PROCESSING IMAGES FROM THE ZWICKY TRANSIENT FACILITY

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ABSTRACT

The Zwicky Transient Facility is a new robotic-observing program, in which a newly engineered 600-MP digital camera with a pioneeringly large field of view, 47 square degrees, will be installed into the 48-inch Samuel Oschin Telescope at the Palomar Observatory. The camera will generate ~ 1 petabyte of raw image data over three years of operations. In parallel related work, new hardware and software systems are being developed to process these data in real time and build a long-term archive for the processed products. The first public release of archived products is planned for early 2019, which will include processed images and astronomical-source catalogs of the northern sky in the g and r bands. Source catalogs based on two different methods will be generated for the archive: aperture photometry and point-spread-function fitting.

Keywords: asteroids — stars: variables, binaries, supernovae, cataclysmic variables — galactic: active nuclei — techniques: image processing, photometric — methods: observational, data analysis

1. INTRODUCTION

The Zwicky Transient Facility (ZTF[1]) is a new program for ground-based, optical, time-domain astronomy (Bellm et al. 2015), which goes well beyond its immensely successful predecessor programs, the Palomar Transient Factory (PTF[2]) and eponymous intermediate program (iPTF). A digital camera specially developed for the ZTF, with a faster readout time and a much larger field of view, along with other enhancements relative to the PTF camera, such as a fast exposure shutter, is nearing the completion of its development phase, and installation into the 48-inch Samuel Oschin Telescope at the Palomar Observatory is planned for late summer of 2017. Substantial telescope and dome upgrades are part of this effort, including faster drives and improved optics. In addition, the parallel development of hardware and software systems that can handle real-time post-processing of the massive amount of image data from the camera in normal operations, as well as the development of a long-term archive for the processed products, is underway. The data processing will be performed at IPAC, and the ZTF archive will be hosted by the NASA/IPAC Infrared Science Archive (IRSA[3]). The data-processing system and archive will rely heavily on relational databases to consolidate and warehouse information that can be later queried in a historical context for the discovery of astrophysical transient phenomena. The major science goals for the ZTF include discovering young supernovae, searching for electromagnetic counterparts to gravitational wave sources, identifying stellar variables, and detecting near-Earth asteroids.

In Section 2, we give background information on the ZTF project, some camera details, and highlights of the observing strategy. In Section 3, the focus of this paper, we outline our design of the ZTF data-processing system and discuss our recent performance-test results. We emphasize that the system design is still evolving and the results up to this point in time are preliminary. We briefly describe the ZTF archive in Section 4. Finally, we provide a summary and outlook in Section 5.

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2. PROJECT BACKGROUND

2.1. *Programmatics*

The ZTF's precessor programs, PTF and iPTF, have led to the publication of 185 papers in peer-reviewed journals (at the time of this writing – more PTF/iPTF papers are forthcoming).[4] As an example, a paper on a regular type II supernova based in part on PTF data was recently published in *Nature Physics* (Yaron et al. 2017). The iPTF project officially ended in March of 2017. A separate enterprise has been underway since then to reprocess the PTF Galactic-plane data for inclusion in a future public data release.

The ZTF is a consortium of several U.S. and global institutions, known as the "collaboration".[5] Both private funds from the members and public (National Science Foundation) have been received for this project. Work on the ZTF began in earnest in 2014, and the current plan is for the ZTF to collect data for three years after regular operations begin.

Data from the ZTF will fuel research projects for students, postdocs, and scientists at institutions in the collaboration and the public at large. There is also a related new initiative for undergraduate research known as the Summer Undergraduate Astronomy Institute (Penprase & Bellm 2017).

2.2. *Camera*

Detailed engineering papers on the development of the ZTF camera are given by Smith et al. (2014) and Dekany et al. (2016). A definitive instrument paper is in preparation by Dekany et al., and is due out by end of 2017 or early 2018. First light with the camera permanently mounted to the telescope is scheduled for October 2017.

The ZTF-camera field of view is truly groundbreaking, and it will enable imaging of the entire Palomar sky each night. Figure 1 compares it to the field of view of other large-survey cameras, either currently in operation or under development. Table 1 lists the salient attributes of the camera for the planned observing.

Table 1. ZTF camera and nominal observing attributes

Attribute	Value
Field of view	47 square degrees
Pixel scale	1 arc second per pixel
Pixel size	15 μm
CCD readout channels	4
Exposure time	30 seconds
Readout time	≈ 10 seconds
Slew & settle time	$+5$ seconds
Optical filters	ZTF g, r, and i
Limiting magnitude	20.4 (r-band, 5 σ)
Mosaic of CCDs	4×4 layout (16 CCDs)
Pixels per CCD	$\sim 6K \times 6K$
Total number of pixels	≈ 600 megapixels

The median image quality delivered by the 48-inch telescope optics on Palomar mountain is ≈ 2 arc seconds. This motivated the design choice of 1 arc second Nyquist sampling for the camera.

2.3. *Observing Strategy*

The acquisition of science exposures will occur throughout each observing night, weather permitting. We are budgeting for 260 good-weather nights in our estimates. Depending on the time of year, we expect to acquire 600-800 science exposures per night, assuming one exposure taken every 45 seconds, which allows for 30-second camera exposures and the fixed readout time and concurrent slew & settle times of the camera and telescope (see Table 1). Scanning at least 3760 square degrees of the sky per hour will be possible.

Calibration exposures (biases, dome flats, darks, etc.) will be acquired during the day. Fresh calibration products will be made before the nightly processing of science exposures begins.

During the first year and a half of operations, ZTF will conduct two general-purpose public surveys: a three-night cadence survey of the visible Northern Sky, and a nightly sweep of the Galactic Plane. For both programs, fields will be visited twice each night they are observed, with approximately one hour separation between a g-band exposure and an r-band exposure.

3. DATA PROCESSING

Laher et al. (2014) describe the image-processing system for the ZTF's precessor programs, PTF and iPTF. This experience is leveraged in our new design for the ZTF. Below we give an overview of the ZTF Data System. A more detailed description will appear in a future publication.

The science exposures will be processed in real time, throughout the observing night. This requires a data-processing system that can keep up with the incoming data.

Figure 2 depicts the ZTF processing system that is currently under development at IPAC. It features 64 pipeline machines, four file servers, two database machines (primary and secondary/backup), a private web server, a Kafka[6] cluster, and an IRSA public web interface. The local network is proficient at data rates of up to 10 gigabits per second.

The pipeline machines are for running ZTF real-time pipelines in parallel. This part of the system is inherently scalable, and more machines can be added as needed. The CPU of each pipeline machine has 16 cores (2 threads per core), and 16 pipeline instances per machine are typically run. The open-source, workload-manager software, SLURM[7], is used to farm out pipeline instances to pipeline machines in the proper order and number. The real-time pipeline generates many interim files at its various steps, and these files typically become inputs to a subsequent step. The interim files are written to the local disks of pipeline machines for speed and avoidance of unnecessary congestion

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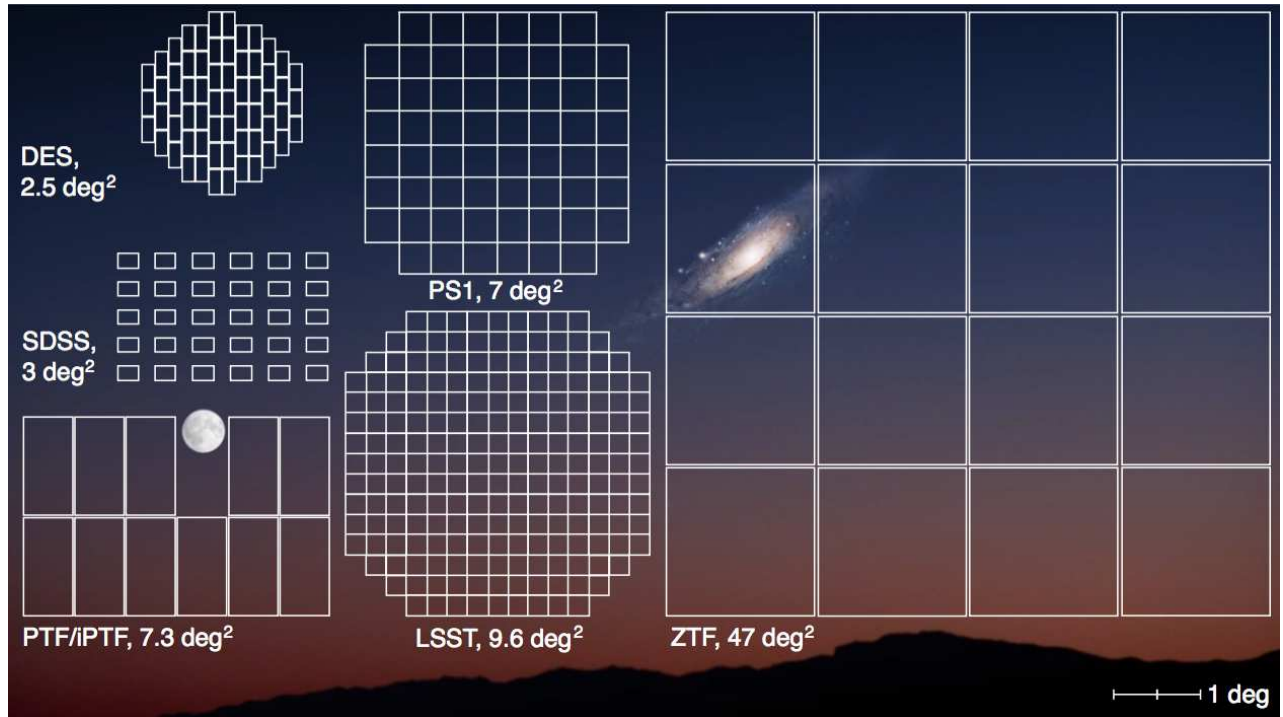
Figure 1. Field of view of the ZTF camera compared to that of other large-survey cameras. The Moon and the Andromeda Galaxy (Messier 31) are shown to scale. (With the permission of Joel Johansson.)

on the local network.

The four file servers allow parallel file transfer across the local network. Files copied from pipeline-machine local disks to and from the sandbox filesystem are expected to generate the most traffic. Products ultimately copied to the archive filesystem will add marginally to the load. This part of the system is also scalable and more machines could potentially be added to service additional load.

Our data-processing system features a PostgreSQL[8] relational database running on the primary database machine, equipped with 384 gigabytes of memory. Since this element is not scalable, careful, disciplined database design, and both hardware and software tuning have proven to be absolutely essential. Database tables and indexes are strategically micromanaged so that heavily accessed data are stored on solid-state devices (SSDs) as opposed to spinning disks. The large database-machine memory and judicious database tuning ensure a very high cache-hit rate. Daily database vacuuming is required for regular maintenance. The database is replicated onto a second database machine, so that design-team members can query it without affecting the primary database. Candidate transients are stored in database tables partitioned by observing date and readout channel. A set-up process that creates database views over the correct candidate partitions is executed daily.

The web server will allow ZTF personnel to perform quality analysis on the raw data and processed products. It will also serve as a staging ground for initial access for archive products as well as disseminate products for solar system science.

The Kafka cluster is a set of machines at IPAC and a set of machines at the University of Washington (UW) that facilitates the distribution of transient-event alerts to the ZTF collaboration and eventually the community. Once the event data has been sent to Kafka, which is facilitated by pipeline packaging the data in Avro format,[9] the Kafka software handles mirroring between IPAC and UW over the Internet.

Figure 3 gives a flowchart of the ZTF real-time pipeline. The CCD-image files received from Palomar consist of one multi-extension FITS file for each CCD and exposure. These are split into readout-channel quadrants for smaller images to facilitate the subsequent parallel processing, in which the quadrant images are processed independently. Bias and flat-field corrections are applied to the applicable raw images. The processing involves instrumental calibration, which consists of astrometric and photometric calibration, followed by image differencing with a reference image for finding transients. Scamp[10] is used in conjuction with the GAIA catalog (Gaia Collaboration et al. 2016) to perform the astrometry and compute a World Coordinate System for each science image. Absolute photometry is done using the Pan-STARRS DR1 catalog as the standard (Flewelling 2017). Reference images, which are needed for image differencing, are made within the first few months of operation. The image differencing includes a combination of the steps de-

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[8] https://www.postgresql.org

[9] E.g., https://avro.apache.org/docs/1.8.2/

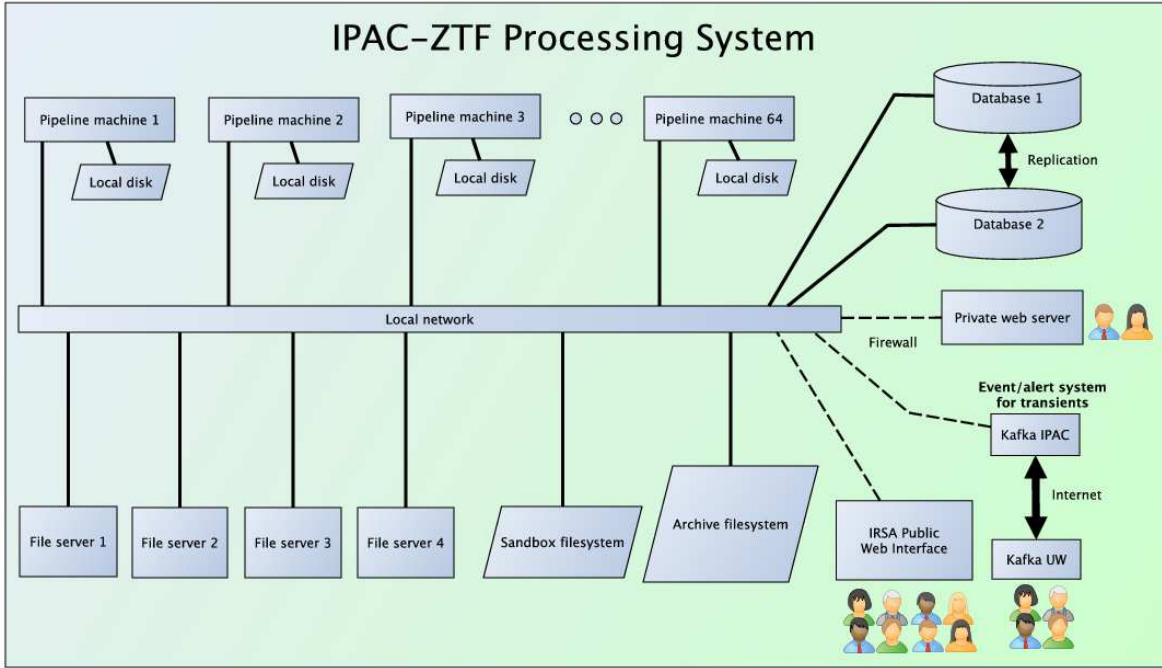[10] https://www.astromatic.net/software/scamp

Figure 2. ZTF data-processing system.

scribed in Masci et al. (2017), as well as an implementation of the ZOGY algorithm (Zackay et al. 2016). Candidate transient events are detected in thresholded difference images, and then vetted with machine learning provided by JPL, for example, using the real/bogus framework of Bloom et al. (2012). Asteroid streaks are found in the difference images using the *findstreaks* module (Waszczak et al. 2017), and subsequently checked for reliability using a new deterministic algorithm that accounts for the point-spread function of the streak.

Figure 4 gives preliminary performance test results for the ZTF real-time pipelines processing a night's worth of simulated data. The density plot includes 28,505 independent pipeline instances running on 32 pipeline machines, and shows that a night spanning ~ 7.5 hours can be processed in ~ 6.2 hours, which is better than real time. The median run time for a pipeline instance in this test is 275.5 seconds. The primary factors that affect the pipeline run times include: 1) The number of astronomical sources extracted from the images (e.g., Galactic-plane observations are much more stressing); and 2) The fraction of images for the night that actually have reference images available (this was $\sim 75\%$ for our simulated data). The simulated data for the test includes random transients at a rate of 10 per CCD. Future tests will involve simulated transient rates that are up to $8\times$ higher.

4. PRODUCT ARCHIVE

As illustrated in Figure 2, IRSA will set up infrastructure for a long-term archive and a web interface for the distribution of ZTF-survey products to the collaboration and public. The web interface will have similar functionality as those available to IRSA archives for other projects. The entire archive is expected to grow to ~ 3 petabytes by the end of
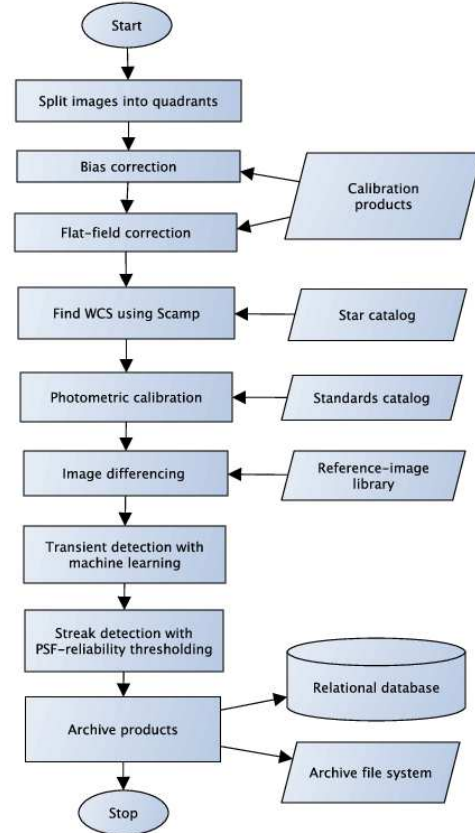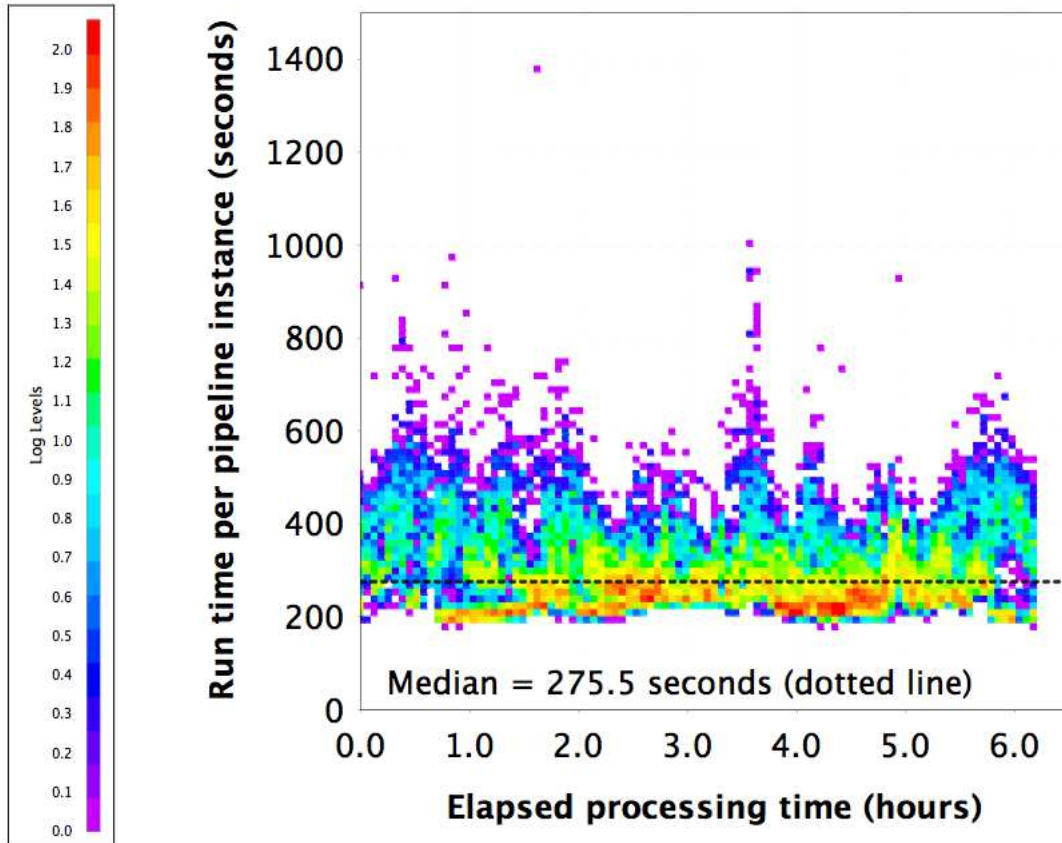

Figure 3. Flowchart of the ZTF real-time pipeline.

Figure 4. Preliminary ZTF benchmark-test results.

ZTF's three-year program. Table 2 lists the product types that will be archived, which will include both images and astronomical-source catalogs. Two different methods will be used to generate source catalogs for the archive, namely, aperture photometry and point-spread-function (PSF) fitting.

The first public release of archived products is planned for early 2019. This release will include only products from the ZTF public surveys. Products from collaboration observing programs will be included in later releases.

5. CONCLUSIONS

This paper gives an overview of the ZTF project, camera, observing strategy, data-processing system, preliminary benchmark results, and product archive, with an emphasis on describing the data-processing system and archive. In the coming months, the data-processing system will be exercised on real data from the observatory-mounted camera. Building upon our past successes gives us confidence in a favorable outcome for this endeavor. Exciting new discoveries await astronomers analyzing ZTF products!

Table 2. ZTF archive products

Product
Raw images
Processed images
Image masks
Difference images
SExtractor catalogs
PSF-fit catalogs (DAOPHOT)
Reference images, catalogs, etc.
Calibration products
Light curves

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