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D18 – Potentials and limitations analysis for CHIME and LSTM

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Contents

Executive Summary

The overall aim of the "D18: Potentials and limitations analysis for CHIME and LSTM missions" is a critical analysis of the impact that future missions like CHIME and LSTM could have on the specific subject of the Afri4Cast project. This analysis will be carried out considering the experience gained by trying to use hyperspectral (PRISMA) and thermal (ECOSTRESS) imagery as a source of information for implementing services that stand on two pillars: food security and safety in Africa.

1. Introduction

1.1. Technical Description

AFRI4CAst aims to provide scientific and technical support to Food Security and Safety policies in Africa. One of its core functionalities is centered on the provision of timely in-season crop yield forecasts and disease outbreaks warnings for the major cereals wheat, maize and rice. The system aims at monitoring wheat, maize and rice growth and include the short-term effects of meteorological events on crop production, disease outbreaks and mycotoxin formation. Among the EO satellite data which will be employed the hyperspectral sensor PRISMA and the thermal sensor ECOTRESS should be mentioned. A second core functionality is to monitor crop development, forecast crop production and mycotoxin risk and provide information on vulnerability in specific areas through multiannual crop and mycotoxigenic fungi projections. The project aims at assessing the added value that EO satellite based products could provide taking into account the specificity of the area of interest located in the equatorial belt.

2. Terms, Definitions and Abbreviation Terms

Table of Acronyms

AFB1	Aflatoxin B1
AfSoilGrids250m	African SoilGrids database at 250 m spatial resolution
APSIM	Agricultural Production Systems Simulator
ASI	Italian Space Agency (Agenzia Spaziale Italiana)
asl	Above Sea Level
BBCH	Biologische Bundesanstalt, Bundessortenamt and CHemical industry
BOA	Bottom-Of-Atmosphere
CC	Canopy Cover
CCx	Maximum Canopy Cover
CDC	Canopy Decline Coefficient
CDS	Copernicus Climate Data Store
CHIME	Copernicus Hyperspectral Imaging Mission for the Environment
CNES	National Centre for Space Studies
cos	Cosine
CropSyst	Cropping Systems Simulation Model
D6	Deliverable 6
DI	Disease Index
DLR	Germa Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt)
DSSAT	Decision Support System for Agrotechnology Transfer
ECOSTRESS	ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station
EFSA	European Food Safety Authority
EO	Earth Observation
EPIC	Environmental Policy Integrated Climate
ERA5	ECMWF Atmospheric Reanalyses of the global climate
ESA	European Space Agency
ET	EvapoTranspiration
EU	European Union
FAO	Food and Agriculture Organization
fAPAR	Fraction of Absorbed Photosynthetically Active Radiation
fCOVER	Fraction of soil surface covered by the green canopy
GML-LOOC	(Gaussian Maximum Likelihood classifier with Leave-One-Out-Covariance Estimator)
HSI	Hyperspectral Sensor Imager
ISRIC	International Soil Reference and Information Centre.
ISRO	Indian Space Research Organisation
KF	Kalman Filter
L-2A	Sentinel-2 Level 2A
LAI	Leaf Area Index
LDA	Linear Discriminant Analysis
LSTM	Land Surface Temperature Monitoring

LTDN	Local Time at Descending Node
MADIS	Meteorological Assimilation Data Ingest System
MCMC	Markov Chain Monte Carlo
MODIS	Moderate Resolution Imaging Spectroradiometer
MSI	Multispectral Instrument
NASA	National Aeronautics and Space Administration
NRT	Near Real-Time
NSSO	Non Sun-Synchronous Orbit
OBS	Observed
PLSR	Partial Least-Squares Regression
PRISMA	PRecursore IperSpettrale della Missione Applicativa
PROJ	Projections
PSO	Particle Swarm Optimization Algorithm
S-2A	Sentinel-2A
S-2B	Sentinel-2B
SAR	Synthetic-Aperture Radar
SBG-TIR	Surface Biology and Geology-Thermal InfraRed
SNAP	Sentinel Application Platform
SNR	Signal to Noise Ratio
SRF	Spectral Response Function
SSO	Sun-Synchronous Orbit
STICS	Simulateur multidisciplinaire pour Les Cultures Standard
SVM	Support Vector Machine
SWAT/SWIM	Soil and Water Assessment Tool / Soil and Water Integrated Model
SWIR	Short-wave infrared
SZA	Solar Zenith Angle
TOA	Top-Of-Atmosphere
TOC	Top Of Canopy
TRISHNA	Thermal infraRed Imaging Satellite for High-resolution Natural resource Assessment
VI	Vegetation Index
VIS-NIR	Visible-Near infrared
WOFOST	WOrld FOod Studies model

3. CHIME

3.1. Mission

CHIME (Copernicus Hyperspectral Imaging Mission for the Environment) is an ESA mission that will carry a unique visible to shortwave infrared spectrometer to provide routine hyperspectral observations to support new and enhanced services for sustainable agricultural and biodiversity management, as well as soil property characterization. The mission will complement Copernicus Sentinel-2 for applications such as land-cover mapping.

The system will consist of two satellite, CHIME-A and CHIME-B, and the first launch is planned for December 2029 with an 8-years estimating operational life. The HyperSpectral Imager (HSI) will be able to image in more than 200 bands covering the wavelength range from 400 nm to 2500 nm in the Visible (VIS), Near Infrared (NIR) and Short-Waver Infrared (SWIR) region of the electromagnetic spectrum with a spectral bandwidth less the 10 nm. It will be able to measure at a ground resolution of 30 m for a swath width of 130 km with high radiometric accuracy for Level-1B data.

CHIME satellites will be in a sun-synchronous orbit at an altitude of 632 km with an orbital inclination of 97.9°. The orbital period of these satellites will be 97.5 minutes with a repeat cycle of, at least, 21 days for a single satellite to guarantee the full coverage of the equatorial belt. Therefore, when both satellites will be in opportunely phased orbit, a revisit frequency of 10.5 – 11 days will be achieved.

For the observation (overpass) time a LTDN (Local Time Descending Node) of 10:30 has been considered as preferrable for compatibility with Sentinel-2, with an acceptable range up to 11:30. This time is a good compromise between illumination conditions (better towards noon), cloud coverage (higher towards noon), and angular effects (higher for low sun elevation angles in the morning).

Compared to the two hyperspectral precursor missions, EnMAP (DLR) and PRISMA (ASI), CHIME will provide an enhancement allowing continuous and fully operational hyperspectral mapping of the Earth’s surface.

3.2. Hyperspectral Sensor

The hyperspectral sensor (HIS) on board of CHIME is a pushbroom-type grating Imaging Spectrometer with high signal-to-noise ratio and data uniformity. The Next Generation Airborne Visible Infrared Imaging Spectrometer, AVIRIS-NG, instrument resembles the capabilities that CHIME will have once in orbit. Measurements taken with AVIRIS over many test sites that represent different types of ecosystems are helping scientists and engineers prepare for and ensure that CHIME will be able to take up duty delivering high-quality diagnostic and quantitative data as soon it is in orbit and operational.

Most of these flights coincide with measurements taken on the ground to further help evaluate the data collected by the airborne instrument.

Figure 1: An artistic sketch of CHIME satellite. It will carry a unique visible-to-shortwave infrared spectrometer to provide routine hyperspectral observations, (image credit: Thales Alenia Space).

The main characteristics of the sensor are given in Table 1 (Buschkamp et al., 2022).

Table 1: CHIME HSI Instrument Key-Performance parameters.

Parameter	Design Value
Spectral range	400 nm – 2500 nm
Spectral resolution	< 11 nm
Spectral Sampling Interval (SSI)	8.4 nm

Spectral Stability	< 0.2 nm
Spatial Sampling Distance (SSD)	< 31 m
SNR	~300-400 up to 1350 nm ~> 200 up to 1750 nm ~50-150 up to 2500 nm
MTF (@ Nyquist)	>0.25
Field of View (FOV) (Swath)	< 11.7° (~130 km)

The main radiometric performance figure is the signal to noise ratio (SNR), which is shown in Figure 2. The figure shows the signal to noise ratio of the PDR status for realistic worst-case assumptions for the detector performance. The realistic worst-case assumptions consider all bottom-up analysis available at PDR (Preliminary Design Review) as well as assumptions on the detector read noise and quantum efficiency based on the detector predevelopment phase (Buschkamp et al., 2022). As a comparison Figure 3 shows the corresponding SNR behavior for PRISMA.

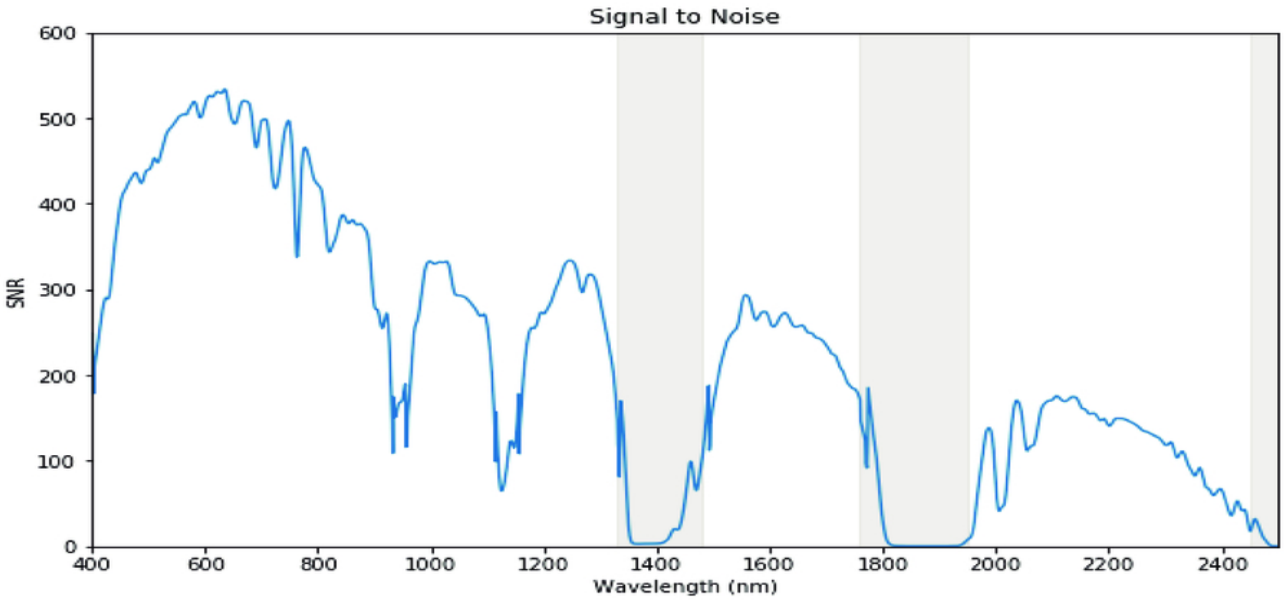


Figure 2: CHIME HSI Signal to Noise graph; grey bars are exclusion zones (set by atmospheric absorption).

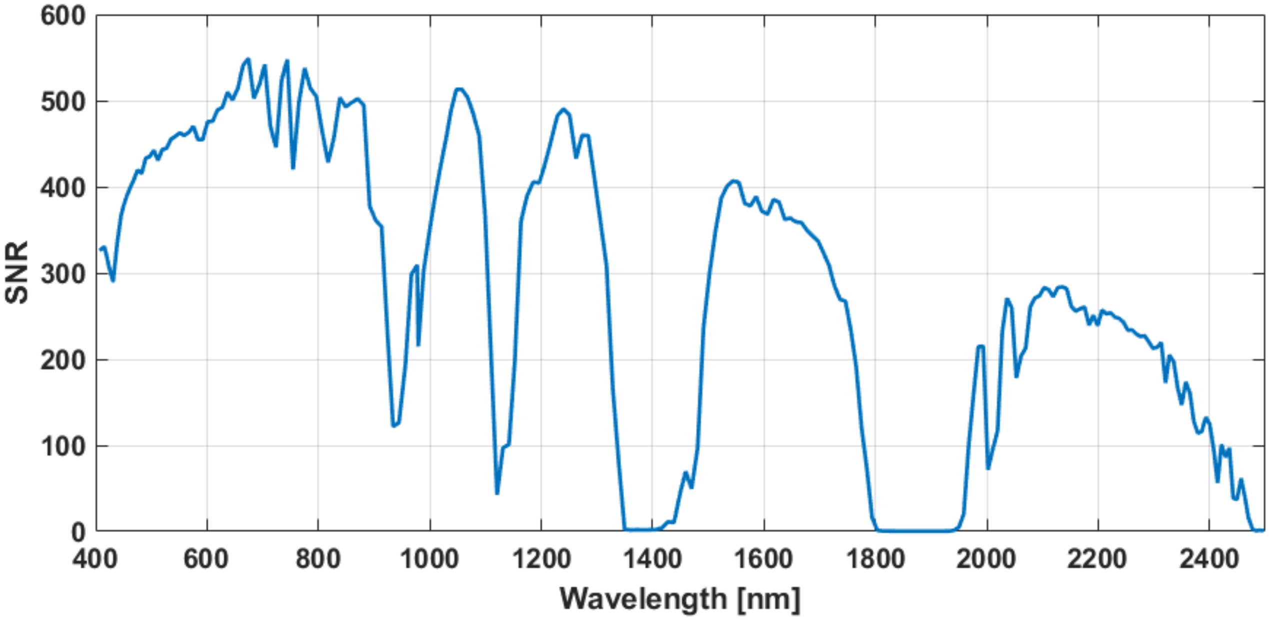


Figure 3: PRISMA Signal to Noise graph.

3.3. CHIME – PRISMA Comparison

As previously described (D3: "State-of-the-art review report on the EO analysis methods and algorithms"), PRISMA is a hyperspectral satellite launched by ASI in 2019. From the point of view of the spatial resolution, orbit altitude, LTDN and the range of the electromagnetic spectrum covered by the two sensors (HSI and PRISMA), the two missions appear to be very similar to each other, both in terms of orbit and sensor. This feature, in view of future developments, makes all the product chains so far developed and applied to PRISMA applicable on CHIME, providing consequentiality and great potential to the project.

But at the same time, this could mean that CHIME will also be affected by the same issues that we are currently experiencing with PRISMA when we try to use this sensor to implement some of the services planned for Afri4Cast, namely a limited availability of usable imagery over the specific areas of the project.

In the case of PRISMA, the main causes for the reduced number of images made available for the project are logistical and geographical. Logistical one refers to the probable low priority given to the image acquisition requests of Afri4Cast compared to other ASI projects, which allows the possibility of acquiring data only when the request does not in conflict with other requests. The geographic one refers to the fact that the areas of interest, located in the equatorial belt, are frequently subject to heavy cloud cover.

CHIME, differently from PRISMA, and EnMAP, will acquire continuously along the descending segment of the orbit with SZA < 80° as the other satellites of the Copernicus constellation. Further, the swath of the sensor is significantly higher than PRISMA (and EnMAP), 130km versus 30km. As a consequence, the revisit frequency will be much lower of that one guaranteed by PRISMA (and EnMAP): 21 days with a single satellite and 10.5 – 11.0 days with two satellites. PRISMA (and EnMAP) with is swath, to cover the whole equator, requires more than 2 months. However, thanks to its possibility of tilting the instrument of ±20° off-nadir, it allows to observe the same area with a maximum frequency of 7 days (Table 2). But, in general, the area covered instantaneously (30km) is much smaller of the one covered by CHIME (130km).

The problem of the unavailability of remotely sensed images due to the frequent cloud cover of the area of interest will remain unresolved. This problem can be partially resolved increasing the frequency of observation of the area by phasing opportunely the orbits of CHIME A e B, PRISMA, EnMAP and any other hyperspectral sensor that will be launched in the next years. In order to reach a frequency of probability (in case of no clouds) of observation of 2 – 3 days.

Figure 4 shows the difference between the spectral resolution of PRISMA and the one expected for CHIME (Table 1) which seems significantly better between 600 nm and 2200 nm.

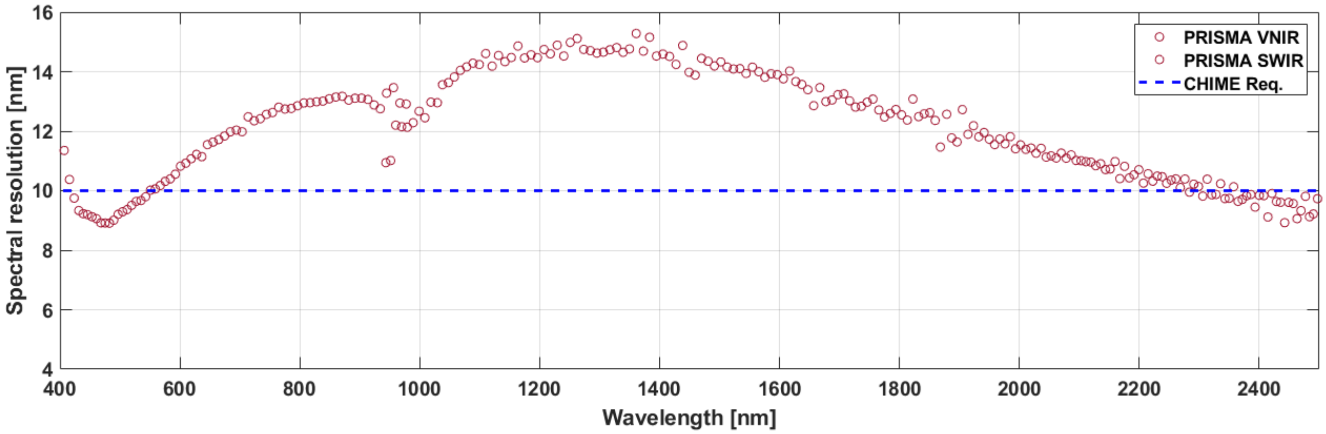


Figure 4: Comparison of the PRISMA spectral resolution with the one expected for CHIME.

3.4. Potential

The application of hyperspectral imaging in the field of agriculture and food security involves at least three areas:

- Assessment of biophysical and biochemical variables related to the crops and of agronomic interest;
- Topsoil properties retrieval, related to soil fertility and degradation;
- Detection of crop stress due to different causing agents.

The variables of interest are those characterizing the structure of the vegetation cover (Leaf Area Index, fraction of photosynthetically active absorption absorbed), those describing the biochemistry of the leaves (pigment content) and the water content (Normalized Difference Water Index, Live Vegetation Moisture Content). Plant canopy structure properties affect most processes that couple plants to their surrounding environment, such as radiation interception and hence photosynthesis and evapotranspiration. The biochemical parameters give a characterization of the structure and the functioning of vegetation, with implications in the prediction of crop growth and yield estimations and allow the extraction of information on the physiological state of leaves or plants.

Chlorophyll is sensitive to soil nitrogen availability, making it probably the most effective biophysical indicator of nitrogen deficiency, one of the main limiting factors (together with water) affecting plant growth and production. Due to the importance of these pigments in the photosynthetic function, variations in pigments content could provide information on the physiological and nutritional status of leaves or plants. Even changes of carotenoid content in plants are closely related with environmental stress, including water shortage or low nitrogen supply.

Understanding the variability of soil properties between and within agricultural fields allows for more efficient use of resources, improving agronomic and environmental management. The qualitative information included in existing soil maps is often insufficient for site-specific management strategies concerning water, fertilizers, herbicides or harvest. For these purposes, the quantitative estimation of soil properties (e.g., soil salinity, texture, organic carbon and mineralogical composition) over the field is necessary.

The deliverable D1.3 (‘State-of-the-art review report on the EO analysis methods and algorithms’) contains a list of spectral indices able to retrieve specific vegetation traits (structure, chlorophyll, carotenoids, water content, dry matter). As is shown there, such indices are designed to work at best when spectral reflectance at specific wavelengths are available. As we move away from those, or the spectral resolution decreases, the prediction accuracy of such indices decreases.

In particular, with reference to the estimate of the vegetation traits, the potential improvement deriving from the enhanced spectral resolution of CHIME, with respect to PRISMA (Figure 4), can be explained through Figure 5 in which the absorption profiles of different vegetation pigments are shown. Pigments produce a unique absorption pattern in the visible spectrum, higher the spectral resolution higher the probability to correctly estimate there presence in the leaves.

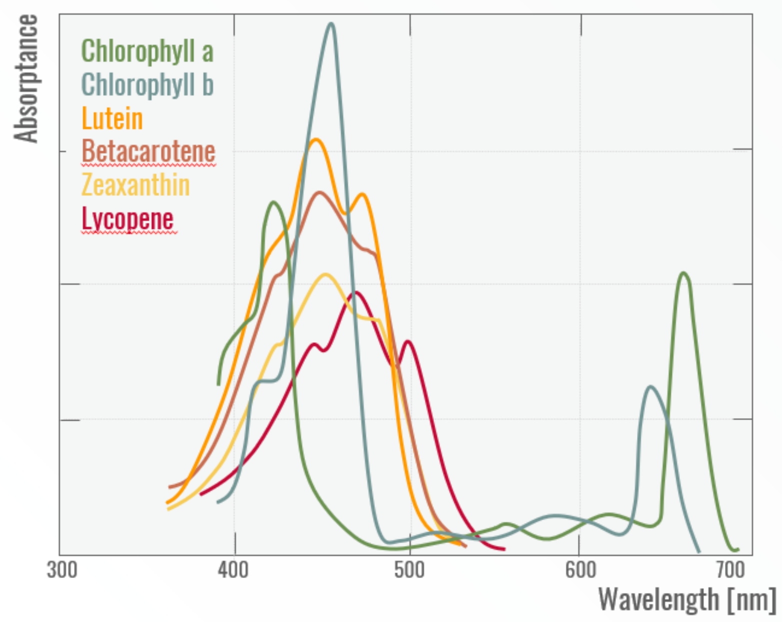


Figure 5: Absorption pattern for different vegetation pigments in the visible region of the electromagnetic spectrum (from EnMAP Education Initiative).

Also, the accuracy of the image classification could be improved as consequence of an enhanced spectral resolution. An example of this improved capability is reported in Dalponte et al. 2009 (Figure 6). The figure refers to the *Bosco della Fontana* and *Val di Sella* (Italy) datasets, both the SVM (Support Vector Machine), LDA (Linear Discriminant Analysis) and GML-LOOC (Gaussian Maximum Likelihood classifier with Leave-One-Out-Covariance Estimator) classifiers reduced their accuracy as the spectral resolution of the sensor was reduced. In particular the LDA classifier was strongly influenced by the spectral resolution. It reduced noticeably its accuracy as the spectral resolution decreased. Also, the SVM classifier decreased its accuracy as the spectral resolution was reduced (approximately 1% from 4.6 nm to 9.2 nm, and 5% from 9.2 nm to 36.8 nm).

Concerning the topsoil property, Valentini et al. (2022) confirm that the SWIR spectral range 2,000–2,400 nm is the most relevant part of the spectrum for topsoil properties retrieval. One of the issues with hyperspectral satellite sensors is related to the fact that the quantitative predictions of soil properties were hampered by a very low SNR ratio in the SWIR region (i.e., Hyperion onboard EO1 satellite and CHRIS onboard PROBA satellite). Unfortunately, the sensor's noise generally increases when increasing the spectral resolution. This effect can be observed by comparing SNR behavior in Figure 2 and Figure 3. Anyway, it should be observed as in CHIME, notwithstanding the improved spectral resolution, a good value of SNR is preserved. In Adeline et al. (2016), the ability to predict soil properties from initial to degraded spectral configurations was assessed for clay, free iron oxides, CaCO3 and pH, with PLSR (Partial Least-Squares Regression) models and spectra acquired on an ASD portable field spectrometer. The estimation of soil properties involving specific spectral features (i.e., clay, iron and CaCO3) is qualitatively sensitive to spectral degradation. Of course, this decrease in performance was low, especially when the spectral feature was large and pronounced (e.g., iron) or the correlation between soil properties was strong. On the other hand, soil properties with no spectral features such as pH only relied on the beneficial effect of correlations (in the mentioned paper dataset, CaCO3-pH) and their prediction was is sensitive to spectral degradation because less soil information is progressively contained in the spectra.

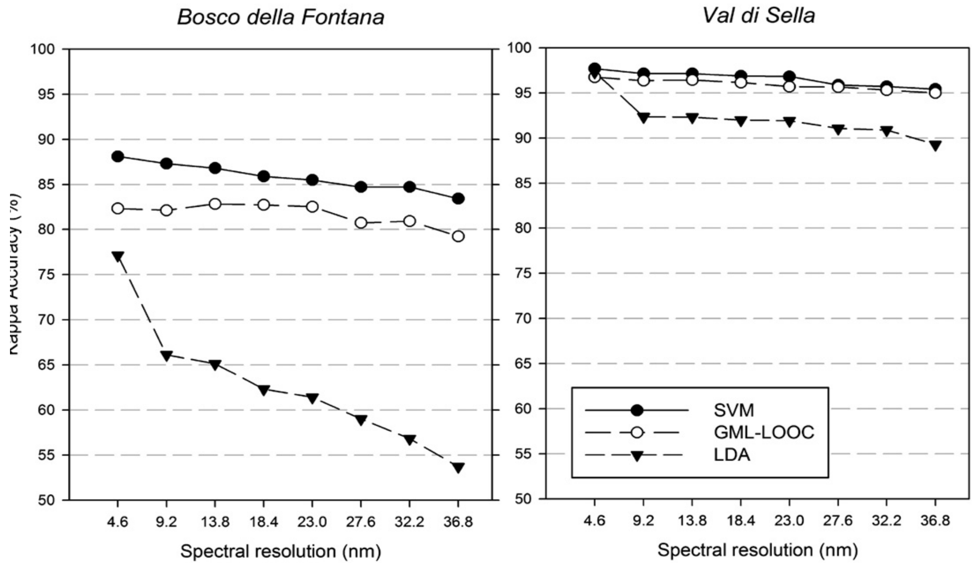


Figure 6: Behavior of the kappa accuracy of the analyzed classifiers versus the spectral resolution for the two datasets considered (Dalponte, 2009).

3.5. Limitations

The main limitation in the use of hyperspectral sensors like CHIME to support agriculture management in the equatorial area is represented by the frequent presence of clouds. As you can see from Figure 7, the agricultural areas where field data were collected in 2023 the probability of presence of clouds reaches the 37%. It means, that in about 2 cases over 5 the observation of the area of interest could be hampered by clouds. However, this explains only partially the reason why we have only few hyperspectral PRISMA and EnMAP images available on the area of interest (Table 2). Another relevant reason might be found in the way these two missions operate.

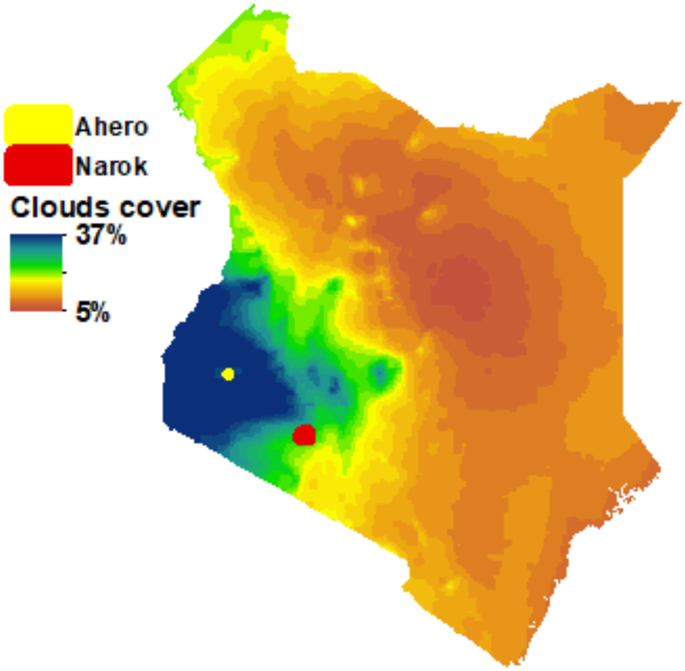


Figure 7: Distribution of the cloud cover frequency for Kenya computed by using 10 years of the SEVIRI geostationary sensor images. Red and yellow areas represent the area on which the field data have been collected

In fact, both sensors, differently from CHIME, do not collect images routinely along the descending part of the orbit but following an acquisition plan based on users requests or needs coming from project funded by the ASI (Italian Space Agency) and DLR (German Aerospace Center). Therefore, CHIME, thanks to its systematic acquisition at 11 days revisit frequency (2 satellites), would significantly increases the opportunity of observations of any area of the Earth. In the specific case of agriculture application, it allows tracking the phenology phase of the crops for detecting possible stress conditions of the crop (lack of water, diseases, etc.) and the estimate of yield based on models fed by information (LAI, vegetation water content, soil moisture, etc.) retrieved from hyperspectral images. The obstacle represented by clouds remains.

Table 2: List of hyperspectral images available on the agricultural areas in which field data were collected.

Area	PRISMA	EnMAP
Ahero	08/10/2023, 14/10/2023, 06/11/2023, 08/01/2024	No image available
Narok	18/06/2020	No image available

To further highlight the impact of the clouds on the possibility of exploiting remote sensing images to monitor agricultural areas we have analyzed the Sentinel-2 cloud free images available in the period 2019 – 2023 on the two crop areas (Ahero and Narok, Figure 7) sampled by local partners in 2023.

Figure 8 shows the distribution, in percentage, of the cloud free images according with the period of the year during the 5-year interval between 2019 to 2023. The analysis refers to the two crop areas for which ground data were collected in 2023.

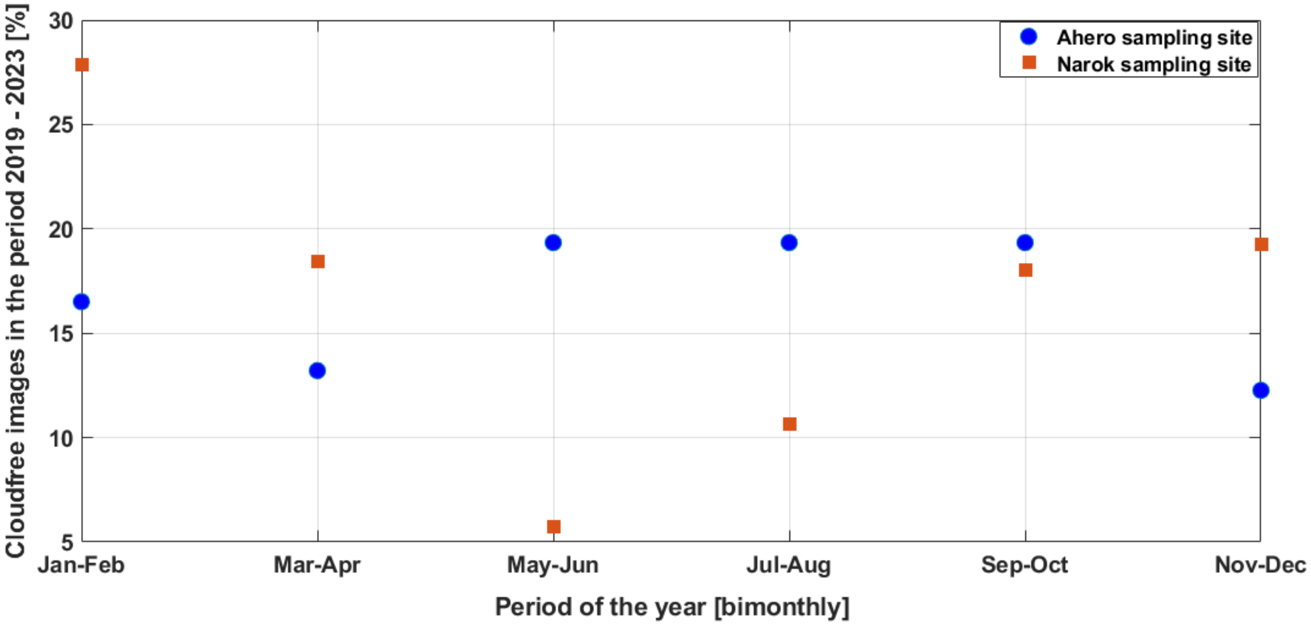


Figure 8: Distribution as function of the period of the year (in percentage) of the Sentinel-2 cloud free images available for the two crop areas on which field data were collected in 2023.

Figure 9 shows the number per year of Sentinel-2 cloud free images available, bimonthly on the two areas selected for the in situ measurements. The average refers to the 5-years period 2019-2023. From both figures we can see as for the Aharo area, located near the Lake Victoria, the number of cloud free images is almost constant during the year whereas in Narok the seasonal variability of the availability of cloud free images is more evident, reaching a minimum during the long raining season between May and August and a maximum during the dry season, from December to February.

Other interesting results of the analysis are shown in the Table 3, that shows:

- The averaged time distance between two cloud free images of each one of the two sites of interest;
- The maximum time interval without useful images;
- The dispersion of a time differences relative to its mean (standard deviation).

Table 3: Statistic values for the Sentinel-2 cloud free images on the crop sites monitored in 2023

Time period: 2019 – 2023	Ahero	Narok
Averaged revisit frequency in 5 years [days]	9	8
Maximum interval without images [days]	55	52
Standard Deviation [days]	7	9

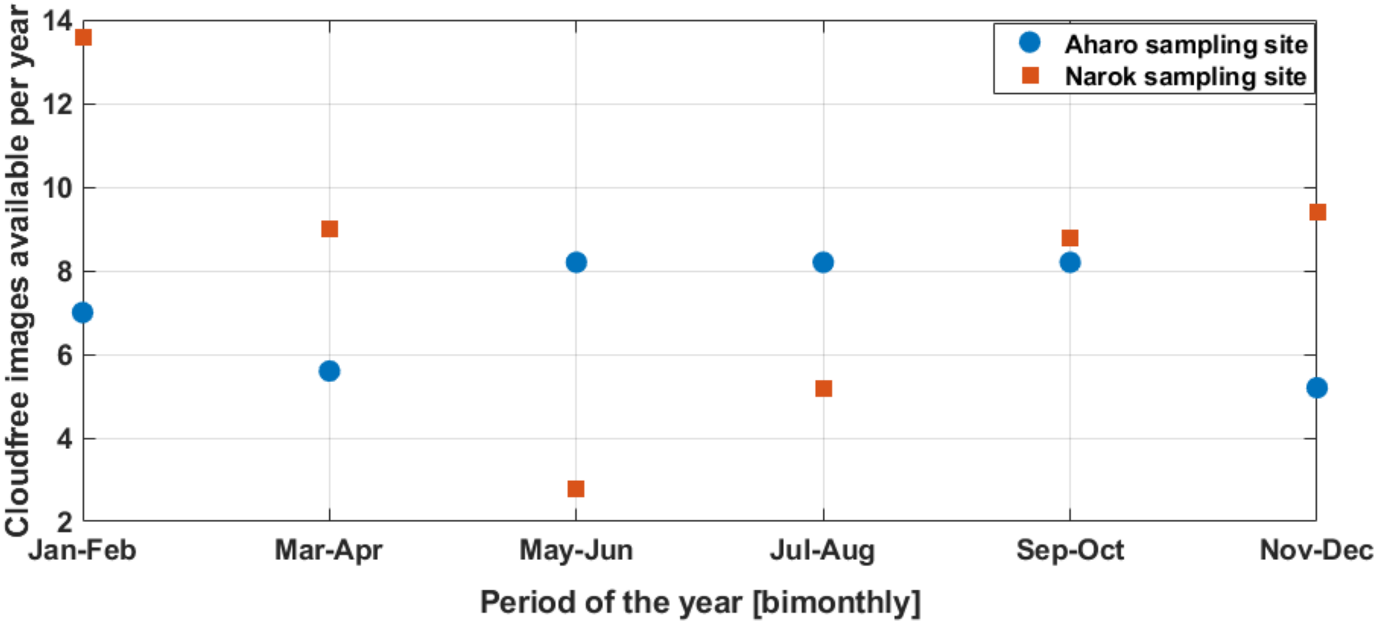


Figure 9: Number of Sentinel-2 cloud free images acquired, in average per year [2019 – 2023], on the two crop areas for which field data were collected in 2023.

The results shown in Figure 8, Figure 9 and Table 3 refer to Sentinel-2 constellation that has a nominal revisit frequency of 5 days and even less at medium/high latitude. We can observe as during the May-June period, corresponding to the raining season, 2 cloud free images are, in average, available. This means 1 (one) image per month. Now, if we consider the expected revisit frequency of CHIME (11 days) we can assume that in the same period of two months a single image will be made available. This means that, probably, we cannot aspect to be able to perform, with CHIME, a crop monitoring at the requested frequency of 10 or 15 days. Therefore, we have to find a way to combine multi and hyperspectral images to exploit the advantages of the higher revisit frequency of multispectral sensors and the higher spectral resolution of hyperspectral sensors.

In the document “Survey on current hyperspectral applications and identification of novel applications” prepared by e-GEOS (e-GEOS-HYP-TN-0006) in the framework of the Hyperspectral Imaging Mission Concepts project funded by ESA is written that, for crop mapping and monitoring, a monthly revisit frequency would be enough, but due to the cloud cover usual risk, acquisitions every 10-15 days would be more appropriate to be sure of receiving around one image per month, to be inserted in the workflow. In agriculture sector, especially in CAP (Common Agricultural Policy) tasks, near real time provision is generally not necessary: a few days’ provision after acquiring does not affect the information value. This phrase refers to the application of the European new “Greening CAP” that requests to identify with high accuracy individual crops. An example is the "crop diversification" application, imposed by the new “Greening Policy”, where it is necessary to separate barley and wheat (impossible through simple multispectral data) on the same farm declaration.

4. LSTM Mission

4.1. Mission Description

LSTM (Land Surface Temperature Monitoring) is an ESA mission developed by Airbus Defense and Space, set to join the Copernicus Sentinel system in 2028. The satellite will have Thermal Infrared (TIR) observation capabilities over land and coastal regions in support of agriculture management services, and possibly a range of additional services. The LSTM mission will consist of two satellites, LSTM-A and LSTM-B.

The mission's primary objectives are to monitor evapotranspiration (ET) rates by capturing the variability of Land Surface Temperature (LST), as well as map and monitor soil composition. LSTM also has a range of TIR observational applications including coastal zone management, and monitoring of High-Temperature Events (HTE) and urban heat islands.

The TIR instrument will operate in Very Near Infrared (VNIR), Short Wave Infrared (SWIR), and Thermal Infrared (TIR) spectral bands. The instrument has a spatial resolution of 50 m, making observations covering a wide temperature range, from approximately 253 K to 350 K with a precision of 0.3K. The imager can provide daily measurements from five bands in the TIR spectral range 8 - 12.5 µm complemented by bands in the visible and NIR.

LSTM will operate in a low-Earth polar orbit, with a four-day revisit period. The mission will map the surface temperature of Earth and rates of evapotranspiration every 1 - 3 days.

Figure 10: Artist's rendition of the deployed LSTM spacecraft (image credit: Airbus).

Table 4: LSTM mission requirements.

Parameter	Value
Revisit time	2 days
Constellation characteristics	2 satellites

Swath	670 km
Orbit altitude	651 km
Min. elevation angle	28.0 deg
Acquisition system	Whiskbroom scanner
LTDN	12:30
SSD	50m (37m at nadir)
Geolocation accuracy	25m with GCPs (50m otherwise)

4.2. Sensor Description

Some details on the sensors which will fly on board of the LSTM mission are given herein. Table 5 shows the spectral bands of both VNIR-SWIR and TIR instruments with the corresponding SNR values. In the same Table, for comparison, the spectral bands of the ECOSTRESS sensor flying on the ISS (International Space Station) are shown. In fact, our idea is identifying limits and opportunities of the future LSTM mission starting from the experience gained with ECOSTRESS. As you can see the two sensors share similar thermal bands, whereas LSTM has more VNIR/SWIR bands useful to support the objective of the mission. VNIR/SWIR channels helps a good georeferentiation of the thermal images, improve the cloud masking, identify land cover type to enhance the surface emissivity estimation. This choice is justified by the ESA initiative to implement the European Ecostress Hub which focuses on the development and implementation of the European Ecostress Hub (EEH) in support of the Copernicus Land Surface Temperature Monitoring mission (LSTM). ECOSTRESS data acquired over Europe and Africa together with user interfaces and application programming interfaces, e.g. scene and area selection, selection of different retrieval methods, different parametrisation and auxiliary information, etc.) shall be made available.

Table 5: Spectral channels of the LSTM sensor, in comparison with ECOSTRESS.

LSTM Sensors Characteristics			**ECOSTRESS Sensor Characteristics**	
Channel	**Wavelength**	**SNR**	**Wavelength**	**SNR**
VNIR0	0.490 µm	162	--	--
VNIR1	0.665 µm	142	--	--

VNIR2	0.865 µm	100	--	--
VNIR3	0.945 µm	114	--	--
SWIR1	1.380 µm	100	--	--
SWIR2	1.610 µm	133	1.60 µm	--
TIR1	8.600 µm	0.15K	8.29 µm	0.15K
TIR2	8.900 µm	0.15K	8.78 µm	0.15K
TIR3	9.200 µm	0.15K	9.20 µm	0.15K
TIR4	10.900 µm	0.15K	10.49 µm	0.15K
TIR5	12.000 µm	0.15K	12.09 µm	0.15K

4.3. LSTM vs ECOSTRESSS

To compare information retrieved from ECOSTRESS images, mainly in support of agricultural management, with those potentially obtainable from LSTM, when in orbit, let us underline the main differences between the two missions (Table 6). As shown in the table the most relevant difference between the mission is due to the fact that ECOTRESS in flying on the ISS (International Space Station) on a not sun-synchronous orbit, therefore the revisit time and the local time of the observation is not constant. The true revisit period for a given location is variable based on the instrument's orbital cycle aboard the ISS. This could be a limitation but an opportunity also. In fact, the collection of data at different time of the diurnal cycle enables the study of a specific location on a diurnal scale (e.g. vegetation water stress assessments). This is not the case for LSTM in which, due to the large swath, at maximum, the local time can vary of half an hour with respect to the local time of the crossing at descending node.

Table 6: Difference between LSTM and ECOSTRESS missions.

Parameter	LSTM	ECOSTRESS
Spatial resolution	50m	70m
Revisit frequency	2 days (two satellites)	Variable (4 days in average)
Swath	670 km	384 km
Coverage	Almost global	Below 52deg latitude
Orbit	SSO, retrograde	NSSO = 51.6deg
Dynamic range	270 – 350K	200 – 435K

Figure 11 shows an example of a time series of ECOSTRESS acquisitions on a certain area of interest in Uganda.

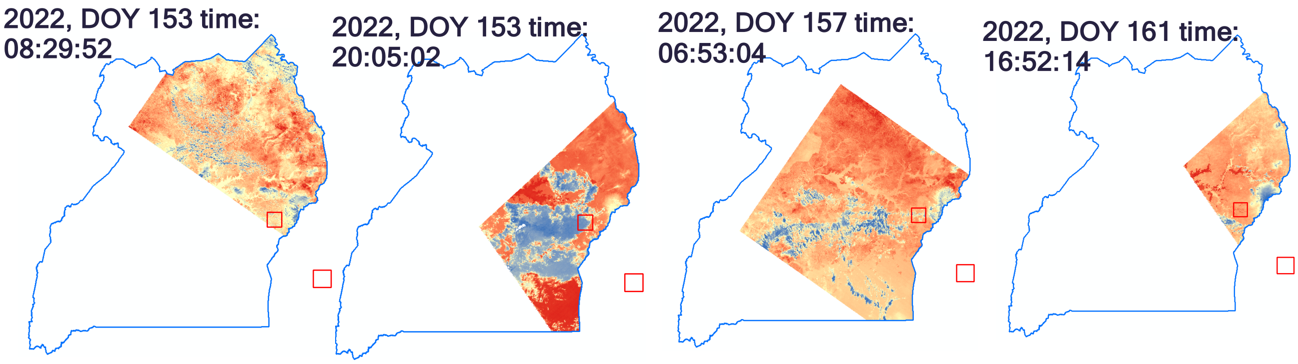


Figure 11: Example of time series of ECOSTRESS image on a certain area in Uganda. The area of interest is represented by the two red squared boxes.

An analysis using ECOSTRESS LST to reconstruct the daily land surface temperature cycle was performed. Initially, images were downloaded, through the use of AppEEARS tool, related to the period when measurement campaigns were carried out on the Narok area. Unfortunately, the clouds presence did not allow enough data to reconstruct the daily thermal cycle. To try to remedy this problem, all images related to the Narok area of interest were downloaded from the beginning of 2023 until the end of June 2024, this resulted in enough data for a total of 74 images.

The analysis was conducted by considering 3 different points within the monitored areas (Fig. 12). The partial presence of clouds within the images involved some of the points of interest reducing the number of usable images from 74 to: 45 for the Point-1, 46 for the Point-2, and 43 for the Point-3.

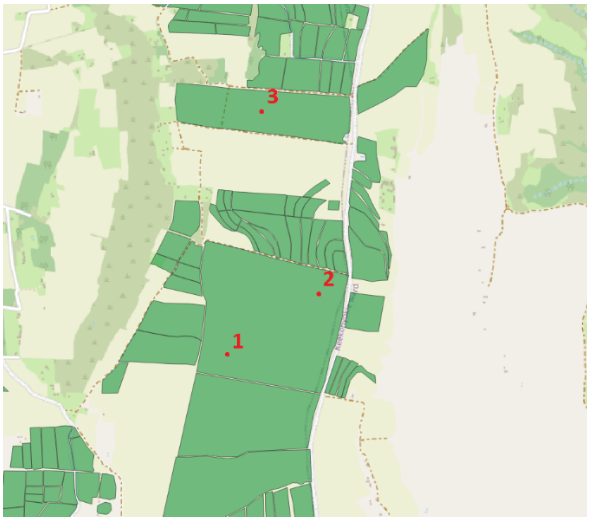


Figure 12: The three points examined to analyze changes in surface temperatures.

Subsequently, the images were sorted by time of acquisition (0-24) and then grouped and averaged over bi-hourly bands. Since the acquisitions are for different dates and seasons (e.g., summer-winter), causing appreciable variations within the same time slot, these were in turn averaged to achieve more uniform behavior.

The 24-hour temperature trends for the three different points examined can be seen below (Fig. 13).

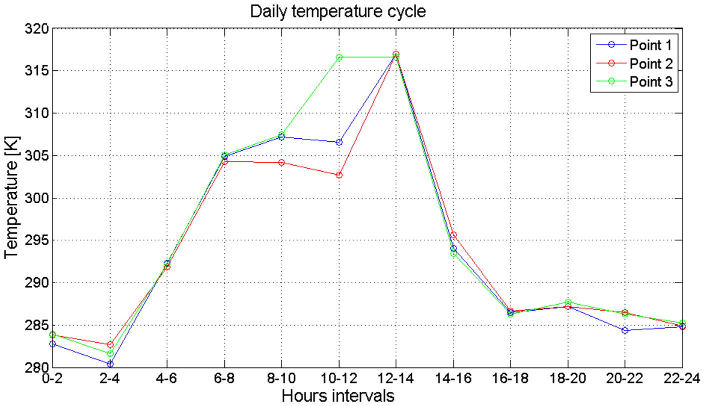


Figure 13: Daily temperature cycle observed at the three analysis points for the period from January 2023 to June 2024.

One could extend this analysis by considering the entire period of availability of ECOSTRESS images, i.e., from 2019 to 2024, also in order to observe any climate changes over the years.

4.4. Potential

The LSTM mission aims, as primary objective, to support monitoring evapotranspiration (ET) rate at field scale by capturing the variability of Land Surface Temperature (LST) (and hence ET) enabling more robust estimates of field-scale water productivity.

Its secondary objective is to support mapping and monitoring the soil composition (mineralogy and organic matter) and its dynamics through emissivity estimates.

There is a range of additional services which would benefitting from TIR observations (e.g. coastal zone management, High-Temperature Events (HTE), urban heat islands).

In general, the spatial resolution of the LSTM images is sufficient to allow, at field scale, the monitoring of LST in African countries characterized by very fragmented crop fields: from 2.5 ha in average in Kenya to 5.5 ha in average in Uganda, (source FAO). In terms of pixels these sizes correspond to 10 and 22 pixels, respectively.

Therefore, potentially, LSTM allows to monitor the LST (and ET) at field scale, even in regions of fragmented crop filed distribution areas, with a revisit frequency suitable to allows the status of crop water and overall water stress to be assessed, supporting irrigation management and the optimisation of scarce water resources for crop production, and further allows essential soil parameters that cannot be retrieved in the VNIR/SWIR spectral range to be derived. This supports the implementation of resilient agricultural practices, maintaining ecosystems and progressively improving land, soil and water quality, thus leading to more sustainable agriculture.

4.5. Limitations

From the paragraphs above it is possible to identify limitations in the use of LSTM imagery, in particular when we aim to monitoring the equatorial areas.

However, the high frequency of cloud coverage represents an obstacle for all EO optical satellite missions which can be partially overcome increasing the revisit frequency but maintaining a good spatial resolution as it is the case for LSTM.

Another potential limitation concerns the impossibility of studying the diurnal cycle of the LST and evapotranspiration due to the sun-synchronism of the orbit which guarantee that the observation is done at constant the local time, differently from ECOSTRESS (Figure 11 and 13). With reference to this last point, the potentiality of ECOSTRESS to reconstruct the temperature diurnal cycle, again, the analysis conducted, showed that the presence of clouds does not allow for a sufficient number of usable images, in a narrow time period (e.g. seasonal). In order to reconstruct the diurnal temperature cycle, it was necessary to use images over an 18-month period. This gave an idea of the temperature trend, but having values averaged over different seasons (summer/winter) does not make it a reliable data.

4.6. Potential of the LSTM, SBG-TIR and TRISHNA missions harmonization

There is a consensus of the need of having high spatial resolution LST products to monitor the surface temperature (and ET) at field scale, even in regions of fragmented crop filed distribution areas. In addition, in order to improve temporal sampling, to overcome the limitation due to frequent cloud cover conditions (mainly in tropical areas) the LSTM mission will be complemented by two additional polar-orbiting thermal imagers from NASA's and ASI SBG-TIR (Surface Biology and Geology-Thermal InfraRed) and the Thermal infraRed Imaging Satellite for High-resolution Natural resource Assessment (TRISHNA) planned by CNES and ISRO. The desired harmonization of observations from these multiple platforms implied the need for inter-calibration techniques, which likewise underscored the further need for collaborative sharing of instrument characterization data, the use of common reference data, and the implementation of data harmonization. According to the present plan (Figure 14) TRISHNA will be launched in 2026, SBG-TIR in 2028 and LSTM in 2029. This allows for a continuous record of LST (and ET) and possibly some periods, when all 3 satellites are available, along which daily coverage would be allowed.

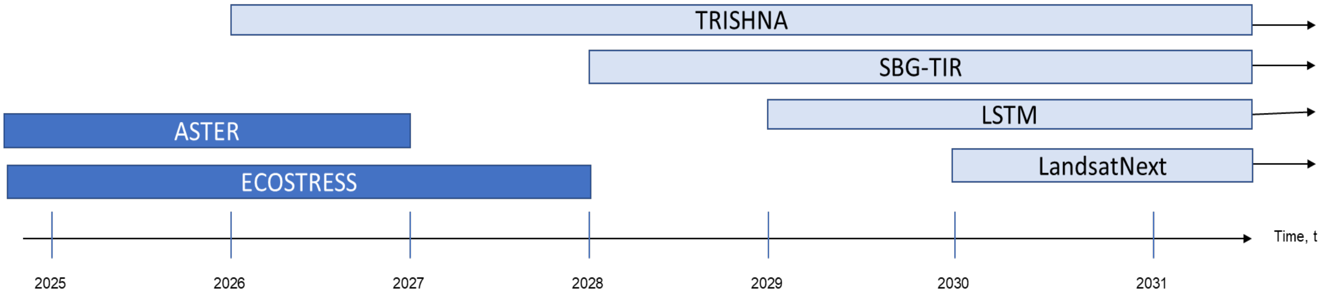
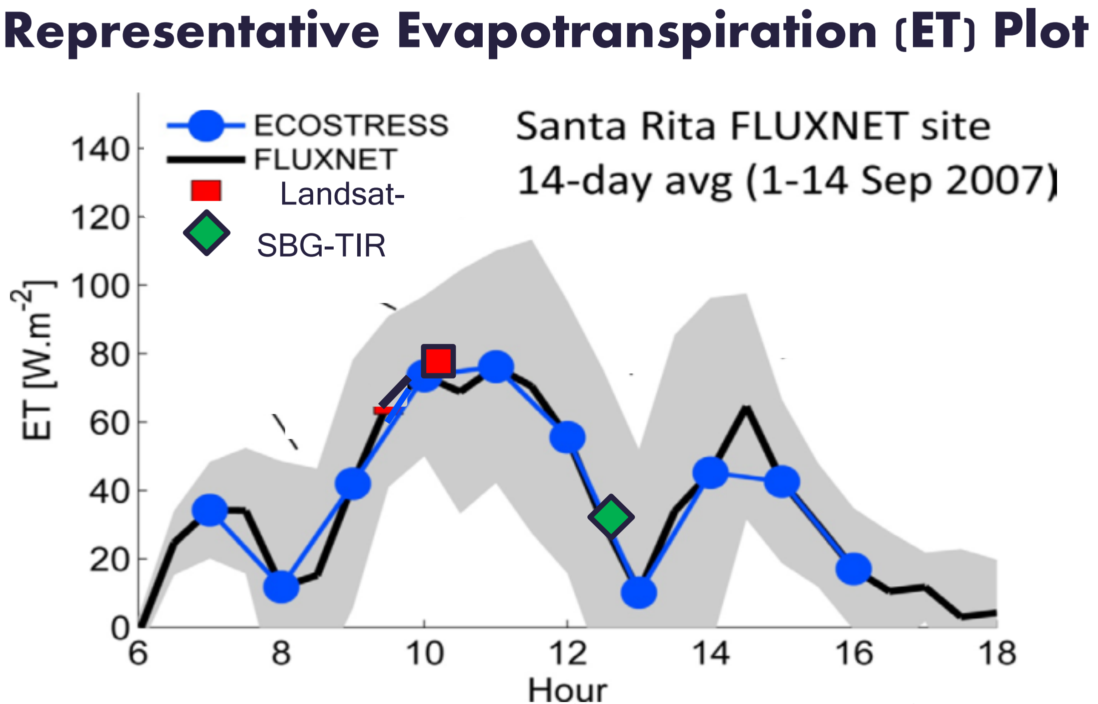


Figure 14: Planned schedule of the launches of the three missions mentioned in the text. For completeness, the alleged launch date of the next Landsat mission is also reported.

The possibility to obtain such high spatial and temporal resolution performances will be made possible if the sensors share similar spectral channels and orbital characteristics. This is the case, as shown in Table 7. In particular, for all the sensors the equator overpass time is around 13:00 PM on the descending node. It was selected to capture the peak afternoon plant stress, as shown in Figure 15.

Table 7: Comparison between the characteristics of three TIR sensors.

Main characteristics	**LSTM**	**SBG-TIR**	**TRISHNA**
Swath width [km]	734	935	1026
Pixel size [m]	50	60	70
Revisit frequency [day]	4	3	3
TIR bands	8.60 µm, 8.90 µm, 9.20 µm, 10.90 µm, 12.0 nm	8.32 µm – 8.63 µm – 9.07 µm – 10.30 µm – 11.35 µm –12.05 µm	8.65 µm – 9.0 µm – 10.6 µm – 11.6 µm
FWHM per band	0.36 µm – 0.36 µm – 0.36 µm – 0.9 µm - 0.94 µm	0.3 µm – 0.3 µm – 0.3 µm – 0.3 µm – 0.5 µm –0.5 µm	0.35 µm – 0.35 µm – 0.7 µm – 1.0 µm
Radiometric accuracy	< 1 K	0.5 K at 300 K	0.7 K at 300 K
NedT	0.15 K at 300 K	0.2 K	0.15 K at 300 K
Dynamic range	250 K – 350 K	200 K – 500 K	250 K – 400 K
Overpass at equator	12:30	13:30	13:00


Representative Evapotranspiration (ET) Plot

[Stavros, N. et al., ISS observations offer insights into plant function, September 2017, Nature Ecology & Evolution 1(10), DOI:10.1038/S41559-017-0327-z]

Figure 15: Plant daily evapotranspiration behavior. Plant stomata close in the early afternoon (max water stress and heat stress). The observed heat signature is highest during this time period.

Through periodic meetings between the space agencies supporting the three missions the harmonization process to produce inter-consistent observations of the Earth surface will be carried out. To facilitate this, participating agencies are committed to keep as much information and steps in common as possible for a suite of standard data products across missions. This starts with sharing prelaunch characterization reference sources and techniques; exchanging instrument characterization data; sharing field observation data to execute validation and potential inter-calibration; establishing common standardized reference datasets and models; and identifying standard data products and algorithms. Therefore, at present the discussion on harmonization includes:

- the harmonization of the products;
- the coordination of the orbit;
- the in-flight inter-comparison;
- a common Cal/Val approach;

- common airborne campaigns.

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