Earth Observation, Climate and Optical Measurements @ NPL

Joanne **Nightingale**, Kim **Calders**, Niall **Origo**, Tracy **Scanlon**, Ally **Barker**, Andrew **Banks**, Paul **Green**, Emma **Woolliams**, Claire **Greenwell**, Nigel **Fox**

Metrology for Earth Observation and Climate

Outline

Supporting climate research and a low carbon future

1. **What is the NPL & What do we do there?**
   a) **Basic concepts of measurement**
   b) **Earth Observation, Climate & Optical group**

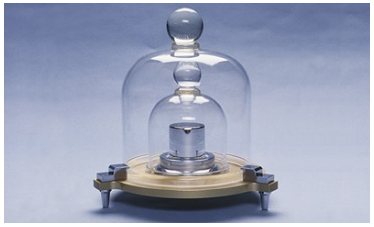
2. **Traceability & Quality for EO derived products**
   a) **Copernicus and QA4ECV**

3. **Application to Vegetation - TREES**
   a) **Vegetation sensor calibration**
   b) **Field network deployment**
   c) **Validation of EO products**

NPL

National Physical Laboratory
SW London, UK

NPL: UK's National Standards Lab



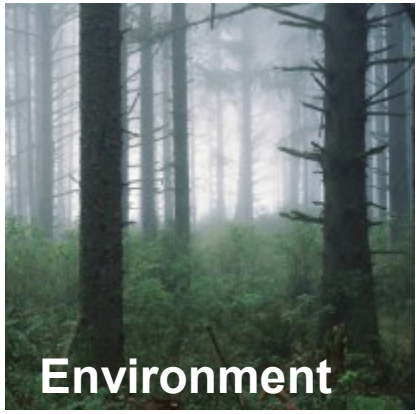
- Founded in **1900**
- World leading **National Measurement Institute**
- 450+ specialists in **Measurement Science**

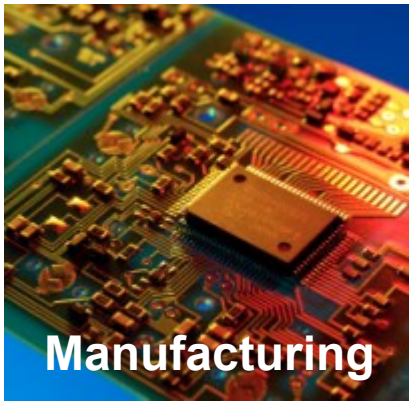
Magna Carta - 1215

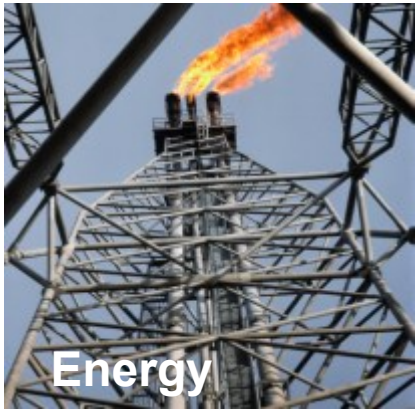
"There is to be one measure of wine and ale and corn within the realm, namely the London quarter, and one breadth of cloth, and it is to be the same with weights."

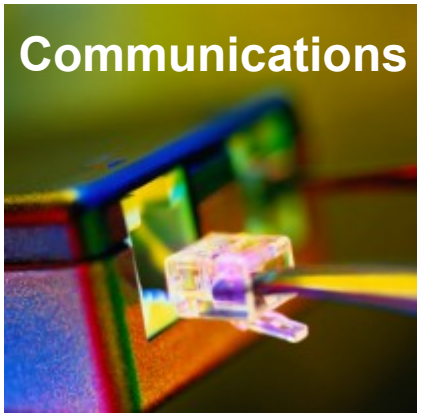
One of the oldest documents formalising measurement in the UK

Growing demand…





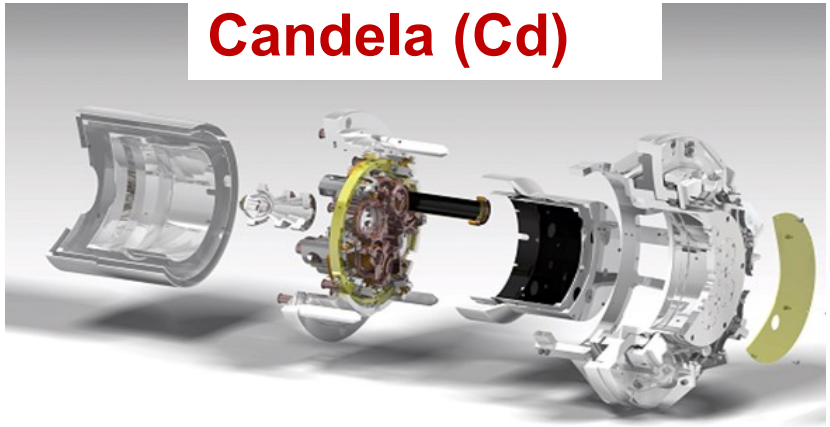




For *robust*, *consistent*, *traceable* measurements

Measurement Metrology

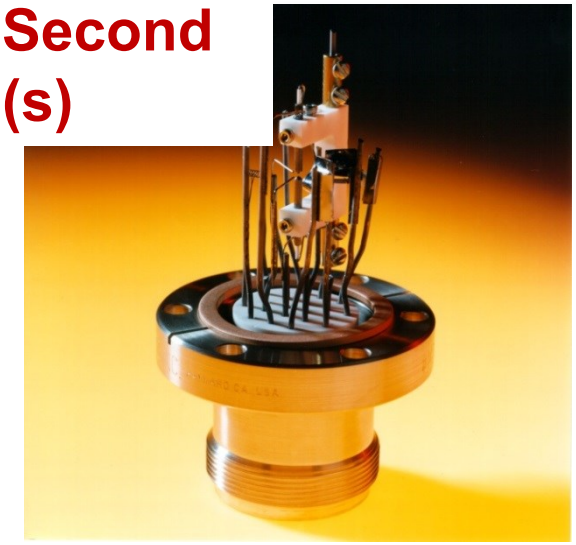
Candela (Cd)



Kelvin (K)

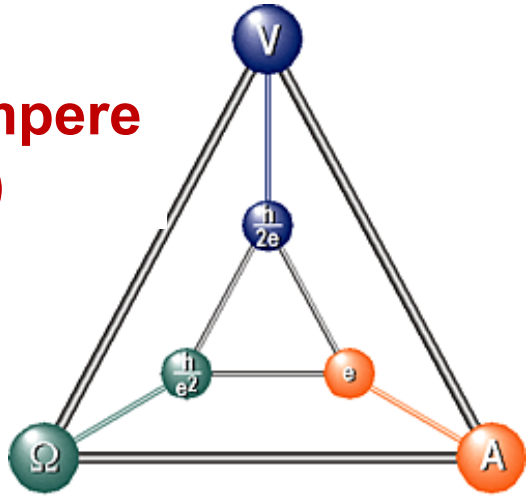
Kilogram (kg)

Second (s)

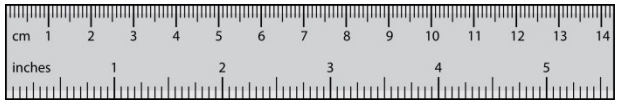


Hertz (Hz)

Ampere (A)

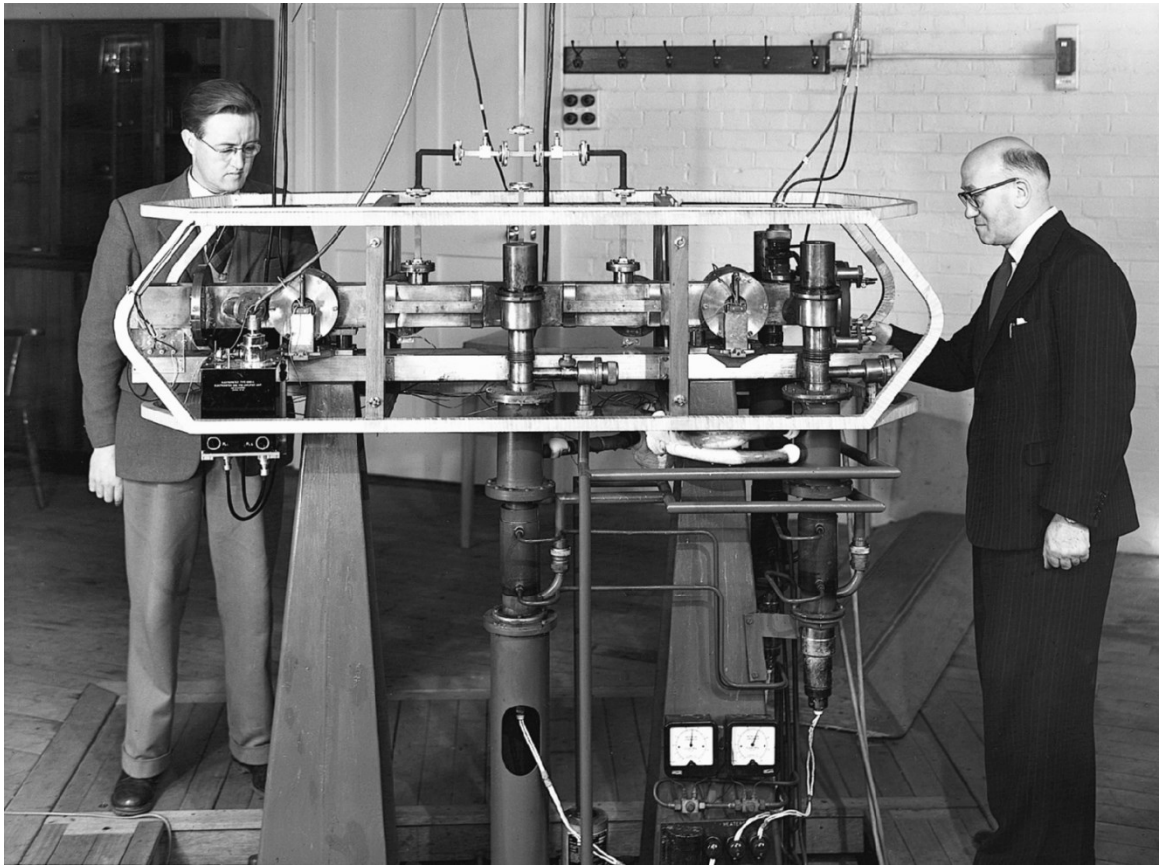


Metre (m)



$6.02214129(27)\times10^{23}$ Mole (mol)

Optical Atomic Clocks



World's first Caesium Atomic Clock 1955

NPL has been working with ESA and partners to develop optical atomic clock technology for future space missions with accuracies of one part in 10^{17}

Safe use of Healthcare Radiation

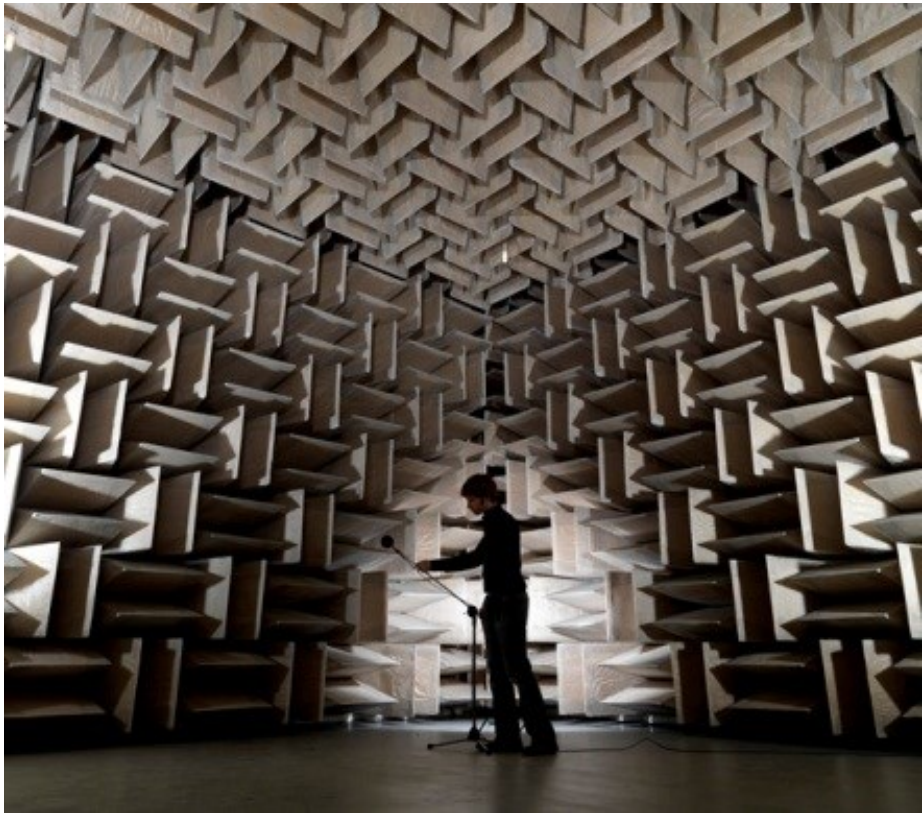
- The NHS use ionising radiation extensively for diagnosis and treatment
- NPL provides ionisation radiation standards and guidance to ensure safety and effectiveness of treatment
- These standards minimise the risk to the thousands of people exposed to ionising radiation

Approximately 145 cancer patients survive each year in the UK as a result of NPL's impact on the accuracy of the radiation dose they receive

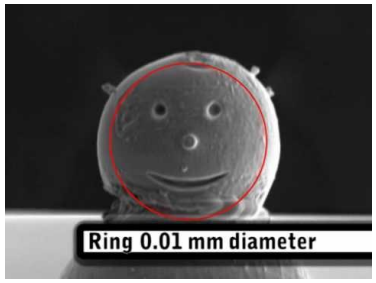
How loud does the cookie crumble?

- Customer satisfaction of many crispy/crunchy foods depends largely on its texture and the sounds emitted when eaten

- NPL's hemi-anechoic chamber was used to test a Texture Analyser instrument developed by a local company, that is used quantify the texture of food when it is snapped, cut, punctured or crushed



The World's smallest snowman



- 10 µm across, 1/5th the width of a human hair.
- Made from two tin beads used to calibrate electron microscope astigmatism.
- The eyes and smile were milled using a focused ion beam, and the nose, which is under 1 µm wide (or 0.001 mm), is ion beam deposited platinum.

Centre for Carbon Measurement

Supporting climate research & a low carbon future

CCM Technical Work-programme

- Energy efficiency:
- Fuel Cells & PV:
- Energy distribution:.
- Offshore renewables:
- Life Cycle analysis:
- Eco Design:

Accelerate development and assess performance of low-carbon technology

- Current trading:
- Emerging instruments
- Interoperability:
- Harmonised reporting:
- Long-term issues:

Support existing and emerging tax, trade and regulatory instruments for carbon pricing and reporting

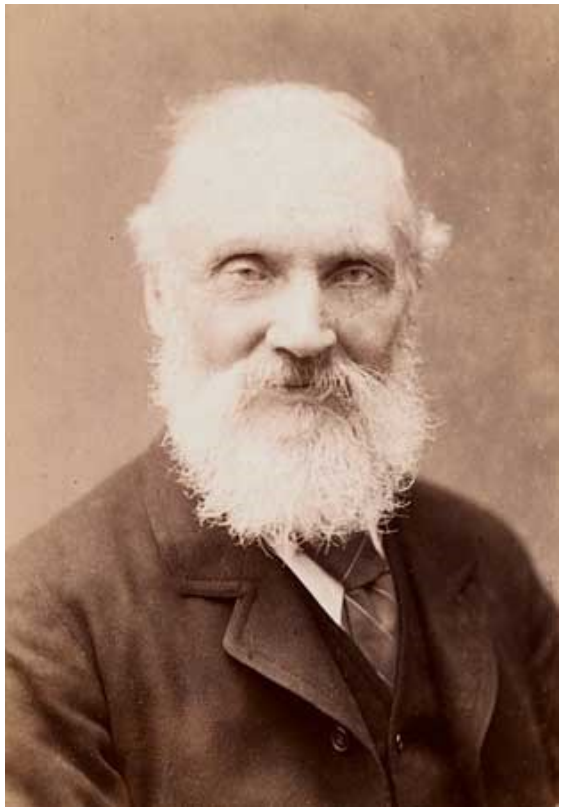
- Climate data:
- EO:
- Instrumentation:
- UK forum:

Provide confidence and reduce uncertainties in climate data used to monitor and to model climate change

NPL

Measurement Concepts

What is Measurement?



"I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it"

Lord Kelvin

Measurement
"process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity"

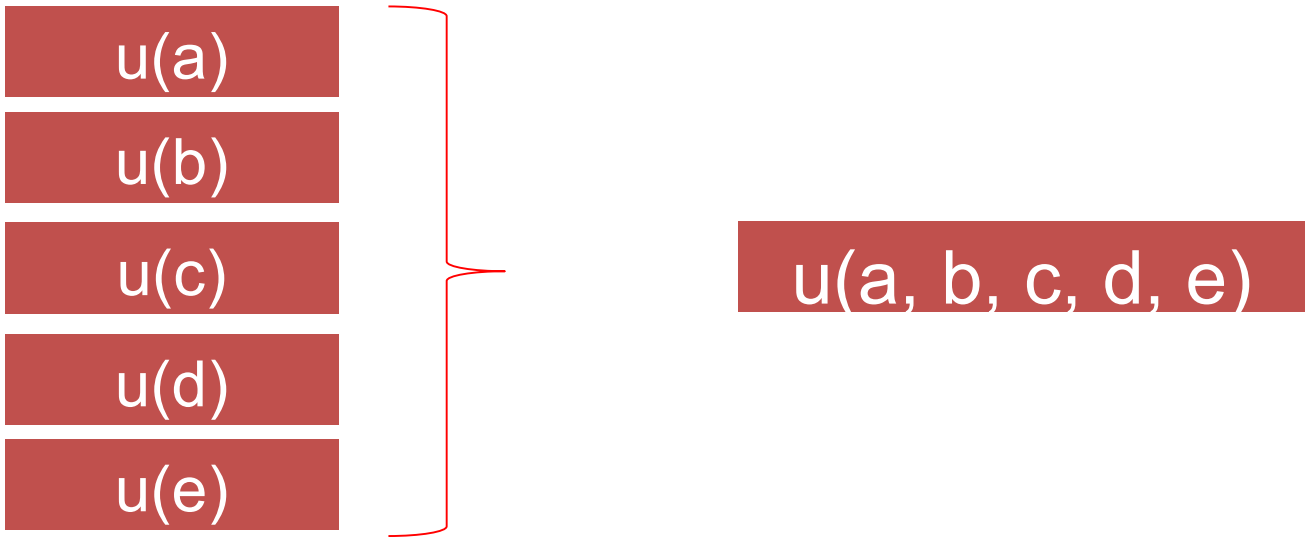
Uncertainty in Measurement

Doubt that exists about the result of any measurement

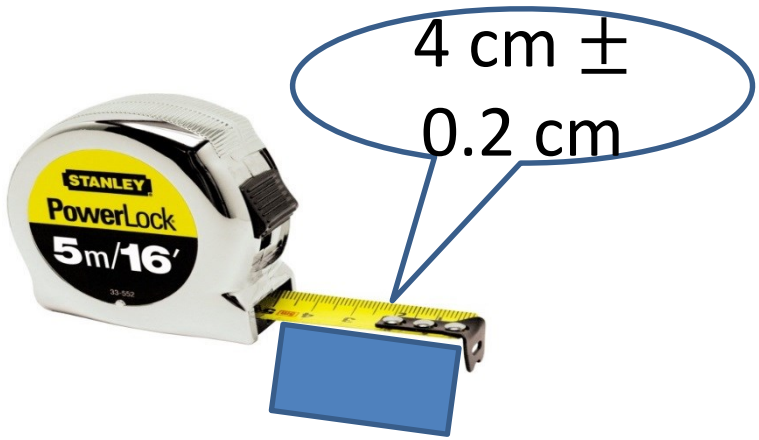
"Measure thrice, cut once"….

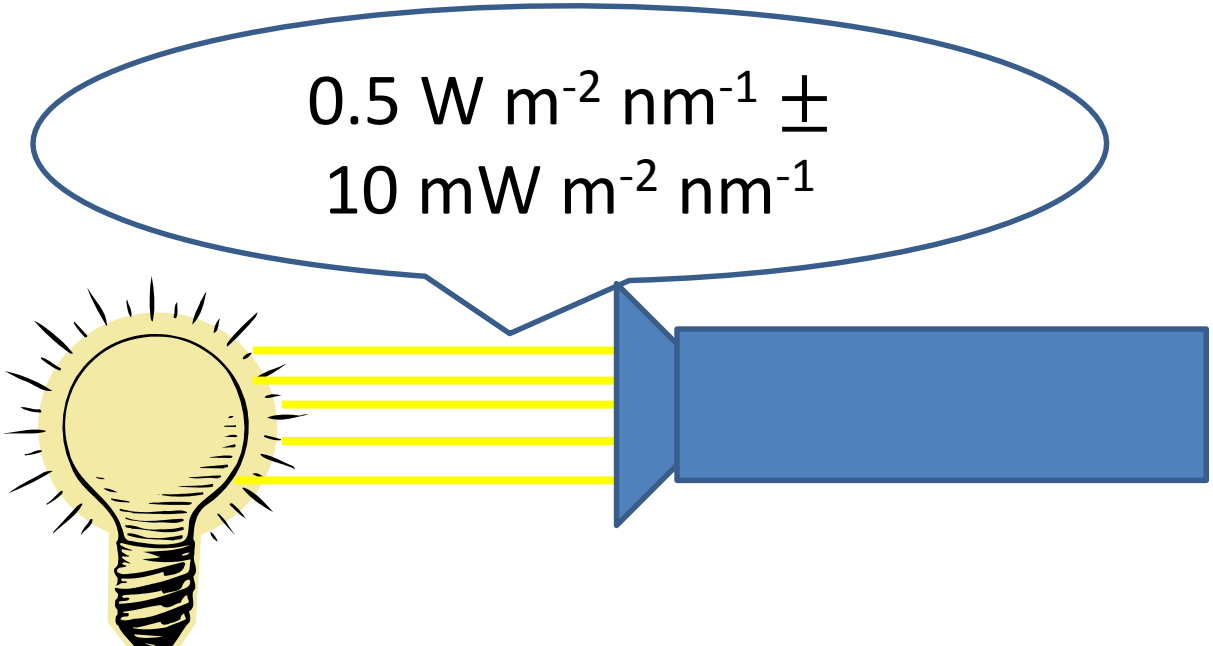
Uncertainty Analysis

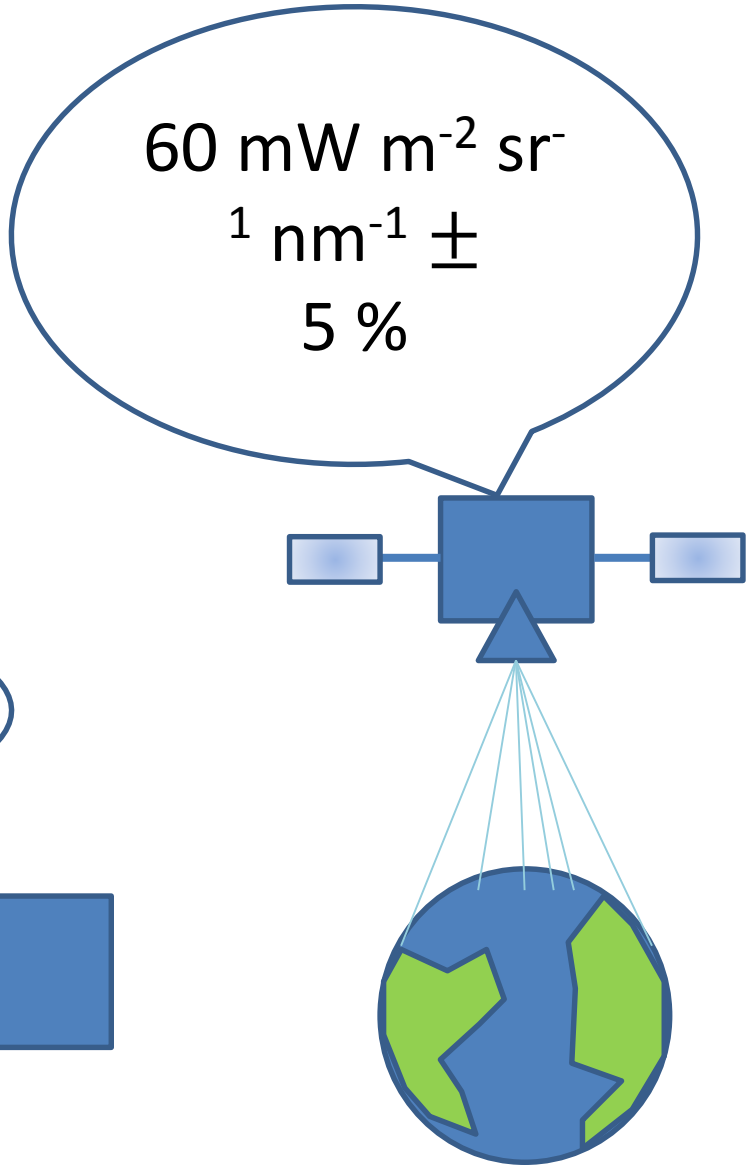
- Ascertaining the uncertainty associated with a measured value
- Consideration of all (within reason) factors / parameters contributing to the uncertainty
- Propagation of uncertainty associated with parameters to that associated with the final result



Expressing Uncertainty

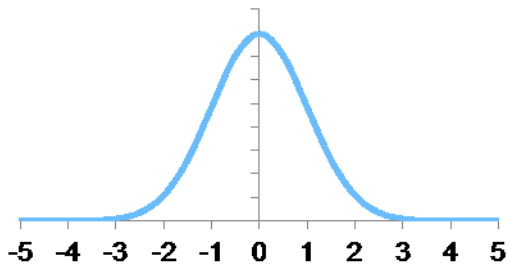






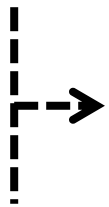
Uncertainty – Error - Correction

Uncertainty



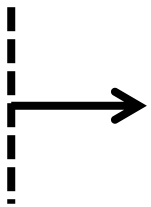
Describes the spread

Error



Difference to the true value

Correction



Known offset from true value

Drawn from a probability distribution described by uncertainty

Residual, uncorrectable, unknown error

Sources of errors & uncertainties

1. The measuring instrument
   - Sensor ageing, drift, noise
2. The item being measured
   - May not be stable
3. The measurement process
   - Measurement might be difficult to make
4. Imported uncertainties
   - Unknown instrument / sensor calibration

Traceability

1. Data provenance

2. Assessment to a known metrological reference (*not necessarily SI*) through an unbroken chain of calibrations of a measuring system or comparison

Traceability – why do we need it?

- By linking back to a primary standard we provide a reference for our measurements
- This reference is (ideally) non-changing e.g. based on a fundamental constant of nature (e.g. Boltzmann constant)
- Therefore our measurements will be reliable and reproducible in time (over decades)

Validation

Process of assessing, by independent means, the quality of the data products derived from the system outputs

(Justice, *et al*., 2000))

For EO data, governed by CEOS WGCV

www.ceos.org/

GUM – Guide to Uncertainty in Measurement


BIPM

JCGM 100:2008
GUM 1995 with minor corrections

Evaluation of measurement data — Guide to the expression of uncertainty in measurement

Évaluation des données de mesure — Guide pour l'expression de l'incertitude de mesure

ΜΕΤΡΩ ΧΡΩ

First edition September 2008

© JCGM 2008

- The foremost authority and guide to the expression and calculation of uncertainty in measurement science
- Written by the JCGM and BIPM

http://www.bipm.org/en/publications/guides/gum.html

NPL involved in development of the GUM for EO

NPL Training Course

Uncertainty for Earth Observation Training Course

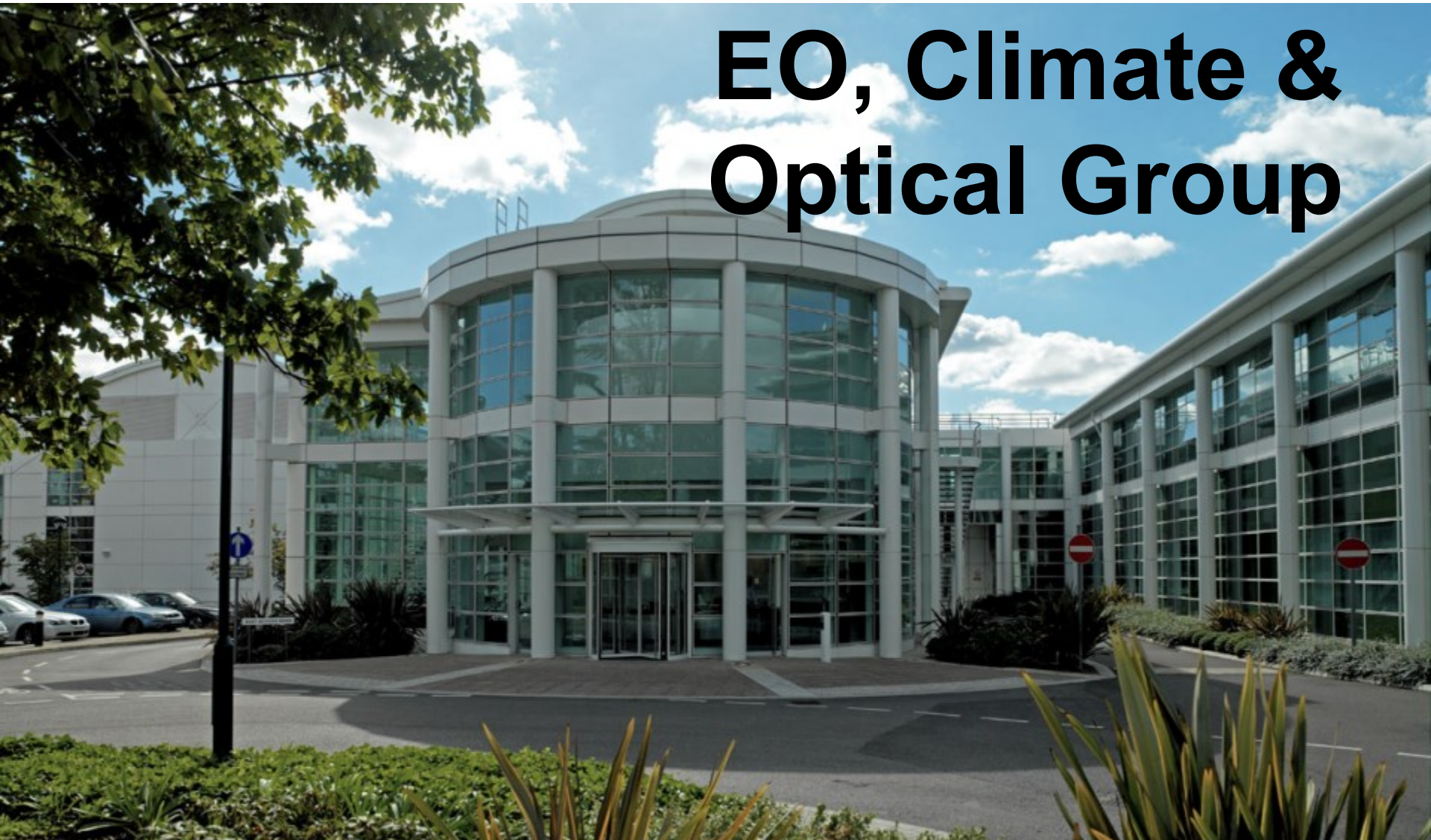
- Textbook, presentations and future course information can be found here:

http://www.meteoc.org/training.html

Metrology for Earth Observation and Climate

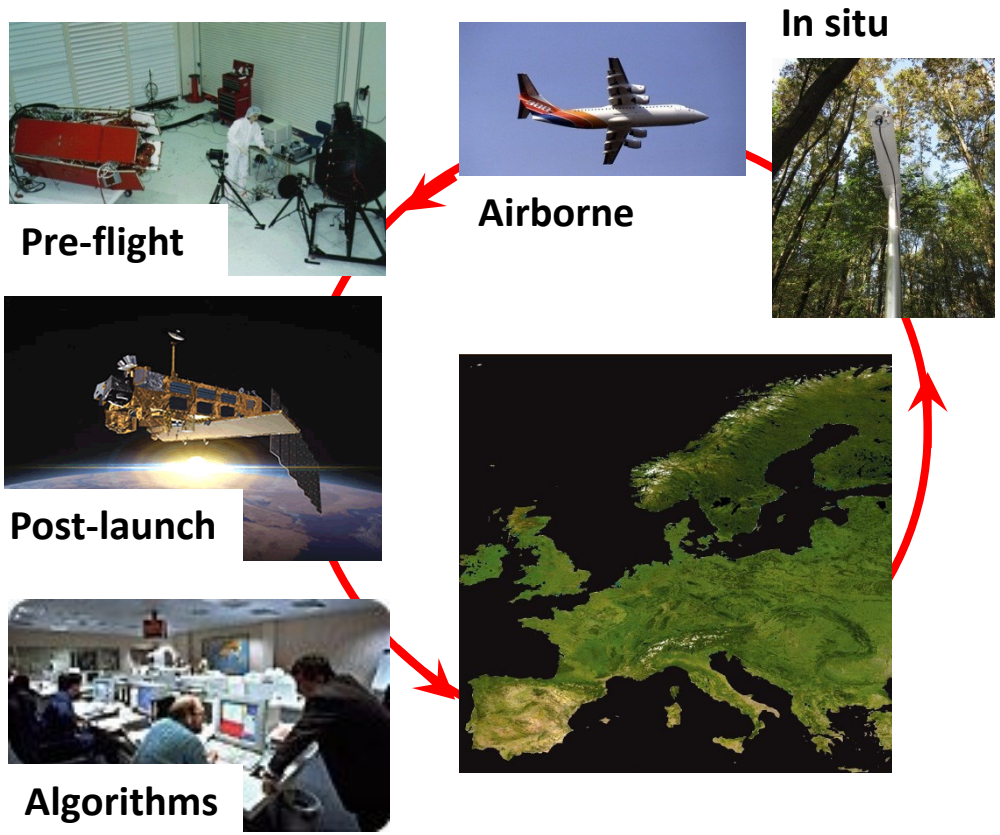
NPL

EO, Climate & Optical Group



ECO Group

- Establish a virtual European centre and operational service to provide **traceability** for all ESA/EU generated EO data products



- Transfer standards
- Comparisons
- Innovation on techniques
- Measurement protocols
- International linkages
- Independence

NPL National Physical Laboratory | Centre for Carbon Measurement

A QUALITY ASSURANCE FRAMEWORK FOR EARTH OBSERVATION

http://qa4eo.org/

GROUP ON EARTH OBSERVATIONS

- Quality Assurance for Earth Observation
- Support GEO in the delivery of comprehensive and timely "knowledge / information" to meet the needs of its Societal Benefit Areas

QA4EO Principle

Data and derived products shall have associated with them a fully traceable indicator of their quality

Quality Indicator

A Quality Indicator (QI) shall provide sufficient information to allow all users to readily evaluate the "fitness for purpose" of the data or derived product

Traceability

A QI shall be based on a documented and quantifiable assessment of evidence demonstrating the level of traceability to internationally agreed (where possible SI) reference standards

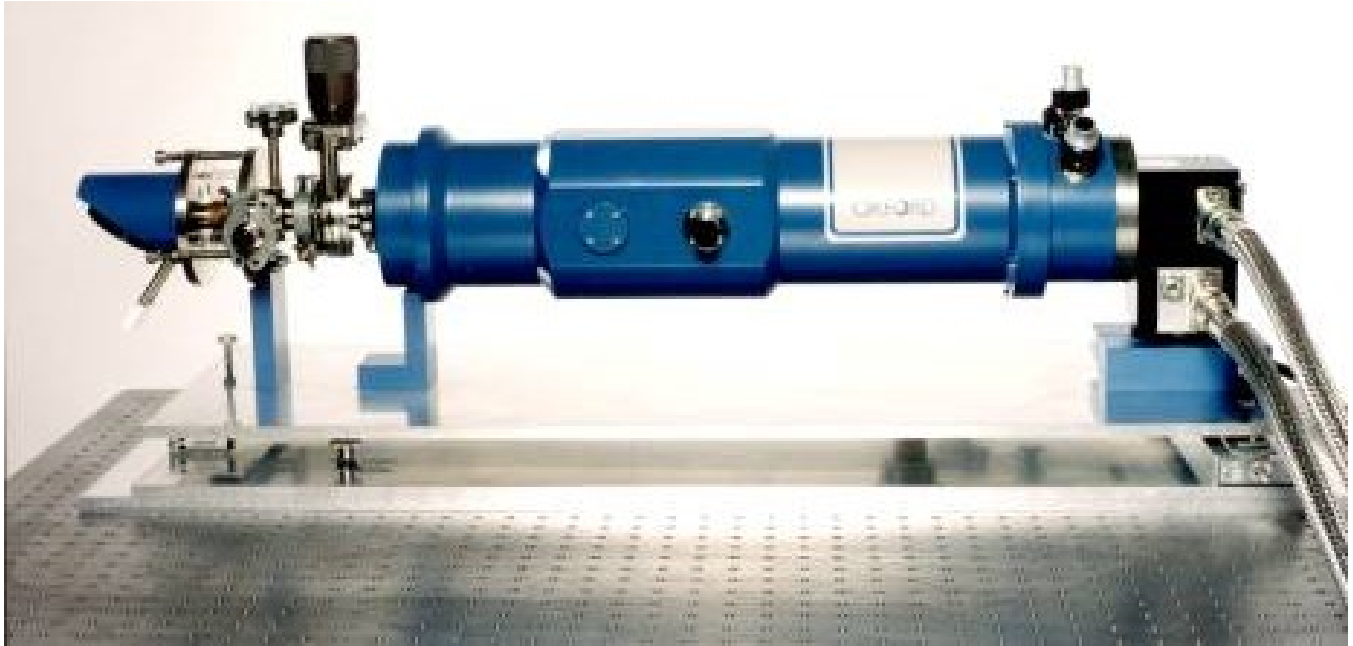
Understanding Data, Products & Differences

- Robust and independent Quality Assurance frameworks and procedures
  - Pre flight calibration
  - Post-launch calibration
  - Quality and traceability assessment
  - Validation

Pre-flight Calibration - Cryogenic Radiometry

- Primary standard for the measurement of optical radiant power
- Uses the electrical substitution technique, whereby the optical power incident on an absorbing cavity is compared with the electrical power required to heat the cavity to the same temperature.

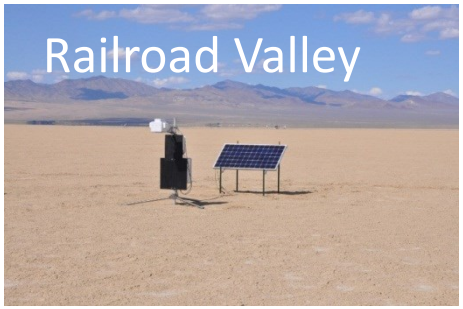
26 years of development at NPL



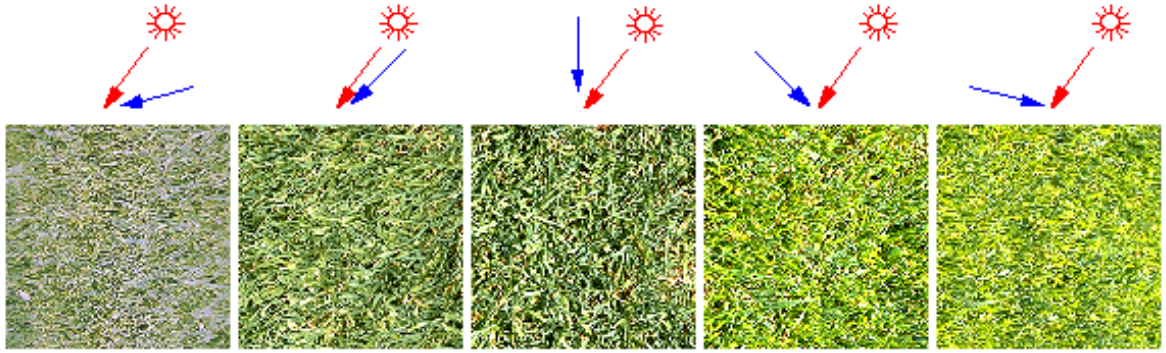
Vicarious Post-Launch Calibration

- RADCALNET
- Ensure radiometric integrity of space-borne instruments
- Spatially uniform, bright, large targets (pixels from 10's to 100's m)
- Flat, "No Atmosphere" i.e. low cloud levels, easily accessible with GSM coverage!

- Standardised procedures to aid characterisation
- Comparisons of field instruments & techniques to ensure consistency and traceability



Even easy test sites have challenges



+75° (backscatter) | +45° (backscatter) | 0° (nadir) | -45° (forward scatter) | -75° (forward scatter)

- Representative-ness over large areas in short time scales (i.e. sun angles, flooding, grass)
- Extremes of temperature
- Atmospheric effects
- Animals…

In-orbit Calibration – NPL in Space

TRUTHS: **T**raceable **R**adiometry **U**nderpinning Terrestrial- and **H**elio- **S**tudies

- A primary radiometric facility in space
- On board cryogenic radiometer for calibrating an Earth Imager
- Measures incoming (total and spectrally resolved) and reflected solar radiation (320 – 2350 nm @ ~5 nm bandwidth) 10 times more accurately than currently possible
- Provides means to upgrade performance of other EO sensors through in-flight cross-calibration.

NPL

QA4ECV, FOREST & Copernicus

EO Data Product Quality

- Independent Quality Assurance frameworks and procedures
- C3S (formerly GMES) will deliver data and products that must be:
  - relevant to the service users
  - fit-for-purpose
  - quality assured
  - fully traceable
  - adequately documented
  - provided in a timely and efficient manner
- NPL and partners working toward EO data QA for C3S

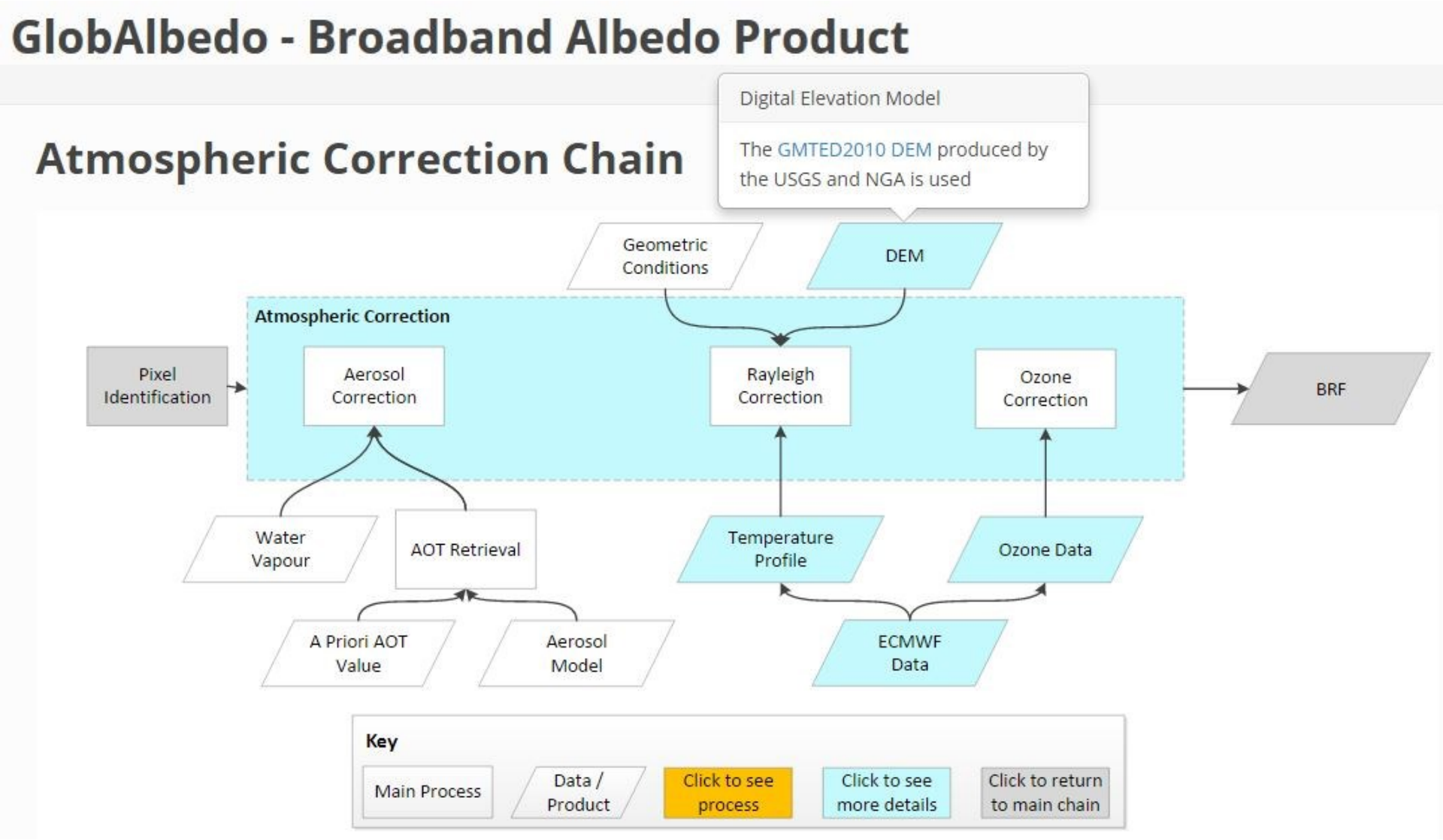
QA Service Specification

- Provide ECV data product **producers** / science teams with the necessary resources to develop “QA compliant” products

- Provide data **users** with robust QA information and a means to quantitatively assess confidence and uncertainty, *presented in a common way throughout the community*

- User and product developer engagement throughout

Traceability Diagrams



Traceability Chains

- Distil complex ATBDs and PUGs
- Provide uncertainty information at each processing step (along with what that means to the user!)
- Being developed for 3 land and 3 atmosphere products, plus several ESA CCI products

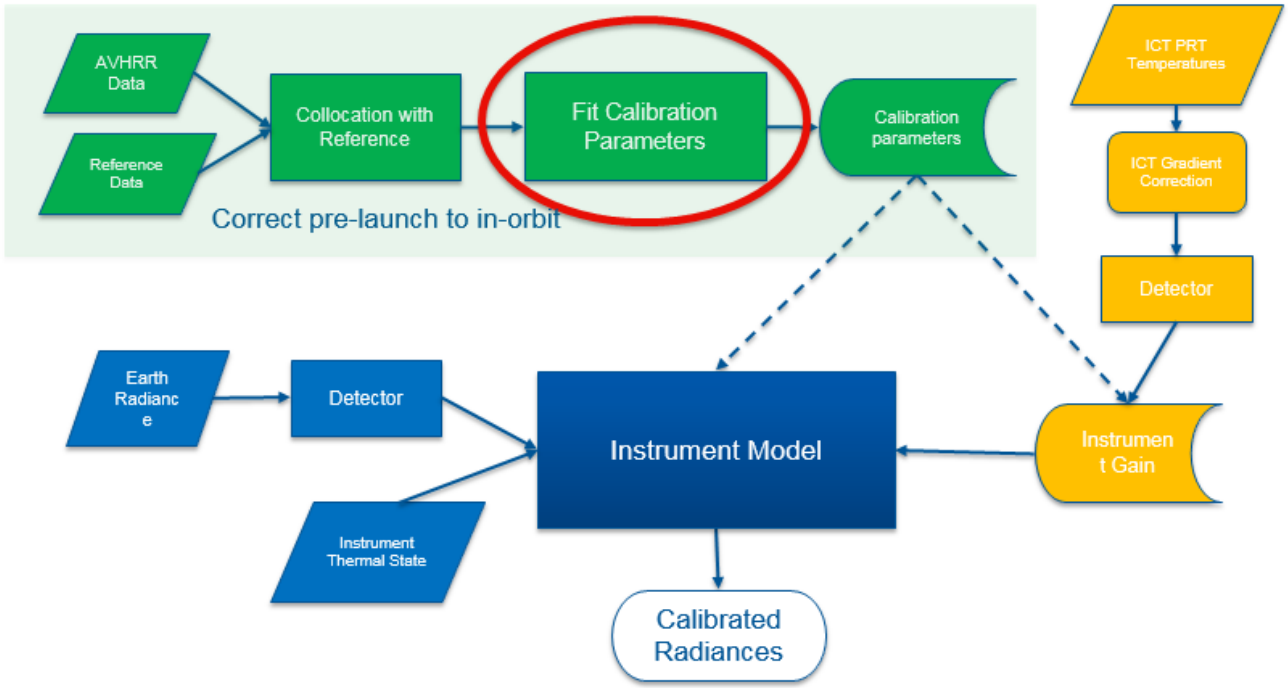
- Tool to draw and display being developed as part of QA4ECV project

www.qa4ecv.eu

FIDUCEO

Fidelity and Uncertainty in Climate data records from Earth Observation

Systematically reviewing the instrumentation, calibration and post-launch corrections for satellite sensors from 1980s to present day – providing uncertainties in radiance (level 1 product)



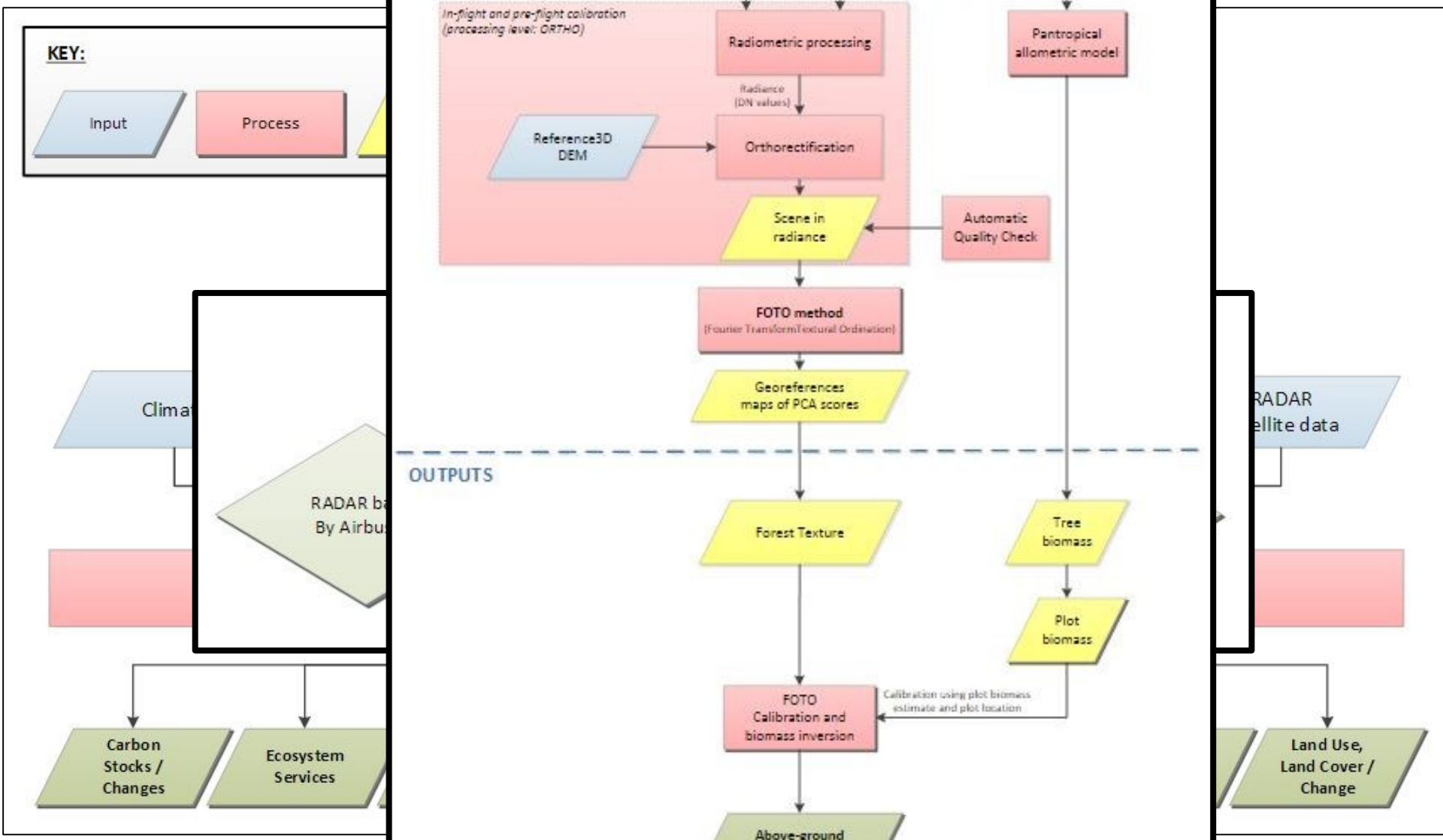
FOREST

Fully **O**ptimised and **R**eliable **E**mission**S** **T**ool

Respond to the growing demand of forest carbon stakeholders for trusted, fully integrated and cost effective MRV service components, enabling forest carbon projects and initiatives to achieve carbon goals.

http://projects.npl.co.uk/forest/FOREST.html

FOREST


KEY:
Input
Process
Clima
RADAR ba
By Airbus
RADAR
ellite data
Carbon Stocks / Changes
Ecosystem Services
Land Use, Land Cover / Change

INPUTS
SPOT 6 / NAOMI
Pleiades-1A / HiRI
Field data
(stem diameter at 1.3m along stem, tree height, species identification)
PROCESSING
Tree DBH, tree height, tree wood specific gravity
In-flight and pre-flight calibration (processing level: ORTHO)
Radiometric processing
Radiance (DN values)
Reference3D DEM
Orthorectification
Scene in radiance
Automatic Quality Check
Pantropical allometric model
FOTO method
(Fourier TransformTextural Ordination)
Georeferences maps of PCA scores
OUTPUTS
Forest Texture
Tree biomass
Plot biomass
FOTO Calibration and biomass inversion
Calibration using plot biomass estimate and plot location
Above-ground Biomass

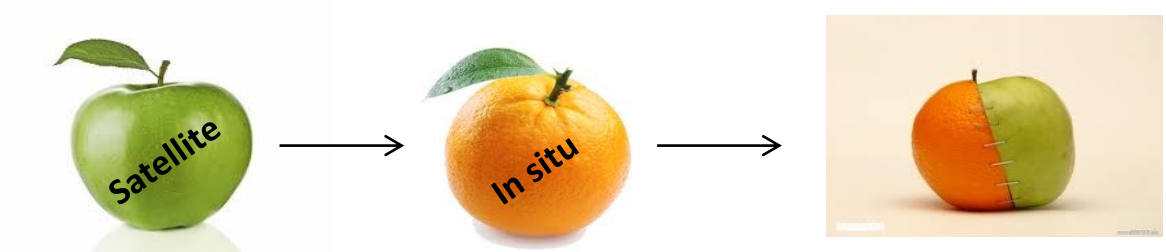
NPL

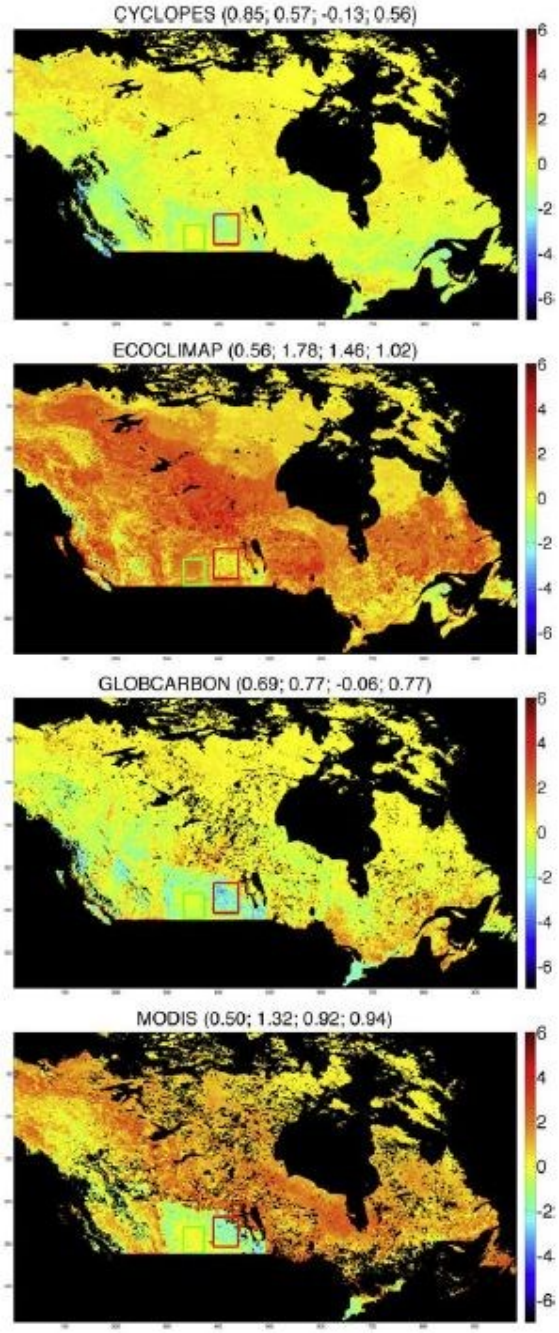
TREES – sensors, calibration, validation and field campaigns

Vegetation products

- Many sensors
- Similar products
- Different algorithms
- Limited validation data

- What is the “truth”?
- Most in situ methods do not measure the target quantity directly



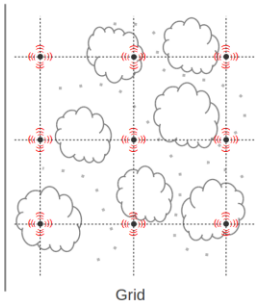


TREES: TRaceability in tErrestrial vEgetation Sensors and biophysical products

- Establishing ECV traceability through modelling, reference measurements and test-site characterisations

Instrument characterisation in lab and field conditions

Testing and evaluation of sampling schemes (Temporal, Spatial)



3D Radiative Transfer model
- Simulate a virtual validation site (algorithm quantification)
- Simulate real-world test site

Comparison of in situ with satellite data with full traceability and known uncertainties

ECVs of Interest

fAPAR

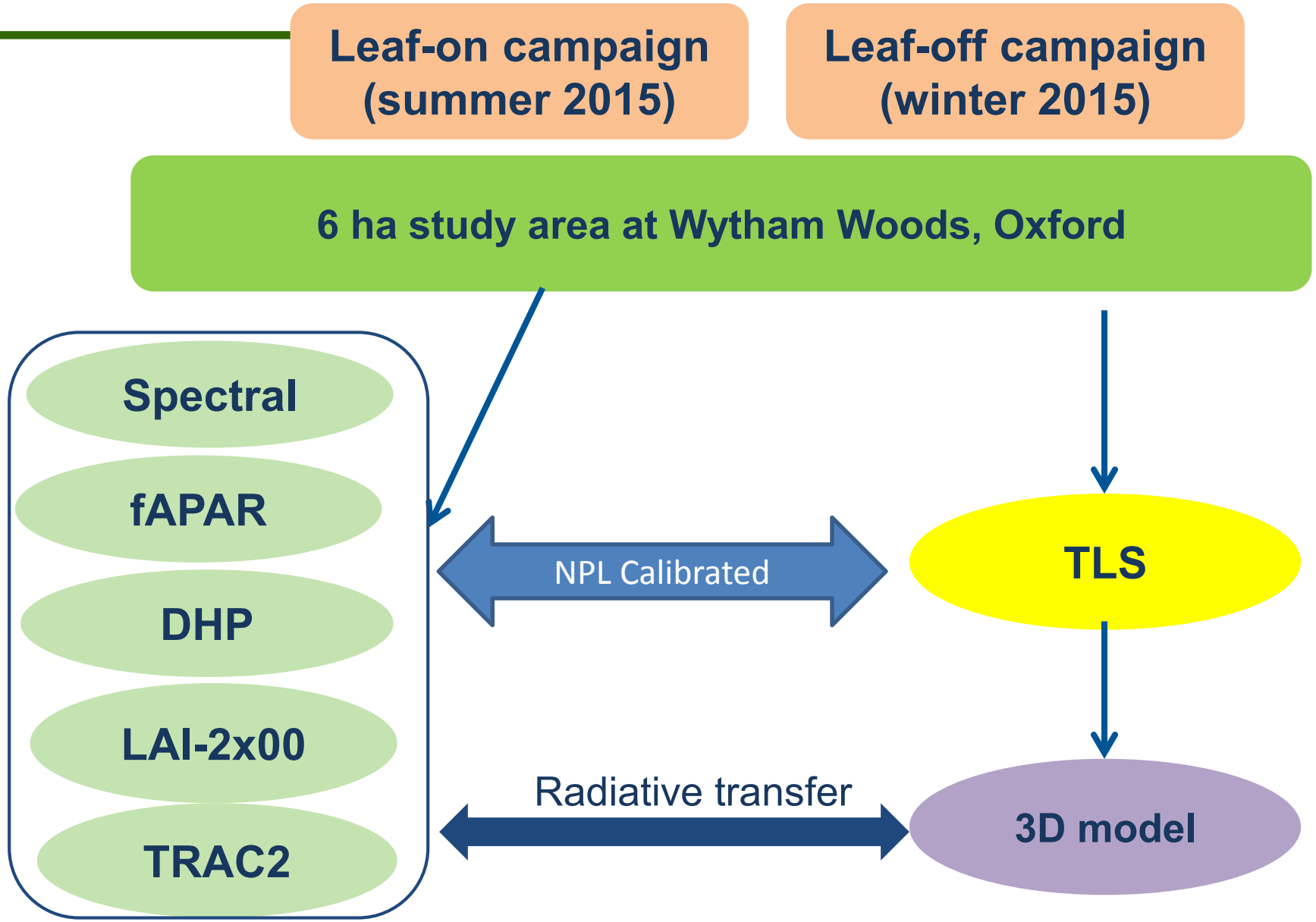
Fraction of PAR that a plant canopy absorbs for photosynthesis and growth in the 0.4 – 0.7nm spectral range

(Green, Brown, Instantaneous, Daily…???)

Leaf Area Index

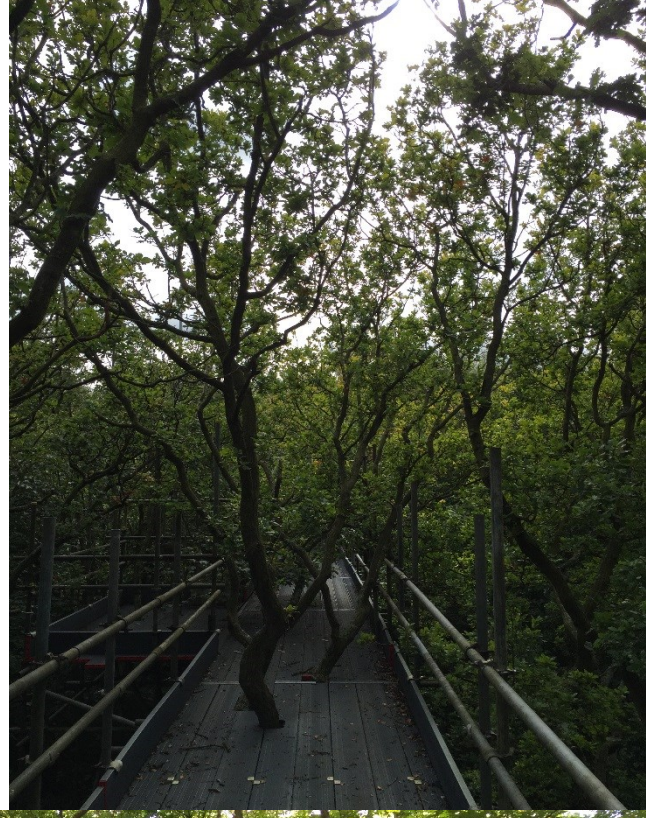
the biomass equivalent of FPAR, and is also a dimensionless ratio (m2/m2) of leaf area covering a unit of ground area

Methods


Leaf-on campaign (summer 2015)
Leaf-off campaign (winter 2015)
6 ha study area at Wytham Woods, Oxford
Spectral
fAPAR
DHP
LAI-2x00
TRAC2
NPL Calibrated
TLS
Radiative transfer
3D model

Wytham Woods, Oxford

- 416ha of ancient and secondary semi-natural woodland
- Local collaborators & existing resources, AERONET, Flux tower, Canopy walkway, NERC hyperspectral and LiDAR flights



Instrument Characterisation

Forest Spectral Properties

Spectrometer:

The ASD measures reflectance in the 350 nm – 2500 nm wavelength range.

Spectral measurements of the leaves, bark and understory were acquired. This information will be used in conjunction with the 3D tree models to provide replica scenes for radiative transfer modelling of forests.

ASD calibrated at NPL

Instrument Characterisation

Leaf Area Index

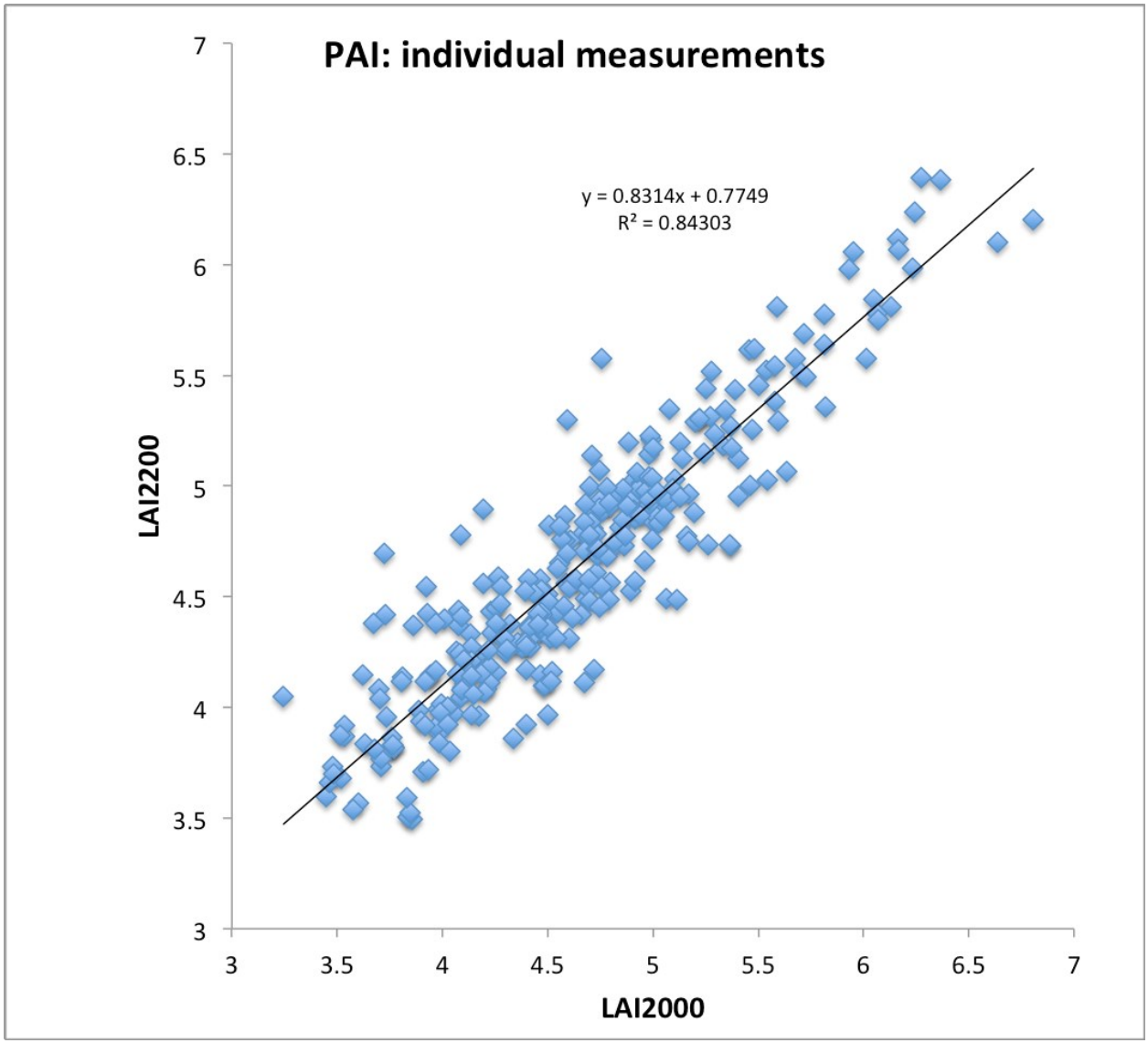
LAI 2000 and LAI 2200: compute leaf area index from measurements made above and below the canopy by determining light interception made at 5 angles

TRAC: (Tracing Radiation and Architecture of Canopies) measures canopy ‘gap size’ distribution in addition to canopy ‘gap fraction’. Gap fraction is the percentage of gaps in the canopy at a given solar zenith angle

DHP: Digital Hemispherical Photography is a technique to characterize plant canopy geometry using photographs taken below the canopy (looking upward) through a fisheye lens

Instrument Characterisation

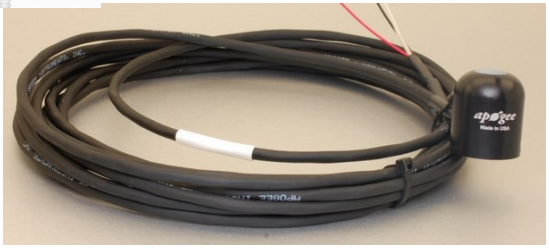
Comparison of LAI 2000 and LAI 2200



Instrument Characterisation

fAPAR

- Four widely used and deployed brands of PAR sensors
- Differing in:
  - Cost
  - Robustness
  - Power requirements
- Do they measure the same thing?



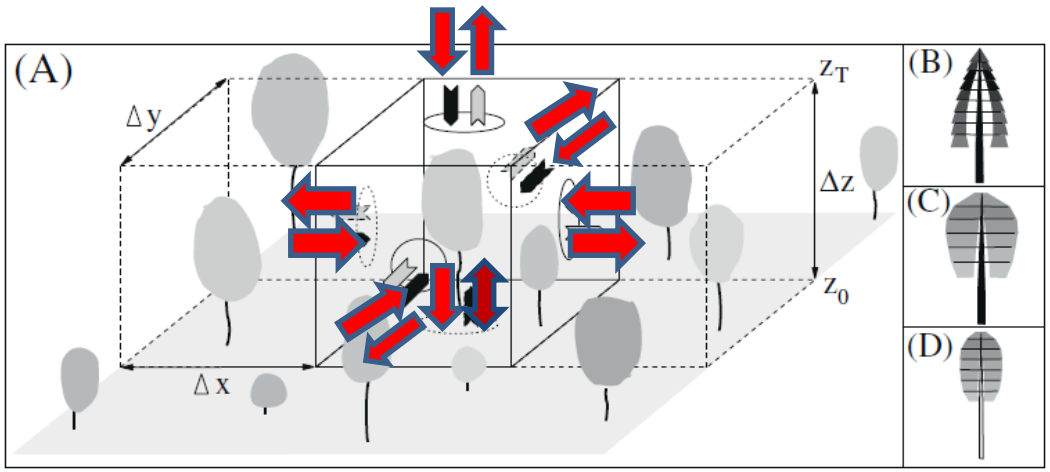
Sensor Brand	Model
Apogee	SQ-110
Apogee	SQ-212
Apogee	SQ-215
Apogee	SQ-311
LiCOR	LI-190
Kipp and Zonen	PQS1
Delta-T	QS5
Delta-T	Sunscan

Estimating fAPAR

To estimate it we think of the forest as a collection of voxels

We can't measure the absorption directly so we use the principle of energy conservation.

By measuring the other components we can infer what the absorption is.



From Widlowski (2010) On the bias of instantaneous fAPAR estimates in open canopies…

$$fAPAR = \frac{PAR_T^{\downarrow} - PAR_T^{\uparrow} - PAR_B^{\downarrow} - \Delta PAR^{\leftrightarrow}}{PAR_T^{\downarrow}} + \frac{PAR_B^{\uparrow}}{PAR_B^{\downarrow}} \frac{PAR_B^{\downarrow}}{PAR_T^{\downarrow}}$$

Soil albedo

canopy transmittance

Irradiance at the top of the canopy;

amount of PAR is coming into the system

amount of PAR leaving through the top of the canopy

Ideal vs how it's actually measured

IDEALLY

- 8 sensors at each point
- Full PAR region equally
- Sensors levelled perfectly

REALITY

- Practicality
- Large enough separation to ignore HPAR (???)
- One set of above canopy sensors
- Spectral response of sensors isn't a perfect top hat
- Sensors are never levelled perfectly!

Calibration – what your sensor actually measures to what you want to measure

Voltage → PAR

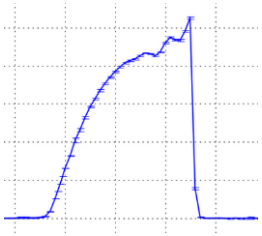
Need to know the functional relationship between the two:

e.g. $V = m \int E(\lambda) R(\lambda) d\lambda$ irradiance; spectral response

… or m

Known spec. response

Sensor

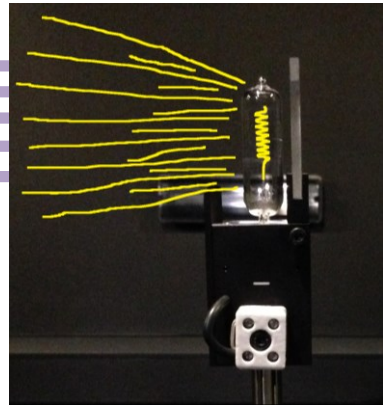


Known spec. response

Known irradiance

Known irradiance

Calibration lamp



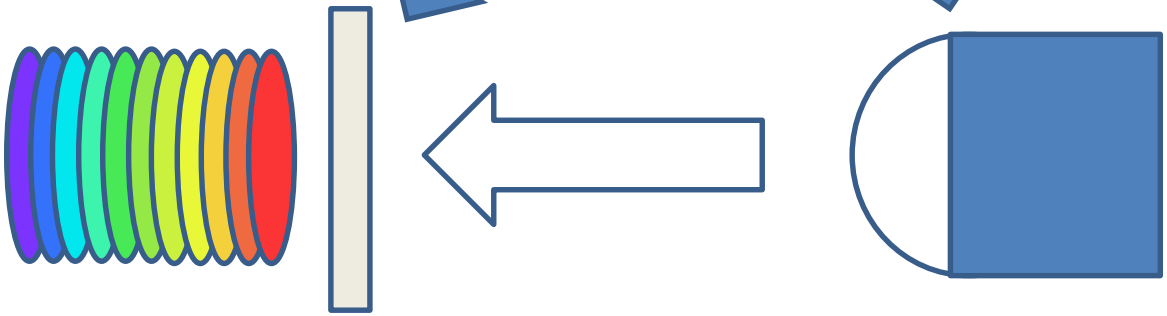
Spectral response

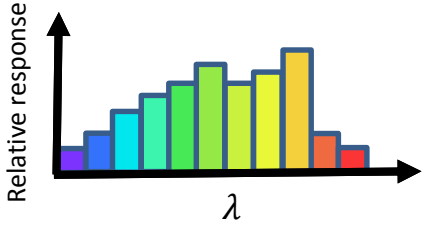
Needed in order to:

- Retrieve m
- Do spectral corrections

Process:

- Broadband source
- Wavelength grating
- Records sensor response whilst exposing it to different wavelengths





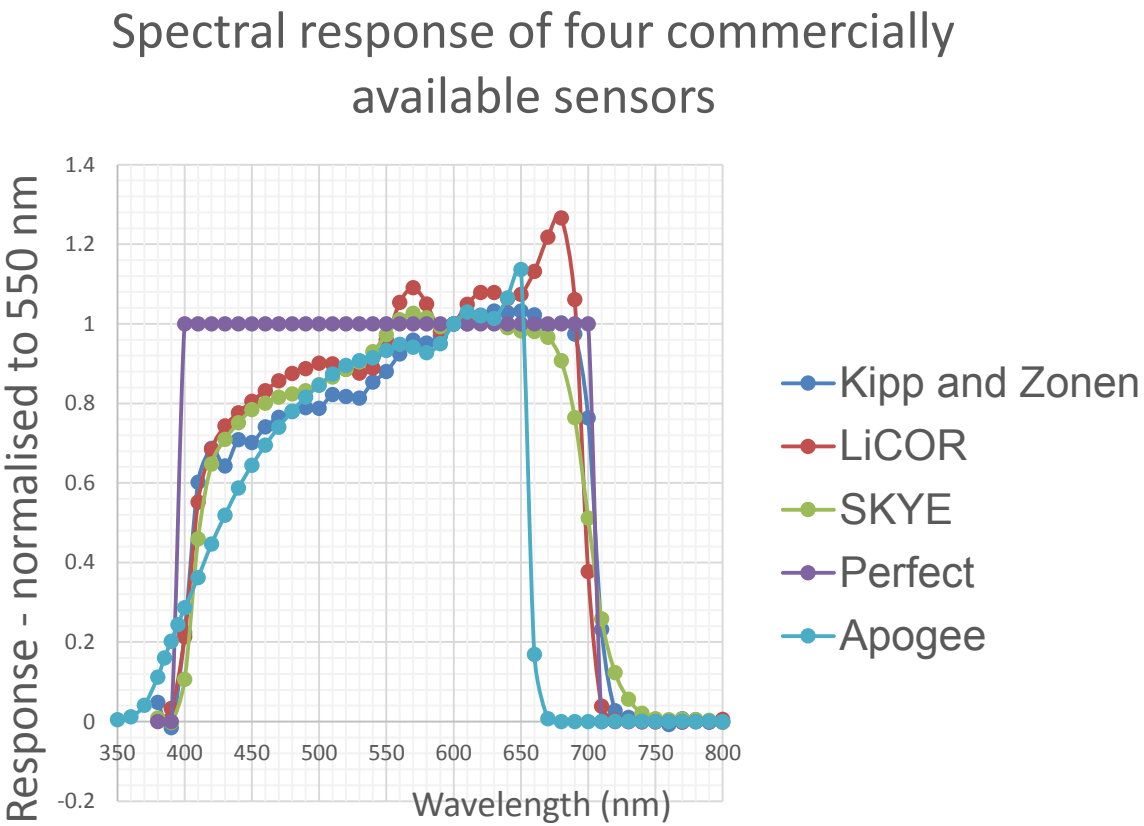
Determines how the sensor 'sees' different wavelengths

Prelim. results

The spectral response of these sensors gives us an idea about:

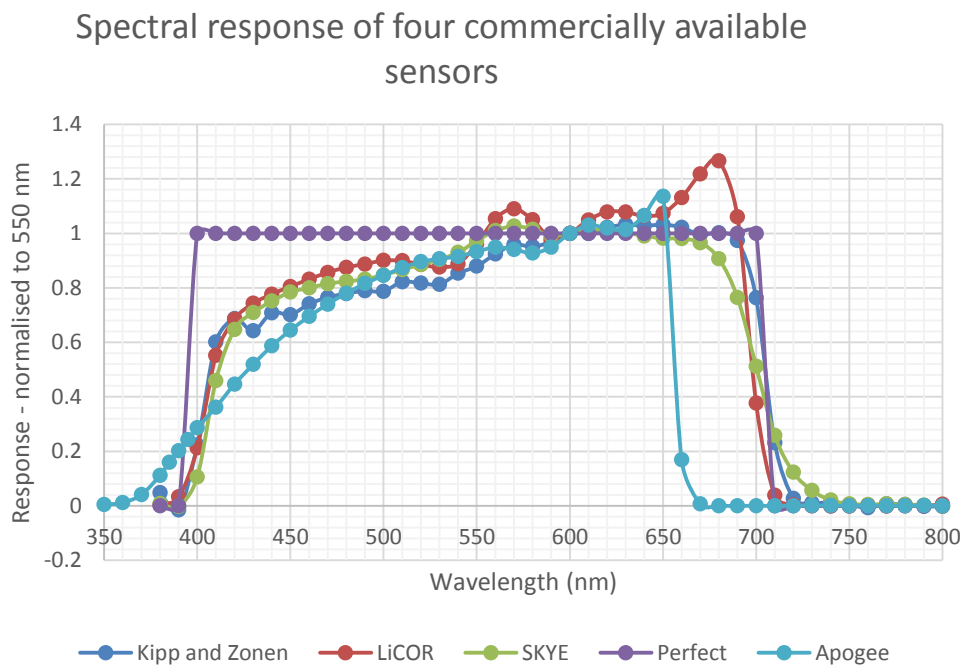
- How consistent they are with each other
- How closely they come to measuring *what we actually want*

Differences come from the materials used for the detectors and filters



Why does this matter?

Because PAR units refer to the no. of photons rather than their energy, the imperfect spectral response results in spectral errors.



PPF Spectral Errors – Relative to Sunlight (Clear Sky)

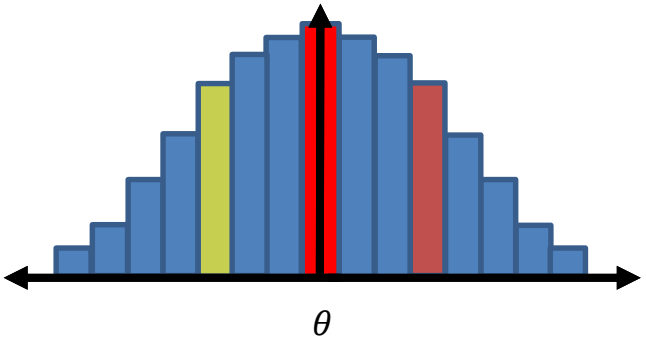
Radiation Source	LI-COR New	LI-COR 20-year Old	Apogee Blue Filter
Sun Clear Sky	0.0	0.0	0.0
Sun Cloudy Sky	0.2	-0.2	0.8
Under Corn Leaf	-0.8	4.7	9.9
Under Pepper Leaf	-0.8	4.6	10.4

From Blonquist & Bugbee (2009)

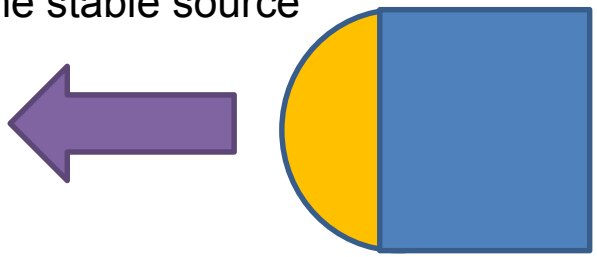
Angular response

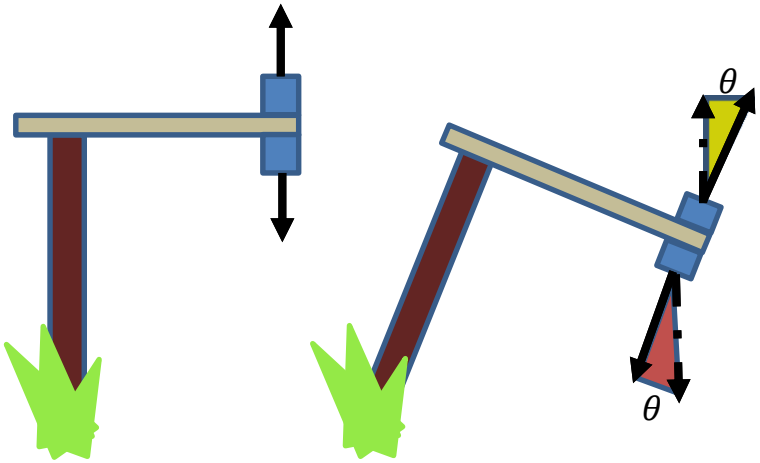
Needed in order to understand effect of alignment uncertainty in the calibration procedure and in the field

Normalised response



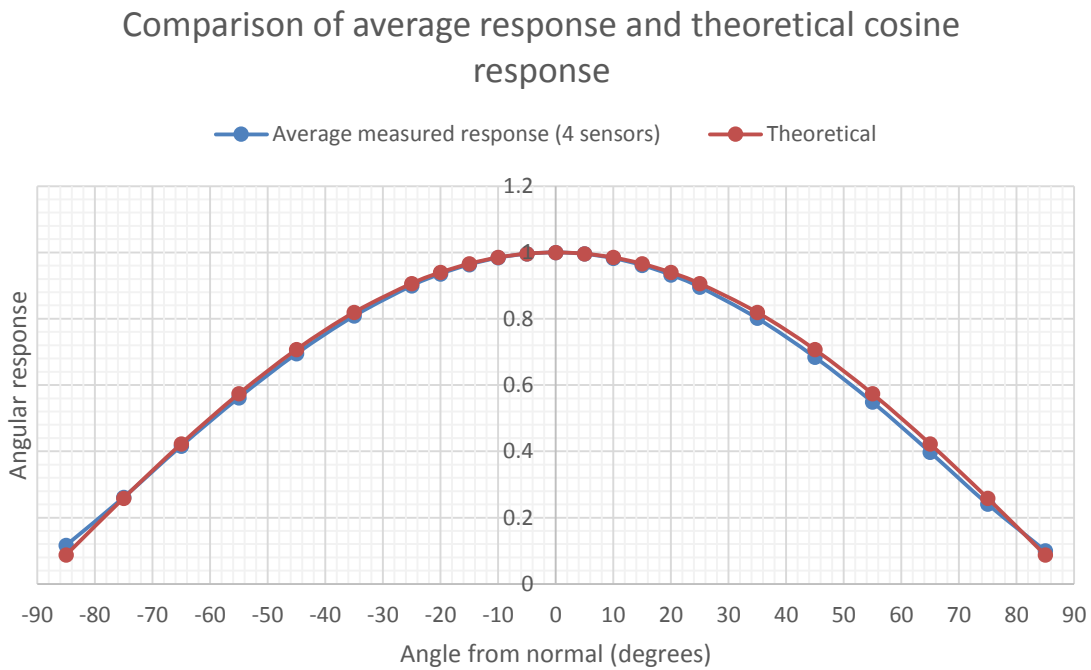
Time stable source



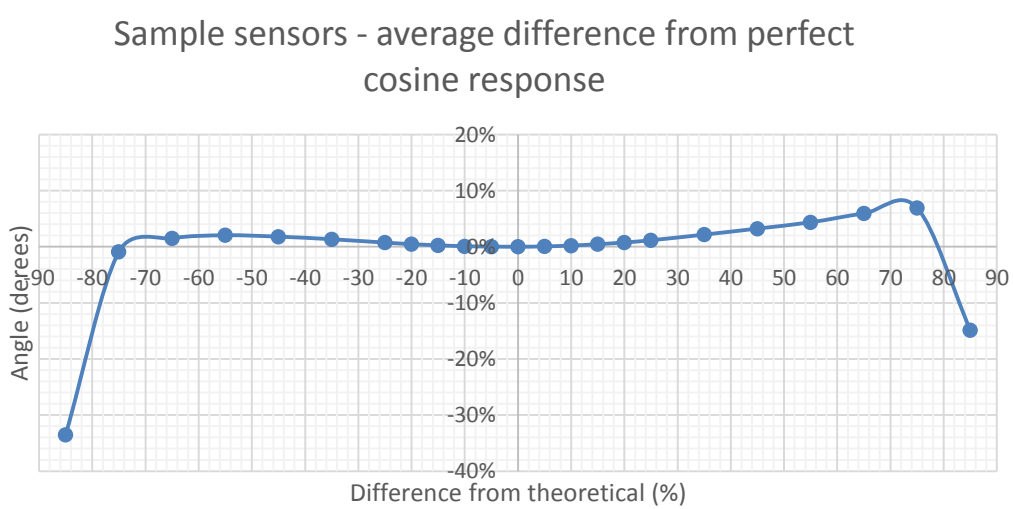


Prelim. results

The apogees have a good angular response, particularly near 0 degrees.



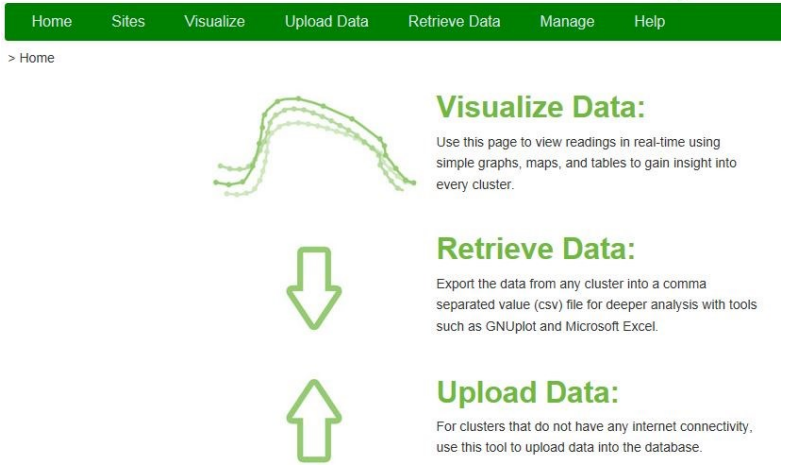
Lack of incoming light at the extreme angles causes the larger standard deviation in these regions.



Wireless Sensor Networks

TROPI-DRY

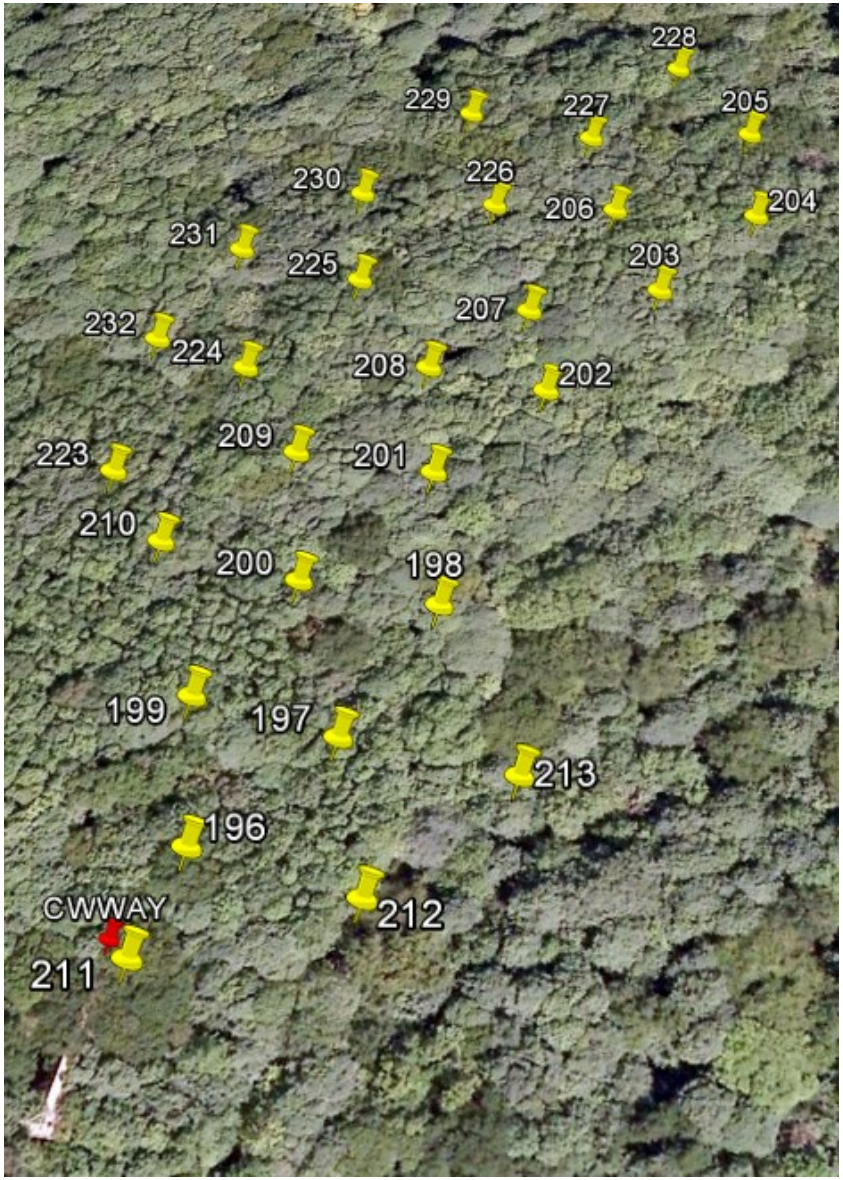
University of Alberta's Enviro-Net



- PAR ↓, ↑, transmitted
- Soil moisture, temperature
- Temp, RH, Rainfall, Wind speed
- Albedo
- Phenology (and multi-layer)
- Samples multiple spatial footprints

fAPAR WNS @ Wytham Woods

- 31 node locations on the ground covering 150m^2
- Nodes 30m apart, hexagonal
- 1 pair on canopy walkway



TLS

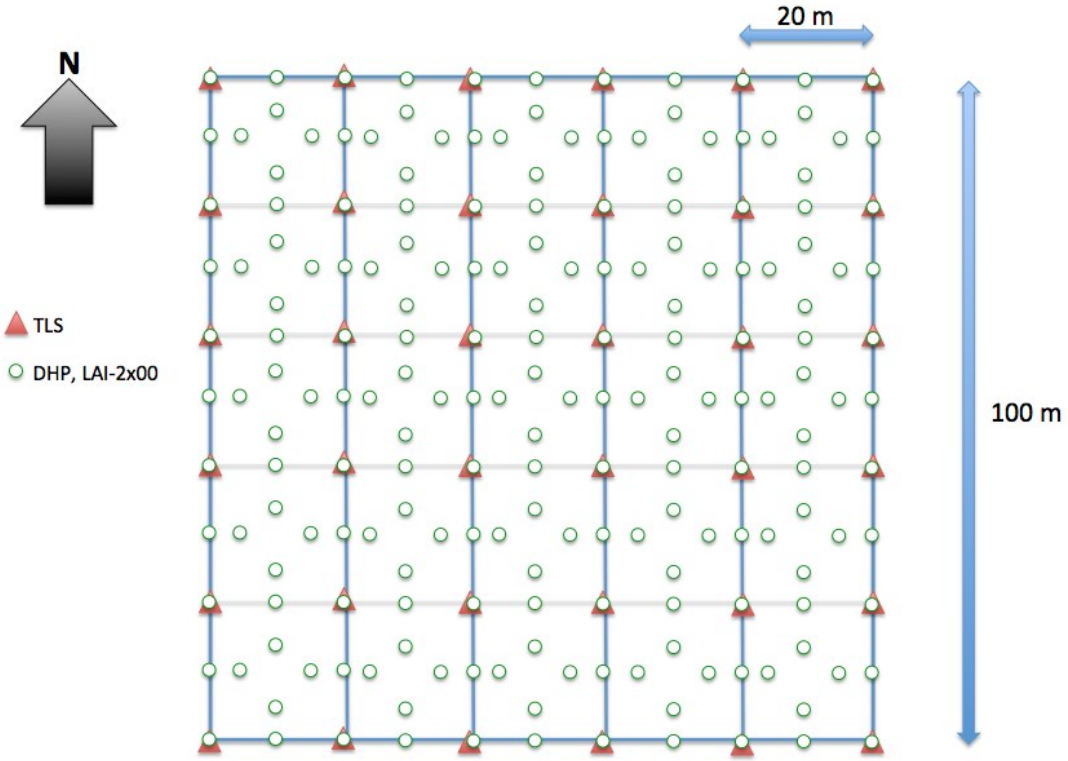
Forest Structure

Terrestrial Laser Scanner (TLS):

A ground-based full-waveform LiDAR system which measures the position and reflectance of objects in three dimensional space. These data will provide a 3D reconstruction of the trees at the Wytham Woods test site.

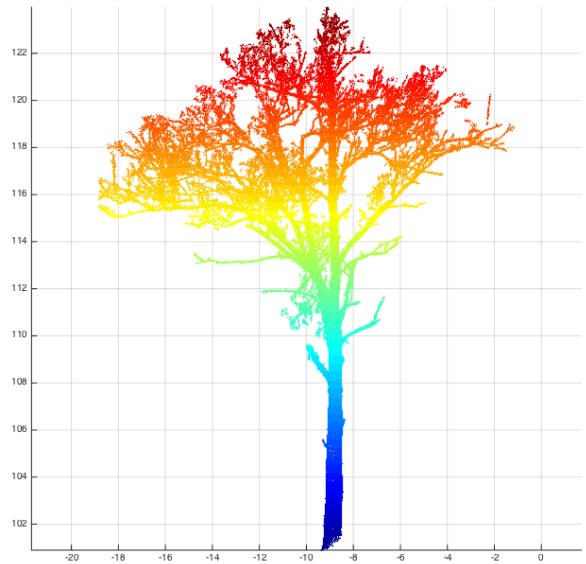
TLS Sample Design in 6ha site

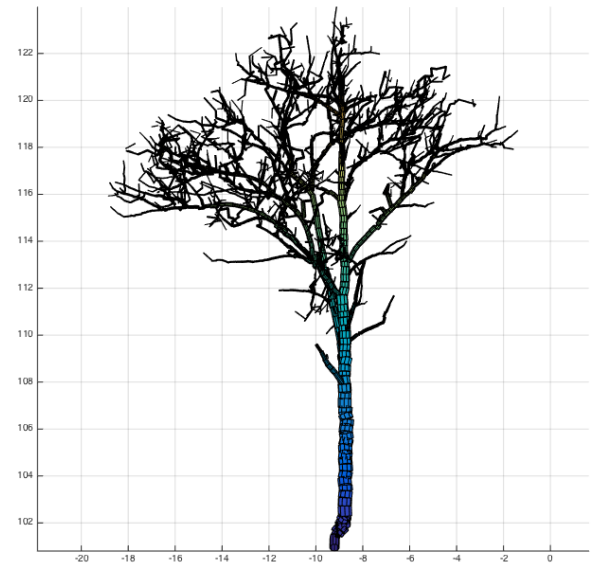
- Scans every 20 m (total: 176 scan locations)
- Optical sensors: site-wide coverage with VALERI design (total: 1800 sample locations)



TLS Site Visualisation

Building a virtual forest





6 ha pointcloud

↳ Tree identification

↳ Model woody skeleton

↳ Add foliage

Building a virtual forest

Adding foliage:

- In example: located leaves randomly around branch
- Further work required for leaves:
    - Amount of leaves?
        - Plant profiles, use of leafy pointcloud, …
    - Orientation?
    - Location?
- High-res scans from different levels

What’s next

- Creating a large virtual 3D validation site to test assumptions of other sensors:
  Tree identification (Burt et al, in prep.) + **3D modelling**

- Finalising sensor characterisation (LAI, fAPAR sensors) in lab and field conditions (takes time!)

- Methods for in situ reference generation for satellite product validation

- Recruiting!

Thank you!

For More Information visit: www.npl.co.uk/TREES