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How does a thermal instrument work and how do you calibrate one?

Dr Dave Smith

with thanks to Tim Nightingale and Dan Peters

Thermal Remote Sensing Workshop 02/03 December 2024

Thermal Infrared Measurements

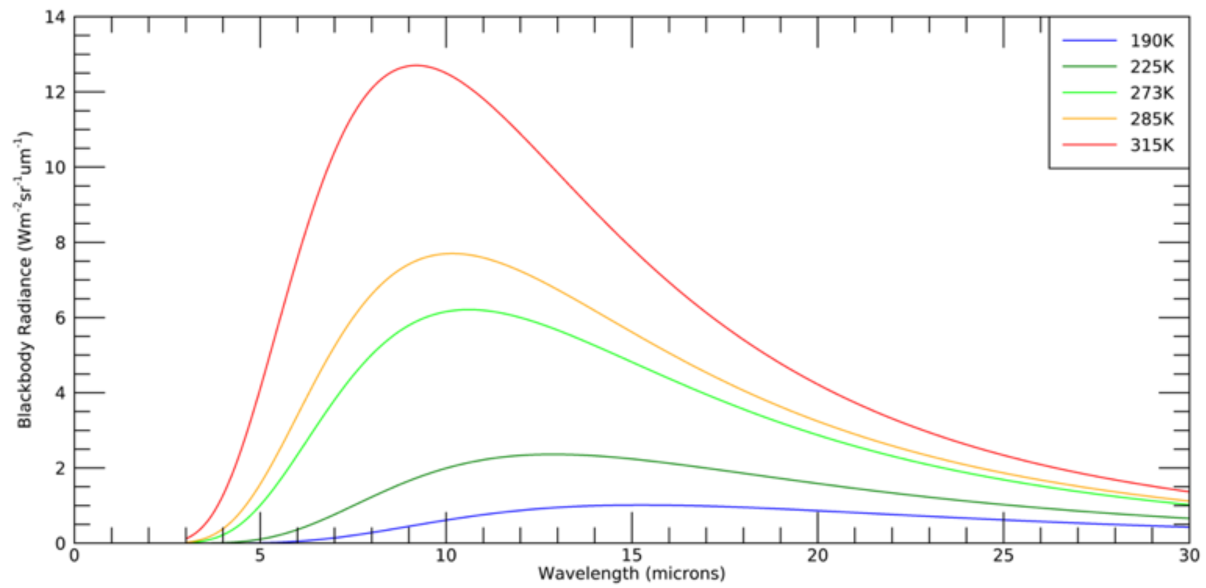
- Observations in the thermal infrared wavelength range (3-20microns) are useful for measurements of:

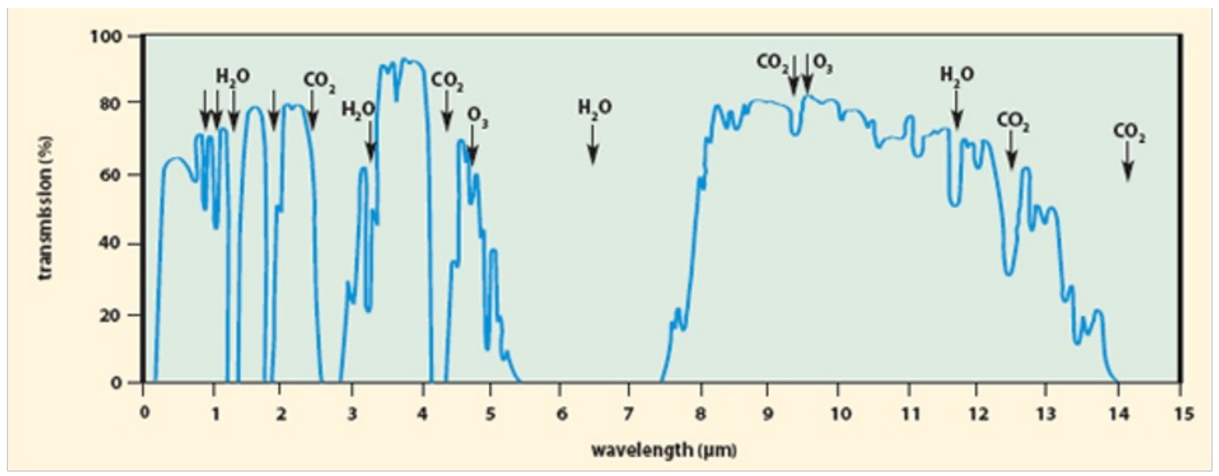
- Surface Temperature Measurements
  - Oceans
  - Inland waters
  - Land
  - Fires
  - Volcanoes

- Atmospheric Sounding
  - Temperature
  - Trace gases
  - Aerosols
  - Clouds

$$B(\lambda, T) = \frac{2hc^2}{\lambda^5\left(exp\left(\frac{hc}{\lambda k_b T}\right) - 1\right)}$$

h = Plank's constant
c = the velocity of light in vacuum
K_b= Boltzmann's constant





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Applications for Thermal Imagers

Domain	Application
Volcanoes and Earthquakes	Detection of Earthquakes and Pre-eruptive volcanoes
	Hot spots and active lava flows
	Post eruptive studies on lava flows
	Eruption clouds and Tropospheric plumes
Fires	Detection of fires, potential coal fires, coal mine fires
	Estimation of burnt area, fire intensity and severity
Hydrology	Detection of water stress in crops and forests
	Detection of evapotranspiration in crops, river basins, and continents
	Prediction and monitoring of floods
	Mapping irrigated land
	Cooling Degree Day estimations
	Growing Degree Day estimations and mapping

Domain	Application
Urbanisation	UHI: Surface temperature maps, Vegetation maps, Land cover/Land Use, Building Information, Air Quality
	Security and surveillance
	Industrial/power plant monitoring
	Air pollution
	Differentiate between urban and industrial zone
	Detection of Oil spill and Plume
	Mapping malaria and/or cholera potential regions
	Arthropod vector ecology and disease distribution
	Mapping meningitis outbreak
	Asbestos-cement detection (non-accessible areas)
	Detection of minefields
	Trafficability (off-road soil moisture content)
Surface Variability	Soil composition
	Identifying geothermal resources
	Mapping geothermal anomalies
	Mapping dynamic variability of surface temperature and emissivity

Courtesy University of Leicester

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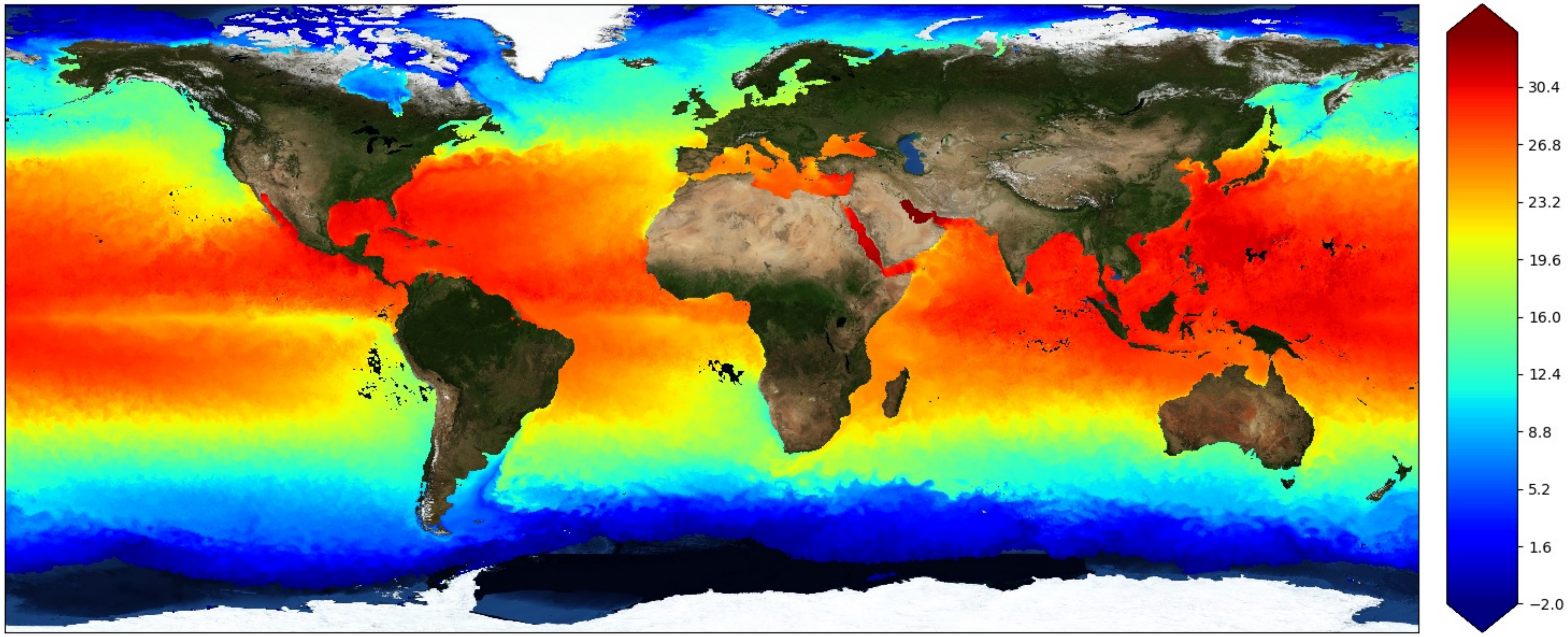
Sentinel-3A SLSTR Sea Surface Temperature – August 2016



EUMETSAT Copernicus

"Measuring the small changes associated with long-term global climate change from space is a daunting task. For example, the satellite instruments must be capable of observing atmospheric and surface temperature trends as small as 0.1C decade^{-1}, ozone changes as little as 1% decade^{-1}, and variations in the sun's output as tiny as 0.1% decade^{-1}."

Ohring, G.B., B. A. Wielicki, R. Spencer, B. Emery, and R. Datla, 2005: Satellite instrument calibration for measuring global climate change: Report on a workshop. Bull. Amer. Meteor. Soc., 86, 1303–1313

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Why measure sea surface temperature?

Sea Surface Temperature is the interface between the earth's ocean and atmosphere. It is an important indicator of the Earth's climate system and is used for weather predictions, atmospheric models, study of marine ecosystems.

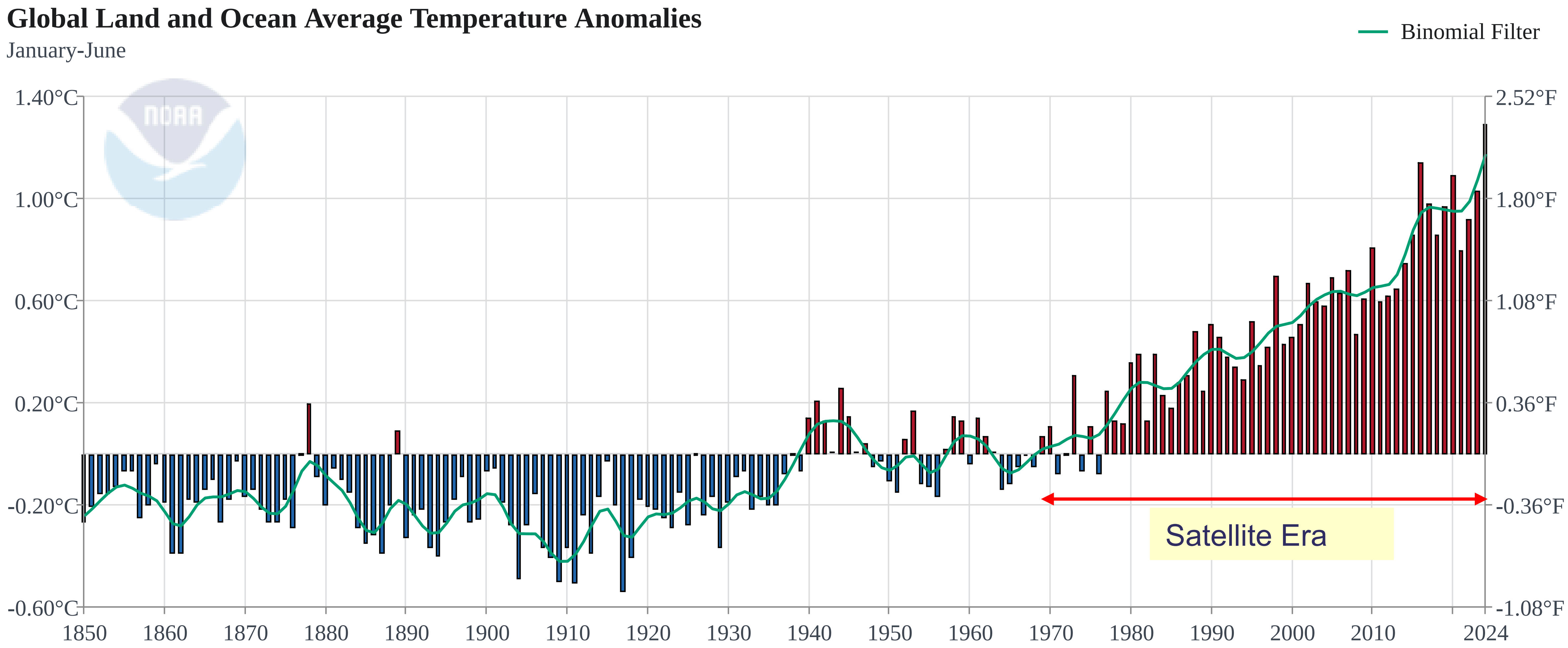

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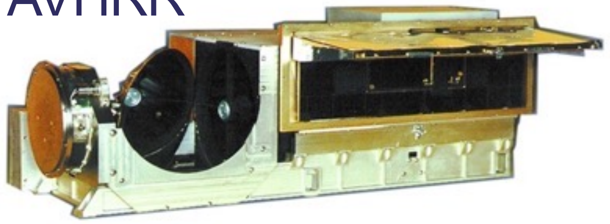
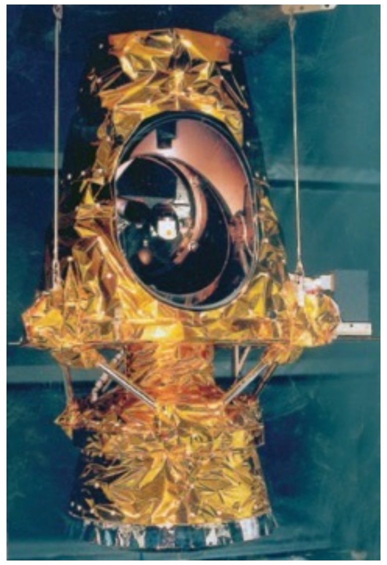
Chart from NOAA National Centers for Environmental Information, State of the Climate: Global Analysis, published online May 2023, from https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/global/time-series/globe/land_ocean/ytd/6/1880-2024

Example Satellite IR Instruments

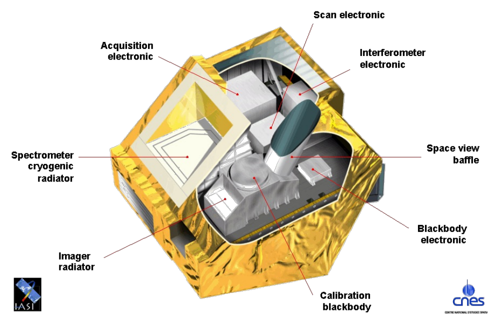
AVHRR



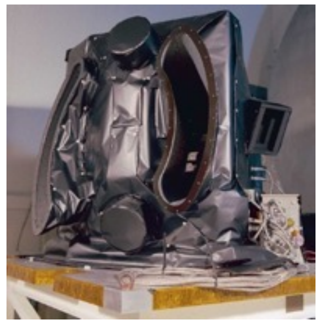
SEVIRI



IASI

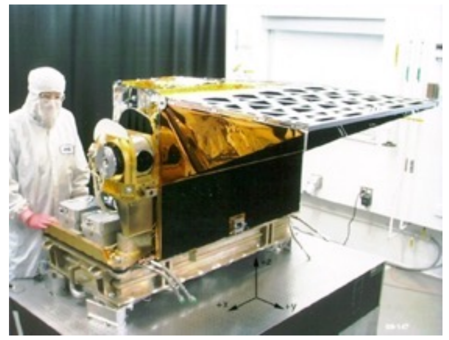


(A)ATSR

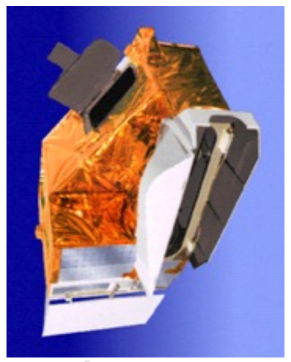


SLSTR

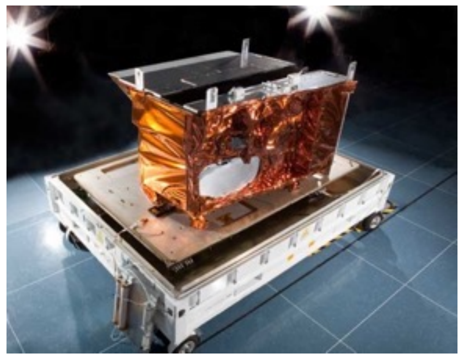
AIRS



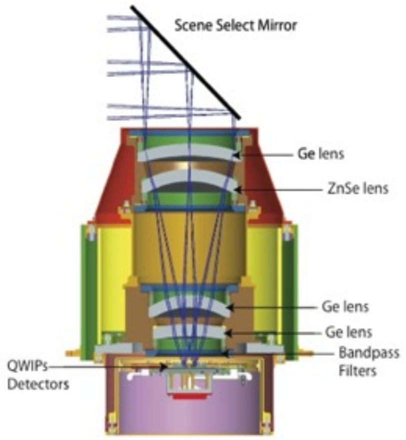
MODIS



VIIRS



Landsat 8 – TIRS



ECOSTRESS

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Field Instruments

ISAR (NOC Southampton)

SiSTeR (RAL Space)

JPL Self Nulling Radiometer

Heitronics KT 15-II

FLIR Premium-X Thermal Camera

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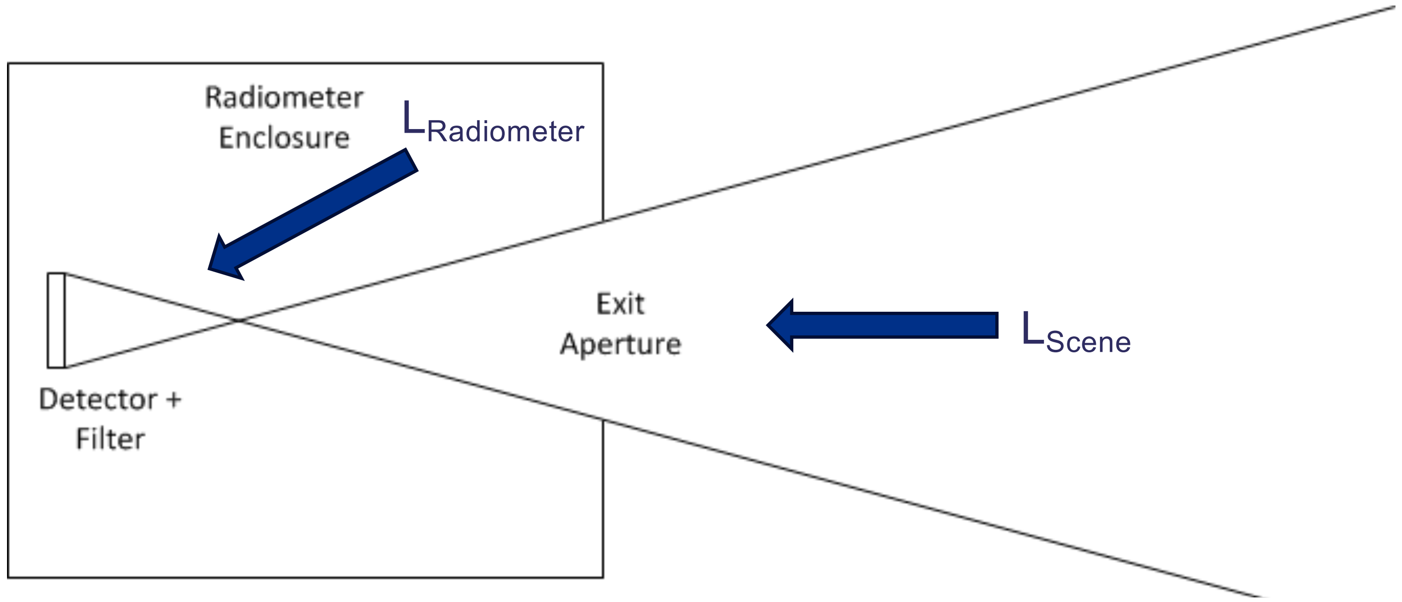
Basic Radiometer



The basic components of a radiometer are:

- Detector + Amplifier
- Filters to select the required wavelength of interest
- Optics to collect the signal and focus onto detector
- Light tight enclosure to and stray light control to minimise background signal
- Calibration sources

Power at detector

$P_{det} = A\,\tau_{filter}(\Omega\, L_{Scene} + (\pi - \Omega)L_{Radiometer})$

$A\Omega$ = Optical etendue of system (this is conserved)

A = area of detector

Ω = solid angle subtended from detector to main aperture

τ_{filter} = transmission of filter

Detector Types for IR instruments

- Semiconductor Photo-Voltaic (PV)
  - Photons falling on PV devices excite electrons from valence to conduction band, creating a photo-current. MWIR instruments (3-6µm) use detectors based on this principle.

- Semiconductor Photo-Conductive (PC)
  - Photons falling on PC devices excite electrons from valence to conduction band, causing a change in the resistance.

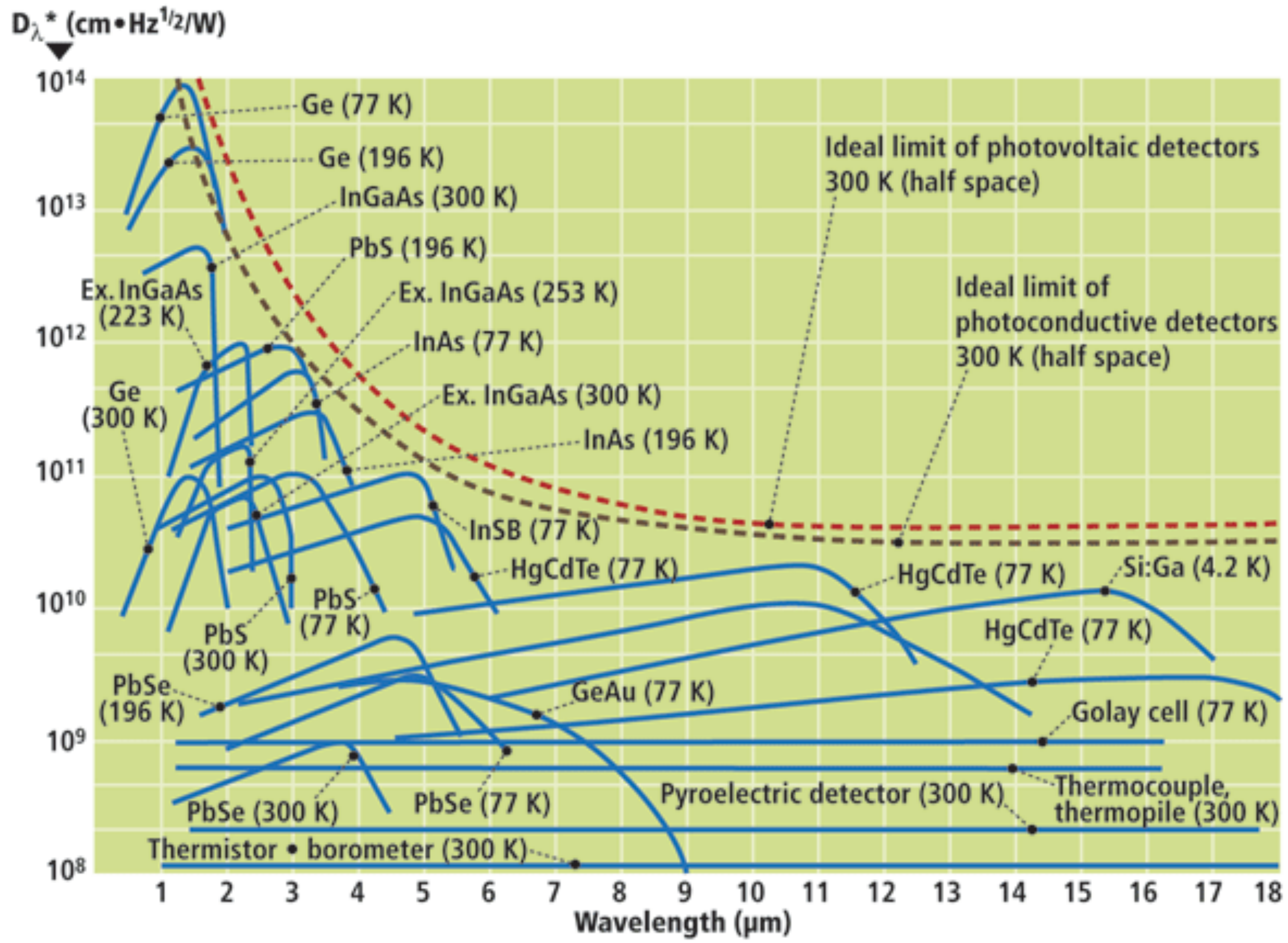
- Pyro-Electric Detectors
  - Thermal radiation heats detector and generates a voltage - used in passive IR instruments such as Heitronics KT-15 radiometers, FTIR spectrometers.

- Micro-Bolometers
  - Incident radiation heats detector and changes resistance. Most common type of detector used in commercial TIR cameras.

IR Detectors

- Performance of detector is usually defined by D* ($Wcm^{-1}Hz^{-½}$)
- For TIR wavelengths
  - MCT PhotoConductive D* ~ $5x10^{10}$
  - microBolometers D* ~ 10^9
  - Pyro-Electric Detectors D* ~ $3x10^8$
- For MWIR
  - MCT PhotoVoltaic D* ~ $7x10^{10}$
  - InSb Photovoltaic D* ~ 10^{11}

(D* quoted for available devices)



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Impact of Detectivity

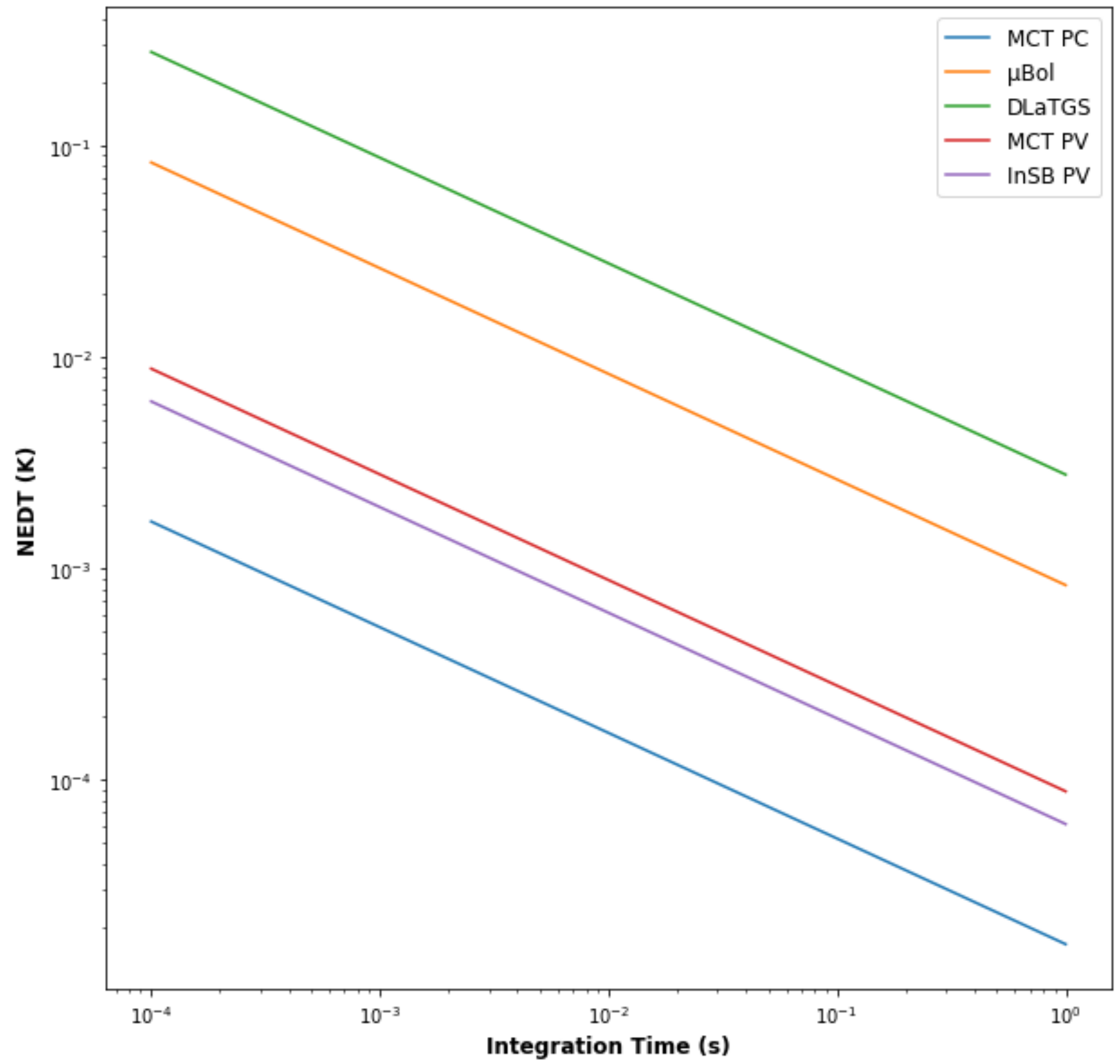
- $NEP = \sqrt{A_{det} f} / D^*$ W
  - f is the sampling frequency

- $SNR_{det} = P_{det} / NEP$

  (excl. other noise sources)

- P_{det} depends on source radiance, optical etendue, optics transmission, spectral response.

- $NE\Delta T = NEP \frac{\partial T}{\partial P}$ K



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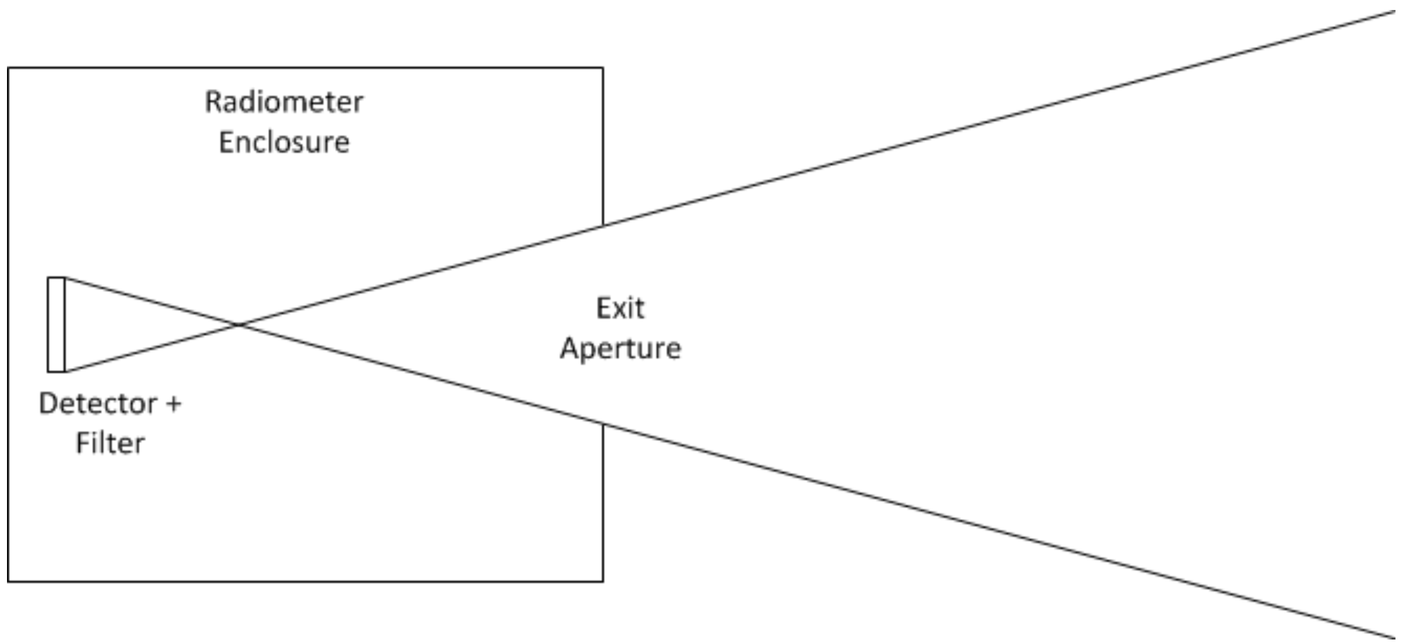
Improving the design?



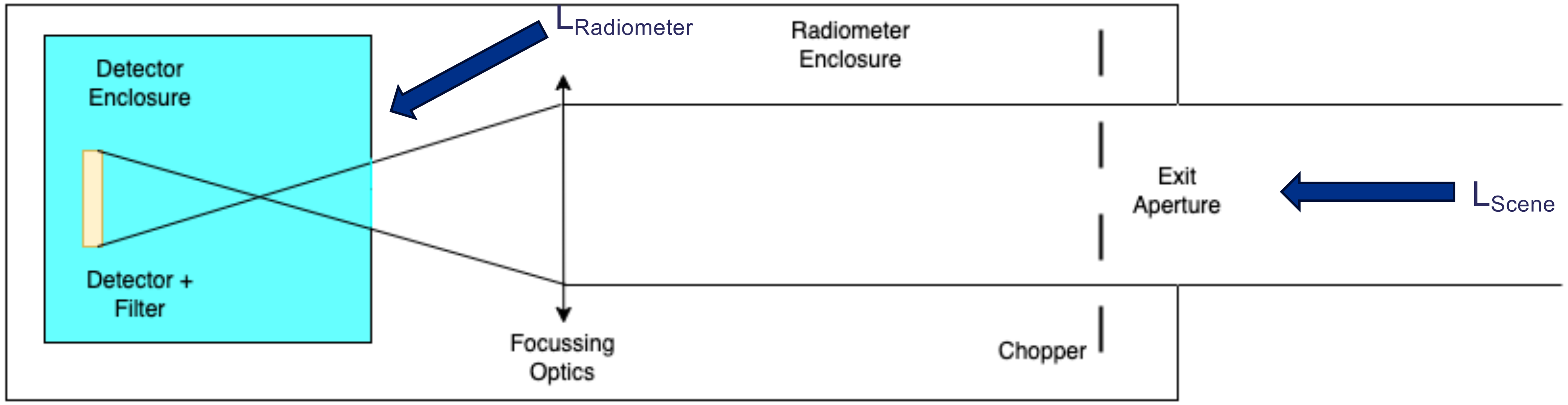
Problem with the ‘simple’ design is that the enclosure also emits radiation at a similar temperature as the scene.

Changes in thermal background (even < 1K) have significant impact on calibration.

Also, optical beam is defined by geometric apertures. Ok for scenes close to the instrument but limits where instrument can be deployed and cannot be used for imaging.

Need to think about the size of source.

Improving the design



- $P_{det} = A\,\Omega\tau_{filter}(\tau_{opt}\,L_{Scene} + (1-\tau_{opt})L_{Radiometer})$
- τ_{opt} = transmission of optics

We can improve by put the detector in a cooled enclosure so that background signal is minimised (though not useful for uncooled detectors).

Also introduce a focussing optics to constrain the field of view

Use a chopper to modulate between scene and instrument to account for thermal drift and 1/f noise.

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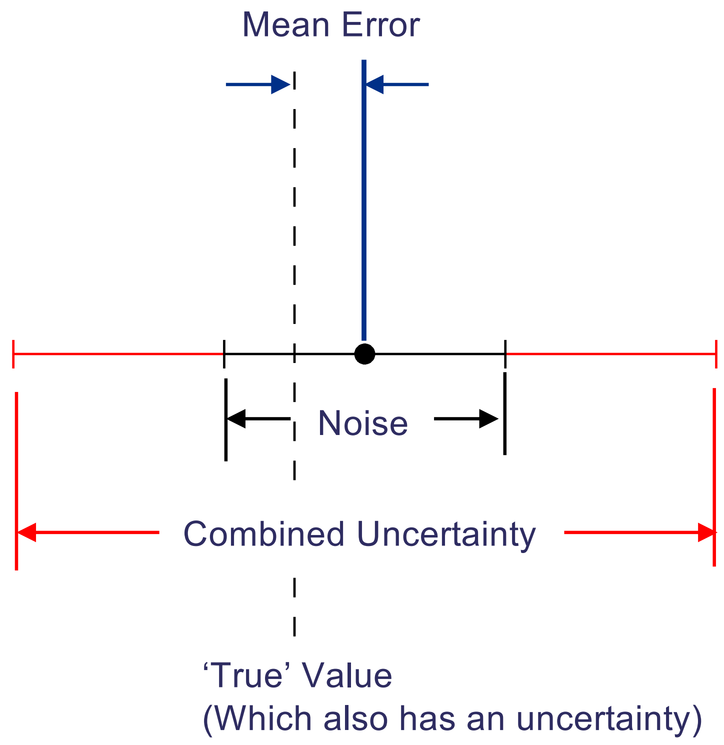
What do we mean by Calibration?

Calibration is the operation that […] establishes a relation between the quantity values with measurement uncertainties provided by measurement standards […] with corresponding […] measurement uncertainties and […] uses this information to establish a relation for obtaining a measurement result from an indication.   **Bureau International des Poids et Mesures**

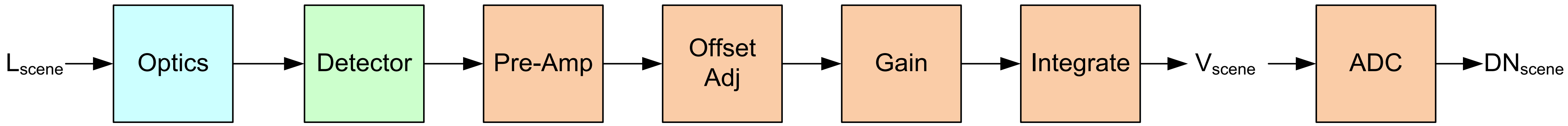
Traceability is the property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties

Error is defined as the difference between a result obtained and the 'true' value.

Uncertainty parameter associated with the result of a measurement, that characterises the dispersion of the value that could reasonably be attributed to the measurand.



Calibration Model



Typically, detector counts will be some function of the scene **radiance**

$$C_{scene} = F_{ADC}\left(V\left\{A\Omega\left(\left(\tau_{opt}L_{scene} + (1-\tau_{opt})L_{inst}\right)\right\} + V_{off}\right)$$

which reduces to

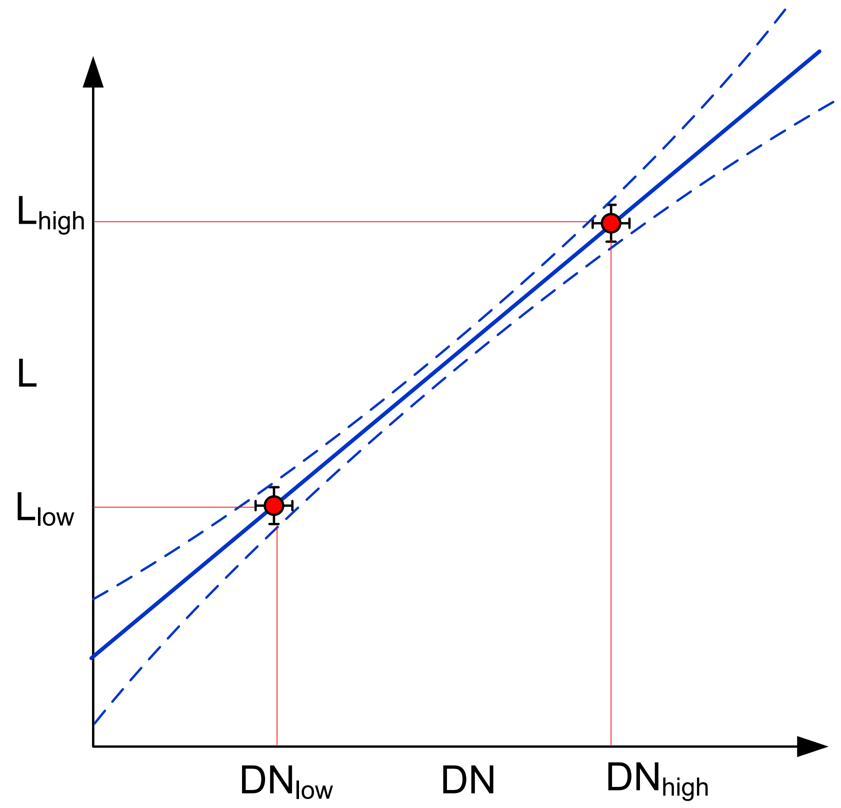
$$C_{scene} = gain(L_{scene}) + C_{offset}$$

Both gain and offset must be stable during calibration interval

We invert this to get scene radiance as a function of detector counts

$$L_{scene} = gain^{-1}(C_{scene} - C_{offset})$$

$\approx a_0 + a_1 C_E$ (assuming linear function)



Calibration coefficients are derived via reference to known calibration sources

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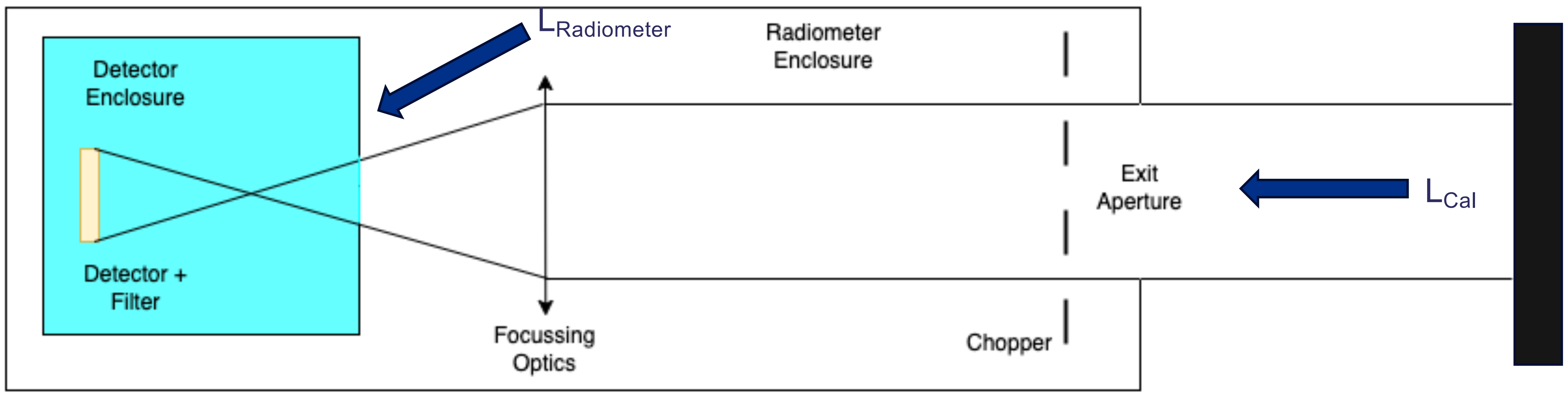
Calibration



We can determine the calibration gain and offset by pointing the instrument at an external reference source.

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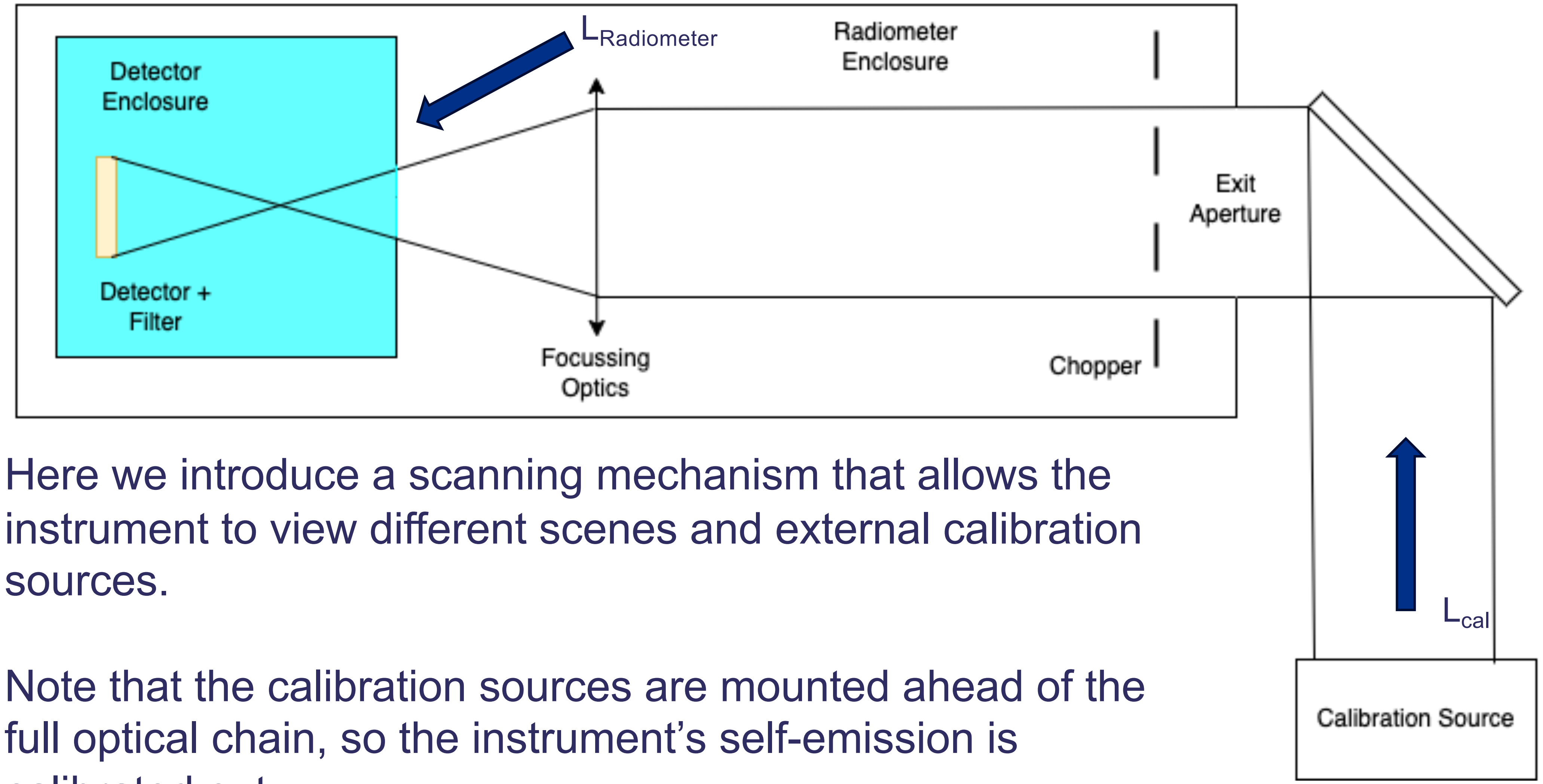
Improving the design further



Here we introduce a scanning mechanism that allows the instrument to view different scenes and external calibration sources.

Note that the calibration sources are mounted ahead of the full optical chain, so the instrument's self-emission is calibrated out.

This is the basis of a self-calibrating radiometer

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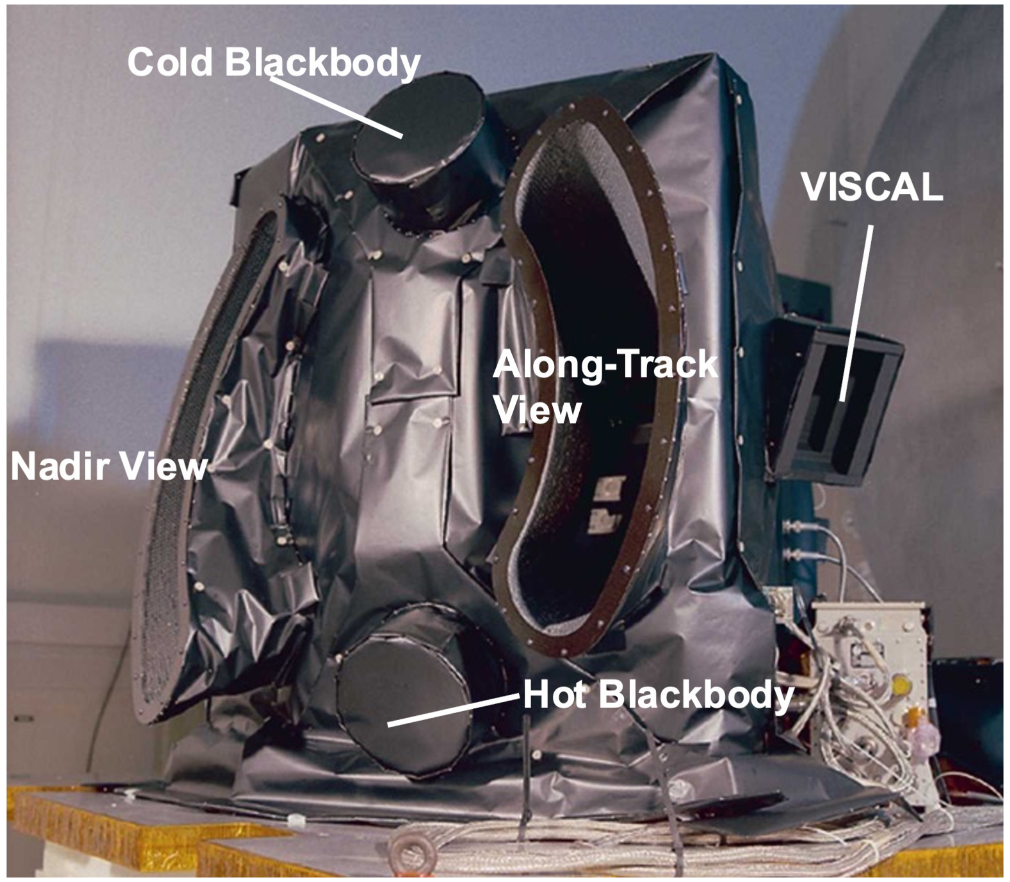
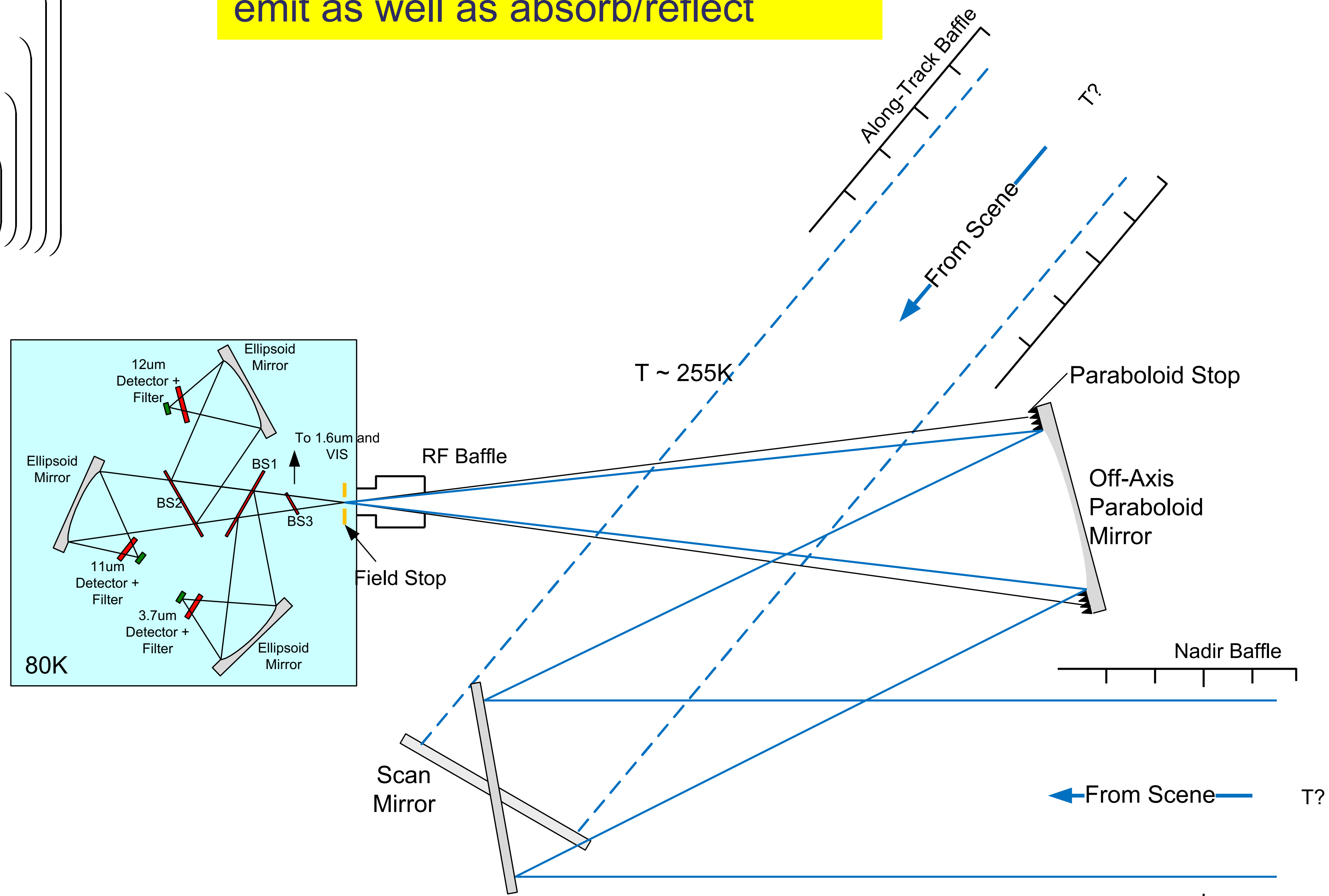
Optical Chain (from (A)ATSR)

$$\phi_\lambda = A_\lambda\left(\begin{array}{l}(\pi-\Omega_\lambda)L_{FPA,\lambda}+\\ \Omega_\lambda\left(\begin{array}{l}(1-\tau_{FPA,\lambda})L_{FPA\lambda}+\\ \tau_{FPA,\lambda}\left(\begin{array}{l}(1-\xi_\lambda)L_{surr,\lambda}+\\ \xi_\lambda\left(\begin{array}{l}(1-r_{para,\lambda})L_{para,\lambda}+\\ r_{para,\lambda}\left(\begin{array}{l}(1-r_{scan,\lambda})L_{scan,\lambda}+\\ r_{scan,\lambda}L_{scene,\lambda}\end{array}\right)\end{array}\right)\end{array}\right)\end{array}\right)\end{array}\right)$$

At TIR wavelengths ALL surfaces emit as well as absorb/reflect





Self-calibration

- Recall the instrument calibration model

  $$L_{scene} = a_0 + a_1 C_{scene}$$

- We want to determine the scene radiance L_{scene} from a measurement count C_{scene}, but don't know the coefficients a_0 or a_1. What to do?
- Point the instrument at a known source of light:

  $$L_{cal1} = a_0 + a_1 C_{cal1}$$

- If we know L_{scene} we could derive the coefficients a_0 and a_1, but we don't, so we need a measurement at a second source radiance, L_{cal2}. We can then derive the coefficients using simultaneous equations so that:

  $a_0 = (C_{cal1}L_{cal2} - C_{cal2}L_{cal1})/(C_{cal1} - C_{cal2})$ and $a_1 = (L_{cal1} - L_{cal2})/(C_{cal1} - C_{cal2})$

- Or we can rewrite the calibration model as:

  $$L_{scene} = XL_{cal1} + (1 - X)L_{cal2}$$

  where $X = (C_{scene} - C_{cal2})/(C_{cal1} - C_{cal2}) = (L_{scene} - L_{cal2})/(L_{cal1} - L_{cal2})$

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Calibration of IR instruments

For Thermal IR instruments such the traceability of the measurements to SI units is achieved via internal BB sources.

For temperature this is defined by the Boltzmann constant realised through the International Temperature Scale of 1990

For an ideal blackbody where $\varepsilon = 1.0$ $B(\lambda, T) = \frac{2hc^2}{\lambda^5(\exp\left(\frac{hc}{\lambda k_b T}\right) - 1)}$

Instrument

←


Blackbody Source

←


S-PRT (ITS-90)

←


Fixed Point Cells

← $k_B = 1.38064852 \times 10^{-23}$ JK^{-1}

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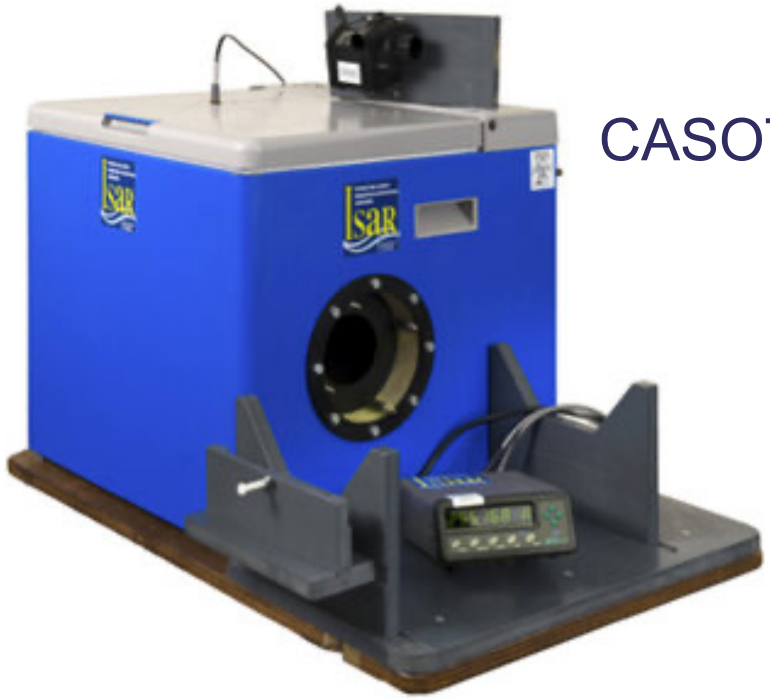
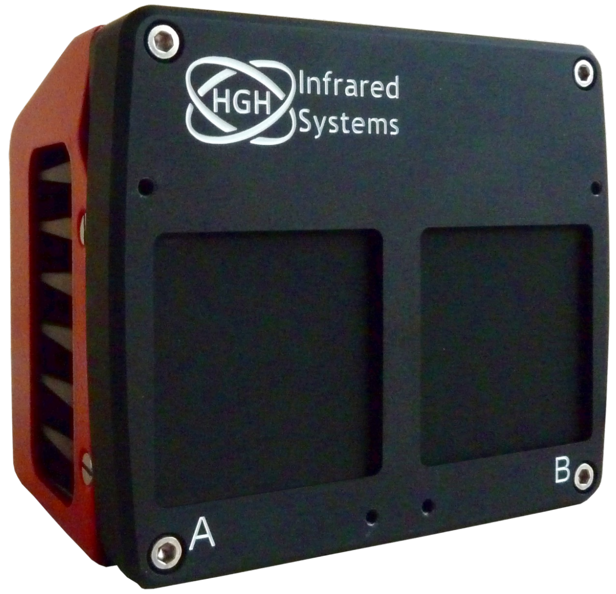
Ground BlackBody Sources



CASOTS-II BB Source

HGH Double BB source



Isotech Hyperion BB source

Isotech 989 Source

Fluke Custom BB source

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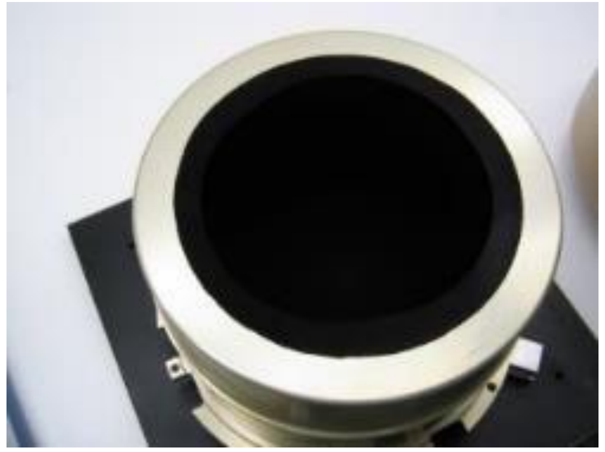
Example flight BB Sources

AATSR

ABSL/MSSL

SLSTR



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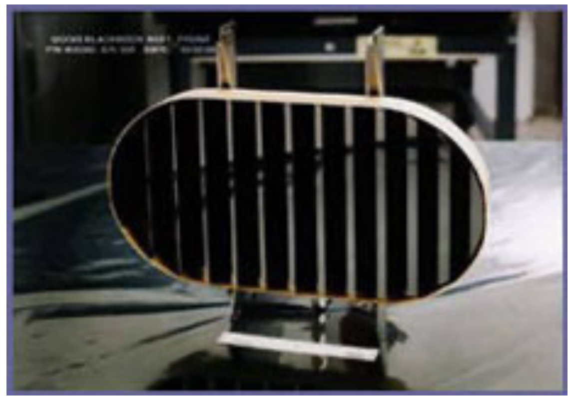
IASI

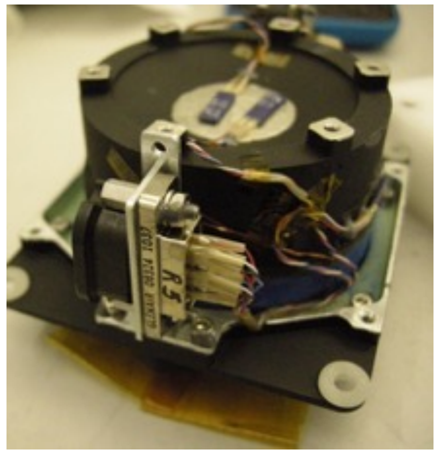
ABSL ltd.

MODIS/VIIRS



NASA-GSFC

EarthCARE BBR



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FCI – Meteosat 3rd Gen

Proceedings Volume 10563, International Conference on Space Optics — ICSO 2014; 1056323 (2017) https://doi.org/10.1117/12.2304144

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Blackbody Design Considerations

- Emissivity, ε
  - Most practical blackbody sources are not completely black, so have an emissivity < 1.
  - Sensitivity to reflected radiance from instrument & surroundings, smallest when surroundings at the same temperature as cavity.

- Temperature knowledge, T
  - Thermometry readout electronics
  - Thermometry sensors
  - Thermometry calibration and traceability (ITS-90, end to end)
  - Thermal gradients

- Knowledge of both has a first-order effect on knowledge of the radiance leaving the black body

Emissivity

- The **emissivity** ε of a surface is its effectiveness in emitting energy as thermal radiation and has a value between 0 (non-emitting) and 1 (perfectly emitting)
- The emissivity of a surface is exactly equal to its **absorptance**, or ability to absorb thermal radiation
- The sum of the emissivity ε, **reflectance** ρ and **transmittance** τ of a surface is one:

$$\varepsilon + \rho + \tau = 1$$

- For practical black bodies, τ = 0 and we're left with:

$$\varepsilon + \rho = 1$$

- This equation tells us that not only does the emissivity scale the amount of Planck radiance leaving our black body, but any deficit is made up with radiation reflected from elsewhere in the instrument:

$$\boldsymbol{L_{BB}(T,\lambda) = \varepsilon B(T,\lambda) + (1-\varepsilon)L_{back}} \quad \text{assuming } \rho = 1-\varepsilon$$

- The reflected radiation term L_{back} is often poorly known or controlled, so it's important to use a black body target whose emissivity is as high as possible

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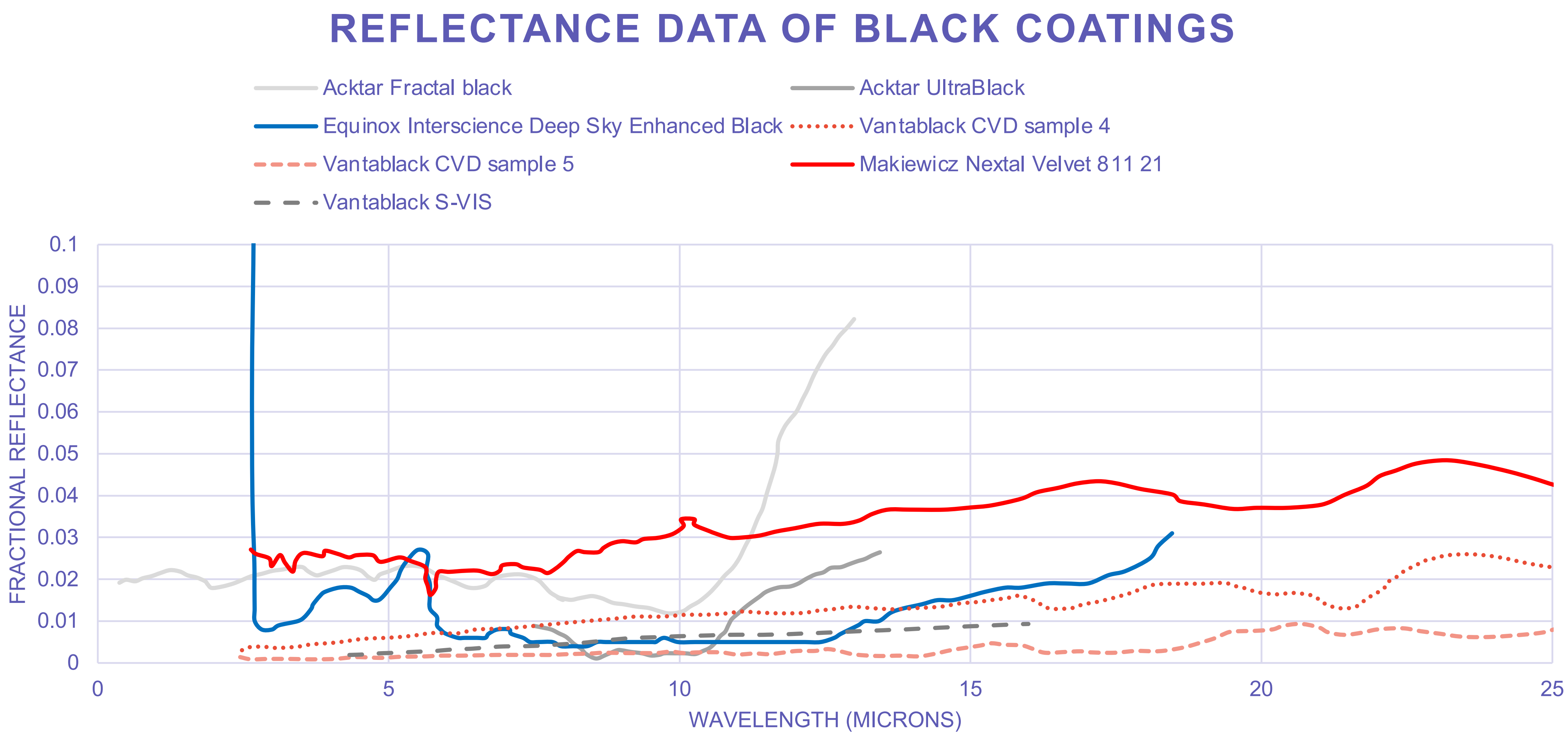
More emissivity

- The overall emissivity of a practical black body comes from two sources:
  - Surface coating
  - Internal geometry
- A number of coatings are available for the thermal infrared part of the spectrum, including:
  - Nextel velvet black (paint)
  - Chemglaze/Aeroglaze (paint)
  - Martin black (chemical etch + dye)
  - Vantablack (carbon nanotubes)
- Emissivity varies with wavelength but typically $\varepsilon = 0.95$ to > 0.99
- Diffuse and specular coatings available (those listed are diffuse)
- Professional finishing recommended!

Black Coating Materials



Most black coatings used have some reflectance in TIR range

Even carbon nanotubes have reflectance ~1% at 12um (Emissivity ~0.99)

Hence need for structured baseplate or cavity to increase emissivity >0.999

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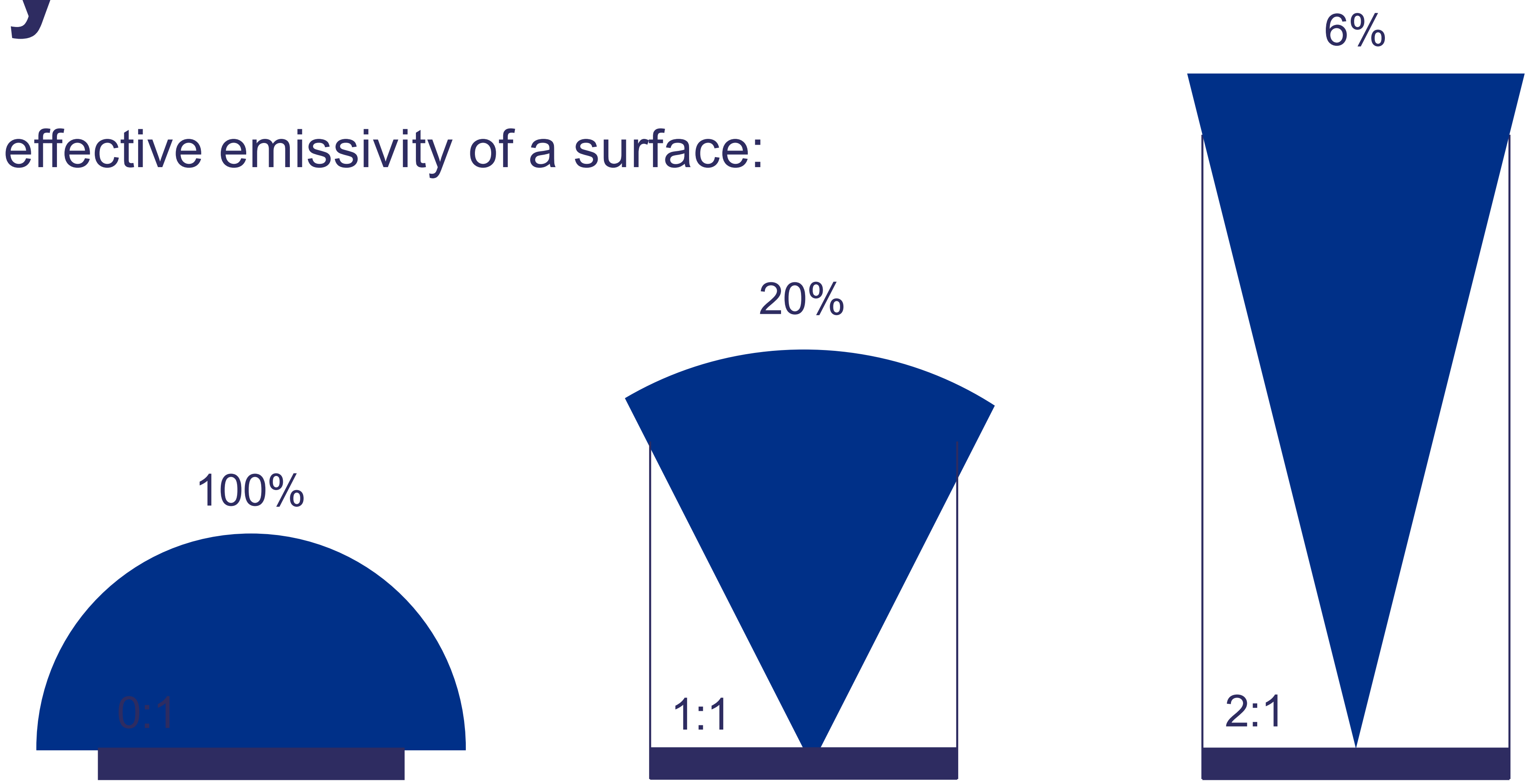
Geometry

Geometry alters the effective emissivity of a surface:

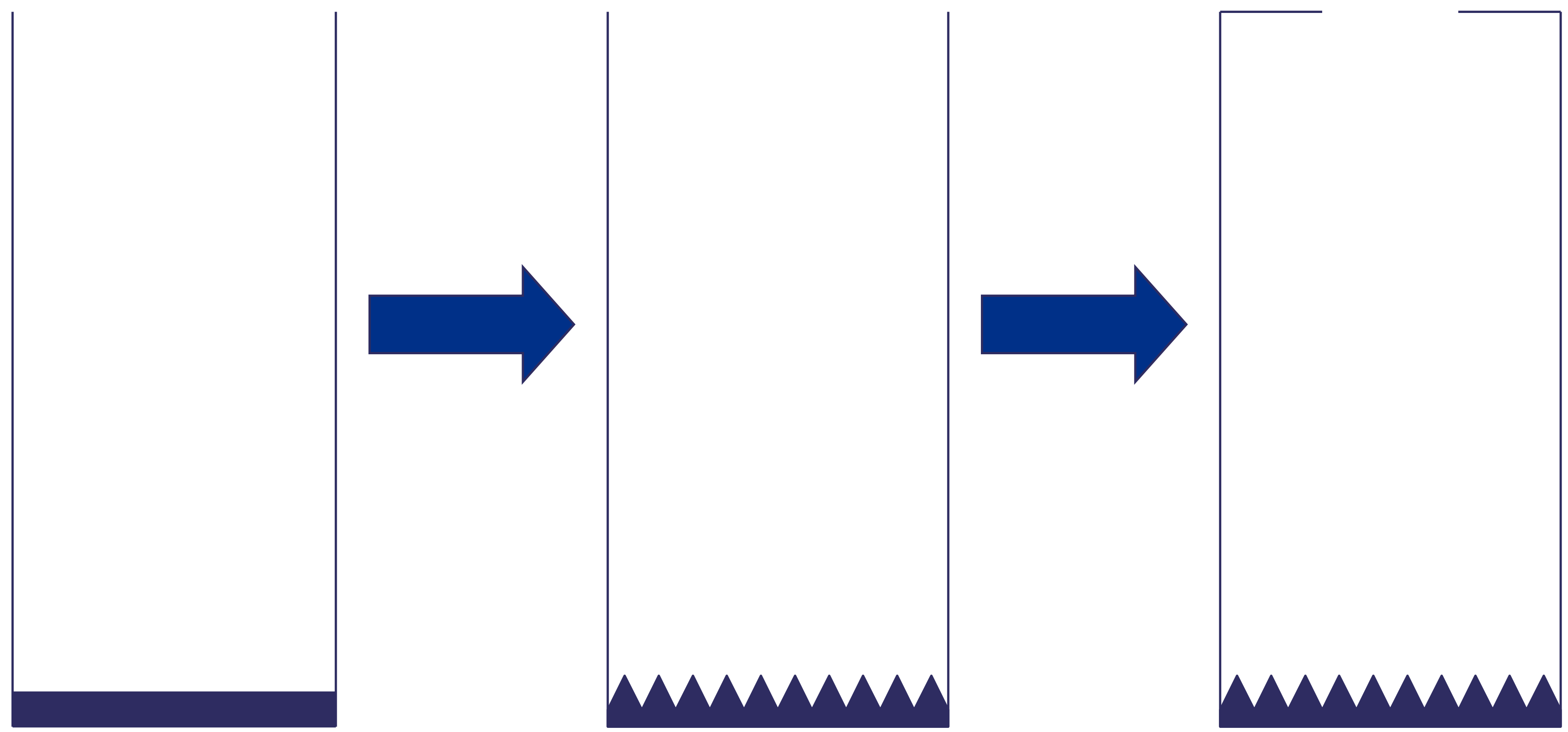


The longer the side walls:

the smaller the fraction of external radiances reflected into the instrument calibration view

the lower the radiative loading on the viewed surface

Yet more emissivity



We can enhance the emissivity by adding structure to the cavity that has the effect of increasing the number of reflections within the cavity before any reflected signal reaches the instrument.

Temperature

- The current best practical temperature scale is the International Temperature Scale of 1990 (ITS-90)
- Defined temperatures correspond to phase transitions in various pure elements and compounds
- ALL readily available thermometers are calibrated against ITS-90
- You get what you pay for with thermometers: If you need 10 mK accuracy (you might do) and excellent stability over time, you should budget a reasonable amount for the thermometer(s), readout electronics and a traceable calibration
- For the 0 ˚C – 100 ˚C range, platinum resistance thermometers (PRTs), rhodium-iron thermometers (RIRTs) and thermistors are all possibilities
- A good thermometer alone won't solve all your problems. It must also accurately represent the temperature of the emitting surface in the black body, so:
  - The paint or surface coating should be as thin as possible and the radiative heat load on it should be small
  - The principal thermometer must be embedded in the viewed surface
  - The thermometer wires need to be in good thermal contact with the black body walls
  - Keep temperature gradients in the directly viewed surface under control

Spectral Response

Measuring the spectral response $R(\lambda)$ of your sensor is critical if you really need accurate measurements because:

$$L_\lambda(T) = \int B(T_{scene}, \lambda)\, R(\lambda) d\lambda \bigg/ \int R(\lambda) d\lambda$$

... for an ideal BB source.

For ‘real’ scenes the measured radiance will be affected by atmospheric absorption and emission lines, spectral variations in emissivity.

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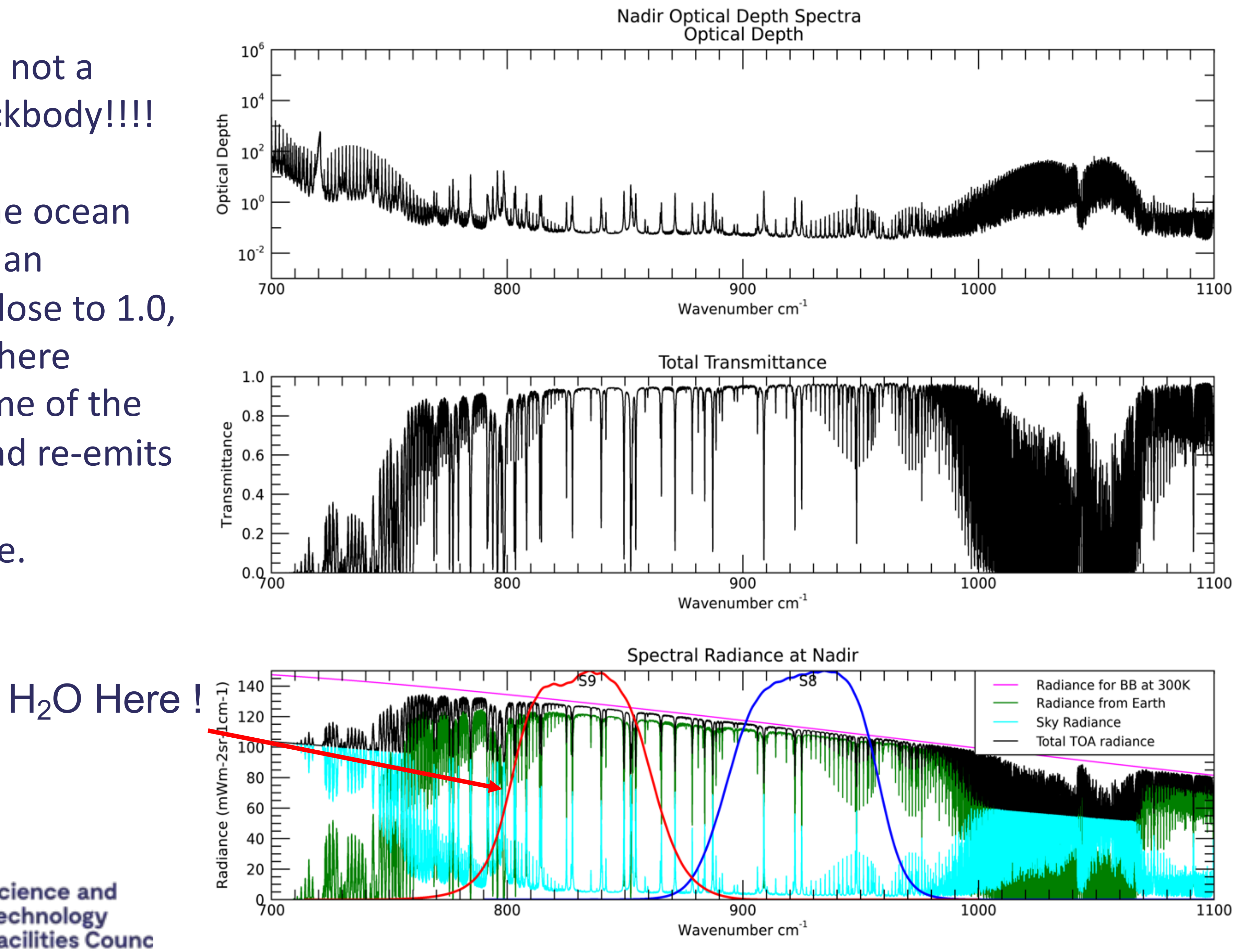
Spectral Response

The Earth is not a perfect blackbody!!!!

Although the ocean surface has an emissivity close to 1.0, the atmosphere absorbs some of the radiation and re-emits at a lower temperature.



Simulated atmospheric transmissions over the wavelength range 9-19µm for nadir view 0-40km vertical path generated by Fastcode, line-by-line code.

The profiles used were 'typical' mid latitude. Note that the spectral radiance reported here is in units of wavenumber.

H_2O is assumed ~10kgm^{-2}

Note – this is a particularly dry atmosphere and H_2O can go up to 60kgm^{-2}

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Spectral Response Calibration

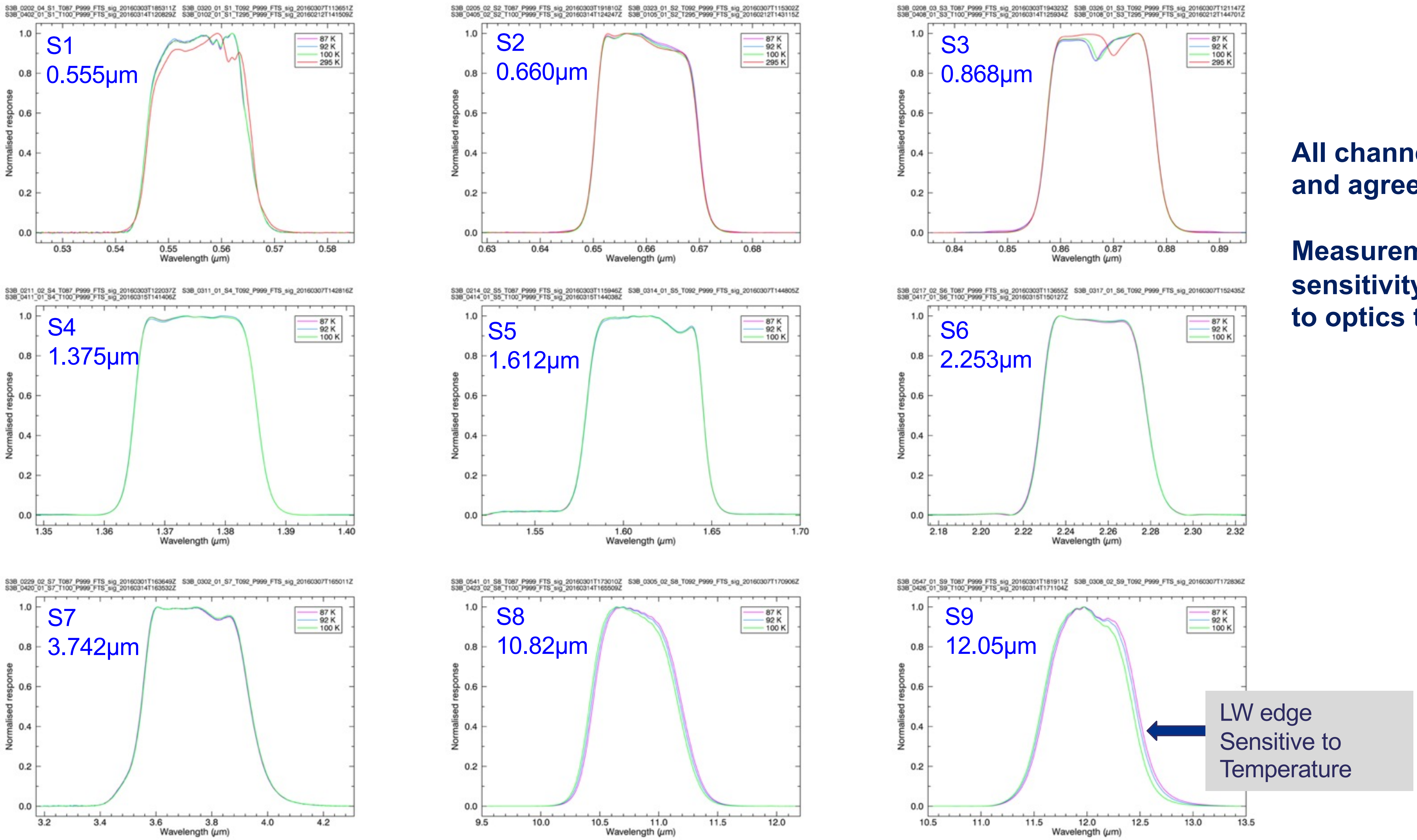
Measurement technique:

- Operated the SLSTR focal plane array as the detector in a Michelson Fourier transform spectrometer
- Derived spectral responses from time-resolved interferograms collected by the FPA detectors

Characterised:

- Spectral responses of all standard channels (S1 – S9) at FPA temperatures from 87K (flight operational temperature) to 100 K
- Spectral polarisation (depth, plane and unpolarised response) of longwave channels (S7 – S9) at an FPA temperature of 87K

Spectral Response Measurements



All channels meet requirements and agree well with predictions

Measurements show expected sensitivity of spectral responses to optics temperatures

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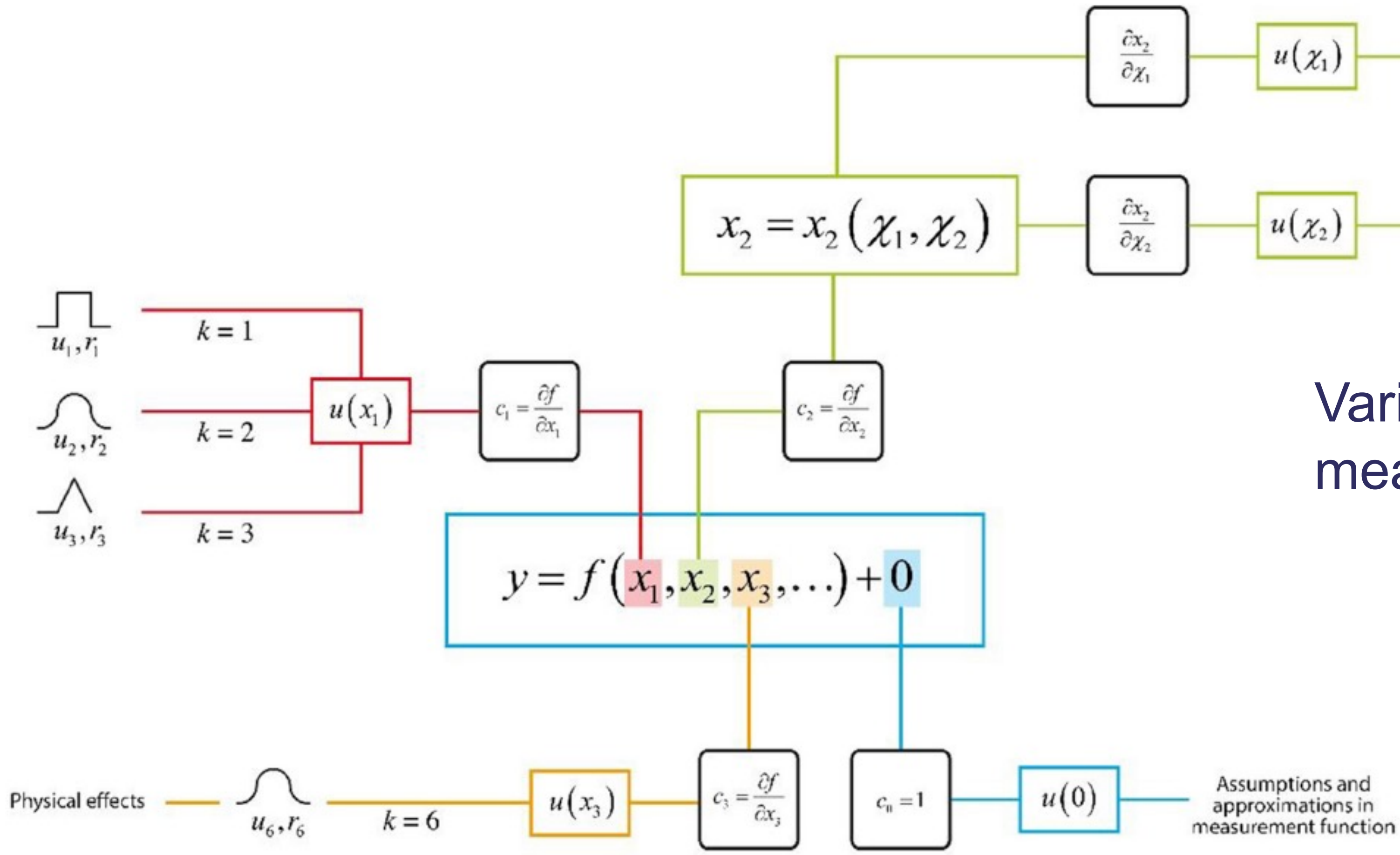
Other Error Sources

- Thermal drift
  - Just because you pointed your instrument at a blackbody in the lab doesn't mean your instrument calibration is valid in the field.
  - Remember, the calibration is very sensitive to changes in thermal environment.
  - This is why 2 BB sources are used for satellite instruments
- Non-Linearity
  - TIR detectors generally have a non-linear response (especially MCTs)
- Stray Light
  - Optics design is critical to minimise internal and external strays. Use of black coatings on optics mounts, baffles to avoid direct illumination of external heat sources.
- Size of source effects
  - Need to be aware of the beam geometry. If calibration source is too small or too far away, then the source does not fill the full optical beam - not recommended.

Law of Propagation of Uncertainties



From - Mittaz, J., Merchant, C. J. and Woolliams, E. R. (2019) Applying principles of metrology to historical Earth observations from satellites. Metrologia, 56 (3). ISSN 0026 1394 doi: https://doi.org/10.1088/16817575/ab1705

Variance of measurand

Variance of input quantity x_i

Correlation coefficient between input quantities x_i, x_j

$$u^2(y) = \sum_{i=1}^{N} \left(\frac{\partial y}{\partial x_i}\right)^2 u^2(x_i) + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} \frac{\partial y}{\partial \mathrm{x_i}}\frac{\partial y}{\partial \mathrm{x_j}} u(x_i)\, u(x_j) v(x_i, x_j)$$

Sensitivity of measurand to effect x_i

Ref: Evaluation of Measurement Data. Guide to the Expression of Uncertainty in Measurement (JCGM 100:2008).

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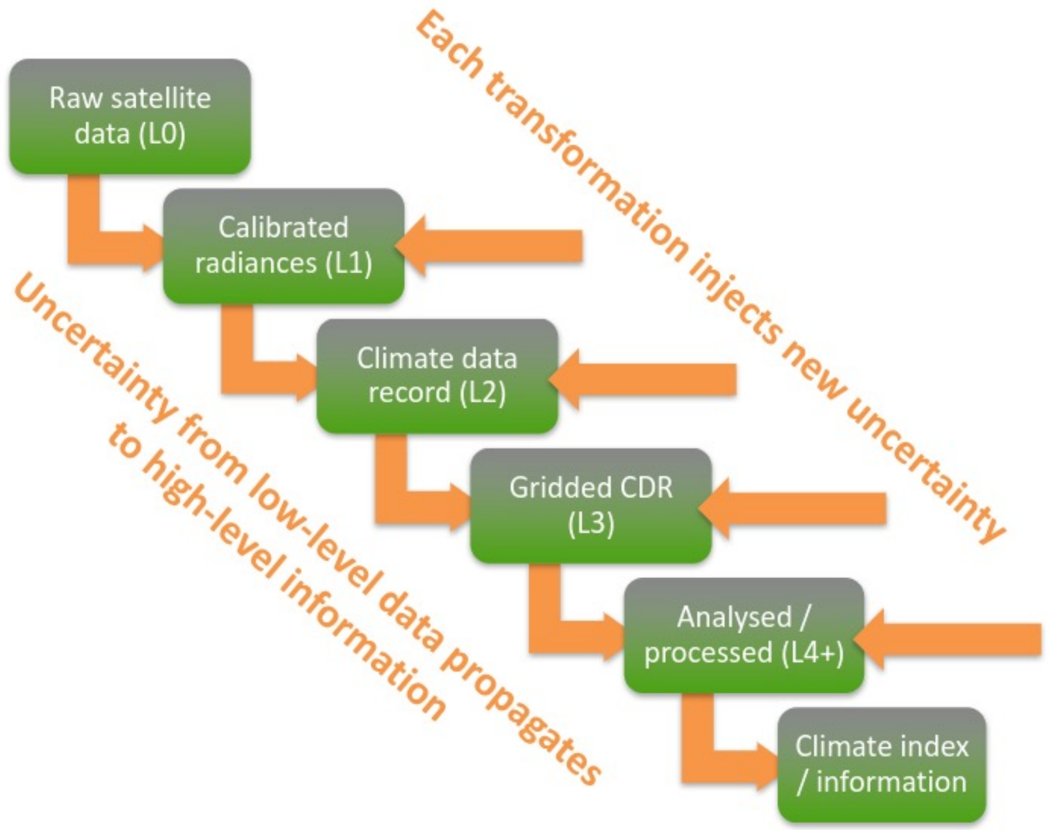
Propagation of Uncertainties in EO data

- Uncertainties from low level propagate to higher levels.
- E.g. L1 BTs affect L2 SST and beyond.
- Challenge is to trace uncertainties through full process



University of Reading

FIduceo

Merchant, Christopher J (2017). Propagation of uncertainty in Earth Observation. figshare. Journal contribution. https://doi.org/10.6084/m9.figshare.4924175.v1

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Uncertainty Propagation

SLSTR shown here

Starting point is the measurement equation

We include +0 term to account for additional effects

$$L_E = X L_{BB1} + (1 - X) L_{BB2} + 0$$

Uniformity around scan

Stray Light

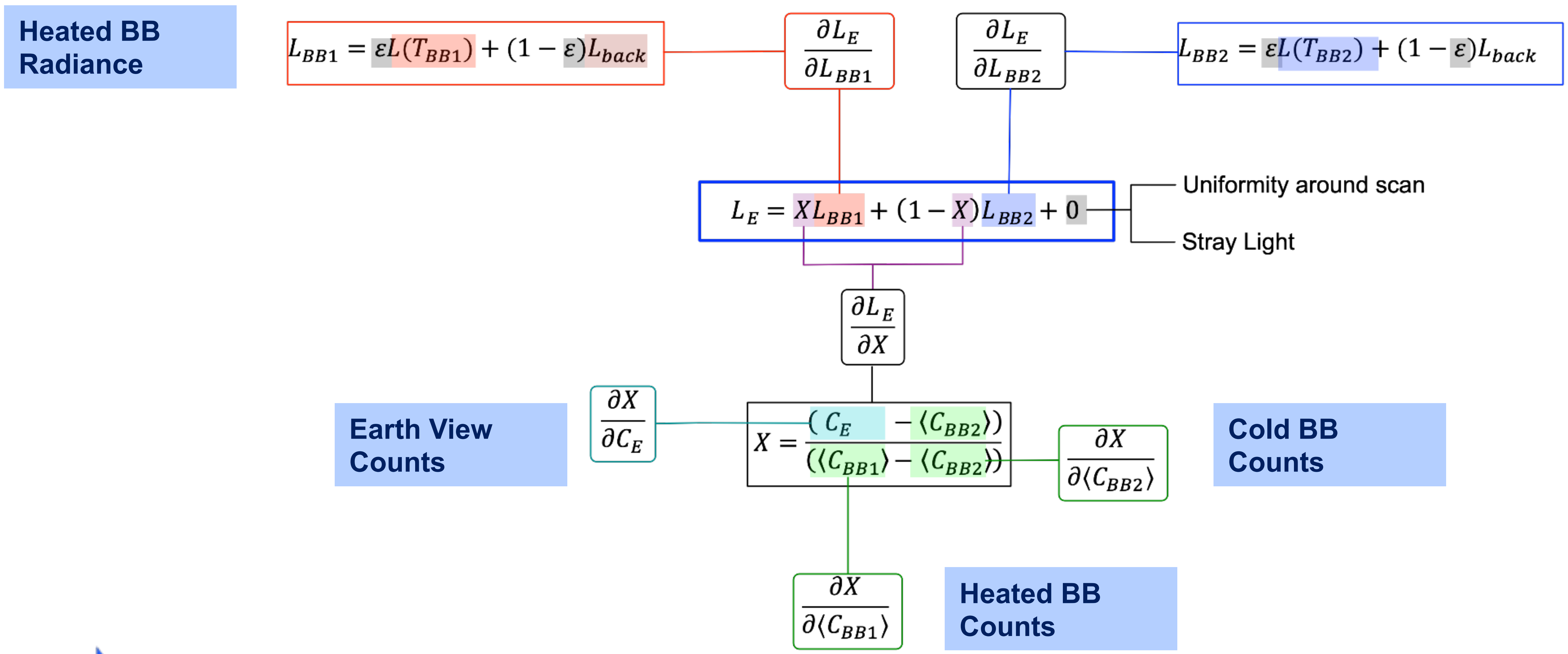
$$\frac{\partial L_E}{\partial X}$$

$$X = \frac{(C_E - \langle C_{BB2} \rangle)}{(\langle C_{BB1} \rangle - \langle C_{BB2} \rangle)}$$

Uncertainty Propagation

SLSTR shown here

We work outwards to determine all measurement effects



Uncertainty Propagation

SLSTR shown here

Heated BB Thermometry

Cold BB Thermometry

Spectral Response

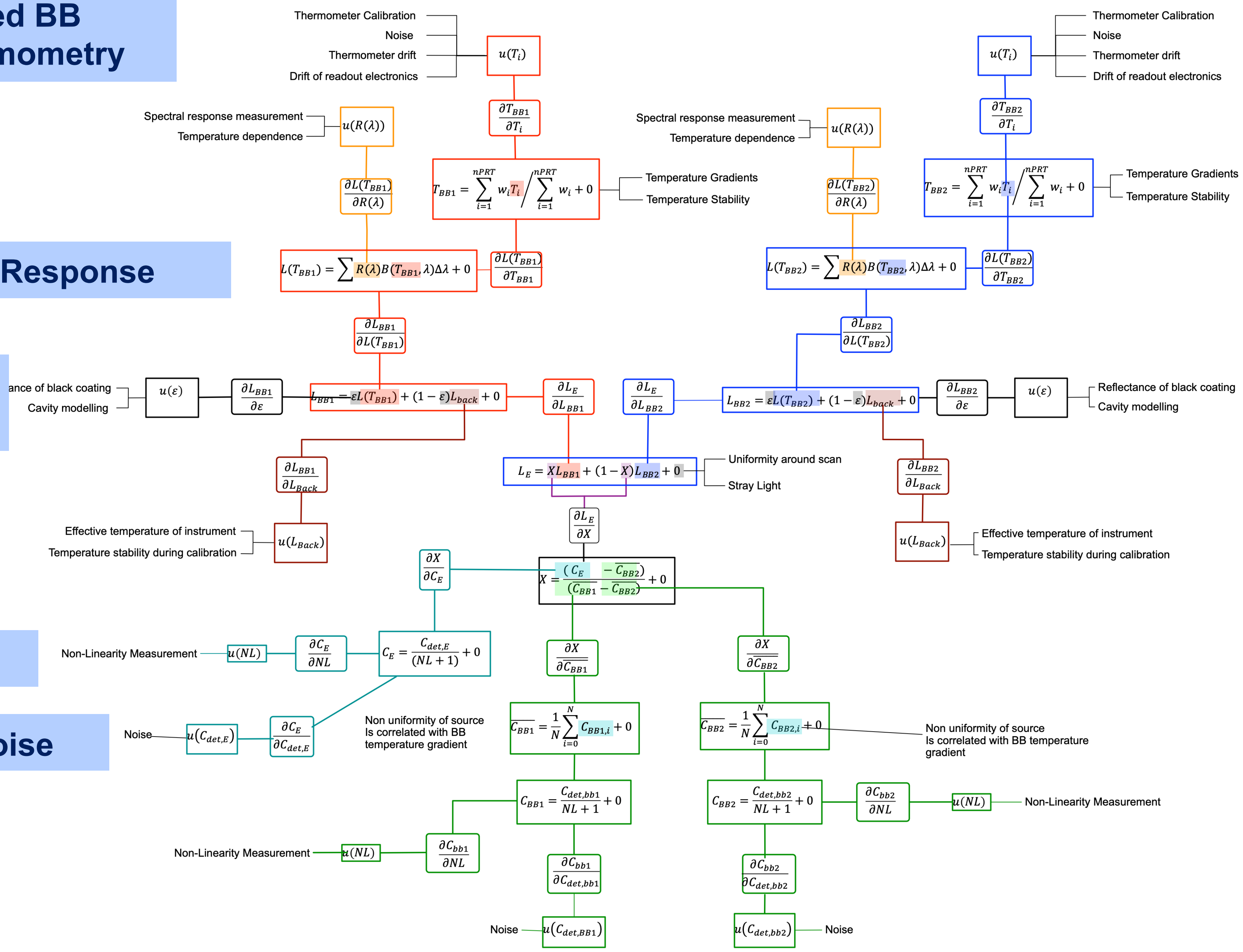
Spectral Response

Heated BB emissivity

Cold BB emissivity

Non-Linearity

Noise



We work outwards to determine all measurement effects

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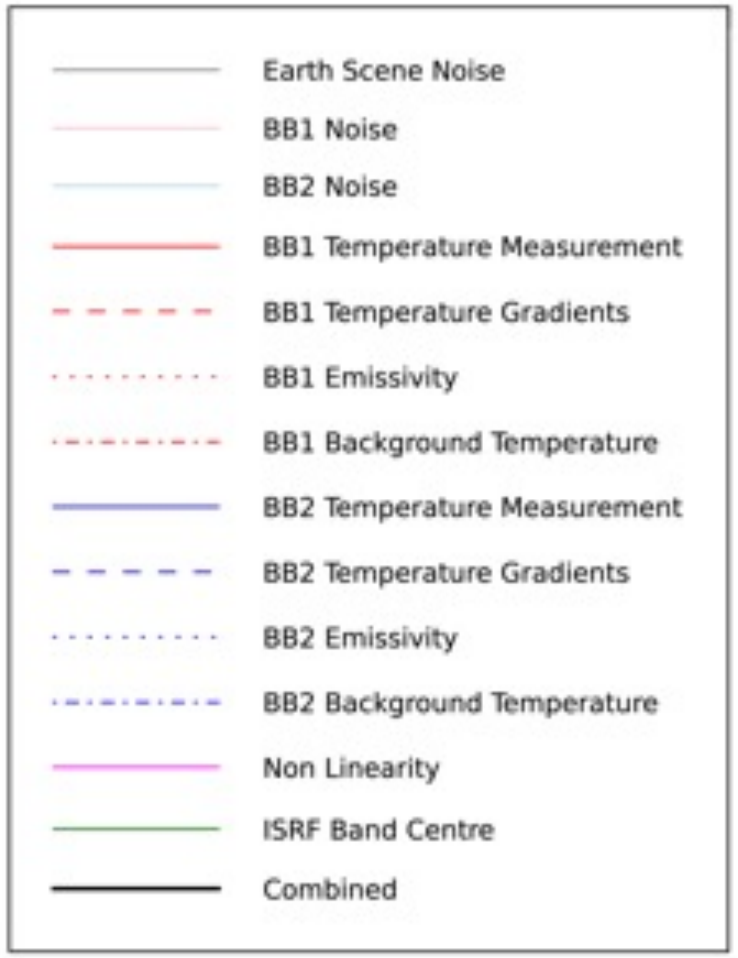
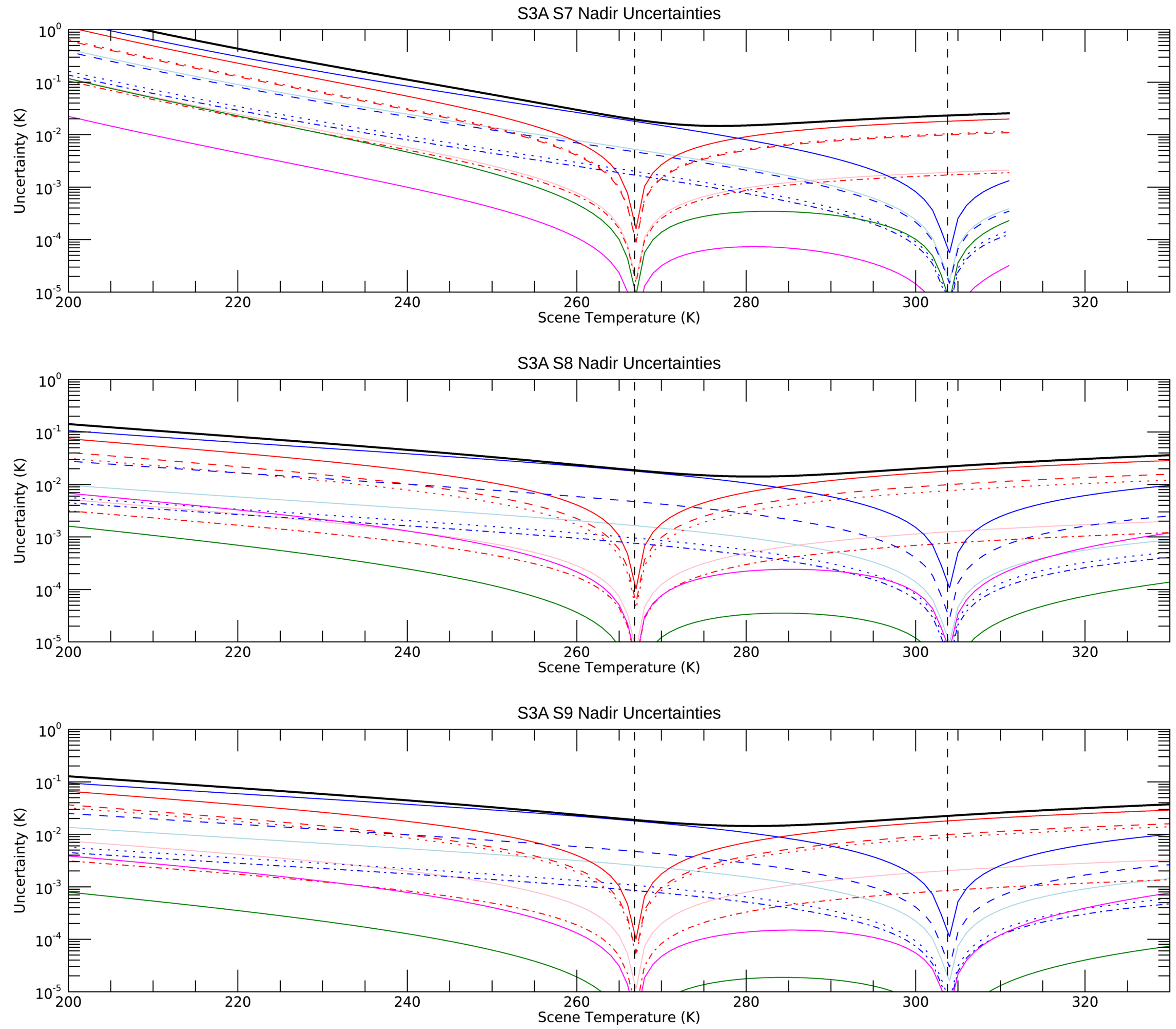
SLSTR Uncertainty Budget





SLSTR-A shown here for clarity

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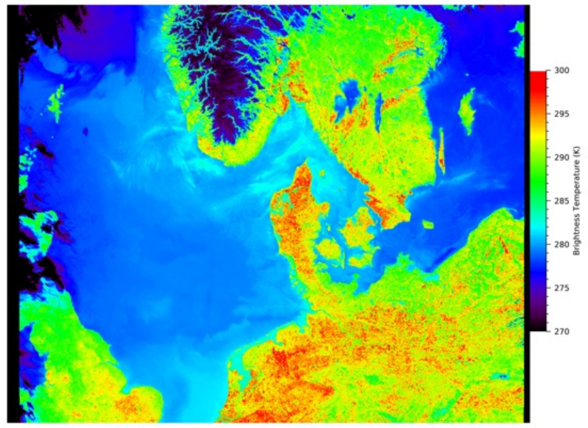
Uncertainties in SLSTR L1 Products

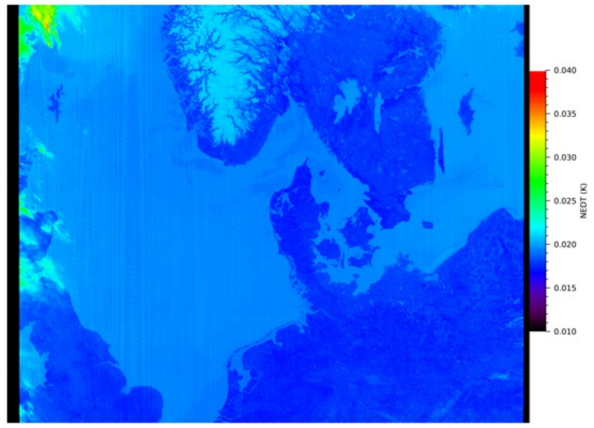
- Random effects - detector noise expressed as NEDT (TIR channels) and NEDL (VIS/SWIR channels) for each scan line
- Systematic effects – radiometric calibration - tables of uncertainty vs. temperature type-B (a-priori) estimates based on the pre-launch calibration and calibration model
- MapnoiS3 tool developed by RAL allows mapping of uncertainty information to L1 images

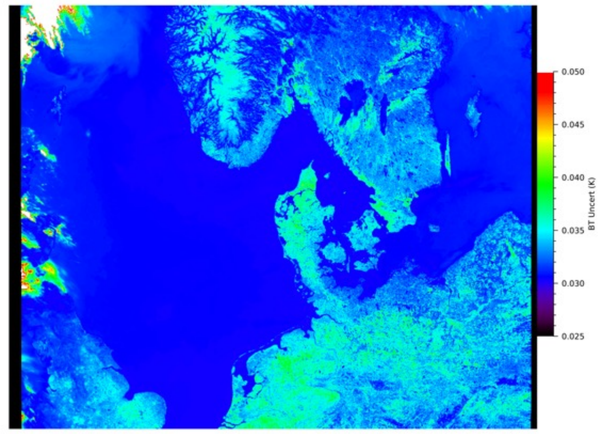
12µm BT

12µm NEDT (Random)

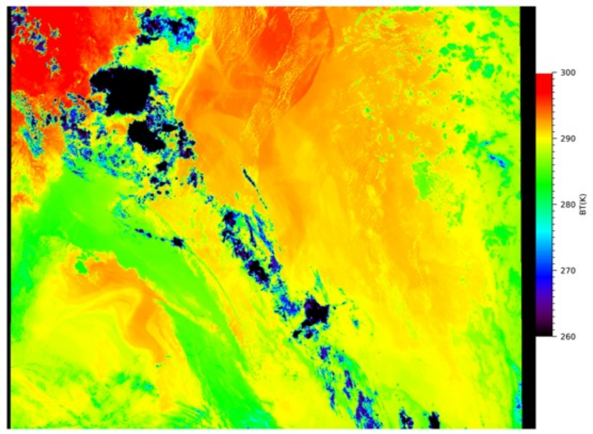
12µm uBT (Systematic)

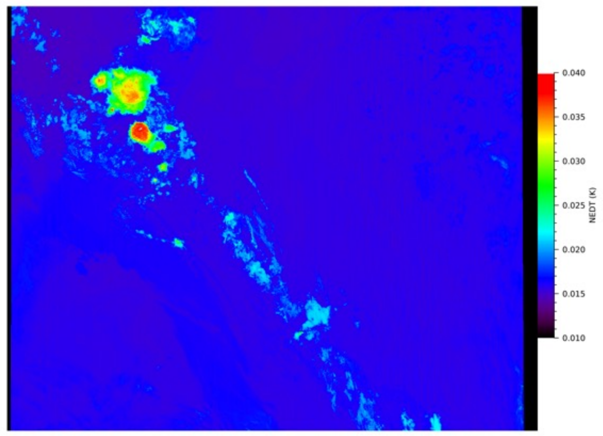


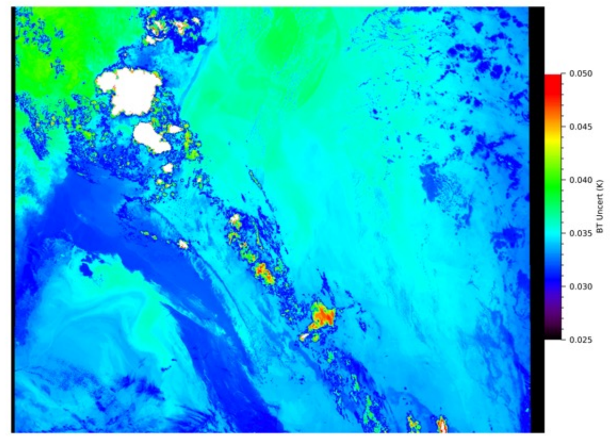




North Sea on 22-April-2020







Australia on 01-Jan-2020

Images from Smith D. et al, **Traceability of the Sentinel-3 SLSTR Level-1 Infrared Radiometric Processing** , Remote Sens. 2021, 13(3), 374; https://doi.org/10.3390/rs13030374

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Thank you!

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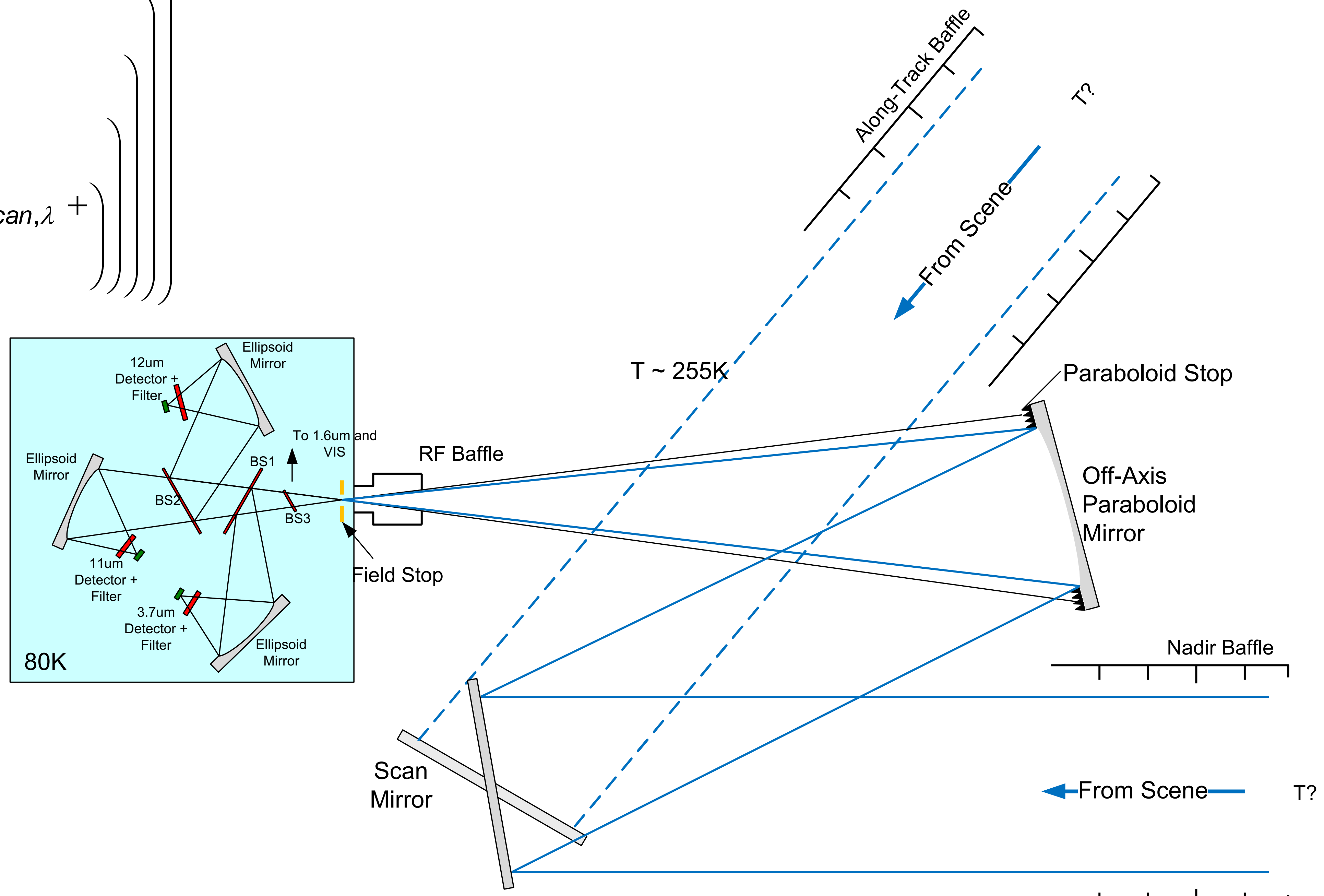
Optical Chain (from ATSR)

$$\phi_\lambda = A_\lambda\left((\pi-\Omega_\lambda)L_{FPA,\lambda} + \Omega_\lambda\left((1-\tau_{FPA,\lambda})L_{FPA\lambda} + \tau_{FPA,\lambda}\left((1-\xi_\lambda)L_{surr,\lambda} + \xi_\lambda\left((1-r_{para,\lambda})L_{para,\lambda} + r_{para,\lambda}\left((1-r_{scan,\lambda})L_{scan,\lambda} + r_{scan,\lambda}L_{scene,\lambda}\right)\right)\right)\right)\right)$$

At TIR wavelengths ALL surfaces emit as well as absorb/reflect



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