8th ADVANCED TRAINING COURSE
ON LAND REMOTE SENSING

10–14 September 2018
University of Leicester | United Kingdom
Measuring the surface temperatures of the earth from space

Darren Ghent, University of Leicester
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Contents

Background
Challenges of measuring Land Surface Temperature
Applications
Current capability
What is Land Surface Temperature

- Land Surface Temperature (LST) is a measure of how hot or cold the surface of the Earth would feel to the touch.
- For ground-based, airborne, and spaceborne remote sensing instruments it is the aggregated radiometric surface temperature of the ensemble of components within the sensor field of view.
- LST is an independent temperature data set for quantifying climate change complementary to the near-surface air temperature ECV based on in situ measurements and reanalyses.
- From a climate perspective, LST is important for:
  - evaluation of land surface and land-atmosphere exchange processes
  - constraint of surface energy budgets and flux variations
  - global and regional observations of surface temperature variations
- LST can be determined from thermal emission at wavelengths in either infrared (IR) or microwave (MW) atmospheric windows.
Sentinel-3 Land Surface Temperature
Sentinel-3 Land Surface Temperature
Importance of LST for climate

LST increasingly recognised as an essential parameter for diagnosing Earth System behaviour and evaluating Earth System Models:

- provides a globally consistent record from satellite of radiative temperatures of the Earth’s surface
- provides a crucial constraint on surface energy budgets, particularly in moisture-limited states - the LST record contains the imprint of climate events related to water stress and availability
- provides a metric of surface state when combined with vegetation parameters and soil moisture, and is related to the driving of vegetation phenology.
- an important source of information for deriving surface air temperature in regions with sparse measurement stations, such as parts of Africa and the Arctic
- A long, stable record of LST is particularly useful for model evaluation in regions where few in situ measurements of surface air temperature exist and for attribution of observed changes in such regions to their possible causes

The climate user community already use and need LST data.
How we measure Surface Temperature

How is it measured?
- Planck Function Radiation Curves
- Radiative Transfer Equation
- Thermal Infrared (TIR) atmospheric Window (~8-13μm)
- Split-Window and/or Dual angle Algorithms
- Mean radiative temperature over pixel area

\[ L^{sat} = L^{ground} + L^{atm} + L^{atm\_reflected} \]

- \( L^{sat} \) is the radiance measured by the satellite sensor
- \( L^{ground} \) is the upwelling radiance emitted by the ground
- \( L^{atm} \) is the upwelling radiance emitted by the atmosphere
- \( L^{atm\_reflected} \) is the down-welling radiance emitted by the atmosphere and reflected by the ground
A Simple Radiative Transfer Approach

\[ B_i(T_{sensor}) = \left[ \varepsilon B_i(LST) + (1 - \varepsilon) L_i \downarrow \right] \tau + L_i \uparrow \]

- Radiometers are used to measure the top-of-atmosphere brightness temperature (BT).
- To obtain ST from infrared satellite measurements, we need to correct for the effects of the atmosphere and non-unity of surface emissivity.
- Sea: The surface emissivity is very well behaved. The atmosphere tends to be spatially homogeneous except for some aerosol advection/broken cloud.
- A split-window algorithm is used (11/12 μm with addition of 3.7 μm channel at night for SST). Atmospheric effects and emissivity correction are implicitly handled through a coefficient approach.
Infrared or Microwave Retrievals?

- Microwaves are able to penetrate clouds and so offer a more continuous source of data
- However:

  The signal originating from Earth is stronger at IR wavelengths
  The Planck function peaks in the IR
  Higher surface emissivity of terrestrial materials in IR

Rate of change of radiance is lower in the microwave
A higher radiometric resolution is required to obtain the same precision
Measurements from microwave instruments are at a lower spatial resolution
Atmospheric effects

- Even in the atmospheric window of high transmission attenuation is still significant
- Most attenuation at these wavelengths is due to water vapour absorption
- Stratospheric and tropospheric aerosols also depress infrared radiances
- Both atmospheric effects and emissivity variability need to accounted for to avoid retrieval errors of up to 12K (Sobrino and Raissouni, IJRS, 2000; Sobrino et al., IJRS, 2003)
- Most common approach is the Generalised Split-Window (GSW) algorithm
- GSW corrects the atmospheric effects based on the differential absorption in adjacent channels
- Transmission is highest in the 8-13μm window
Thermal infra-red Emissivity

Emissivity is the relative ability of the surface to emit radiation.

It is quantified as the ratio of energy radiated by the surface with respect to the energy radiated by a black body ($\varepsilon = 1$) at the same temperature.

Surface emissivities can be highly variable owing to the heterogeneity of the land. Factors influencing emissivity include:

- Surface type
- Fractional vegetation cover
- Soil moisture

Can range from less than 0.94 for some sandy soils to over 0.99 for some regions of inland water or snow and ice.

Variability of surface emissivities is amplified in regions of high topographic variance and for larger viewing angles.

Need to accurately deal with uncertainties otherwise biases can occur in LST retrieval of several degrees (Schaadlich et al., RSE, 2001).
Thermal infra-red Emissivity

Emissivity 11μm channel

Emissivity 12μm channel

Biome - Globcover

LST
Long-term multi-channel IR LST

**AATSR**
ENVISSAT, Polar Orbiting
Sun-Synchronous (~10.00a.m. descending)
Launched 2001, EOL 08/04/2012
Mission Series (ATSR-1 and ATSR-2) since 1991
SST derived from TIR channels: 3.7, 11 and 12 μm
High Spatial Resolution (1 km²)
Narrow swath width (512 km)
Exceptional radiometric calibration; dual-view

**AVHRR**
NOAA + METOP, Polar Orbiting
Sun-Synchronous (a.m. descending)
Mission Series stretching back to 1979.
SST derived from TIR channels: 11 and 12 μm
High Spatial Resolution (1 km²)
Wide swath width (~2500 km)

**MODIS**
2 Polar Orbiting satellites: Terra and Aqua
Terra: Sun-Synchronous (~10.30a.m. descending)
   Launched 1999
Aqua: Sun-Synchronous (~13.30a.m. descending)
   Launched 2002
SST derived from TIR channels: 11 and 12 μm
High Spatial Resolution (1 km²)
Wide swath width (2330km)

**SEVIRI**
Meteosat9/MSG2
Geostationary (0° latitude, 0° longitude)
Launched 2005, EOL 2015
SST derived from TIR channels: 10.8 and 12 μm
High Temporal Resolution (15mins)
Coverage within +/- 60°
Spatial Resolution: 3km at nadir; +6km above 60°
How does LST compare with $T_{\text{air}}$?

- Strong diurnal cycle
- Differences of as much as 20K for same scene
- Stronger non-uniformity within a landscape

Comparison example:

- GlobTemperature MODIS (Aqua) – GHCN/D
  
  (results courtesy of L. Good, Hadley Centre in framework of EU H2020 EUSTACE Project)

- $LST_{\text{min}} - T_{\text{min}}$ [range between -0.13 K (MAM) and 0.79 K (JJA)]
- $LST_{\text{max}} - T_{\text{max}}$ [range between -2.56 K (DJF) and 1.76 K (JJA)]
- $LST_{\text{ngt}}$ often reasonable proxy for $T_{\text{min}}$
LST Split Window Algorithm

AATSR/SLSTR
Nadir retrievals only (dual angle only for SST)

\[ LST = a_{f,i,pw} + b_{f,i}(T_{11} - T_{12})^{p(\theta)} + (b_{f,i} + c_{f,i})T_{12} \]

\( T_{11} \) and \( T_{12} \) are 11 and 12 \( \mu \)m channel brightness temperatures (BT)

\( a, b, c \) – retrieval coefficients dependent on:
- Surface/vegetation type \( (i) \) - biome
- Vegetation fraction \( (f) \) – seasonally dependent
- Precipitable water \( (pw) \) – seasonally dependent
- Satellite zenith view pointing angle \( (p(\theta)) \)

Emissivity dependence encapsulated in biome and fractional vegetation factors
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Validation

**Category A: Comparison of satellite LST with in situ measurements**

This is the traditional and most straightforward approach to validating LST. It involves a direct comparison of satellite-derived LST with collocated and simultaneously acquired LST from ground-based radiometers.

**Category B: Radiance-based validation**

This technique uses top-of-atmosphere (TOA) brightness temperatures (BTs) in conjunction with a radiative transfer model to simulate ground LST using data of surface emissivity and a atmospheric profiles of air temperature and water vapour content.

**Category C: Inter-comparison with similar LST products**

A wide variety of airborne and spaceborne instruments collects thermal infrared data and many provide operational LST products. An inter-comparison of LST products from different satellite instruments can be very valuable for determining LST.

**Category D: Time series analysis**

Analysing time series of satellite data over a temporally stable target site allows for the identification of potential calibration drift or other issues of the instrument that manifest themselves over time. Furthermore, problems associated with cloud contamination for example may be identified from artefacts evident in the time series. Care must be taken in distinguishing between instrument-related issues such as calibration drift and real geophysical changes of the target site or the atmosphere.
In-situ Validation Stations

- Large, **homogeneous** sites
- Well **characterised**
- Different climates & biomes
- **Dedicated** to LST validation

- Portugal, Evora
- Senegal, Dahra
- Namibia, Gobabeb, Farms
- Semi-arid (tiger bush)
- Kalahari bush
- Temperate vegetation
- Desert
Validation challenges

- Geolocation accuracy and overpass timing

- Landscape heterogeneity
  Simultaneous measurements of each surface class ('endmember')

- LST from satellite depend upon angle of observation
  Upscaling of nadir in situ measurements biased towards sunlit scenes
  Angularly anisotropic surface emissivity at the microscopic scale
  Requires measurements of shadow scenes and geometric projection modelling

- Upscaling assumptions:
  precise geolocation and surface area of a satellite pixel can be guaranteed
  for each pixel validated the same generic land cover classes can be reliably classified
  within and between each pixel the thermal behaviour of each land cover class remains invariant
Validation challenges
Challenges: Sensor Intercomparison

Daytime MODIS view for nadir viewing angles (left) and for positive viewing angles (right)
Challenges: Sensor Intercomparison

LST differences between MODIS and SEVIRI as a function of zenith viewing angle by day and night

LST differences between MODIS and SEVIRI as a function of zenith viewing angle by day and night
### Challenges: Uncertainty Budgets

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<th>Map Representation</th>
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Applications for LST Data

- Climate change
  - Urban heat islands, land/atmosphere coupling, surface energy balance
- Modelling studies
  - Model validation, data assimilation
- Land cover change
  - Desertification, change detection
- Crop management
  - Irrigation, drought stress
- Water management
  - Evapotranspiration, soil moisture retrievals
- Fire monitoring
  - Burned area mapping, fuel moisture content
- Geological applications
  - Geothermal anomalies, volcanic activity
Applications - Heat Waves

AATSR LST daytime anomalies during relative heatwaves
Applications - Data Assimilation

Modelled vs. assimilated mean daily LST compared with NCEP skin temperature

Time series of mean daily surface soil moisture in the top 5cm of the soil profile with and without LST data assimilation for values over West Africa from 1st January – 31st May 2007. ERS scatterometer surface soil moisture observations are plotted for comparison.
Applications - Hydrology

Why is accurate LST data important in hydrological applications?

- For non-vegetated surfaces water shortage at the surface of the soil causes the temperature to rapidly increase, with more energy partitioned into sensible heat. For vegetated surfaces root zone water shortage leads to stomatal closure, reduced transpiration, and higher canopy temperatures.
- 0.5K LST error can result in a 10% error in sensible heat flux (Brutsaert et al., 1993).
- 1.0K LST error can lead to a 10% error in ET (Moran and Jackson, 1991).
- LST Errors between 1.0K and 3.0K can lead to errors as much as 100Wm$^{-2}$ in heat fluxes (Kustas and Norman, 1996).
Applications - Urban Heat
Applications - Urban Heat

The high spatial resolution of LANDSAT comes at the cost of temporal resolution, with 16 day image separations and the accuracy with which temperatures can be established given the need for additional input variables.

Surface temperature plot over central London using LANDSAT 7 thermal data 90m resolution. LST accuracy limited by a lack of high resolution urban emissivity data.
LST applications: Drought mapping
LST applications: Drought mapping
Improving LST representations

- Comparisons of LST and near-surface air temperature provide information on surface energy budget where coincident measurements are available.
- LST delivers unique information on surface temperatures in sparsely observed regions for near-surface air temperature.
- Consistent representations of surface temperature from LST can inform historical reconstructions.
- LST from IR is currently used more for climate studies.

Time series from ATSR LST CDR vs. CRU for North Africa (E. Good, Met Office)
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Current capability I (products)

Single-sensor IR LST data-products from satellite have greatly improved:

- High accuracy of IR LST data:
  - validation shows LST biases < 1.0 K from AATSR (eg Coll et al., 2012)
  - emissivity accuracy < 0.015 (1.5%) from MODIS and ASTER (eg Hulley et al., 2012)
- Advances in cloud detection (dynamic probabilistic approaches)
- Approach to uncertainties consistent with Sea Surface Temperature (SST) including validation

![Image of Random and Locally correlated ESA GlobTemperature MODIS uncertainties](http://www.globtemperature.info)
Current capability I (uncertainties)

Uncertainties categorised by effects whose errors have distinct correlation properties:
- Random
- locally systematic
- (large-scale) systematic

This three-component model applies to all processing levels and LST products

Propagation of uncertainties:
- L1 → L2 → L3 → L4 (Merged Product)
Current capability II (quality)

LST data, particularly I/R, are of much higher quality than previously:
- Demonstrated against accurate and highly stable in situ instruments
- Biases against in situ are stable, small (often < 1 K) and well documented.
- Standardised protocols
- Validation of LST uncertainties

Complementing IR LST with MW LST:
- Retrievals in the IR are generally more accurate than MW retrievals due to smaller variation of surface emissivities
- However, MW LST is complementary to IR LST due to their lower sensitivity to clouds and therefore helps us quantify the clear-sky bias

GlobTemperature MODIS LST Validation
Current capability III (diurnal cycle)

Global LST data which resolve the diurnal cycle becoming available:

- Merged geostationary (GEO) and low earth orbit (LEO) data giving high spatial resolution, sub-diurnal sampling; estimates of cloud-bias.
- Intercalibrated LST using SEVIRI as a reference sensor
- 15-day LEO composite product at local solar time
- Combined GEO+LEO 3-hourly product at UTC

15-day Merged LEO composite LST Product from 1st Jan to 15th Jan 2012

Merged GEO (SEVIRI, GOES, MTSAT) + LEO (ATSR, MODIS) LST Product at 21:00 UTC on 1st January 2013
Current capability IV (CDRs)

Increasing confidence in traceability and stability of LST

- Traceability of globally robust algorithm coefficients and uncertainties
- Quantitative assessments of biases between consecutive instruments such as ATSR-2/AATSR and MODIS/VIIRS
- Homogenisation of BTs and aerosol detection within ATSR Climate Data Record (CDR)

**ATSR LST CDR (September 2002)**
Towards a CDR from the ATSRs I

Increasing confidence in observations of LST

- Cloud clearing is the largest unknown in the retrieval of LST from IR
- Limitations with threshold-based approaches have been improved with dynamic, probabilistic methods
- These methods are adaptable to other instruments

Example of the improved probabilistic approach for ATSR (right) compared to the existing operational approach (left)
Towards a CDR from the ATSRs II

Increasing confidence in observations of LST

- The retrieval of LST is usually performed under the assumption of clear-sky conditions.
- In the thermal infrared window region the effect of aerosols is not negligible and will have impact on the observed LST.
- Within the ATSR CDR an aerosol flag (created from Swansea University CCI aerosol product Grey et al. 2006) informs users of possible aerosol contamination.

Comparison of SU OD550_DU with Aeronet (left); CDR aerosol flag created from the dust optical depth product from U. Swansea (right). Credit http://aerocom.met.no/cgi-bin/aerocom/surfobs_annualrs.pl
CDR Assessment

Explore using satellite LST retrievals to augment information from meteorological stations.
CDR shows consistent and strong relationship with 2m air temperature.
Very good agreement between CDR anomalies and CRUTEM4 anomalies
  - Day: ATSR-2 warmer than AATSR - likely non-optimal temporal adjustment
  - Night: Much smaller difference

Independent confirmation of CRUTEM4 monthly anomaly variation.

Good et al., 2017, JGR-Atmospheres
User requirements for Climate

Climate users require LST data
Baseline requirements have been determined by user survey (ESA DUE GlobTemperature Requirements Baseline Document http://www.globtemperature.info/)

- Horizontal resolution - Threshold: 0.05°
- Temporal resolution - Threshold: Day-night
  Target: ≤ 3-hourly
- Accuracy - Threshold: <1 K
- Precision - Threshold: <1 K
- Stability - Threshold: <0.3 K per decade
  Target: <0.1 K per decade
- Length of record - Threshold: 20 years
  Target: >30 years

LST is now an ECV in the GCOS 2016 Implementation Plan
ESA Climate Change Initiative (LST CCI)

12 international partners

UK lead (U. Leicester) with other UK partners (U. Reading, Met Office)

Algorithm development
  Retrieval algorithm consistency across LST ECV products

Ensure consistency of uncertainty approach
  Components separated according to correlation properties

Optimisation of best cloud clearing detection
  Best cloud clearing approaches for IR CDRs

Long-term CDRs
  25 years (1995 to 2020) from ATSR to Sentinel-3 IR CDR
  22 years (1998 to 2020) for Passive microwave time series
  10 years (2010 to 2020) for Merged IR CDR

Website: cci.esa.int/lst
The next generation of LST observations has begun with Sentinel-3

**Sentinel-3A:**
- Launch 16 February 2016
- LST operational 5 July 2017

**Sentinel-3B**
- Launch 25 April 2018
- LST to be operational autumn 2018

Achieving its mission requirements
- LST accuracy < 1K

U. Leicester lead the LST activities for Sentinel-3
An international effort

NCEO are coordinating The International Land Surface Temperature and Emissivity Working Group (ILSTE):

- Represents the best available expertise in LST & Emissivity data techniques and LST-related science, sharing best practice amongst providers, experts and users
- Act as an international forum for regular interactions between LST Measurement Teams, enabling improvements in data algorithms and data quality, and increased understandings of user requirements
- Delivers a range of user-provider meetings and workshops, increasing links across the community
- Supports the alignment of LST best practice with the planned activities and data provision of operational agencies
- Agrees standardised protocols for data formats and access to data, appropriate to key sectors of the LST user community
- Supports a dedicated validation group, supporting a consistent approach to data validation, in line with CEOS-LPV Best Practices
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Thank you
Questions?