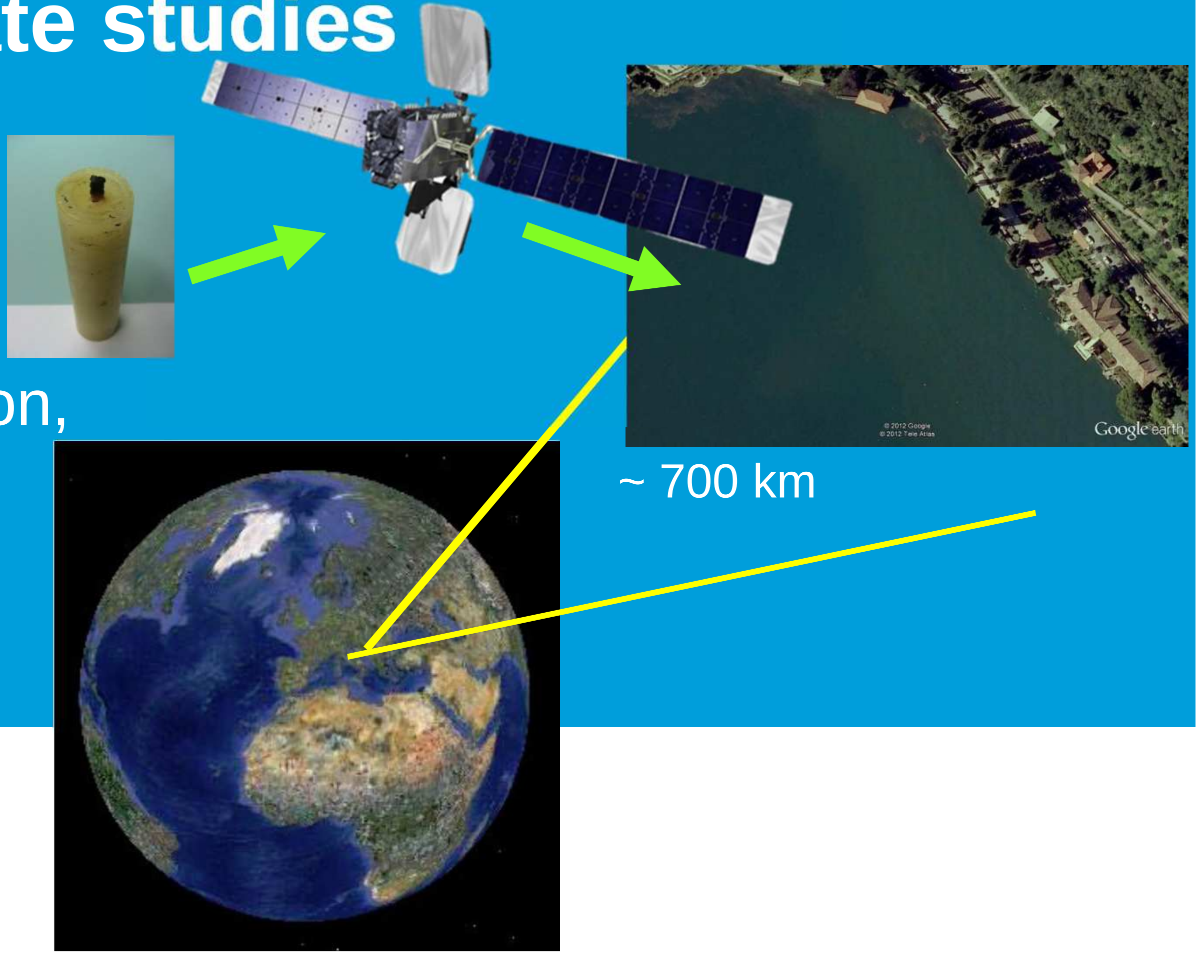
NPL National Physical Laboratory | Centre for Carbon Measurement

Metrology from : meeting the needs of climate studies



Nigel Fox

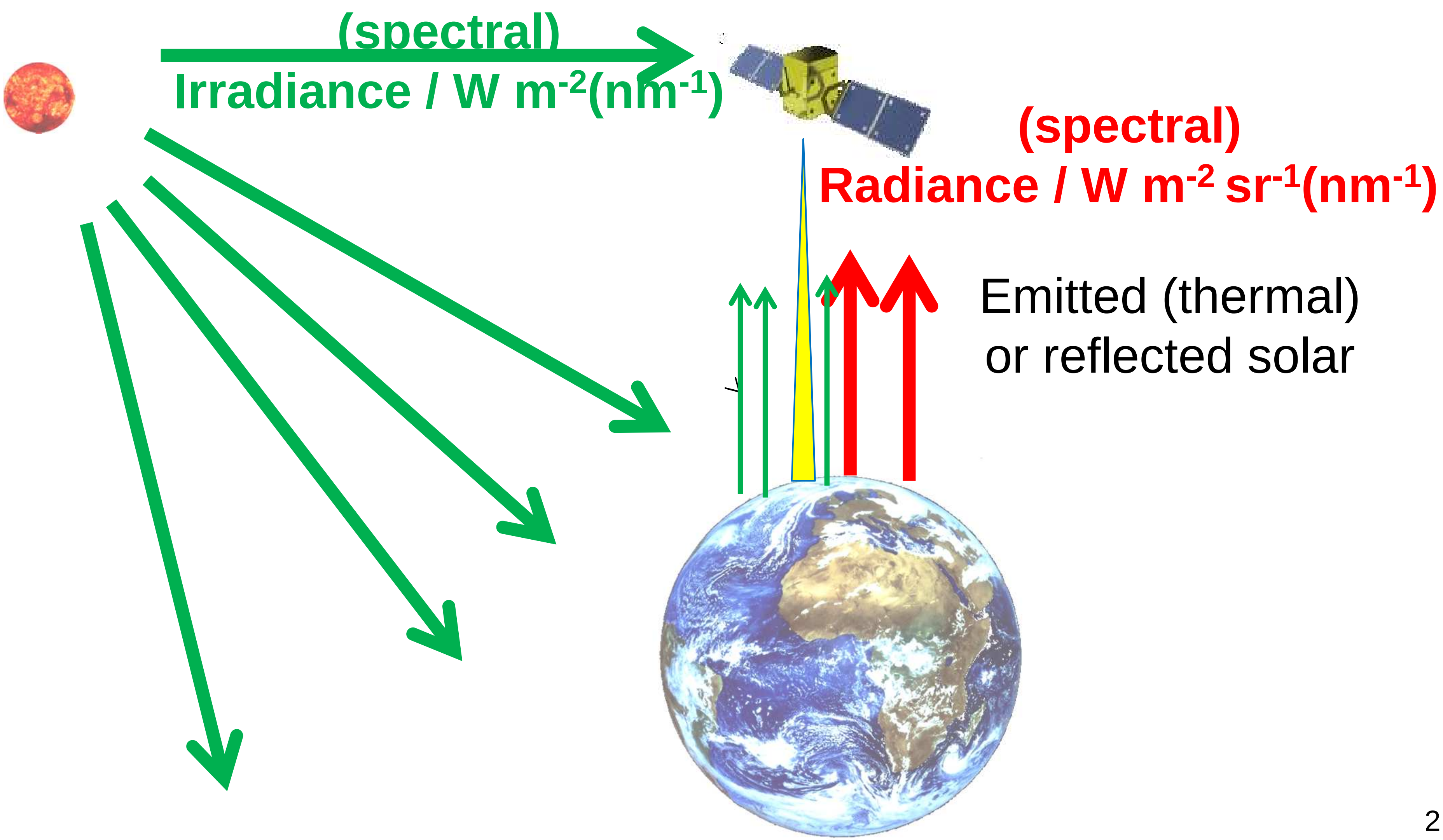
Head of Earth Observation,

Climate and Optical

Varenna 2016

National
Measurement
System

Some simple radiometric definitions



(spectral)
Irradiance / W $m^{-2}(nm^{-1})$

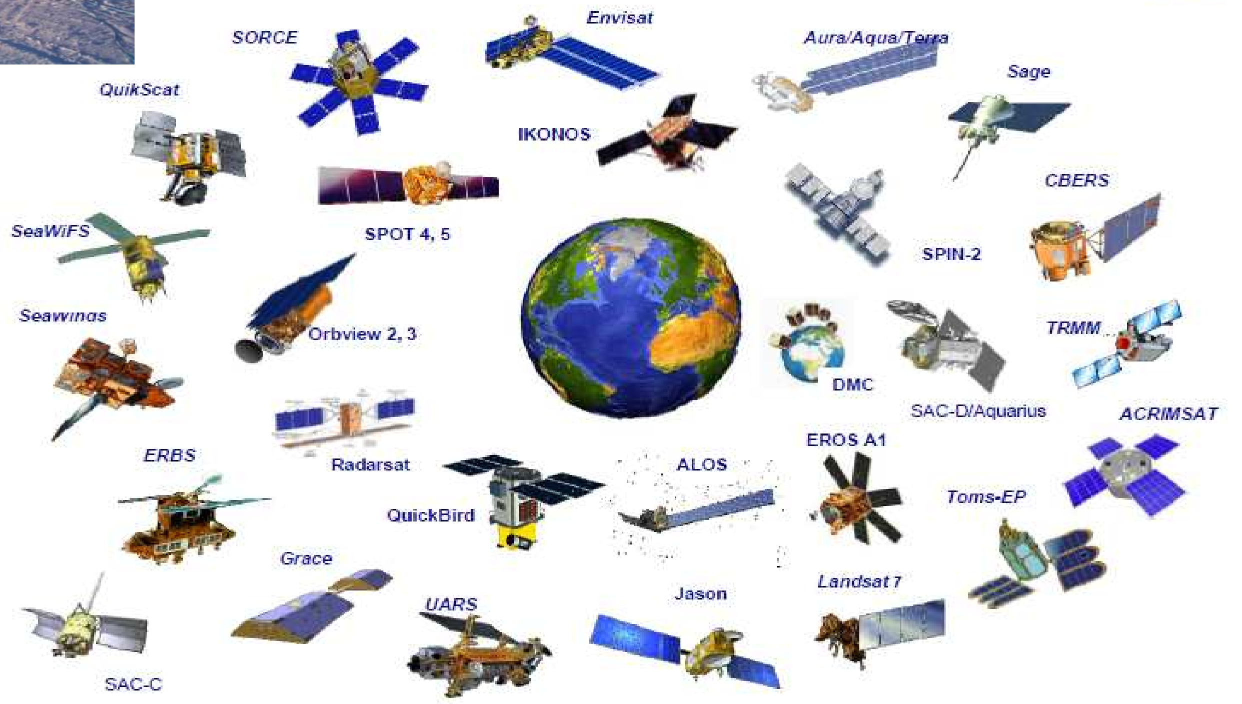
(spectral)
Radiance / W m^{-2} $sr^{-1}(nm^{-1})$

Emitted (thermal)
or reflected solar

What is Earth Observation?

But also In-situ

Remote sensing of the Earth from Space: Utilising full EM spectrum



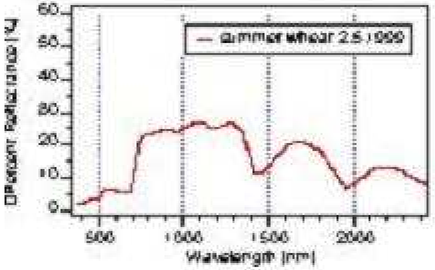
>100 EO satellites launched in 2000 – 2010 **~900 viewing Earth for defence**

>200 expected to be launched in current decade at a cost of $20B

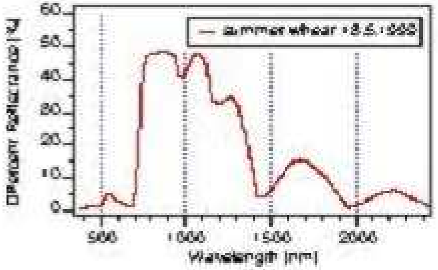
Operated by > 34 countries **Surface resolutions <1 m**

Life cycle of Wheat

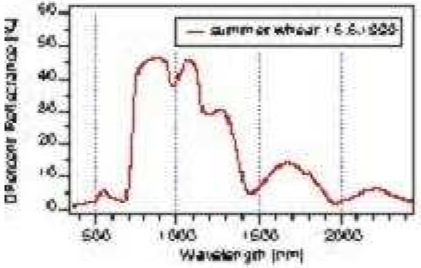
May 2



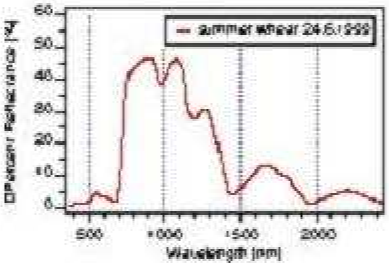
May 18



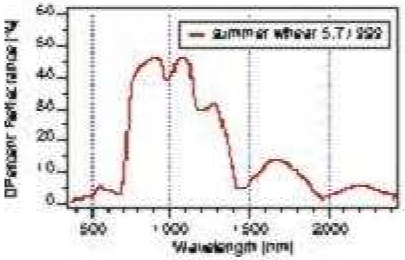
June 16



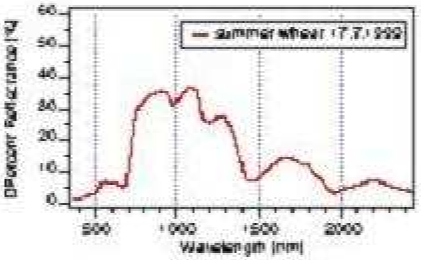
June 24



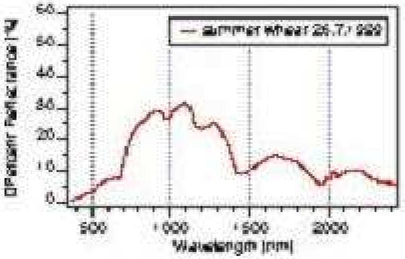
July 5



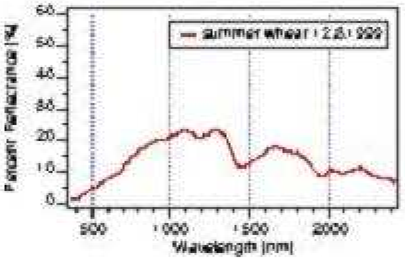
July 17



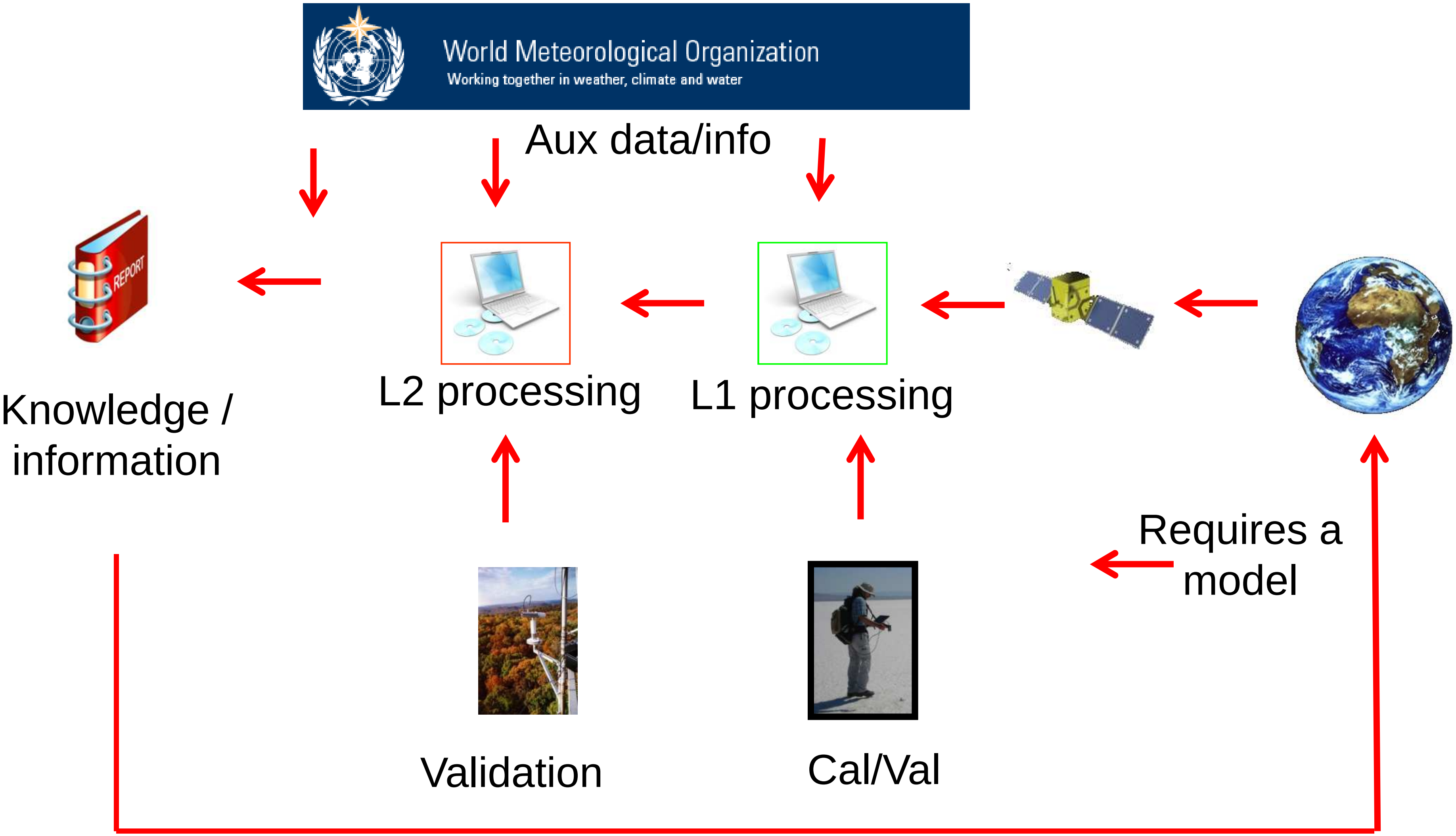
July 26



August 12



Earth Observation is dependent on models and their uncertainty – often very complex, poorly understood and difficult to robustly validate



World Meteorological Organization

Working together in weather, climate and water

Aux data/info

Knowledge / information

L2 processing

L1 processing

Requires a model

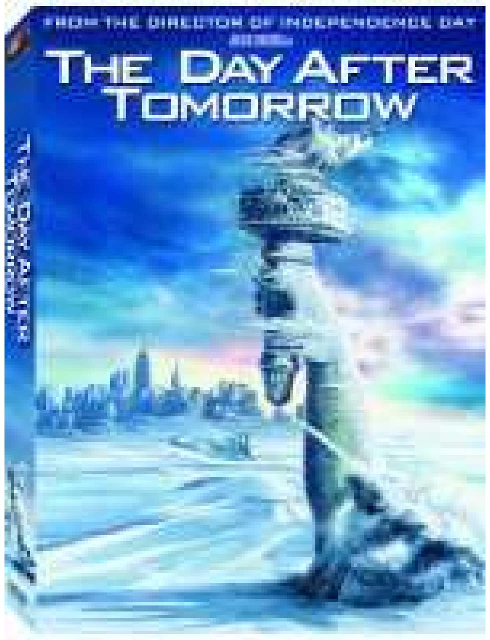
Validation

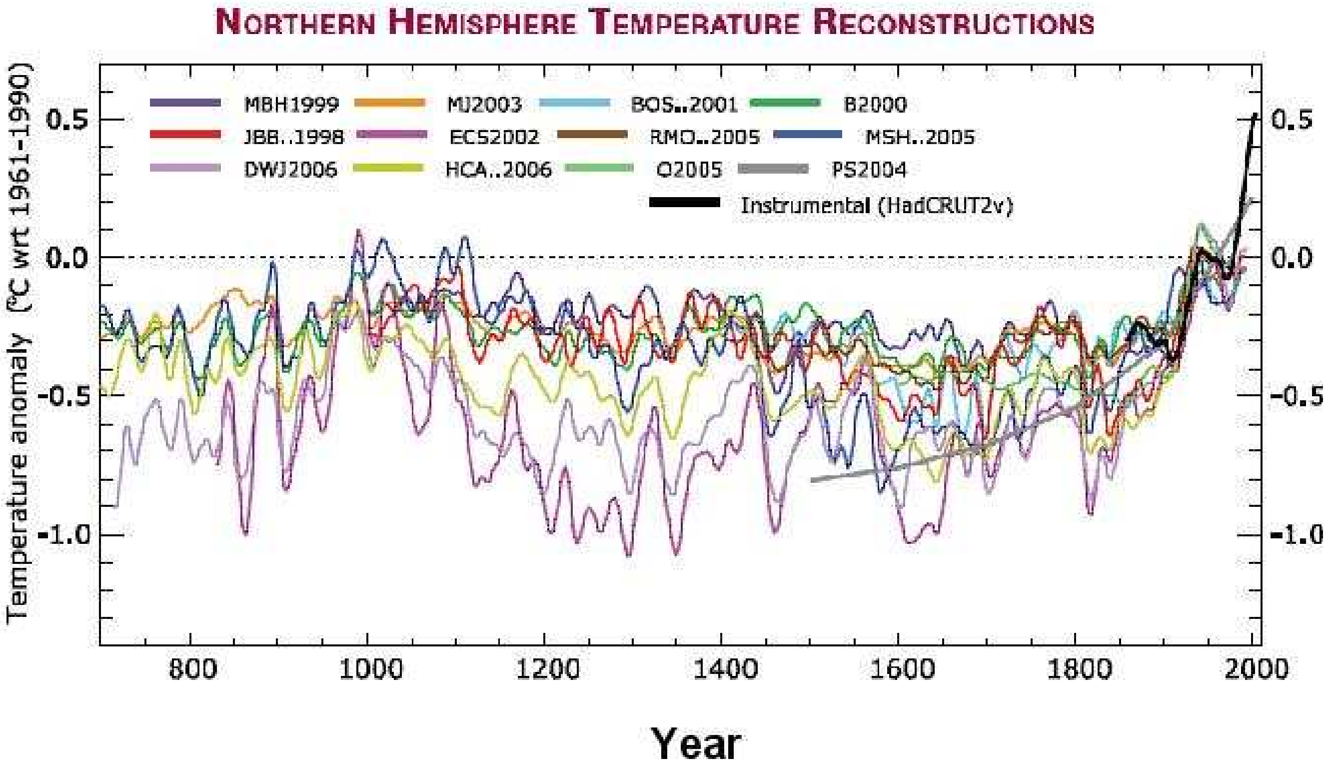
Cal/Val

Climate Change

Key Societal Questions

- Is the Earth warming ?
- If so how much ?
    - And by when?
- What is the cause ?
- Can we detect it ?
- Can we stop it ?
- Do we care ?





Climate Change

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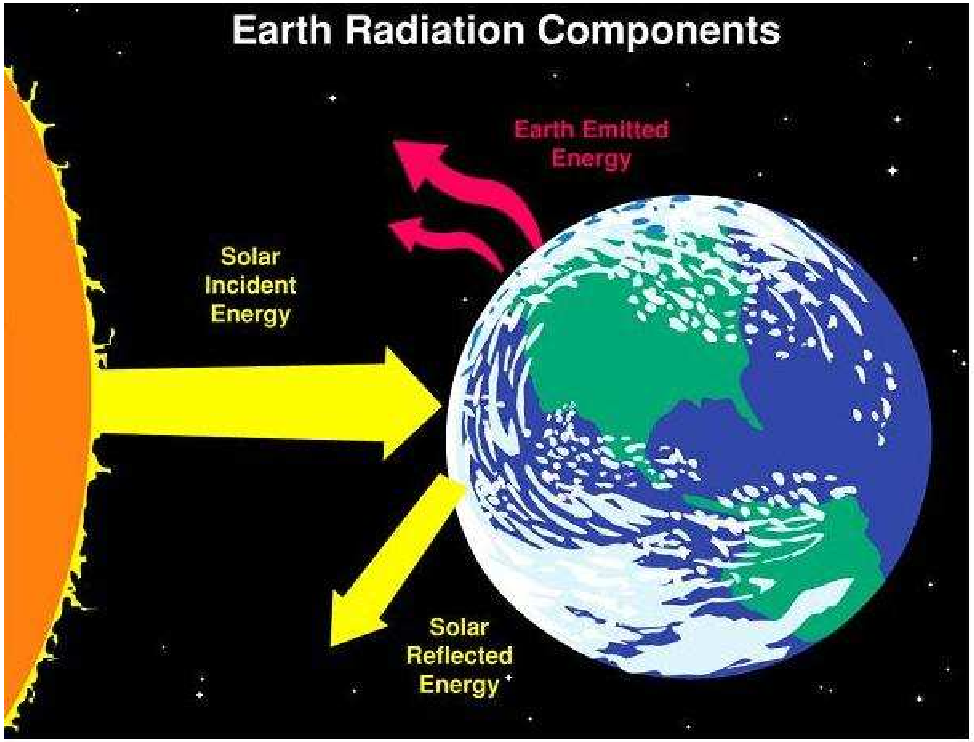

Earth Radiation budget (balance)

Energy in = Energy out

No additional warming

∴ No Climate change

Climate Change

Key Societal Questions

- Is the Earth warming ?
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  and by when?
- What is the cause ?
- Can we detect it ?
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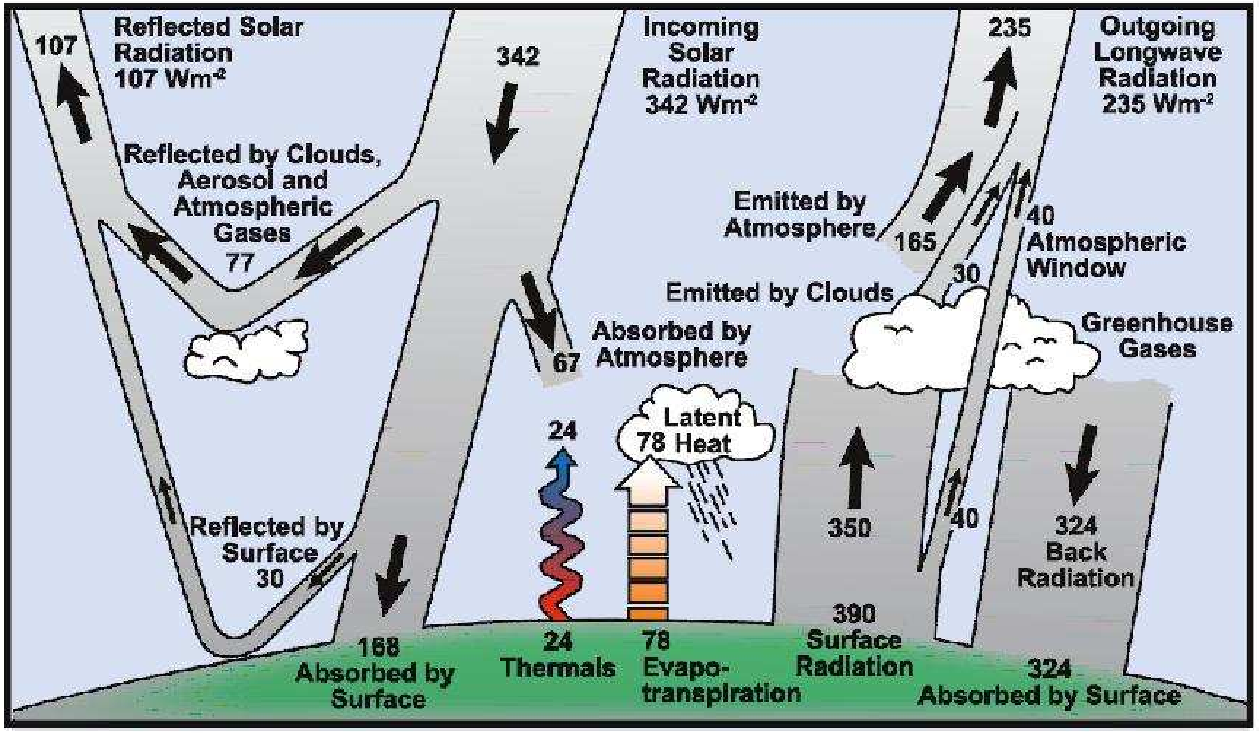
Radiation Budget



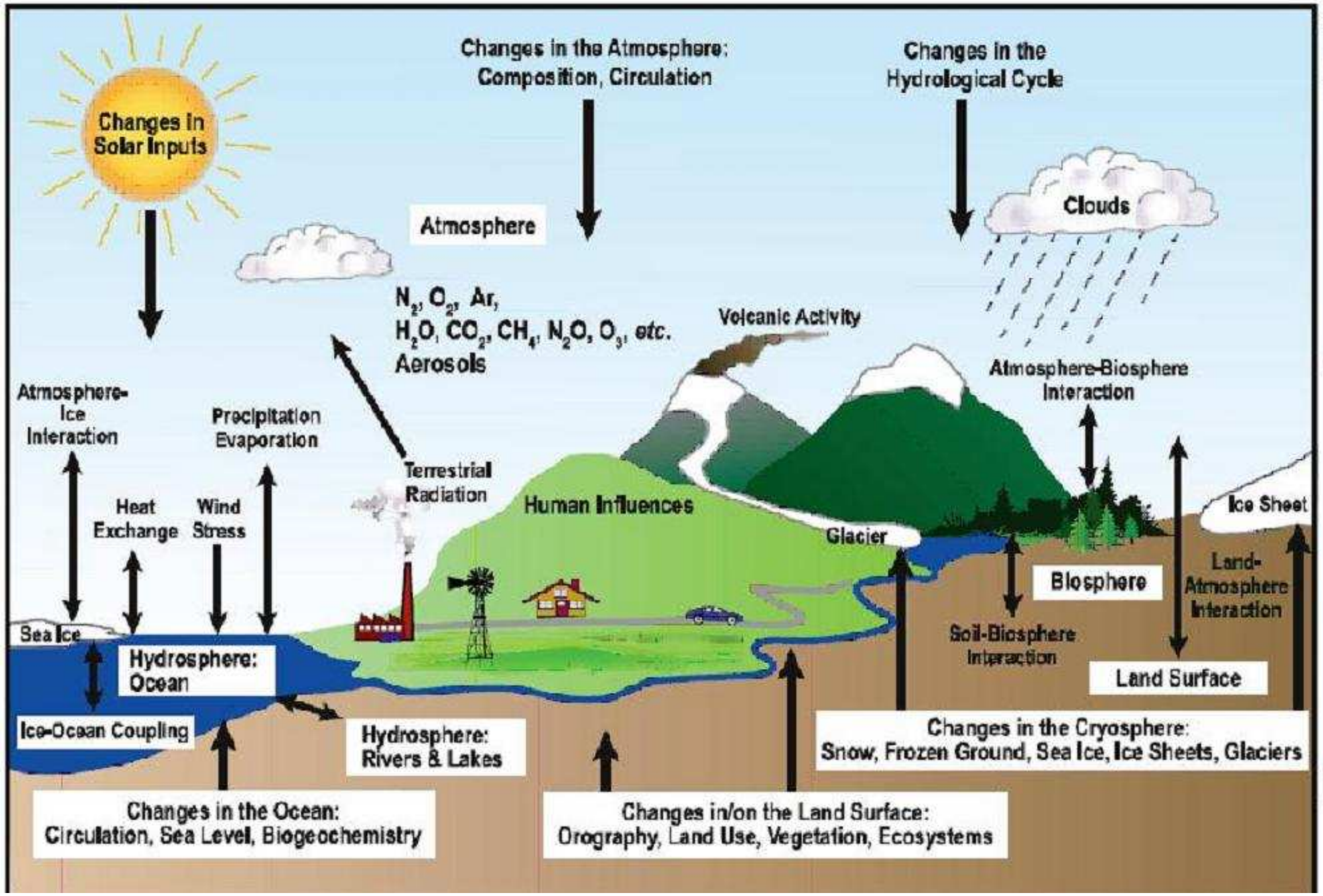
Climate Change

Key Societal Questions

- Is the Earth warming ?
- If so how much ?

  and by when?
- What is the cause ?
- Can we detect it ?
- Can we stop it ?
- Do we care ?

Earth System is very complex



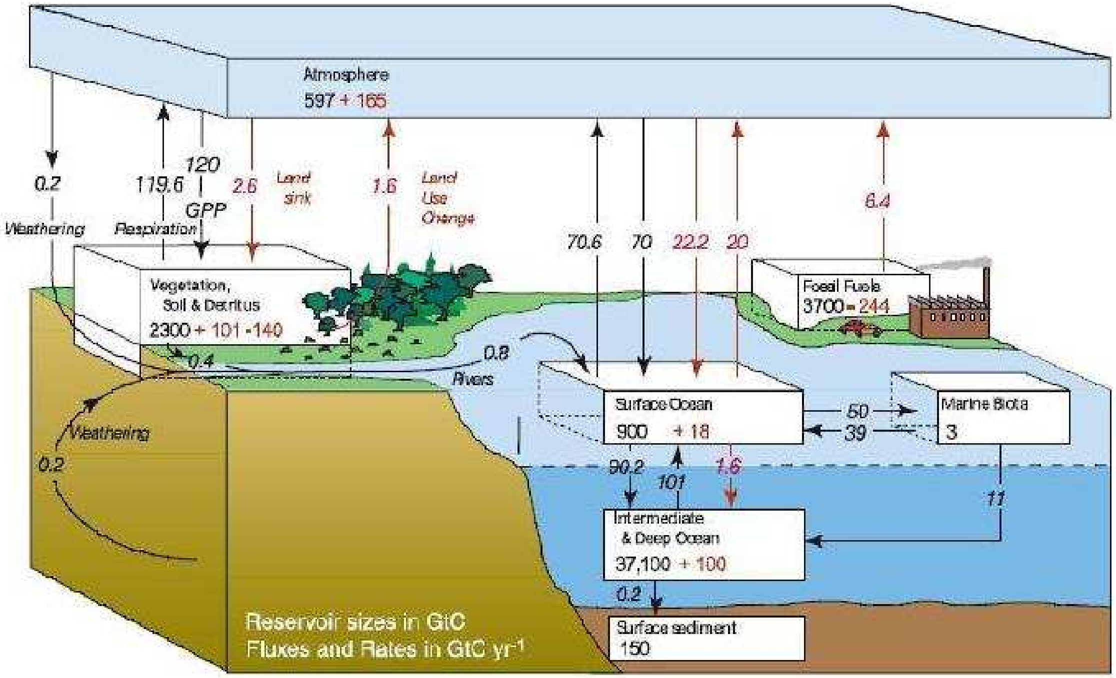
Climate Change

Key Societal Questions

- **Is the Earth warming ?**
- **If so how much ?**

  and by when?
- **What is the cause ?**
- **Can we detect it ?**
- **Can we stop it ?**
- **Do we care ?**

Carbon Fluxes

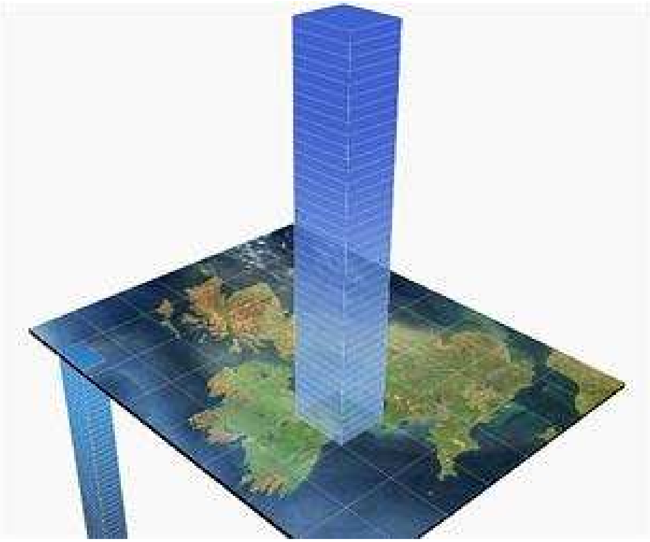


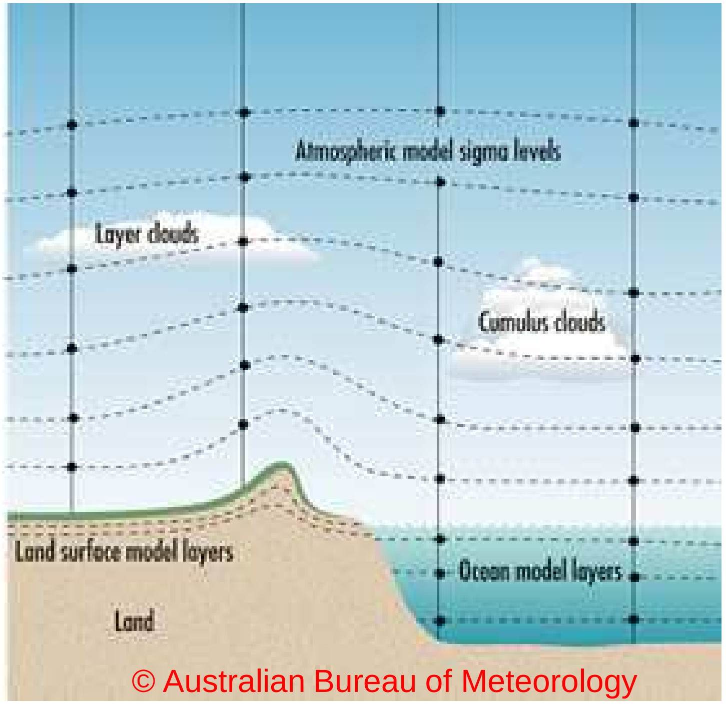
Sources of Carbon (colour Key)

- Anthropogenic
- Pre-industrial (Natural)

Climate Models or “Long-range weather”

- High complexity
- Based on linkages of many models
- Computationally hungry
- Reliable?





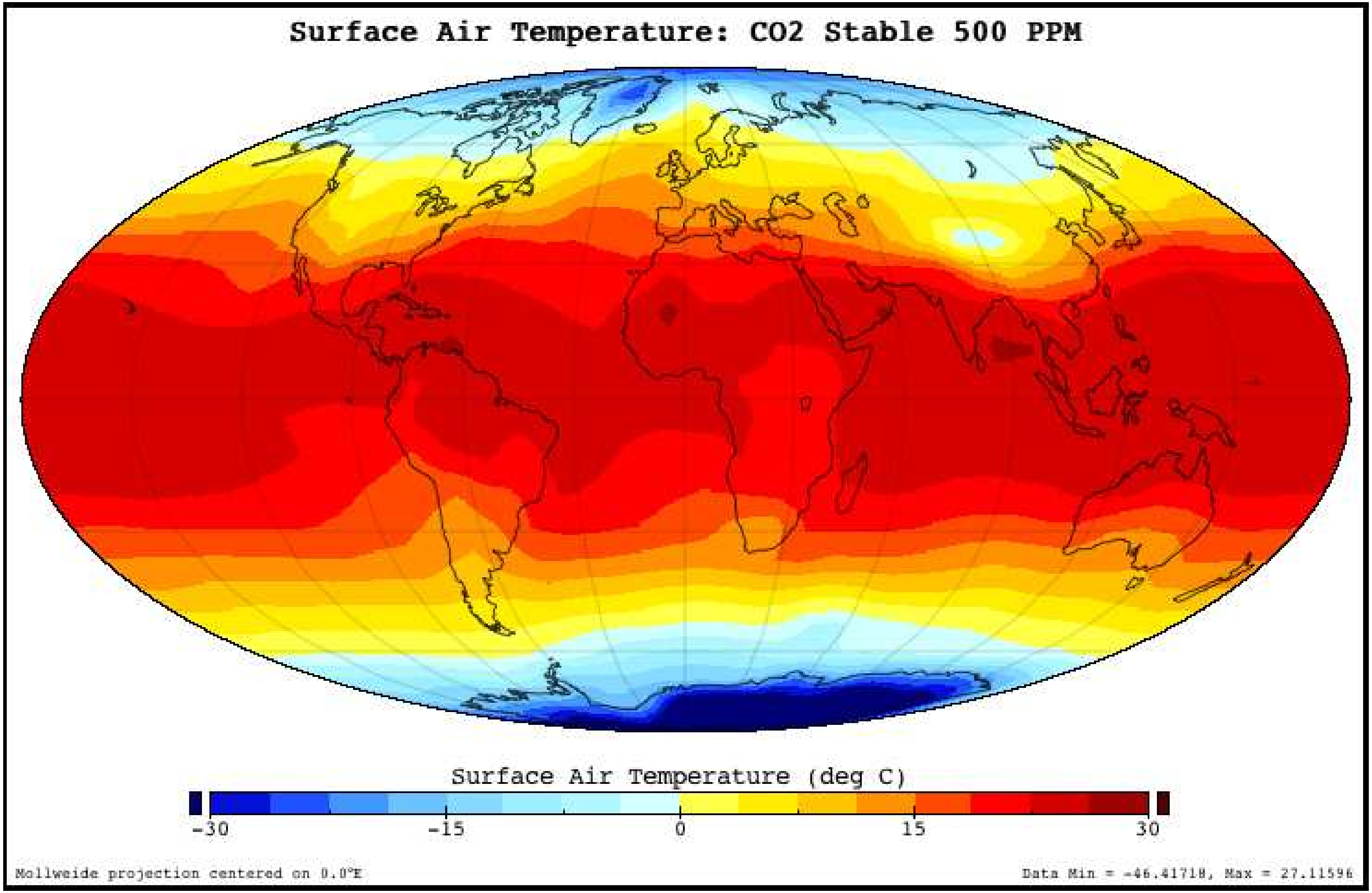
© Australian Bureau of Meteorology

UK Met office

HadGEM2-ES

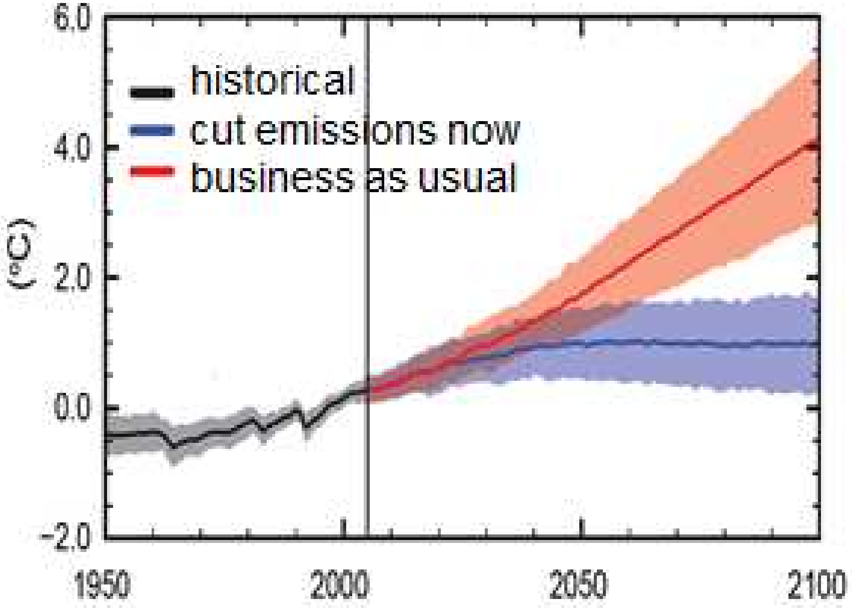
135 km Sq grid
38 vertical levels

Climate Models: Forecast the future state of the planet due to changes in key variables e.g. CO_2



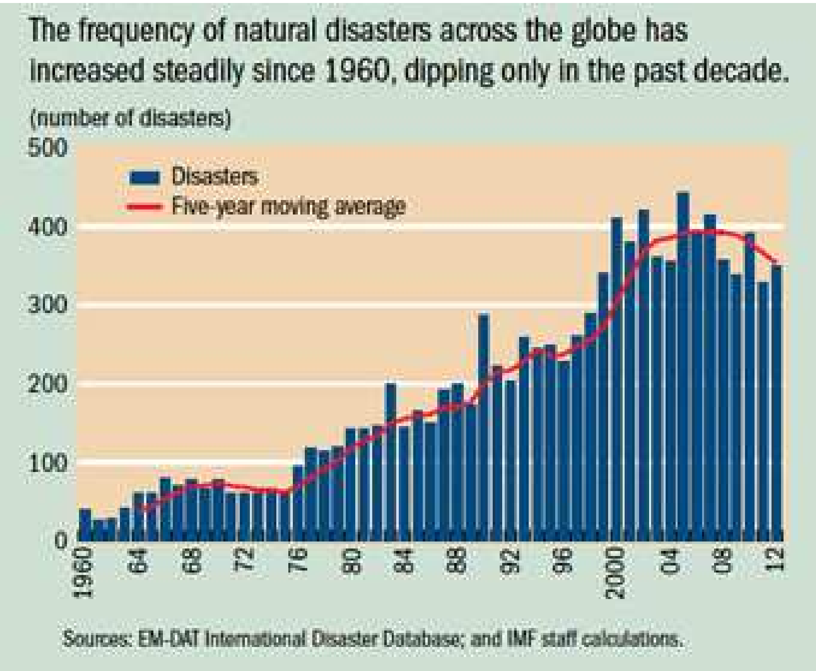
“A warming Earth” - How Much?

All climate models reliably predict the past (nearly) but provide wide variances in their prediction of the future.



Uncertainty in data/ feedbacks limits ability to discriminate to ~ 30 yrs!!

Need to test and constrain models with data more accurate than natural variability.

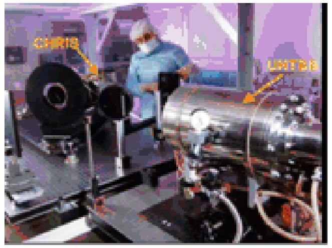


The frequency of natural disasters across the globe has increased steadily since 1960, dipping only in the past decade.

Sources: EM-DAT International Disaster Database; and IMF staff calculations.

Data to Decision

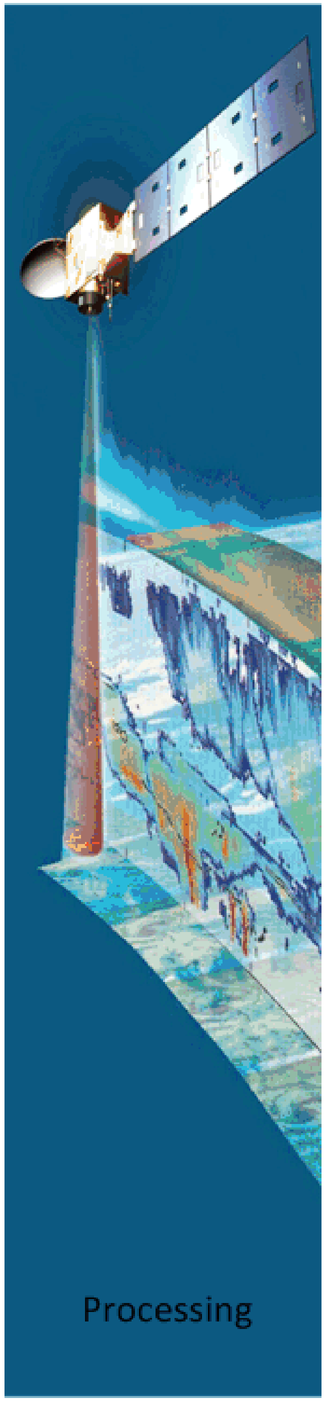
Preflight calibration



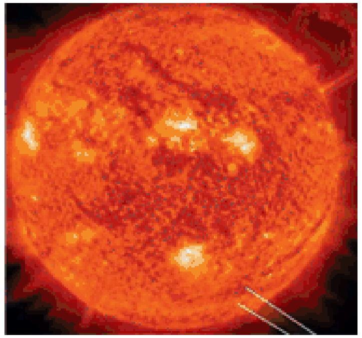
Fundamental
Climate
Data Record

Post-launch
validation

Every step introduces new uncertainty

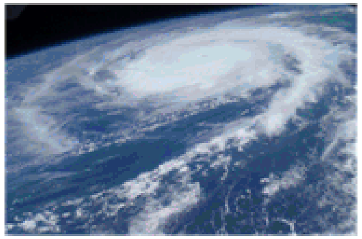


Processing

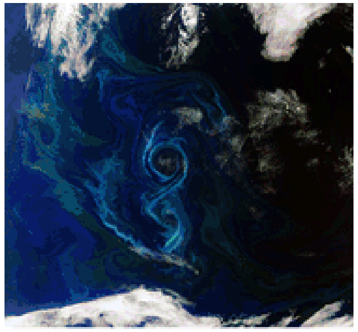


Essential

Climate

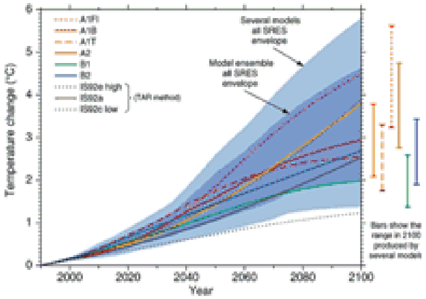


Variables



Climate Models

Predictions



Governments

Action

Fundamental Climate Data Records

Long-term (30+years) records from space

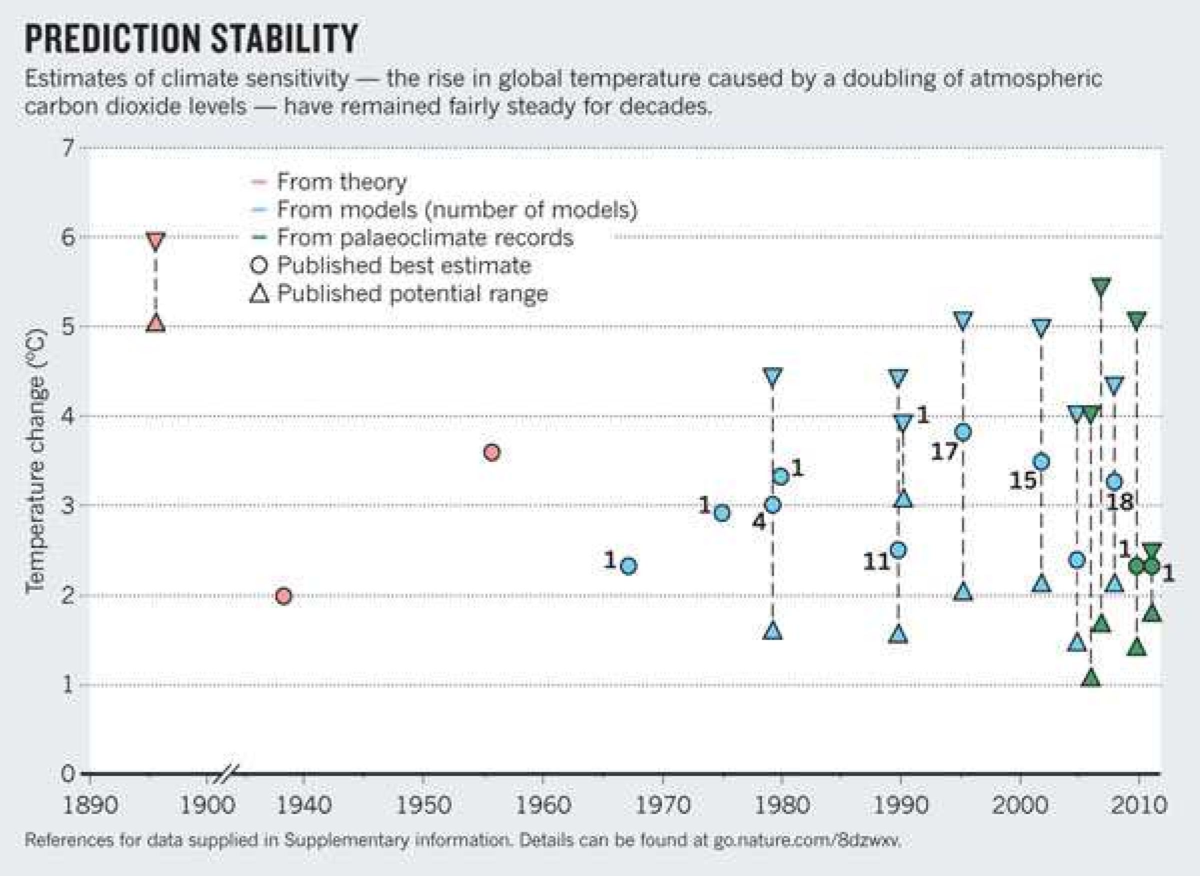
With robust uncertainty estimation and traceability

FCDRs: harmonised records of radiance / reflectance / brightness temperature

CDRs: records of geophysical parameters (e.g. ECVs) built from FCDRs

Climate sensitivity (& uncertainty) to 2X CO_2

Maslin & Austin Nature V486 p182 June 2012



PREDICTION STABILITY

Estimates of climate sensitivity — the rise in global temperature caused by a doubling of atmospheric carbon dioxide levels — have remained fairly steady for decades.

References for data supplied in Supplementary information. Details can be found at go.nature.com/8dzwxv.

Uncertainty may increase as models get more sophisticated

- Increased spatial resolution – precipitation less well known
- Include Carbon cycle – some input parameters high uncertainty
- Clouds/aerosols/atmospheric chemistry

ECV's of WMO-GCOS (Global climate observing system)

GCOS

ICSU

WORLD METEOROLOGICAL ORGANIZATION

INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION

IMPLEMENTATION PLAN FOR THE
GLOBAL OBSERVING SYSTEM FOR CLIMATE
IN SUPPORT OF THE UNFCCC

(2010 UPDATE)

Need to detect small decadal trends from background of natural variability (weather +)

Requires trustable global observations over decades

NEEDS:

- **Satellites**
- **In-situ validation**
- **Interdependent measurands/algorithms**

- SI TRACEABILITY

50 ECV's with monitoring requirements, short and long term

~50% only measured from Satellites

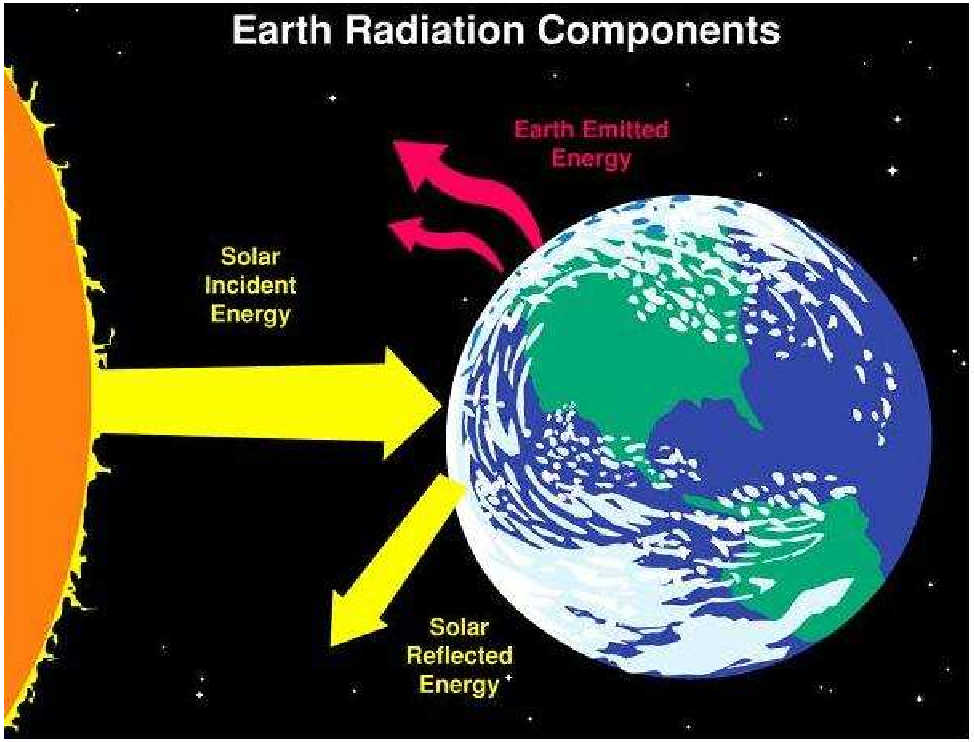
Further 25% Satellites & in-situ

~ 2/3 need optical radiometric measurements

Atmospheric	Surface:	Air temperature, wind speed and direction, water vapour, pressure, precipitation, surface radiation budget
	Upper-air:	Temperature, wind speed and direction, water vapour, cloud properties, earth radiation budget (including solar irradiance)
	Composition:	Carbon dioxide, methane, other long-lived greenhouse gases, ozone and aerosol, supported by their precursors
Oceanic	Surface:	Sea-surface temperature, sea-surface salinity, sea level, sea state, sea ice, surface current, ocean colour, carbon dioxide partial pressure, ocean acidity, phytoplankton
	Sub-surface:	Temperature, salinity, current, nutrients, carbon dioxide partial pressure, ocean acidity, oxygen, tracers
Terrestrial	River discharge, water use, groundwater, lakes, snow cover, glaciers and ice caps, ice sheets, permafrost, albedo, land cover (including vegetation type), fraction of absorbed photosynthetically active radiation, leaf area index, above-ground biomass, soil carbon, fire disturbance, soil moisture	

http://www.wmo.int/pages/prog/gcos/Publications/gcos-138.pdf

Climate Change



Earth Radiation budget (balance)

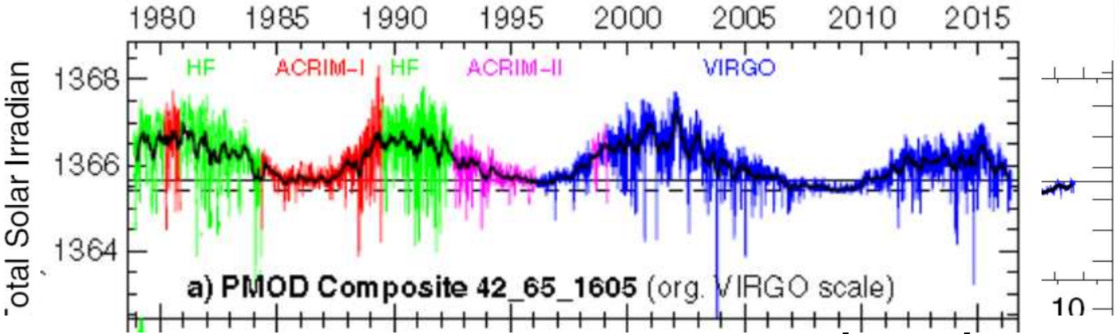
Energy in = Energy out

No additional warming

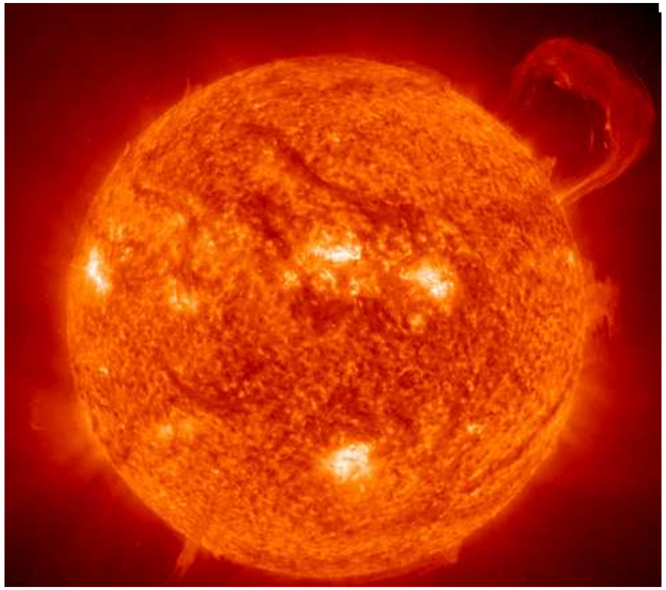
∴ No Climate change

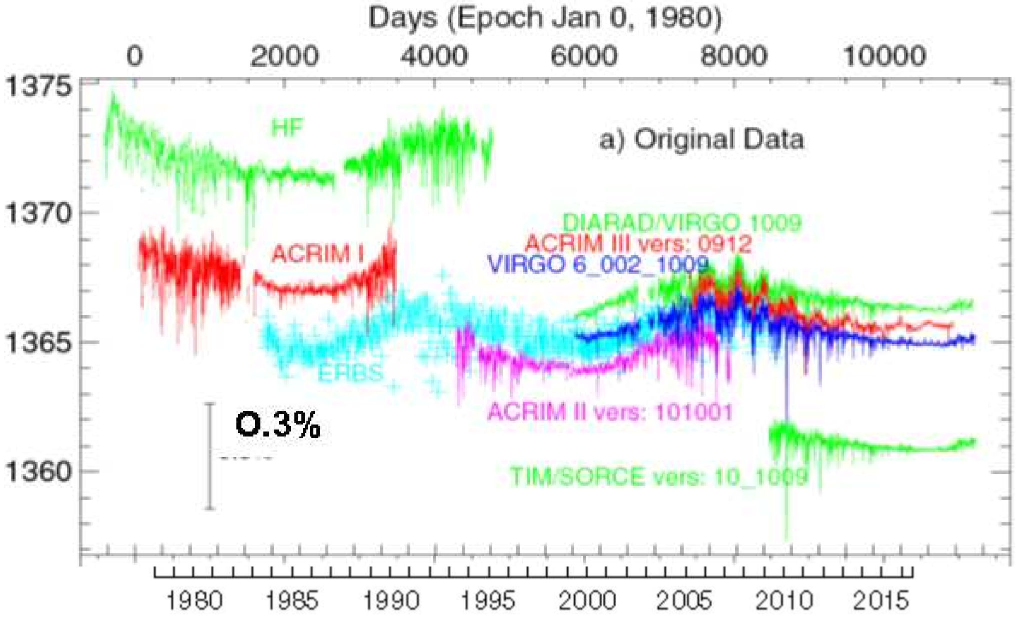
Total Solar Irradiance (TSI) or “solar constant”: the driving force of the planet

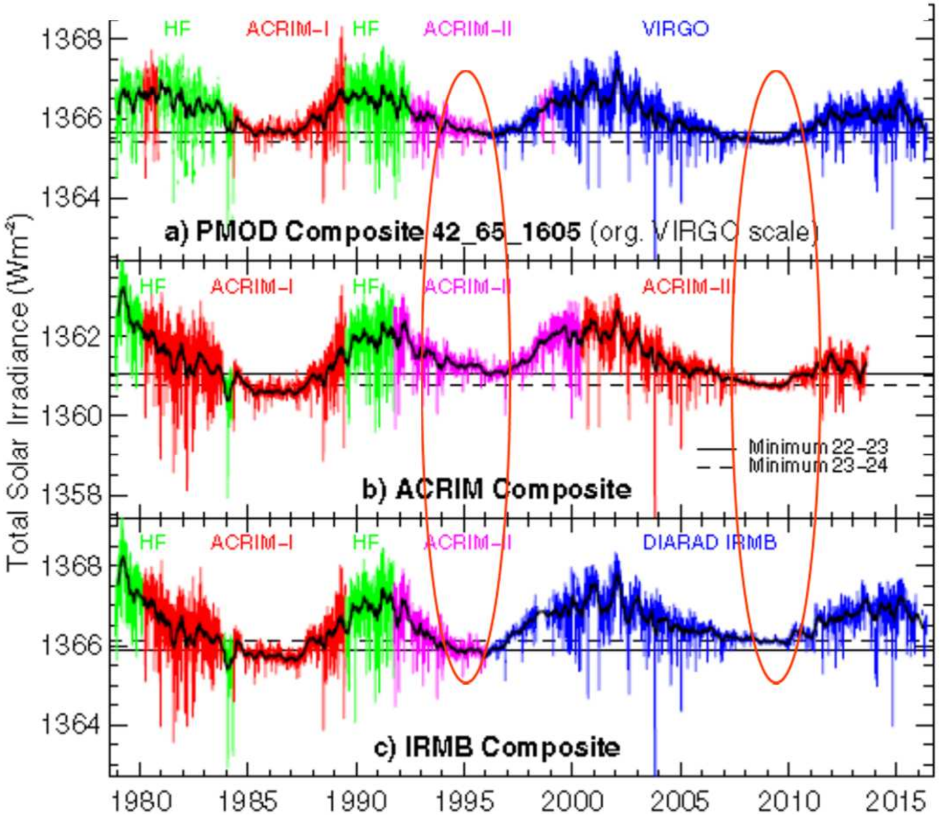
30 yr record shows “regular” 11 yr cycle
and <u>No</u> significant Variation
Thus <u>No</u> impact on climate



www.pmodwrc.ch







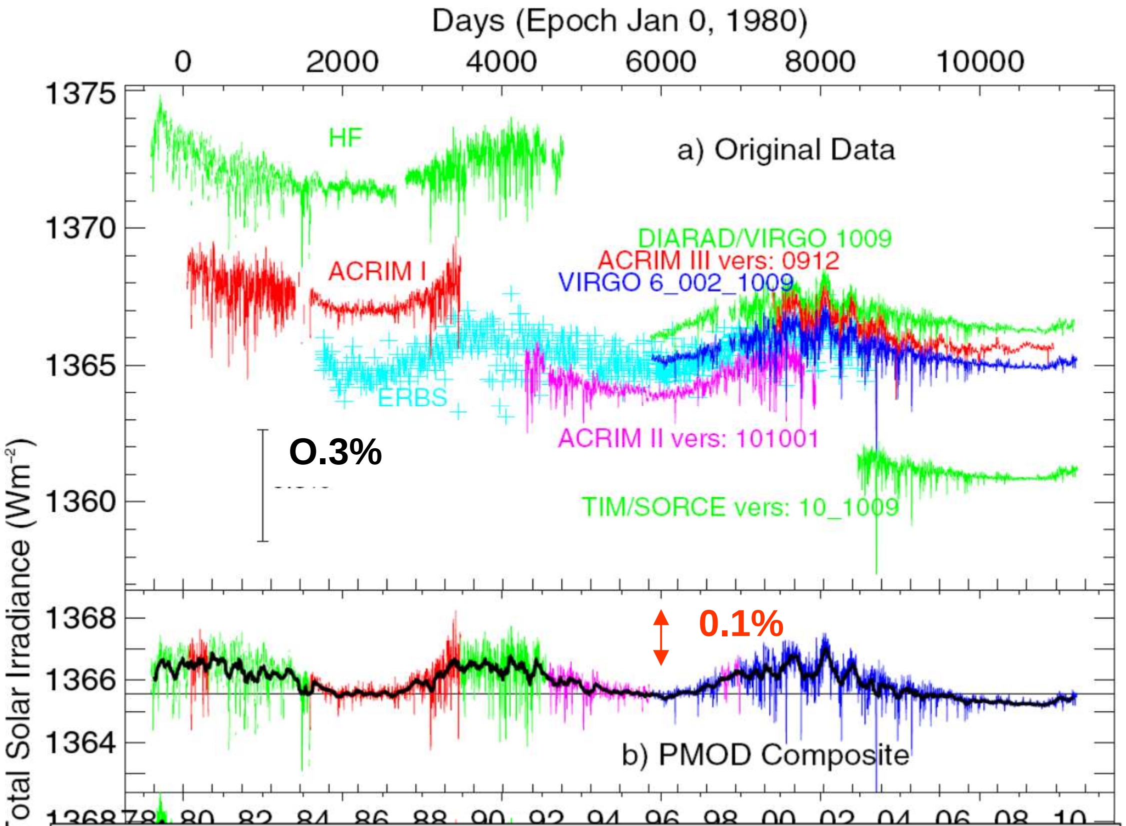

Thames Frost Fair (1684)

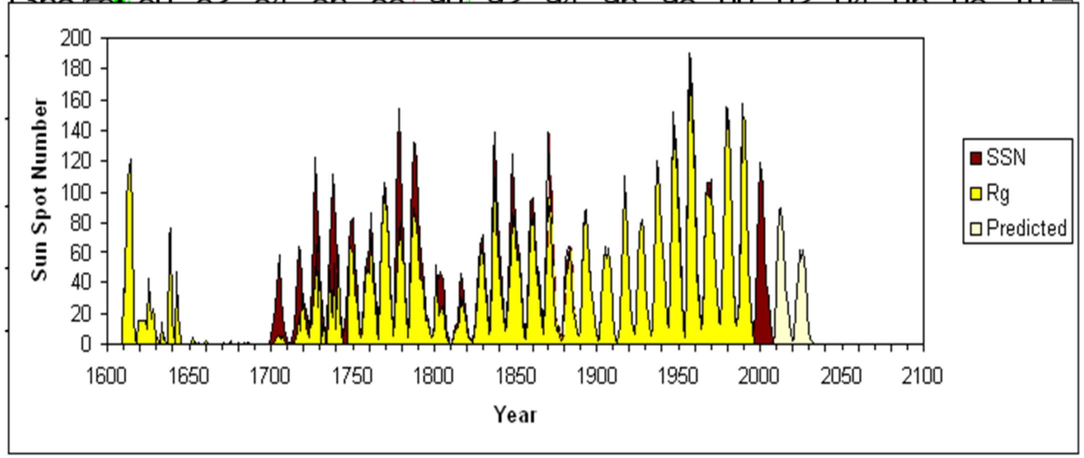
Mini-Ice age caused by ~ 0.3 % reduction in solar output.

- **No sunspots for 50 yrs**

- **2008 to 2010 (unusually low sunspot activity!!!)**

Can we rely on 30 yrs of ??? measurements to rule out a significant solar contribution to climate ?



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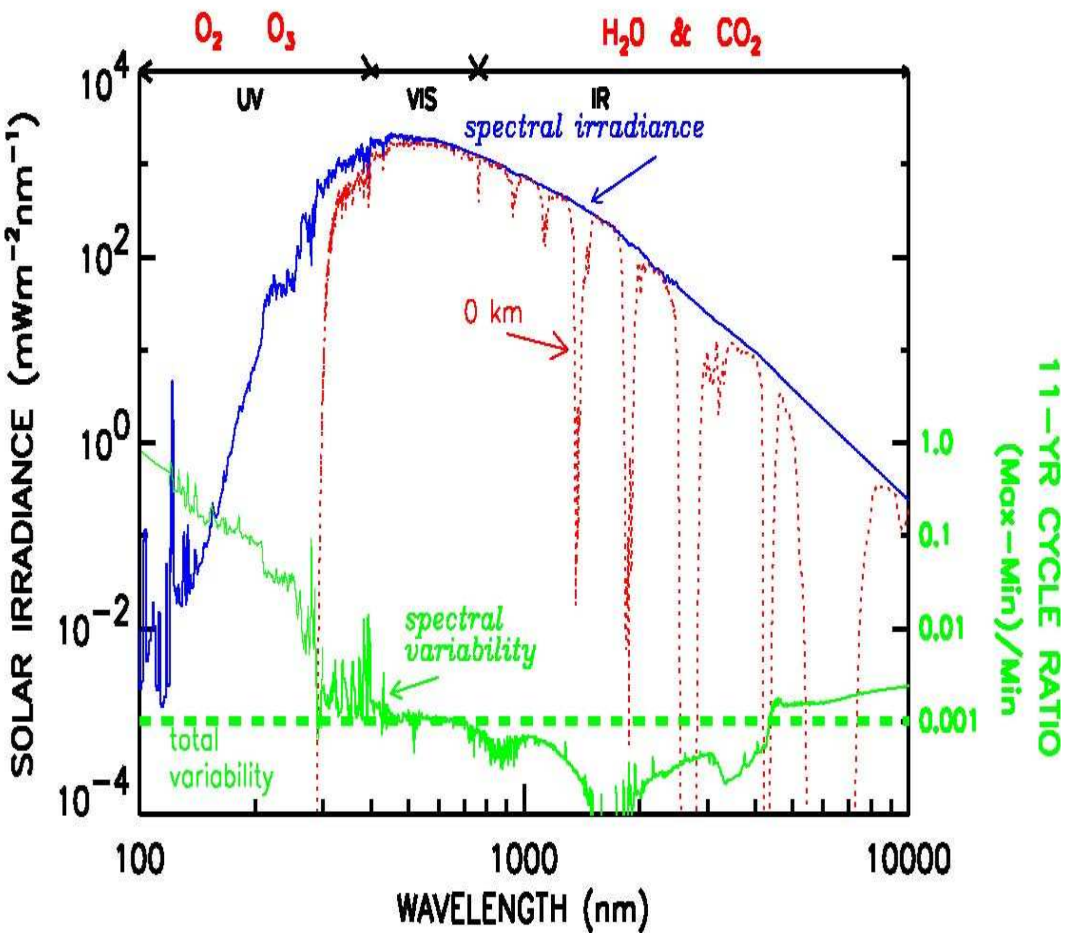
Non-linear aspect of Solar radiation on climate

TOTAL Irradiance = $\int$SPECTRAL Irradiance ~ 1366 Wm^{-2}



Variation of Solar Spectral Irradiance

- Visible similar to TSI
- UV 10 to 100 X greater

UV drives atmospheric chemistry

- middle and upper atmosphere

Vis-NIR absorbed in Oceans

- Sea temperature, Weather

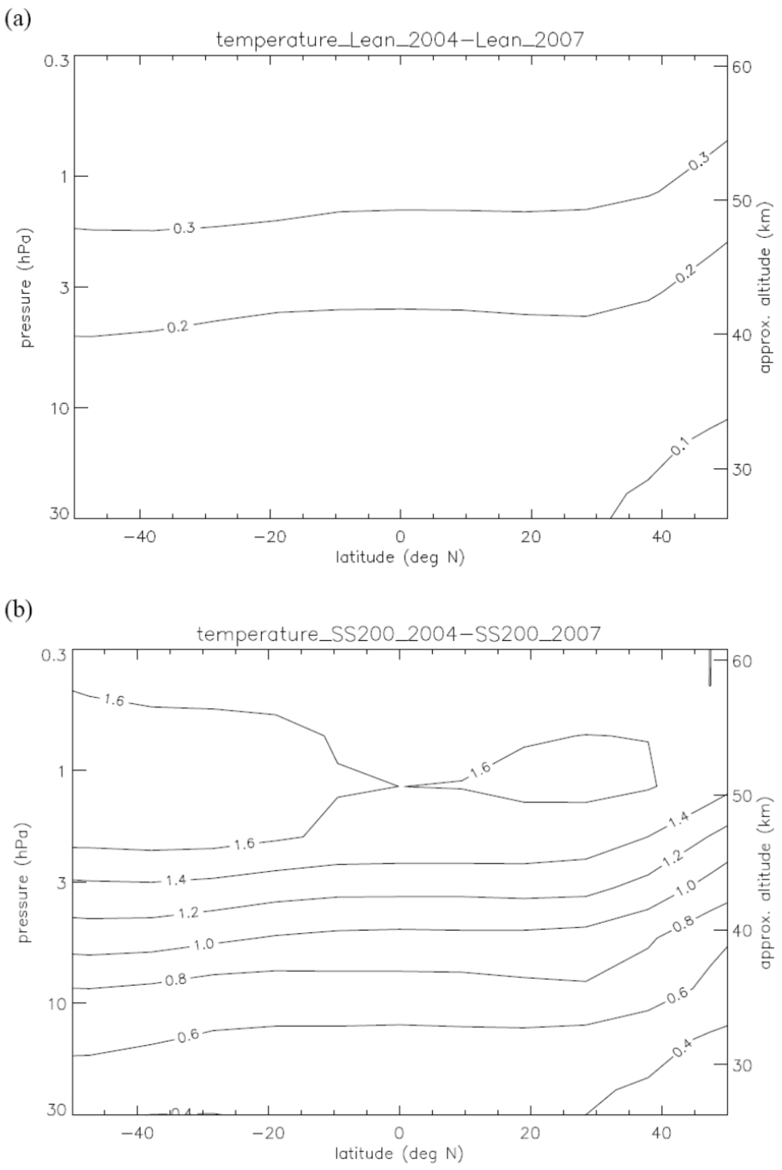
NIR absorbed in Atmos. H_2O and CO_2

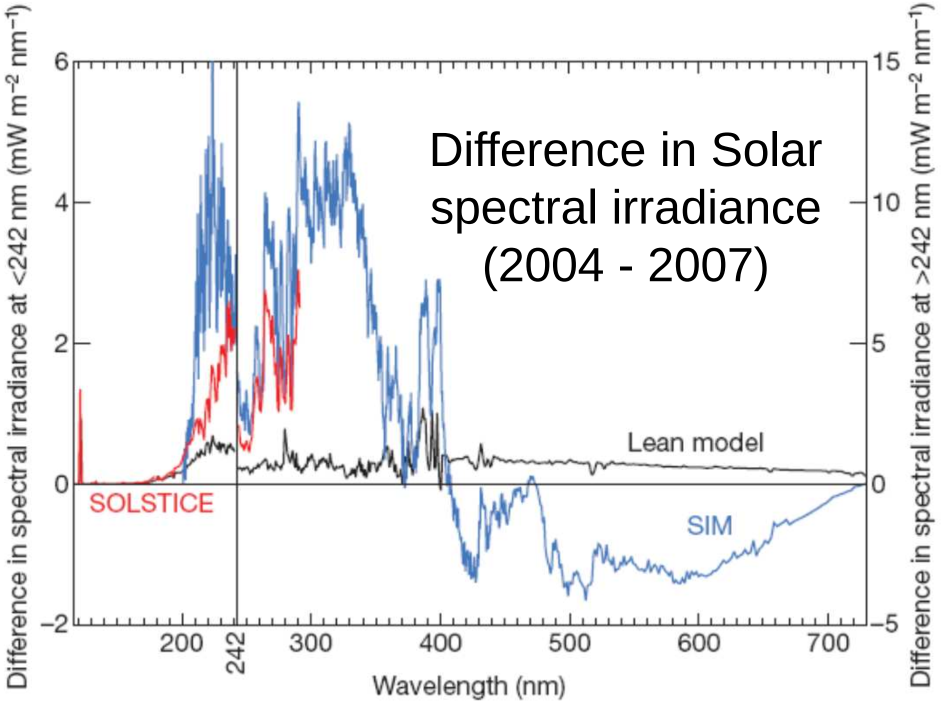
- Vis scattered by aerosols

May trigger El Nino with ~ 18 mth time delay

Solar Spectral variability may lead to surprises!

J D Haigh et al Nature 467 p696 Oct 2010





Difference in Solar spectral irradiance (2004 - 2007)

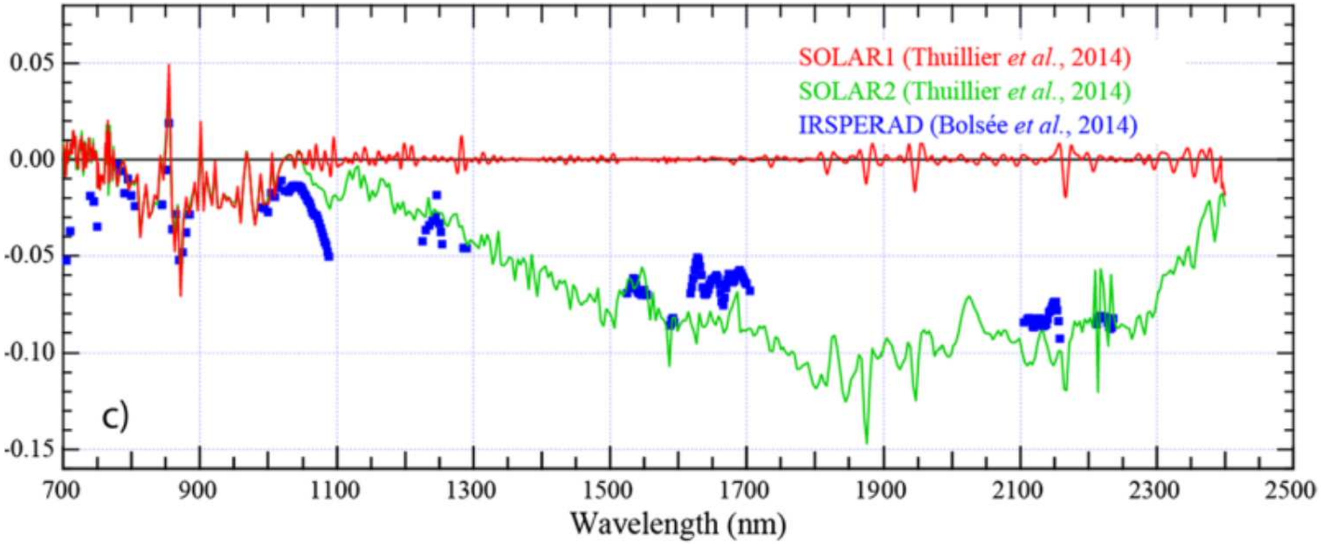
TOA measurements of Solar Spec irradiance by NASA SIM indicate significant variance in expected spectral content at end of solar cycle 23. ⇒ surprises when used in and compared to models:

2004 - 2007 TSI↓ UV ↓↓ Vis↑

O_3 (>45 km ↓ ~35 km ↑) T ↑

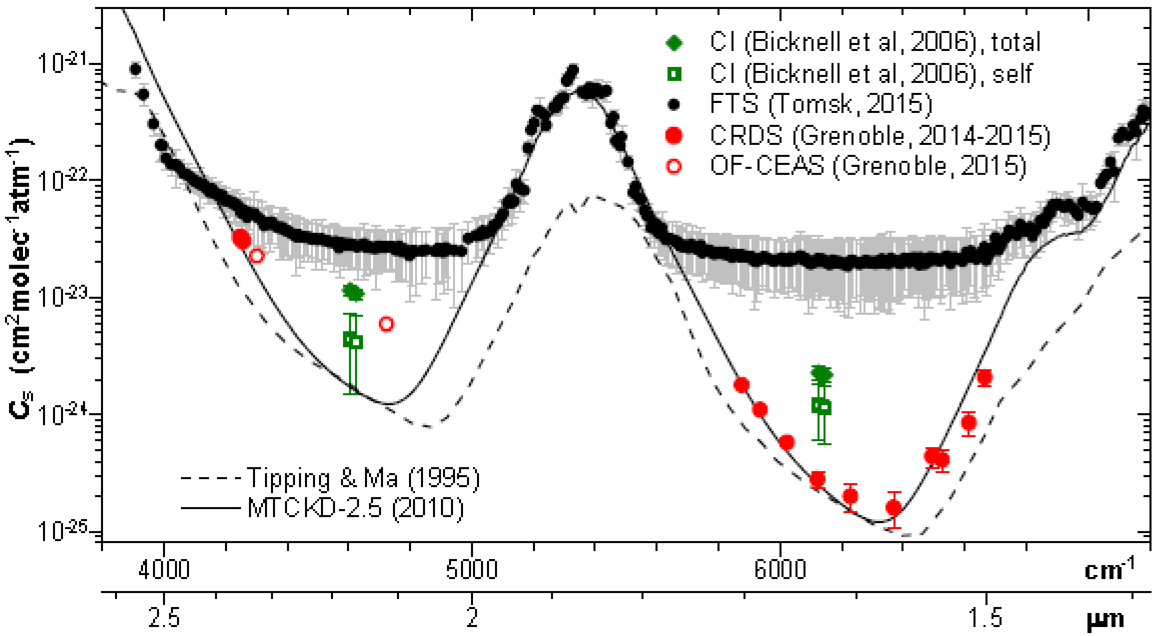
Cooler Sun - Warmer Earth!

Anomalies!!!



Variations in SSI

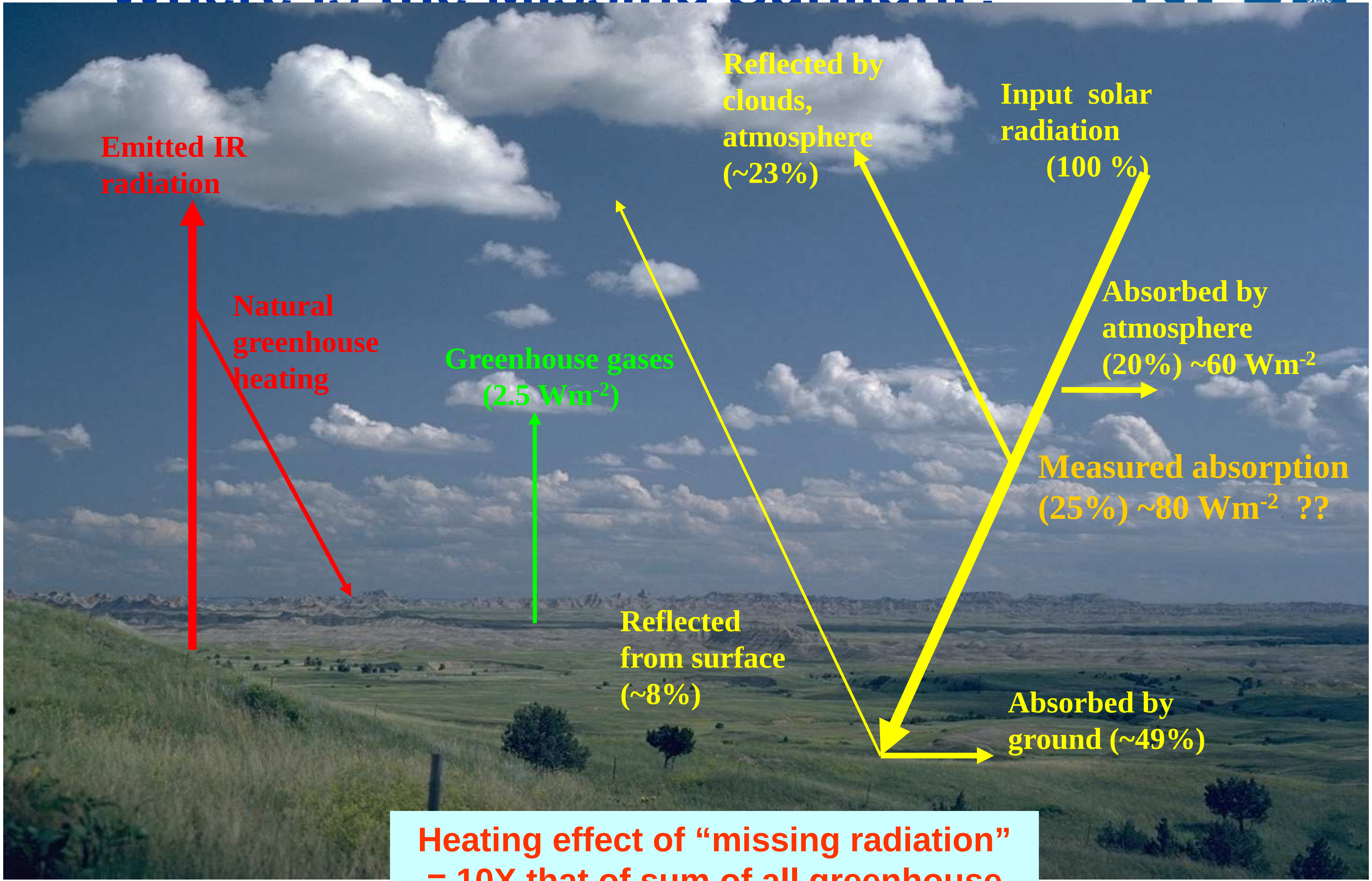
When integrated to TSI (7% diff!!!)



SSI absorption by atmosphere water vapour

Measurement Vs model

Where is the Missing Sunlight?



Emitted IR radiation

Natural greenhouse heating

Greenhouse gases (2.5 Wm^{-2})

Reflected by clouds, atmosphere (~23%)

Input solar radiation (100 %)

Absorbed by atmosphere (20%) ~60 Wm^{-2}

Measured absorption (25%) ~80 Wm^{-2} ??

Reflected from surface (~8%)

Absorbed by ground (~49%)

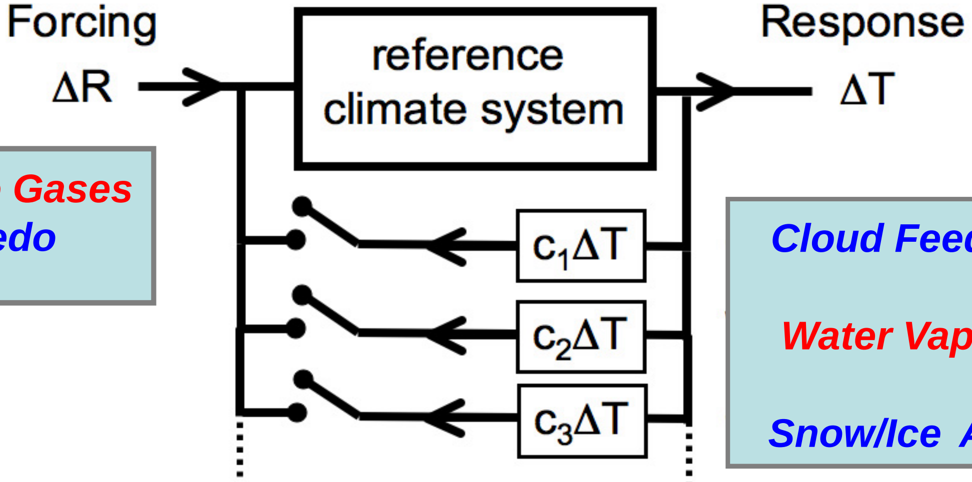
Heating effect of “missing radiation” = 10X that of sum of all greenhouse gases

Reducing uncertainty in impact by constraining the models

Blue = Solar reflective (SR)
(0.3 – 2.3 μm)

Red = Infra-Red (> ~5 μm)

Earth's Climate



- *Temperature*
- *Water Vapour*
- *Clouds*
- *Radiation*
- *Snow/Ice Cover*

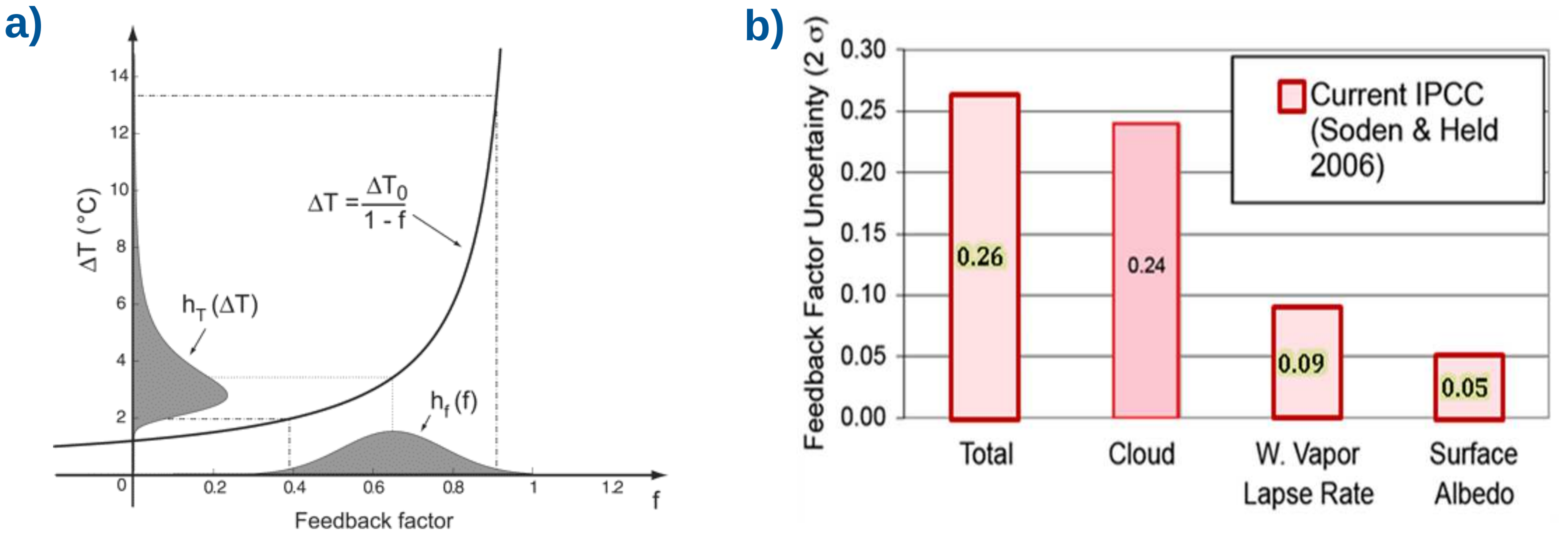
- *Greenhouse Gases*
- *Surface Albedo*
- *Aerosols*

Cloud Feedback

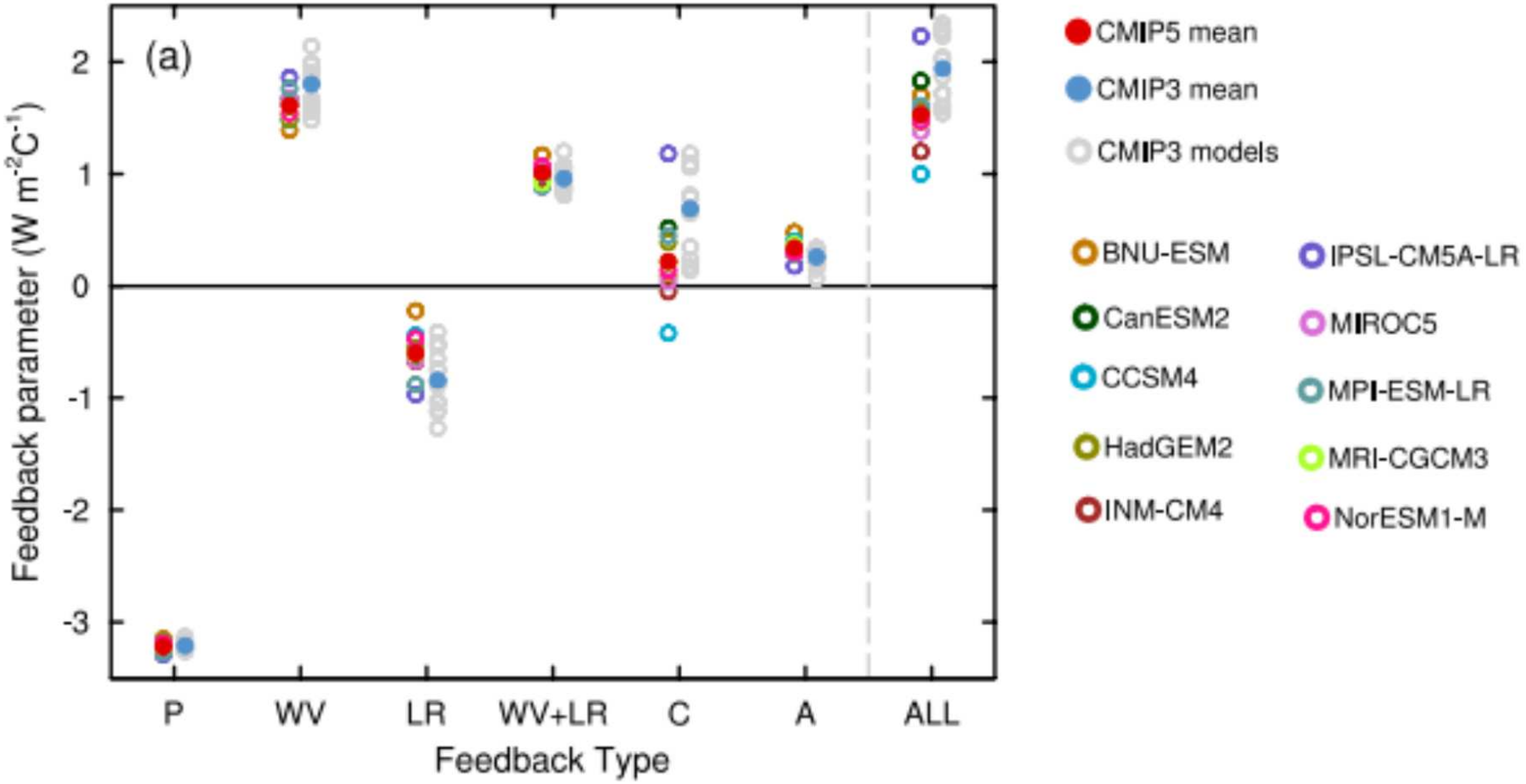
Water Vapour/Lapse Rate Feedback

Snow/Ice Albedo Feedback

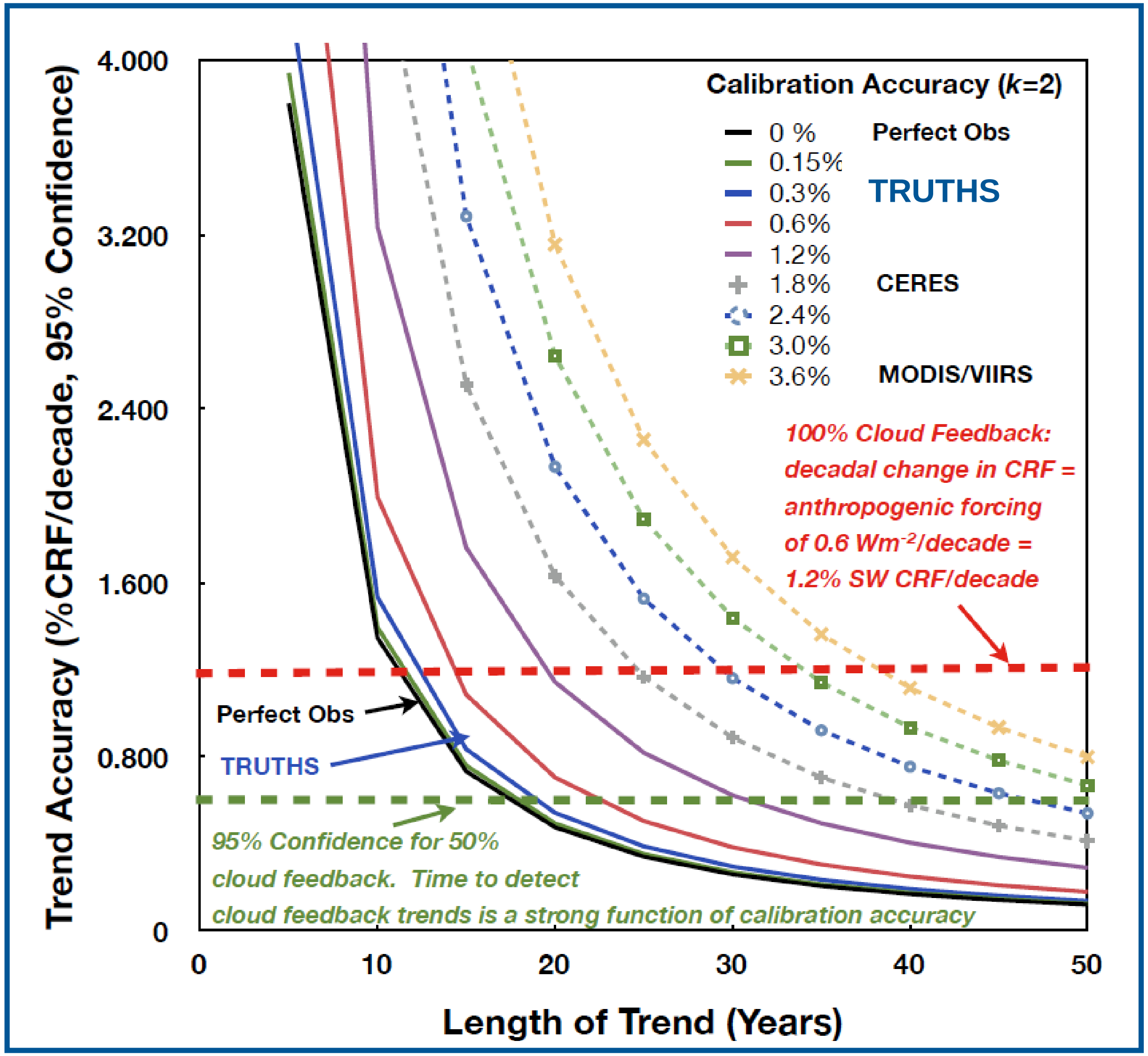
Roe and Baker, 2007



Source of variance in climate models: Radiation Feedbacks



Time to detect Cloud Radiative Forcing (CRF) from natural variability



Wielicki et al 2010

TRUTHS or (CLARREO) (proposed satellites) accuracy (0.3% k=2) near optimum to the perfect observing system

for 100% cloud feedback

TRUTHS ~ 12 yrs

CERES ~ 25 yrs

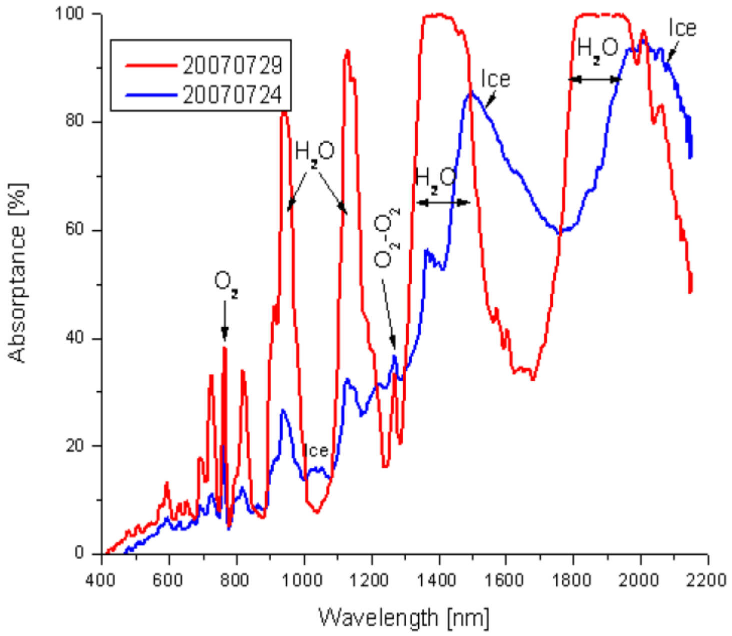
MODIS ~ 40 yrs

For 50% difference > 20 yrs

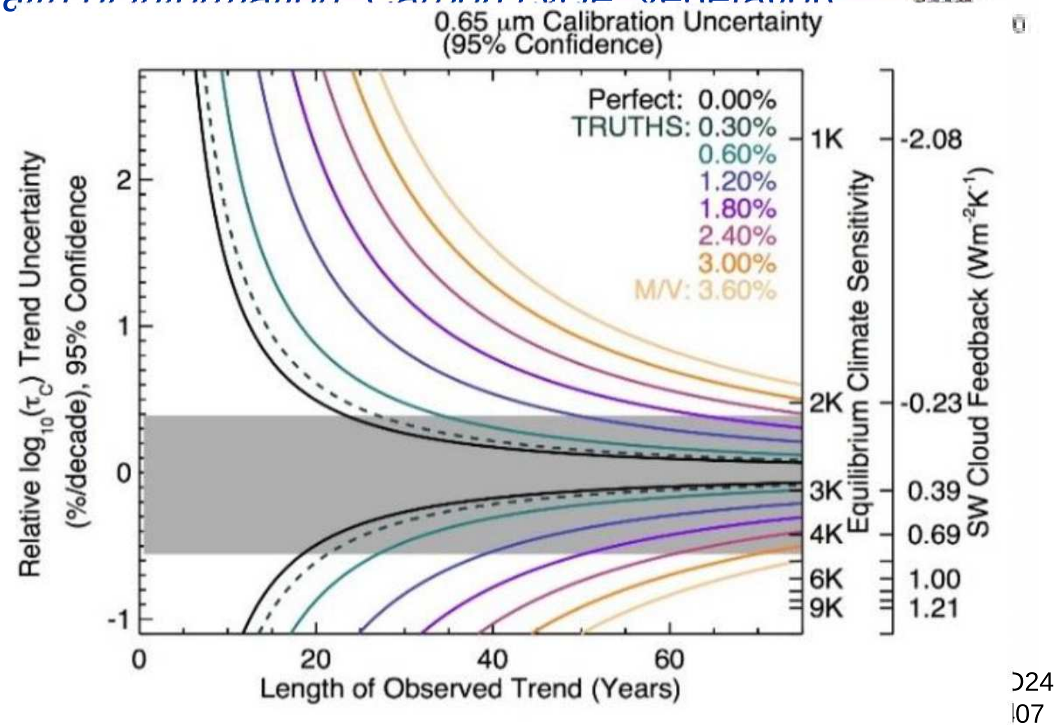
Other parameters e.g. Albedo have similar curves

Importance of spectral Information

- Reflected solar radiation as indicator of absorbed energy - from the Earth-Atmosphere system is a strong forcing.
- Benchmarking provides a measure of the current climate state for change detection.
- Require zonally-averaged global TOA spectrally-resolved spectra to compare with model.
- Climate feedback are main uncertainties in model predictions (cloud, water vapour lapse rate & surface albedo)
- Some signals are broadband – but accurate attribution needs spectral resolution across full UV-VIS-NIR bands.
- Spectral fingerprinting potentially powerful multi-parameter diagnostic
- ^**Secondary bi-product-** provides wealth of information, Carbon cycle, vegetation



% spectral absorptance of low altitude stratus (water) & high (ice) clouds

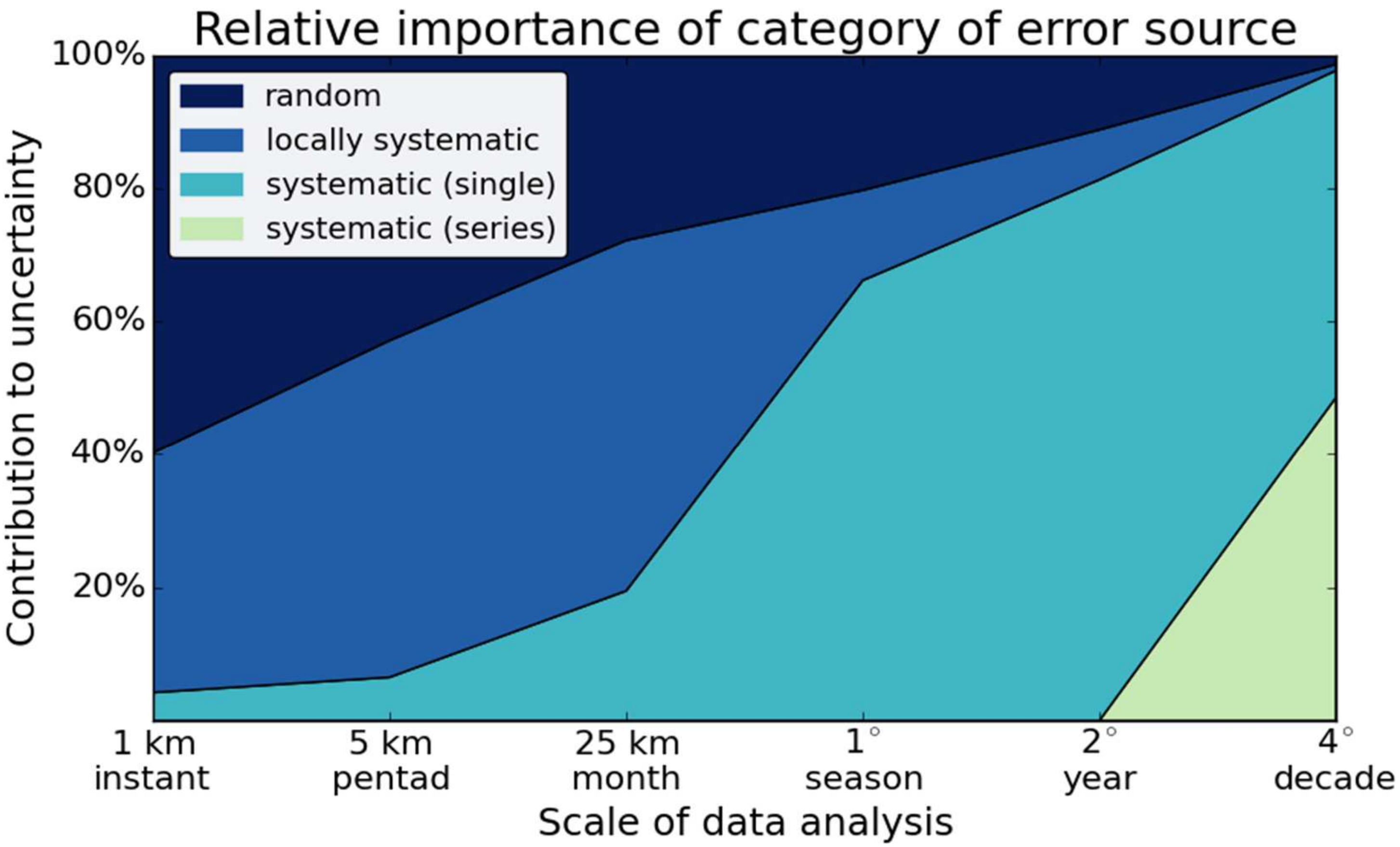


24)
07

Time to detect trend in Cloud optical thickness (@0.65 um) (Shea et al 2016)

Model predicted time to detectable change in TOA spectral reflectance with TRUTHS/CLARREO (Uc)

FCDR and uncertainty info



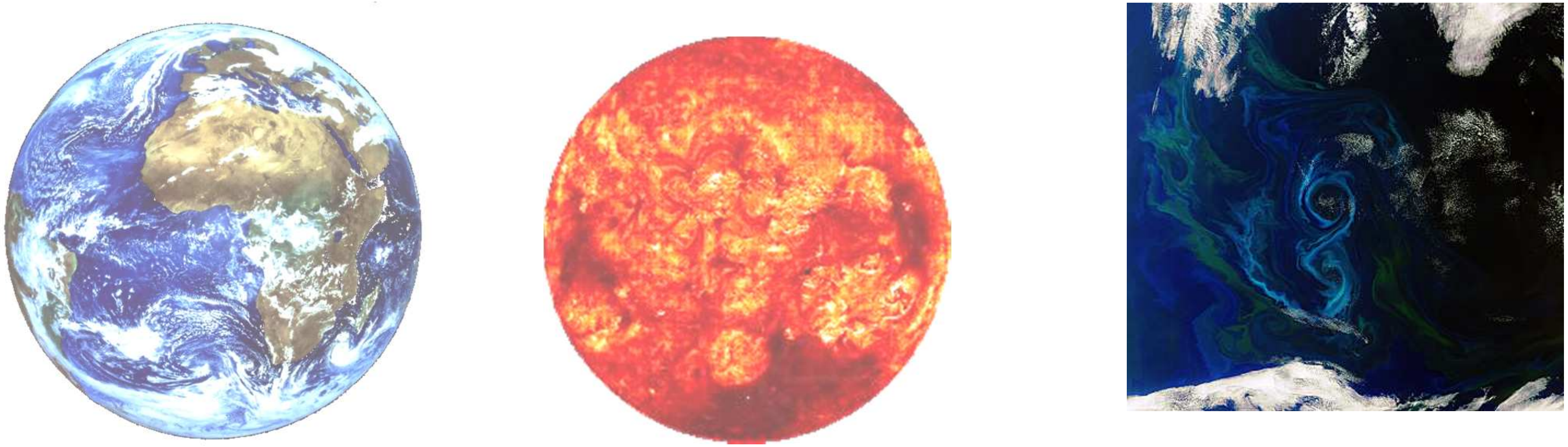
https://figshare.com/articles/Importance_of_error_sources_in_climate_data_on_different_analysis_scales/1483408

http://www.fiduceo.eu/content/why-worry-about-all-sources-errors

University of Reading

Optical (SR) uncertainty requirements (GCOS) for decadal climate change UN Global Climate Observing System

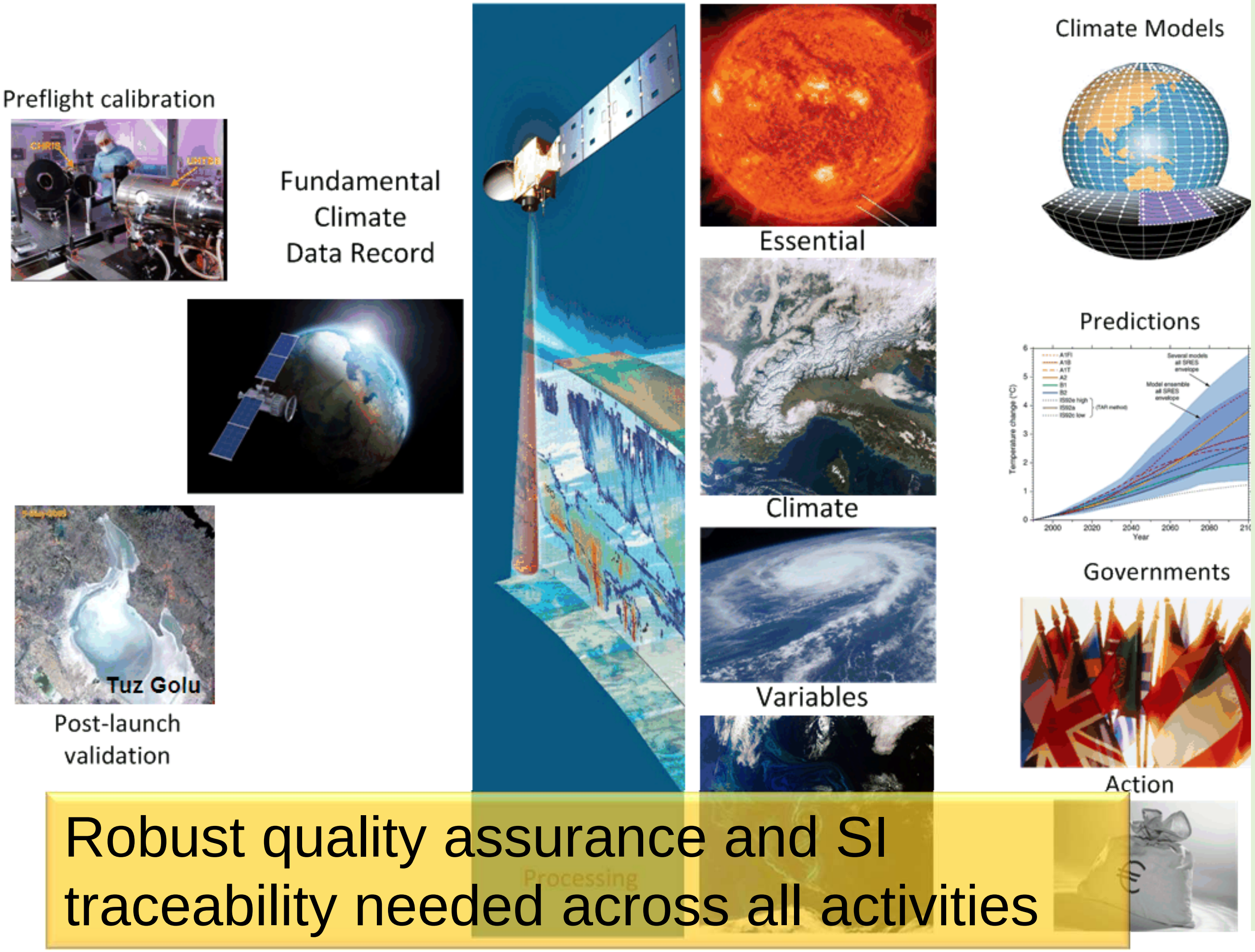
Objectives for SI traceability	Climate Requirement	Pre-flight	In-flight	Terrestrial	Primary
Solar Irradiance	0.01%	0.2%	?	0.2%	0.01%
Spectral radiance (clouds, albedo)	0.3%	2% - 5%	?	-1%	<0.05%
Water-leaving radiance (Ocean Colour)	1%	5%	-5%	-1%	<0.05%



Summary of measurand Requirements (SR domain)

Mission requirement	Parameter: proposed value	Driving mission objective	Required	Desired
SI traceable measurement of the solar reflected spectrum	Spectral range: 320 nm – 2450 nm	Nadir Reflectance Spectral Climate Change Benchmarks	320 nm – 2350 nm	
	“	Earth Radiation budget		From 320 to 2500 nm
	“	Plant optical traits and minerals	380 nm – 2450 nm	Up to 2500 nm
	Accuracy: 0.3% (2σ)	Trend estimation of cloud feedback	0.3 % (2σ)	
	Spectral resolution: 1-10 nm	Nadir Reflectance Spectral Climate Change Benchmarks	1-10 nm	
	40 m (land) 200 m (ocean)	Cloud masking	< 500 m	<100 m
SI traceable measurement of total solar irradiance	Spectral range: 0.2 to 35 μm	Solar variability and Earth Radiation Budget	0.2 to 35 μm	
	Accuracy: 0.01% (2σ)	Solar variability and Earth Radiation Budget	< 0.01% (2σ)	
SI traceable measurement of spectral solar irradiance	Spectral range: 200-2500 nm	Solar variability and ozone	200-2500 nm	
	Accuracy: 0.1% (2σ)	Solar variability	0.1% (2σ)	
Reference calibrations	As for radiance above	Reference Intercalibration	320 nm – 2450 nm	

Climate requires adequate, consistent accuracy at every step, over decades, independent of satellite or observing system



Robust quality assurance and SI traceability needed across all activities

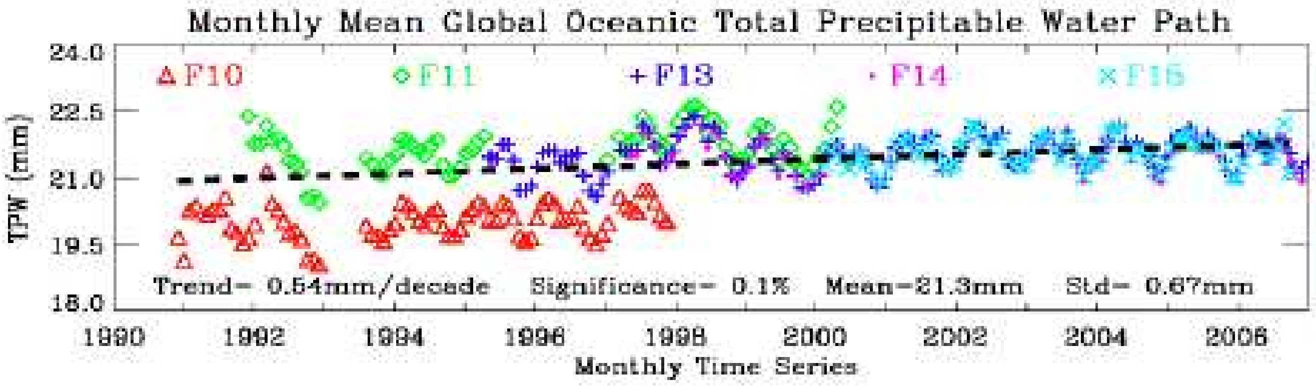
Monitoring strategy

“Only need to measure change, therefore only need sensitivity and overlaps!”

High Risk

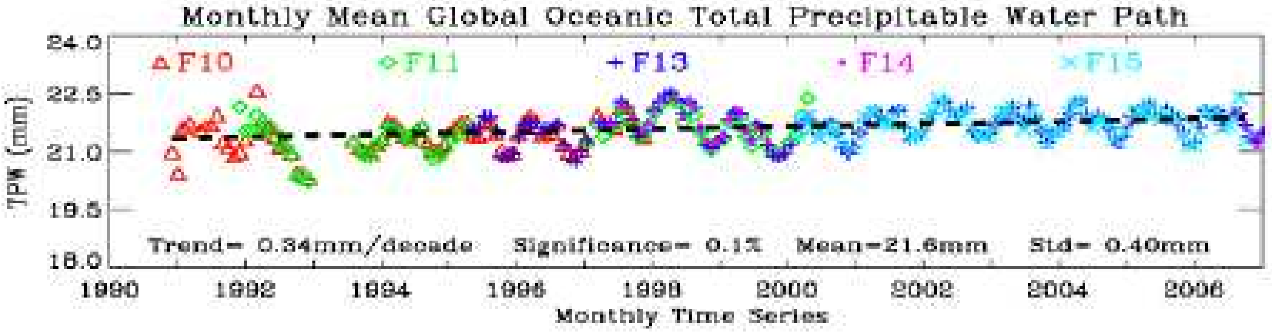
- Guaranteed continuity of data
- Small drifts may propagate undetected
- Natural variability during overlaps
- Emphasis on heritage not innovation

Calibration is Critical for Climate Change Detection



Without intercalibration:
Apparent trend is
0.54 mm/decade

GCOS requires ~0.1 mm/decade



After intercalibration:
corrected trend is
0.34 mm/decade

GSICS
Global Space-based Inter-Calibration System

Must have confidence in the "weights" and any reference sensor performance as model inputs

Primary Radiometric Reference:

Two communities
Two methods:

SI

Earth Observation

MetEO**rology**

Metrology

Metre convention (1875)

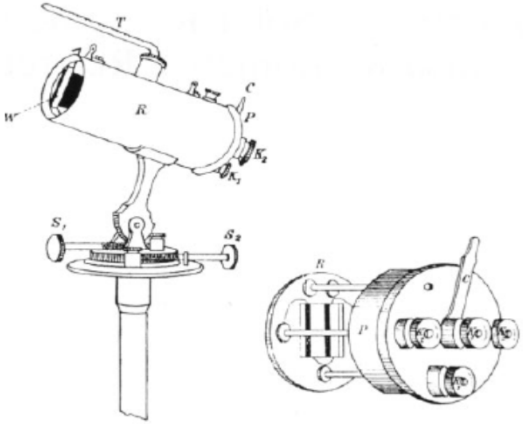
Std light source

Calorimeters (Std Detectors)

UK Parliamentary Candle (1860)

Pouillet pyroheliometer

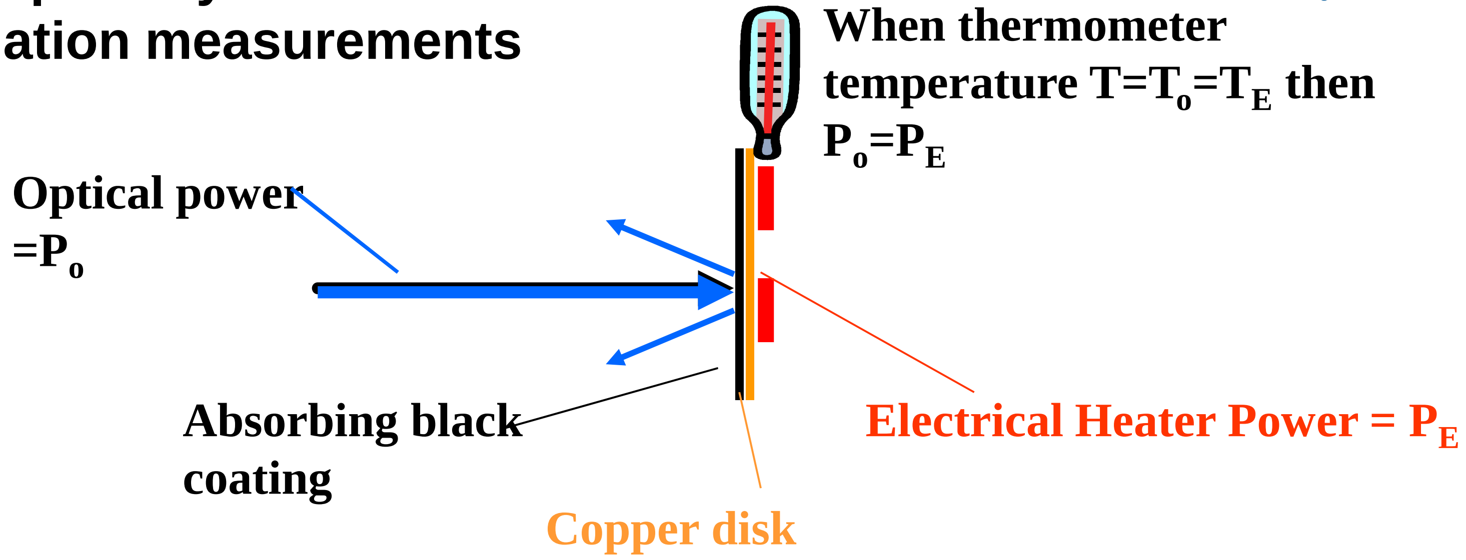
1837



Ångström compensation pyroheliometer (1893)

To the 1980s!!!!

Electrical Substitution Radiometry: A 100 yr old technology - SI primary standard of choice for optical radiation measurements



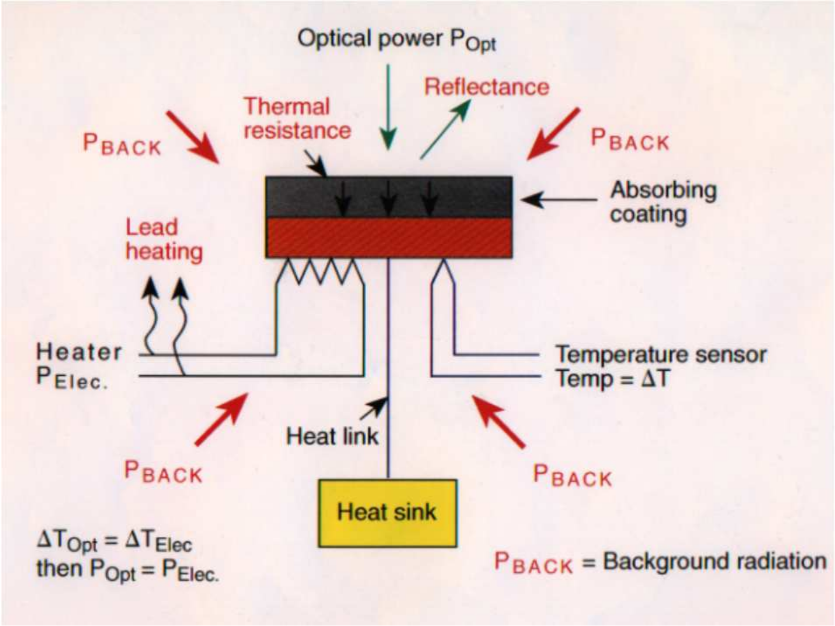
When thermometer temperature $T=T_o=T_E$ then $P_o=P_E$

Optical power $=P_o$

Absorbing black coating

Electrical Heater Power = P_E

Copper disk

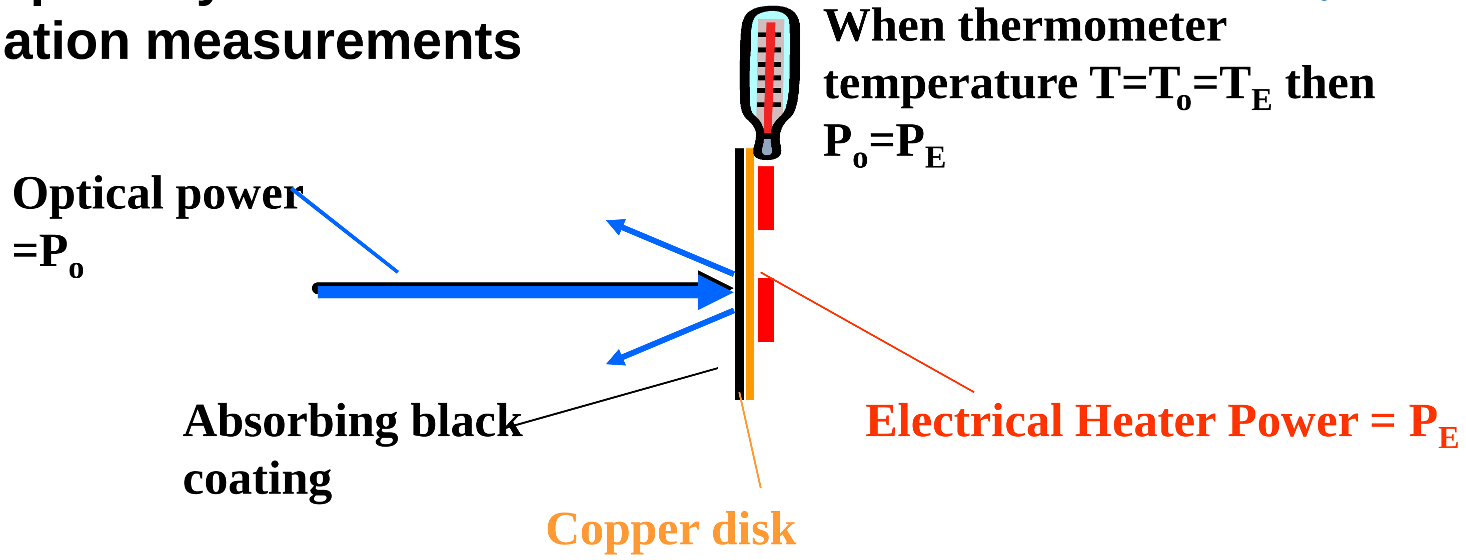


Main Sources of Uncertainty

- **Surface Reflectance**
- **Lead (Joule) heating**
- **Background Temperature/radiation changes**
- **Electrical/optical non-equivalence**

- **Typical overall uncertainty ~0.1-0.3%**

Electrical Substitution Radiometry: A 100 yr old technology - SI primary standard of choice for optical radiation measurements



When thermometer temperature $T=T_o=T_E$ then $P_o=P_E$

Optical power $=P_o$

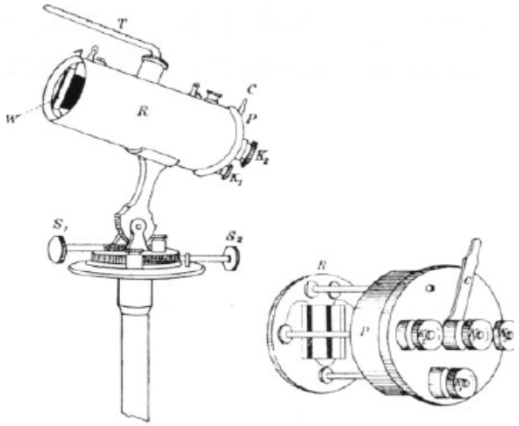
Absorbing black coating

Copper disk

Electrical Heater Power = P_E

Callendar radio balance

(1910)



Ångström compensation pyroheliometer (1893)

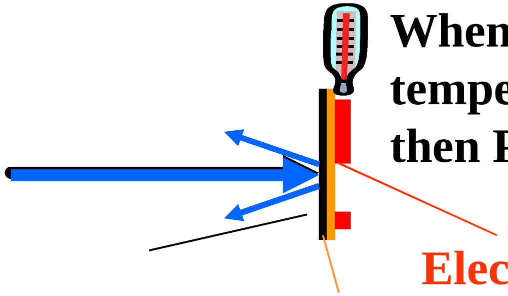
Total Solar Irradiance from Space (1975)

Electrical Substitution Radiometry: A 100 yr old technology - SI primary standard of choice

National Physical Laboratory

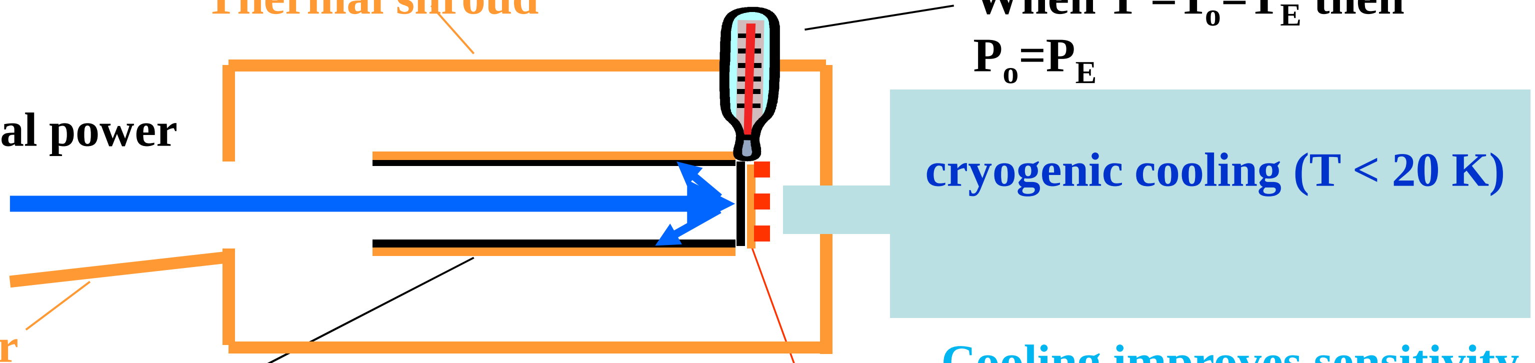
Benefits of Cryogenic operation

- Super-conducting leads
- High thermal diffusivity
  - Reduced non-equivalence
  - Large cavity – high absorptance
- Low radiative coupling
- Achievable Uncertainty ~ <0.002 %



When thermometer temperature $T=T_o=T_E$ then $P_o=P_E$

Electrical Heater Power = P_E



Thermal shroud

Optical power $=P_o$

When $T=T_o=T_E$ then $P_o=P_E$

cryogenic cooling (T < 20 K)

Shutter

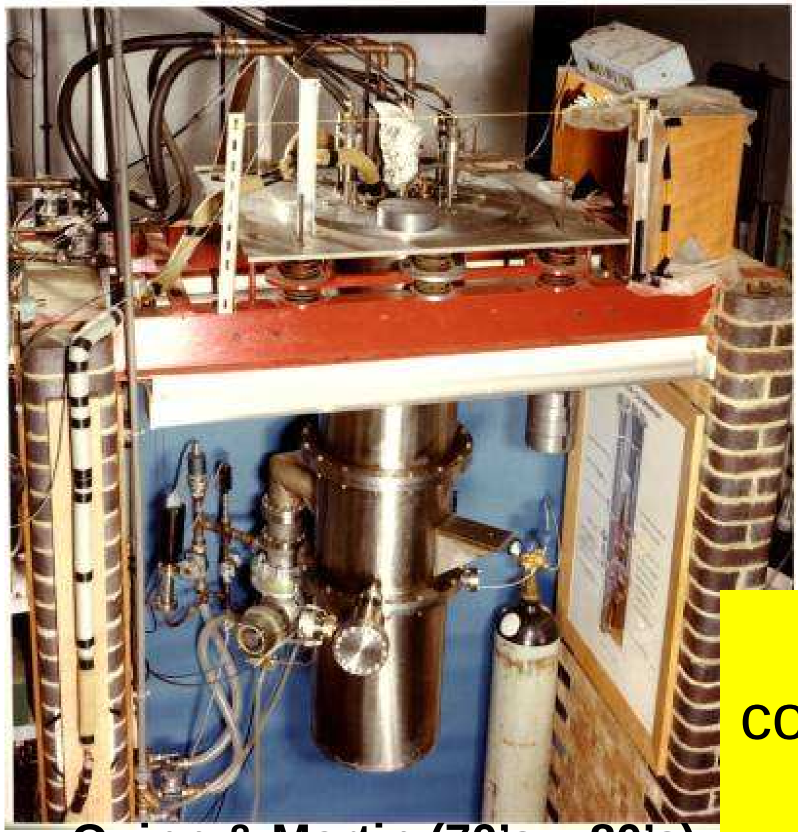
Absorbing cavity (~ 0.99999)

Cooling improves sensitivity by 1000 X

Electrical Heater Power = P_E

Principle of Cryogenic radiometry

History of Cryogenic Radiometers - NPL



Quinn & Martin (70's – 80's)
(Designed for σ & T)

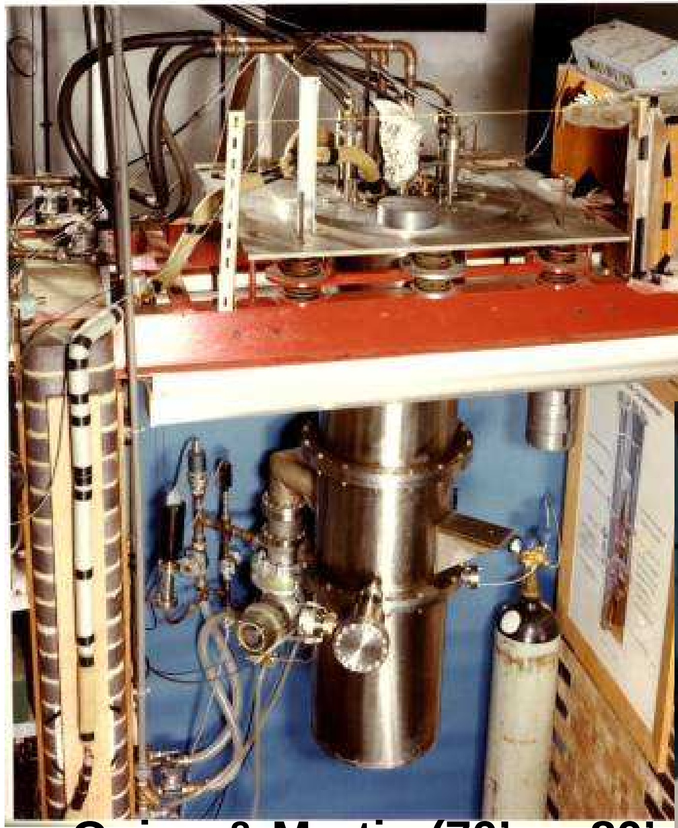
Liquid Helium

~2 – 5 K

Confirmation of concept through
comparison to a fundamental constants
Measuring radiant excitance of
black body at triple point of water

$$M = \frac{2\pi^5 k^4}{15 c^2 h^3} T^4 = \sigma T^4$$

History of Cryogenic Radiometers - NPL

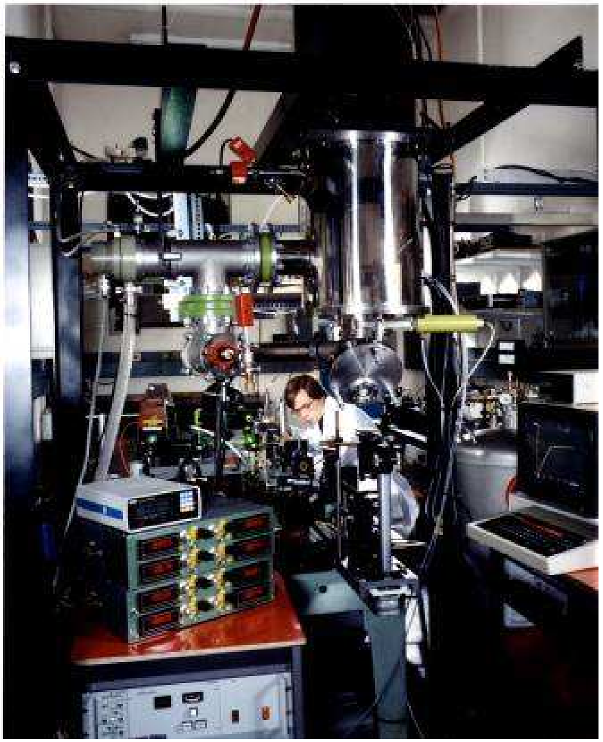


Quinn & Martin (70’s – 80’s
(Designed for σ & T)

Liquid Helium

~2 – 5 K

(2015) Terrestrial Solar irradiance std for WMO

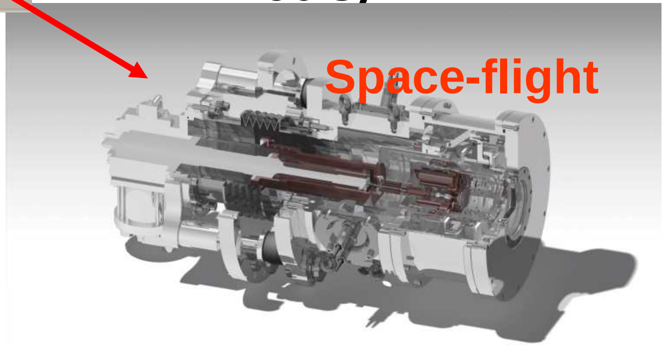


Martin, Fox, Key (80’s – 90’s)

Fox, Martin, Haycock (90’s –)

Mechanically cooled

~10 – 20 K



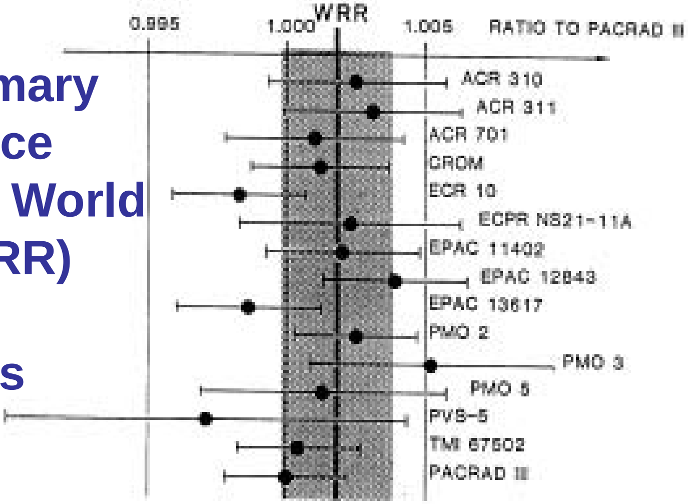
Space-flight

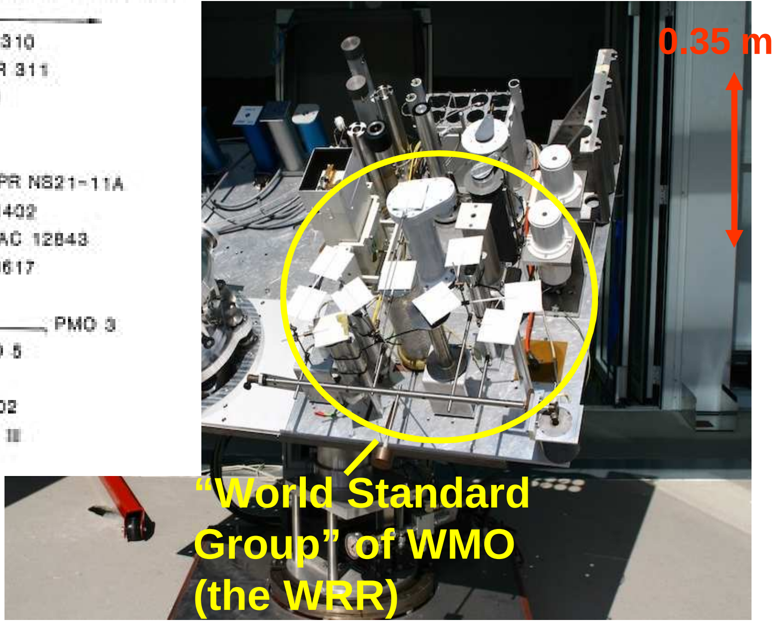
Winkler, Fox, Usadi, Finsterle
Fehlman, Blattner (10’s –)

Solar Irradiance:
Replacing the WRR of WMO with SI

Since 1975 WMO has a primary (independent of SI) reference scale for solar irradiance – World Radiometric Reference (WRR)

- mean of ~7 radiometers
- aim to be "stable"
- 5 yearly comparisons





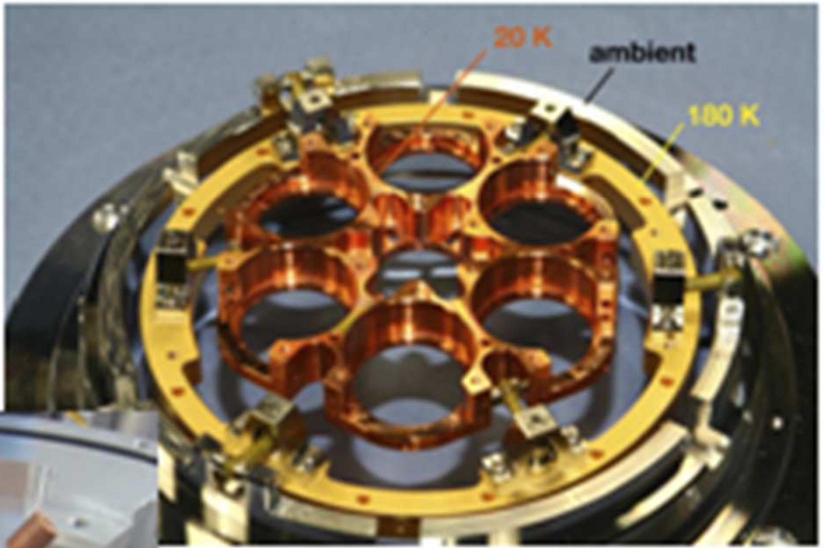
"World Standard Group" of WMO (the WRR)

Reference for Climate and PV efficiency

IPC XI (2010) Davos Switzerland
120 instruments 40 countries

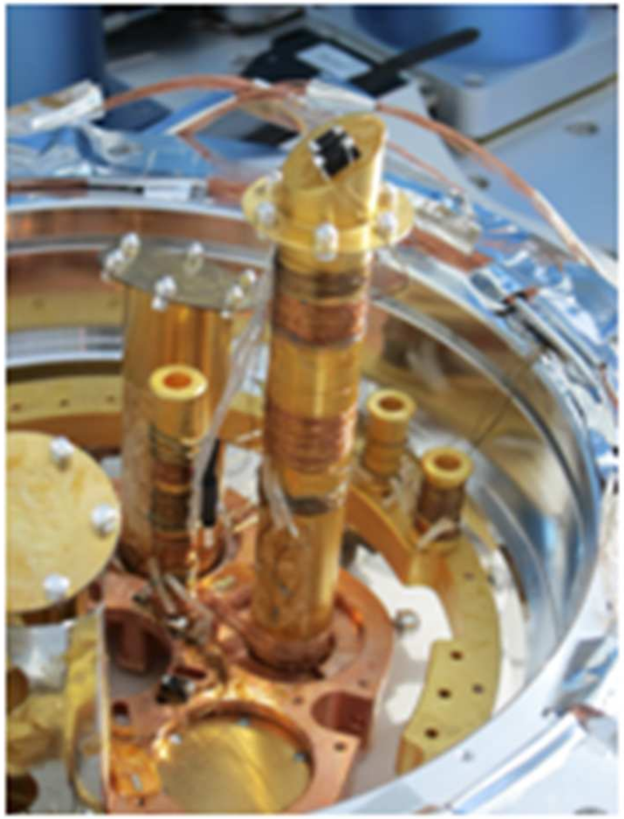
Cryogenic Solar Absolute Radiometer (CSAR)

20 K reference block made for 4 TSI cavities and 2 radiant power detectors.



110 mm long, 15 mm diameter TSI cavity with electrical foil heater.

Heat sinking of wires minimizes ambient temperature influences.



Flexible heat links connect the 20 K reference block to the cooler.

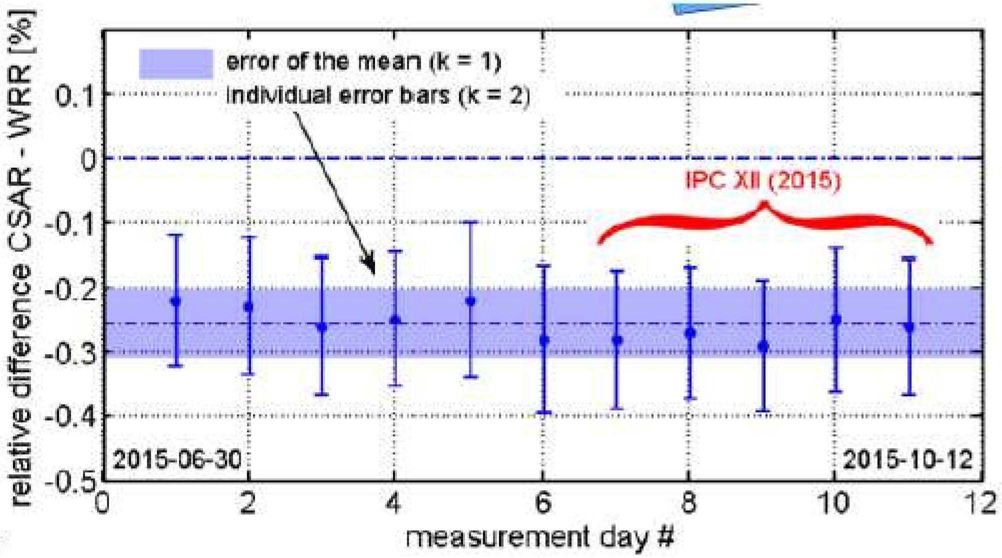
A lead block damps the temperature variations caused by the mechanical cooler.

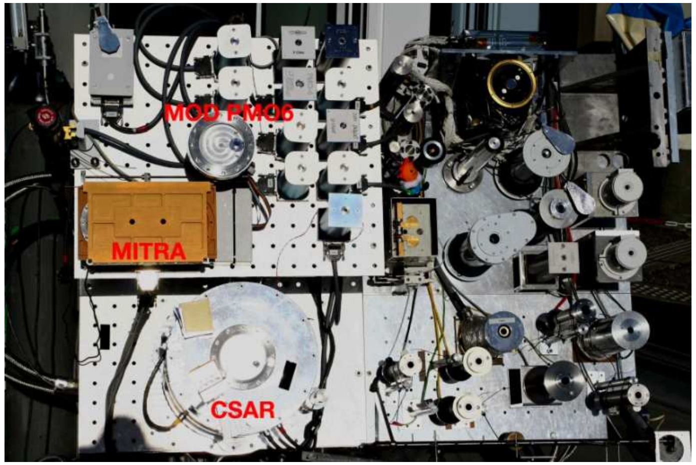
First Results

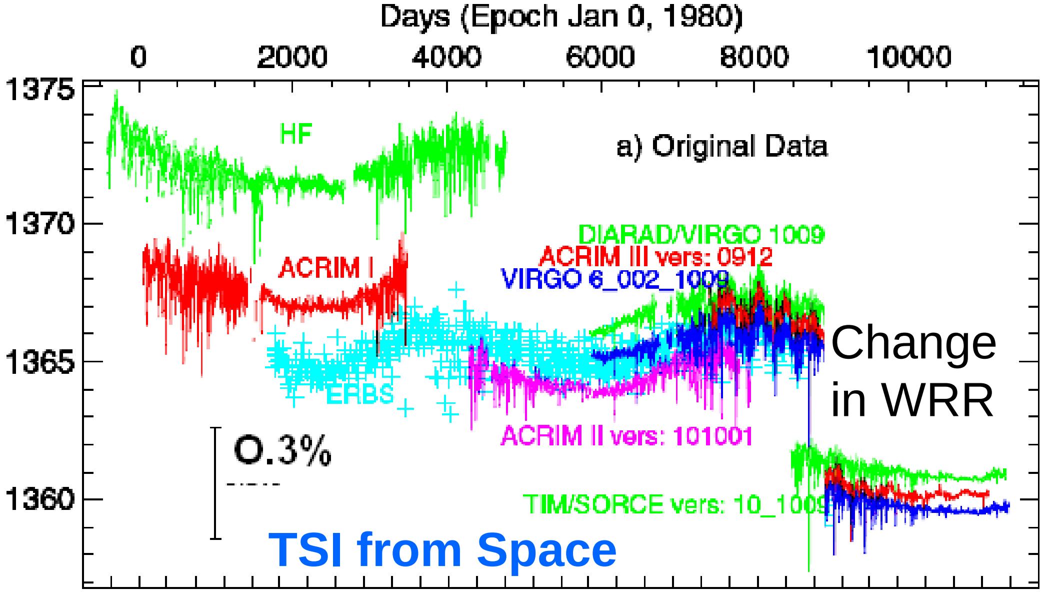
SI power comparison at the NPL confirms equivalence of CSAR and primary standard measurements.

WRR to SI comparison made with PREMOS, independently confirms the CSAR to WRR difference of 0.3 %.

(Fehlmann et al. 2011, Metrologia



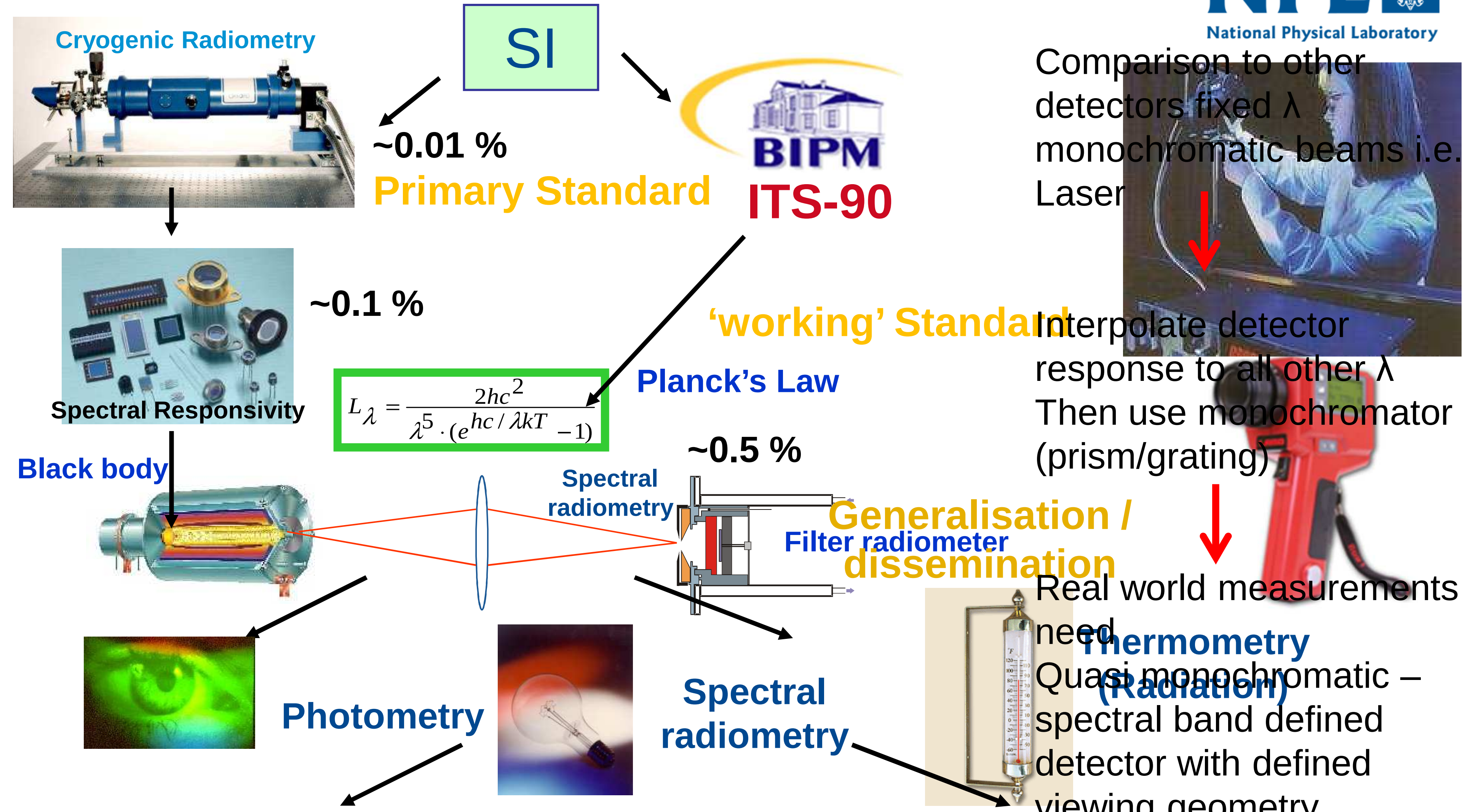




Change in WRR

TSI from Space

Optical Radiometric Traceability



SI

Cryogenic Radiometry

~0.01 %

Primary Standard

BIPM

ITS-90

~0.1 %

Spectral Responsivity

'working' Standard

$$L_\lambda = \frac{2hc^2}{\lambda^5 \cdot (e^{hc/\lambda kT} - 1)}$$

Planck's Law

Black body

Spectral radiometry

~0.5 %

Filter radiometer

Generalisation / dissemination

Photometry

Spectral radiometry

Thermometry (Radiation)

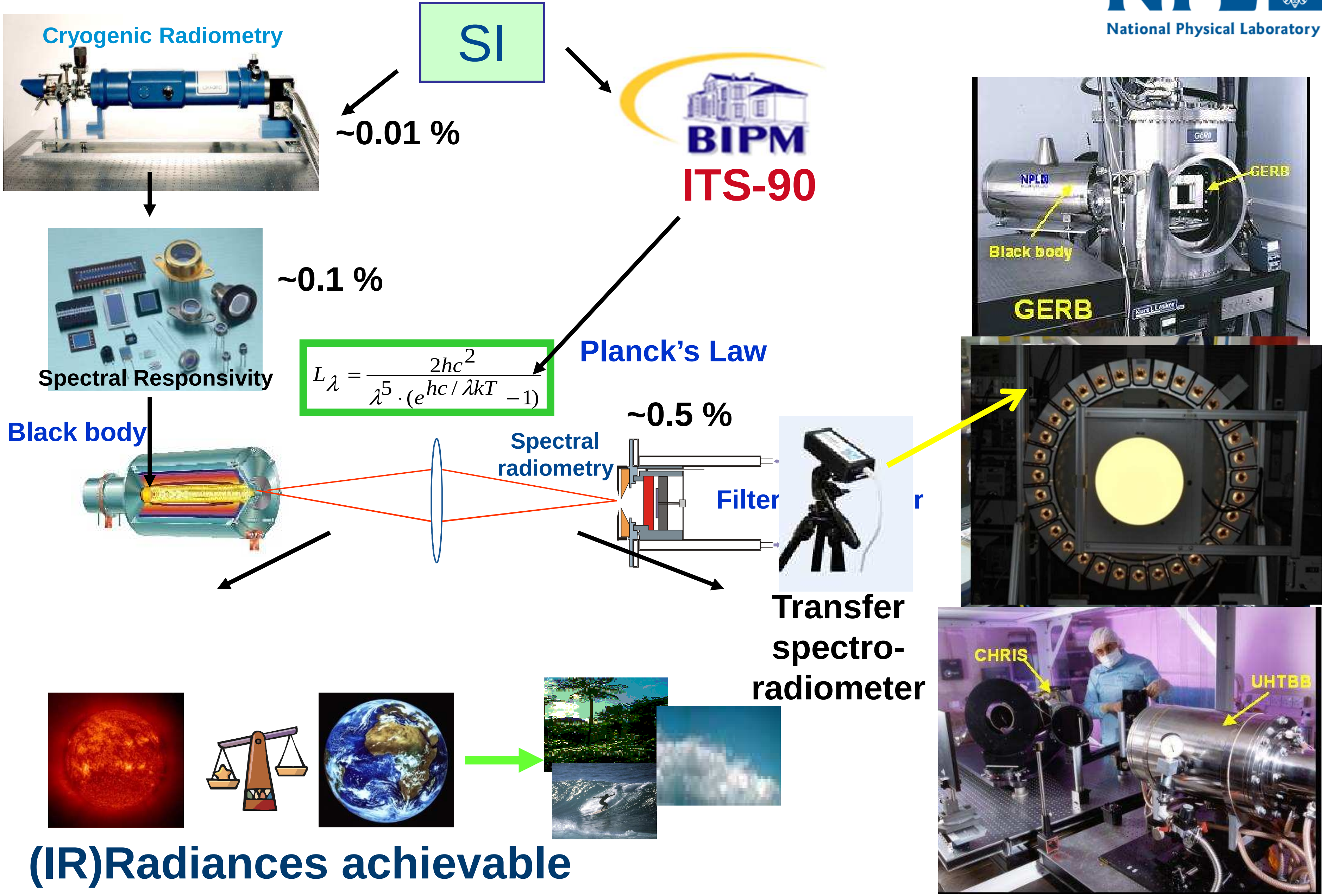
Comparison to other detectors fixed λ monochromatic beams i.e. Laser

Interpolate detector response to all other λ Then use monochromator (prism/grating)

Real world measurements need Quasi monochromatic – spectral band defined detector with defined viewing geometry

Aerospace

Radiometric traceability for EO sensor



SI

Cryogenic Radiometry

~0.01 %

BIPM

ITS-90

~0.1 %

Spectral Responsivity

$$L_\lambda = \frac{2hc^2}{\lambda^5 \cdot (e^{hc/\lambda kT} - 1)}$$

Planck's Law

Black body

~0.5 %

Spectral radiometry

Filter **r**

Transfer spectro-radiometer

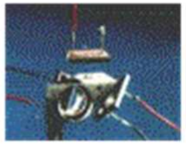
(IR)Radiances achievable but challenging !

SI Units

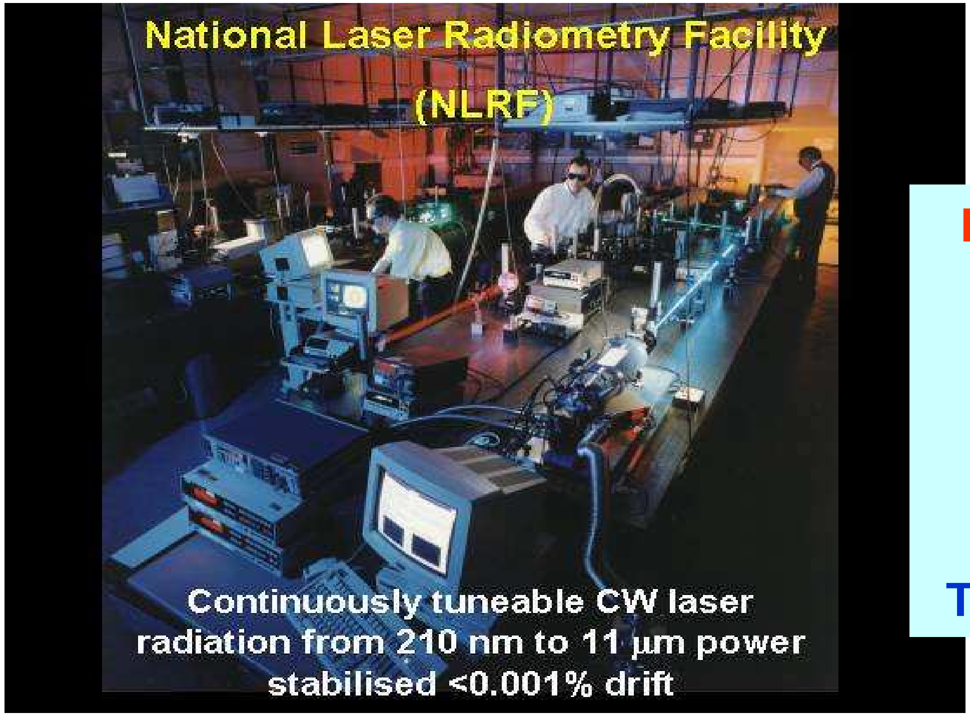
Cryogenic radiometer

Primary Standard

Laser



Reference photodiode



National Laser Radiometry Facility (NLRF)

Continuously tuneable CW laser radiation from 210 nm to 11 µm power stabilised <0.001% drift

Recent use of:

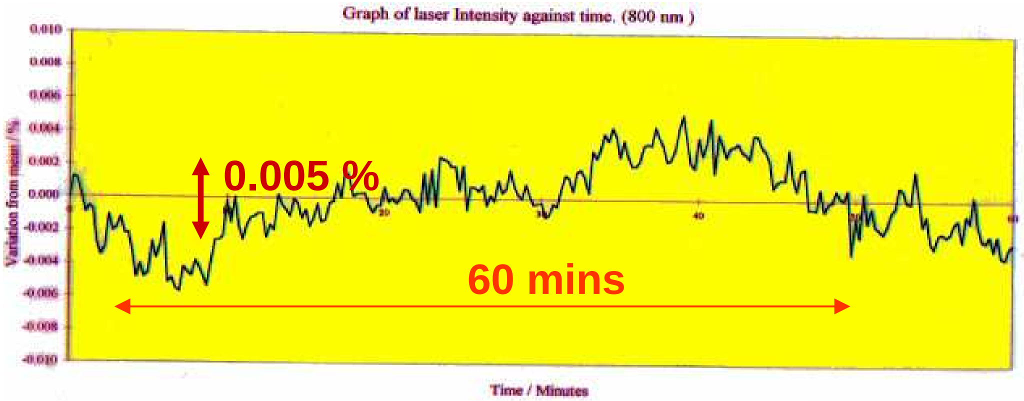
OPO

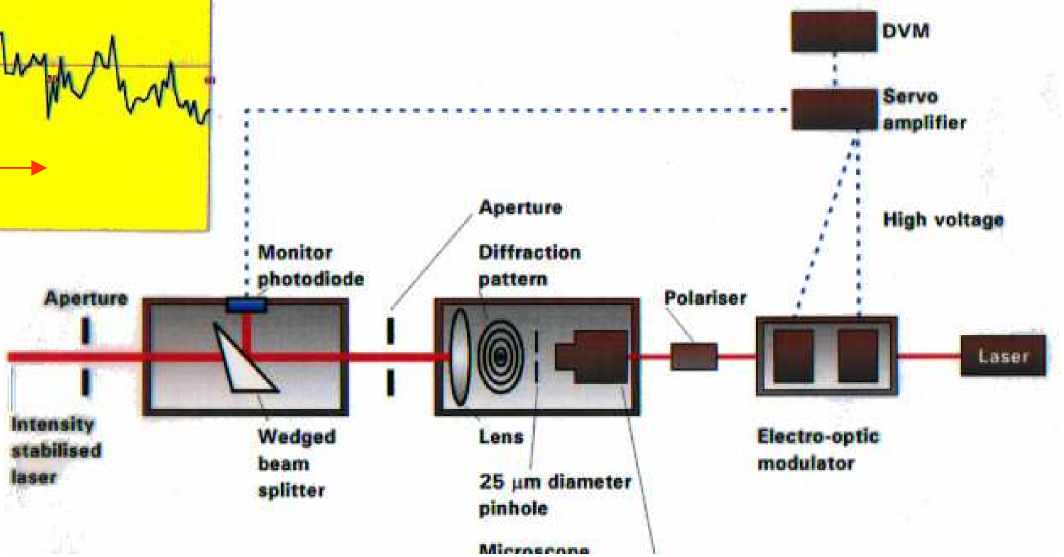
Ease of use

fibre lasers

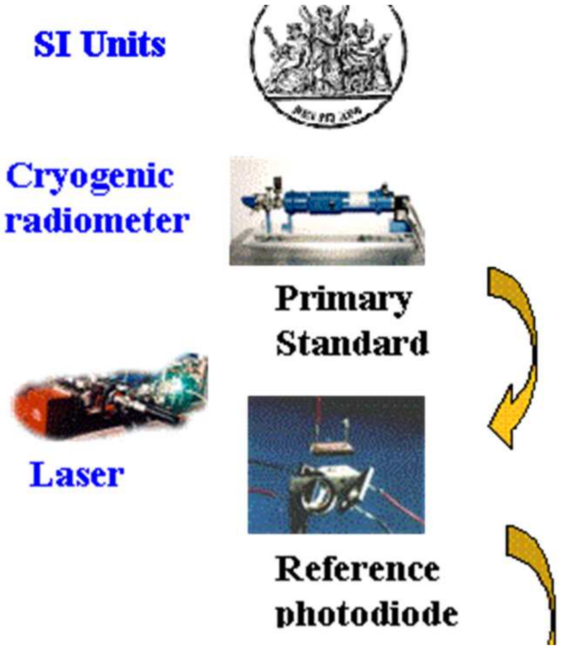
"White light"

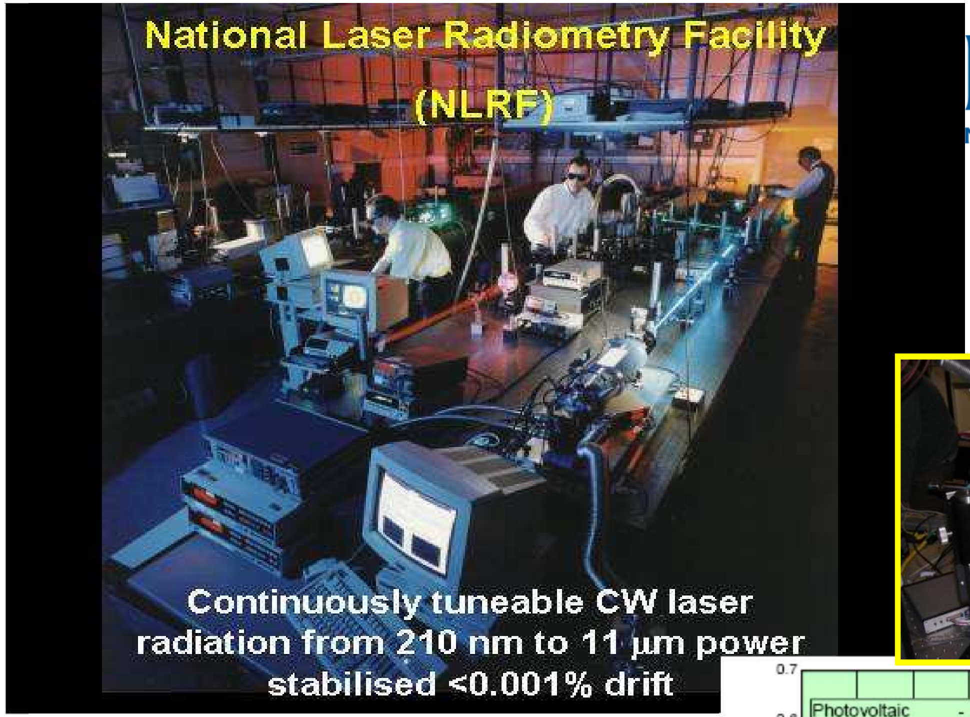
Transportability





Lasers allow very high accuracy to be achieved for monochromatic based measurements and also flexible tool.

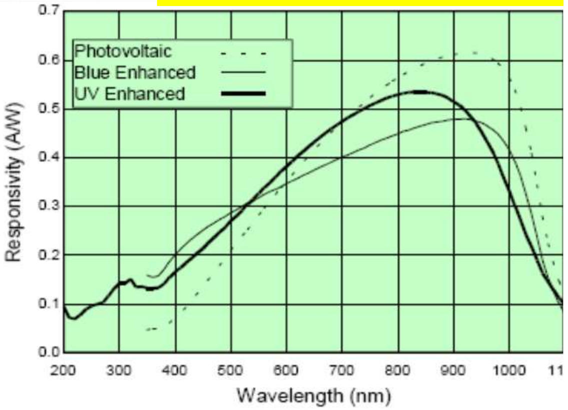


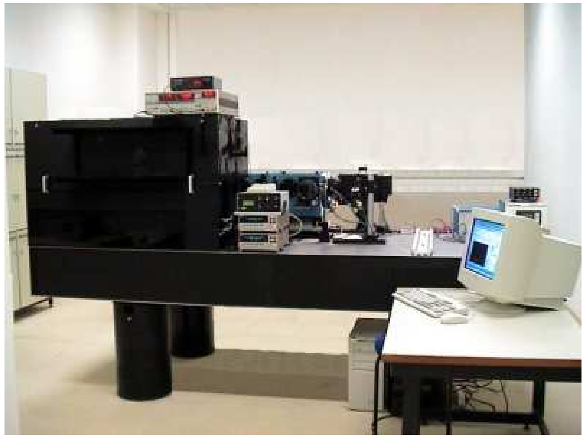


Continuously tuneable CW laser radiation from 210 nm to 11 µm power stabilised <0.001% drift

NPL
National Physical Laboratory

(RAL) BBR of EarthCARE at NPL





Monochromator based facilities for general dissemination

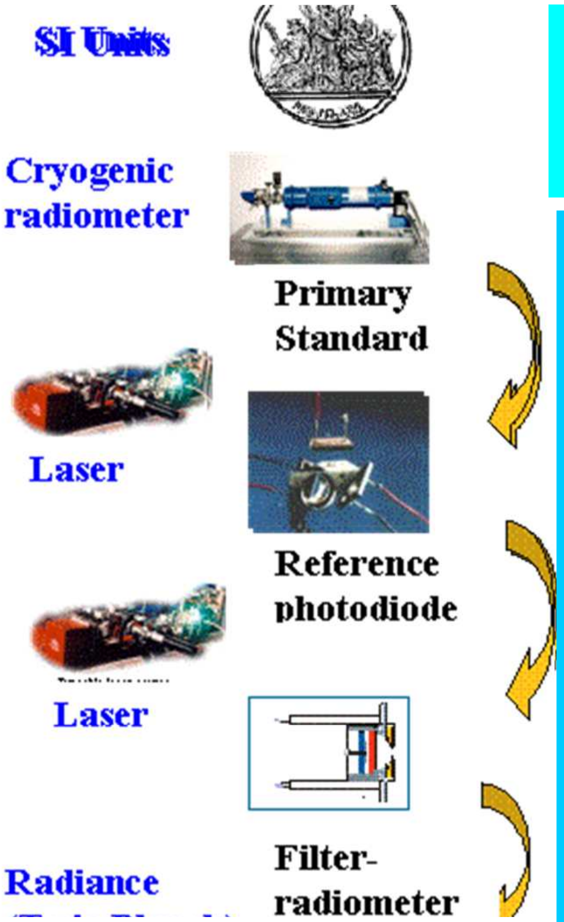
Full spectral responsivity of detectors can be measured by comparison to a primary standard detector and interpolated via validated model

200 nm to ~30 µm

Photon and themal detectors

- uniformity issue with IR & UV
- blackened pyroelectrics to extend spectral range from vis

The interface between monochromatic "primary spectral responsivity" and the "real world"


SI Units

Cryogenic radiometer

Primary Standard

Laser

Reference photodiode

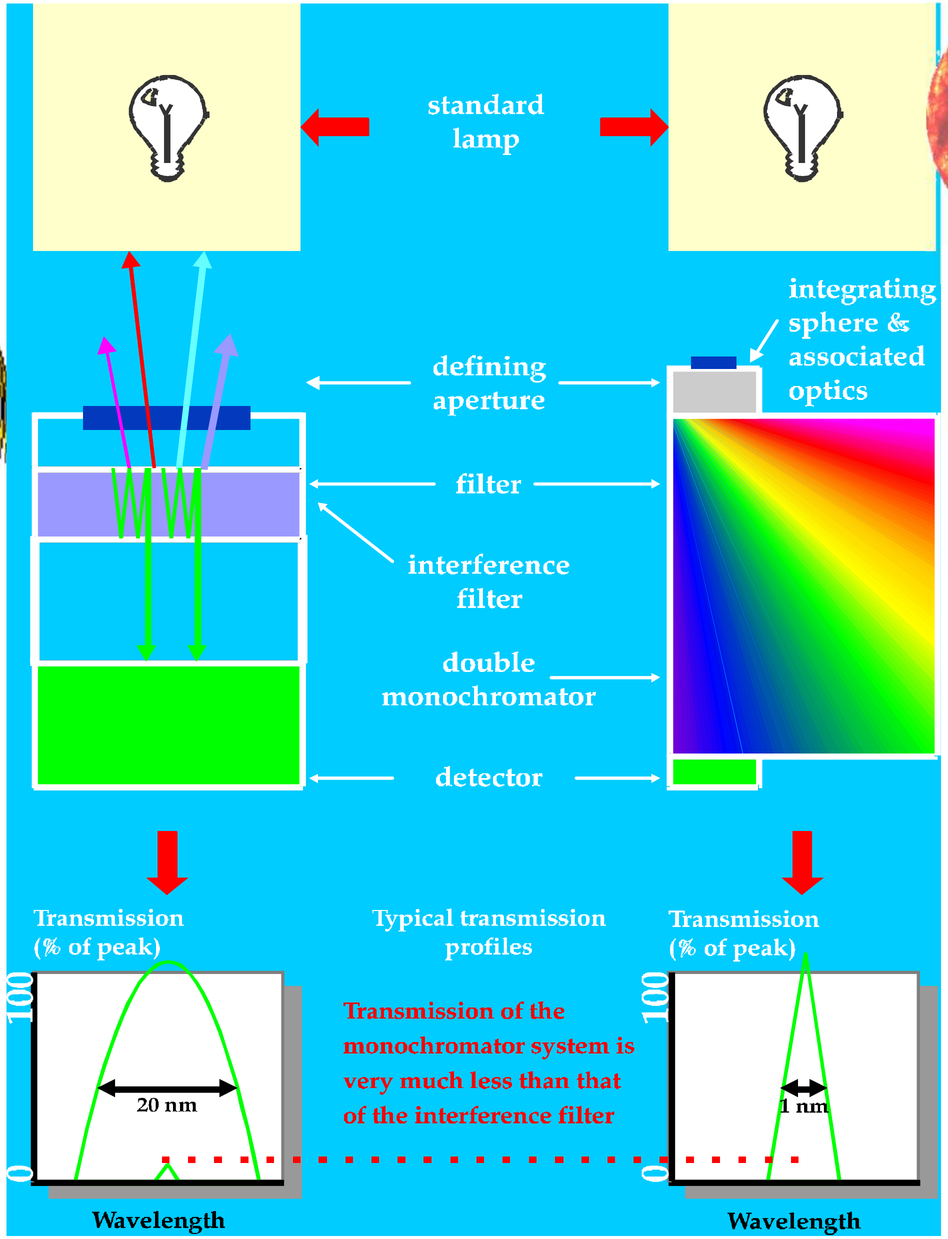
Laser

Filter-radiometer

Radiance

With appropriate geometry defining optics measure spectral radiance/irradiance

Multi-spectral (dispersive) system also Filter Rad


standard lamp

defining aperture

integrating sphere & associated optics

filter

interference filter

double monochromator

detector

Transmission (% of peak)

100

0

20 nm

Wavelength

Typical transmission profiles

Transmission of the monochromator system is very much less than that of the interference filter

Transmission (% of peak)

100

0

1 nm

Wavelength

NPL
National Physical Laboratory

EO instruments are just

filter-radiometers

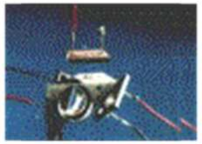
SI Units

Radiometrically calibrated filter radiometers

Cryogenic radiometer

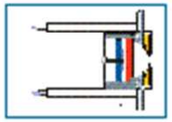
Primary Standard

Laser



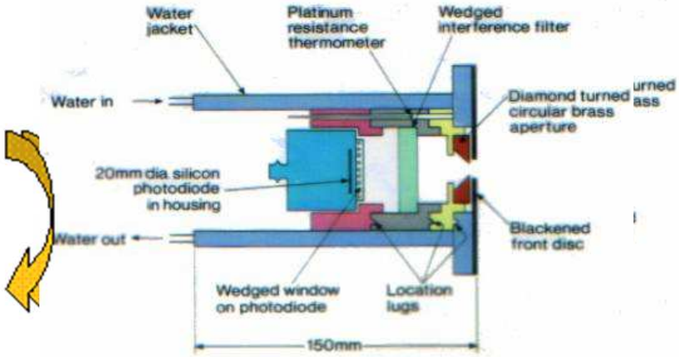
Reference photodiode

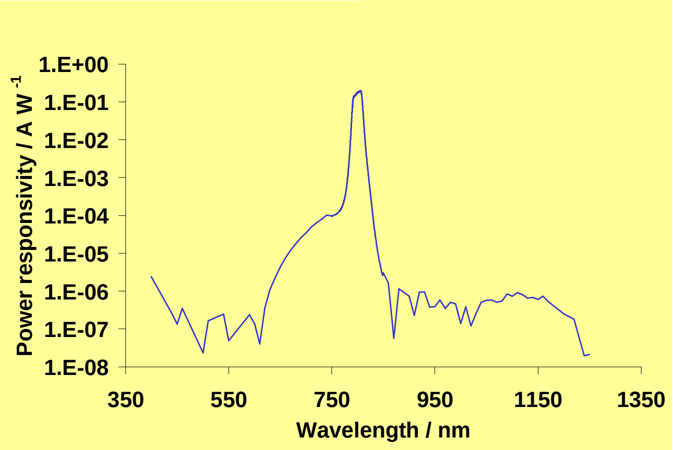
Laser



Filter-radiometer

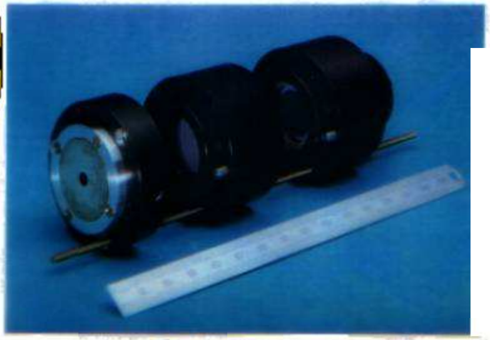
Radiance (T via Planck)



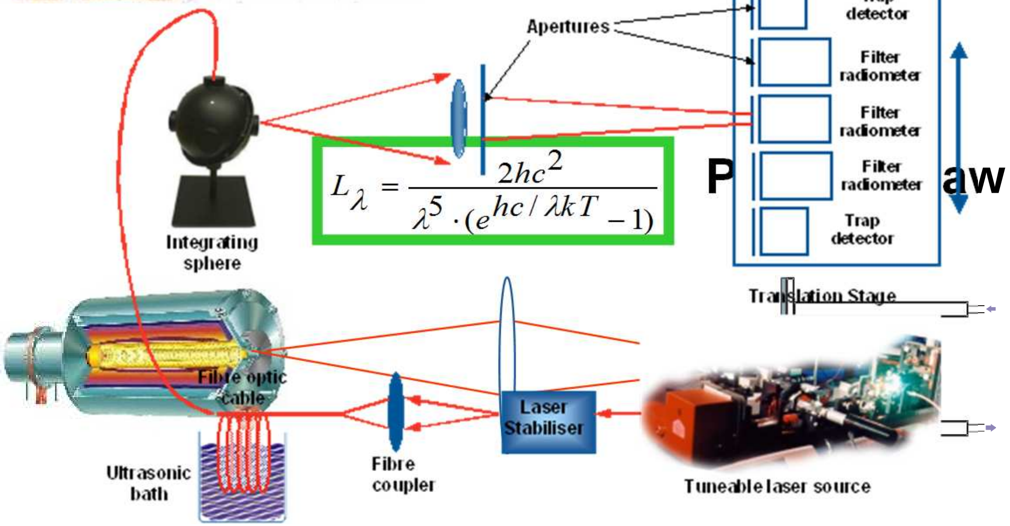


Spectral response of filter radiometer determined over full spectral bandwidth using tuneable lasers:

Uncertainty in spectral radiance ~0.02%



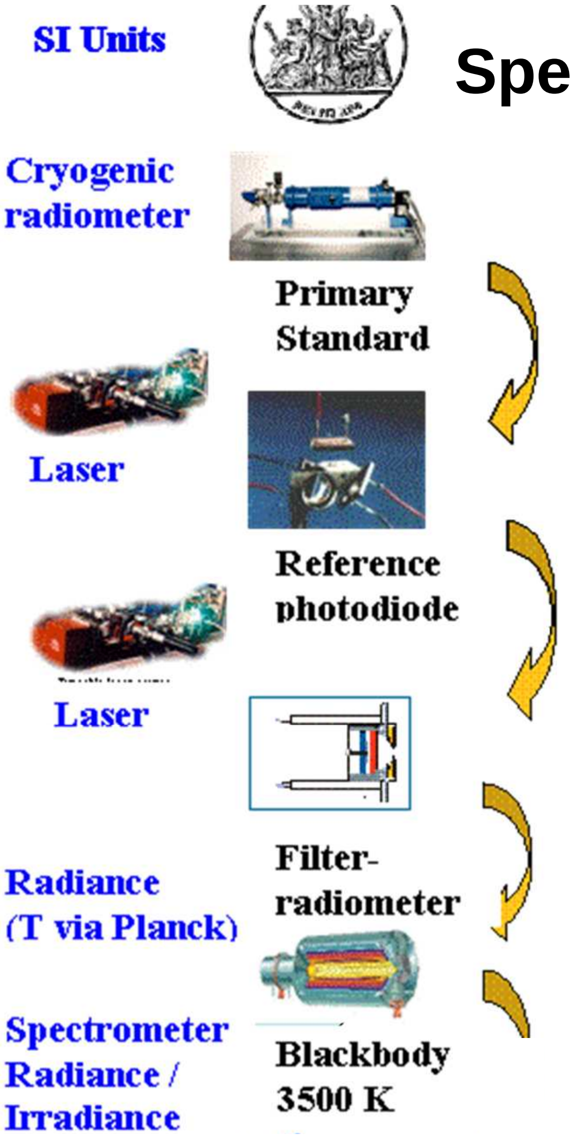
Filter radiometer



$$L_\lambda = \frac{2hc^2}{\lambda^5 \cdot (e^{hc/\lambda kT} - 1)}$$

Spectral (Ir)radiance Dissemination

National Physical Laboratory



SI Units

Cryogenic radiometer

Primary Standard

Laser

Reference photodiode

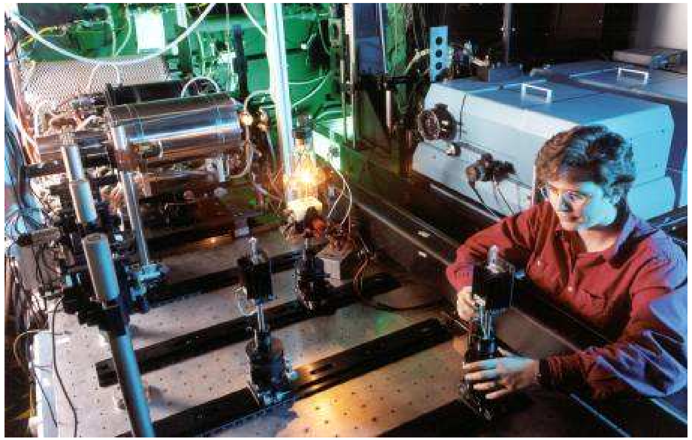
Laser

Filter-radiometer

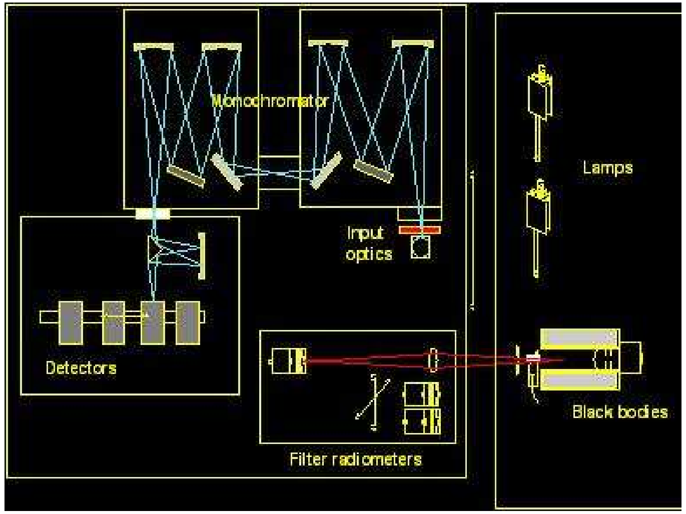
Radiance (T via Planck)

Blackbody 3500 K

Spectrometer Radiance / Irradiance



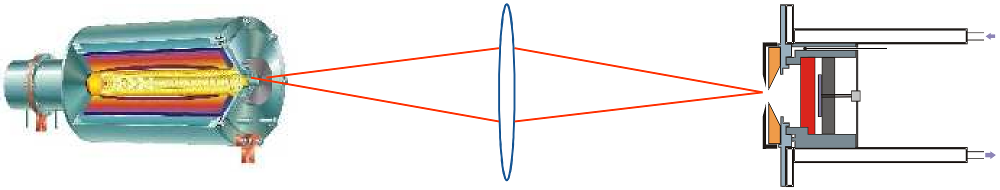
High T (3500 K) BB becomes absolute (Planck) spectral radiance source



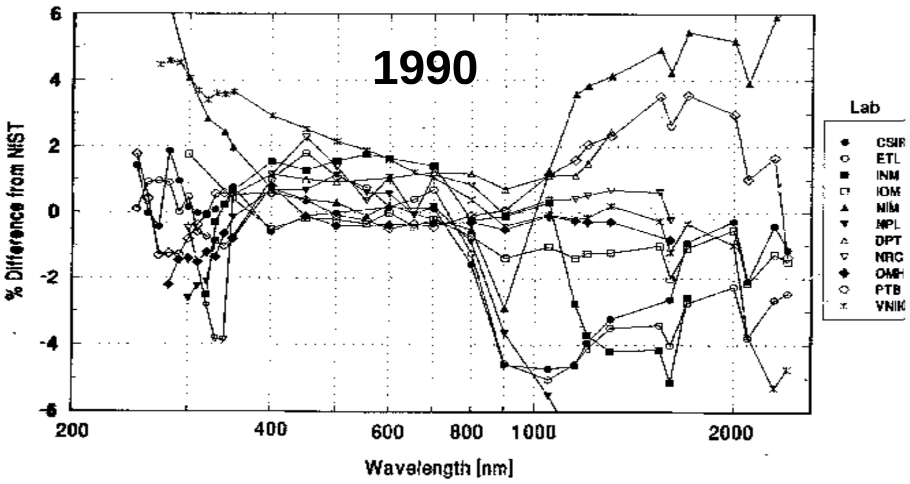
Can then be used to calibrate (filter radiometer) spectro-radiometer which in turn can measure another source (or instrument directly)

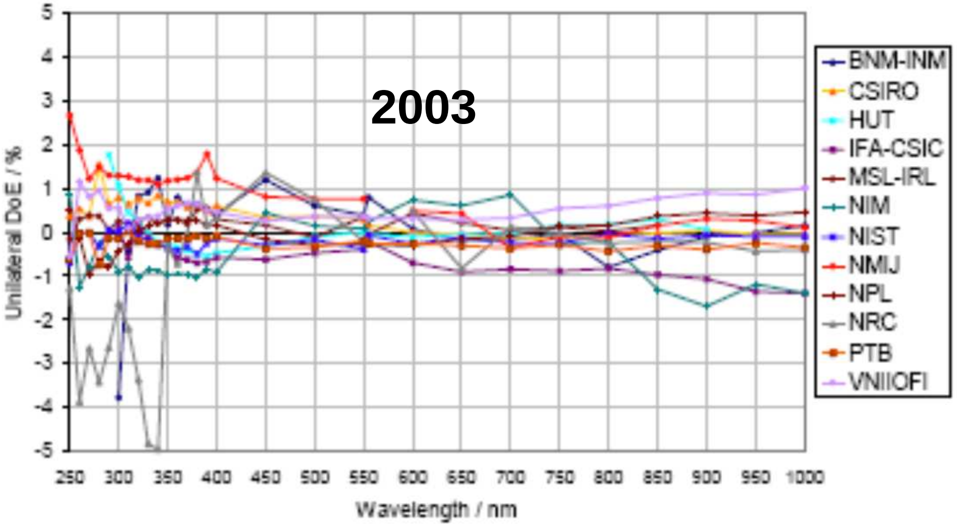
$$\boxed{L_{\lambda} = \frac{2hc^{2}}{\lambda^{5} \cdot (e^{hc/\lambda kT} - 1)}}$$

Spectral Radiance/Irradiance

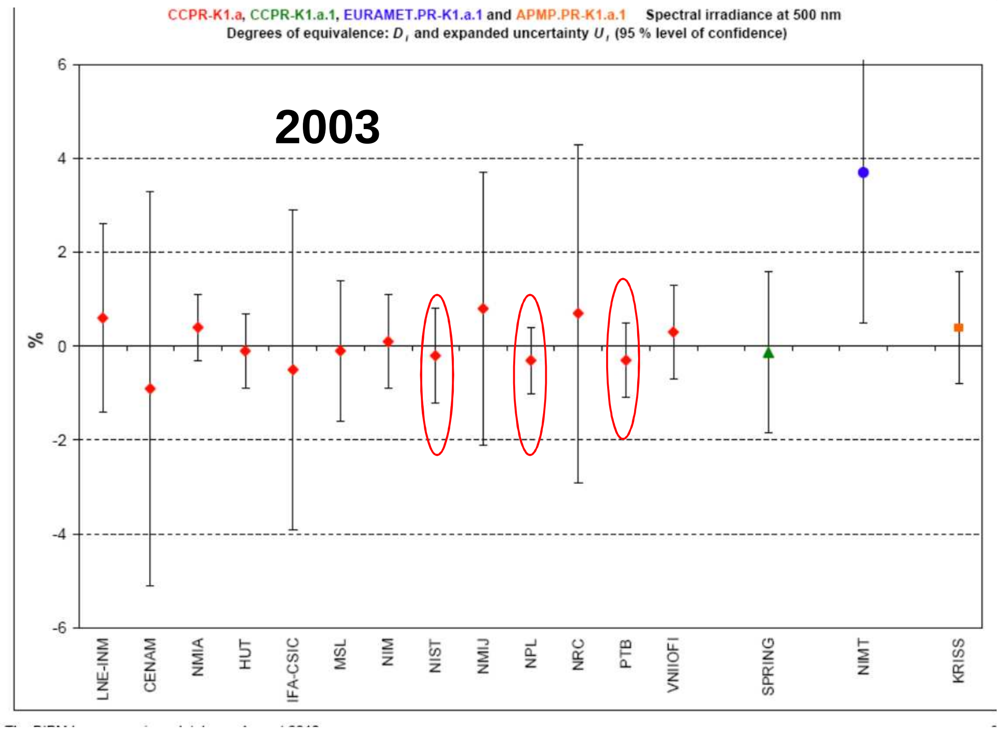


International equivalence



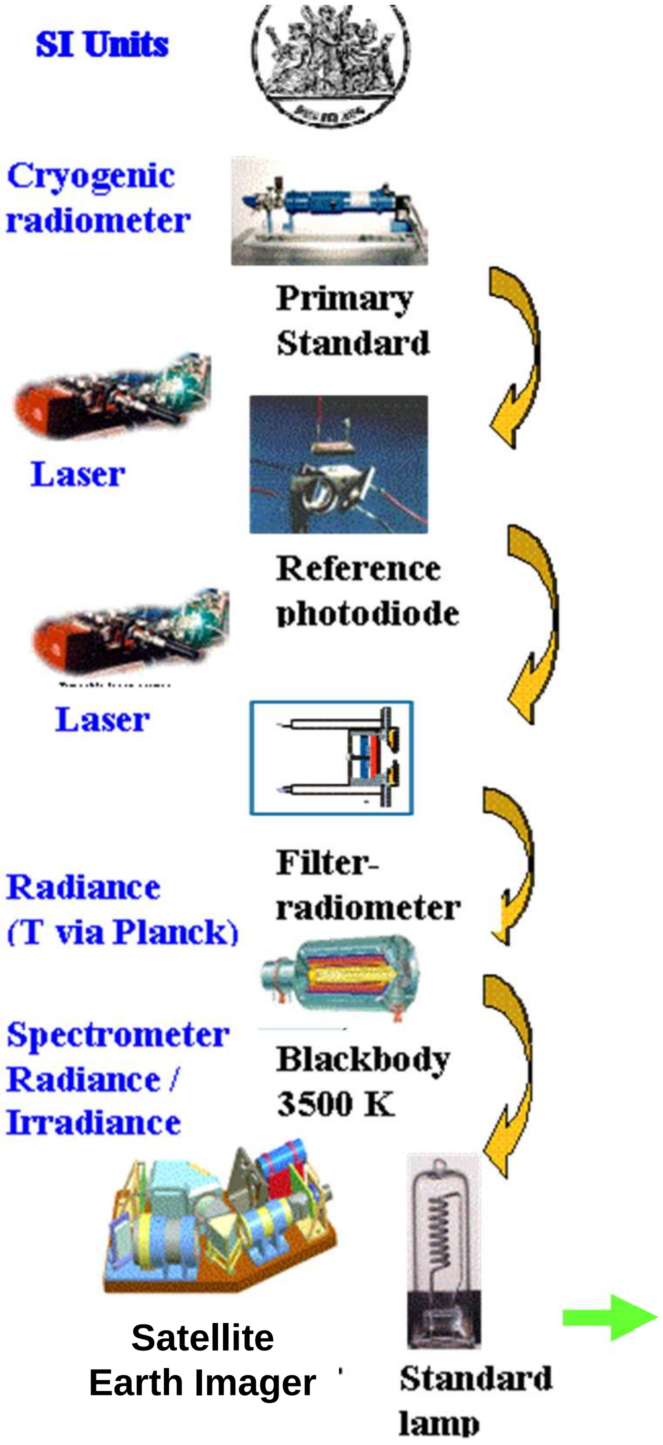


Spectral Irradiance
Comparisons
between NMIs



Spectrally Tuneable Laser based radiance/Irradiance source

NPL National Physical Laboratory



SI Units

Cryogenic radiometer

Primary Standard

Laser

Reference photodiode

Laser

Filter-radiometer

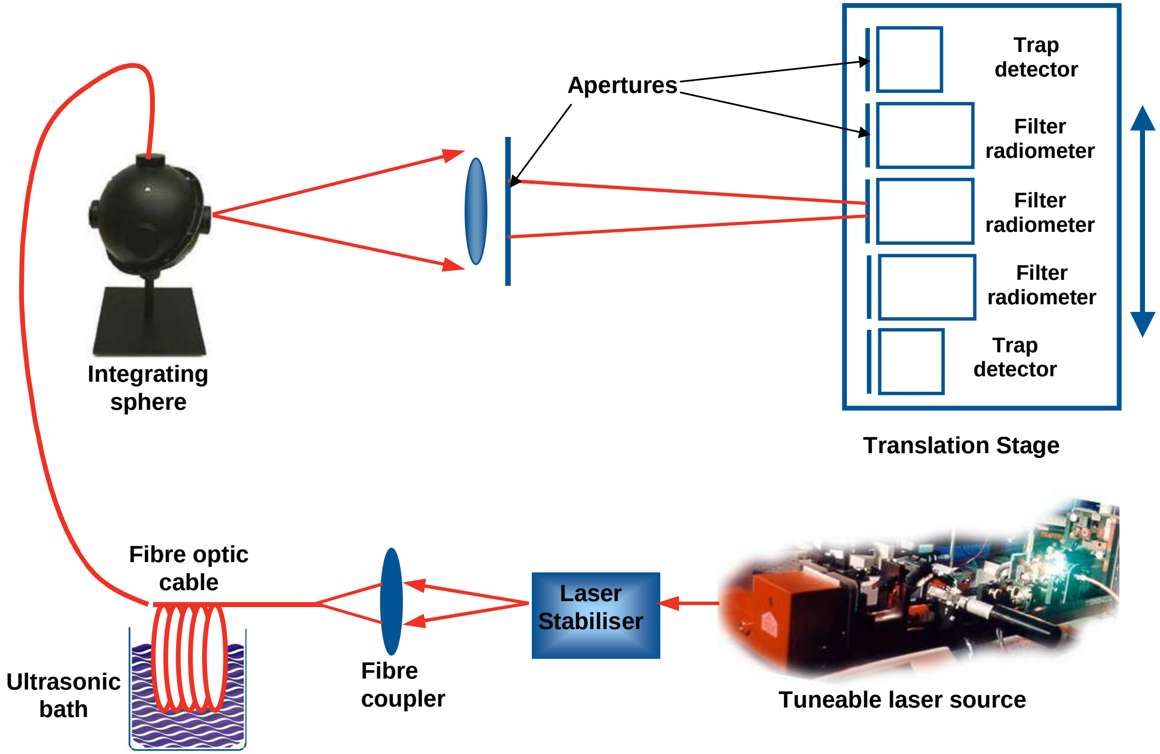
Radiance (T via Planck)

Blackbody 3500 K

Spectrometer Radiance / Irradiance

Satellite Earth Imager

Standard lamp



Apertures

Trap detector

Filter radiometer

Filter radiometer

Filter radiometer

Trap detector

Translation Stage

Integrating sphere

Fibre optic cable

Ultrasonic bath

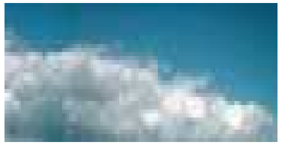
Fibre coupler

Laser Stabiliser

Tuneable laser source

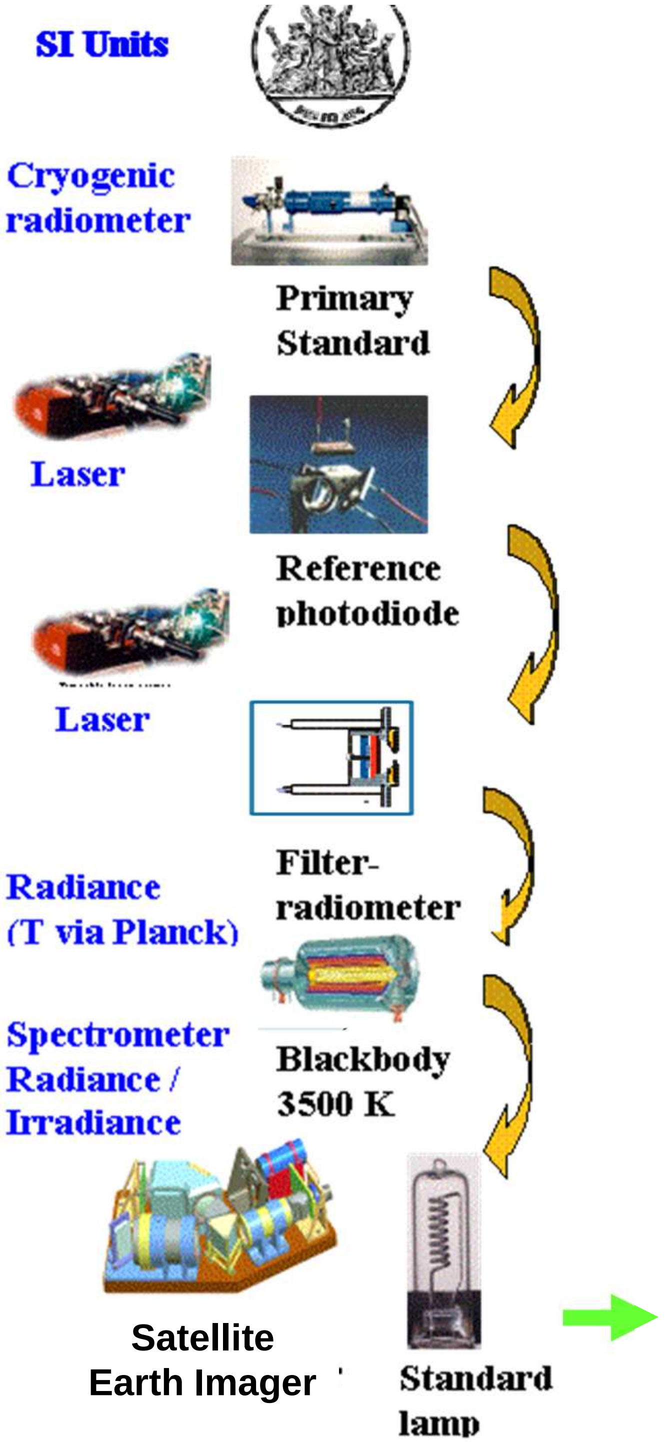
LAND

OCEAN

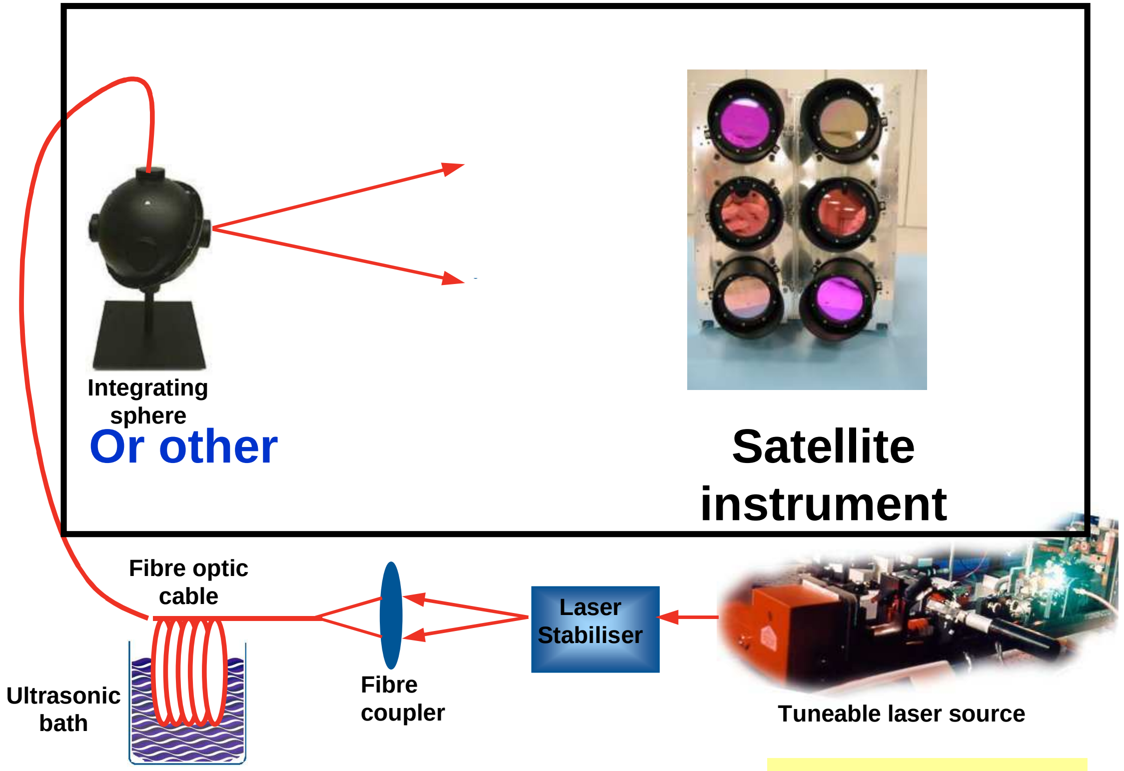


ATMOSPHERE

NPL
National Physical Laboratory



Vacuum Tank

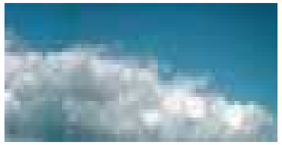


- Spectral (ir)radiance
- + bandwith & wavelength
- Stray-light correction

also Fibre lasers


LAND

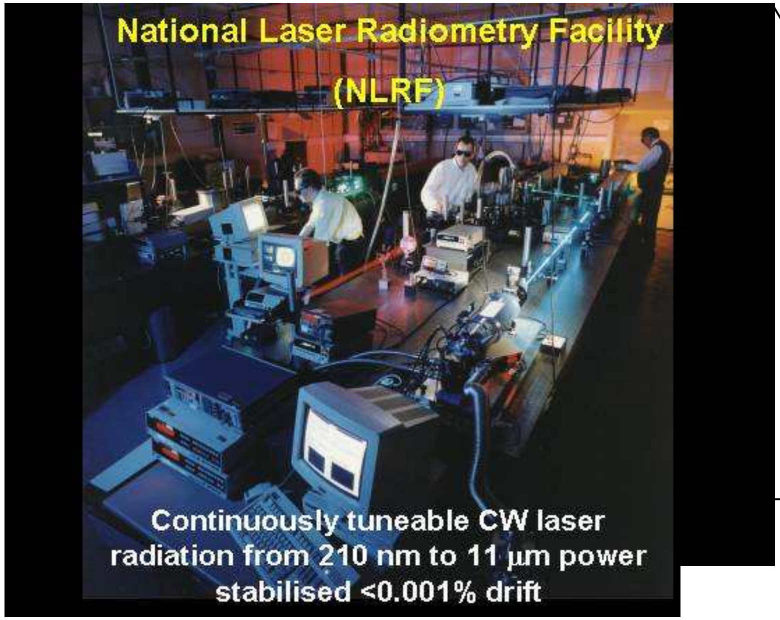

OCEAN


ATMOSPHERE

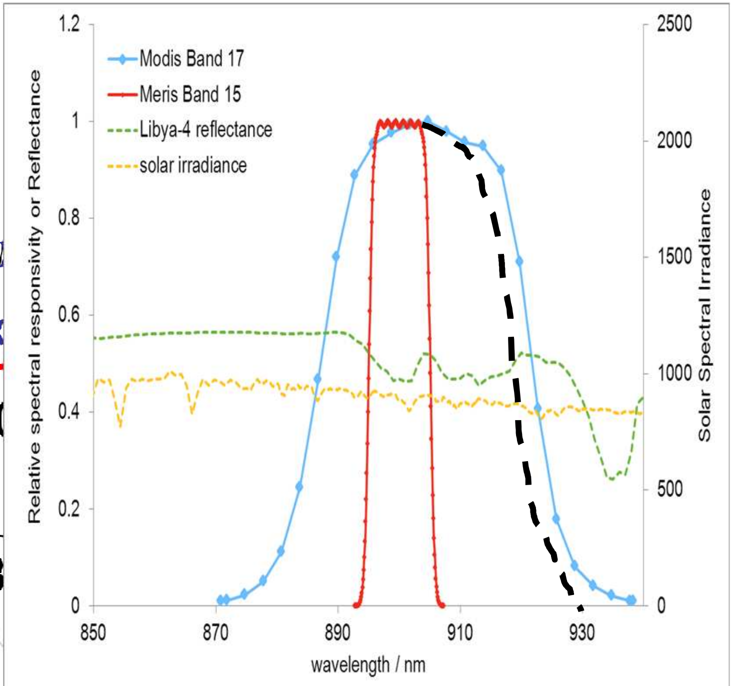
Spectral effects Increasingly important: use of tuneable lasers
(λ knowledge, bandwidth, spectral radiance)

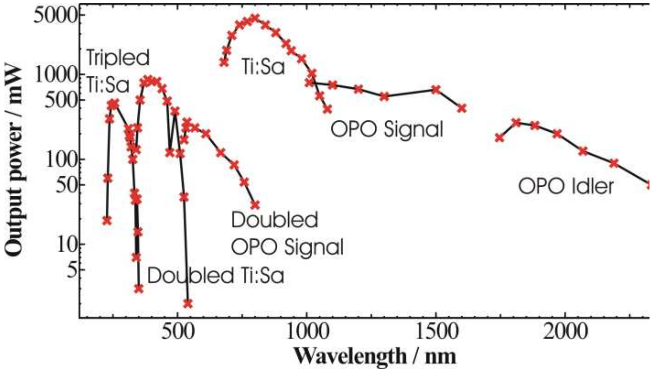
National Physical Laboratory

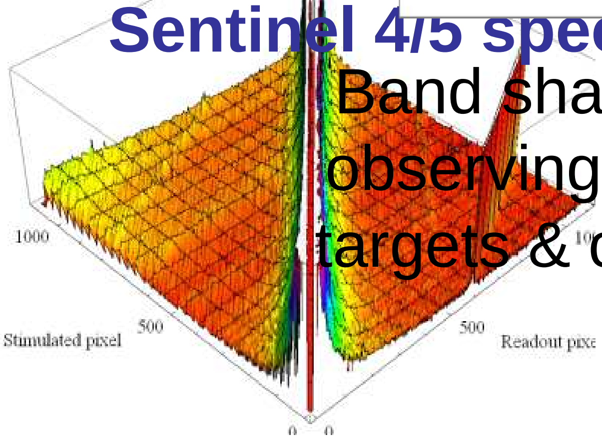
Metrology for Earth Observation and Climate


National Laser Radiometry Facility (NLRF)

Continuously tuneable CW laser radiation from 210 nm to 11 µm power stabilised <0.001% drift







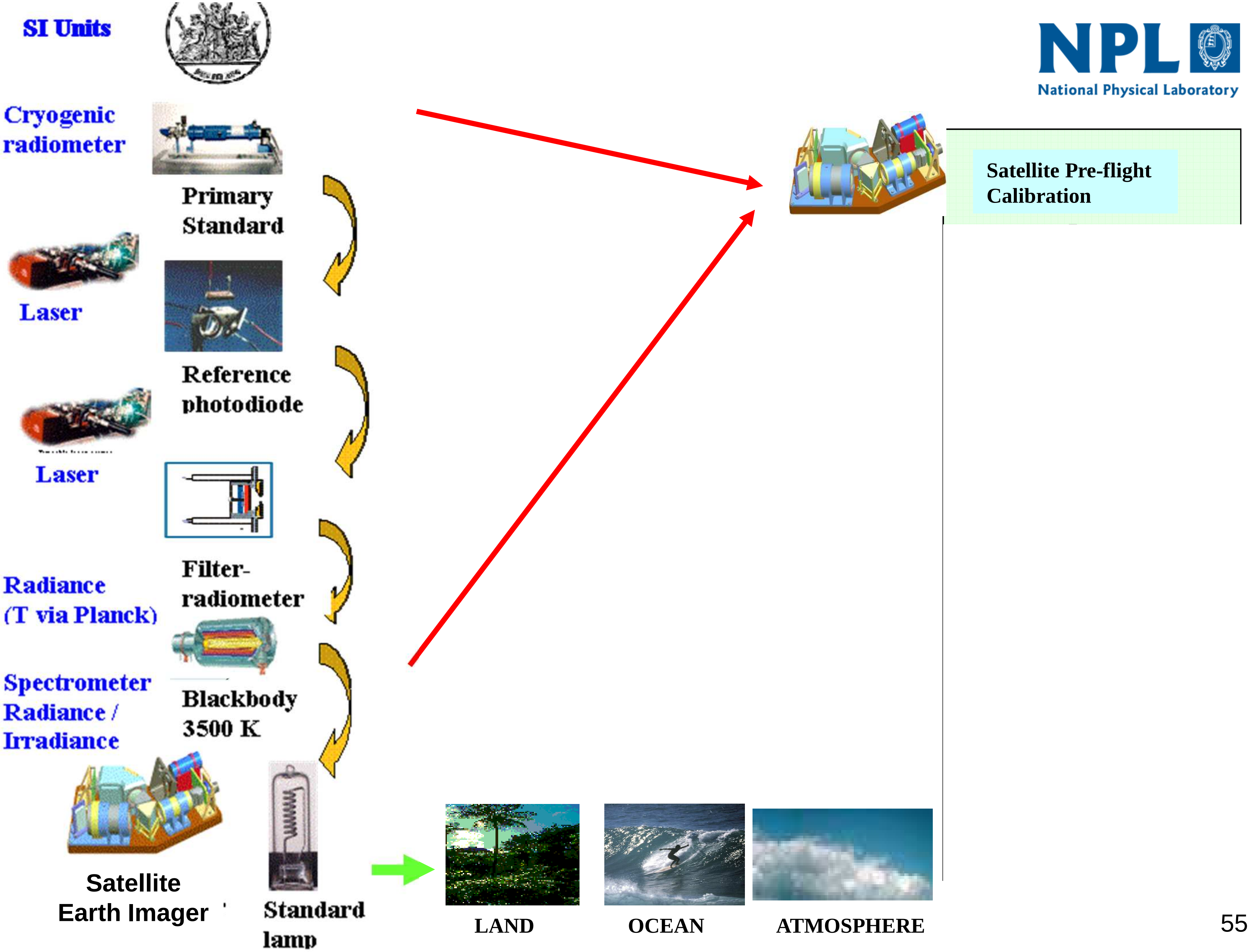
Sentinel 4/5 spectral accuracy

Band shape is critical when observing non spectrally flat targets & comparing sensors

Out of band Stray light

Matrix for imager

NPL
National Physical Laboratory



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Filter-radiometer

Radiance (T via Planck)

Spectrometer Radiance / Irradiance

Blackbody 3500 K

Satellite Earth Imager

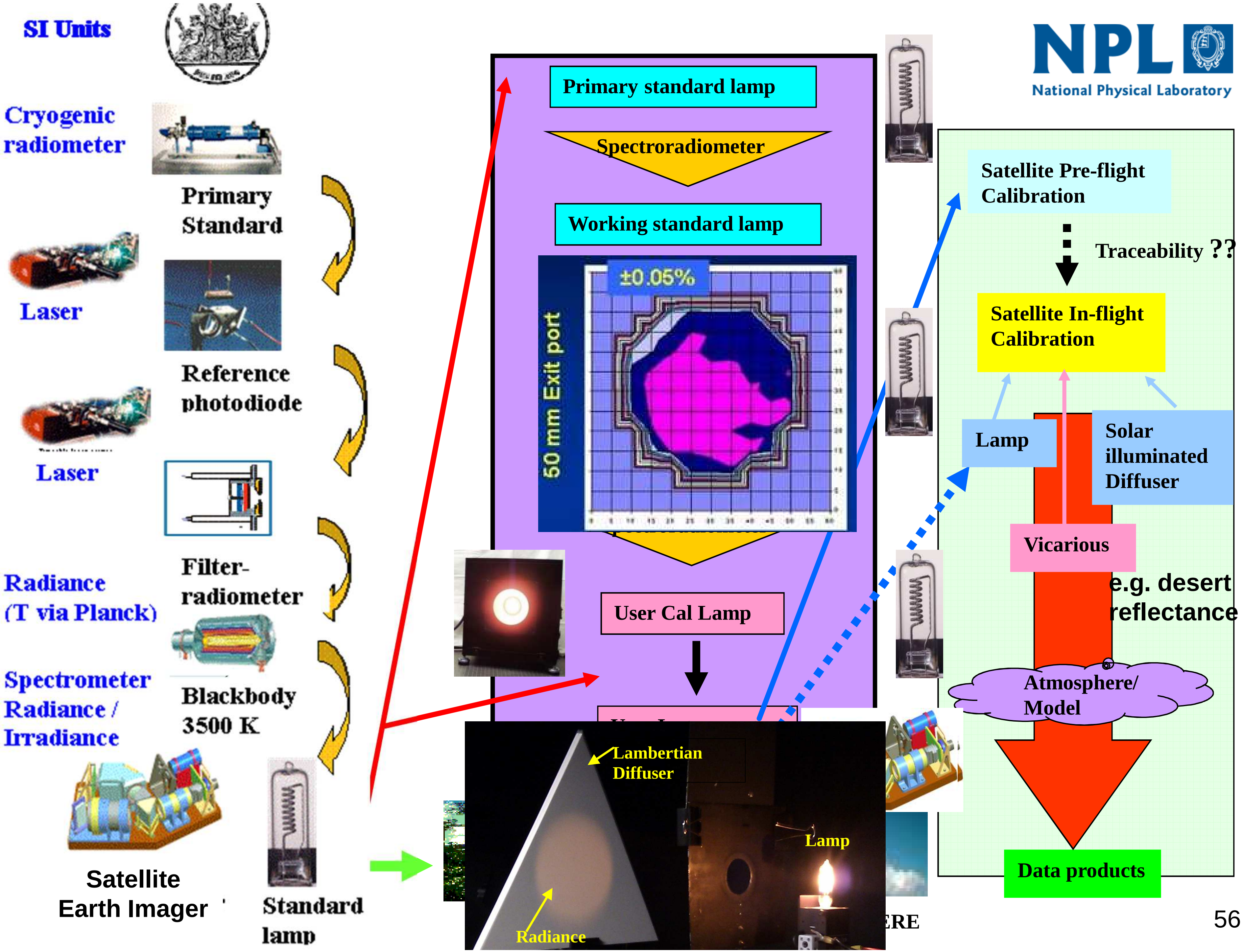
Standard lamp

LAND

OCEAN

ATMOSPHERE

Satellite Pre-flight Calibration



SI Units

Cryogenic radiometer

Primary Standard

Laser

Reference photodiode

Laser

Filter-radiometer

Radiance (T via Planck)

Blackbody 3500 K

Spectrometer Radiance / Irradiance

Satellite Earth Imager

Standard lamp

Primary standard lamp

Spectroradiometer

Working standard lamp

±0.05%

50 mm Exit port

User Cal Lamp

Lambertian Diffuser

Lamp

Radiance

Satellite Pre-flight Calibration

Traceability ??

Satellite In-flight Calibration

Lamp

Solar illuminated Diffuser

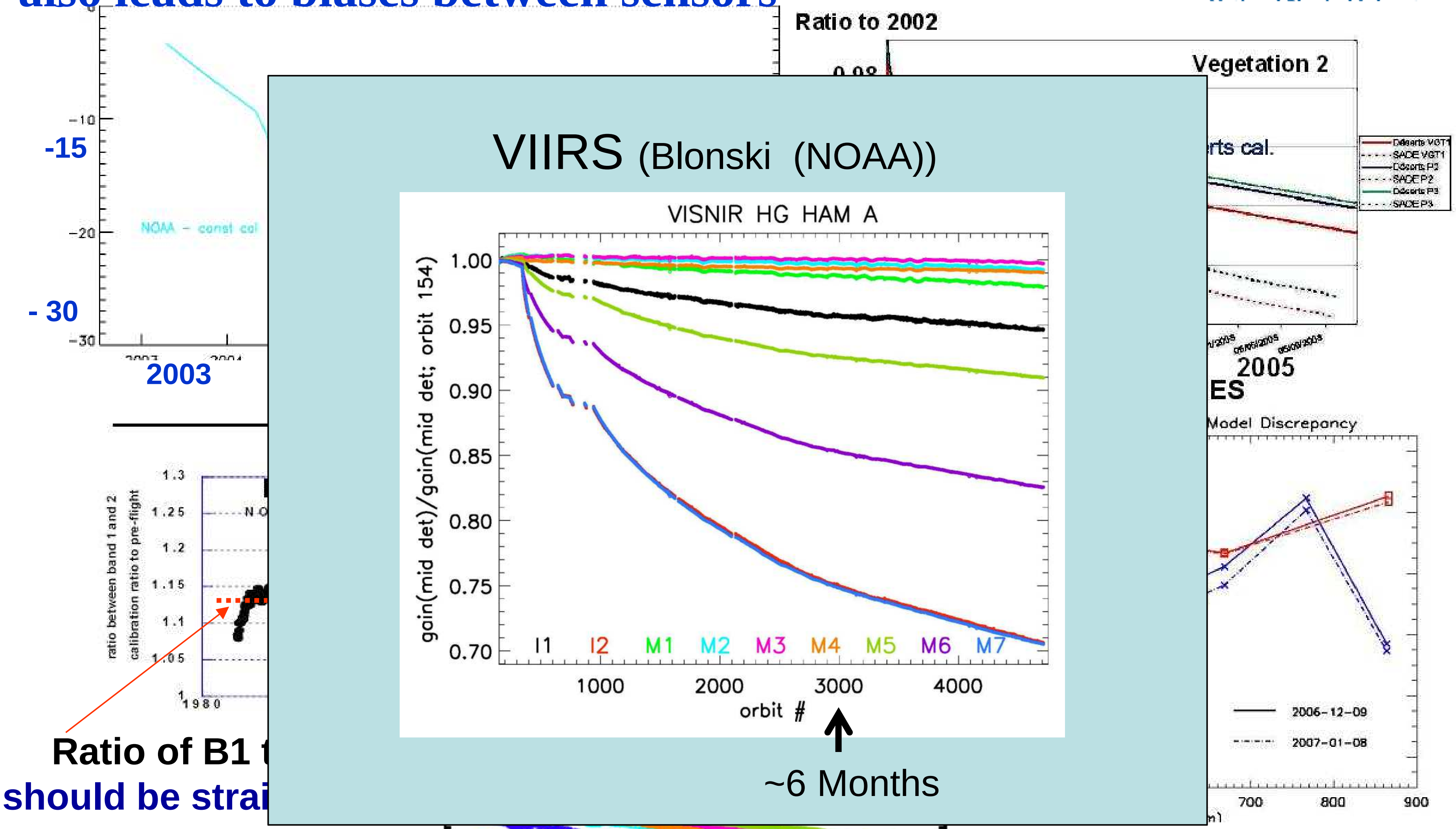
Vicarious

e.g. desert reflectance

Atmosphere/ Model

Data products

All SR optical sensors drift from pre-flight calibrations – also leads to biases between sensors

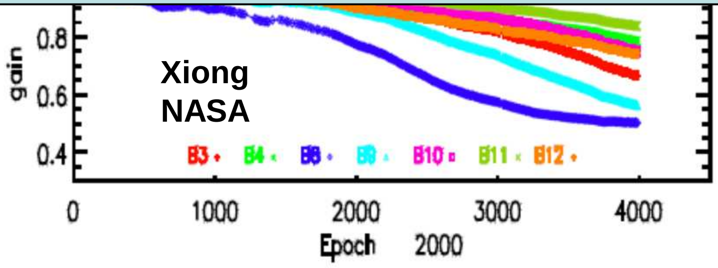


VIIRS (Blonski (NOAA))

~6 Months

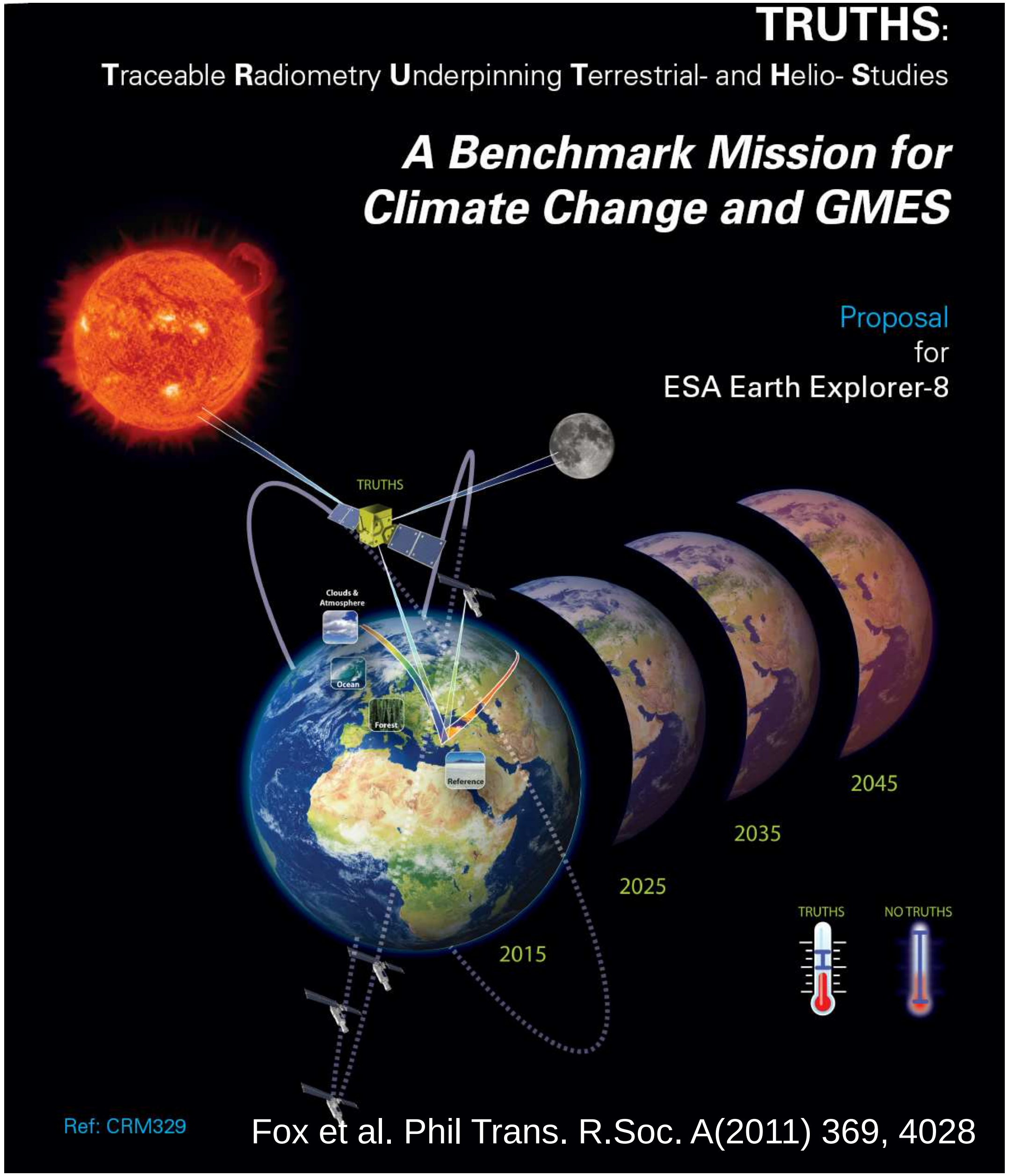
Ratio of B1 t

should be strai



Xiong NASA

Pre-flight calibration is still essential to help understand: changes, ensure correct build & performance meets specn



TRUTHS:

Traceable **R**adiometry **U**nderpinning **T**errestrial- and **H**elio- **S**tudies

A Benchmark Mission for Climate Change and GMES

Proposal
for
ESA Earth Explorer-8

Ref: CRM329

Fox et al. Phil Trans. R.Soc. A(2011) 369, 4028

For more details:
http://www.npl.co.uk/celebrating-science/seeking-the-truths-about-climate-change

Climate studies require:

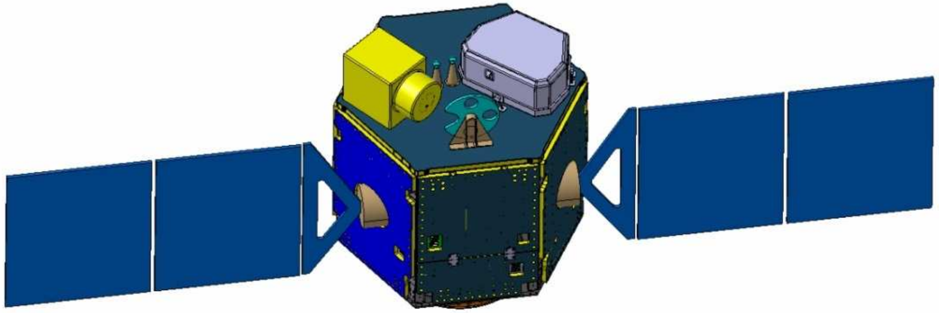
- **Global coverage**
  - ***observations (insensitive to time/location/scale)***
- **Decadal time scales**
- **Uncertainties close to primary SI standards/realisations**

Solution:

Establish and maintain SI traceability directly in Space on-board the spacecraft

– Adapt terrestrial methodologies and primary standards

Achieving Climate Benchmark – Challenge is:



Not sensing technology

Not sampling / platform

to achieve ‘in-orbit’ SI traceable uncertainties of:

$<0.3\ \%\ \ k=2\ (2\sigma)$

in spectrally resolved solar reflectances / radiances)
~ 10X performance improvement on existing sensors

Can only be achieved by novel ‘on-board’ calibration method

THIS IS: TRUTHS

National Physical Laboratory

CLARREO

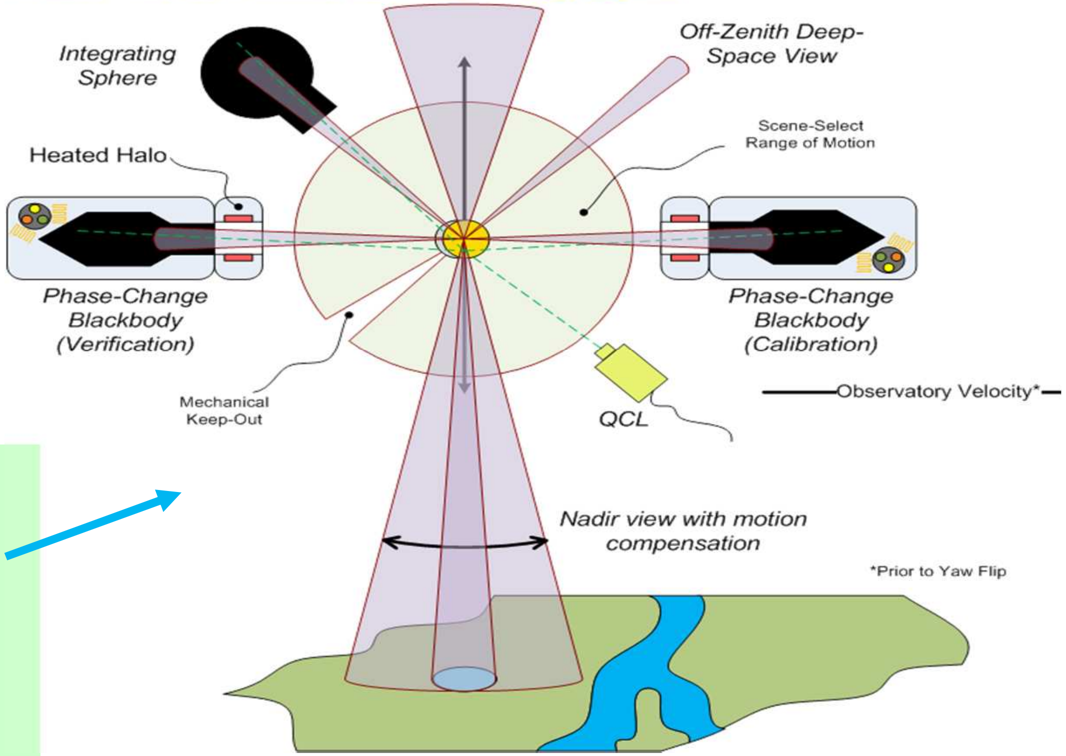
IR full on-board SI primary standard

SR relative to another satellite

SR GIFOV (500 m)

Global mean nadir averages

Ref calibration (multi-angle)

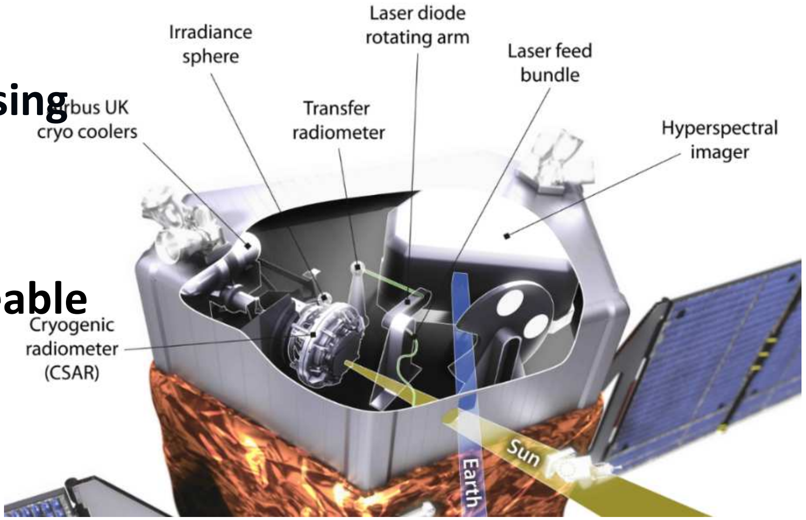


IR Spectrometer calibrated on-board against “transition point” (Ga melt) blackbody - emissivity monitored using Quantum cascade laser.

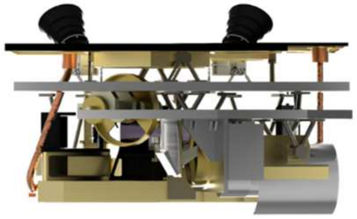
TRUTHS: What is it?

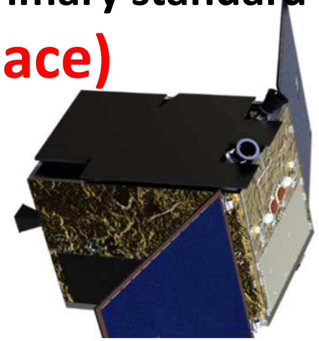
Traceable Radiometry Underpinning Terrestrial- & Helio- Studies

- A small satellite mission, to improve the quality of EO data to meet needs of climate
  - Initiating a space climate observatory (requested by climate community Strategies)
  - Establishing a benchmark (trustable ‘snapshot’ of climate state) from which to monitor change & test climate model forecasts in shortest possible time (compliments NASA CLARREO)
- Measures incoming (total and spectrally resolved) and reflected solar radiation (320 – 2350 nm @ ~5 nm bandwidth & 50 m) 10 X more accurately than currently possible
  - Fundamental climate data to anchor ECVs, CDRs and monitor mitigation strategies
- Provides means to upgrade performance of other EO sensors through in-flight cross-calibratio
  - A ‘plug in’ to Copernicus to increase utilisation
  - Designed for Climate, but delivers free and open access L1 data for science and commercial processing to L2 and subsequent knowledge information services: Land cover, agriculture, Forest, pollution ….
  - Heritage payload but innovative on-board SI traceable calibration system including primary standard



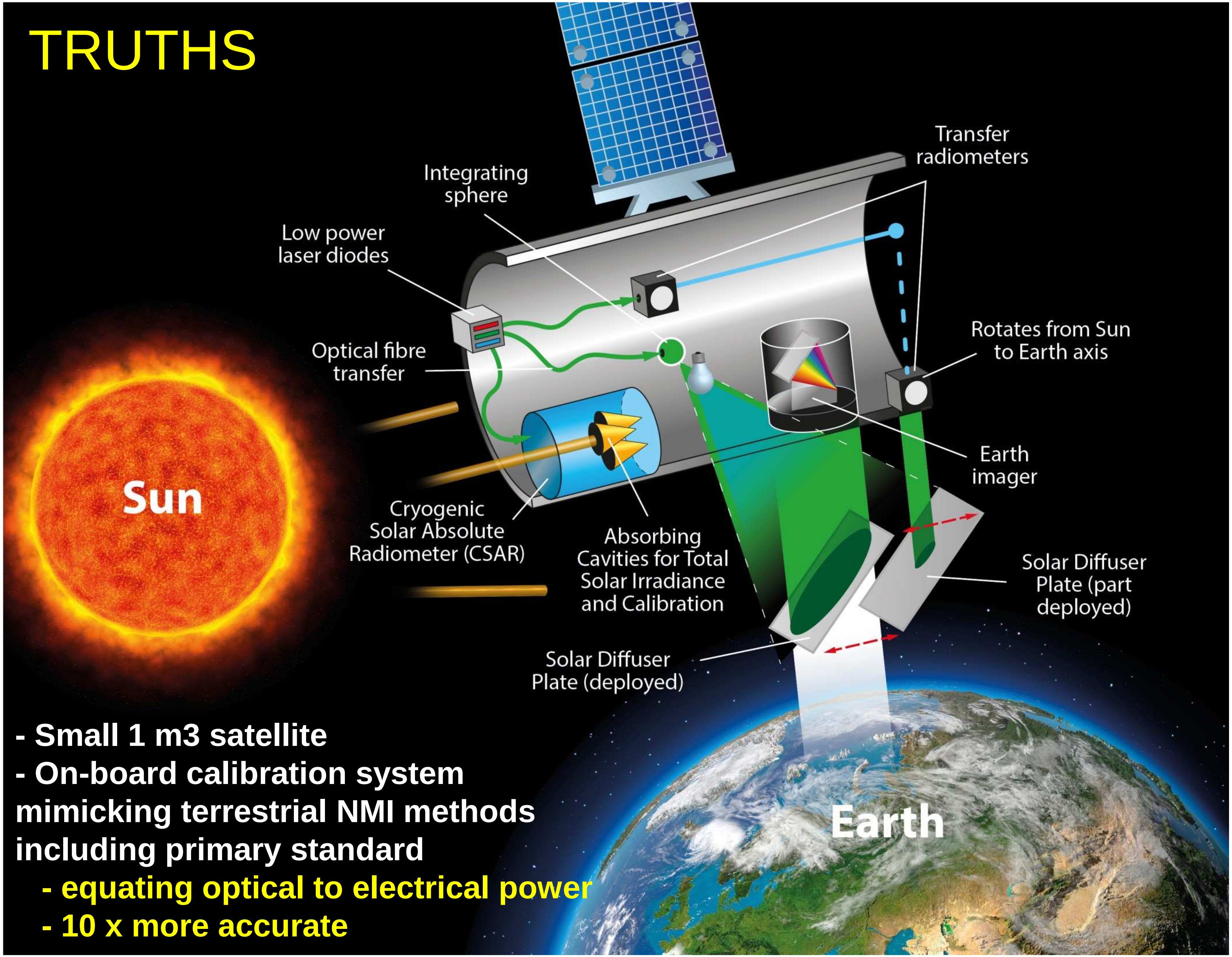
(An NMI in space)





Currently configured for both Airbus and SSTL platforms

TRUTHS



- **Small 1 m3 satellite**
- **On-board calibration system mimicking terrestrial NMI methods including primary standard**
  - **equating optical to electrical power**
  - **10 x more accurate**

TRUTHS imaging spectrometer: SSTL

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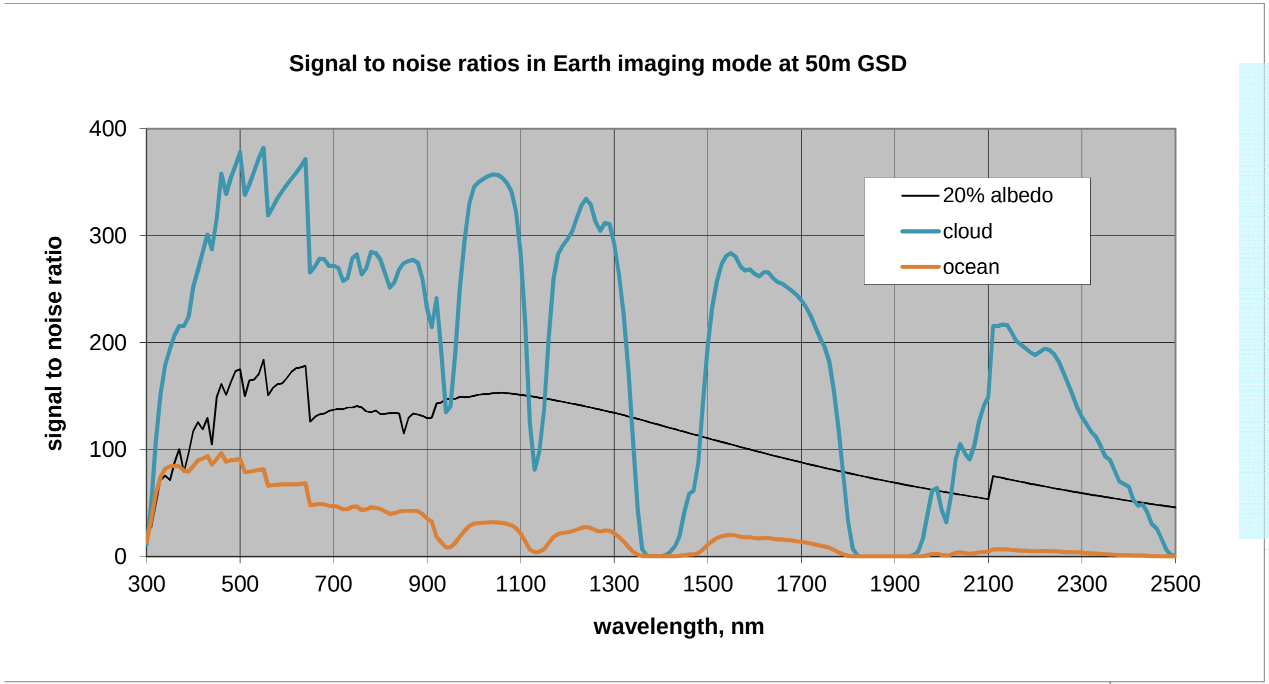
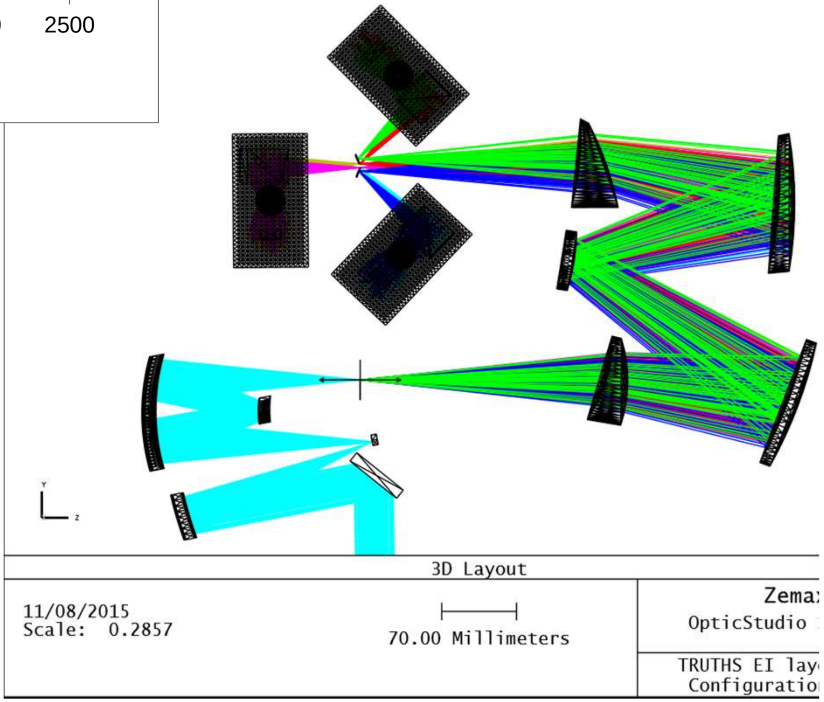
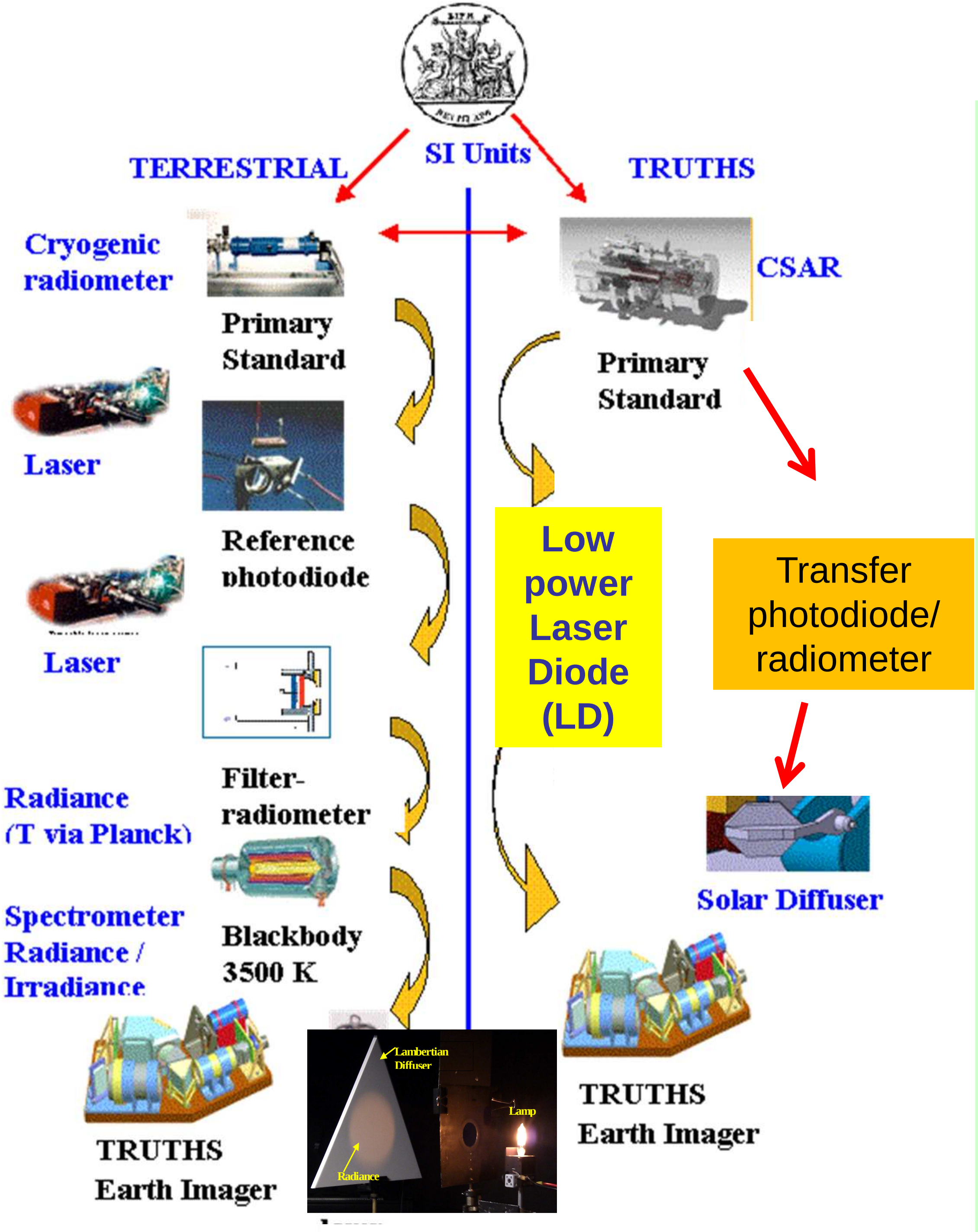


- SNR for 50 m GIFOV
- Ocean = 100 @420 nm
- Bin to 250 m = ~X5 gain
  Ocean = 500 @420 nm
- Cross-Cal/special targets increase dwell time ~ X3
- Ocean = 1500 @420 nm



Evolution of CHRIS and EnMAP



SI Units

TERRESTRIAL

TRUTHS

Cryogenic radiometer

Primary Standard

Laser

Reference photodiode

Laser

Filter-radiometer

Radiance (T via Planck)

Blackbody 3500 K

Spectrometer Radiance / Irradiance

TRUTHS Earth Imager

CSAR

Primary Standard

Low power Laser Diode (LD)

Transfer photodiode/ radiometer

Solar Diffuser

TRUTHS Earth Imager

Traceability Strategy:

- mimic that used on ground at standards labs

- Primary reference standard is cryogenic radiometer (CSAR)
- compares heating effect of monochromatic optical power to electrical power

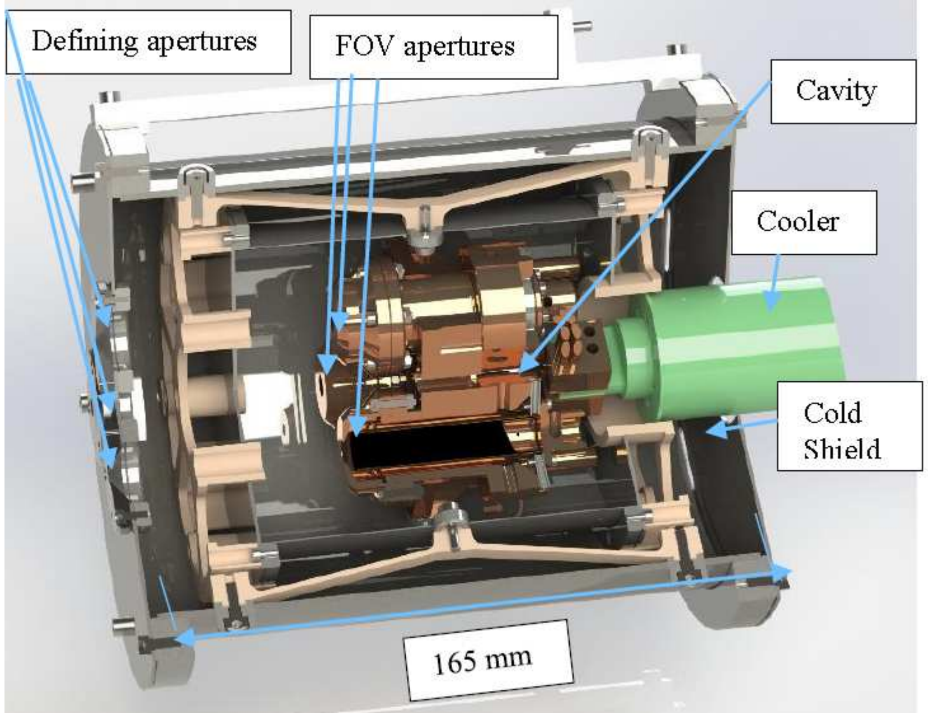
- Low power Laser diode (few λ) Calibrates Transfer radiometer against primary standard CSAR

- LD illuminates lambertian diffuser - fills aperture of imager (monochromatic radiance)

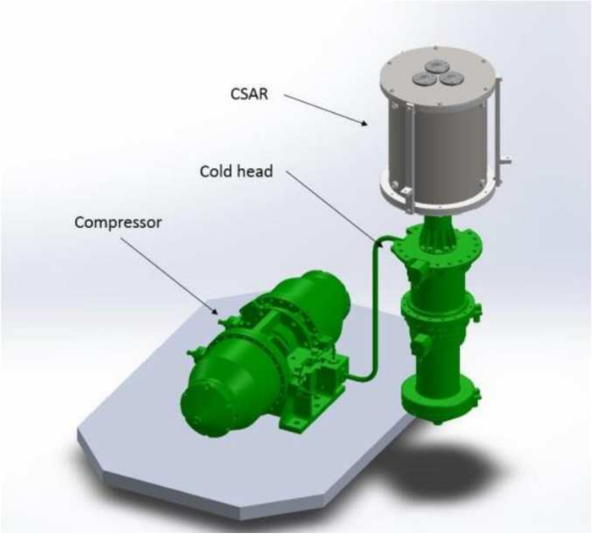
- Calibrated Transfer radiometer measures radiance of diffuser

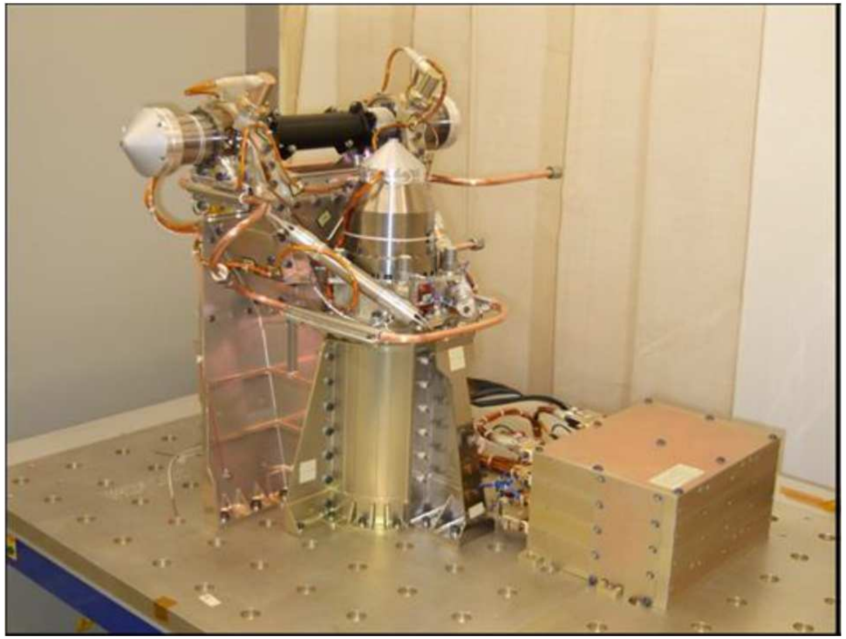
- Repeat for other λ
- smooth spectral shape of diffuser minimises number

CSAR V-2: Space engineering model

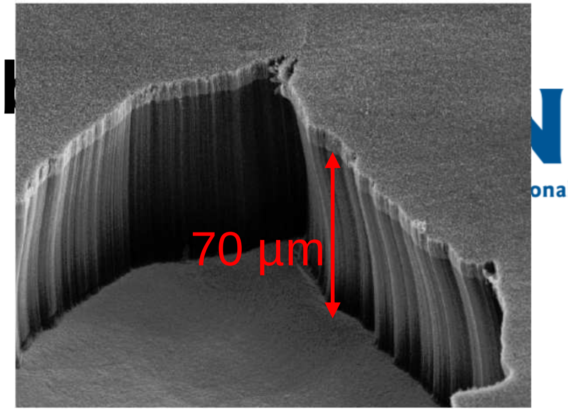


- Coupled to Airbus space cooler
- Mass = 25Kg inc cooler
- Power = 200 W
- 3 cavities   ~ 0.99998
- $\tau \sim 1$ s
- CNT black

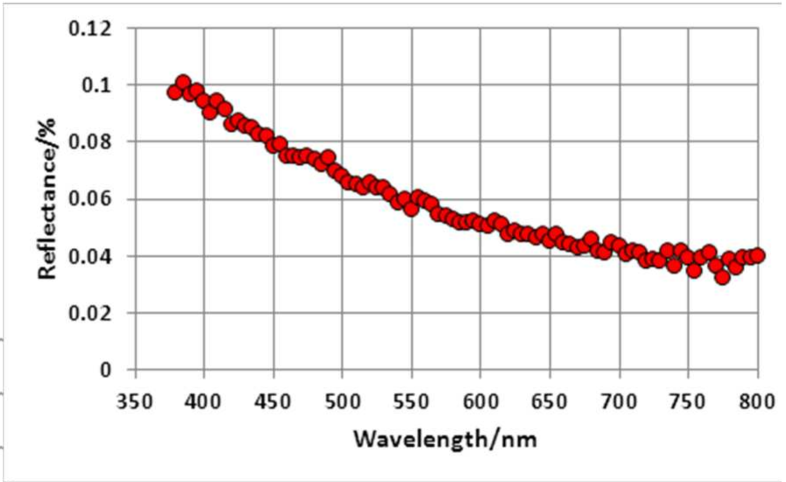


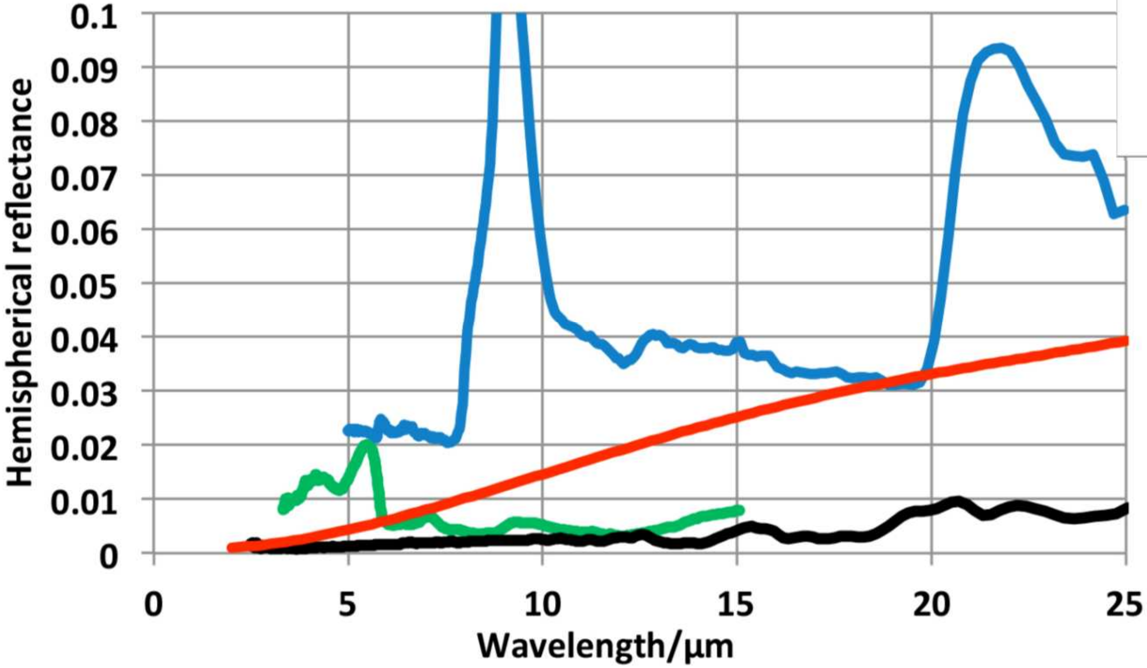


Carbon Nano-tube

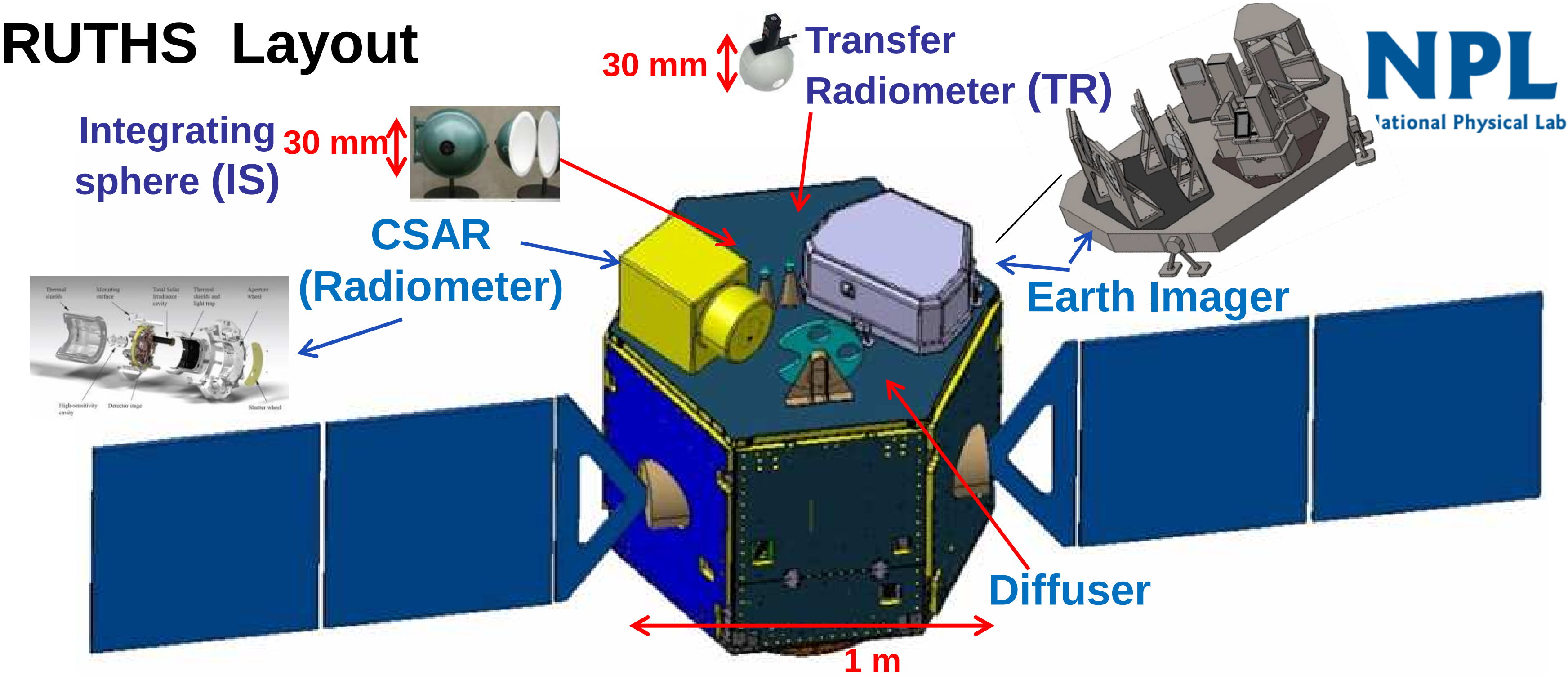


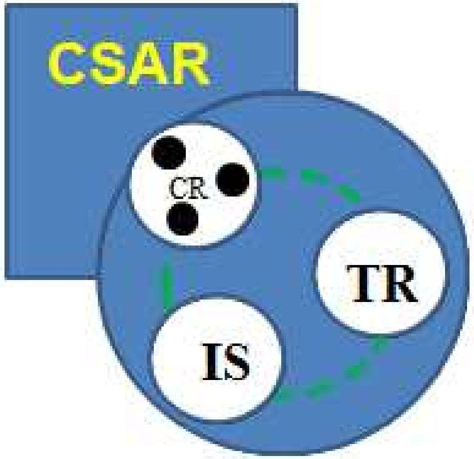
- Coating can be applied to many materials
- VERY black <1% in IR and <0.1 % in Vis
  - Suitable for Cryogenic temperatures
    - Space qualified
      - Outgassing
      - Vibration



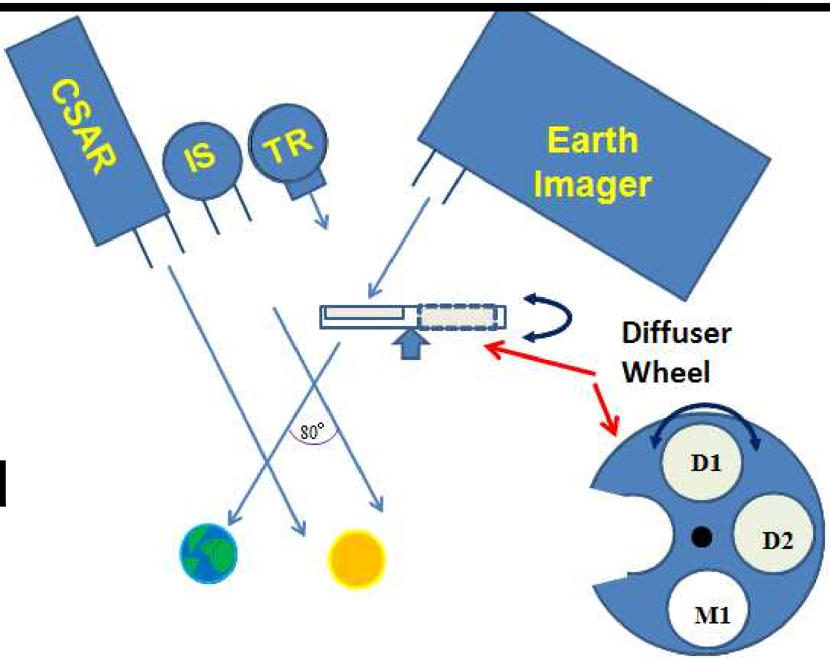


TRUTHS Layout



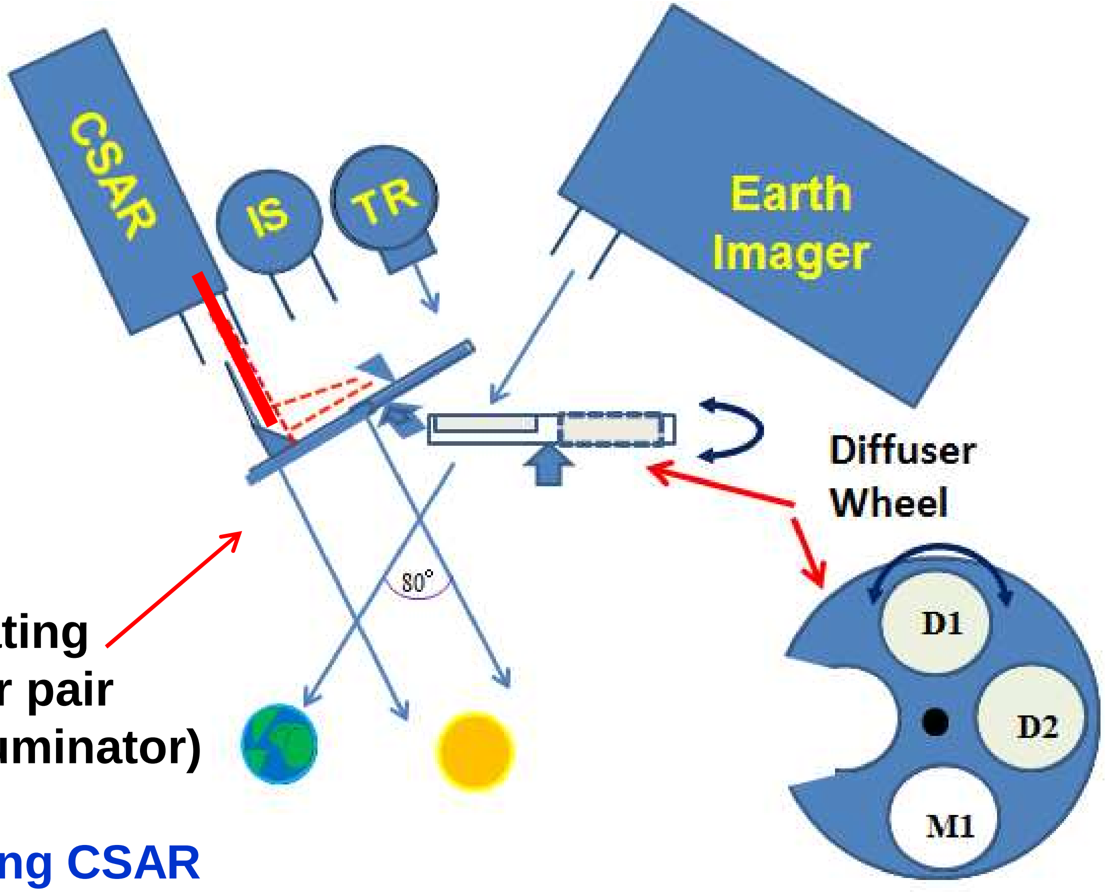


TRUTHS Layout simplified

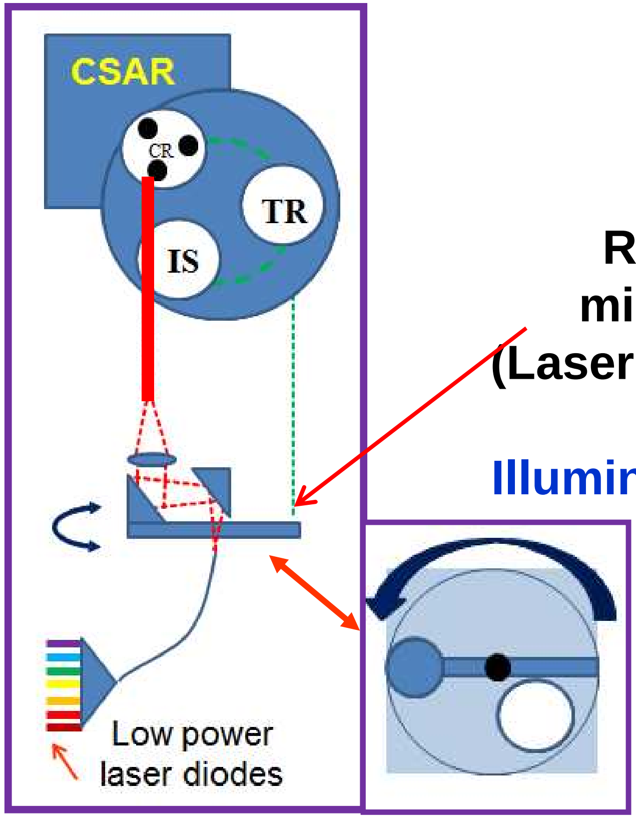


TRUTHS Calibration system: including on-board laser suite

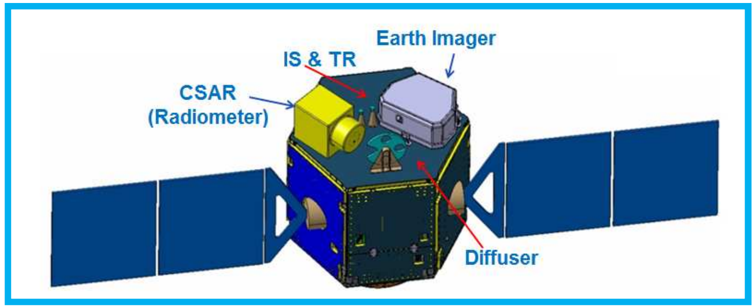
Step 1. Calibrate Laser beam power with CSAR



Rotating mirror pair (Laser illuminator)



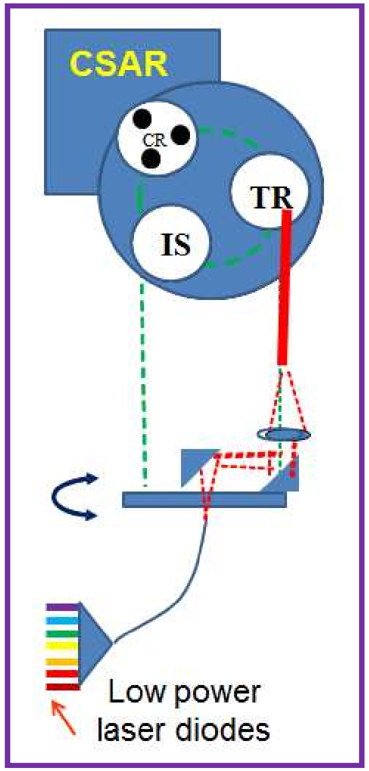
Illuminating CSAR



TRUTHS Calibration system:

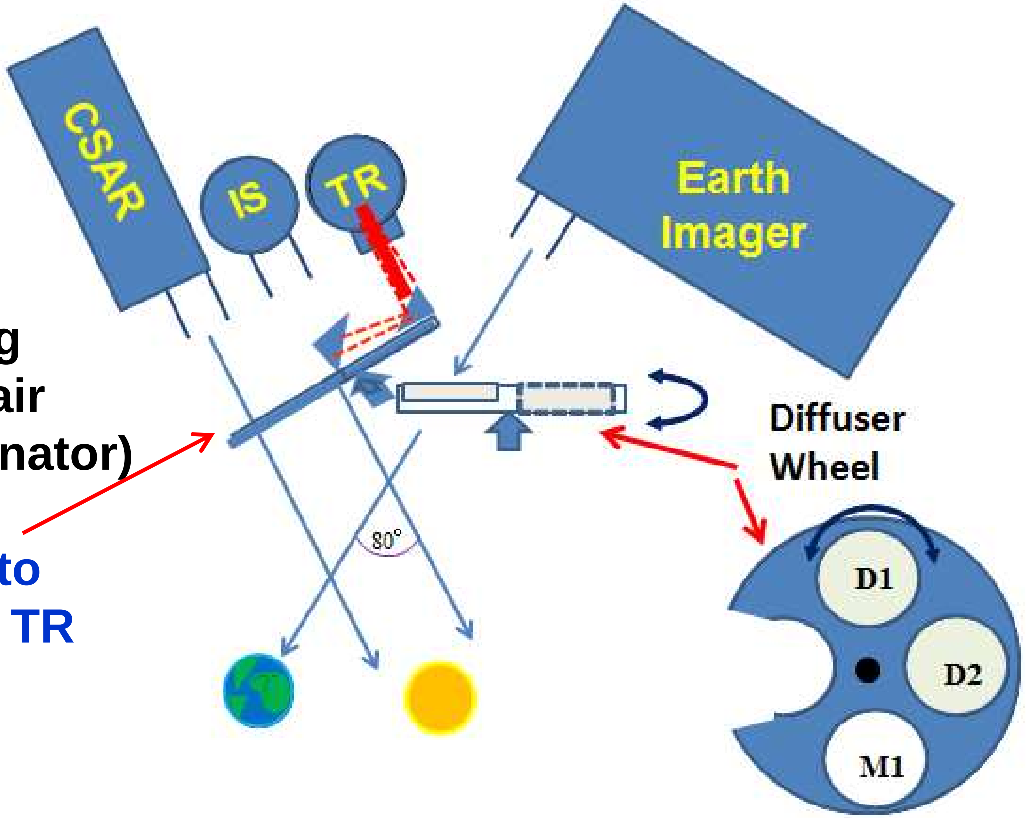
Step 2. Calibrate Transfer Radiometer (TR) using laser beam (power measured by CSAR)

(underfills entrance apertures (define FOV for radiance) of TR)



Rotating mirror pair (Laser illuminator)

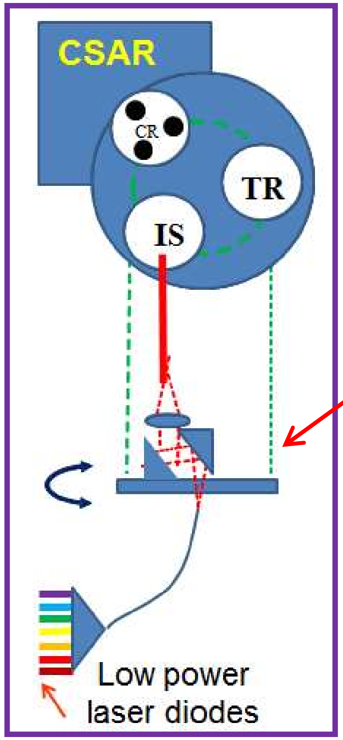
Rotates to illuminate TR



TRUTHS Calibration system:

Step 3. Laser illuminates full aperture of imager via IS and diffuser.

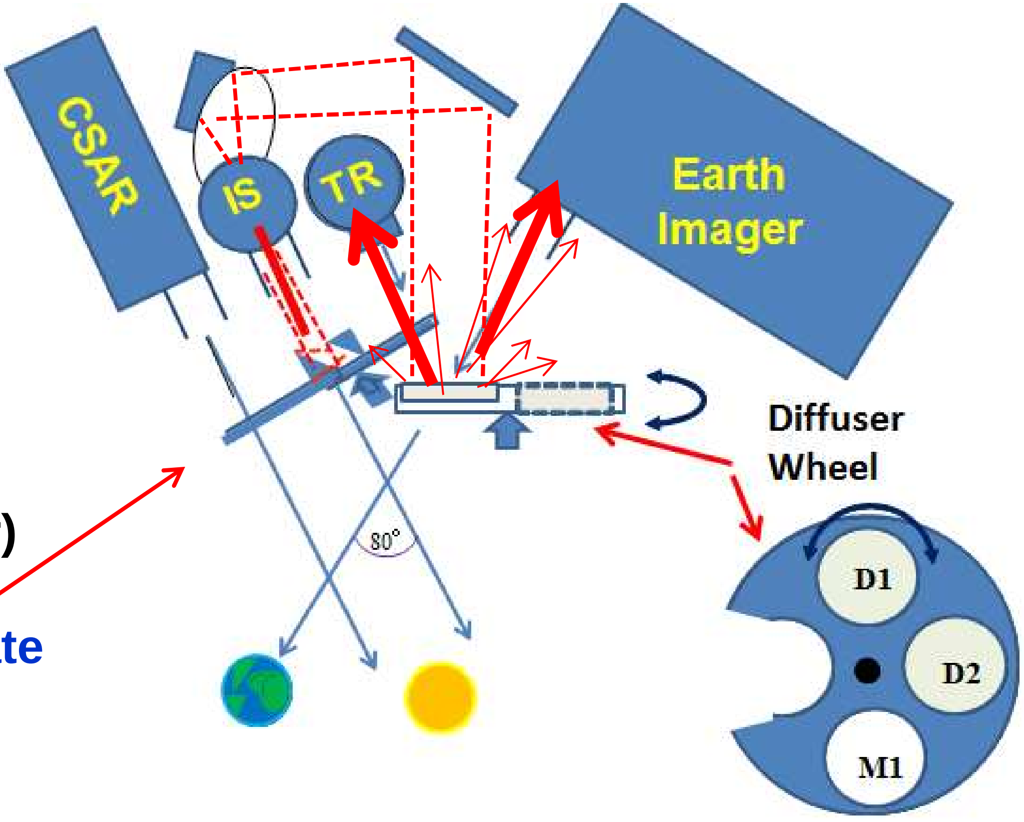
Absolute Radiance level from Diffuser measured by now calibrated TR (overfilling FOV limiting apertures of TR)



Rotating mirror pair (Laser illuminator)

Rotates to illuminate IS & thus diffuser

Scattered 'lambertian' radiation then viewed by Imager and TR at same angle

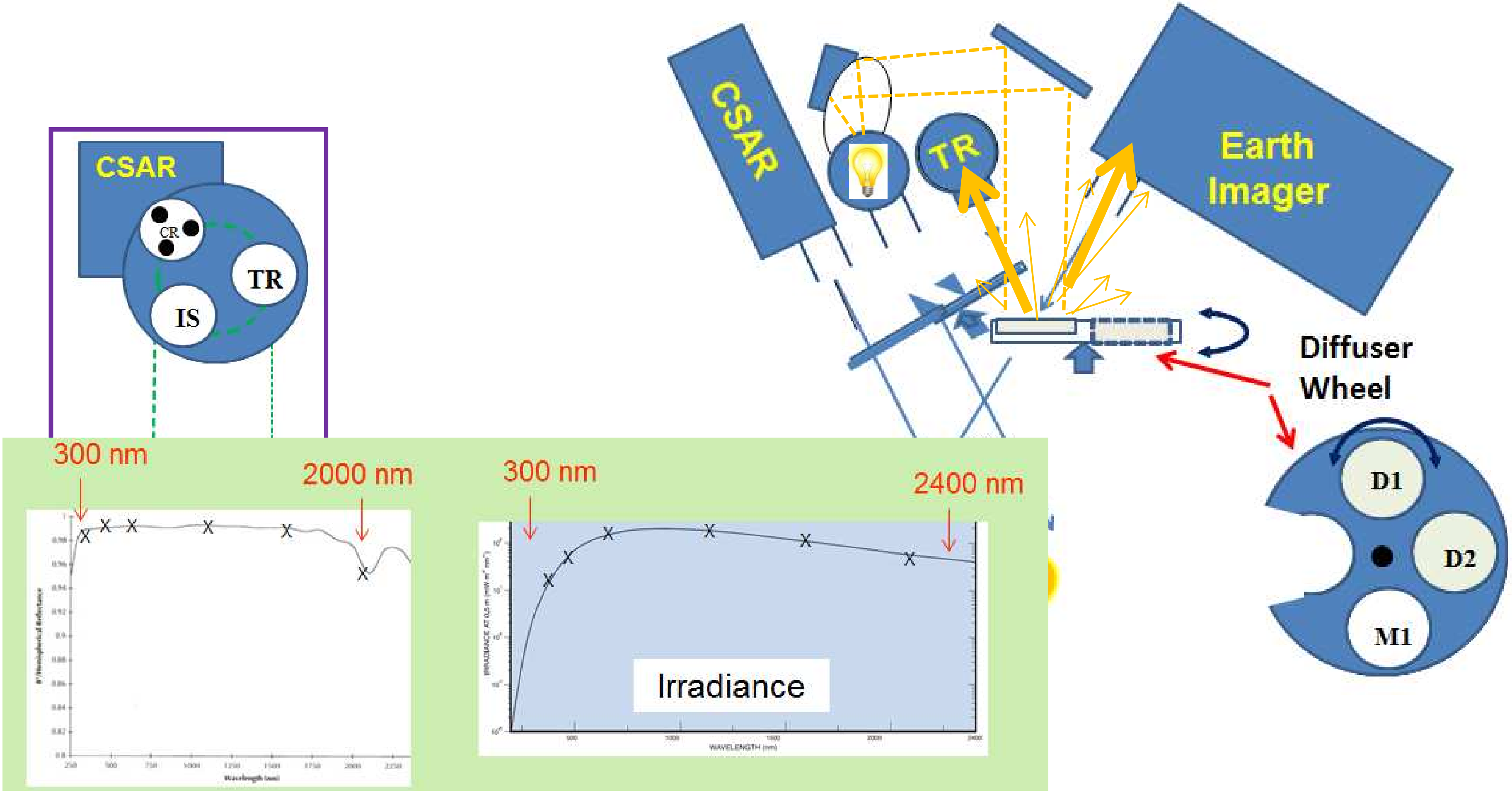


Note two diffusers for redundancy & reduced exposure/degradation. Mirror for higher illumination levels

TRUTHS Calibration system:

Step 4. Laser Off Lamp (white light) illuminates IS and full aperture of imager via IS and diffuser.

Only Relative spectral shape is needed
Absolute level and small spectrally smooth degradation changes anchored by laser measurements

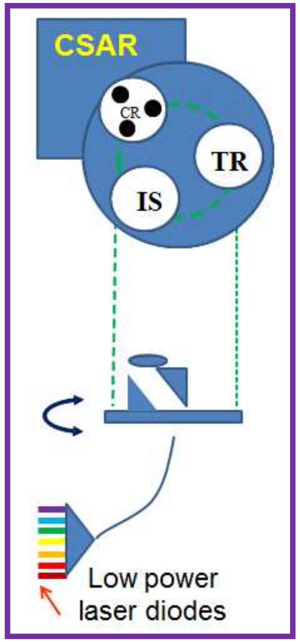


TRUTHS Observations:

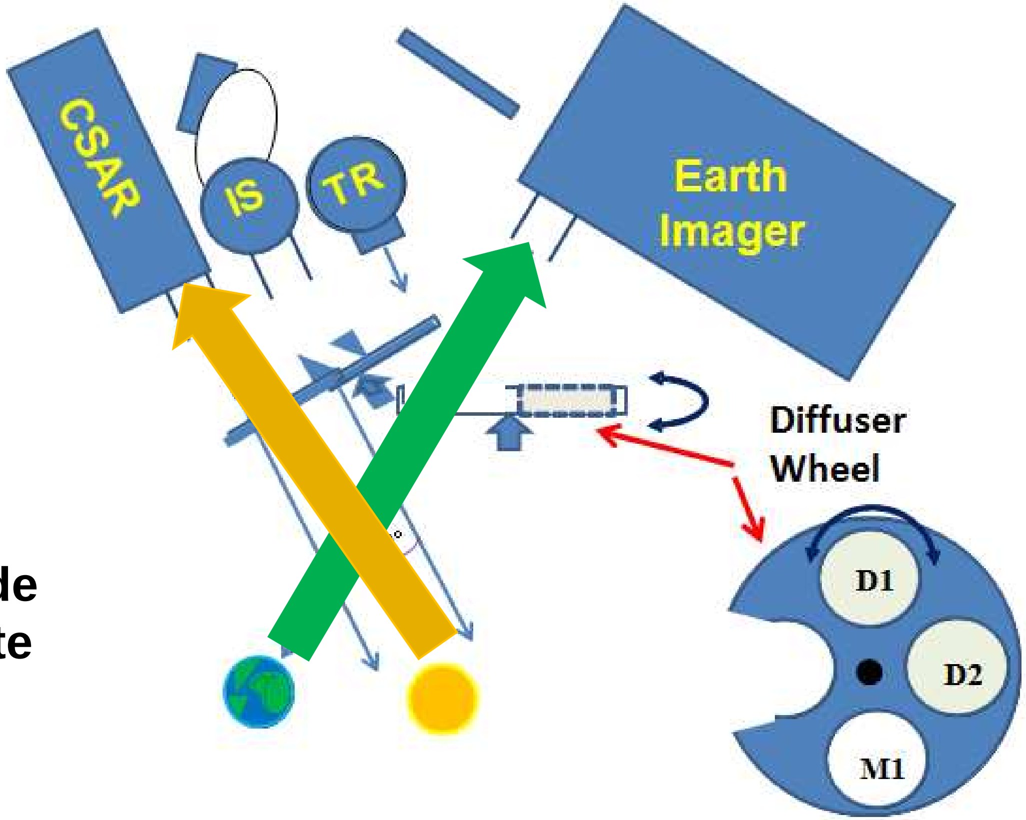
Step 5 Diffuser wheel rotates to allow imager to view the Earth

Absolute spectral radiance measurements now possible using calibrated Imager

CSAR also able to measure total solar irradiance by platform movement



TRUTHS in observation mode collecting climate data

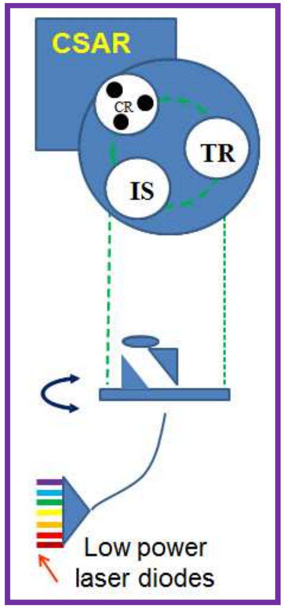


TRUTHS Measuring Solar spectral Irradiance:

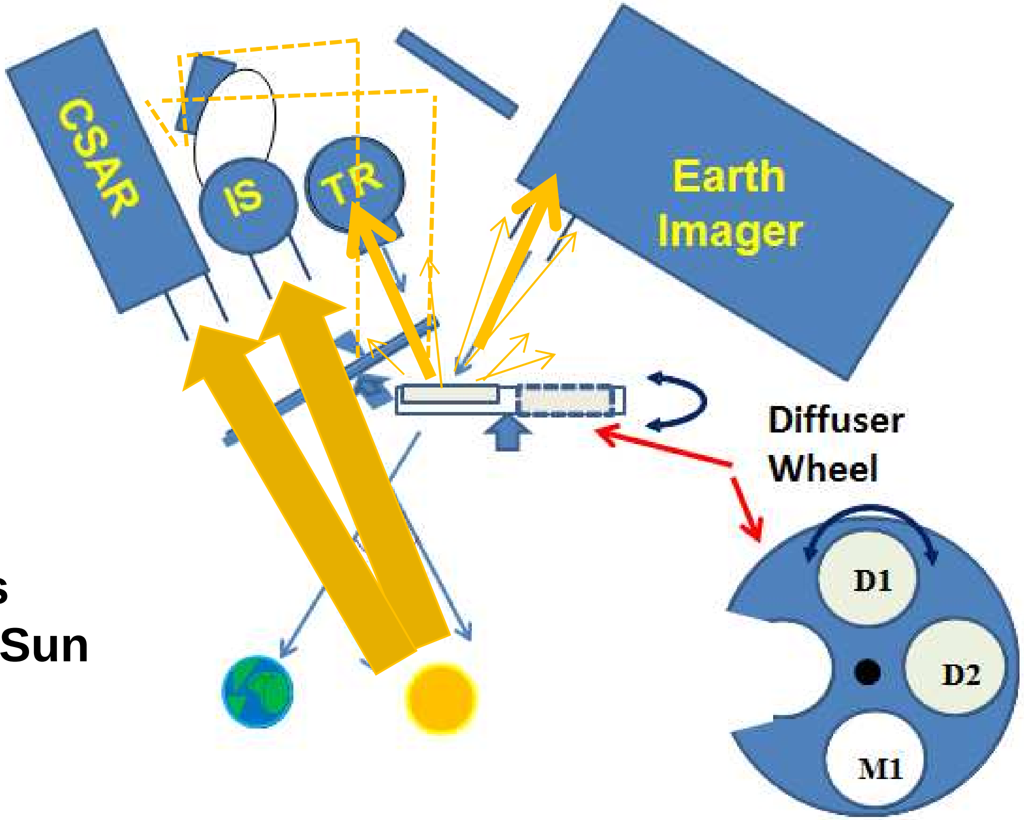
Step 6. Laser illumination (mirror) system rotated to allow Sun to illuminate entrance aperture (defined) of IS

Light path from IS same as for laser and lamp on to diffuser and Imager.

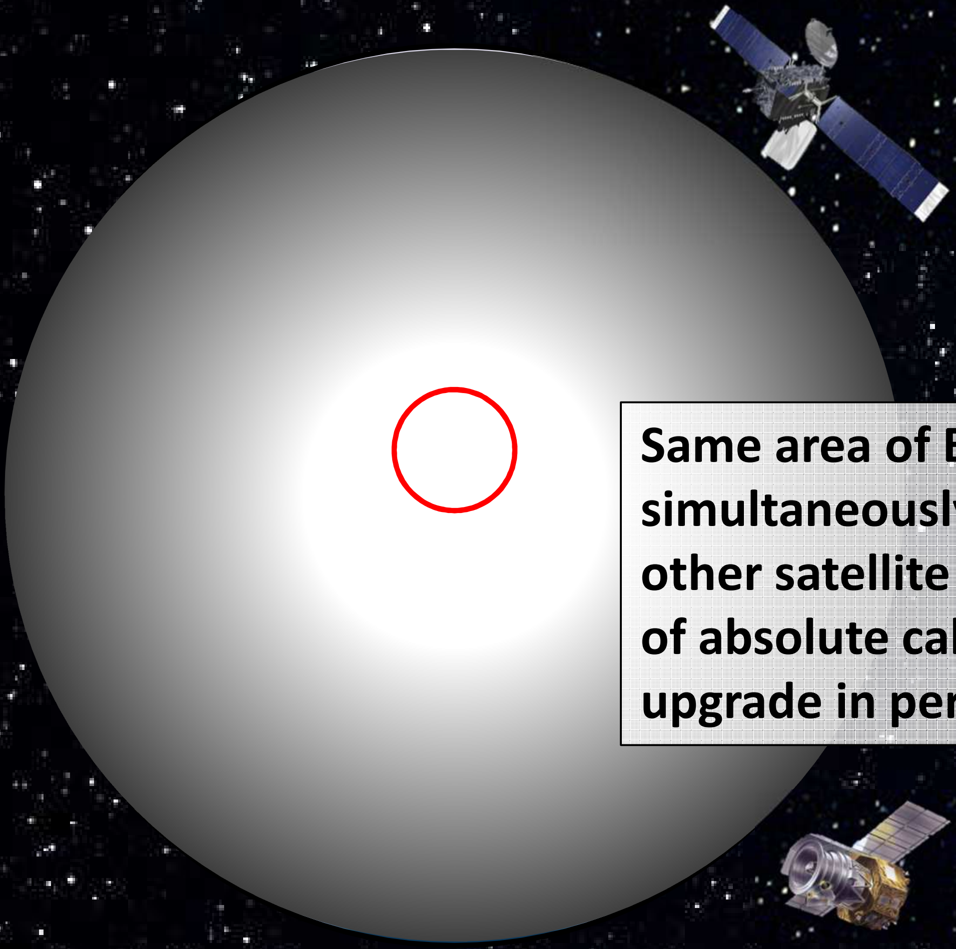
Imager, diffuser, IS light path calibrated by laser/lamp allowing Solar spectral irradiance to be determined



For solar measurements satellite points to Sun

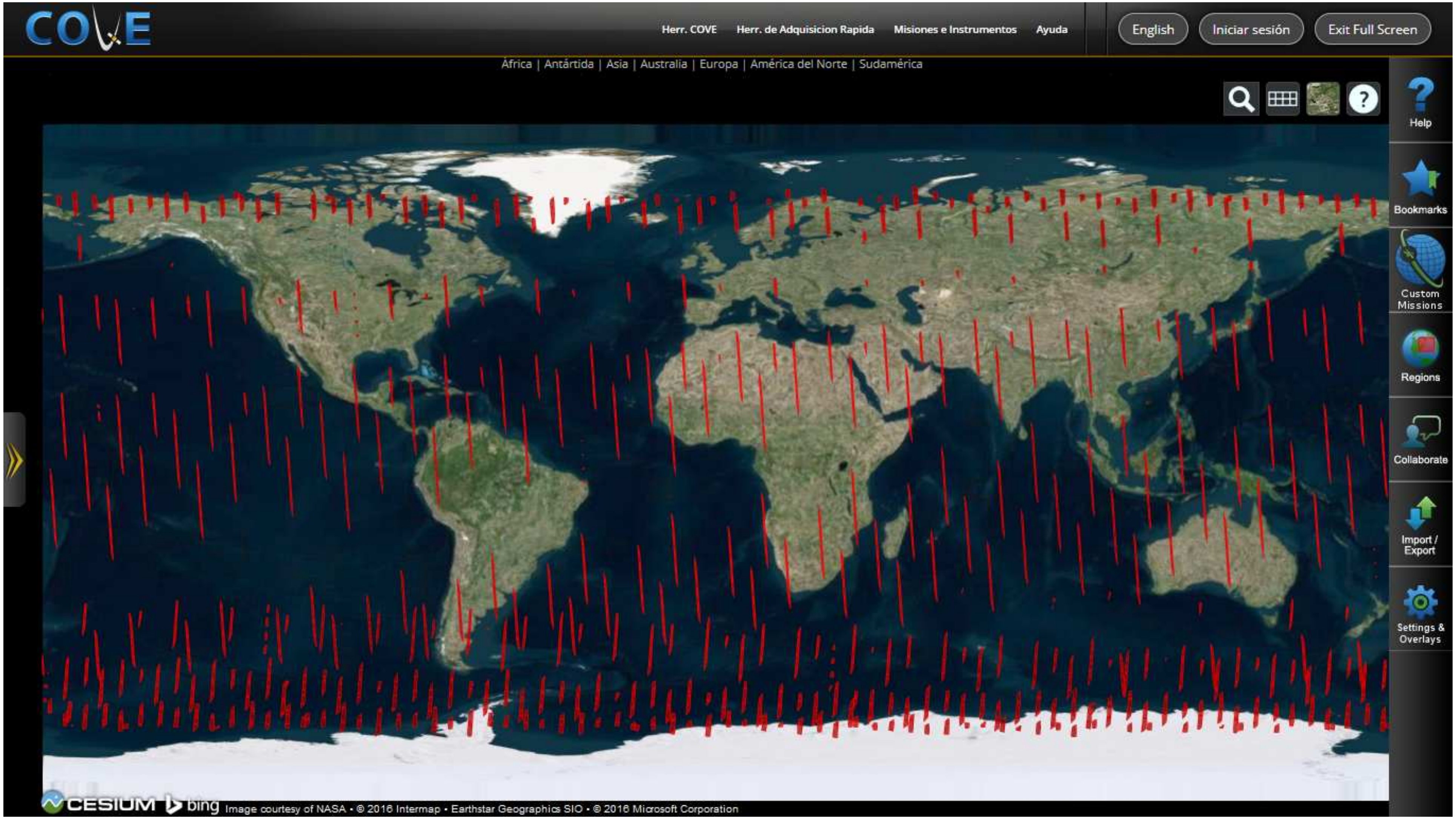


Upgrading Earth observing system for climate

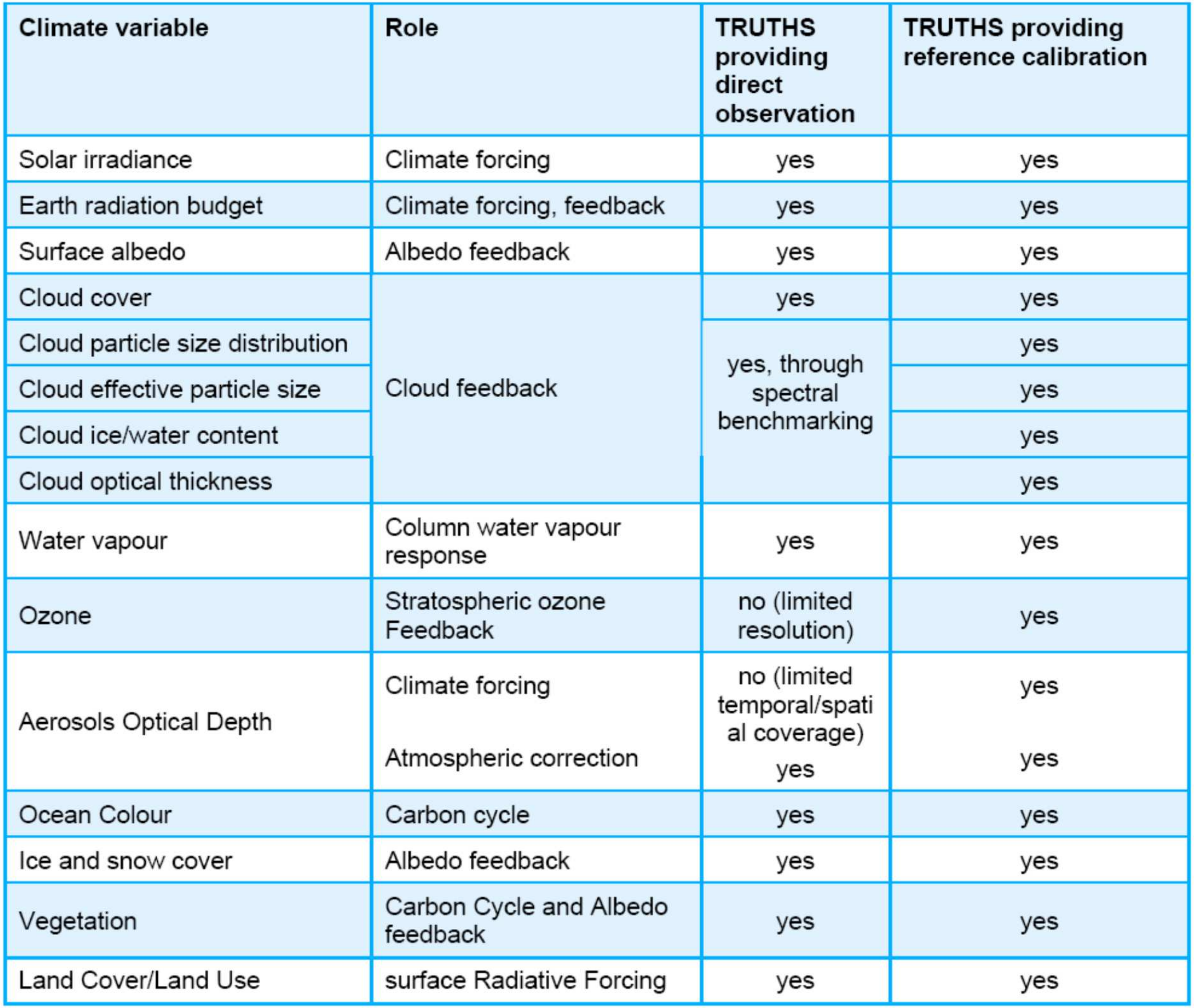


Same area of Earth viewed simultaneously by TRUTHS and other satellite enables transfer of absolute calibration and upgrade in performance

SNO (30 minute window) with Sentinel 2 in 1 yr



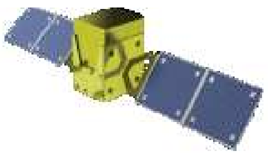
Needs of ECV's



Climate variable	Role	TRUTHS providing direct observation	TRUTHS providing reference calibration
Solar irradiance	Climate forcing	yes	yes
Earth radiation budget	Climate forcing, feedback	yes	yes
Surface albedo	Albedo feedback	yes	yes
Cloud cover	Cloud feedback	yes	yes
Cloud particle size distribution		yes, through spectral benchmarking	yes
Cloud effective particle size			yes
Cloud ice/water content			yes
Cloud optical thickness			yes
Water vapour	Column water vapour response	yes	yes
Ozone	Stratospheric ozone Feedback	no (limited resolution)	yes
Aerosols Optical Depth	Climate forcing Atmospheric correction	no (limited temporal/spatial coverage) yes	yes yes
Ocean Colour	Carbon cycle	yes	yes
Ice and snow cover	Albedo feedback	yes	yes
Vegetation	Carbon Cycle and Albedo feedback	yes	yes
Land Cover/Land Use	surface Radiative Forcing	yes	yes

Summary

TRUTHS



In

- International community have aceability, accuracy a ty as key drivers for Earth Observation: GEOSS / GMES and in pa climate studies
    - WMO/BIPM MoU
    - NMIs must work closely with community to develop “transportable/field-solutions”
    - Uncertainty demands (radiometry) most challenging of any sector
- All aspects/steps of producing EO data products needs validation and traceability (instrument calibration (pre- and post- launch) and algorithms/models) QA4EO (http:www.QA4EO.org) provides a focus
    - European Metrology Centre for Earth Observation and Climate (EMCEOC) (EMRP project) linked through NPL Centre for Carbon Measurement (CCM) will be a key facilitator to address this in conjunction with space agencies (CEOS)
- Traceability (benchmark measurements) from space seen as only plausible solution for studies of decadal climate and the data needed by policy makers to make informed decisions on mitigation and adaptation strategies
    - Need international “climate and calibration observatory (constellation) with in-flight traceability to SI (ideally at least two methods to allow comparisons) CLARREO (US) and TRUTHS (Europe)
- A “grand challenge project” demonstrating impact and criticality of metrology and the SI

In conclusion …

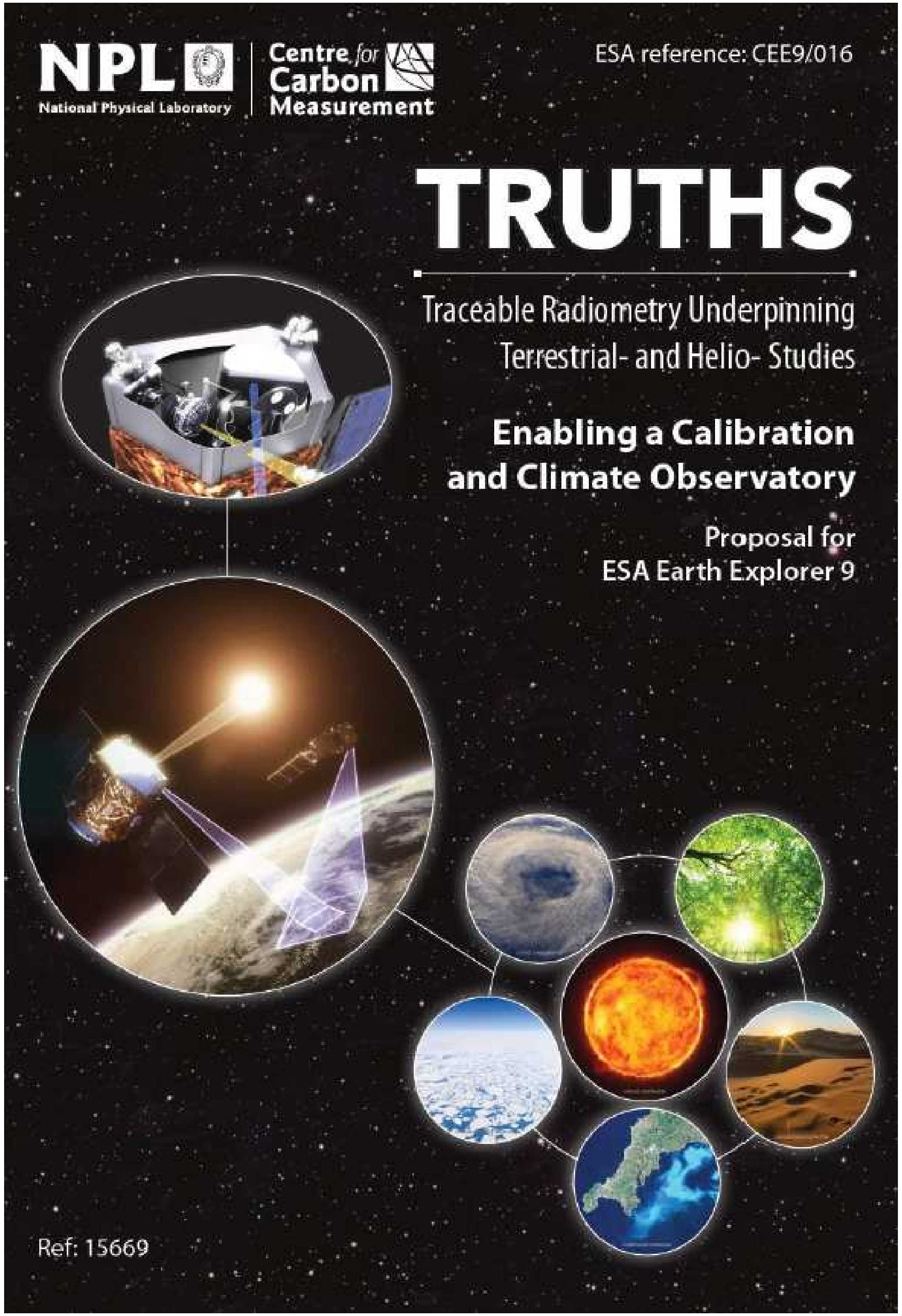
Observing the Earth Is relatively easy

Using EO Data for quantitative applications particularly long-term studies e.g. climate

Requires

SI Traceable, Validated measurement systems, including models, with “fit for purpose” quality indicators (uncertainties)

But it is hard!



NPL National Physical Laboratory | Centre for Carbon Measurement

ESA reference: CEE9/016

TRUTHS

Traceable Radiometry Underpinning Terrestrial- and Helio- Studies

Enabling a Calibration and Climate Observatory

Proposal for
ESA Earth Explorer 9

Ref: 15669

STATUS

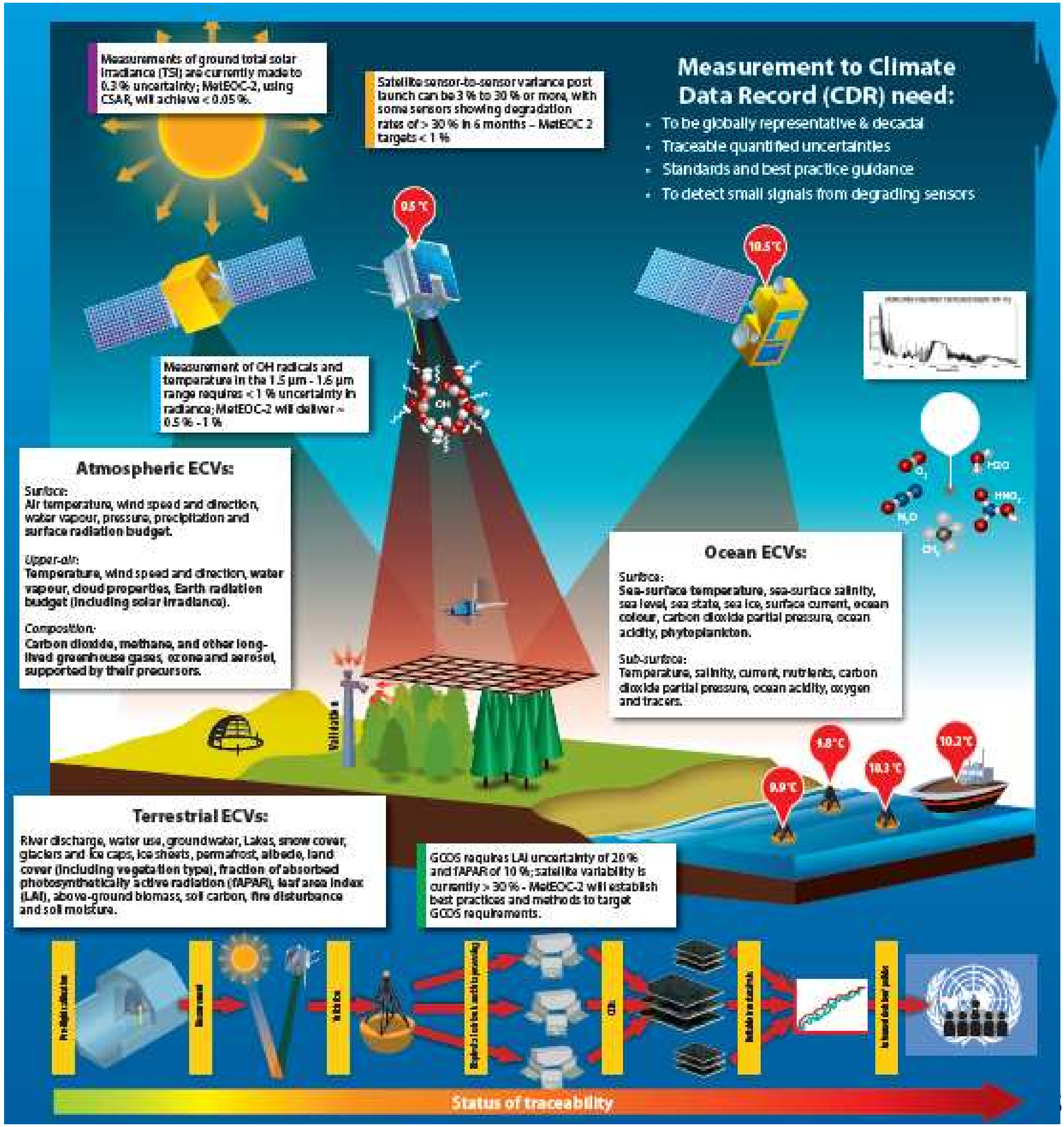
**Submitted to ESA
June 24 2016**

Decision Dec 2016

WEDNESDAY

Traceability for other ECVs

Bio-Geo Physical



Measurements of ground total solar irradiance (TSI) are currently made to 0.3 % uncertainty; MetEOC-2, using CSAR, will achieve < 0.05 %.

Satellite sensor-to-sensor variance post launch can be 3 % to 30 % or more, with some sensors showing degradation rates of > 30 % in 6 months – MetEOC 2 targets < 1 %

Measurement to Climate Data Record (CDR) need:

- To be globally representative & decadal
- Traceable quantified uncertainties
- Standards and best practice guidance
- To detect small signals from degrading sensors

Measurement of OH radicals and temperature in the 1.5 µm - 1.6 µm range requires < 1 % uncertainty in radiance; MetEOC-2 will deliver ~ 0.5 % - 1 %

Atmospheric ECVs:

Surface:
Air temperature, wind speed and direction, water vapour, pressure, precipitation and surface radiation budget.

Upper-air:
Temperature, wind speed and direction, water vapour, cloud properties, Earth radiation budget (including solar irradiance).

Composition:
Carbon dioxide, methane, and other long-lived greenhouse gases, ozone and aerosol, supported by their precursors.

Ocean ECVs:

Surface:
Sea-surface temperature, sea-surface salinity, sea level, sea state, sea ice, surface current, ocean colour, carbon dioxide partial pressure, ocean acidity, phytoplankton.

Sub-surface:
Temperature, salinity, current, nutrients, carbon dioxide partial pressure, ocean acidity, oxygen and tracers.

Terrestrial ECVs:

River discharge, water use, groundwater, Lakes, snow cover, glaciers and ice caps, ice sheets, permafrost, albedo, land cover (including vegetation type), fraction of absorbed photosynthetically active radiation (fAPAR), leaf area index (LAI), above-ground biomass, soil carbon, fire disturbance and soil moisture.

GCOS requires LAI uncertainty of 20 % and fAPAR of 10 %; satellite variability is currently > 30 % - MetEOC-2 will establish best practices and methods to target GCOS requirements.