Ensuring traceability of L1 optical radiometric products

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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.”

‘measurements’ (as opposed to observations) of the Earth if they are to be trusted, meaningful and reliable should be treated in the same way to international agreed standards. Documented methods, estimated uncertainties, supporting evidence.

The concept “any data is better than no data”

User beware!
Traceability: property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty (ISO).

- Geographical regions have localised coordination/comparisons of NMIs to enable ALL to demonstrate “level of equivalence”

Calibrated instrumentation, agreed procedure, trained practitioner, (verification/accreditation)
EU FP7: Metrology for Earth Observation and Climate (MetEOC)
Project coordinator: (Nigel.Fox@npl.co.uk)

Partners:

NPL, PTB, INRIM, WRCL, MIKES, LNE, EURAMET, JRC, BERG, DLR, A!

Oct 11 – Sep 14
- Only funds NMI's
- Project team:
  - UK, D, F, I, CH, Fi & JRC
  - MetEOC 2 now in bid
  - EU 2020 follow-on program (10 yr projs)

Towards a European Metrology centre for earth observation and climate
http://www.emceoc.org

Creating Impact
- Uncertainty Training
- Best practices

An ‘NMI in Space’ for Benchmark Measurements of Climate

WP1 Pre-flight Laboratory-based Calibration Standards and Methodologies

WP2 Establishing In-flight Traceability through Reference Standard Measurements and Test-sites

WP3 Ocean colour from "Venice tower"

WP4 Cryogenic Solar Absolute Radiometer (CSAR)

WP5 Uniform source of radiance

WP Leader PTB

WP Leader NPL

WP Leader JRC

Collaborators:

WP2

WP3

WP4

WP5

SI traceability in Vacuum

FP Leader

On-board Calibration Standards

Premier

Hyerspectral Imager GLORIA AB

Towards a European Metrology centre for earth observation and climate
http://www.emceoc.org

JRP ENV-04
Why and what is Calibration?
Since it usually changes on launch
- **Pre-flight calibration (characterisation)**
  - confirms understanding, design and build of sensor
  - Baseline to help understand and **correct** post-launch changes
  - From above - allows any measurements/science to have credibility
    - Starting point for accuracy claim
    - Allows linkage to internationally consistent physical units
  - Needs to be performed to reflect operational conditions
    - Thermal / Vacuum
  - As comprehensive and detailed as possible sub-system & integrated
    - Radiometric, stray-light (spectral & spatial) MTF, polarisation ....
- **Method (radiometric - optical)**
  - compare response of sensor and/or sub-system to a **known** stimulus representative of intended observation.
    - Radiance (broad-band / Monochromatic)
    - Irradiance “
    - Radiant power (beam)
  - “known” requires linkage to SI (NPL) via transfer standard and evidence to confirm method of use (facility/process etc)
    - includes (dimensionless quantities) e.g. transmittance/reflectance
Radiometric traceability at sensor

Cryogenic Radiometry

SI

Primary Standard

% ~0.01

ITS-90

% ~0.1

% ~0.5

Planck’s Law

\[ L_\lambda = \frac{2hc^2}{\lambda^5 \cdot \left( e^{\frac{hc}{\lambda kT}} - 1 \right)} \]

Black body

‘working’ Standard

Photometry

Spectral Radiometry

Solar

Remote Sensing

Lighting

Transport

Aerospace

Medicine

Industry

Environment

Generalisation / dissemination

Transfer spectro-radiometer

Filter radiometer

Transfer spectro-radiometer

Generalisation / dissemination

Solar Remote Sensing Lighting Transport Aerospace Medicine Industry Environment
Thermal IR (ambient Temperatures)

For emitted Earth radiance

Use Planck's law with high emissivity Black Body

However

- Large aperture areas make: \( \varepsilon \sim 1.000 \) difficult to achieve and prove
  - Models
  - Black coatings (witness samples)
  - Uniformity of \( T \) and \( \varepsilon \)

Is sensing thermometer \( T = \text{surface} \varepsilon T \)?
Spectral effects increasingly important: use of tuneable lasers
(\(\lambda\) knowledge, bandwidth, spectral radiance)

**National Laser Radiometry Facility (NLRF)**

Continuously tuneable CW laser radiation from 210 nm to 11 \(\mu\)m power stabilised <0.001% drift

**Sentinel 4/5 spectral accuracy**
Band shape is critical when observing non spectrally flat targets & comparing sensors

Matrix for imager
Spectrally tuneable transportable source for calibration in vacuum etc

Spectrally Tuneable Absolute Irradiance and Radiance Source (STAIRS) – also aim to have as vacuum ‘flat panel’ by October

Fianium supercontinuum laser

Power: 6 W
Wavelength range: 400 - 2500 nm

LLTF

Power: 0.2-3 mW
Bandwidth 1-2 nm
Tuneability: 400 – 2300 nm
Irradiance calibration of an ocean colour validation radiometer (Satlantic) with STAIRS
All SR optical sensors drift from pre-flight calibrations – also biases between sensors?

Pre-flight calibration is still essential to help understand changes, ensure correct build & performance meets spec.
Reliable satellite data quality

Ideally Requires:

Pre-flight instrument design conformance

  Traceable sub-system characterisation/calibration
  "  End-to-end calibration

  Maintenance/life-test of witness samples/sub-systems

Post-launch design/performance conformance

  Traceable calibration/validation of all key characteristics (or harmonisation!)
  - on-board calibration/monitor system!
  - comparison with physical parameter ("test site"
  - "  with reference data/method/instrument
    (comparison with existing similar sat instrument)
Satellite Pre-flight Calibration

Satellite In-flight Calibration

Data products

LAND

OCEAN

ATMOSPHERE

NPL

National Physical Laboratory

Operational mission

Satellite Pre-flight Calibration

Traceability ?

Lamp

Solar illuminated Diffuser

Vicarious

e.g. desert reflectance

Atmosphere/Model

Data products
CEOS WGCV:IVOS “instrumented sites” (LandNet) (pre-cursor)

- Spatially uniform, bright, large (pixels from 10’s to 100’s m)
- Standardised procedures to aid characterisation (and for new sites)
- Comparisons of “field measurement” instruments & techniques to ensure consistency and “traceability”

Equivalent for vegetated validation sites, Oceans, & technology domains e.g. SAR
Do not have to be geographically fixed (e.g. SST)
CEOS WGCV IVOS: “stability” Reference standards:

inaccessible for direct surface measurements but temporally stable
good for sensor to sensor cross-comparison
“intrinsic standards” (methods) & transient stds

Rayleigh Calibration Sites – Choice of oligotrophic areas with 2 years of SeaWiFS data made in 2001 with ACRI and LOV (CLIMZOO zones)

Sun glint

Clouds

Radiation Transfer model intercomparison (RAMI) of JRC

“test data sets” to evaluate models, algorithms and software

Ocean buoys & ships
Reference standards for SAR (Synthetic Aperture Radar) imagers

Isotropy
Temporal stability
Spatial uniformity
Well characterized radiometrically

1978 Seasat (L)
1985 SIR-B (L)
1991 ERS-1 (C)
1992 ERS-2 (C)
1994 SIR-C (X)
1992 JERS-1 (L)
1996 RADARSAT-1 (C)
2002 ENVISAT (C)
2006 PALSAR (L)
2008 RADARSAT-2 (C)

Combinations of Natural and man-made standards
Atmospheric composition: Reference standard sites (core instruments and procedures)
Post-launch Cal/Val: Test-sites, comparisons has its challenges!  

http://calvalportal.ceos.org

- Representativeness over large areas in short time scales e.g. (sun) angle moves
- Laboratory instruments/concepts need to be adapted to the field – establish ‘traceability’
- Extremes of temperature
- Atmosphere well-characterised & no clouds
- Comparisons not to be biased by protocol
MIAMI III: CEOS IR radiometer inter-comparison (2009)

- Third in a series of inter-comparisons establish degree of equivalence (biases) between participant’s
  - Reference black bodies
  - IR radiometers under lab ‘controlled’ conditions
  - IR radiometers as used viewing Ocean (SST)

- Ensure robust traceability to SI (via NIST and NPL)

- Establish protocols based on QA4EO principle to facilitate future comparisons and strategy for maintenance of long-term traceability
  - Blind measurements
  - full uncertainty budgets (advance)
  - ALL results reported *(can add corrections with evidence as well)*
Sea-surface “brightness temperature”
Methodology:

• 1/ Compare black bodies to a reference standard black body using SI traceable and characterised radiometer
  (AMBER NPL and TXR NIST)
• 2/ Compare radiometers to a reference standard black body
• 3/ Compare radiometers to a common view of the Ocean

Task 1 and 2 (lab based) to be carried out in UK (NPL) and USA (Miami) linked by common radiometers.

30 radiometers (lab)
13 Radiometers (Ocean)
5 black bodies
9 participants plus NPL and NIST for traceability
Results of radiometers to a “standard black body” in Lab (NPL and RSMAS)

- Excellent agreement near ambient but increased variance between participants at cooler temperatures
- Results in UK and US consistent showing stability of radiometers and also agreement between NPL and NIST
Differences to “selected radiometer” (ISAR) for simultaneous measurements of Ocean (nominal 28 °C)
## Uncertainties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Type A Uncertainty in Value / %</th>
<th>Type B Uncertainty in Value / (appropriate units)</th>
<th>Uncertainty in Brightness temperature K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repeatability of measurement</td>
<td>0.12K / 0.040%</td>
<td></td>
<td>0.12K</td>
</tr>
<tr>
<td>Reproducibility of measurement</td>
<td>0.06K / 0.020%</td>
<td></td>
<td>0.06K</td>
</tr>
<tr>
<td>Linearity of radiometer</td>
<td></td>
<td>0.10K</td>
<td>0.10K</td>
</tr>
<tr>
<td>Primary calibration</td>
<td></td>
<td>0.20K</td>
<td>0.20K</td>
</tr>
<tr>
<td>Drift since calibration</td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>RMS total</td>
<td>0.13K / 0.045%</td>
<td>0.22K</td>
<td>0.26K</td>
</tr>
</tbody>
</table>

Few provided this level of detail although with guidance situation improved
CEOS WGCV ‘Miami’ 4: start 2014 in readiness for SLSTR

• Laboratory comparisons – vary environmental conditions
• Ocean bi-laterals – transects, range of conditions
• Planning to start in Autumn
• Possibly include satellite sensor pre-flight black bodies
CEOS WGCV comparison of techniques/instruments used for vicarious calibration of Land surface imaging through a ground reference standard test site: Tuz Golu, Turkey

Nigel Fox on behalf of Tuz Golu Team
Tuz Golu Team: - Co-authors (alphabetical by institute)

CNSMC (China)
  L. Yuan
CSIR (South Africa)
  D. Griffith
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  M. Kaewmanee
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  H. Ozen
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VITO (Belgium)
  E. Knaeps
  D. Raeymaekers
  S. Sterckx
Sponsor ESA: P Goryl
1. Evaluate differences in field instrument primary calibrations
   - Reference standards used and traceability (based on declared information)
   - On-site calibrations/validations

2. Evaluate differences in methods for characterising and assigning
   “radiometric value” to a site, for multiple view angles
   - Small area for high-resolution imagers
   - Large area for medium-resolution imagers

3. Establish formal traceability of Tuz Gölü reference site based on an
   evaluation of all comparison results.

4. Basis for “best practice” guidance for above and/or knowledge of variance
   between methodologies.

5. A multi-sensor (satellite and aircraft) comparison linked to the ground
   calibration derived from the multi-team comparison.

CEOS WGCV IVOS (2008/9) initiated comparison
- Organised by NPL and TU with sponsorship from ESA
- 2009 European Pilot (France, Germany, UK, Turkey)
- 2010 International comparison (10 countries)
- Defined agreed protocol before comparison

Comparison Objectives
Tuz Golu test site:
Land surface reflectance

~2000 sq km of salt

~50 m sq of black plastic

Targets (M1 to M8)
100 x 300 m

M9 1 x 1 km
Stability check on Spectroradiometers

NPL - Transfer Standard Absolute Radiance Source (TSARS) provides known, spatially uniform, stable radiance for lab testing

Difference between Pre & post comparison (normalised to mean of group)
- Illustrates value of this type of check!
- Similar can be done in field using sun/diffuser
Reflectance Panel Comparison - lab

Reflectance panel measurements relative to NPL standard (0/45° (lamp 45))
- Stability check

Difference in panel reflectance factor values before and after the field campaign.

Differences are within measurement uncertainty.
Reflectance Panel Comparison

Reflectance of NPL reference panel used for laboratory and in-situ panel comparisons:
As measured 2009 & 2010

Uncertainty of measurement of panel using “simple site facility” in Lab in Turkey two operators and re-setup of panel.
Reflectance Panel Comparison

Goniometric data provided by SDSU and CMA (China) - consistent with that of NPL
Laboratory & In-field panel calibration

In situ calibration

NPL laboratory calibration

Reported calibration value
Reasons for difference in panel reflectance factor values

- Labsphere calibration → Diffuse illumination, 8º view
- NPL laboratory calibration → Bidirectional illumination 45º, nadir view, and 1 kW FEL lamp
- In field calibration → Diffuse and Direct illumination, Sun zenith & irradiance variability

Community agreement to use gonio-based calibration as general case (~3% difference) and to recommend its use going forwards.
Defined agreed protocol: comparison approach – not specific measurements

All teams to look at selected group of sites in a rotational manner

1 large (1 X 1 km)
8 medium (100 X 300 m)
(some reserved for satellite acquisitions)

“Thome Strip” (3 x 50 m) rapid evaluation between teams

Timings to match similar solar angles of satellite overpass

Site area pre-selected for uniformity and accessibility
Pre-Campaign at Tuz Gölü

Measurement Site Setup

By Tubitak Uzay
Thome’s Strip

Data not used in calculation of the mean

Combined uncertainty of measured site
M1 mini-Strip Variability

- Reflectance variability for limited location, limited time on the order of 0.01 reflectance.
  - 8 days of consecutive data is shown
  - Black lines represent absolute standard deviation $\pm 0.01$ in reflectance
Large Site temporal Variability

- M1 has a difference in reflectance as compared to the M1 mini-strip. The change is on the order of 0.02 reflectance, in the VNIR.
- Standard deviation of M1 data, is similar to the standard deviation of M1 mini-strip.
Variance within and between sites: in terms of Landsat 7 bands.

<table>
<thead>
<tr>
<th></th>
<th>Reflectance M1 mini-Strip 9 day Ave</th>
<th>Reflectance Thome Strip 9 day STD</th>
<th>Reflectance M1 Site 9 Day Ave</th>
<th>Diff From Strip</th>
<th>M1 Site 9 Day STD</th>
<th>Reflectance Combined All M site Ave</th>
<th>Diff From Strip</th>
<th>Combined All M Site STD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band 1</td>
<td>49.1%</td>
<td>0.62%</td>
<td>46.8%</td>
<td>2.3%</td>
<td>0.55%</td>
<td>47.7%</td>
<td>1.4%</td>
<td>1.31%</td>
</tr>
<tr>
<td>Band 2</td>
<td>55.0%</td>
<td>0.50%</td>
<td>52.4%</td>
<td>2.6%</td>
<td>0.47%</td>
<td>53.5%</td>
<td>1.5%</td>
<td>1.49%</td>
</tr>
<tr>
<td>Band 3</td>
<td>60.6%</td>
<td>0.48%</td>
<td>57.9%</td>
<td>2.7%</td>
<td>0.43%</td>
<td>59.1%</td>
<td>1.5%</td>
<td>1.72%</td>
</tr>
<tr>
<td>Band 4</td>
<td>58.5%</td>
<td>0.42%</td>
<td>55.7%</td>
<td>2.8%</td>
<td>0.39%</td>
<td>56.7%</td>
<td>1.8%</td>
<td>1.44%</td>
</tr>
<tr>
<td>Band 5</td>
<td>13.4%</td>
<td>0.75%</td>
<td>13.0%</td>
<td>0.4%</td>
<td>0.52%</td>
<td>12.9%</td>
<td>0.5%</td>
<td>0.74%</td>
</tr>
<tr>
<td>Band 7</td>
<td>7.5%</td>
<td>0.45%</td>
<td>7.5%</td>
<td>0.0%</td>
<td>0.32%</td>
<td>7.4%</td>
<td>0.1%</td>
<td>0.42%</td>
</tr>
</tbody>
</table>
Multiple sampling strategies
Site M4

Results of all participants measurements for site M4
Land surface reflectance:
Site reflectance from different participants
- Reasonably good consistency between participants
- Site calibrated to ~1 to 2%

Comparison of results as supplied inc biases and uncertainties from primary calibrations of reference panels.

Comparison of methodologies – type B uncertainties are not considered nor is the uncertainty from the NPL reference panel – tougher test.
## Support measurements

### Meteorology
- Temperature
- Wind speed
- Solar Irradiance
- Precipitation
- Pressure
- Humidity

<table>
<thead>
<tr>
<th>Day</th>
<th>N</th>
<th>AOT (340) mean ± Stdev%</th>
<th>AOT (440) mean ± Stdev%</th>
<th>AOT (675) mean ± Stdev%</th>
<th>AOT (1020) mean ± Stdev%</th>
</tr>
</thead>
<tbody>
<tr>
<td>17/08/2010</td>
<td>4</td>
<td>0.418 ± 2.01%</td>
<td>0.354 ± 2.02%</td>
<td>0.232 ± 2.56%</td>
<td>0.152 ± 3.06%</td>
</tr>
<tr>
<td>18/08/2010</td>
<td>5</td>
<td>0.534 ± 1.78%</td>
<td>0.438 ± 1.63%</td>
<td>0.293 ± 2.02%</td>
<td>0.211 ± 2.40%</td>
</tr>
<tr>
<td>19/08/2010</td>
<td>3</td>
<td>0.417 ± 2.44%</td>
<td>0.347 ± 1.86%</td>
<td>0.231 ± 2.05%</td>
<td>0.163 ± 1.86%</td>
</tr>
<tr>
<td>20/08/2010</td>
<td>4</td>
<td>0.445 ± 0.76%</td>
<td>0.371 ± 0.79%</td>
<td>0.247 ± 1.79%</td>
<td>0.174 ± 2.79%</td>
</tr>
<tr>
<td>21/08/2010</td>
<td>4</td>
<td>0.416 ± 1.84%</td>
<td>0.332 ± 1.75%</td>
<td>0.210 ± 1.64%</td>
<td>0.145 ± 1.74%</td>
</tr>
<tr>
<td>22/08/2010</td>
<td>3</td>
<td>0.166 ± 2.01%</td>
<td>0.138 ± 1.95%</td>
<td>0.103 ± 5.48%</td>
<td>0.09 ± 7.11%</td>
</tr>
<tr>
<td>23/08/2010</td>
<td>4</td>
<td>0.207 ± 2.46%</td>
<td>0.169 ± 2.52%</td>
<td>0.120 ± 3.66%</td>
<td>0.100 ± 4.14%</td>
</tr>
<tr>
<td>24/08/2010</td>
<td>4</td>
<td>0.203 ± 4.35%</td>
<td>0.167 ± 3.79%</td>
<td>0.123 ± 4.30%</td>
<td>0.105 ± 4.08%</td>
</tr>
</tbody>
</table>

### BRDF

- Location: Turkey
- Date: 24/08/2010
- Sun angle: 35° 31° 11°
- Wavelength: 705 nm

![BRDF Diagram]
Specific actions/recommendations

- Use of invariant standard before/after site characterisations to evaluate instrumentation performance
  - Also seek to establish method to achieve above during campaigns

- Develop a standardised radiometer to act as transfer standard to link test-sites traceability.

- Perform “repeatability measurement” before and during site characterisation based on ratio of panel to surface

- Individual site “point Measurements” should consist of a statistically significant number typically 10.

- Assignment of RF to a panel and subsequently site should be based on a Bi-directional (Gonio) characterisation at an appropriate angle(s) (in some cases with solar Zenith near nadir a hemispherical based calibration may be adequate.
  - A look-up table of panel BRF for range of angles will be published on cal/val portal as a first order correction

- A standardised format to enable data from such site characterisations to be easily compared will be established
Conclusion + Future

Comparisons are key requirement to evaluate international consistency

- Must be SI traceable
- Must be regular and assess all measurement processes
- Do not necessarily need to be carried out on a single site

Sampling strategy (for Tuz Golu) not a significant variable
Sites can be characterised and relied upon for <~1-2% accuracy + atmosphere (~1-2%)

CEOS agreed Strategy:
Establish set of (5) instrumented and automated sites with minimal set of standardised specification instrumentation as CEOS LANDNET complimented with campaign and temporal limited instrumented sites with pseudo-invariant deserts/Moon as baseline surface infrastructure of land radiance Cal/Val system.

For more info/full report: http://calvalportal.ceos.org
Prototyping LandNET

New focus group – Marc Bouvet ESA (chair), Kurt Thome (NASA), Patrice Henry/Aime Meygret (CNES), Nigel Fox (NPL) Ling-Ling Ma (AOE/CAS)

- Identify small group of test sites/operators/experts
  - La Crau (CNES)
  - Rail road Valley (NASA/UofA)
  - A new ESA/CNES site (to be found and established) (start summer 2013)
  - China

- Establish protocols and strategy for a network of automated test sites
  - Measurements
  - Formats
  - Traceability / harmonisation
  - Processing to a product (sensor)
  - Coordinating/traceability lab

- Collect/analyse/compare data sets (<50 m resolution sensors) over all sites
  - Landsat 8
  - Hj-1A/B
  - Spot?, Pleiades?, DMC?
  - Sentinel 2 (future)
Summary/Conclusion

• Pre- & post- launch calibration, characterisation & validation traceable to international agreed standards is a fundamental requirement
  • Needs to be documented with supporting evidence
  • Need uncertainty analysis
  • Comparisons good way to obtain evidence
  • New methods, tools and reference standards are under development
  • Strategy should be determined at start of mission concept
    • driven by clear link to requirements

• Internationally coordinated infrastructure / comparisons (CEOS) very effective: drives innovation, cost effective, learning opportunity

• National Metrology Institutes (e.g. NPL – EMCEOC) are here to help
  • What are the priority needs for new Standards?
  • “” “” “” new Methods/tools ?
  • MetEOC 2 (July/August) contact me (nigel.fox@npl.co.uk)