Data Processing Methods for the SAGE Photometric Survey (Postprint)

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Abstract

SAGE is a self-designed photometric system capable of accurately calculating stellar atmospheric parameters and extinction. A photometric survey using the SAGE system has been conducted for the northern sky, covering approximately 12,000 square degrees excluding the Galactic disk, with plans to obtain high-precision photometric data for approximately 500 million stars. Under single-exposure conditions, the 100 limiting magnitudes are uSC ~ 17.3 and vSAGE ~ 16.8 (AB magnitude). This provides valuable photometric data for Milky Way research. This paper introduces the research and development of dedicated data processing pipelines for the survey, focusing primarily on the rapid automated processing of individual frames, with emphasis on data correction, astrometric calibration, photometry and flux calibration procedures, as well as data products and data quality assessment.

Full Text

Research on the Data Reduction of the SAGE Photometric Sky Survey

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Abstract

The SAGE photometric system is a self-designed system capable of accurately determining stellar atmospheric parameters and interstellar extinction. We are conducting a SAGE photometric survey of the northern sky, covering approximately 12,000 square degrees (excluding the Galactic plane) and targeting over 500 million stars. The single-epoch 100 limiting magnitudes are uSC ~ 17.3 and vSAGE ~ 16.8 (AB magnitude). This survey will provide valuable photometric data for Milky Way research. This paper introduces the development of a dedicated data reduction pipeline for the survey, focusing on the automated processing of single-exposure images. We describe in detail the procedures for data correction, astrometric calibration, photometry, flux calibration, and data quality assessment.

Keywords: photometry; sky survey; photometric system; data reduction pipeline

1. Survey Observations

The SAGE survey covers the northern sky with declination Dec > -5°, while avoiding the crowded Galactic plane (|b| < 10°) to prevent contamination from excessive bright stars. Additionally, to optimize observing conditions during autumn and winter at Kitt Peak and Nanshan stations, the region with right ascension 12 hr < R.A. < 18 hr is excluded. Figure 2 [Figure 2: see original paper] illustrates the survey footprint of approximately 12,000 square degrees.

To facilitate flux calibration, each survey field overlaps with its adjacent fields. The survey area is organized into declination strips, with adjacent fields along the same declination having approximately 20% overlap. Similarly, there is about 20% overlap between north-south strips at different declinations. Figure 3 [Figure 3: see original paper] shows the overlap pattern for field 6352 observed with the Bok telescope; the Nanshan 1m telescope has a similar overlap pattern, though the field divisions differ due to varying field-of-view sizes. Note that the figure only shows the outer field boundaries without indicating the CCD chip gaps.

Three telescopes are employed for the survey: the 90-inch (approximately 2.3 m) Bok Telescope at Steward Observatory of the University of Arizona, USA; the 1m Wide-Field Telescope at Nanshan Station of Xinjiang Astronomical Observatory, Chinese Academy of Sciences (hereafter Nanshan 1m telescope, NOWT); and the 1m Zeiss telescope at Maidanak Astronomical Observatory of the Ulugh Beg Astronomical Institute, Uzbekistan Academy of Sciences (MAO Zeiss-1000 Telescope, hereafter MAO telescope).

1.1 Bok Telescope

The Bok telescope is a 90-inch (approximately 2.3 m) equatorial telescope located at Kitt Peak (latitude 30°57’ 46’ ‘.5 N, longitude 111°36’ 01’ ‘.6 W, altitude 2017 m) with typical seeing better than 1.5’ ‘. The survey utilizes the 90Prime wide-field camera at the prime focus, which consists of four blue-sensitive, back-illuminated 4K×4K CCDs tiled together. The field of view is approximately 1.08° × 1.03°, with a pixel scale of about 0.454’ ‘. The CCDs have gaps between them (approximately 166’’ in right ascension and 54’’ in declination). To increase readout speed, each CCD is read out through four amplifiers. In slow readout mode, the full field requires about 37 s to read out, with read noise of 6–10 electrons. The 90Prime layout is shown in Figure 4 [Figure 4: see original paper] (units in pixels, not to scale).

Due to its relatively large aperture, strong light-gathering capability, high atmospheric transparency at the site, and high blue-end efficiency of the camera, the Bok telescope is used for observations in the two narrow blue bands uSC and vSAGE.

1.2 Nanshan 1m Telescope

The 1m wide-field telescope of Xinjiang Astronomical Observatory, Chinese Academy of Sciences is located at Nanshan Station near Urumqi (latitude 43°16’ 45’ ‘.0 N, longitude 87°10’ 38’ ‘.3 E, altitude approximately 2081 m) [3], with average seeing of about 2.0’’ . This altitude-azimuth telescope is equipped with a wide-field camera at the prime focus, providing an effective field of view of approximately 1.5° × 1.5° with a 4K×4K blue-sensitive back-illuminated CCD read out through four amplifiers. The typical readout time is about 40 s, with read noise of 8–10 electrons. The survey uses SDSS g, r, i filters available on this telescope, which is controlled by software developed in [4].

Since SDSS has already covered most of the northern sky, with approximately 9,000 square degrees overlapping the SAGE survey area and meeting the depth requirements, only about 3,000 square degrees outside the SDSS coverage require supplementary observations.

1.3 MAO Telescope

The MAO telescope at the Ulugh Beg Astronomical Institute, Uzbekistan Academy of Sciences is currently undergoing technical upgrades that will provide a 37’ × 37’ field of view. This equatorial 1m reflecting telescope is located at Maidanak Observatory (latitude 66°53’ 47’’ N, longitude 38°40’ 22’’ E, altitude approximately 2593 m) [5]. It is planned to conduct H w and H n observations with this telescope.

1.4 Observation Progress

The survey began formal observations in autumn 2015. Table 2 summarizes the progress by the end of 2017. The uSC and vSAGE observations with the Bok telescope are expected to be completed by 2019, while the g, r, i bands at the Nanshan 1m telescope should be finished by 2018. The MAO telescope is currently being upgraded and is expected to begin observations in 2018.

2. Image Preprocessing

Image preprocessing aims to correct instrumental effects and eliminate inconsistencies and defects introduced by the equipment. The main steps include overscan correction, bias correction, flat-field correction, and crosstalk correction, while dark current correction is not performed.

2.1 Overscan Correction

Images from both the Bok and Nanshan 1m telescopes include overscan regions that represent the voltage level during readout and serve as the bias for each individual frame. Figure 5 [Figure 5: see original paper] shows the layout of overscan and image regions for each amplifier of the Bok telescope (units in pixels, not to scale). The Nanshan 1m telescope has a similar overscan distribution, but with a width of 32 pixels.

During correction, the program computes the median value for each row in the overscan region of each amplifier, then subtracts the corresponding median from each pixel in the image rows. Since the overscan data can be noisy, a Gaussian smoothing is applied to the derived medians. Figure 6 [Figure 6: see original paper] shows a segment of overscan values before and after smoothing.

All single-exposure images, including biases, flats, and science frames, undergo overscan correction before subsequent processing.

2.2 Bias Correction

At the beginning and end of each observing night, observers obtain a set of bias frames (typically 10 each). After overscan correction, a master bias is created by taking the median of each pixel across multiple frames. This master bias structure is then applied to flat-field and science images after their own overscan correction.

2.3 Dark Current

Both the Bok and Nanshan 1m telescopes use liquid nitrogen cooling, resulting in very low dark current. Measurements show the Bok CCD dark current is about 7.2 e /pixel/hr, while the Nanshan 1m telescope' s is no more than 2 e /pixel/hr. Since all survey exposures are shorter than 60 s, the impact of dark current is negligible compared to read noise, and therefore no dark current correction is applied.

2.4 Flat-Field Correction

2.4.1 Bok Telescope Flat-Field Correction For the Bok telescope, dome flats are obtained for each filter at the beginning and end of each night (typically 10 frames per filter) and combined. Dome flats have the advantage of being weather-independent, with high ADU values (typically 20,000–30,000) and high signal-to-noise ratio, effectively revealing pixel-to-pixel variations. However, dome flat illumination does not accurately represent the actual sky illumination. Conversely, super flats created by median-combining all science images from a night (approximately 200–400 frames) reflect the true telescope illumination pattern but have low ADU values (sky background of 20–40 ADU per frame) and insufficient signal-to-noise to capture pixel-to-pixel variations.

Following the approach used in the Beijing-Arizona Sky Survey (BASS) [6], we apply large-scale illumination correction to dome flats using two-dimensional Gaussian-smoothed super flats. This method leverages the super flats to correct large-scale illumination patterns while utilizing the high signal-to-noise dome flats to correct pixel-to-pixel sensitivity variations.

2.4.2 Nanshan 1m Telescope Flat-Field Correction The Nanshan 1m telescope does not provide dome flats. Instead, twilight sky flats are obtained for each filter during evening and morning twilight. Sky flats offer both high signal-to-noise and realistic illumination, making them ideal for flat-field correction. However, they are weather-dependent and have limited observing windows, sometimes resulting in insufficient or unsuitable flats. Additionally, due to the large field of view of the Nanshan 1m telescope, sky flats suffer from illumination non-uniformity and also require correction using super flats.

When suitable sky flats are not available for a given night, the most recent sky flats are used as substitutes.

2.5 Crosstalk and Correction

In multi-amplifier cameras, crosstalk occurs when saturated stars appear in one amplifier, creating mirrored signals in other amplifiers. The typical ratio between the mirrored and original signals is on the order of 10 . Intra-CCD crosstalk (within the same CCD) shows larger positive correlation coefficients, while inter-CCD crosstalk shows smaller coefficients, mostly negative.

Crosstalk is corrected by analyzing the correlation coefficients between source and mirrored signals in affected images and subtracting the mirrored signals. A similar method is employed by the BASS survey [6], which also uses the Bok telescope. Figure 7 [Figure 7: see original paper] shows a typical crosstalk pattern in Bok telescope images and the corrected result. Panel (a) shows crosstalk caused by a bright star in other amplifiers, while panel (b) shows the corrected data. The bottom-right amplifier contains the original saturated source, the top two amplifiers belong to other CCDs, and the bottom three amplifiers are other amplifiers on the same CCD as the source.

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3. Astrometric Calibration

Astrometric calibration establishes the transformation between image and celestial coordinate systems, correcting the telescope pointing to determine precise celestial coordinates for each detected source.

3.1 Positional Calibration and Distortion Correction

Our pipeline employs the mature and widely-used astronomical software SCAMP [7] for astrometric calibration. A two-pass iteration scheme is used to accommodate large initial errors and achieve high final precision. The first pass uses large matching tolerance to handle imprecise FITS header information, while the second pass uses tighter constraints to obtain precise results based on the initial correction. Table 3 lists key SCAMP parameters.

For reference stars, we use the PPMX (Position and Proper Motions eXtended) catalog [8]. PPMX contains approximately 18 million stars with uniform sky distribution and high coordinate precision (about 0.02’ ’ error in both RA and Dec). The catalog’ s magnitude range (85% of stars have 10.0 mag $<$ V $<$ 15.0 mag) matches our survey depth well, enabling good matches with detected sources. Its relatively small size also facilitates rapid on-site data processing. Future processing will use higher-precision catalogs such as PPMXL [9].

Astrometric calibration typically fits a transformation from image coordinates (x, y) to celestial coordinates (,). First, image coordinates are transformed to a system centered on the image center, denoted as (u, v). Without considering distortion, the linear transformation matrix CD from the FITS header (CDi_j fields, where i, j = 1, 2) converts (u, v) to intermediate plane coordinates (,) in angular units. Spherical projection (currently using the TANGential, or TAN, projection) then yields celestial coordinates (,). The linear transformation is:

$$\begin{pmatrix} \xi \\ \eta \end{pmatrix} = CD \times \begin{pmatrix} u \\ v \end{pmatrix}, \quad CD = \begin{pmatrix} CD_{11} & CD_{12} \\ CD_{21} & CD_{22} \end{pmatrix}$$

Given the large field of view (>1 square degree) and prime-focus configuration with curved focal planes, distortion correction is necessary. We adopt the Simple Imaging Polynomial (SIP) convention [10] to express distortion. SIP modifies the (u, v) coordinates using polynomial correction functions f and g:

$$\begin{pmatrix} \xi \\ \eta \end{pmatrix} = CD \times \begin{pmatrix} u + f(u,v) \\ v + g(u,v) \end{pmatrix}$$

In the correction functions f and g, coefficients Apq and Bpq correspond to the upvq polynomial terms:

$$f(u,v)=\sum_{2\le p+q\le A\_ORDER} A_{pq}u^p v^q$$

$$g(u,v)=\sum_{2\le p+q\le B\_ORDER} B_{pq}u^p v^q$$

where A_ORDER and B_ORDER represent the polynomial orders in the u and v directions, typically equal. Based on testing, we adopt A_ORDER = B_ORDER = 3.

3.2 Astrometric Calibration Errors

Astrometric errors arise from multiple sources: (1) errors in centroid determination through fitting; (2) inherent errors in the reference catalog (PPMX has about 0.02' ' error in RA and Dec); (3) errors in proper motion information; and (4) coordinate matching tolerance between reference and image sources. Consequently, final celestial coordinates contain errors relative to true values.

3.2.1 External Astrometric Errors External errors are assessed by comparing detected sources with reference catalog positions (PPMX). Figure 8 [Figure 8: see original paper] shows the external error distribution for a randomly selected image, demonstrating high astrometric precision with a standard deviation of about 0.1'' and minimal systematic offsets in RA and Dec.

3.2.2 Internal Astrometric Errors Internal errors are determined by matching sources in overlapping regions between adjacent fields. Multiple observations of some fields and multi-band observations of the same field also provide internal error estimates. Figure 9 [Figure 9: see original paper] shows internal errors from two observations of the same field, yielding R.A. = 0.014'' ± 0.145'' and Dec = -0.002'' ± 0.166'' , indicating small scatter and negligible systematic offsets.

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4. Flux Calibration

Two primary flux calibration methods exist: (1) observing photometric standard stars throughout photometric nights to derive atmospheric extinction curves as a function of airmass, then applying extinction corrections to each image; and (2) using existing survey catalogs overlapping the observed fields. The former is complex and requires photometric nights but provides high precision and independence, while the latter is simpler but depends on the precision of reference catalogs and loses accuracy when calibrations are propagated through overlapping regions.

4.1 Calibration Method

For the SDSS g, r, i bands, we use APASS (The AAVSO Photometric All-Sky Survey) [11], SDSS, and Pan-STARRS1 [12] as flux calibration references. APASS provides photometry for over 60 million stars with all-sky coverage; more than 90% of stars have $10.0 \text{ mag} < V < 17.0 \text{ mag}$, and over 70% have g, r, i band errors smaller than 0.1 mag, overlapping our survey depth and making it suitable for calibration. Future observations of flux standards will improve calibration precision.

For the uSC, vSAGE, DDO51, H w, and H n bands, we select stars from the high-precision flux-calibrated stellar spectral libraries CALSPEC [13] and NGSL [14]. We choose non-variable stars in or near our survey fields with spectral types from A to K (including white dwarfs), magnitudes of 12–15, and convolve their spectra with the filter transmission curves to derive apparent magnitudes for use as flux standards.

Each night, standard stars are observed 5–8 times to fit atmospheric extinction curves described by:

$$u_{cal,i} - u_{inst} = k_{u,a} \times airmass + k_{u,c} \times (u_{cal,i} - v_{cal,i}) + k_{u,0}$$

$$v_{cal,i} - v_{inst} = k_{v,a} \times airmass + k_{v,c} \times (u_{cal,i} - v_{cal,i}) + k_{v,0}$$

where kx,a is the airmass correction coefficient, kx,c is the color correction coefficient, and kx,0 is the instrumental zeropoint. Instrumental magnitudes are normalized to 1-second exposures for analysis.

Figures 10 [Figure 10: see original paper] and 11 [Figure 11: see original paper] show extinction curves derived from Bok telescope observations in September 2017: uSC on September 23 (0.612 × airmass + 0.338 mag, residual standard deviation 0.0033 mag) and vSAGE on September 24 (0.443 × airmass + 0.241 mag, residual standard deviation 0.0154 mag), meeting the survey' s precision requirements.

Future photometric nights will involve 20–30 standard star observations per night to achieve higher calibration precision, with all fields expected to be calibrated in 5–7 photometric nights.

4.2 Calibration Errors

As shown in Figure 3 [Figure 3: see original paper], each field overlaps adjacent fields by about 20%, enabling error analysis through matched sources in overlapping regions. Some fields have also been observed multiple times for quality assessment. Figures 12 [Figure 12: see original paper] and 13 [Figure 13: see original paper] show calibration differences from two observations of a field, with red curves indicating the standard deviation of magnitude differences as a function of magnitude.

5. Source Detection and Photometry

5.1 Image Source Detection

Our pipeline employs the mature and widely-used photometry software Source Extractor (SE) [15] for source detection, positioning, and flux measurement. Table 4 lists key SE parameters. Compared to the traditional IRAF (Image Reduction and Analysis Facility) [16], SE is more convenient, faster, and easier to integrate into automated pipelines. SE performs source detection and photometry in a single step, supports multiple aperture sizes simultaneously, and offers higher efficiency.

SE provides various photometry modes, including traditional circular aperture photometry (FLUX_APER, MAG_APER) with calculated flux errors (FLUXERR_APER, MAGERR_APER) based on sky background and Poisson statistics. Multiple apertures can be specified, with results output for each. SE also offers model-based photometry such as MAG_AUTO (automatic aperture), MAG_ISOCOR (isophotal), and MAG_PETRO (Petrosian). Although extragalactic objects are not the primary science target, recording and processing them is valuable.

Following SDSS and BASS, we adopt MAG_AUTO as the primary output. This mode automatically selects aperture size based on the source’ s FWHM and uses elliptical rather than circular apertures, providing comprehensive and accurate flux estimates for stars. Multiple photometry modes and aperture sizes are provided for user selection, and aperture corrections using growth curves are applied to improve photometric precision.

5.2 Aperture Photometry and Aperture Correction

Our pipeline uses SE’ s APERTURE mode to compute circular aperture fluxes. Aperture size selection critically affects photometric quality: larger apertures include more source flux but also more sky noise, particularly impacting faint sources. To improve signal-to-noise for faint objects while maintaining uniform measurement across an image, we use isolated, high signal-to-noise, unsaturated bright stars to derive aperture growth curves (instrumental magnitude vs. aperture radius). These curves are then used to correct photometry for other sources, providing better results than single-aperture photometry [17, 18].

Since the point spread function (PSF) varies across the focal plane, growth curves differ for each amplifier region. Our pipeline performs corrections separately for each amplifier. For the Bok telescope’ s 16-amplifier readout, Figure

14 [Figure 14: see original paper] shows typical growth curves for each amplifier, with green markers indicating bright star magnitudes at various apertures and red curves showing the adopted correction functions.

6. Observing Conditions

Based on 15 nights of Bok telescope observations in September 2017, we analyzed seeing, photometric zeropoints, and sky brightness.

6.1 Seeing

Seeing is estimated from the FWHM of isolated bright stars measured by SE. The distribution yields a typical seeing of 1.5' ' ± 1.0' ' at Kitt Peak, slightly worse than the site' s intrinsic seeing due to telescope and camera contributions. Figure 15 [Figure 15: see original paper] shows the seeing distribution for these observations.

6.2 Photometric Zeropoint

The photometric zeropoint is the constant relating instrumental and apparent magnitudes, reflecting atmospheric and instrumental effects. To avoid exposure time dependencies, all images are normalized to 1-second exposures. Figure 16 [Figure 16: see original paper] shows the zeropoint distribution for September 2017, comprising 1,612 uSC images and 1,465 vSAGE images.

6.3 Sky Brightness

Sky background brightness affects limiting magnitude and data quality. Figure 17 [Figure 17: see original paper] shows the sky background distributions for uSC and vSAGE bands. Sky brightness is calibrated using stellar zeropoints, which are affected by airmass, resulting in slight differences from true sky values. The brightness levels are consistent with previous Kitt Peak monitoring [19].

7. Summary and Outlook

This paper describes the data reduction procedures and pipeline principles for the SAGE photometric survey, along with precision analysis. The pipeline can uniformly process data from different telescopes to achieve sufficient precision. Currently, it primarily handles single-exposure images; stacking multiple observations and cross-calibration will be implemented in future development.

The SAGE photometric system is a self-designed system highly sensitive to stellar atmospheric parameters. Since 2015, the SAGE survey has used three telescopes to observe approximately 500 million stars in eight bands. The photometric data will yield high spatial resolution maps of interstellar extinction and provide a valuable legacy for studies of stellar physics, Galactic structure, and evolution, while also contributing data for extragalactic research.

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