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Searching for Optical Transients in Real-Time: The RAPTOR Experiment

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Abstract. A rich, but relatively unexplored, region in optical astronomy is the study of transients with durations of less than a day. We describe a wide-field optical monitoring system, RAPTOR, which is designed to identify and make follow-up observations of optical transients in real-time. The system is composed of an array of telescopes that continuously monitor about 1500 square degrees of the sky for transients down to about 12th magnitude in 60 seconds and a central fovea telescope that can reach 16th magnitude in 60 seconds. Coupled to the telescope array is a real-time data analysis pipeline that is designed to identify transients on timescales of seconds. In a manner analogous to human vision, the entire array is mounted on a rapidly slewing robotic mount so that the fovea of the array can be rapidly directed at transients identified by the wide-field system. The goal of the project is to develop a ground-based optical system that can reliably identify transients in real-time and ultimately generate alerts with source locations to enable follow-up observations with other, larger, telescopes.

INTRODUCTION

A surprising fact about modern optical astronomy is that the nightly variation of the optical sky is largely unmonitored [1]. The fact that spectacular celestial transients are being missed was clearly demonstrated by the detection of an optical transient associated with a Gamma Ray Burst (GRB) at redshift $z=1.6$ [2]. That cosmological optical transient reached an astounding peak apparent magnitude of 9---making it the most luminous optical source ever measured. However, without the real-time position provided by a high-energy satellite that cued robotic optical telescopes to slew to the correct position, the remarkable transient, which was observable potentially even with binoculars, would have been missed.

There are reasons to suspect the existence of celestial optical transients that cannot be found through sky monitoring by high-energy satellites. For example, it has been suggested that there may be a class of orphan transients that are detectable as off-axis optical emission from beamed GRBs [3,4]. It

has also been suggested that optical transients could be precursors to GRBs [5]. But an equally exciting possibility is that there are new, as yet undiscovered, classes of rapid optical transients that are completely unrelated to high-energy transients.

In this paper we briefly discuss the RAPTOR (**R**apid Telescope for **O**ptical **R**esponse) project at Los Alamos National Laboratory. The primary goal of the project is to construct an autonomous robotic system for monitoring the sky that is capable of both independently discovering optical transients and instantly following-up to verify the discovery.

THE RAPTOR SYSTEM: AN ANALOGUE OF HUMAN VISION

As predators, we humans have evolved a highly sophisticated vision system for both imaging and change detection. The human eye has a wide-field, low-resolution, imager (rod cells of the retina) as well as a narrow-field, high-resolution imager (cone

cells of the fovea) [6]. Both eyes send image information to a powerful real-time processor, the brain, running “software” for the detection of interesting targets. If a target is identified, both eyes are rapidly slewed to place the target on the central fovea imager for detailed “follow-up” observations with color sensitivity and higher spatial resolution. Human Vision also employs two spatially separated eyes viewing the same scene both to eliminate image faults like “floaters” and to extract distance information about objects in the scene.

The system concept for RAPTOR is best understood as an analogue of Human Vision. RAPTOR employs two primary telescope arrays (RAPTOR A and B) that are separated by a distance of 20 miles to provide stereoscopic imaging. Each telescope array simultaneously images the same 1500 square-degree field with a wide-field imager and a central 16 square-degree with a narrow-field “fovea” imager. Real-time processors instantly analyze images from RAPTOR A and B and the positions of interesting transients are fed back to the mount controllers with instructions to point the fovea telescopes at the transient. The two fovea cameras then image the transient with higher spatial resolution and at a faster cadence to gather light curve information. Each fovea camera also images the transient through a different filter to provide color information. Altogether, the RAPTOR system therefore acts as a closed loop system that autonomously identifies and makes detailed follow-up observations of optical transients in real-time.

The RAPTOR Wide-Field Telescopes

The RAPTOR A and B wide-field imaging arrays are each composed of four Canon 85mm f/1.2 lenses with CCD cameras at the focal planes. The cameras are thermo-electrically cooled Apogee AP-10 cameras, which employ a 2Kx2K format Thomson 7899M CCD chip with 14-micron pixels. Each camera of the array covers a $19.5^\circ \times 19.5^\circ$ field with a single-pixel spatial resolution of 34 arcseconds. Together the mosaic of the four fields for each array enables simultaneous monitoring of approximately 1500 square-degrees. The limiting magnitude of this wide-field system is $m_R \sim 12$ for a sixty-second exposure (see Figure 1).

In the center of each wide-field array is a fovea telescope (see Figure 2). It is composed of a large 400mm focal length telephoto lens with a 5.6-inch objective diameter and, at least initially, an AP-10 CCD camera. In this configuration the fovea cameras

will cover a $4^\circ \times 4^\circ$ field-of-view and have nearly five times the spatial resolution of the wide-field array. Further, to provide color information about the transient, the fovea camera for RAPTOR A will have a Johnson I filter and RAPTOR B will employ a Johnson R Filter. Later versions of the fovea telescopes are likely to employ more sensitive back-illuminated CCD chips with V and R filters.

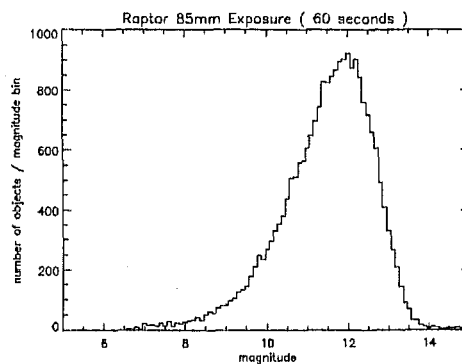


FIGURE 1. The number of objects detected per magnitude bin by the wide-field array in a random mosaic tile. The exposure had a sixty-second duration and was taken at the RAPTOR site with higher sky brightness. The limiting magnitude for same array is approximately 0.5 magnitude deeper at the darker site.

Both RAPTOR telescope arrays are mounted on rapidly slewing, robotic, mounts. The mounts were designed to have the capability to place the fovea camera on the transient and to begin follow-up observations within a few seconds no matter where the transient occurred in the 1500 square-degree monitoring field. Tests of the completed mounts indicate that they can accelerate at rate of up to 400 degrees/sec² and reach speeds of 200 degrees/sec. In practice this means that the arrays can be slewed from horizon to horizon in 1.5 seconds and, after waiting another second for mount and telescope vibrations to damp, begin imaging. To our knowledge, the RAPTOR mounts are the swiftest ever constructed for astronomical purposes.

The Real-Time Pipeline

A key enabling aspect of the RAPTOR system is the fast analysis pipeline that is designed to identify transients in real time. Immediately upon completion of each exposure, the raw images are combined with flat-field and dark frames to form corrected images.

Sources are then extracted using a modified version of the SExtractor package [7] to form a source-object file for each corrected image. Using the Tycho star catalog as a reference, the extracted source-object files are then image registered to calculate the source coordinates and the relative photometry is derived to form a calibrated object file for each image. The entire process of calibrated list extraction is accelerated to take less than 10 seconds and runs in parallel for all ten of the array cameras.

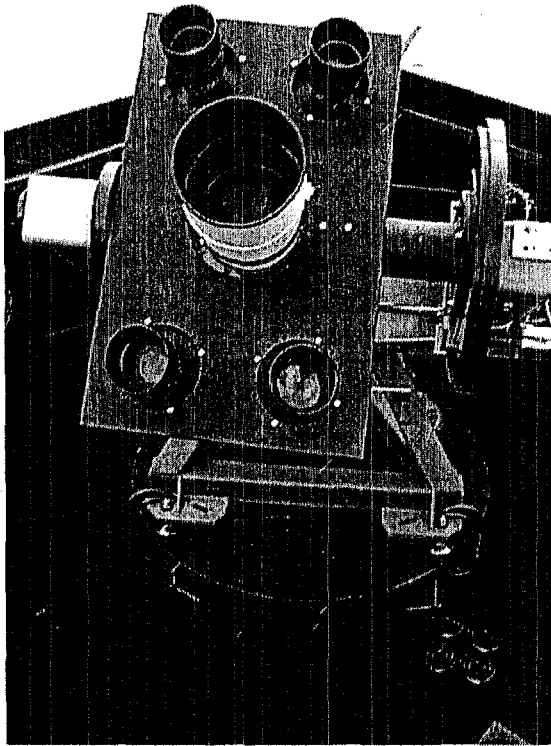


FIGURE 2. A RAPTOR wide-field telescope array. The 5.6-inch central "fovea" telescope is surrounded by an array of four 85mm lenses with large format CCD cameras that constitute the wide-field monitoring system. The entire array is mounted on a rapidly slewing telescope mount that can point the "fovea" telescope at the location of any transient identified by the wide-field system in one second.

To identify astrophysical transients, the calibrated object files from pairs of consecutive RAPTOR A mosaic images and the simultaneous RAPTOR B pair are compared. To minimize the number of false positives generated by hot CCD pixels and cosmic ray hits, the pointing directions are slightly dithered between each exposure. Only sources that are detected at the same sky position in both images of the pair are identified as potential celestial sources. This list of potential sources is then compared to an internal source catalog at each telescope site. If the

transient is identified in each mosaic image of the pair then it is flagged as a potential astrophysical transient. The two lists of candidate transients from each array are then compared. If the transient is present in the image pair from both arrays and no parallax shift is observed, then the transient is identified as a real astrophysical transient and an alert is generated. The position of the transient is then fed back to the mount and telescope arrays are rapidly slewed to point the fovea telescopes at the transient to begin follow-up observations.

MINING THE SKY IN REAL-TIME

The RAPTOR project is developing hardware and software that will enable autonomous robotic searches of the optical sky in real-time. Further, the RAPTOR system is designed to filter out the myriad of non-celestial signals that can mimic celestial transients in order to allow robust identification of real celestial transients. Ultimately, our goal is to monitor a sizable fraction of the sky and to generate alerts with source locations that will enable follow-up observations with other telescopes. Such a system will open an exciting new area of discovery space.

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