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Detection and removal of artifacts in astronomical images

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ABSTRACT

Astronomical images from optical photometric surveys are typically contaminated with transient artifacts such as cosmic rays, satellite trails and scattered light. We have developed and tested an algorithm that removes these artifacts using a deep, artifact free, static sky coadd image built up through the median combination of point spread function (PSF) homogenized, overlapping single epoch images. Transient artifacts are detected and masked in each single epoch image through comparison with an artifact free, PSF-matched simulated image that is constructed using the PSF-corrected, model fitting catalog from the artifact free coadd image together with the position variable PSF model of the single epoch image. This approach works well not only for cleaning single epoch images with worse seeing than the PSF homogenized coadd, but also the traditionally much more challenging problem of cleaning single epoch images with better seeing. In addition to masking transient artifacts, we have developed an interpolation approach that uses the local PSF and performs well in removing artifacts whose widths are smaller than the PSF full width at half maximum, including cosmic rays, the peaks of saturated stars and bleed trails. We have tested this algorithm on Dark Energy Survey Science Verification data and present performance metrics. More generally, our algorithm can be applied to any survey which images the same part of the sky multiple times.

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1. Introduction

In the last two decades, many optical wide-field photometric surveys using new, state of the art multi-megapixel cameras have started taking data and mapping out large portions of sky. A pioneering effort on this front has been from the Sloan Digital Sky Survey (SDSS) (York et al., 2000). In the last few years many surveys deeper than SDSS have commenced operations. These include DES (DES Collaboration, 2005, 2016), KiDS (de Jong et al., 2013), and HSC (Miyazaki et al., 2012). Within a decade, LSST will start taking data mapping half the sky with unprecedented depth (Ivezic et al., 2008). The main science goal of these surveys is to constrain cosmological parameters and provide insight into the underlying causes of the cosmic acceleration and the characteristics of dark matter and inflation. These studies rely on techniques that require observations of Type 1a supernovae, galaxy clusters, weak lensing, and baryon acoustic oscillations, as well as measurements within our own galaxy. These homogeneous, wide field survey datasets enable a plethora of astrophysical studies and studies of structure formation in general.

To achieve these myriad science goals, it is important to identify and remove both transient and persistent artifacts from the images prior to production of the science-ready catalogs. The transient artifacts are those features such as cosmic rays, satellite trails, scattered light and artifacts due to malfunctioning CCDs that appear in only one of a series of observations of the same sky location. The artifacts that persist among an ensemble of observations of the same sky location include saturated bright stars, bleed-trails, and diffraction spikes. These artifacts can be detected and characterized as objects, contaminating the science catalogs produced in these surveys. Moreover, these artifacts can in principle affect photometric and astrometric calibration, degrading the cataloged information from surrounding objects.

In creating a deep, coadded image of a sky location one can simply apply an outlier rejection routine or even median filter the input single epoch images (e.g. Gruen et al., 2014). While this works well in identifying transient artifacts that appear in

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empty, sky dominated regions of the sky, it fails in identifying artifacts that lie on or near real objects because of the image PSF variations over time that are generic in the acquisition of large survey datasets. These seeing variations generically result in large apparent variations in star and galaxy morphologies that then can be incorrectly identified as artifacts. Thus, a method that works robustly within a dataset that includes multiple visits to each location on the sky under different imaging conditions is needed. Moreover, many surveys are now focused on cataloging the single epoch images – using the appropriate PSF for each single epoch image and producing a single combined catalog – rather than first producing PSF homogenized coadd images where the noise is necessarily correlated among neighboring pixels and then cataloging them. Such an approach requires that the artifact be detected and masked within the full single epoch imaging dataset.

It is often convenient also to remove the artifacts from the single epoch images once they have been identified. One motivation for this is that in those surveys that catalog using the coadd images, it has now become common to transform to a common PSF before coaddition. This approach avoids spatial discontinuities in the effective PSF within the coadd image that then make it impossible to extract accurate PSF corrected object photometry or even to simply identify unresolved objects (see, e.g., Desai et al., 2012). An efficient way of doing this involves application of a spatially varying convolution kernel and fast Fourier transform techniques. In such an approach a single pixel artifact becomes a lower amplitude artifact with the scale of the homogenizing kernel, which is characteristically the size of the PSF. In the case of artifacts whose dimension is smaller than the width of the PSF, interpolation to remove them works quite well with only a slight increase in noise. For artifacts that are comparable to or larger than a PSF there is no way to recover the information loss in the image and there is no real gain in removal of the artifact.

While significant effort has already been invested in the development of algorithms to detect cosmic rays in single epoch images (Rhoads, 2000; van Dokkum, 2001; Bertin, 2001; Farage and Pimbblet, 2005; Ipatov et al., 2007), these new survey datasets and the availability of large scale computing facilities enable new, more robust techniques to be applied. Most of these algorithms suffer from some weaknesses, and either do not correctly identify all the cosmic rays or sometimes identify faint objects as artifacts. Also these algorithms tend to have difficulty in detecting cosmic rays that lie within real astrophysical objects. To remove satellite tracks from individual images, Hough transform techniques are often used (e.g., Vandame, 2001). To the best of our knowledge, there is currently no automated algorithm to detect scattered light within single epoch astronomical images, and sometimes these are manually identified through painstakingly scanning each image (Jarvis et al., 2015).

In this paper, we describe a new method to detect and remove artifacts in astronomical images. We briefly describe the data management system used for this test in Section 2. Section 3 contains a description of our artifact detection and masking algorithm, which operates autonomously on transient artifacts. It relies on (1) a dataset that contains multiple visits to the same portion of the sky, (2) accurate modeling of the position variable PSF on single epoch images, (3) the construction of deep, PSF homogenized artifact-free images, (4) model fitting cataloging of that image and (5) the production of position variable PSF convolved simulated images using these model fitting catalogs and PSF models. Our approach is notionally related to the widely used `Drizzle` algorithm (Fruchter and Hook, 2002), which is applied in the processing of HST data but operates within a context of uniform, space-based imaging and does not rely on PSF corrected model fitting. Section 4 contains a description of our techniques for removing artifacts, which, depending on the width of the artifact, employ either interpolation or replacement using a PSF convolved object model constrained by surrounding, uncontaminated pixels. Section 5 describes a test of our algorithms using science verification data from the Dark Energy Survey and a demonstration of the depth improvements that accompany the improvements in image quality. In Section 6 we discuss the shortcomings of our algorithm and future improvements, and we present our conclusions in Section 7.

2. Input data preparation with CosmoDM

The artifact removal tools we describe here have been developed as part of the Cosmology Data Management system (CosmoDM). CosmoDM has been developed at Ludwig-Maximilians-Universität (LMU) in Munich since 2011; it arose from a development version of the Dark Energy Survey Data Management system (DESDM; Ngeow et al., 2006; Mohr et al., 2008, 2012). CosmoDM and its precursor have been applied to a variety of data including those from the Mosaic-2 and DECam imagers on the Blanco telescope as well as data from Pan-Starrs, CFHT MegaCam, SOAR, and WFI to support the optical confirmation and photometric redshift measurement of galaxy cluster candidates detected through both Sunyaev–Zeldovich effect surveys (Staniszewski et al., 2009; Song et al., 2012; Desai et al., 2012; Liu et al., 2015; Desai et al., 2015) and X-ray surveys (Šuhada et al., 2012). The science codes and quality assurance framework from CosmoDM serve as a prototype for the ground-based external dataset calibration pipelines needed for the Euclid satellite mission (Laureijs et al., 2011).

CosmoDM is an automated system that includes, among other components, pipelines for processing and calibrating single epoch images and for building and cataloging coadd images. In our system we differentiate between single epoch exposures (raw data from the telescope), single epoch images (the detrended and calibrated CCD-sized images—$\sim 10' \times 20'$ for DECam) and deeper, stacked coadd images that are built from all the available single epoch images in a particular sky location. Typically these CosmoDM pipelines are run in a fashion where one wishes to build deep, coadd images in a particular sky region or tile (typically $1^\circ \times 1^\circ$ sky regions); the system first finds all single epoch exposures that overlap the coadd tile, prepares the associated single epoch images and then combines them into a coadd image for each photometric band. The single epoch processing and calibration starts from the raw exposures and ends with astrometrically calibrated, fully flattened and detrended single epoch images, position variable PSF models and associated PSF corrected model fitting catalogs. The detrending corrections include crosstalk corrections, overscan subtraction, bias corrections, flat fielding, photometric flattening and astrometric calibration. Noise is tracked for each pixel in an associated weight map and bad pixel maps (BPMs) encode any special actions taken on particular pixels. Astrometric calibration is done with `SCAMP` (Bertin, 2006), where for DECam (Flaugher et al., 2015) we employ a third-order polynomial distortion correction and use a DECam extracted distortion catalog to constrain the field distortions and the 2MASS (Skrutskie et al., 2006) catalog for absolute astrometric calibration,respectively. For the PSF corrected model fitting catalogs, we use PSF models extracted using `PSFEx` (Bertin, 2011) together with `SExtractor` (Bertin and Arnouts, 1996). We use the model fitting capabilities added to `SExtractor` as part of the DESDM development program and extract more than 100 morphological and photometric parameters for every detected object.

Once the basic single epoch image processing and calibration is complete, we use the catalogs to determine relative photometric zeropoints among the ensemble of images within each band and refine the astrometric solutions within the single epoch

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