Measuring and modelling directional effects in the frame of TIRAMISU (Thermal InfraRed Anisotropy Measurements in India and Southern eUrope)

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Keywords: Thermal Infrared, measures, directional effects, mock-up, inverse modeling

Abstract

TRISHNA (Thermal infraRed Imaging Satellite for High-Resolution Natural resource Assessment) is a cross-purpose thermal infrared (TIR) Earth Observation (EO) mission designed to deliver images at high spatial (60 m) and temporal (3 days) resolutions. Its launch is foreseen in 2026 with a nominal mission duration of 5 years. This Indo-French polar-orbiting mission will overcome the limitations of thermal-optical observations from Landsat series and ASTER: low revisit, morning observations. TRISHNA scenes will be fully harnessed to pioneer the first cutting-edge high-resolution global maps of the land surface temperature (LST) and land surface emissivity (LSE) of natural and managed agroecosystems, man-made structures, water bodies, bare soils, rocks, snow, ice and sea. The quality of the preprocessing (radiometric calibration, atmospheric and directional corrections) is mandatory to satisfy the specifications with an expected precision of 1 K on LST in order to meet the targeted objectives. For such, it will be necessary to correct LST from directional effects with emphasis on the hot spot effect that can have an impact on LST up to several K. This is the goal of the TIRAMISU project to analyze TIR multiangular signatures over various biomes thanks to a pivoting system of cameras and a multi-model approach (1D, 3D, paramaterization). The modeling tools include 3 categories of models: SCOPE 1D, DART 3D and parametric BRDF models that are computationally efficient to perform inversion at global scale.

1. Introduction

TRISHNA (Thermal infraRed Imaging Satellite for High-Resolution Natural resource Assessment) is a cross-purpose thermal infrared (TIR) Earth Observation (EO) mission jointly conducted by CNES (Centre national d'études spatiales) and ISRO (Indian Space Research Organisation). TRISHNA is designed to distribute optical (at 0.485µm, 555nm, 0.670µm, 0.860µm, 0.910µm, 1.610µm, 1.380µm) and thermal (8.65µm, 9µm, 10.5µm, 11.5µm) satellite images at high spatial (60 metres) and temporal (3 days at least) resolutions with an orbit overpass of 12:30 local time at equatorial latitude, for both daytime and nighttime.

The launch is foreseen in mid 2026 with a nominal duration of the mission of 5 years. This Indo-French polar-orbiting mission will overcome the limitations of the current thermal-optical observations issued from LANDSAT and ASTER, i.e. a low revisit and morning observations. A full harnessing of TRISHNA images will pioneer cutting-edge high-resolution global maps of the land surface temperature (LST) and land surface emissivity (LSE) in regard to natural and managed agroecosystems, man-made structures, bare soils, rocks, snow, and ice. In addition, high-resolution sea surface temperature (SST) will be generated for water bodies (inland water, shoreline, deep ocean). Other deliverables of the TRISHNA mission are the evapotranspiration, which is the main design driver of this mission, and the detection and monitoring of water stress. The quality of the preprocessing (radiometric calibration, atmospheric and directional corrections) is expected to satisfy the specification on LST which is of 1 K expressed as a requirement in order to meet the scientific targeted objectives. Worth outlining that the benefit of the TRISHNA mission regarding radiative and heat transfer processes over terrestrial and marine ecosystems will pave the way for impactful applications in water resources, urban climate, cryosphere and biogeochemical cycles.

The high field of view (HFOV) of 35° will permit to achieve a global coverage but it will be accompanied by directional effects due to the anisotropy nature of most terrestrial targets. In the tropics, between March and October, TRISHNA will capture the hot spot phenomena, which corresponds to a radiometric peak when the view and sun geometries coincide (e.g. Lacaze et al., 2000; Roujean, 2000). Duffour et al., 2016) have shown that maximum directional effects occur in the hot spot geometry, thus adding significance to anisotropy effects in LST measurements beside HFOV. Hot spot features can lead to LST measurements being in error up to 7K. This propagates in the estimation of the evapotranspiration, which is a major outcome of TRISHNA mission. It is mandatory to pay attention to the observations that are impacted by the hot spot, either for discarding them or to perform an angular correction. On the one hand, data located very near the hot spot geometry may not be processed as hot spot characteristics are susceptible to the architecture of the canopy, and such information will not be available globally. On the other hand, regarding the cloudiness in certain regions, any clear data should be harnessed.

Hitherto, several studies about the impact of the hot spot phenomenon on radiometry broadly concentrated in the optical domain and inadequately in the TIR range. The reason for that is the difficulty to accumulate information for TIR. Hot spots for TIR are also influenced by some environmental factors (wind, soil wetness, atmospheric humidity) in addition to the structure of the medium, the only driver for optical. Directional effects, either for thermal or optical, can be resumed by the BRDF (Bidirectional Reflectance Distribution Function) (Julien et al., 2023). The starting point is collecting directional measurements for various environmental conditions and biomes. This fostered the implementation of the TIRAMISU (Thermal InfraRed Anisotropy Measurements in India and Southern eUrope) project.

Algorithms for TRISHNA are for the most part generic. This may lead to an uncertainty assessment in some situations. State-

This contribution has been peer-reviewed. The double-blind peer-review was conducted on the basis of the full paper.
https://doi.org/10.5194/isprs-annals-X-3-2024-325-2024

of-art radiative transfer models such as 1D SCOPE (Soil-Canopy-Observation of Photosynthesis and Energy fluxes) (Van der Tol et al., 2009) and 3D DART (Discrete Anisotropic Radiative Transfer) (Gastellu-Etchegorry et al., 2017) are considered to conduct R&D studies and depict CalVal sites serving for reference. These two sophisticated models include an energy balance and simulate hot spot depending on structural and environmental factors. SCOPE is reserved for homogeneous vegetation canopies whereas DART mock-up can simulate any target at any scale, notably including cities. CalVal activities will allow verifying that the deliverables of he TRISHNA mission will satisfy to users requirements.

2. Material and methods

The aim of TIRAMISU is to cross-calibrate SCOPE and DART models with in-situ measurements, then to use them to simulate dynamic BRDF datasets and perform study analysis. Effort is given on the strategy adopted to correct directional effects and perform normalization. The outcome will be calibrating a meticulously selected parametric model with retrieved parameters that can be implemented in the TRISHNA data processing chain.

TIRAMISU is an experiment designed to acquire optical and thermal vegetation BRDF simultaneously during the growing season. The equipment consists merely of an optical multi-spectral sensor plus a high-resolution thermal sensor, also other instruments to log meteorological data for thermal analysis to ensure continuous crop monitoring during the growing season with emphasis on water stress periods. The experimental design also allows data acquisition at high frequency in the TIR to characterize the turbulence and have an integrated BRDF. The equipment is moved or duplicated between stations to acquire a maximum of knowledge. Results are shown here for a paddy rice crop located at Nawagam site in Gujarat, south of Ahmedabad (India) in partnership with the Space Application Center and Anand Agricultural University (Figures 1 and 2).
Detailed instrumentation encompasses a MicaSense camera operating at 475nm, 560nm, 628nm, 717nm and 842nm plus an Optris camera measuring the thermal signal in the range 7.7µm-13µm. An Apogee sensor captures the thermal radiometry to serve as reference to cross-check the calibration with the Optris camera. The scanning system was positioned on a rotating turret in order to sample the BRDF in a few minutes. Windmaster device measured wind characteristics (direction, intensity). Data were continuously acquired day and night from July to October 2023. Ancillary measurements consisted on routine LAI collection and canopy height plus hyperspectral measures.

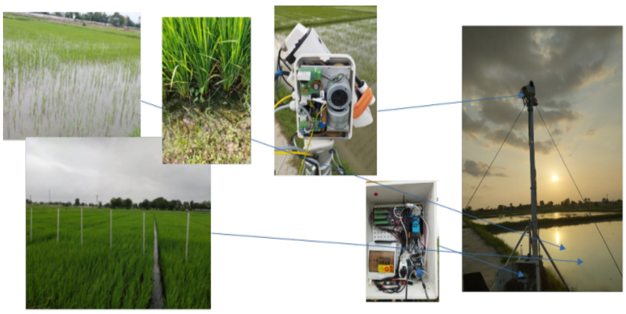


Figure 1. Overview of the paddy rice crop of the Nawagam site.

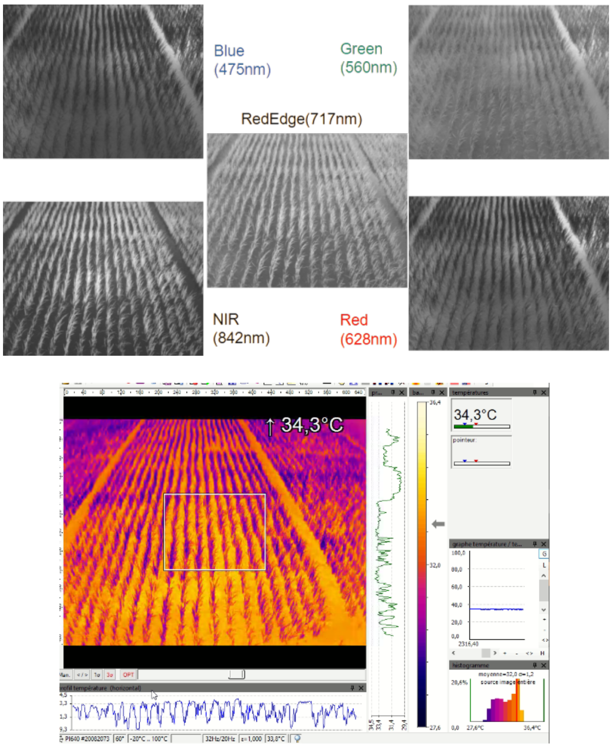


Figure 2. Sample image datasets over a paddy rice crop. Top: Micasense RedEdge-M five optical monobands. Bottom: Optris thermal image visualised in PIX connect software.

Simulated datasets using SCOPE 1D and DART 3D models aim at characterizing anisotropy effects in the thermal infrared with the help of similar optical information.

The Discrete Anisotropic Radiative Transfer (DART) model is one of the most comprehensive physically based 3D models simulating the Earth-atmosphere radiation interaction from visible to thermal infrared wavelengths. It models optical signals at the entrance of imaging radiometers and laser scanners on board of satellites and airplanes, as well as the 3D radiative budget, of urban and natural landscapes for any experimental configuration and instrumental specification.

DART provides a support to the investigations about atmosphere properties and Earth surface 3D architecture that often confound their interpretation. Radiative transfer models like DART that are capable to simulate the Earth and atmosphere complexity are, therefore, ideal tools for linking remotely sensed data to the surface parameters. Still, many existing models are oversimplifying the Earth-atmosphere system interactions and their parameterization of sensor specifications is often neglected or poorly considered.

The Soil Canopy Observation of Photosynthesis and Energy fluxes (SCOPE) model aims at linking satellite observations in the visible, infrared, and thermal domains with land surface processes in a physically based manner, and quantifying the microclimate in vegetation canopies. It simulates radiative transfer in the soil, leaves, and vegetation canopies, as well as photosynthesis and non-radiative heat dissipation through convection and mechanical turbulence. More recently, SCOPE has been applied in remote sensing studies of solar-induced chlorophyll fluorescence (SIF), energy balance fluxes, gross primary production (GPP), and directional thermal signals.

A DART mock-up was built to cross-calibrated with in-situ images and to investigate directional effects features by generating a spectral BRDF continuum (Figure 3). SCOPE-simulated datasets of the same scene reconfirm the accuracy and support parametric studies.

The ongoing development of DART initiates the capability of the DART model to reproduce observations in the TIR domain with more precision. It has been upgraded to include the energy budget, so-called DART-EB (-EB for energy budget with an integration using the SCOPE model). Figure 3 shows for instance the vertical temperature profile for rice crop.

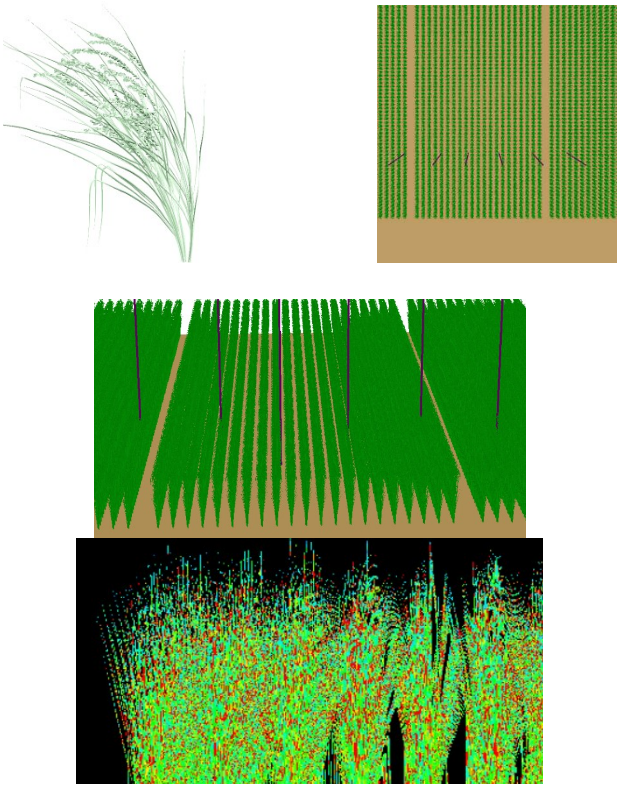
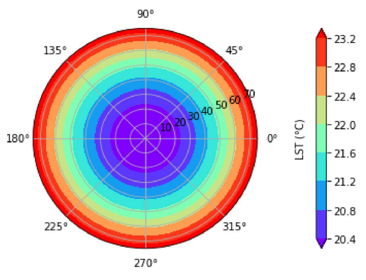
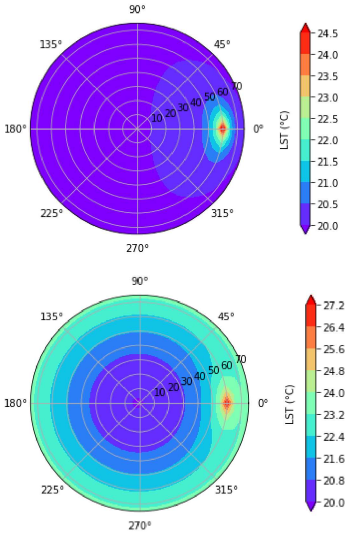


Figure 3. 3D Rice mock-up from DART. Stem design, top view (top), front view (middle) and DART-EB (bottom).

Physical models simulate accurately the measures but require many parameters, making them inappropriate in practice to process large data sets. Parametric models offer a good compromise between computation and accuracy and are suitable for operational purposes. Semi-empirical kernel-driven (or so-called kernel-driven model KDM) models in TIR like RL (Roujean-Lagouarde) (Duffour et al., 2016; Cao et al., 2021) will be considered for TRISHNA based on assessment studies (Cao et al., 2021; Sofia et al., 2018). KDMs impose constraints on physical coefficients to best fit the empirical values. Figure 4 illustrates a generic KDM.



a)



b)

c)

Figure 4. Contour plots of kernels a) Baseshape kernel b) HotSpot Kernel c) Modeled BRDF with KDMs

Three variables must be estimated in the case of RL model: the temperature difference between the nadir and hot spot, a structural parameter, and the nadir temperature. RL model is calibrated with physical variables issued from DART and SCOPE simulations in order to normalize LST which depends on several parameters in TIR, such as emissivity, soil moisture content, and environmental factors (Duffour et al., (2016) [7]) in addition to the structure.

The hot spot is intense when Leaf Area Index is large because it relates to the probability of a photon to reach the soil background and to escape in the same direction. This is equivalent to see all sunlit areas and no shadows. The amplitude of the phenomenon both depends on canopy depth and leaf size. The more is dense the canopy and small leaves the more hot spot peak is narrow and marked. On the opposite, sparse canopies with big leaves would create a large hot spot task with poor intensity.

3. Results and discussion

The expected results from TIRAMISU experiment are several. First it is expected to characterize directional effects as a function of time (both on daily and hourly basis), of the growing season (phonological stage), and on environmental conditions (radiation, wind, air temperature and humidity). LST is an ephemeral variable and it may be complicated to disentangle time variations from directional effects. In other words, how directional effects impact on DTC (Diurnal Temperature Cycle) is a central question, in particular if the hot spot effect is noticeable as other peaks like solar radiation and emissivity may also combine and their timing may be uncertain.

Actually, how these directional effects vary with the wavelength is also central because vegetation indices (notably the Normalized Difference Vegetation Index NDVI) are very exploited and also contaminated by directional effects.

From the simulations over crops, using directional gradients of NDVI and LST, it is possible to find simple relationships about the hot spot geometry driven by leaf area index and leaf size compared to canopy depth. However, these relationships vary with dry versus wet conditions for the vegetation canopies, soil moisture and resistance, and wind speed. Analysis of DTC is performed for several groups of pixels (averaged 10 by 10) of Nawagam station (Figure 5).

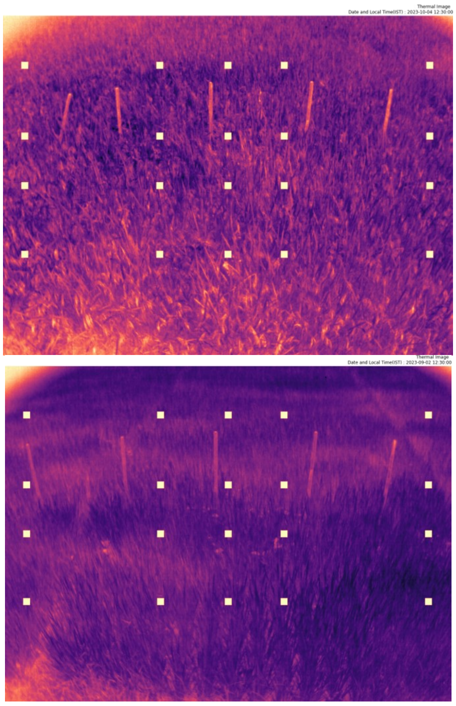


Figure 5. Images of the thermal cameras with selected areas.

It shows a high dispersion around noontime due to turbulence, less shadows, changing humidity and thermal inertia (Figure 6).

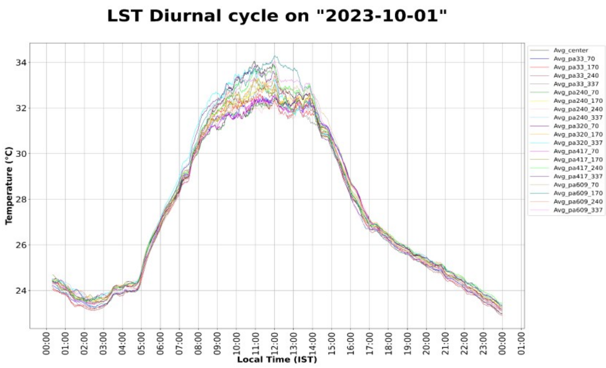


Figure 6. DTC for various samples of paddy rice crop of Nawagam.

The impact of directional effects is revealed when estimating the difference in LST for pixels located in the center of the camera with other pixels of the image. This difference can reach up to 2K (Figure 7).

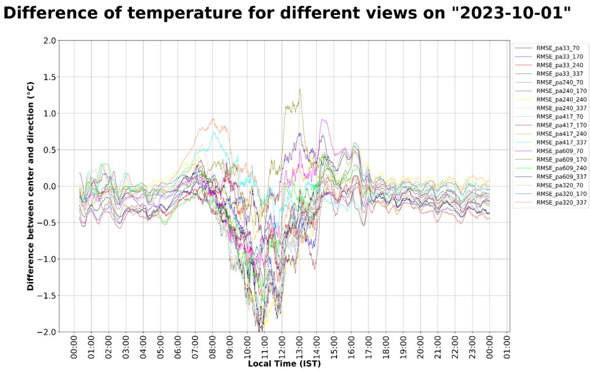


Figure 7. DTC for pixels directional difference of paddy rice crop of Nawagam.

Results of KDM model inversion including time component will be tested against TIRAMISU data sets to evaluate the model coefficients evolution during the growing season and as a function of changing structure and environmental factors measured in situ routinely.

The main outcomes of TIRAMISU experiment concern the next issues :

- Hotspot conditions are tracked ($\cos\xi = \cos(\theta_s).\cos(\theta_v) + \sin(\theta_s).\sin(\theta_v).\cos(\varphi_s - \varphi_v)$) for the clear data, and DTC plots are studied against other radiometric and air temperature acquired at the site.
- Similar work is underway to study diurnal reflectance cycles for optical images from the sensor.
- Solar peak, directional conditions, and thermal inertia are considered to completely understand thermal anisotropy.
- Fluctuations in temperature measurement are highly proportional to the wind speed.
- The difference between Apogee radiometric and thermal image temperature varies based on the directional conditions and the pixel scene (temperature gradient between background and vegetation).

Period of time integration is important to minimize the undesirable effects due to environmental factors, in priority turbulence and wind. Turbulence operates at high frequency and averaging over 1 minute for instance solves generally the problem. The wind influence is more complicated to circumvent. Actually, it has various effects. From the thermal point of view, it can either cool down the target or warm it up and then change the air temperature just above the canopy, thereby enhancing air motion just above the canopy layer and the turbulence regime. It can also modify the geometry of the canopy by letting observe more soil background. In the present case, the soil background represented by water has a different emissivity than the paddy rice crop. Therefore, the wind may act at discovering different parts of the canopy and the integrated emissivity may change from the point of view of the observer.

Figure 8 reveals the impact of wind and thermal measurements collected at the same time. No clear correlation is evidenced however.

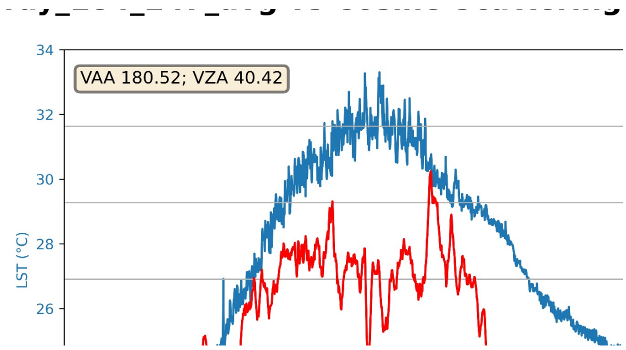


Figure 8. Thermal image pixel group DTC (1-minute interval) positioned at the center (blue line) and wind speed in m/s (red line).

We further investigated the directional effects in analyzing the DTC for pixels observed under different angles. The tools for analysis are on one hand the radiometer measurements from the Apogee that is well-calibrated and can serve of reference to make reliable the Optris measurements with the thermal camera.

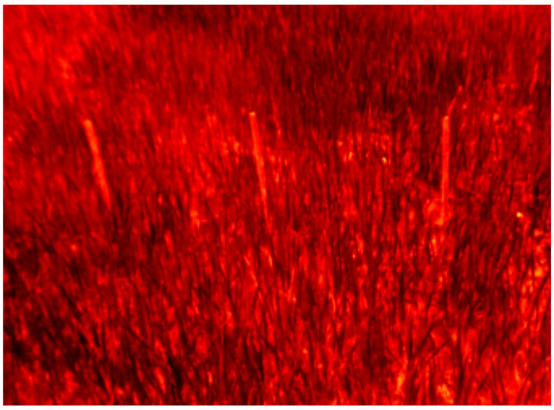


Figure 9. Square (group of pixels) over acquired thermal image representing the principal plane (PP) indicating the hotspot conditions on -02-10-2023.

The examination of the pixels potentially contaminated by the hot spot relies on the identification of the pixels located in the Principal Plane (PP), i.e. when the source of illumination, the observer and the target are aligned. Figures 10-11-12 exemplifies the location of these pixels.
DTC have been extracted for a set of pixels.

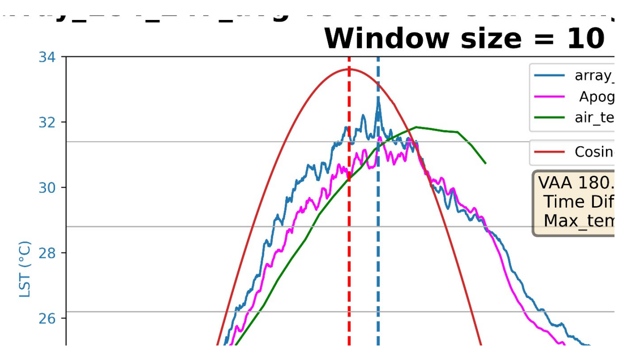


Figure 10. DTC (averaged over 10-minute intervals) plus Apogee radiometric temperature, and air temperature. This corresponds to the central pixel of the image.

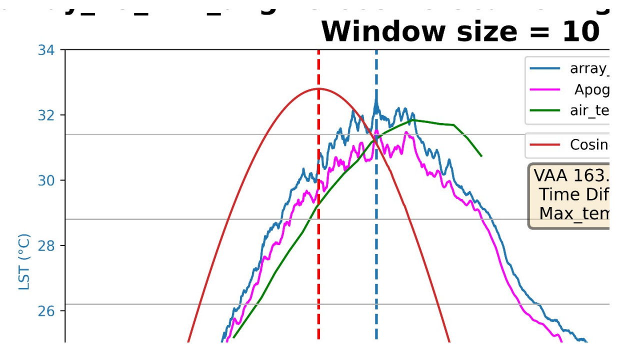


Figure 11. Idem Figure 10 for a pixel located in the center top of the image.

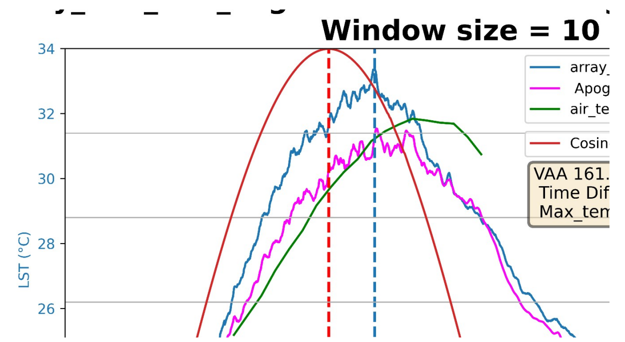


Figure 12. Idem Figure 10 for a pixel located in the bottom right of the image.

The results show a good level of correlation between DTC for the 3 extracted pixels and the DTC for the air temperature, particularly in the morning. Also a good correlation exists between the signal from camera pixels and the Apogee whereas the more important bias is conspicuous for the pixel located on the edge of the image as it could be expected.

The red curve shows variations of the cosine of the scattering angle. As it approaches the value of 1, the hot spot effect is present and a thermal peak is expected. Nevertheless, no clear signal appears here and although the hot spot effect is certainly present, other sources of perturbations such as wind seem to mask the amplitude of the phenomenon.

Another explanation could be that the projections of shadow cast from the rice stems are scattered in the field of view of the camera. Moreover, these darkness spots are hardly detectable from the underlying water which has a dark reflectance.

In addition, diffusion radiation from the sky may dampen the phenomenon. Still some residue of air pollution was observable on site actually.

4. Conclusion

The objective of the TIRAMISU project is to acquire on hourly and seasonal basis simultaneously high-resolution images of canopy elements in the optical and thermal spectral ranges plus environmental variables. From this, it is expected to better target which factors primarily play on TIR BRDF, to be further considered to perform a directional correction.

Herein, the DTC shape doesn’t get shifted based on directional conditions and is more dependent on the solar peak. The absolute value of the DTC peak depends on the directional conditions and several other factors. Significance of anisotropy effects on Nawagam datasets are reduced due to the water background. This will be further investigated based on DART simulations. Combining a DTC model with a BRDF model will help investigating the thermal anisotropy more deeply and less affected by invalid observations.

TIRAMISU initiative aims at federating activities related to CalVal. The overal objective is to establish a protocol of measurements in accounting for perturbing effects on the TIR signal, merely directional anisotropy and environmental factors. It is foreseen to reproduce TIRAMISU for other types of crops or ecosystems, with maybe some customized protocols. The outcomes of this research work will benefit to future TIR missions such as TRISHNA and later in time SBG from NASA and LSTM from ESA, in regard to the dependence of LST on surface anisotropy properties and the need to apply angular correction procedures.

Acknowledgements

This work was supported by TOSCA (CNES funded programme supporting the space research).

Chandrika Pinnepalli received a doctoral fellowship from CNES and ACRI.

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