CALIBRATION AND VALIDATION (CALVAL) OF TELEOS-1 SATELLITE IMAGERY

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ABSTRACT: Singapore’s first commercial NEqO Earth Observation satellite, TeLEOS-1 was successfully launched on 16 December 2015 and the first image was acquired on 23 December 2015. In-Orbit Test (IOT) phase was conducted in the six months after launch. The IOT phase included the calibration and validation (CalVal) activities related to imagery. This paper gives the main results achieved after the CalVal activities.

1. INTRODUCTION

TeLEOS-1, Singapore's first commercial Near Equatorial Orbit (NEqO) Earth Observation satellite was successfully launched on 16 December 2016. The Satellite is owned by ST Electronics (Satcom & Sensor Systems) Pte Ltd, and built by ST Electronics (Satellite Systems) Pte Ltd. TeLEOS-1 carries a high resolution camera that produces 1 metre resolution imagery from an altitude of 550 kilometres, and offers an average revisit time of 12 to 16 hours in the NEqO orbit with inclination of 15°.

TeLEOS-1 acquired its first image successfully on 23rd December 2015 as part of a transmission checkout during the LEOP phase. The IOT phase commenced in January 2016 and concluded in June 2016. During the IOT, the main activities were in the area of CalVal of the TeLEOS-1 satellite imagery. This paper will report the activities, methodology and results of the various CalVal activities covering the following major areas:

1) Focusing and Modulator Transfer Function (MTF) estimation
2) Signal to Noise Ratio (SNR) estimation
3) Geometry Calibration and Validation
4) Relative Radiometric Normalisation
5) Absolute Radiometric Calibration

2. FOCUSSING AND MTF ESTIMATION

The initial task of CalVal was to focus the camera. For the TeLEOS-1 camera, focusing was done by adjusting the M2 mirror location to give the maximum MTF. The MTF is the normalised Fourier transform of a line through an edge. It is common industry practice to quote the MTF at Nyquist frequency. To provide edges for MTF estimation, a 2 by 2 black-white square target, measuring 40m by 40m, was painted on an off-shore island. The target is shown in Figure 1.

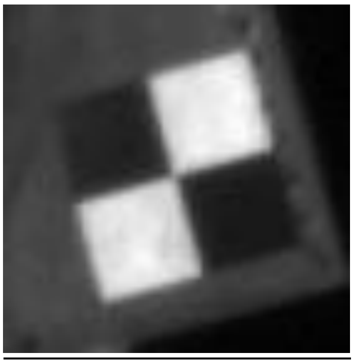


Figure 1: MTF target

When viewed from the satellite image, it is about 40 by 40 pixels wide. The well published edge method was used to compute the MTF from the imaged target. From the target imaged, a best fit line through the middle of the 'black and white' transition was established. Once the location of the edge is defined, for every pixel in the target image, the amount of pixels along its row to a point of an edge is calculated to sub-pixel accuracy. The digital number (DN) of this point and its corresponding distance to edge are recorded. The collection of all points to the left and right of the edge in the image target forms an Edge Spread Function (ESF). An analytic function of the ESF is then extracted by performing a LOESS fit, which is a local regression model. Next, the Line Spread Function (LSF) is formed by taking the derivative of the ESF, and normalising it to range between 0 and 1. Finally, the normalised amplitude of the Fourier Transform of the LSF gives the MTF curve. Figure 2 below is an example of the ESF, LSF and MTF curve. The MTF at frequency of 0.5 is the MTF at Nyquist frequency.

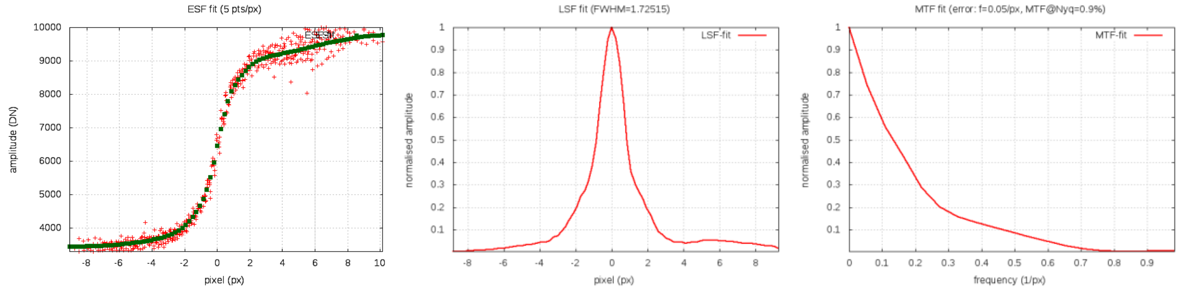


Figure 2 – ESF, LSF and MTF curves

By varying temperature, M2 can be made to move arbitrarily. The initial starting temperature range for investigation was chosen to be between 13°C to 16°C. Due to cloudy condition in the equatorial region, we had a high proportion of unsuccessful attempts. For certain temperatures such as 15°C and 15.5°C, we were not able to image the MTF target, thus we resorted to qualitative judgement of sharpness of other features in the image. Figure 3 shows the MTF vs temperature setting of the successful image. From this exercise, we adopted the temperature setting of 14.5°C as the ideal focus setting.

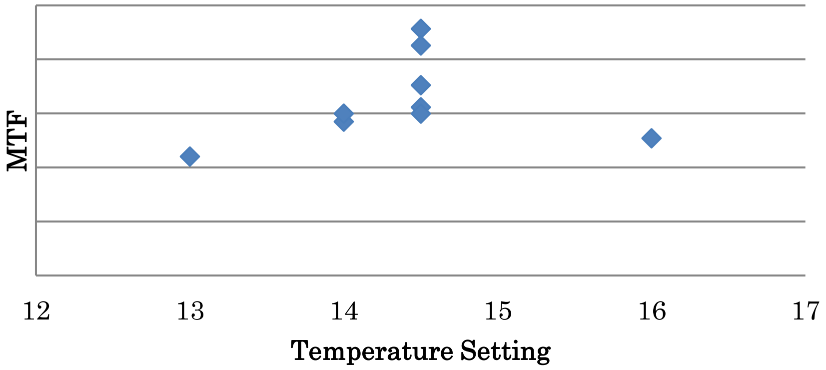


Figure 3 : MTF vs Temperature Setting

2. SIGNAL TO NOISE (SNR) ESTIMATION

The method for estimating the SNR is based on the Homogeneous Area method. The principle of this approach is based on the assumption that the variance of a patch seen by the satellite is dominated by the sum of the variances due to noise and earth surface brightness. For a homogenous area, the variance of the earth surface brightness can be close to zero. The measured variance is thus close to the variance of the sensor noise.

The method starts with choosing an arbitrary window (e.g. 20x20), sliding the window across the image and computing the variance and the mean. The mean is then grouped into bins of 32 DNs. The histogram of variance at each bin is then computed. The lowest 5% variance is assumed to be variance of the sensor noise.

The variance is not constant with image brightness, but varies according to the formula, σ^2 (L)=a+b×L. σ^2 is the variance, the squared standard derivation σ, of a collection of digital numbers (DN) of mean L, a is a coefficient that gives the minimum variance, and b is the coefficient to express the linear relationship between L and the variance. Figure 4 shows the variance vs DN of a chosen scene.

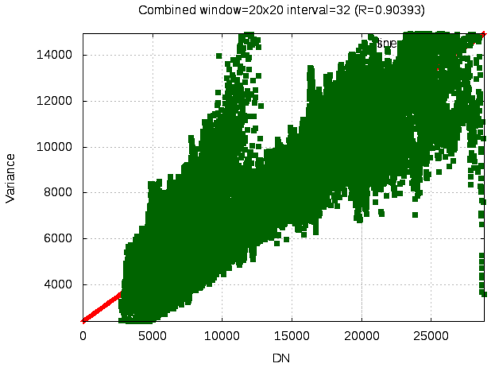


Figure 4 – Sensor noise variance vs DN

The coefficient a is the slope and b the intercept of the regression line. The Signal-To-Noise-Ration (SNR) at a certain digital number (DN) is

$$SNR = \frac{mean}{standard\ deviation}.$$

And so, the SNR at a particular L value is

$$SNR(L) = \frac{L}{\sigma(L)} = \frac{L}{\sqrt{a + bL}}.$$

We ran the exercise over five scenes between March and May 2016. The SNR at L=10000 was found to range from 122 to 152.

3. GEOMERTIC CALIBRATION AND VALIDATION

Geometric calibration involved computing the in orbit camera focal length and the camera angular bias with respect to the satellite body. Prior to calibration, the rigorous model for the satellite and its camera payload need to be developed. The variable parameters were then computed by least squares adjustments with ground control points measured by differential GPS. We obtain the following parameters for the satellite and camera:

$\Delta f / f$ = -0.003,

M_c2b =
0.9997453536070087, -0.014089208592141352, 0.017627312399917508,
0.014170352442753, 0.9998895283456056, -0.004486893853276056,
-0.017562148298124563, 0.0047355365112659266, 0.9998345591352127

$$\Delta t_{sts} = +0.5 \text{ sec}$$

Where $\Delta f / f$ is the change in focal length, M_c2b is the 3x3 transformation matrix representing the camera mounting angular bias with respect to the satellite body frame and Δt_{sts} is a small time stamping bias.

After obtaining the above parameters, more test images were acquired to assess the geometric accuracy. The ground control points (GCP) were now not used for adjustments, but used for checking the residual positional errors. Due to the 15 degrees inclination and non-sun synchronous orbit, the images acquired may either be in ascending or descending orbit. For easier analysis, we decided to transform the residual errors into the along track and across track directions. Figure 5 shows the current without GCP accuracies of the images:

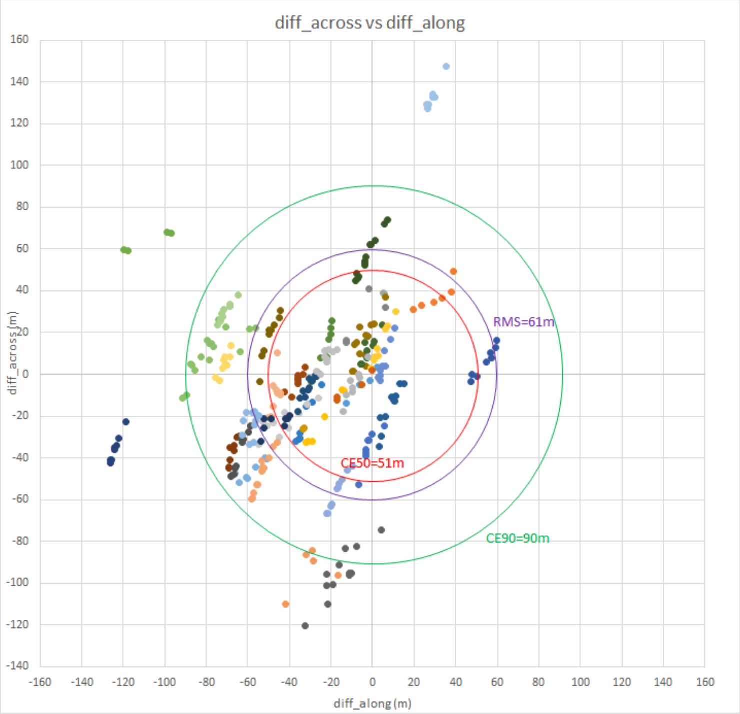


Figure 5 – plot of across track and along track residuals

The RMS accuracy of 61m and CE90 of 90m is within the specifications of the TeLEOS-1 satellite.

4. RELATIVE RADIOMETRIC NORMALISATION (RNN)

Relative radiometric normalization is the process of removing visible striping from the image. This was initially performed in accordance to manufacturer's recommendations and using correction data derived from measurements made prior to launch. After 3 months of imaging, enough data had been collected to experiment with an alternative approach to RRN that used historical cumulative histogram to build an accurate estimation of each individual pixels' response. This potentially allows for more accurate correction of response differences. The vendor's approach assumes that the pixel's response to illumination can be modelled linearly. This assumption may not hold true and may result in a small amount of residual striping. The cumulative histogram approach makes no such assumption and could potentially produce better results. The drawback to this approach is the need for a large amount of data to correctly build an accurate histogram.

The process of cumulative relative normalization is as follows:

1) Obtain large quantities of images of many different locations under many differing imaging conditions
2) Build cumulative histogram of every pixel
3) Select a reference pixel that does not easily saturate, and which exhibits low read noise
4) Map the responses of all other pixels to this reference pixel

Example of the cumulative histogram across the image swath is given in figure 6 below:

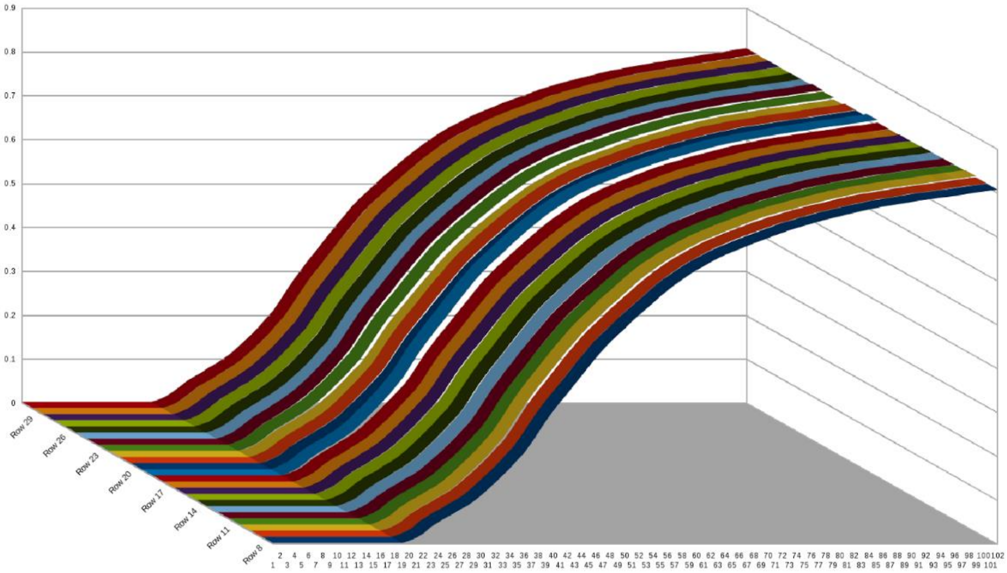


Figure 6 – Example cumulative histogram

Data from any given combination of gain, TDI, sensor and offset cannot be used to correct images that were captured using other combinations. Thus data for each combination would need to be independently collected. For the system with 64 gain setting and 8 TDI setting, that means a lot of work to complete all the RNN for all the gain and TDI settings. We thus choose to start with the more common setting and for non-calibrated setting, we will either use the nearest setting's calibration or interpolate from the setting before and the setting after.

Examples of before and after RRN images is shown in figure 7 below:

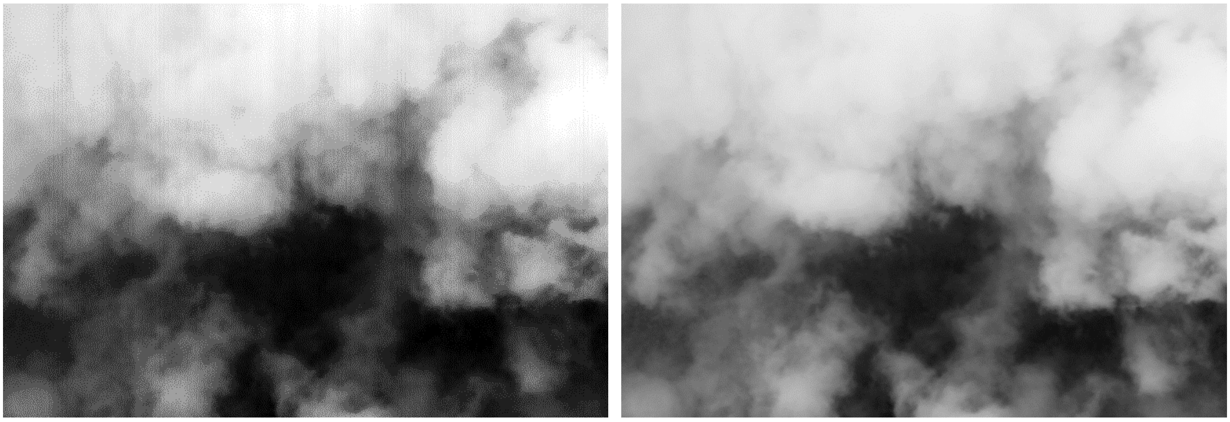


Figure 7 – Before and after Relative Radiometic Normalisation (RRN)

5. ABSOLUTE RADIOMETRIC CALIBRATION

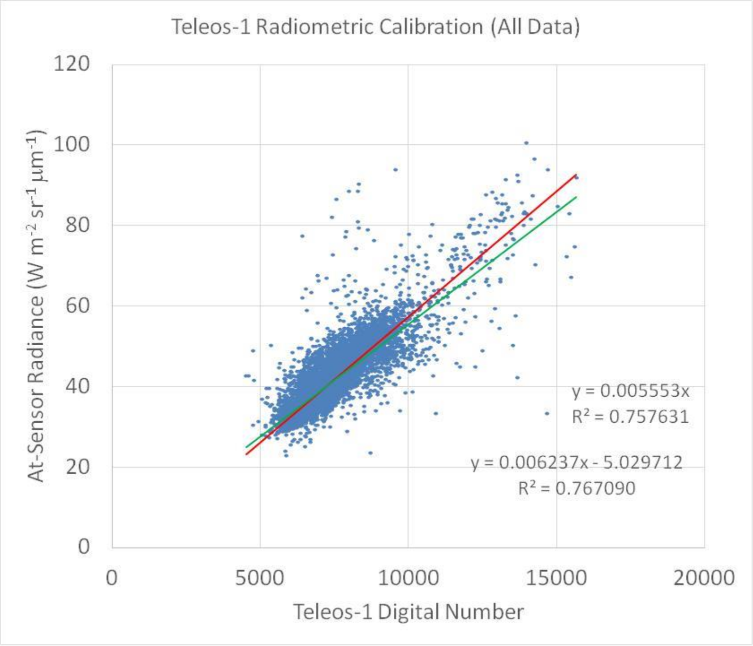
Absolute Radiometric calibration is the process of determining the calibrating coefficients that relate the digital numbers to the at-sensor radiance. The relation between these two quantities is usually represented by a linear equation:

$$L_\lambda = aN + b$$

Where L_λ is the at-sensor radiance (in $\mathrm{Wm^{-2}sr^{-1}\mu m^{-1}}$), N is the digital number and a, b are the calibration coefficients. Before launch, radiometric calibration is often performed in the laboratory using a standard light source. After launch, radiometric calibration needs to be performed at regular intervals in order to monitor the stability of the sensor response and to make corrections to the calibration coefficients if necessary. There are several methods of doing post-launch calibration. vicarious calibration is usually performed using invariant ground targets (e.g. desert, salt pan). In-situ measurements of the reflectance of the ground targets are carried out near to the time of imaging by the satellite sensor. The precise atmospheric conditions need to be known and a radiative transfer routine is used to calculated the to-of-atmosphere radiance for comparison with the digital numbers recorded by the satellite sensor.

TeLEOS-1 is flown in a 15° inclination near equatorial orbit. There are no suitable ground targets within its imaging coverage. We thus adopt a method by comparison with another well-calibrated satellite sensor. We choose the MODIS sensors on the Terra and Aqua satellites for this purpose. MODIS has a wide swath of over 2000 km with global coverage. Hence, it is easier to find coincidental scenes that are acquired at nearly the same time and cover the same area as TeLEOS-1's acquisition.

The first 4 bands of MODIS were used as it is within the spectral response of TeLEOS-1 sensor. Integrating the overlapping spectral response curves, we obtain the weightage of each of the 4 MODIS bands. Thus for each pixel in the overlap region, we can compute the top of atmosphere radiance from the calibrated MODIS data. A plot of radiance vs TeLEOS-1 digital numbers for a gain/TDI setting is shown in figure 8 below:



Regression analysis gives the following values for the calibration coefficients:

$$L_\lambda = aN + b$$

$$a = 0.006237 \pm 0.000034\,\mathrm{Wm^{-2}sr^{-1}}\mu\mathrm{m^{-1}}$$

$$b = -5.030 \pm 0.243\,\mathrm{Wm^{-2}sr^{-1}}\mu\mathrm{m^{-1}}$$

$$R^2 = 0.767,\ \mathrm{RMS} = 4.0726\,\mathrm{Wm^{-2}sr^{-1}}\mu\mathrm{m^{-1}}$$

If the constant b is constrained to be zero, then the following results are obtained

$$L_\lambda = aN$$

$$a = 0.005553 \pm 0.000006\,\mathrm{Wm^{-2}sr^{-1}}\mu\mathrm{m^{-1}}$$

$$R^2 = 0.758,\ \mathrm{RMS} = 4.1543\,\mathrm{Wm^{-2}sr^{-1}}\mu\mathrm{m^{-1}}$$

Both models are comparable in their uncertainties.

6. CONCLUSION

The CalVal activities were successfully carried out within the IOT phase of TeLEOS-1. The image accuracy and quality is within the required specifications. The satellite is now in its commercial operation phase. We will however periodically conduct these CalVal activities to monitor the satellite performance and image quality at least once a year throughout the life of TeLEOS-1.

7. REFERENCES

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