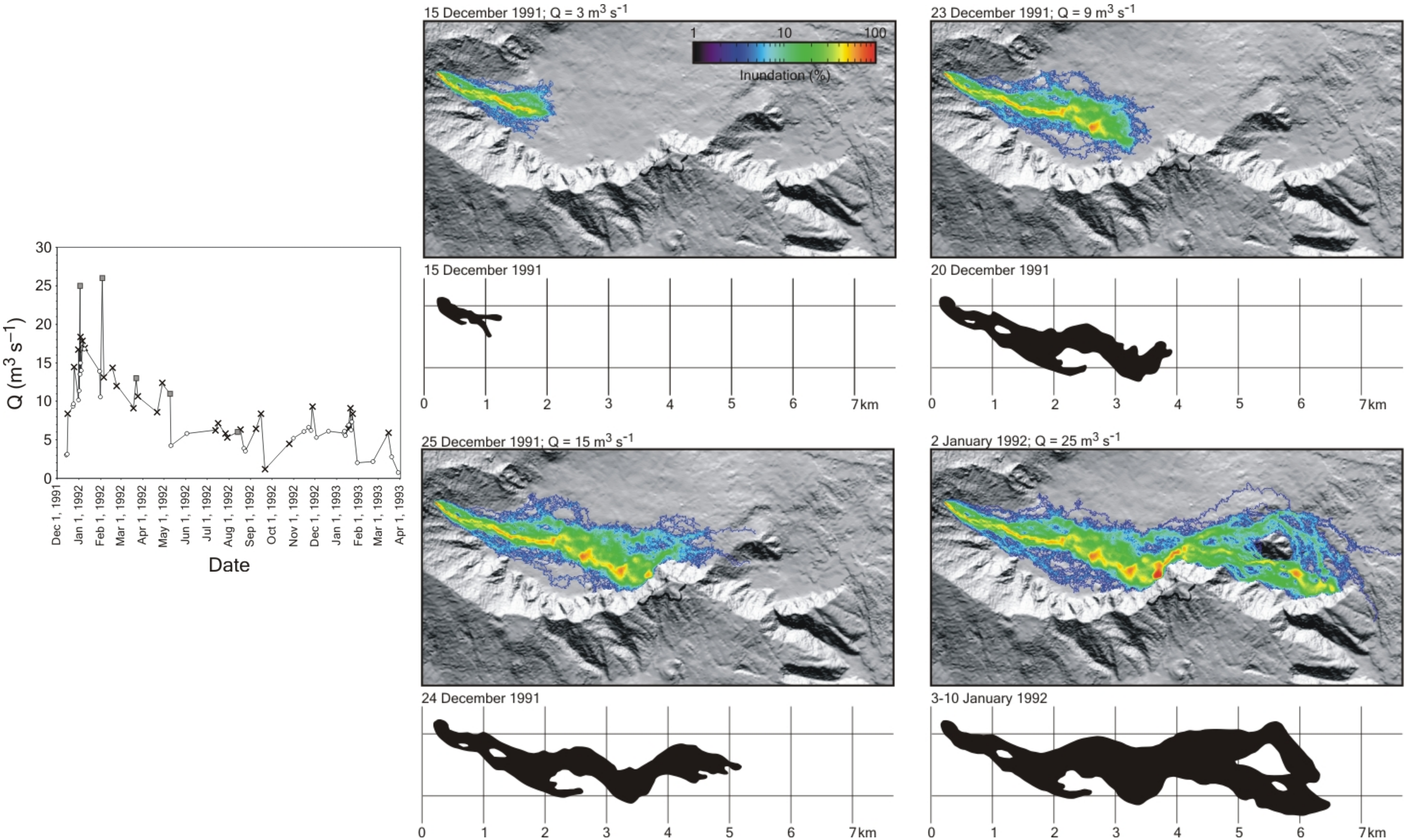




• Low spatial, high temporal resolution satellite data allow lava eruption rates to be estimated many times during an eruption

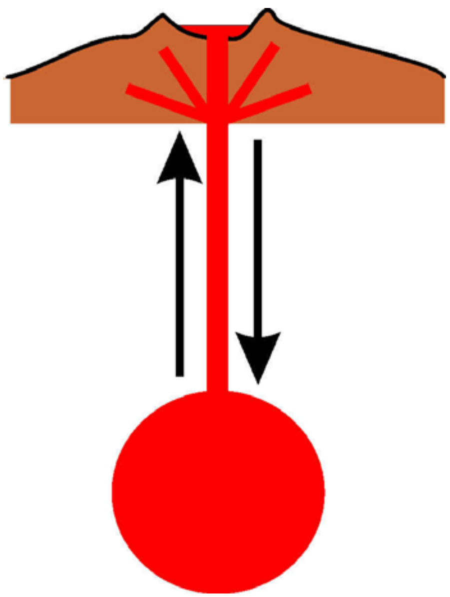
Wright et al., 2001, after Pieri and Baloga, 1986; Harris et al., 1997

Driving numerical flow simulations using thermal satellite data

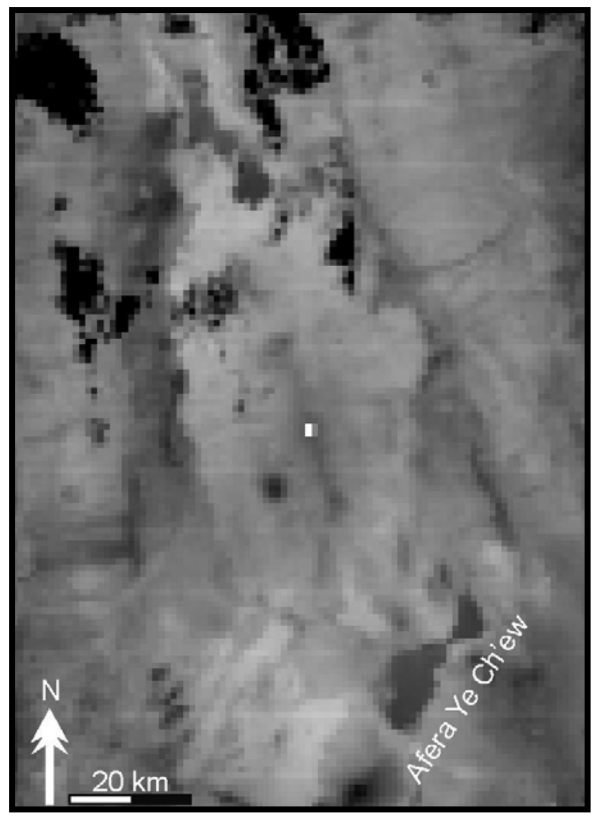


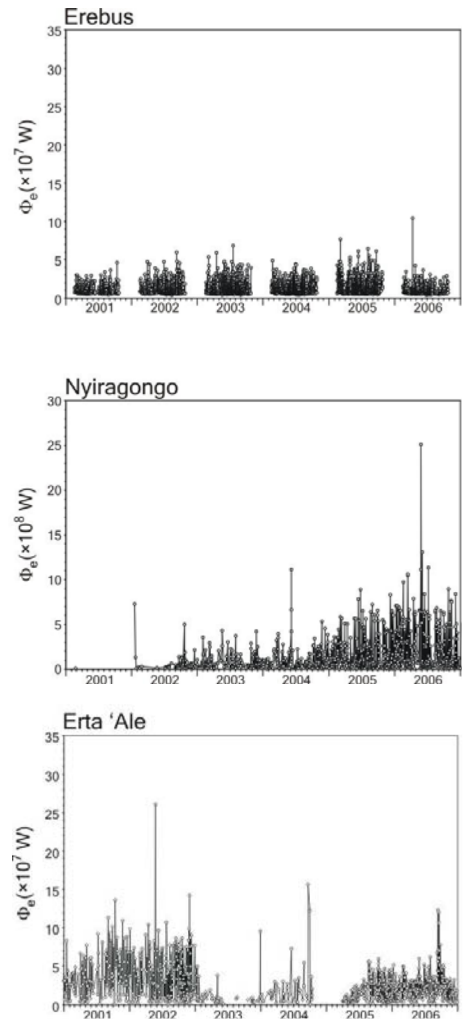
Wright et al., 2008

Estimating mass fluxes at persistently active volcanoes



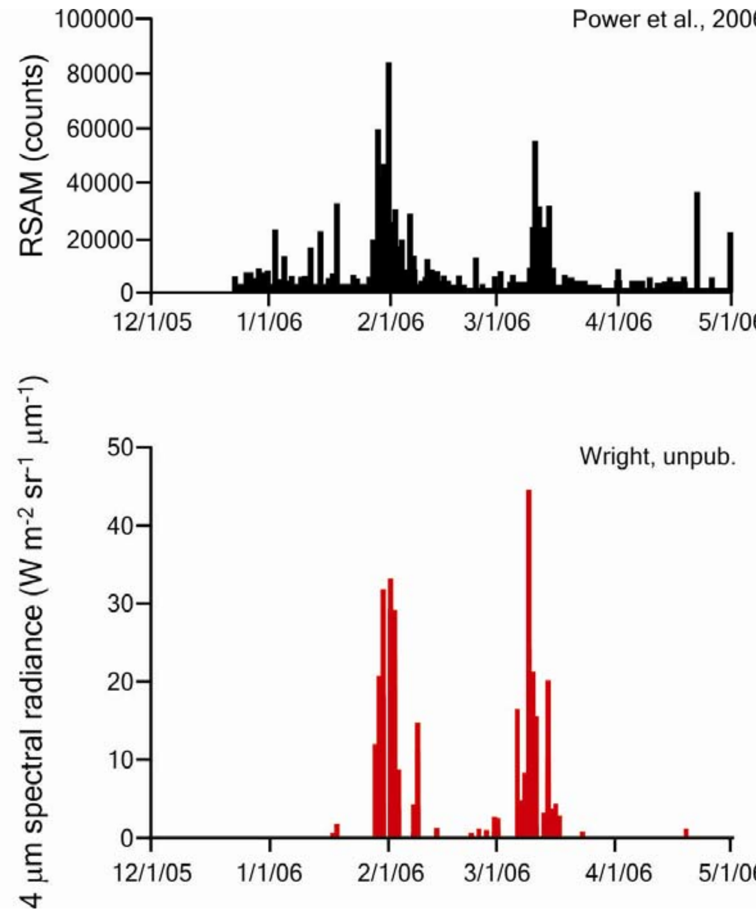
$M = Q/(L\Delta\phi + c\Delta T)$



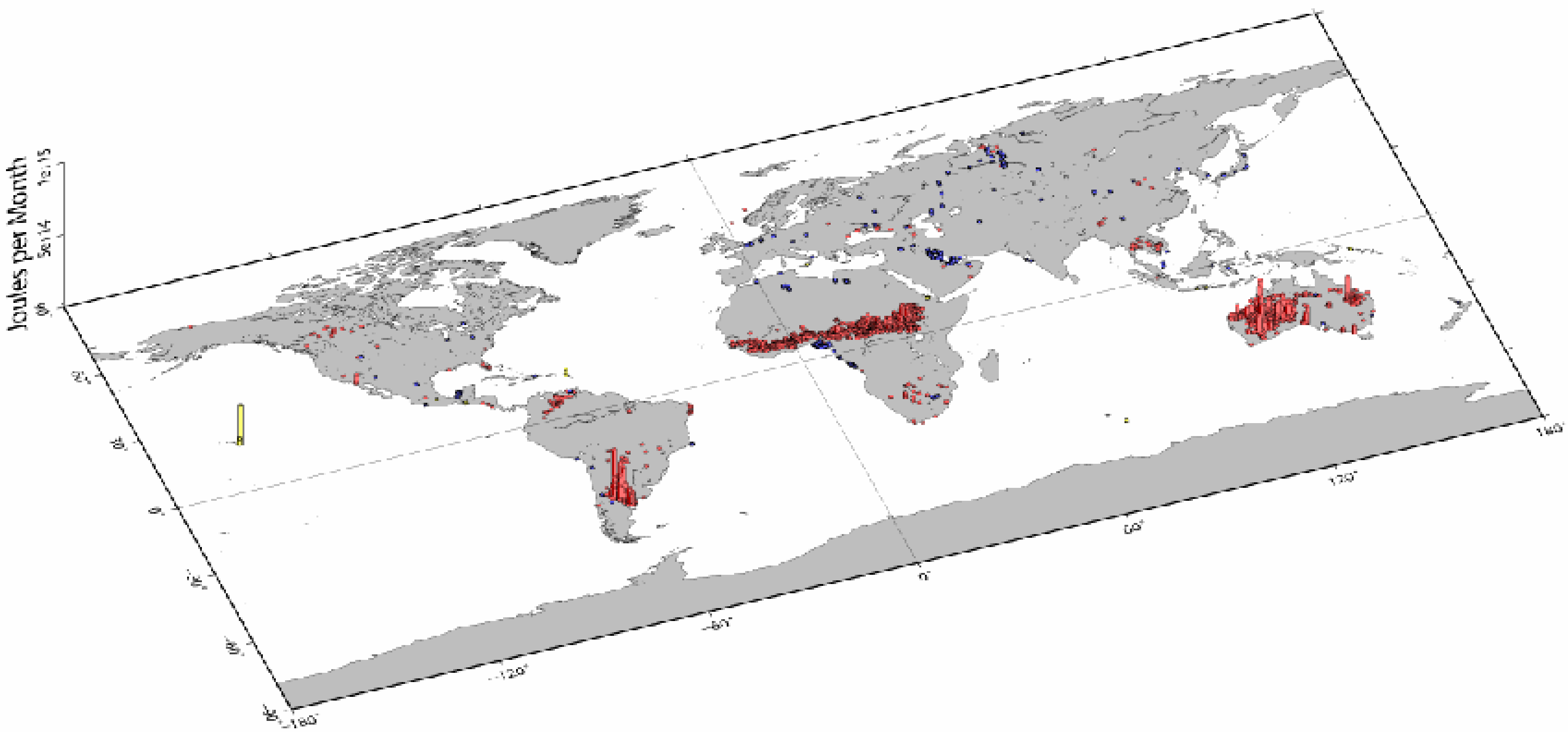


Francis et al., 1993; Harris et al., 1999

P. Izbekov (UAF/AVO)

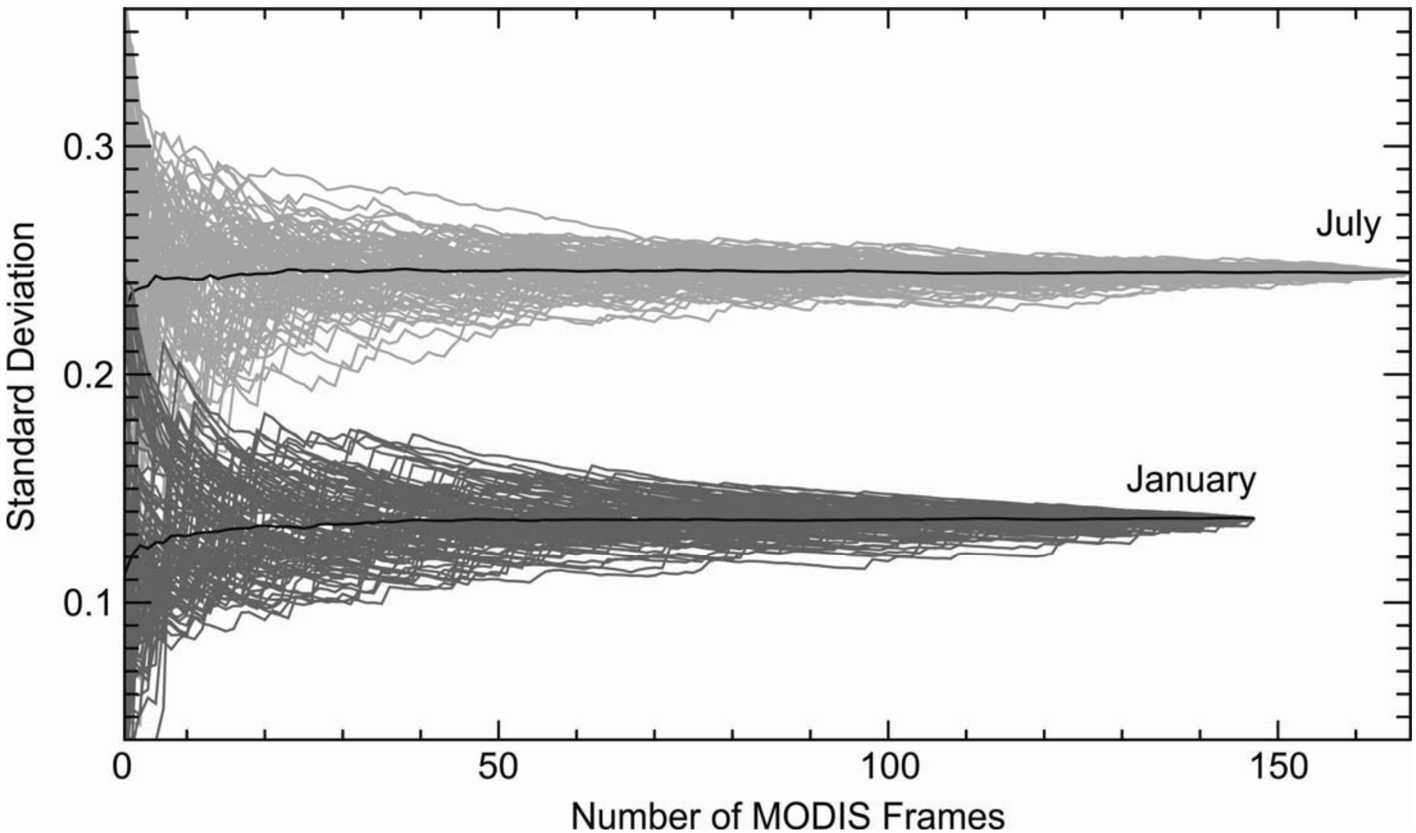


2001_031_31



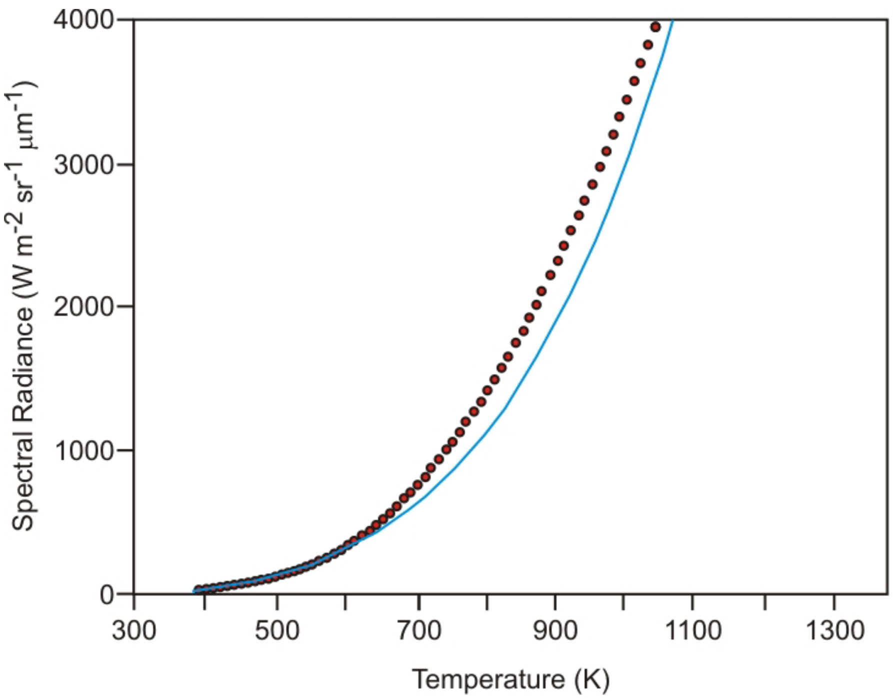
End

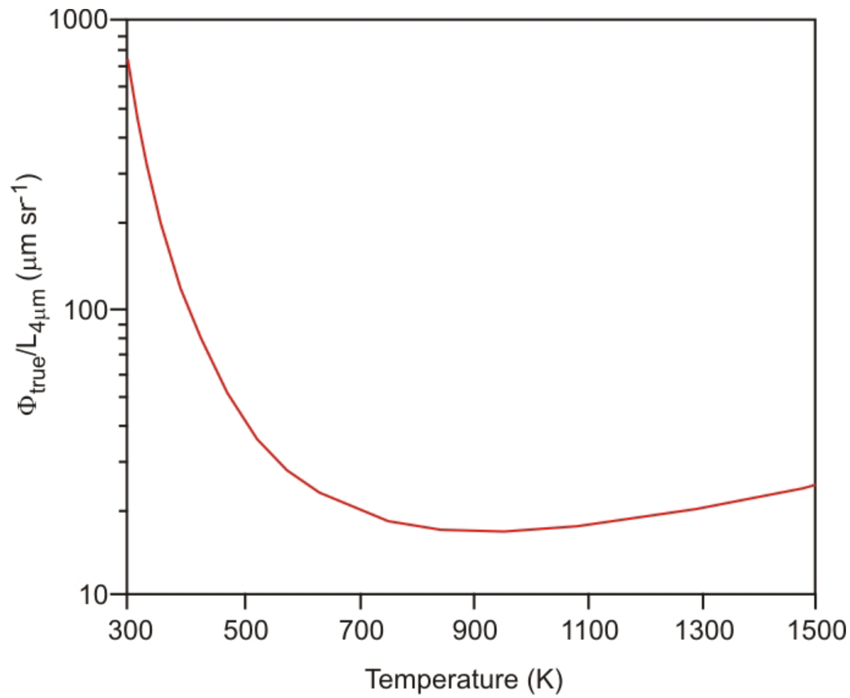
Time-series algorithms: compiling the reference frames is the hardest part



Koeppen et al., 2010

Converting from spectral radiance directly to radiant flux





$L_4 \sim aT^4$ (600K<T<1500K)

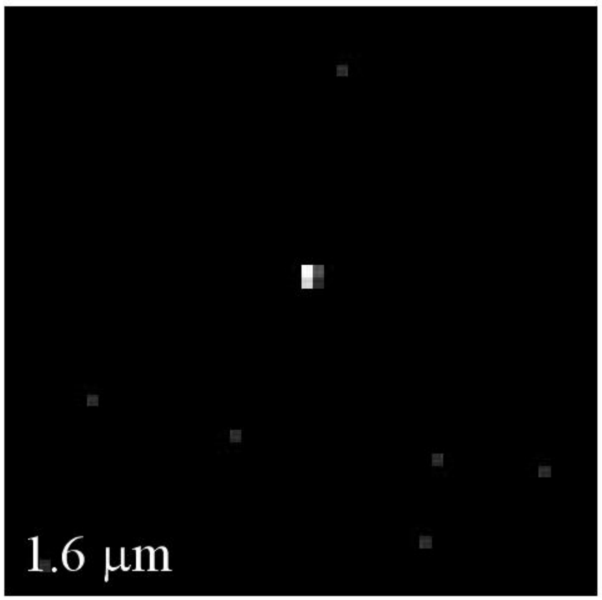
$\Phi = \sigma T^4$ (W m^{-2})

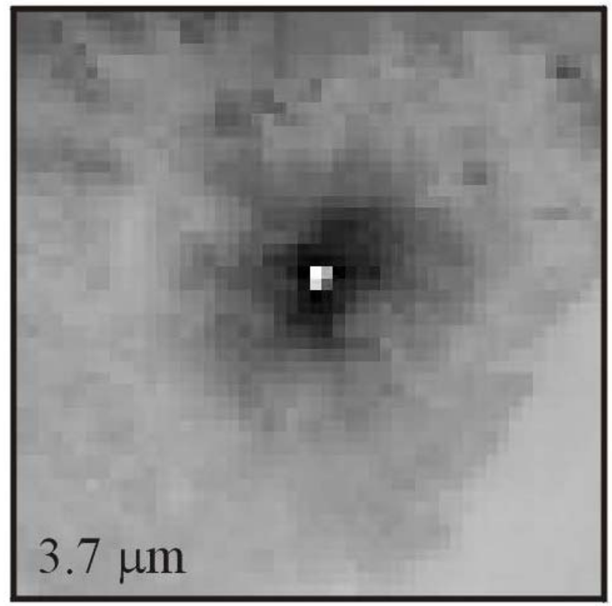
$\Phi = 1.89 \times 10^7 (L_{4,target} - L_{4,bg})$

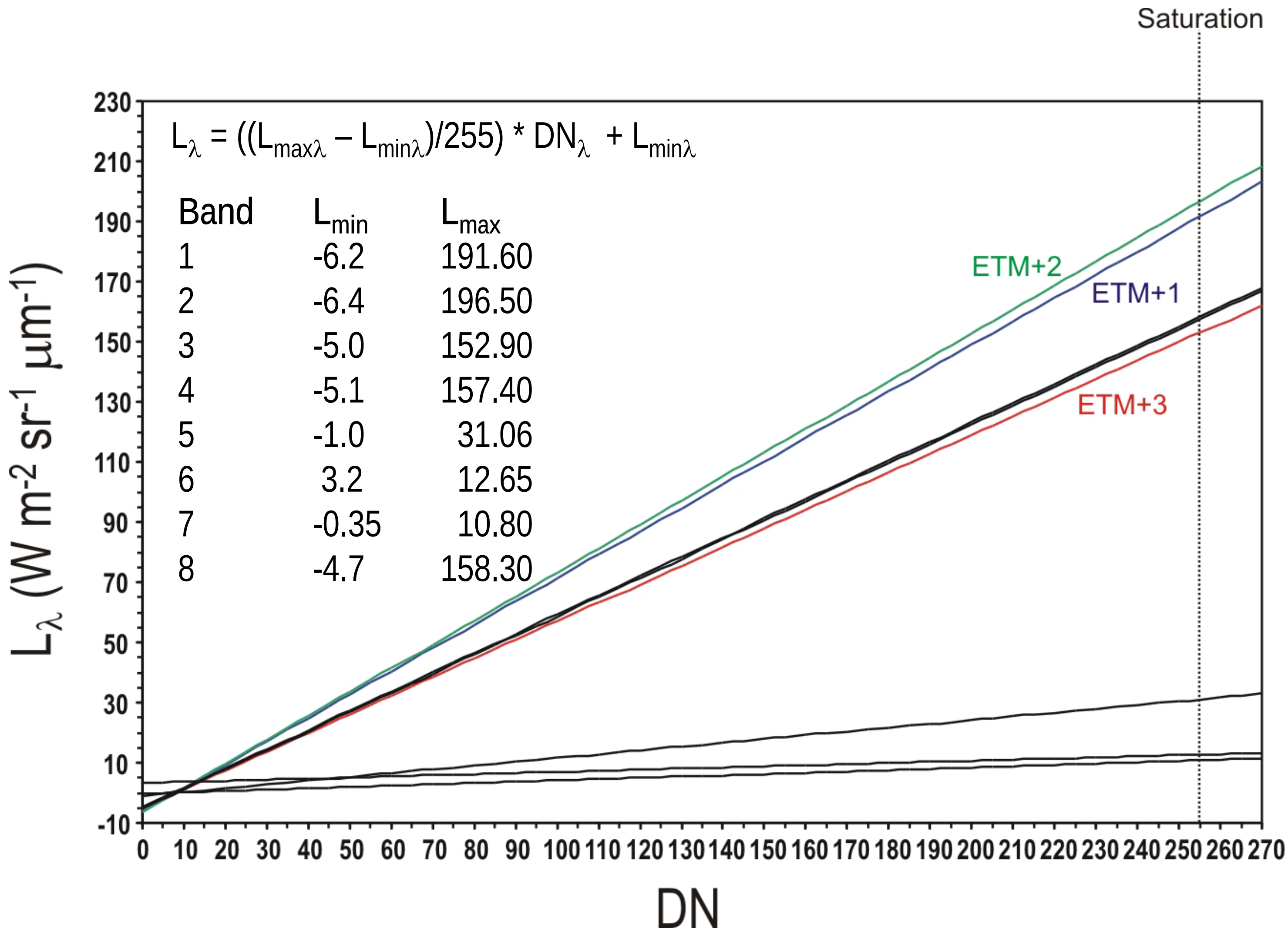
Calibrated for MODIS; L_4 in W m^{-2} sr^{-1} μm^{-1}

Wooster et al.,2003

Single wavelength thresholds

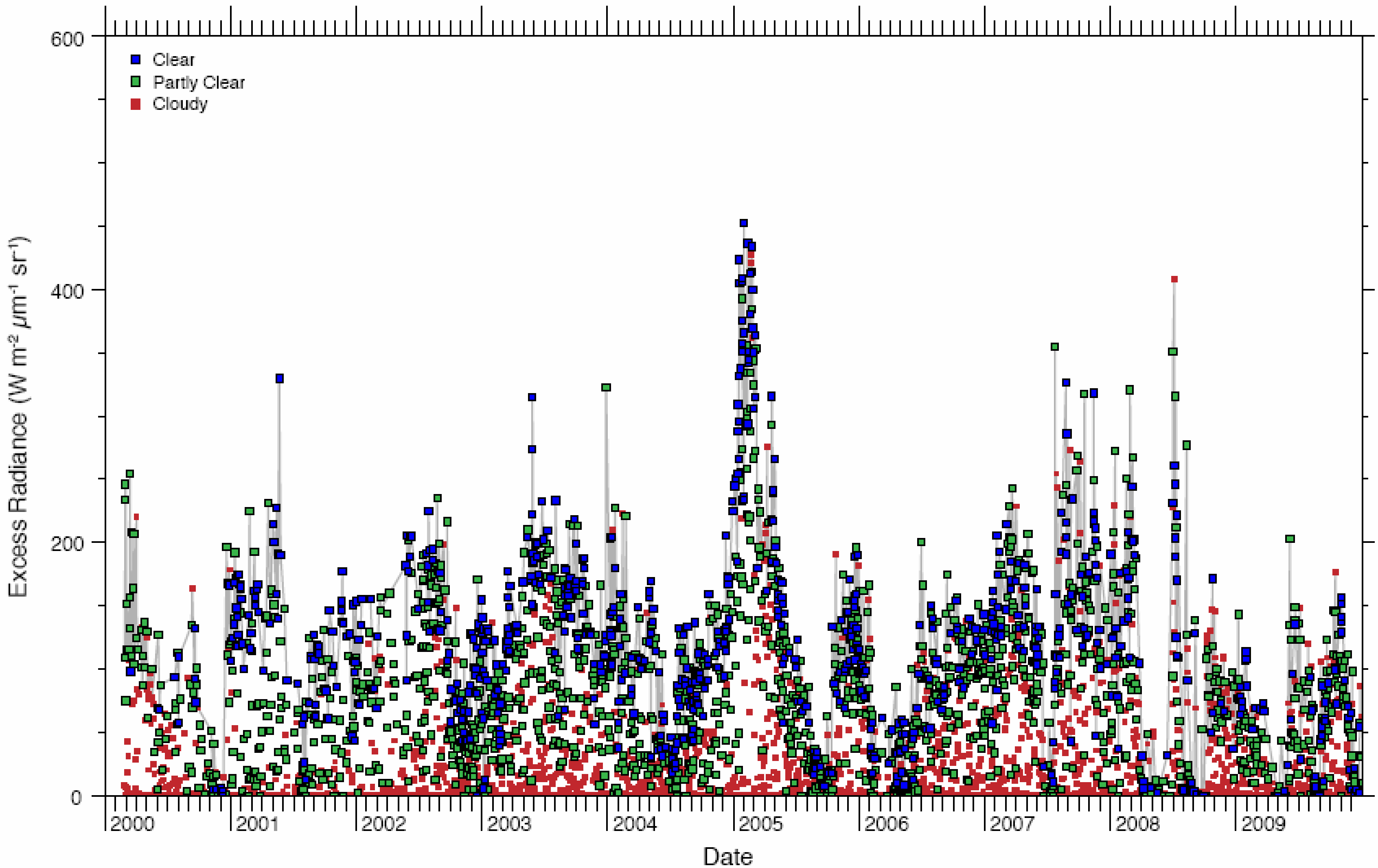


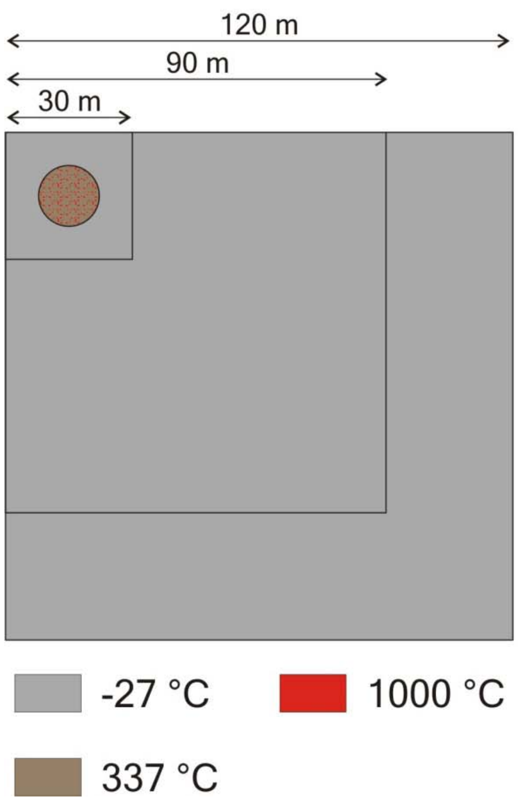


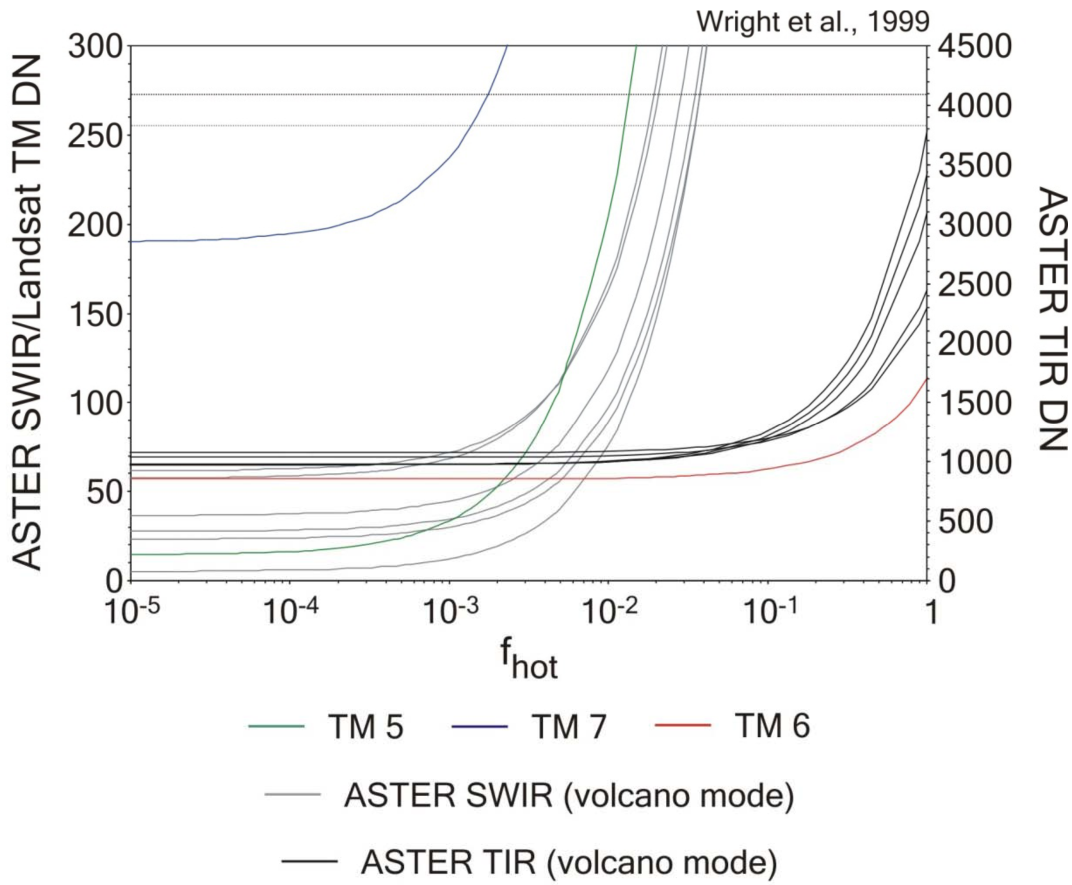


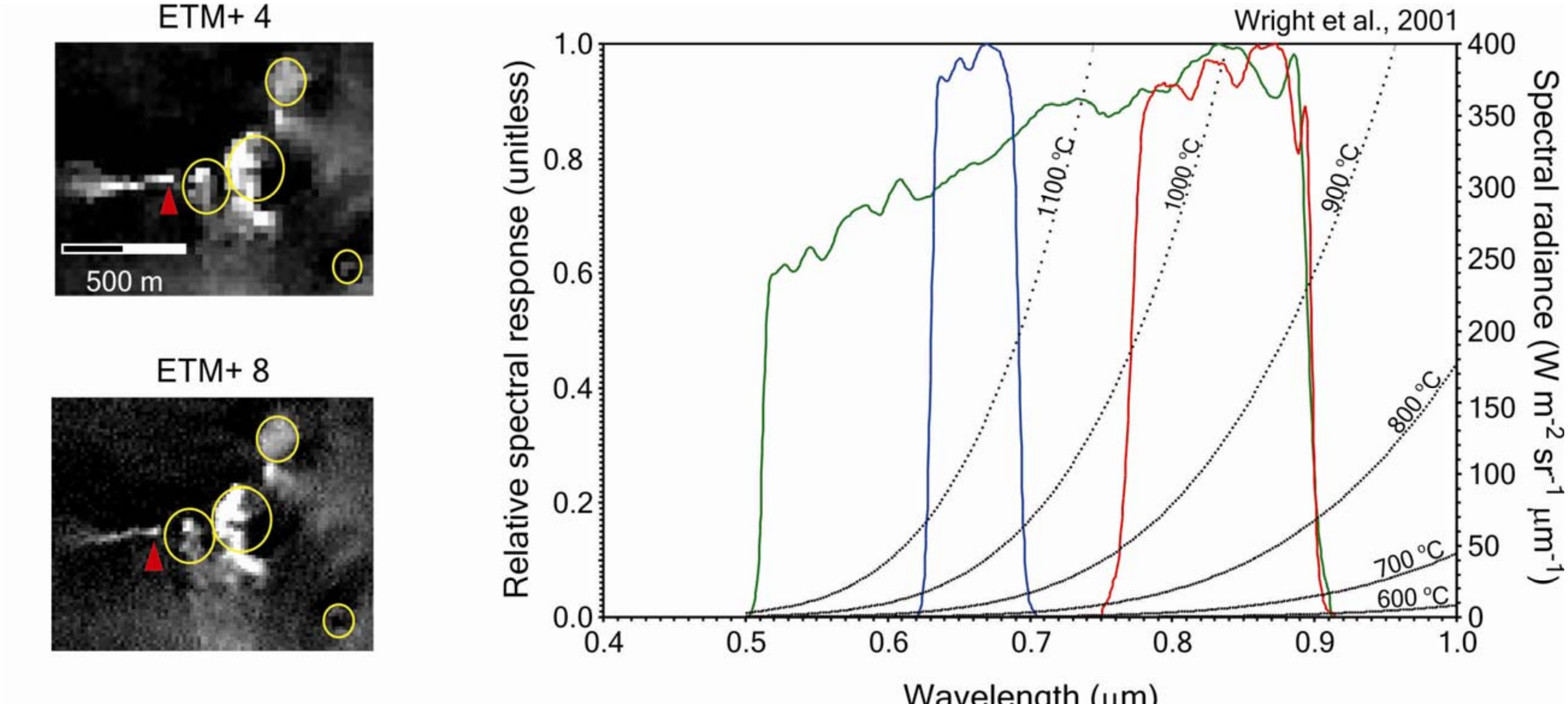
$y = mx + c$ L_λ = "gain" $\times$ DN_λ + "bias"

The impact of clouds




120 m
90 m
30 m
-27 °C
1000 °C
337 °C


Wright et al., 1999
ASTER SWIR/Landsat TM DN
ASTER TIR DN
f_{hot}
TM 5
TM 7
TM 6
ASTER SWIR (volcano mode)
ASTER TIR (volcano mode)



Mount Etna, 28 October 1999

ETM+ 4 = 35.7 W m^{-2} sr^{-1} μm^{-1} = 819 °C
ETM+ 8 = 28.3 W m^{-2} sr^{-1} μm^{-1} = 922 °C

A difference in whole pixel temperature of 100 °C

Wright et al., 2001