KAGUYA TERRIAN CAMERA DEM IMPROVEMENT

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Abstract. *We present a novel stereo matching approach for processing JAXA Kaguya terrain camera (TC) images. This new approach uses two separate solutions for x and y disparity refinements. This has resulted in an order of magnitude improvement in disparity error. An experimental study shows that a Kaguya TC DEM created from the new stereo process is ~5 times more accurate than DEMs generated using traditional stereo matching. The quality of the new DEM is comparable at high latitude to the corresponding gold standard DEMs from the Lunar Orbiter Laser Altimeter (LOLA) aboard the Lunar Reconnaissance Orbiter (LRO).*

Introduction. NASA's Human Landing System (HLS) program is developing ground breaking technology to send crewed spacecraft to the lunar surface. Terrain Relative Navigation (TRN) and Hazard Detection and Avoidance (HDA) are among the most critical enabling technologies needed to land safely and precisely on the Moon[1]. An accurate Digital Elevation Model (DEM) and matching ortho-projected Reference Map are critical to the success of both TRN and HDA.

The Terrain Cameras (TC) aboard JAXA's SELENE spacecraft (aka Kaguya) provide the most complete, high quality image coverage of the lunar surface at mid resolution DEM (~10m/p). The TC are a pair of push-broom stereoscopic imagers with forward-looking and aft-looking optical heads with slant angles of +/- 15 degrees from the nadir (fig. 1)[5]. At 100 km circular orbit, the TC imagers cover a 35km swath with 10m ground resolution.

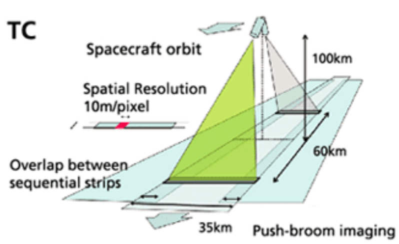

Figure 1: The Kaguya TC stereoscopic imager configuration.

Under this configuration, one-pixel matching error (~10m ground resolution) causes about 18.6m elevation error. It follows that traditional stereo matching error (~0.3 pixel) has ~6 m elevation error. This magnitude of error is reflected in the JAXA processed Kaguya DEMs publicly available from Planetary Data System (PDS) archives (Fig1.2). If we can improve the stereo matching accuracy to better than 0.05 pixel, the associated elevation error becomes sub-meter, which is similar to the accuracy of the best LOLA DEMs[4]. Mid resolution LOLA DEMs of 20m/pxl or better only exists near the poles. This new approach opens an opportunity to create a mid-resolution global DEM map with quality matching LOLA.

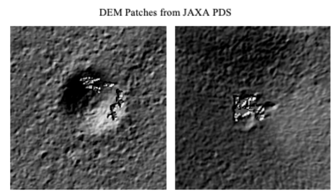

Figure 2: Publicly available DEMs often contain large elevation errors, which makes them less usable for TRN/HDA applications.

Kaguya Stereo image matching Approach

For an image pair (I_1, I_2), consider the stereo matching problem as a pair of mappings from pixel coordinates in I_1 to those in I_2 as follows:

$$X_2 = f(X_1, Y_1) \quad Y_2 = g(X_1, Y_2)$$

The unique forward-looking and aft-looking stereo configuration of Kaguya TC offers a rare opportunity for improving the stereo matching accuracy that does not exist in general (e.g. LROC NAC, MRO NAC).

The TC1 and TC2 sensors are close to parallel and are perpendicular to the flight direction of Kaguya. It follows that the pixel displacement along rows (close to cross-track) between TC1 and TC2 follows a linear relationship over a flat and level surface given by $X_2 = a X_1 + b$.

Due to terrain relief, the pixel displacement along the column direction (close to along-track) is a function of terrain H as dY = 2dH/tan(90-$\boldsymbol{\theta}$), where $\boldsymbol{\theta}$ is the off-nadir angle of each TC imager. For example, a 1000m terrain relief causes about 55 pixels displacement along the Y direction.

The SC attitude change (yaw) within 55 pixels of displacement can be up to 0.05 pixel, but most case it is less than 0.01 pixel, meaning the X disparity can still be approximated by the linear equation above.

If the original 1-$\boldsymbol{\sigma}$ disparity error is 0.3 pixel, and each row is fitted by a linear equation (assume 3000 valid pixels), the disparity error in X can be reduced to a theoretical 1-$\boldsymbol{\sigma}$ value of 0.3/sqrt(3000) = 0.0054 pixel.

Now we will focus on the disparity along y direction.

A common correlation method is the sum of square difference as

$$S = \min\left(\sum\sum(I_f - I_b)^2\right)$$

Once the smallest SSD value, S_0, is identified, the two adjacent SSD values (S_{-1}, S_1) adjacent to it are used together to fit a quadratic polynomial. The subpixel adjustment (Δd) on the integer disparity value is the minimum of the quadratic:

$$\Delta d = \frac{S_{-1} - S_1}{2(S_{-1} + S_1 - 2S_0)}$$

This solution is more precise than the integer solution and in general is assumed to be accurate on the order of 1/3 pixel. However, this subpixel interpolation as well as the SSD solution suffer a few drawbacks:

- The subpixel interpolation is biased towards integer disparity, a well-known problem called pixel locking[2].
- The approach cannot compensate for errors caused by image deformations.
- The approach does not account for differences in radiometry from sensor variation or changes in illumination.

In this paper, we extended the solution suggested in [2] into a special pushbroom camera configuration focused on the Kaguya TC imagers and added a few enhancements to reduce the error .

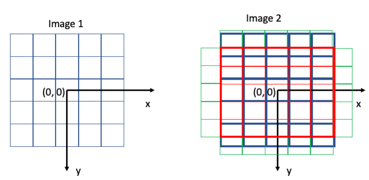

Figure 3: The stereo matching Analogy.

Figure 3 shows a 5x5 correlation, the right is the corresponding correlation window (Bold blue) where the SSD reaches its peak. The red window is the area of the left image correlation window, which is scaled down. yd_y is a scale compensation and xd_x is a shear compensation. Then the image intensity of forward and backward camera can be modeled by this equation.

$$I_f = \begin{cases} s(I_b + (\Delta d + yd_y + xd_x)I') + c = s(I_b + DI') + c, \Delta d \geq 0 \\ s(I_b + (\Delta d + yd_y + xd_x)I'_{-1}) + c = s(I_b + DI'_{-1}) + c, \Delta D < 0 \end{cases}$$

Where s is image intensity scale correction and c is the image intensity offset between the forward and backward camera

Because s is in general close to 1, we can rewrite the equation above into an approximate form as

$$I_f = \begin{cases} I_b + DI' + c + ds(I_b + DI'), \Delta d \geq 0 \\ I_b + DI'_{-1} + c + ds(I_b + DI'_{-1}), \Delta d < 0 \end{cases}$$

where $s = 1 + ds$.

After some manipulation, we obtain for each pixel two equations.

$$S_0 - S_1 = a_0 + a_1 d + a_2 d_x + a_3 d_y + a_4 c + a_5 ds$$
$$S_0 - S_{-1} = b_0 + b_1 d + b_2 d_x + b_3 d_y + b_4 c + b_5 ds$$

In the above, S_0, S_{-1}, S_1 are the SSD scores along the y direction. (a_1, a_2, a_3, a_4, a_5) and (b_1, b_2, b_3, b_4, b_5) can be computed with the backward image only. The only unknowns remaining are: disparity d, image scale ds and offset c. We used a finite element method (FEM) to solve the disparity as well as the scale and offset.

Experimental Study

A pair of Kaguya TC images over the lunar South Pole was used in this study. We generated DEMs from traditional SSD and the new approach. We compare the two DEMs against a 10m/pixel LOLA DEM (Fig. 5, 6). The 1-σ errors are 4.8 m for traditional SSD and 1.2 m for the new method.

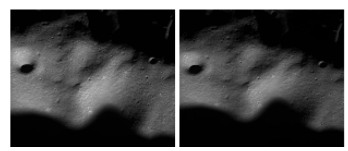

Figure 4: TC1W2B0_01_0480S893E0492 and TC2W2B0_01_04809S891E0496 were used for this study.

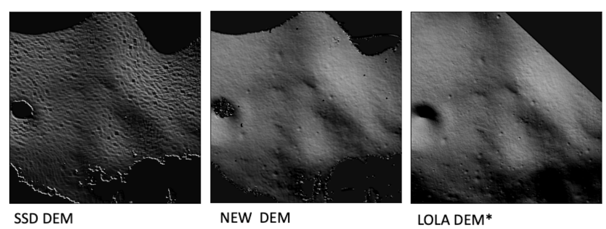

Figure 5: The left figure is the DEM from SSD, the middle figure is the DEM from the new method, and the right figure is the LOLA DEM.

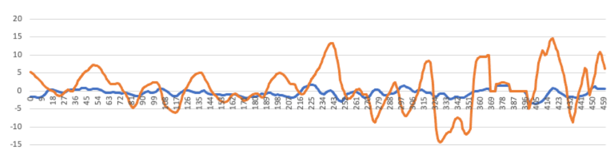

Figure 6: The delta profile between SSD (red) and the new DEM (blue) against a LOLA dem. The new DEM has about 5 times lower elevation error than the SSD DEM.

Conclusions

We developed a new stereo matching approach for Kaguya TC cameras which can effectively reduce the stereo matching error by a factor of 5.

The new approach produces DEMs close to the quality of the best LOLA DEMs (available at the poles) but has the added, potential flexibility of producing such DEMs globally.

This method can be used with other imagers of similar sensor configuration, such as Chang'e 2 or HRSC aboard Mars Express. We expect similar improvements in those cases.
With some additional modifications, the approach may be extendable to single sensor stereo imagery, such as LROC NAC, MRO NAC or HiRISE. We believe the potential applications are far-reaching.

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[1] Cheng, Y., Ansar, A., & Johnson, A. (2021). Making an onboard reference map from MRO/CTX imagery for Mars 2020 Lander Vision System. *Earth and Space Science*, *8*, e2020EA001560.
[2] Y. Cheng and L. H. Matthies, "Stereovision Bias Removal by Autocorrelation," 2015 IEEE Winter Conference on Applications of Computer Vision, Waikoloa, HI, USA, 2015, pp. 1153-1160, doi: 10.1109/WACV.2015.158
[3] Andrew Johnson et al, Mars2020 Lander Vision System Flight Performance, SciTech 2022 Forum.
[4] Barker, M. K., "Improved LOLA Elevation Maps for South Pole Landing Sites: Error Estimates and their Impact on Illumination Conditions", Planetary and Space Science (2020)
[5] Haruyama, J., Matsunaga, et. al. LISM Working Group (2008). Global lunar-surface mapping experiment using the Lunar Imager/Spectrometer on SELENE
[6] Carolina I. Restrepo, et. al. "Building Lunar Maps for Terrain Relative Navigation and Hazard Detection Applications," AIAA 2022-0356. AIAA SCITECH 2022 Forum. January 2022