TOWARDS HIGH-REVISIT, HIGH-RESOLUTION THERMAL MONITORING: LISR - DATA, CALIBRATION AND PROCESSING OF THERMAL INFRARED DATA FROM THE LISR ISS MISSION.

Andreas Brunn(1,2), Marius Bierdel(1, 2), Clemens Horch(1), Konstantin Schäfer(1), Max Gulde(1, 2), Daniel Laun(2), Atin Jain(2), Akshay Myrialkar(1), Stanley George(1), Philipp Weiland(1,2), Robin Speck(1), Frank Schäfer(1)

(1) Fraunhofer Institute for High-Speed-Dynamics, Ernst-Mach-Institut (EMI), Ernst-Zermelo-Str. 4,
79104 Freiburg, Germany, andreas.brunn@emi.fraunhofer.de
(2) ConstellR GmbH, Ernst-Zermelo-Str. 4, 79104 Freiburg, Germany, info@constellr.space

Paper

The Longwave Infrared Sensing demonstratoR (LisR) mission is a longwave infrared camera which is flying outside the ISS on the Nanoracks Experimentak Platform (NREP).

This demonstrator, developed by the founders of ConstellR at Fraunhofer Institute of High-Speed Dynamics in Freiburg/Germany, is a platform to demonstrate the capabilities of cryo-cooled long wave infrared detectors from space. The goal is to derive high accuracy Land Surface Temperature (LST) information to serve the agriculture sector’s need for better planning and efficiency in order to ensure the global food supply. LisR is the precursor of a full satellite constellation called HiVE which is planned to deliver high temporal, spatial and spectral resolution thermal and VisNir information from space from the end of 2023 onwards.

The demonstrator mainly consists of a cryo-cooled thermal infrared frame camera, a free form optical assembly and an on-board data processing unit. It images the earth's surface in two longwave infrared bands which allows the derivation of highly accurate Land Surface Temperature information with high spatial resolution.

The data quality of the camera has been validated in laboratory pre-launch to evaluate its spectral accuracy and stability, preliminary adjust integration times or adjust the focus of the optics of the instrument. After launch effort is taken to process the raw data frames to orthorectified Land Surface Temperature (LST) data. Additionally, orbit data will be taken to perform in-orbit radiometric calibration and validation activities.

1 THE MISSION AND INSTRUMENT

The Longwave Infrared Sensing Demonstrator (LisR) is planned as the demonstrator mission for the for the first privately owned, operated and funded thermal infrared mission carrying a cryocooled longwave infrared camera on a microsat within a New Space approach. This satellite constellation of this mission called HiVE is expected to be launched successively from mid-2023 onwards.

LisR has been launched from Wallops Island Lauch Site on a Cygnus Freighter Mission on February 19, 2022. Its installation onto the Nanorack Experimental Platform (NREP) has been done on Mar

09, 2022 and the instrument has been switched on the first time on Mar 16, 2022. Since then the instrument is taking images continuously. The operation mode of the camera is such that it records imagery steadily when the ISS platform is flying over continental areas and larger islands. Images together with health telemetry and position / attitude information is downlinked to the ground and ingested into the ConstellR image processing and archiving platform daily. Figure 1 shows the main imaging components IDDCA and optics assembled on the base plate in the Fraunhofer EMI clean room.

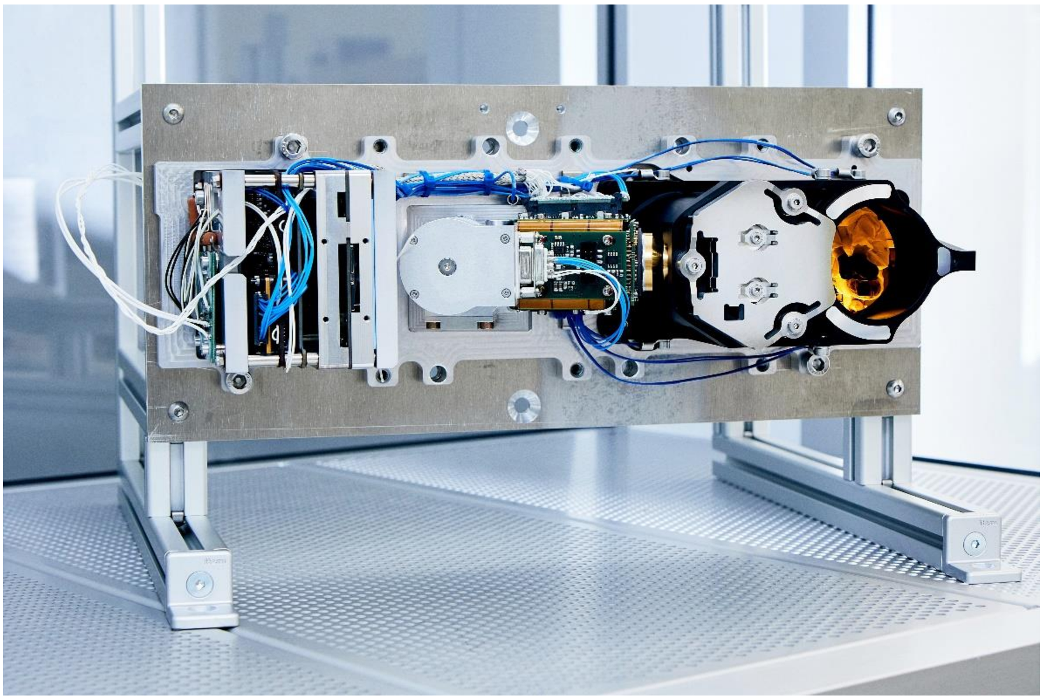

Figure 1. Instrument in the clean room at Fraunhofer EMI

LisRs imaging consists of an off the shelf integrated detector dewar cryocooler assembly (IDDCA). The frame of 320 x 256 imaging pixels is covered with a two-band spectral filter assembly dividing the focal plane into two horizontal halves, one for each band. With these filters the camera images the electromagnetic spectrum of light between 9 and 11µm. Figure 2 shows the optical response of the detectors together with the transmission of the two filters used. Figure 3 convolutes the filter transmission and quantum efficiency to the relative spectral response of the two LisR spectral bands.

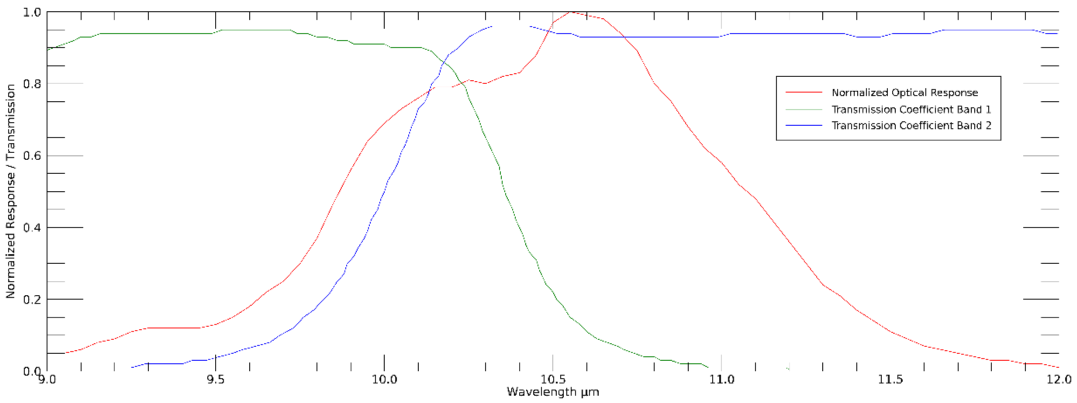

Figure 2. Optical response and filter transmission

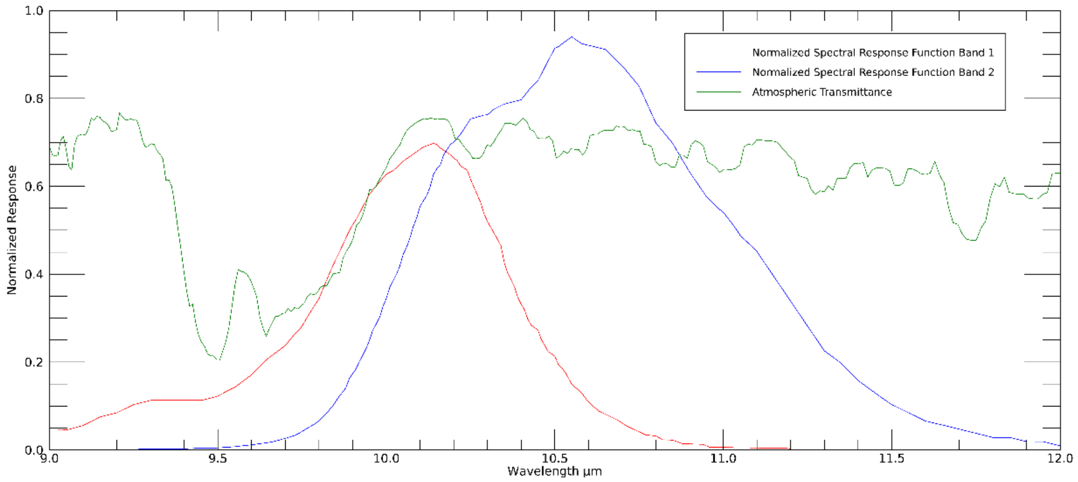

Figure 3. Relative spectral response and atmospheric transmissivity in the sensitive spectral range of the instrument

Table 1 summarizes the most important camera parameters:

Table 1. technical details of the optical assembly and orbit parameters

Target Data Product	L2 Land Surface Temperature
Orbit	ISS Orbit, 370 - 460 km altitude, 51.6° inclination, 7.6 – 7.7 km/s
Revisit Time	non-constant, 3-5 days for many areas and times
Coverage	Land and coastal regions between -51° and +51° Latitude
Max. Spectral Response	Band 1: 10.14µm, Band 2: 10.55µm
Full Width Half Maximum (FWHM)	Band 1: 0.41µm, Band 2: 0.9µm
Detector	Cryocooled Quantum Well Infrared Photodetector (QWIP)
Frame Size	320 x 256 pixels, (320 x 128 per band)
Pixel Pitch	30 µm
Optics	Free Form optical assembly
Initial Integration Time	2250 µs
Imaging sequence	2s
Focal Length	150 mm
GSD	81.5
Swath width	26.1 km

For more detailed information about the mission, instrument and optical design as well as the on-board data processing we refer to other presentations of the same conference. The instrument design is described in detail in Bierdel et. al. [1], the on-board data processor is detailed in Horch et.al. [2] and further details on the optical assembly is given in Zettlitzer et al. [3].

2 ON-GROUND CAMERA CHARACTERIZATION

Fort he on ground camera characterization two laboratory sessions have been performed. The goal for the first campaign was to characterize the camera response, define the expected integration times in orbit and perform an initial absolute calibration of the camera. The second campaign was meant to adjust the focus to a proper infinity setting.

2.1 Radiometric Characterization

The test setup for this task consisted of the camera IDDCA a black body source (Heitronics ME30) combined with a Julabo FL300 chiller and some accessory equipment for power supply and mounting the instrument. Figure 4 shows the used laboratory test setup.

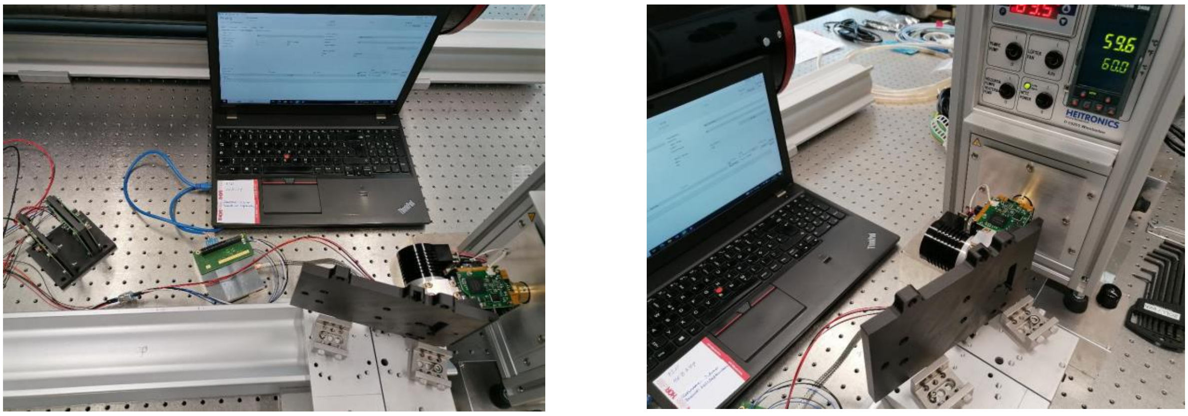

Figure 4. IDDCA laboratory test setup (photos courtesy Paul Loregio, Airbus Defence and Space)

With this equipment imagery of the black body has been taken in the temperature range between -9 and 80°C (-9°C, -5°C, 5°C, 20°C, 40°C, 60°C, 70°C and 80°C) with integration times between 1250µs and 2750µs (1250, 1625, 2000, 2375 and 2750µs). This temperature range represents well the temperature range which is expected to be of interest for the purpose of the LisR mission. The integration time range has been defined previously using the quantum efficiency of the detector, the filter and atmospheric transmissivity as well as the expected radiance levels. For each of the temperature – integration time combinations 100 images were recorded. First of all, the integration time has been adjusted to cover the full expected temperature range in the dynamic range of the detectors as good as possible. Figure 5 shows the two-band image frame and image histograms for an exemplary setting of 40°C and 2000µs integration time. The image and histograms clearly distinguish the brightness levels between the two different spectral bands which is coursed by the different transmissivities of the two filters and the atmospheric transmittance which is limited in the lower parts of Band 1. During operations in orbit it is expected that for the optimization of SNR and well fill levels different integration times will be used for the different bands.

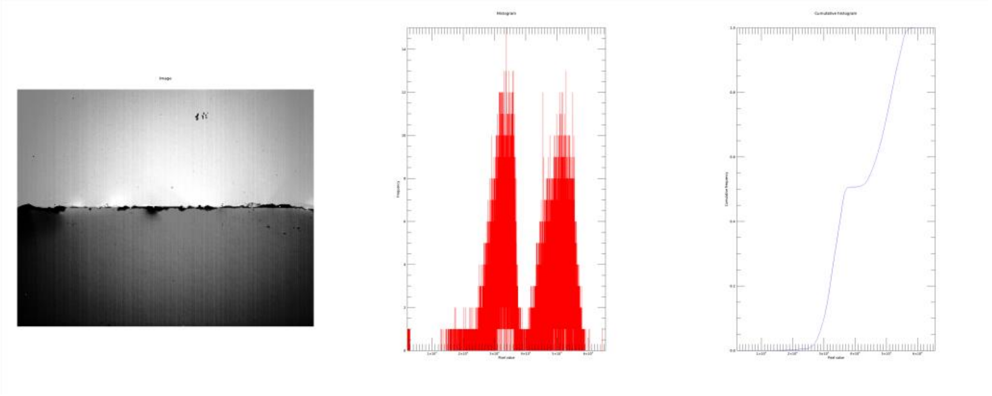

Figure 5. Sample image and image histograms of a black body at 40°C and 2000µs integration

Flatfielding (also known as pixel response non-uniformity (PRNU) correction) is the process of correcting for differences in the spectral response of the individual pixel detector elements of the imaging frame. This correction is done by using a linear correction function like.

$$DN_{corr} = DN_{raw} \cdot gain + offset \tag{1}$$

The gain parameters map can be created from images taken from a homogeneous blackbody (in lab) or area (on orbit) using a linear fit of the detector response to the thermal radiation at the two radiator temperatures T_{Low} and T_{High} and is defined as the inverted difference of the median frames of the of the images at these temperatures normalized to the difference of the median values taken over the image series and array following equations (2):

$$G^{rc} = \frac{median_{rc}\left(median_{n=1\ldots N}\left(S_n^{rc}(T_{high})\right)\right) - median_{rc}\left(median_{n=1\ldots N}\left(S_n^{rc}(T_{Low})\right)\right)}{median_{n=1\ldots N}\left(S_n^{rc}(T_{High})\right) - median_{n=1\ldots N}\left(S_n^{rc}(T_{Low})\right)} \tag{2}$$

The offset parameters map is a corrective matrix bringing the gain corrected pixels to the level of the temperature at which the imagery was recorded and is created following equation (3).

$$O^{rc} = \frac{median_{rc}\left(S_n^{rc}(T_{Low})\right) \cdot \left(S_n^{rc}(T_{high})\right) - median_{rc}\left(S_n^{rc}(T_{High})\right) \cdot \left(S_n^{rc}(T_{Low})\right)}{S_n^{rc}(T_{High}) - S_n^{rc}(T_{low})} \tag{3}$$

In the given case homogeneous images of the blackbody at +5°C and +40°C have been chosen to avoid non-linearity and saturation effects at the borderline areas of the detector sensitivity. Additionally, to avoid random noise the gain and offset parameters have been created from averages of 100 images taken at each of the individual temperature levels.

Figures 6 and 7 are showing the gain and offset maps calculated from the laboratory data to be used for initial data processing. Once sufficient on orbit data has become available the gain and offset maps will be updated from image data taken over cold ocean water and hot homogeneous desert imagery.

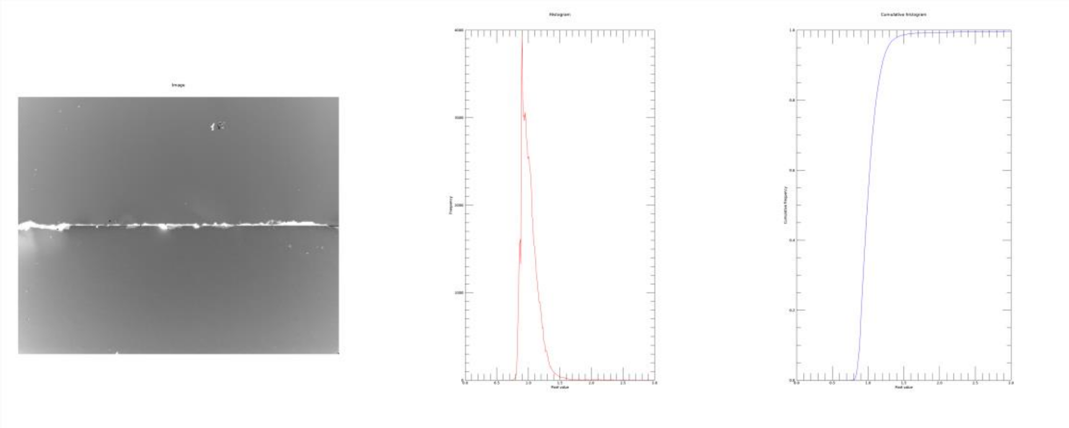

Figure 6. Gain correction map for the nominal integration time

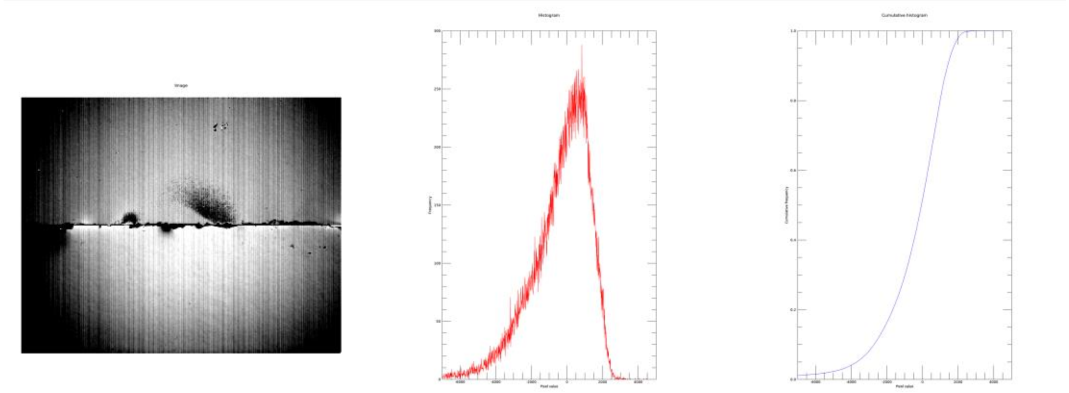

Figure 7. Offset correction map for the nominal integration time

The creation of the link between the sensor digital number (DN) and the physical radiance unit is done by absolute calibration methods. The coefficients for the absolute calibration are in-lab derived by fitting a linear relationship between the average sensor response of a PRNU corrected full frame of a black body image at different temperatures.

To achieve this, the known brightness temperature of the black body are converted into radiance using Plancks law and a linear relationship is fitted between the sensor response and the expected radiance at the given wavenumber and temperature. Figure 8 shows an example linear fit between the image DNs taken at different temperatures and the expected radiance values at these temperatures.

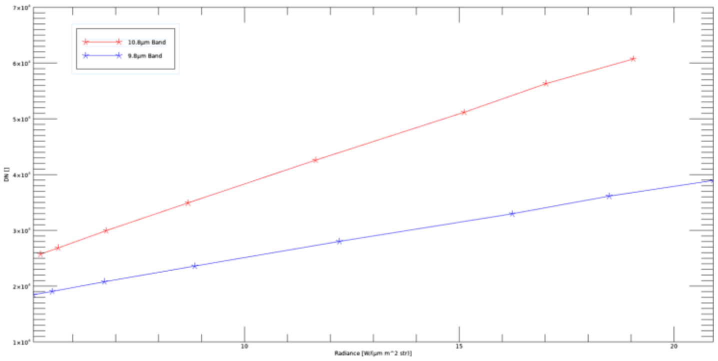

Figure 8. Linear fit between image DN and Radiance

2.2 In-Lab focusing of the Instrument

An optimum focusing to infinity of the instrument is crucial to achieve sharp imagery from space. This is done by adjusting the distance between the entrance pupil of the optics and the focal plane of the IDDCA.

In laboratory it is not possible to achieve parallel radiation between the object and the optical assembly due to limited distance. That's why a large telescope with 1000mm focal length has been used as a collimator between the object and the instrument optics. Figure 9 shows the laboratory test setup.

Figure 9. Test setup for adjusting the focus in lab

With the shown setup imagery of the black body at defined temperatures through a circular aperture are taken at different distances between the focal plane and the optics entrance pupil are made. Considering the parallax effect, it is expected that the projection of the circular blind becomes smallest when the optimum focus is reached. Finally, these images are digitally evaluated using image processing steps to calculate the size of the circle and the number of pixels within the circle to find the ideal setting. Figure 10 shows an example image of the circular blind in optimum focus setting and the plot of the number of white pixels in the images vs. the distance between the entrance pupil of the optics and the focal plane overplayed with a fitted 4th order polynomial. The ideal setting is found by calculating the maximum of the fitted function. Subsequently the distance has been adjusted to this number and fixed in the instrument.

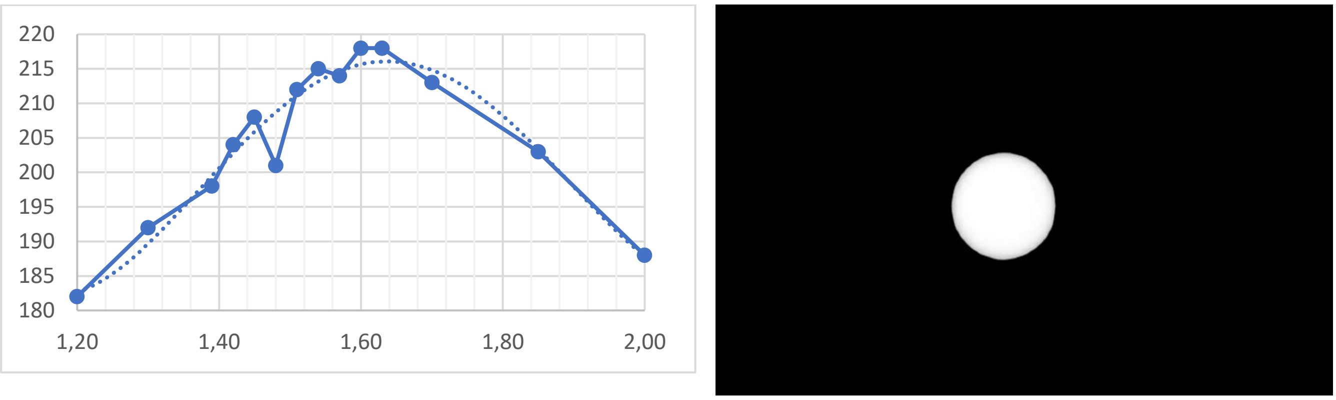

Figure 10. Example of optimally focused circular aperture (right) and the number of bright pixels within the circle plotted over the distance between the optics entrance pupil and the focal plane.

3 IMAGE PROCESSING STEPS

With the initial parameters derived as described in the chapters above the images are processed from raw data into orthorectified Level 2 Land Surface temperature information.

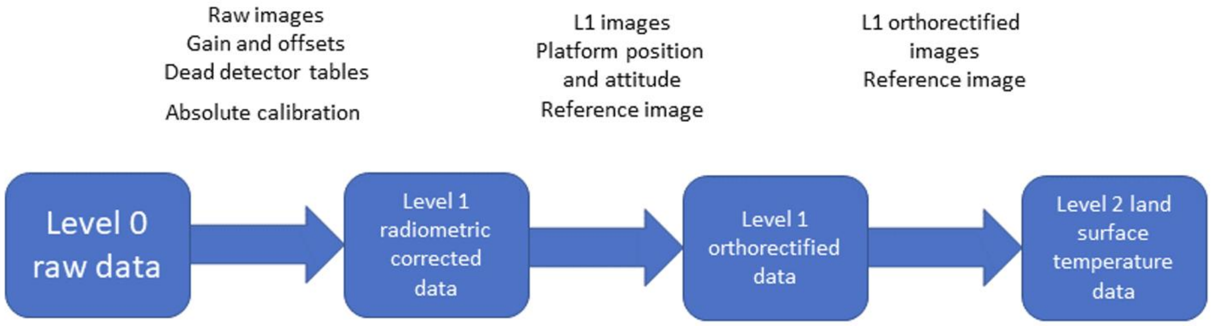

Figure 11. High level processing workflow

On a high level the data processing consists of the archiving of raw data and all according metadata information, the conversion of raw image frames to radiometrically corrected L1 data, the orthorectification and the Land Surface temperature derivation.

Archiving unpacks decrypts the downlinked data packages containing raw image frames, per image metadata files containing spacecraft position and attitude information and instrument health data and feeds all the information into a database. Additionally during this step a rough georeferencing is performed based on the spacecraft attitude and position data and stores the image corner coordinates into the database. This step is necessary to easily query the location and date and time of the available images later on.

L1 radiometric correction uses the raw data DNs, applies non-uniformity correction gain and offset maps to the images, interpolates over dead and degraded detectors and applies the absolute calibration parameters to convert raw DN into physical radiance units. These steps are performed on the geometrically raw image frames.

L1 geocorrection applies the rough georeferencing parameters calculated during archiving to the images and performs a coregistration of the still raw but oriented image frame to an orthorectified thermal image band from ECOSTRESS or Landsat 8/9 if ECOSTRESS imagery is not available. This results in orthorectified and radiometrically corrected LisR images.

LST estimation during the first time of operations before the absolute calibration has been updated with vicarious and cross calibration approaches reference Land Surface Temperature information from coarser spatial resolution satellite instruments but high revisit rate is used for the creation of Land Surface Temperature information from LisR following Gulde (4). For this the LisR spectral response of an area is correlated with the temperature information of a satellite delivering near simultaneous (up to approx. 10 minutes time difference) temperature data like e.g. SEVIRI on the MTG platform. As LisR is sharing the same platform with the NASA ECOSTRESS platform this is an additional high spatial reference instrument for temperature correlation in cases where this data is available. Figure 12 shows the temperature fit between the reference image and LisR overlaid with the correction function. Figure 13 shows the LisR L2 LST image and the temperature histogram. For comparison Figure 14 shows the same image subset imaged simultaneously by ECOSTRESS. The figures clearly show, that the temperatures between the different instruments match very well. Additionally, it can be seen that the LisR image seems to show slightly more details although the nominal spatial resolution of ECOSTRESS is higher.

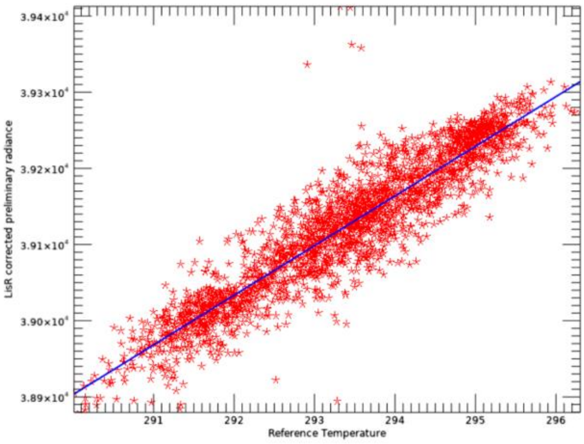

Figure 12. Temperature fit between reference temperature and LisR DN

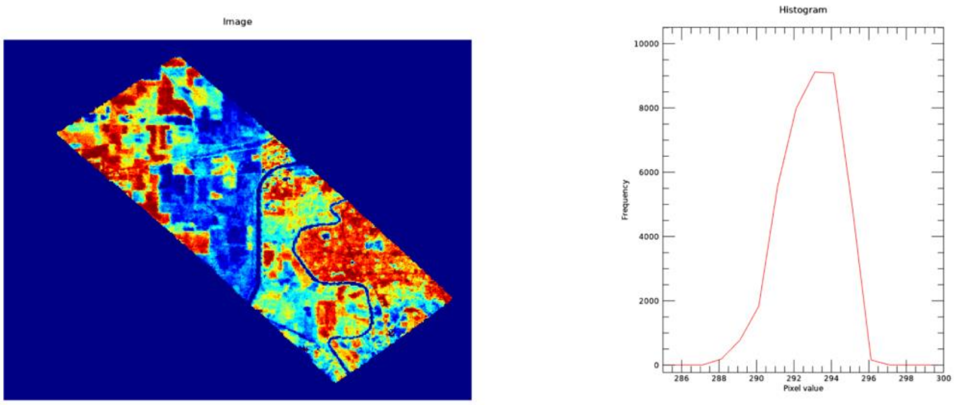

Figure 13. LisR Temperature Image with Temperature Histograms

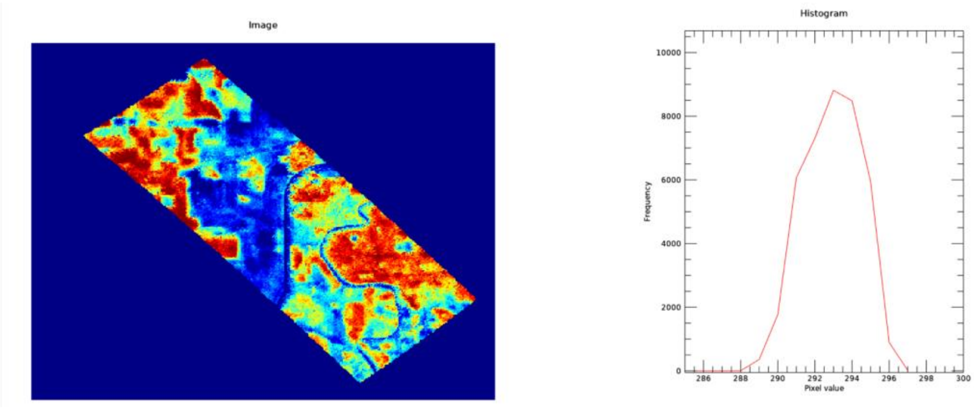

Figure 14. ECOSTRESS Temperature Image with Temperature Histogram

After the in-orbit calibration campaign has been finalized the correlation procedure initially used for LST derivation will be replaced by an adjusted split window approach which allows the immediate derivation of land surface temperature information after the images have been downlinked. The necessity to delay this final processing step until suitable reference information becomes available will be dispensed with this new procedure.

4 CONCLUSION AND OUTLOOK

This paper described the pre-launch calibration, validation and adjustment works in the laboratory. It further described the processing procedure from raw data into orthorectified Land Surface Temperature information. It has been shown that already after few weeks in orbit LisR is capable of delivering high fidelity and accuracy image data in the thermal wavelength ranges.

In the following weeks the geometric and radiometric characterization and calibration of the instrument will be finalized and with this the accuracy and processability further improved.

Finally, proper quality and accuracy measures like absolute radiometric and temperature accuracies, geometric accuracies and MTF measurements will be derived.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

[1] M. Bierdel *et al.*, “Towards high-revisit, high-resolution thermal monitoring: LisR – A land surface temperature monitoring mission on the ISS,” in *4S Symposium 2022*, Vilamoura, Portugal, 2022.
[2] C. Horch et al., “ Autonomous on-board operation for the high-resolution earth observation mission LisR on the ISS” in 4S Symposium 2022, Vilamoura, Portugal, 2022.
[3] L. Zettlitzer, “Design and fabrication of a miniaturized metallic telescope for Earth observation,” in *4S Symposium 2022*, Vilamoura, Portugal, 2022.
[4] M. Gulde, "Correlation of thermal satellite image data for generating termal maps at hig spatial resolution", patent: US 2021/039590 A1, 2021