A new method of CCD dark current correction via extracting the dark information from scientific images

Bin Ma¹, Zhaohui Shang²,¹, Yi Hu¹, Qiang Liu¹, Lifan Wang³,⁴, Peng Wei¹

¹National Astronomical Observatories, Chinese Academy of Sciences, Beijing, China; ²Tianjin Normal University, Tianjin, China; ³Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing, China; ⁴Texas A&M University, College Station, Texas, USA;

ABSTRACT
We have developed a new method to correct dark current at relatively high temperatures for Charge-Coupled Device (CCD) images when dark frames cannot be obtained on the telescope. For images taken with the Antarctic Survey Telescopes (AST3) in 2012, due to the low cooling efficiency, the median CCD temperature was -46°C, resulting in a high dark current level of about 3e⁻/pix/sec, even comparable to the sky brightness (10e⁻/pix/sec). If not corrected, the nonuniformity of the dark current could even overweight the photon noise of the sky background. However, dark frames could not be obtained during the observing season because the camera was operated in frame-transfer mode without a shutter, and the telescope was unattended in winter. Here we present an alternative, but simple and effective method to derive the dark current frame from the scientific images. Then we can scale this dark frame to the temperature at which the scientific images were taken, and apply the dark frame corrections to the scientific images. We have applied this method to the AST3 data, and demonstrated that it can reduce the noise to a level roughly as low as the photon noise of the sky brightness, solving the high noise problem and improving the photometric precision. This method will also be helpful for other projects that suffer from similar issues.

Keywords: CCD, Dark Current Correction, Photometry Precision, Antarctic Astronomy

1. INTRODUCTION
Dark current in the Charge-Coupled Device (CCD) is generated by thermal electrons within the silicon structure of the CCD, and these cannot be distinguished from the actual image photoelectrons. The dark current generation rate essentially depends on the temperature, and could be reduced dramatically as the temperature drops. Thus, the CCDs are commonly cooled to ~ -100°C with liquid nitrogen, Peltier junctions (thermoelectric coolers, TECs), or mechanical pumps (cryo-coolers). Sometimes the total dark current level is less than 1 e⁻ in an image and could be neglected, otherwise, in the very long exposures, the dark current still contributes measurable noises, hence should be corrected. The standard procedures of dark correction are to take the dark frames with the same exposure time at the operating temperature with the shutter closed, combine them to create a high signal-to-noise ratio (SNR) master dark frame, and then subtract it from the scientific images.

The trio Antarctic Survey Telescopes (AST3) are designed for multi-band wide-field survey at Dome A, the highest place of the Antarctic Plateau, which is considered as a candidate of the best optical/IR and sub-mm astronomical site on earth. AST3 has a modified Schmidt system design (with a tube about half the length as that of a traditional Schmidt) with an entrance pupil diameter of 500 mm and the focal ratio of f/3.73. AST3 has full pointing and tracking components. AST3 is equipped with the STA1600FT CCD camera, designed and manufactured by Semiconductor Technology Associates, Inc., with 10560 x 10560 pixels of 9 µm, corresponding to 1 arcsec on the focal plane of AST3. The CCD chip is cooled by TEC to take advantage of the extremely low air temperature at Dome A in the winter, which is about -60°C on average.

The first AST3 (AST3-1) has been deployed to Dome A, Antarctica by the 28th Chinese Antarctic Research Expedition (CHINARE) team in January 2012, and is the largest optical telescope in Antarctica so far. AST3-1
started operation in middle March, when the polar day ended. After the test of focusing, pointing and tracking, it began normal observations, but unfortunately stopped work on May 8 due to some malfunction in the power supply system. Until then, AST3-1 had repeatedly surveyed nearly 500 fields (∼2,000 deg²) with more than 3,000 60-sec exposures, and monitored the center of Large Magellanic Cloud with >4,700 frames and several fields on the Galactic disk with ∼7,000 frames. The data were retrieved by the 29th CHINARE team in April 2013, and consisted of more than 22,000 frames, including both test and scientific images.

However, these data suffer critical dark current issue because the low cooling efficiency resulted in a median CCD temperature of -46 °C, and a large fraction of images were even taken at around -30 °C. According to the lab tests, the temperature of -46 °C corresponds to a dark current level of about 3 e⁻/pix/sec, which is comparable to the sky brightness (10 e⁻/pix/sec). Moreover, the noise caused by nonuniformity of dark current is proportional to the dark current level, while the photon noise is proportional to the square root of the photon flux. As a result, the former will overweight the latter at certain temperature and exposure time, and limit both photometric depth and precision. Therefore the dark current must be corrected well for precise photometry. However, the standard procedure was not possible for AST3, because its camera was operated in frame-transfer mode without a shutter, and it was unattended in winter. So dark frames could not be obtained during the observing season. In addition, dark frames taken in laboratory cannot be used either, because it is found that the patterns in the dark frames changed. In this paper, we will present a new method to derive the dark current without a shutter, and it was unattended in winter. So dark frames could not be obtained during the observing season. In this paper, we will present a new method to derive the dark current.

2. METHOD

The signals in a scientific image contain photons from celestial objects such as stars and galaxies, and photons from the sky background, as well as the dark current from the CCD. The stars are located randomly in different celestial fields, thus can be removed via a median algorithm when combining a large number of images in various fields. The sky brightness is quite flat spatially after twilight, therefore can be taken as a constant. However the celestial fields, thus can be removed via a median algorithm when combining a large number of images in various fields. The sky brightness is quite flat spatially after twilight, therefore can be taken as a constant. However the dark current nonuniformity at temperature T corresponds to a dark current level of about 3 e⁻/pix/sec, which is comparable to the sky brightness (10 e⁻/pix/sec). Moreover, the noise caused by nonuniformity of dark current is proportional to the dark current level, while the photon noise is proportional to the square root of the photon flux. As a result, the former will overweight the latter at certain temperature and exposure time, and limit both photometric depth and precision. Therefore the dark current must be corrected well for precise photometry. However, the standard procedure was not possible for AST3, because its camera was operated in frame-transfer mode without a shutter, and it was unattended in winter. So dark frames could not be obtained during the observing season. In this paper, we will present a new method to derive the dark current nonuniformity from the observational images directly, and demonstrate its correction efficiency on AST3 images.

2.1 Calculating Dark Current

To obtain the dark current, we need both ∆d(T, x, y) and D(T), respectively. In Eq. [4] the sum of the first two constant terms S and D(T) is practically the median value of the full image I₀. Supposing there are two images taken at the same exposure time and temperature T₀, but with different sky brightness, they have different constant terms but the same fluctuation term:

\[
I_1(x, y) = I_{0,1} + \Delta d(T, x, y),
I_2(x, y) = I_{0,2} + \Delta d(T, x, y).
\]

If I₀₂ is brighter, I₁(x, y) can be scaled to the equivalent median level of I₀₂ by multiplying the ratio k ≡ I₀₂/I₀₁:

\[
I'₁(x, y) = kI₁(x, y) = I_{0,2} + k\Delta d(T, x, y).
\]

Then subtracting I₂(x, y) from I'₁(x, y) removes the constant term, and leaves only the fluctuation term. Consequently the dark current nonuniformity at temperature T can be calculated by the image pair:

\[
\Delta d(T, x, y) = \frac{I'₁(x, y) - I₂(x, y)}{k - 1} = \frac{kI₁(x, y) - I₂(x, y)}{k - 1}.
\]
To be more precise, there is another nonuniform factor in the flat correction, the nonuniform response to the light (quantum efficiency) of CCD pixels. Then $S$ should be written as $S(f(x, y) \equiv S(1 + \Delta f(x, y)) = (I_0 - D(t))(1 + \Delta f(x, y))$, where $f(x, y)$ is the normalized flat frame, and $\Delta f$ is the deviation of $f$ from unity. Taking into account the flat’s influence, the image values in Eq. 2 become:

$$I_1(x, y) = I_{0,1} + (I_{0,1} - D(t))\Delta f(x, y) + \Delta d(T, x, y),$$

$$I_2(x, y) = I_{0,2} + (I_{0,2} - D(t))\Delta f(x, y) + \Delta d(T, x, y).$$

Again, $I_1(x, y)$ can be scaled to be:

$$I'_1(x, y) = kI_1(x, y) = I_{0,2} + (I_{0,2} - kD(t))\Delta f(x, y) + k\Delta d(T, x, y).$$

And the difference between $I'_1(x, y)$ and $I_2(x, y)$ results in:

$$I'_1(x, y) - I_2(x, y) = -(k - 1)D(t)\Delta f(x, y) + (k - 1)\Delta d(T, x, y).$$

Therefore $\Delta d(T, x, y)$ is derived instead by:

$$\Delta d(T, x, y) = \frac{kI_1(x, y) - I_2(x, y)}{k - 1} + D(T)\Delta f(x, y).$$

To derive the median dark current level $D(T)$ without simultaneous dark frames, one simple approach is to adopt the previous lab test results, assuming that it would not vary too much during one or two years. Another estimation via observation is to take one frame at temperature $T_0$, then warm the CCD by several degrees, and take another frame at this temperature with the same exposure time. While the sky brightness keeps constant, nevertheless it would interrupt the observation.

Adding the space-varying term $\Delta d(T, x, y)$ to the median level $D(T)$, we can derive the dark frame at temperature $T_0$ and exposure time $t_0$, then we can scale it to the temperature and exposure time that match those of the scientific images for applying the dark correction.

### 2.2 Scaling

Dark current increases exponentially as the temperature of the CCD increases, and for AST3 CCD it doubles for every 7.3°C increase in temperature.[4] However this relationship was obtained in the temperature range between -80°C and -40°C, and we found that this overestimated the dark current level at higher temperature when it was applied to the correction. We developed an alternative way to estimate the dark current ratio directly between the dark frame and a scientific image.

There are a large number of warm pixels in the CCD, whose dark currents are several times higher than the normal pixels, but not as extremely high as those of hot pixels. These warm pixels’ dark currents show similar behavior when increasing with temperature and exposure time as normal pixels. Then the difference value between a warm pixel and its adjacent normal pixel will also increase by the same factor. In the scientific images, because the adjacent pixels are exposed by the identical sky brightness, the difference between the pixel values is just their dark current difference. As a result, the ratio between the pixel value difference of the dark frame and that of the scientific image can be utilized to scale the dark frame at temperature $T_0$ and exposure time $t_0$ to those of the scientific image. Also, using as many of warm pixels could reduce the noise.
2.3 Error

When estimating dark current nonuniformity by Eq. 8, the random noise is mainly contributed by the first term, while the systematic error is dominated by the second term, which are the uncertainties of \( D(x, y) \) and \( \Delta f(x, y) \), and are roughly insignificant compared with random noise. The random noise is:

\[
\sigma^2_{\Delta d}(x, y) = \left( \frac{k}{k-1} \right)^2 \sigma^2_{I_1}(x, y) + \left( \frac{1}{k-1} \right)^2 \sigma^2_{I_2}(x, y).
\]

(9)

where \( \sigma^2_{I_1}(x, y) \) and \( \sigma^2_{I_2}(x, y) \) are the Poisson noises in each pixel if readout noise is negligible, and can be approximate to \( I_{0,1} \) and \( I_{0,2} \) (in unit of electron), respectively, except for the hot pixels. Besides, taking into account \( I_{0,2} = kI_{0,1}, (k > 1) \), the noise is:

\[
\sigma^2_{\Delta d}(x, y) = \frac{k(k+1)}{(k-1)^2} I_{0,1} = K I_{0,1},
\]

(10)

which indicates that it decreases as \( k \) increases. When \( k \) is close to 1, the noise tends to be infinite. This makes sense because nothing can be derived if the image pair are identical. When \( k \) is large enough, the noise is close to the Poisson noise of the image with the lower sky brightness. In practice, due to the saturation problem of the CCD, \( k \) cannot be too large. In addition, a bright sky background, either during twilight or caused by the moon, suffers significant gradient which does not satisfy the assumption of flat background. Therefore \( k \) should be chosen properly. The factor \( K \) in Eq. (10) decreases as \( k \) increases, e.g. its values are 6, 3, 2.2, 1.9, respectively, corresponding to \( k \) = 2, 3, 4, 5. Therefore \( k > 3 \) is less noisy enough, and it corresponds to \( > 1.2 \) mag brighter, and this brightness ratio is available in observations during dark nights.

3. RESULTS

We have applied the method on AST3 images to correct the dark current. We selected 230 pairs of images, which were taken under the temperature of \(-41.9^\circ C\) and with exposure time of 60 sec. We have derived the dark current nonuniformity via Eq. (8) for each pair, and combined them with median algorithm as well as sigma-clipping. The lower brightness images have a median background of \( \sim 660 \) ADU with the gain of \( 1.7 \) e\(^-\)/ADU. The brightness ratios \( k \) in these pairs are required to be greater than 3, and finally have a median of 4.0. Therefore the random noise in one estimation is \( \sim 29 \) ADU according to Eq. (10). After median combination, the noise can be reduced by a factor of \( \frac{1}{\sqrt{230}} \) to 1.9 ADU, which is much lower than the readout noise (7 ADU), thus would not effect the photometric precision. The flat frame is derived by combining hundreds of twilight flat frames. Finally we derive the master dark frame by adding the median dark current level from the lab test result, and normalize it to 1 sec. In Fig. 1 we compare this derived dark frame with lab dark frame, both of which show the similar large scale patterns.

We take image \( a0331.116.fit \), which was taken at temperature of \(-41^\circ C\) and with exposure time of 60 sec, as an example. The raw image is shown in Fig. 2 in which the large scale patterns from dark current are obvious.
Figure 2. Raw image a0331.116.fit as an example. The black region in the bottom-left is bad pixels due to a damage in this engineering grade CCD.

Figure 3. The distribution of all scaling factors derived using warm pixels for a0331.116.fit according to Sec. 2.2. The median value of 69.54 is used to scale the derived master dark frame for dark correction of the example image a0331.116.fit.

We derive scaling factors using a large number of warm pixels according to Sec. 2.2 and adopt a median value of 69.54 (see Fig. 3) to scale the derived master dark frame for dark correction of the example image. The correction results are illustrated in Fig. 4. A small region of the full frame is zoomed in to demonstrate the correction effects. In the raw image, many hot and warm pixels are apparent. They are not corrected well by the lab dark, that some are overcorrected while some are undercorrected, implying that the detailed dark features have changed with time. In contrast, these hot and warm pixels are removed much more cleanly by the derived dark, improving the SNR of the faint stars. The background level of the raw image in the center is 620 ADU, and its RMS of 55.4 ADU is roughly three times of the Poisson noise (19 ADU). The background RMS is only reduced a little to 43.5 ADU if corrected by the lab dark, while it is reduced greatly to 24.9 ADU when corrected by the derived dark. As a result, the derived dark could improve the photometric depth by 0.9 mag, as well as the photometric precision (see Fig. 5).
Figure 4. A small region of the full frame is shown to compare the dark correction effects. Left: raw image; middle: corrected by the lab dark; right: corrected by the derived dark. Compared with the lab dark, the derived dark removes the hot and warm pixels much better, and improves the SNR of the faint stars.

Figure 5. The photometric error as a function of instrument magnitude. Red dots: without dark correction; black dots: corrected by derived dark.

Furthermore, we demonstrate the correction effect as a function of CCD temperature in Fig. 6. The background level of these images are 500 to 600 ADU, which means that they have very close Poisson noise level (about 18 ADU). If dark current is not corrected, the background noise will increase significantly as the CCD temperature rises from -55°C. However, if the derived dark is applied for correction, the background noises are almost constant at the Poisson noise level even when the CCD temperature increases to -40°C. These results demonstrate a remarkable correction efficiency of the derived dark.

4. CONCLUSIONS

A new method has been developed to derive the dark current nonuniformity from the observational images directly. The image values are assumed to consist of the flat sky background, the median dark current level, and
the dark current nonuniformity which is space-varying. A image pair is chosen to have different sky background, but the same temperature and exposure time, so that they have the unequal constant terms, but the equal space-varying term. Scaling one image to the other according to their median values and subtract one from the other could remove the constant term, and derive the nonuniformity. Adding to this the median dark current level from the lab test, we can obtain a derived dark frame. Its noise approaches the Poisson noise of the lower brightness image, and by combining a large number of such derived dark frames from different image pairs, we can obtain a derived master dark frame with much lower noise. The derived master dark frame can be scaled to the same temperature and exposure time with the scientific images for dark correction.

We have applied this method to correct the images from AST3-1 in 2012, which suffered from relatively high CCD temperatures and no available dark frames. We derived the master derived dark frame from 230 image pairs. An example illustrates that after corrected by the derived dark frame, the background noise could be reduced from 55.4 ADU to 24.9 ADU, which is close to the Poisson noise (19 ADU). As a result, the limiting magnitude is improved by about 0.9 mag. Further investigation demonstrates that the background noises, after dark correction, are almost constant at the Poisson noise level even when the CCD temperature increases to -40°C.

We conclude that this method is remarkably efficient in dark correction, and will be helpful for other projects that suffer from similar issues like AST3. Because it is based on the observational images only, this method does not require any extra exposures, saving observing time and operations. In addition, it allows one to obtain the real-time dark current from scientific images. Although in this case, more noises are introduced by the sky background compared with direct pure dark frames, the sky background noise could be reduced dramatically by combining huge amounts of observations and becomes lower than the readout noise, thus this would not degrade the photometric precision.

ACKNOWLEDGMENTS

This work has been supported by the National Basic Research Program of China (973 Program) under grand No. 2013CB834900, the Chinese Polar Environment Comprehensive Investigation & Assessment Programmes under grand No. CHINARE2014-02-03, and the National Natural Science Foundation of China under grant No. 11003027, 11203039, and 11273019.
REFERENCES

[1] Cui, X., Yuan, X., and Gong, X., “Antarctic Schmidt Telescopes (AST3) for Dome A,” *Proc. SPIE 7012*, 70122D (2008).

[2] Yuan, X., Cui, X., Gong, X., Wang, D., Yao, Z., Li, X., Wen, H., Zhang, Y., Zhang, R., Xu, L., Zhou, F., Wang, L., Shang, Z., and Feng, L., “Progress of Antarctic Schmidt Telescopes (AST3) for Dome A,” *Proc. SPIE 7733*, 77331V (2010).

[3] Li, Z., Yuan, X., Cui, X., Wang, D., Gong, X., Du, F., Zhang, Y., Hu, Y., Wen, H., Li, X., Xu, L., Shang, Z., and Wang, L., “Status of the first Antarctic survey telescopes for Dome A,” *Proc. SPIE 8444*, 84441O (2012).

[4] Ma, B., Shang, Z., Wang, L., Boggs, K., Hu, Y., Liu, Q., Song, Q., and Xue, S., “The test of the 10k x 10k CCD for Antarctic Survey Telescopes (AST3),” *Proc. SPIE 8446*, 84466R (2012).