Earth Observation, Climate and Optical Measurements @ NPL

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Outline

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: 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)
- Mole (mol)

6.02214129(27)×10^{23}
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 to 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.
LOW CARBON TECHNOLOGIES
- Energy efficiency:
- Fuel Cells & PV:
- Energy distribution:
- Offshore renewables:
- Life Cycle analysis:
- Eco Design:

Accelerate development and assess performance of low-carbon technology

CARBON PRICING AND TRADING
- 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
- Climate data:
- EO:
- Instrumentation:
- UK forum:

Provide confidence and reduce uncertainties in climate data used to monitor and to model climate change
Measurement Concepts
What is Measurement?

“\textit{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

“\textit{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

\[ u(a, b, c, d, e) \]
Expressing Uncertainty

- 4 cm ± 0.2 cm
- 0.5 W m\(^{-2}\) nm\(^{-1}\) ± 10 mW m\(^{-2}\) nm\(^{-1}\)
- 60 mW m\(^{-2}\) sr\(^{-1}\) nm\(^{-1}\) ± 5 %
Uncertainty – Error - Correction

Uncertainty

Describes the spread

Drawn from a probability distribution described by uncertainty

Error

Difference to the true value

Residual, uncorrectable, unknown error

Correction

Known offset from true value
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

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


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
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
• 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

Baotou  La Crau  Railroad Valley  Gobabeb
Even easy test sites have challenges

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

Gonio-Radiometric Absolute Spectrometer System (GRASS)
In-orbit Calibration – NPL in Space

TRUTHS: Traceable Radiometry Underpinning Terrestrial- and Helio-Studies

- 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.
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

GlobAlbedo - Broadband Albedo Product

Atmospheric Correction Chain

- Pixel Identification
  - Aerosol Correction
    - Water Vapour
    - AOT Retrieval
      - A Priori AOT Value
      - Aerosol Model
    - Rayleigh Correction
      - Temperature Profile
      - ECMWF Data
    - Ozone Correction
      - Ozone Data
- Digital Elevation Model
  - The GMTED2010 DEM produced by the USGS and NGA is used
- BRF
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 Optimised and Reliable EmissionS Tool

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
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
Radiative transfer

TLS
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

PAI: individual measurements

$y = 0.8314x + 0.7749$

$R^2 = 0.84303$
Instrument Characterisation

fAPAR

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

<table>
<thead>
<tr>
<th>Sensor Brand</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apogee</td>
<td>SQ-110</td>
</tr>
<tr>
<td>Apogee</td>
<td>SQ-212</td>
</tr>
<tr>
<td>Apogee</td>
<td>SQ-215</td>
</tr>
<tr>
<td>Apogee</td>
<td>SQ-311</td>
</tr>
<tr>
<td>LiCOR</td>
<td>LI-190</td>
</tr>
<tr>
<td>Kipp and Zonen</td>
<td>PQS1</td>
</tr>
<tr>
<td>Delta-T</td>
<td>QS5</td>
</tr>
<tr>
<td>Delta-T</td>
<td>Sunscan</td>
</tr>
</tbody>
</table>
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.

\[
f_{\text{APAR}} = \frac{\text{PAR}_{\text{T}}}{\text{PAR}_{\text{B}} - \text{PAR}_{\text{T}}} + \Delta \text{PAR}_{\leftrightarrow} \]

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

Known irradianc

Known spec.
response

Calibration
lamp

Sensor
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

Spectral response of four commercially available sensors

- Kipp and Zonen
- LiCOR
- SKYE
- Perfect
- Apogee

Response - normalised to 550 nm

Wavelength (nm)
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)

<table>
<thead>
<tr>
<th>Radiation Source</th>
<th>LI-COR New</th>
<th>LI-COR 20-year Old</th>
<th>Apogee Blue Filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun Clear Sky</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Sun Cloudy Sky</td>
<td>0.2</td>
<td>-0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Under Corn Leaf</td>
<td>-0.8</td>
<td>4.7</td>
<td>9.9</td>
</tr>
<tr>
<td>Under Pepper Leaf</td>
<td>-0.8</td>
<td>4.6</td>
<td>10.4</td>
</tr>
</tbody>
</table>

From Blonquist & Bugbee (2009)
Angular response

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

- 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
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!