A New Serial-direction Trail Effect in CCD Images of the Lunar-based Ultraviolet Telescope

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Abstract

Unexpected trails have been seen subsequent to relative bright sources in astronomical images taken with the CCD camera of the Lunar-based Ultraviolet Telescope (LUT) since its first light on the Moon’s surface. The trails can only be found in the serial-direction of CCD readout, differing themselves from image trails of radiation-damaged space-borne CCDs, which usually appear in the parallel-readout direction. After analyzing the same trail defects following warm pixels (WPs) in dark frames, we found that the relative intensity profile of the LUT CCD trails can be expressed as an exponential function of the distance \(i\) (in number of pixels) of the trailing pixel to the original source (or WP), i.e., \(\exp(\alpha i + \beta)\). The parameters \(\alpha\) and \(\beta\) seem to be independent of the CCD temperature, intensity of the source (or WP), and its position in the CCD frame. The main trail characteristics show evolution occurring at an increase rate of \(\sim(7.3 \pm 3.6) \times 10^{-3}\) in the first two operation years. The trails affect the consistency of the profiles of different brightness sources, which make smaller aperture photometry have larger extra systematic error. The astrometric uncertainty caused by the trails is too small to be acceptable based on LUT requirements for astrometry accuracy. Based on the empirical profile model, a correction method has been developed for LUT images that works well for restoring the fluxes of astronomical sources that are lost in trailing pixels.

Key words: techniques: image processing

Online material: color figures

1. Introduction

The Lunar-based Ultraviolet Telescope (LUT) employs a UV-enhanced CCD operating in its frame transfer mode to monitor brightness variations of astronomical objects in near-ultraviolet (Cao et al. 2011; Wang et al. 2015). It is a scientific payload of the Chang’\textsuperscript{e}-3 lunar lander, which was launched at the moon at the end of 2013. The telescope began to take astronomical images \(\sim2\) days after the moon landing, while it spent \(\sim12\) days in the Earth-to-Moon flight.

It was found that a good number of pixels trail behind relative bright sources in the serial-direction of CCD readout in LUT’s astronomical images (see Figure 1 for an example). This phenomenon was far from expected given that it had never been observed in our intensive ground tests. It was once suspected to be related to CCD pixel bleeding or optical PSF convolving since the profiles of most sources seem normal. However, it was found later that the trails are not related to optics. And, the trails are also discovered in the earliest downlinked data when we re-check the data archive. In order to evaluate its impacts on our photometric measurements and astrometry, we set out to study the behaviors of this image defect.

It has been well known that trails do occur behind bright sources for veteran space-borne CCDs, as demonstrated by many HST astronomical images. Those trails are a result of degradation of the charge transfer efficiency (CTE) of CCDs due to accumulated radiation damage done by high-energy particles in the harsh space environment. However, unlike in the case of LUT, they usually appear in the parallel direction of CCD readout because as a rule the serial CTE is much less susceptible to radiation damage than the parallel one. Many attempts have been made to empirically characterize the CTE-loss phenomena for space-borne CCDs, and various correction methods have been developed. Among those, the pixel-based CTE-correction method (Anderson & Bedin 2010; Massey et al. 2010, 2014) is particularly successful and has become

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Figure 1. A 680 × 446 pixel section centering at (683,563) of an LUT image with an exposure time of 5 s showing a trail behind the flux standard star HD188665 (inset: an enlarged view). The bright background and crosshatch pattern are due to stray light of the Sun and non-uniformity in the CCD response to UV photons, respectively (C. Wu et al. 2015, in preparation).

Figure 2. A 237 × 147 pixel section centering at (184,503) of dark frames taken on the sixth lunar day of LUT. (a) A single raw dark frame; (b) the single dark frame after bias correction (inset: the enlarged view of a typical trail behind a WP); (c) a median-combined dark frame; (d) the combined dark frame after trail correction.
popular, which was based on analyses of the trails behind warm pixels (WPs) in CCD dark current frames.

In this paper, we analyze the dark current images to characterize the trails’ behaviors. Based on the trail behavior model, we develop a trail correction method for LUT CCD images, following the strategies in Anderson & Bedin (2010) in order to restore the observed fluxes and image profiles of astronomical sources and background distributions. Additionally, we estimate the impact of trail effect on photometry and astrometry, based on the trails’ characteristics. In Section 2 we describe the optics and the CCD detector of the LUT, as well as its observational scheme and dark frame acquisitions. Our analyses of trail behaviors are presented in Section 3, which are based on WPs in dark frames. A WP is principally a single-pixel “signal”, so over the multi-pixel bright astronomical sources it has the advantage of providing a well-defined trail profile. In Section 4, our trail correction method is constructed and its efficiency is checked with real LUT astronomical images. We present our estimates on the trail effect impact to photometry and astrometry in Section 5. Finally, we discuss our results in Section 6.

2. Telescope and CCD Detector

LUT is a F/3.75 Ritchey-Chretien telescope fixed inside the payload cabin of the Chang’e-3 lunar lander. A gimbal-mounted flat mirror is placed in front of its aperture to reflect the light from a given sky region into the telescope, basically a siderostat (for details, please refer to Cao et al. 2011 and Wang et al. 2015). Its throughput peaks at 2500 Å in the near-UV band and has an effective width of about 1080 Å.

The imaging sensor mounted at the Nasmyth focus is a UV-enhanced AIMO CCD47-20 manufactured by e2v. It is a frame transfer CCD, so no mechanical shutter is needed. Its image section has 1024 × 1024 active pixels with a pixel size of 13 μm, corresponding to 476 in the sky. On both the left and right edges there are 16 extra pixel columns not exposed to any light, designed to be used as dark reference, and 8 virtual blank columns for bias overscan. On the top there are also 3 pixel rows of dark reference. The store section belowimage one has 1024 × 1033 pixel elements (for details, please refer to e2v technologies 2006). The CCD can be thermoelectrically cooled to −40°C for typical thermal conditions inside the payload cabin.

LUT only operates during lunar daytime due to limited power supply. For the purpose of calibration, CCD frames of bias, dark current, and internal LED flat-field are routinely obtained at each lunar dawn and dusk, i.e., before and after all science exposures of that lunar day are taken. Because the CCD has a relatively high working temperature on the second half lunar day, i.e., about −20°C, while it is also more affected by
Table 1
List of LUT Dark Frames

| Lunar Day | Month | CCD Temperature |
|----------|-------|-----------------|
|          |       | Pre-dark | Mid-dark | Post-dark |
| 0        | 2013-12 | N          | -20°C, -30°C | N          |
| 1        | 2014-01 | -30°C     | N         | -20°C     |
| 2        | 2014-02 | -40°C     | N         | -20°C     |
| 3        | 2014-03 | -40°C     | N         | -20°C     |
| 4        | 2014-04 | -40°C     | N         | -20°C     |
| 5        | 2014-05 | N         | N         | -20°C     |
| 6        | 2014-06 | -40°C     | N         | -20°C     |
| 7        | 2014-07 | N         | N         | -20°C     |
| 8        | 2014-08 | -40°C     | N         | -20°C     |
| 9        | 2014-09 | -40°C     | N         | -20°C     |
| 10       | 2014-10 | -40°C     | N         | -20°C     |
| 11       | 2014-11 | -40°C     | N         | -20°C     |
| 12       | 2014-12 | -40°C     | N         | -20°C     |
| 13       | 2015-01 | -40°C     | N         | -20°C     |
| 14       | 2015-02 | N         | N         | -20°C     |
| 15       | 2015-03 | N         | N         | -20°C     |
| 16       | 2015-04 | N         | N         | -20°C     |
| 17       | 2015-05 | N         | N         | -20°C     |
| 18       | 2015-06 | -30°C     | N         | -20°C     |
| 19       | 2015-07 | N         | N         | -20°C     |
| 20       | 2015-08 | -40°C     | N         | -20°C     |
| 21*      | 2015-09 | -40°C     | N         | -20°C     |
| 22       | 2015-10 | -40°C     | N         | -20°C     |
| 23       | 2015-11 | N         | N         | -20°C     |
| 24       | 2015-12 | -40°C     | N         | -20°C     |

Note. “Pre-dark,” “mid-dark,” and “post-dark” denote dark frames obtained at dawn, in the middle time, and at dusk of each lunar day, respectively. Mid-dark data are available only for lunar days 0, 5, and 7, and neither post-dark for lunar day 0. In 2015, an extending mission life year, many extra tests occupied some pre-dark time. “*”: No WP with value >300 ADU for the −40°C data in this month. We do not use this month data in our analysis.

3. Trail Behavior Analyses

It is unlikely that trails in LUT images are related to the optics. First, they also occur behind WPs in CCD dark frames. Second, as a test of if we chose the right readout amplifier to output the CCD image instead of the left one, which is usually used, the direction of observed trails was also reversed as a consequence (see Figure 3).

3.1. Data and Preprocessing

Following Anderson & Bedin (2010), we used CCD dark frames to quantitatively analyze trail behaviors taking into advantage of the delta function-like appearance of WPs (ignoring the trails behind). They were selected from the LUT data archive up to the end of 2015, which spans 25 lunar days (see Table 1). For convenience we designated the dark frames obtained at dawn, in the middle time, and at dusk of each lunar day as “pre-dark”, “mid-dark”, and “post-dark”, respectively. Our analyses were mainly based on the pre-dark data from nine lunar days, which have our lowest CCD temperature, i.e., −40°C, and hence relatively clean backgrounds.

Each selected dark frame was first bias-corrected using overscan counts of the right side. The residual stripe noise that has been described for HST data by Grogin et al. (2010) was then removed using the technique of the “3rd methodology” in that paper, while a typical result is shown as panel (b) of Figure 2. Next, in order to improve the signal-to-noise ratios (S/N) of WPs and their trails, we used the dark-combine package of IRAF5 to combine all the dark frames from the same lunar day and of the same CCD temperature to make a median-combined one. From that operation cosmic rays were also removed. Finally, we were left with 13 combined dark frames of good S/N and free of cosmic rays (see panel (c) of Figure 2).

3.2. Extraction of Trail Events

Trail events were extracted from the pre-processed dark frames using a method similar to that of Anderson & Bedin (2010). 1) First, a median dark value and its standard deviation were computed in an iterative way by excluding 3σ outlier pixels at each step. 2) Then all pixels with dark counts of more than 5σ above the median were marked as WPs. 3) For each WP, 20 subsequent pixels along the serial readout direction were selected to define the trail event. For the strongest WP, it is until the 20th pixel that the trail intensity drops to the background level. 4) In order to remove the impact of any background variation in the pixel row direction, we subtracted from each trail pixel the median of 10 neighbouring pixels along its column. As an example, 19054 trail events have been extracted from the combined dark frame of lunar day 6.

As demonstrated in Figure 4 with the results of lunar day 6, for any given pixel number in the trails, the intensity correlates

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5 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
well with that of the WP in a linear relationship, that is

\[ I_{\text{trail}} = k \times I_{\text{wp}} + C, \]  

where the slope \( k \) is a function of the pixel number \( i \) (or the distance of the trailing pixel to the WP), which is between 1 and 20. The interception \( C \) is about 0.5 instead of 0, which may

Figure 4. Trail intensity vs. the WP intensity for different trail-pixel numbers (shown as different panels) in the combined dark frame of lunar day 6. Solid lines represent linear fitting to the data, while the shaded areas denote the 3\( \sigma \) error bands. (A color version of this figure is available in the online journal.)
be similar to the small “bias-shift” effect first mentioned in Anderson & Bedin (2010). In fact, C increases to about 1 if instead the above analyses were made on the raw dark frames before bias correction.

Note that our method only extracted trails with an WP intensity typically that was larger than 45 digital numbers (DNs), as limited by the readout noise and crowding effect. The possibility of one trail event being contaminated by another was found to be $\sim 5.6\%$, which may account for the $3\sigma$ outlier points in Figure 4.

3.3. Modeling the Trail Intensity Profile

From the first nine groups of fitting values corresponding to our nine combined dark frames, it was found that the slope $k$ can be expressed as an exponential function of the pixel number $i$, that is

$$k = \exp(\alpha i + \beta),$$

where $k$ can be simply taken as the intensity ratio of the trail pixel to the WP if the marginal interception $C$ is ignored. The best-fitting parameters are $\alpha = -0.182$ and $\beta = -4.881$, which make all data points consistent within a $10\%$ error band except for the first trail pixel and last few, as demonstrated in Figure 5. For the first pixel, the deviation may be due to the fact that the original WP profile is not as perfectly sharp as a delta function, while for the last few it may be due to the relatively low S/N. Note that the fraction of total pixel counts that are located in the trail is about $3.7\%$ as calculated from our best-fitting trail profile. That translates to $\sim 3.5\%$ of the original WP intensity that has been lost in the trail.

Figure 6 shows the ratio of intensity loss in the trail evolution during the $\sim 2$ years after launch. It indicates that there is a small increase at a rate of $(7.3 \pm 3.6) \times 10^{-4}$ per year. However, no parallel CTE trail is found in the dark current frame of lunar day 24.

As a test, we also processed the dark frames of lunar days 0 and 1, which have CCD temperatures higher than $-40^\circ C$, and found no temperature dependence of the trail profile except for the first pixel (see Figure 7). We suspected that the first pixel is slightly affected by the original WP profile.

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6 For a corresponding CCD gain of 1.59.
7 The first nine groups are the data from the designed mission time, while the other four groups are from the extended mission life of 2015. Our main analysis is based on the first nine groups’ data.
Figure 6. Evolution of trail effect during the two operation years. The solid circles with error bars represent the intensity loss ratio of the trail. The linear fit for the evolution is represented by the solid line, the slope of which is $(7.3 \pm 3.6) \times 10^{-4} \ \text{yr}^{-1}$.

(A color version of this figure is available in the online journal.)

Figure 7. Comparison of the WP trail profiles between LUT dark frames with different CCD temperatures.

(A color version of this figure is available in the online journal.)
From the above analysis, the characteristics of the trail are summarized: 1) the trail profile depends on neither the intensity of the WP nor its position in the CCD frame; 2) the trails only appear at serial-direction, and do not exist at parallel direction even after two years of evolution; 3) there is $\sim(7.3 \pm 3.6) \times 10^{-4}$ increased in trail loss per year. Those characteristics are different from the well-studied ones in HST images and dark frames suggested by Cawley et al. (2001). It clearly indicates that the origin of the LUT trail is different from those in HST.

4. Trail Correction

4.1. The Method

Based on the relative intensity profile of the WP trails, we constructed a simple method to remove trails from the LUT
astronomical images and restore the original source fluxes that have been lost in the trails. To do this, we must assume that the same trail profile that we have extracted from dark frames also applies for real images, which may be justified by the fact that similar strategies made by Anderson & Bedin (2010) and Massey et al. (2010) for the HST ACS camera have been successful. Further confirmation of that assumption can be provided by performance testing of our method.

Our trail correction operation always starts from the most left image column, i.e., that nearest from the CCD readout amplifier, and proceeds to the right columns one-by-one. For any pixel in column \( j \) with a current flux of \( F_j \), a correction value \( \Delta_{\text{corr}} \) is calculated as

\[
\Delta_{\text{corr}} = \sum_{i=1}^{20} k(i) \times F_j,
\]

where \( k(i) \) is the trail profile parameter expressed by Equation (2). And the original flux of that pixel in column \( j \), i.e., \( F_{j,\text{orig}} \), is restored as

\[
F_{j,\text{orig}} = F_j + \Delta_{\text{corr}},
\]

while the supposed trail fluxes are stripped from all pixels in the 20 columns to the right, i.e.,

\[
F'_{j+i} = F_{j+i} - k(i) \times F_j,
\]

now one can move to the next column \( j + 1 \) and repeat the above procedures, until the whole CCD frame has been corrected.

4.2. Performance Check

We first applied our trail correction method to the combined dark frames. As demonstrated in Figure 2 (d), all visible trails behind WPs have been removed completely.

Then we made tests using real astronomical images taken with the LUT. The method works well for cleaning trails for all tested images, one of which is shown in Figure 8 as an example. A difference plot (right panel) between the corrected image and the original one indicates that no residual flux is left in the trail pixels after the correction. One can further examine the correction effect on source profiles. The intensity profiles of two bright stars are extracted from Figure 8, both the original and corrected images, and displayed in Figure 9. After the trail correction, the profile symmetry broken by the trail has been greatly restored. Note also that for aperture photometry with an aperture size of 2.5 pixels, the measured fluxes of the two stars increase by 2.7% after the trail correction.

An additional check can be made using the dark reference pixels attached to LUT images of high background counts. The high-level background on the right image edge will leave trails in subsequent dark reference pixels. One such profile is
displayed in Figure 10, which was extracted from row 800 of an LUT image with a background level of $\sim 8000$ DNs. By using our method, the trail can be completely suppressed except for the first three dark reference pixels, which we suspect are dominated by background light leaking from the image region.

5. Estimate of the Trail Impact

From the LUT trail behavior characteristics obtained above, we may estimate the trail impact on photometry and astrometry using an analysis of the simulated and real data. The consistency of the photometry curves of growth for different brightnesses is the main factor affecting photometric uncertainty. To check the consistency, we implement the following procedures. First, we use SkyMaker (Bertin 2009) to simulate an LUT image with 8 groups of various brightness sources from 6 mag to 13 mag, with a bin of 1 mag. Each group has eight sources with the same brightness. The instrumental parameters for SkyMaker are the same as those for LUT except for the noise parameters. Readout noise and skynoise are ignored in order to minimize noise interference. We then add trail effects to the simulated image to make the sources show a trail based on the trail model. Finally, we measure the photometry curve of growth from the two simulated images (one has a trail and the other does not).

Our analysis results provide the caveat that a smaller photometry aperture will bring larger systematic photometric errors for LUT trail-affected data. The photometry curves of

\[\text{(A color version of this figure is available in the online journal.)}\]

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Figure 11. (a) The photometric curve of growth for Gaussian kernel sources. (b) Same as (a) but the trail effect was added. The inset shows the enlarged part of the scatter of various brightness curves. (c) The difference of the photometric curves of growth between sources without trails and with trails. (d) The scatters of photometric curves of growth of different brightnesses around their average values. The inset shows an enlarged part of the scatters.

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8 The designed limiting magnitude of LUT is 13 mag with an exposure time of 30 seconds.
Figure 12. Histogram of the difference of the center position between point sources without trails and those with trails. (A color version of this figure is available in the online journal.)

Figure 13. Same as Figure 10 but for a flat-field image taken on the ground. (A color version of this figure is available in the online journal.)
growth are shown in Figures 11(a) and (b). Each panel shows photometry curves of growth for 6 different brightness except for saturation sources of the 6 and 7 mag. It clearly shows that there are systematic scatters for the trail curves. Panel (d) shows the scatters around their averages for data with and without trails. For the data with trails, the scatter is as large as 0.04 mag at small apertures of ∼0.5 FWHM and then drops to 0.015 mag at 1 FWHM. At the inflection point of 1.5 FWHM, the scatter is reduced to 0.001 mag. For apertures larger than 2.5 FWHM, the scatter decreases to the same level as the result of data without trail. Panel (c) shows the difference magnitude of the photometry curves between the data without trails and those with trails with the same brightness source. Generally, the trails make the intensity lose 0.027 mag at an aperture of 1.6 FWHM. Meng et al. (2015) used magnitudes of aperture of 2.0 FWHM to extrapolate to infinite apertures to obtain the photometric zero points. According to our analysis, the photometry uncertainty should be less than 0.0006 mag, carried by the trail effect.

Our analysis indicates that the LUT trail effect will bring the astrometric error to less than 0.4 arcsec through reprocessing our astrometric pointing calibration data used by Qi et al. (2015). The difference of the center position in the x and y directions is shown in a histogram in Figure 12. The center position difference is less than 0.04 pixels, corresponding to 0.2 arcsec. Compared to the larger pointing error of 0.17, the astrometric error caused by the trail effect could be ignored.

6. Discussions

The trail correction operation will likely introduce some extra noise to the corrected images. By applying our correction method to a simulated image with a flat background of 10 DN and readout noise of 6.8 DN (assuming gain = 1.59), we found an increase of 3.8% in the pixel-to-pixel noise, which is actually small. Moreover, Anderson & Bedin (2010) have developed a technique to suppress the extra noise through simply dividing the image into two parts, one slightly smoother and another noisier, which must also work for the case of LUT images.

It is unclear what causes the trail defects in the LUT images and dark frames. As stated before, trails have neither dependence on the intensity of WP nor its position in the CCD frame, and only appear at serial-directions. This is different from the HST-like CTE faults. We note that the trails have ∼(7.3 ± 3.6) × 10⁻⁴ linear increases based on the two-year data. It looks like the trails defects may be related to operation time and/or its operation environment, such as long
term particle radiation. However, we need more data to confirm this in the future. We searched the test data and calibration data taken with LUT on the ground for any sign of existence of the trails before launch. The results are ambiguous. On one hand, as demonstrated by Figure 13, a trail-like behavior may be identified in the dark reference areas of flat-field images, similar to but less significant than the case of Figure 10. On the other hand, there is no evidence of any visible trail in dark frames obtained in the ground, which may be explained by the relatively weak WPs in the LUT CCD before launch. Additionally, we found no trail event in ground test images of very strong point sources. However, we cannot reach any solid conclusion since the background of the ground images is very high. Our simulations indicate that it is difficult to find trails in such a high background.

By re-checking LUT images one-by-one, we found the first trail-affected sources in the image taken ~2 days after the starting observation, which is shown in Figure 14. The images before that day have few sources and the sources are too faint to be have any trail effects. This indicates that the trail effect may exist at the beginning of observation. If the trail did not exist in the ground image before launch, the space environment could be responsible for the trail effects during flight.

The unknown nature of the LUT trail defects notwithstanding, we have analyzed their behaviors and obtained a uniform profile for their relative pixel intensities. The correction method that we have constructed based on the empirical profile works well for cleaning the LUT images and for restoring the source fluxes lost in trail pixels. Our trail effects correction method will be included in the data processing pipeline of LUT as an optional procedure.

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9 Its peak intensity is up to 40000 DNs.