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# RAPTOR: Closed-Loop monitoring of the night sky and the earliest optical detection of GRB 021211

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**Abstract.** We discuss the RAPTOR (*Rap*id *T*elescopes for *O*ptical *R*esponse) sky monitoring system at Los Alamos National Laboratory. RAPTOR is a fully autonomous robotic system that is designed to identify and make follow-up observations of optical transients with durations as short as one minute. The RAPTOR design is based on Biomimicry of Human Vision. The sky monitor is composed of two identical arrays of telescopes, separated by 38 kilometers, which stereoscopically monitor a field of about 1300 square-degrees for transients. Both monitoring arrays are carried on rapidly slewing mounts and are composed of an ensemble of wide-field telescopes clustered around a more powerful narrow-field telescope called the "fovea" telescope. All telescopes are coupled to real-time analysis pipelines that identify candidate transients and relay the information to a central decision unit that filters the candidates to find real celestial transients and command a response. When a celestial transient is found, the system can point the fovea telescopes to any position on the sky within five seconds and begin follow-up observations. RAPTOR also responds to Gamma Ray Burst (GRB) alerts generated by GRB monitoring spacecraft. Here we present RAPTOR observations of GRB 021211 that constitute the earliest detection of optical emission from that event and are the second fastest achieved for any GRB. The detection of bright optical emission from GRB021211, a burst with modest gamma-ray fluence, indicates that prompt optical emission, detectable with small robotic telescopes, is more common than previously thought. Further, the very fast decline of the optical afterglow from GRB 021211 suggests that some so-called "optically dark" GRBs were not detected only because of the slow response of the follow-up telescopes.

**Key words:** robotic telescopes, gamma rays: bursts



## 1. Introduction

The night sky is alive with the flashes of optical transients. But nearly all of the transients with durations of minutes or less are not celestial transients. These non-celestial transients are generated by a wide range of phenomena from airplane lights and glints from satellites/orbital debris to head-on meteors or cosmic ray hits in the imager. This huge number of non-celestial transients compromised the early attempts to operate optical monitors designed to find celestial transients in real time (e.g. Vanderspek et al. 1994).

Nevertheless, minute-long optical transients of celestial origin do exist. The most spectacular example detected to date is the optical flash associated with Gamma Ray Burst (GRB) GRB990123 (Akerlof et al. 1999). That optical flash of a few minutes duration was generated by a GRB at redshift z=1.6 and briefly reached $\sim 9^{th}$ magnitude—making it the most luminous optical object ever observed by mankind. However, the depth and breath of optical sky monitoring is so incomplete that even this bright celestial transient would have been missed but for the real-time position provided by a high-energy satellite. Furthermore, there are many reasons to suspect the existence of rapid optical transients that cannot be found through sky monitoring by high-energy satellites. To search for and study these fast optical transients, we need robotic sky monitoring systems that can discriminate foreground transients from real celestial transients while the transient is still bright.

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## 2. RAPTOR instrumentation

### 2.1. A design inspired by human vision

As predators, we humans have evolved a highly sophisticated vision system for both imaging and change detection (e.g. Hubel 1995). Human vision 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. Each eye has a wide-field, low-resolution, imager (rod cells of the retina) as well as a narrow-field, high-resolution imager located at a region of the retina called the fovea (a region of densely packed cone cells). Both eyes send image information to a powerful real-time processor, the brain, running "software" for the detection of interesting targets in the images—nearly half of our cerebral cortex is devoted to the processing of visual information. 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. During each step of the process, our brain is running powerful real-time software and comparing with an adaptive catalog—our memory—to identify and study changes in the scene.

The RAPTOR (RAPid Telescopes for Optical Response) system concept (Vestrand et al. 2002) was inspired by human vision. RAPTOR employs two, spatially separated, telescope arrays (RAPTOR-A and RAPTOR-B). Each telescope array monitors the sky with a wide-field, low-resolution, imaging array and a central narrow-field, higher resolution, "fovea" telescope. A real-time software pipeline instantly analyzes images from RAPTOR A and B, potential candidates are identified, and the positions of any interesting transients are fed back to a central decision unit (CDU). If the transient is present in the images from both arrays, the CDU sends the transient position 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. Like human vision, the RAPTOR A and B arrays therefore act as a stereoscopic monitoring system employing closed loop feedback that autonomously identifies, generates alerts, and makes detailed follow-up observations of interesting objects in real-time.

## 2.2. The RAPTOR sky monitoring arrays

Each RAPTOR wide-field sky monitoring array is composed of four wide-field telescopes that as an ensemble simultaneously image a 1300 square-degree patch of sky. The wide-field telescopes are each composed of a Canon 85mm f/1.2 lens with a CCD camera at the focal plane. The cameras are thermo-electrically cooled Apogee AP-10 cameras which employ a 2K×2K format Thomson 7899M front-illuminated CCD chip with 14-micron pixels. Each telescope has a dedicated processing computer that runs a real-time photometry/astrometry pipeline capable of identifying transients in 18 seconds. The limiting magnitude of this wide-field monitoring system is $\sim$ 12.5 magnitude for a thirty-second exposure.

In the center of each wide-field array is a "fovea" telescope. The fovea telescopes are composed of large 400 mm focal length Canon telephoto lenses with a 5.6-inch objective and Finger Lakes Instruments (FLI) MaxCam CM2-1 CCD cameras. The FLI cameras use a TE cooled, 1K×1K format, Marconi CCD-47 back-thinned chip with 13-micron pixels and an 8-second readout time. In this configuration the fovea cameras cover approximately a 2° by 2° field-of-view and have nearly five times the spatial resolution of the wide-field array. The limiting magnitude of these telescopes is $R_c \sim 16.5$ for a 60-second exposure, making them well suited for faster cadence imaging of any transient identified by the wide-field arrays. The two fovea cameras also image the transient through different filters to provide color information.

## 2.3. A self-triggering, closed-loop, system

The RAPTOR sky monitoring system employs identical telescope arrays separated by 38 kilometers for real time identification of rapid celestial transients in the "forest" of non-celestial false triggers. The key to the suppression of false triggers is stereoscopic viewing the same scene to reject image defects that are present in only one image, or candidates in both images that have a measurable parallax. The 38-km separation of the arrays yields a parallax shift of more than 220 arcseconds for non-celestial objects out to the altitude of geostationary orbits at 36,000 kilometers. The wide-field imagers have a single pixel resolution of 34 arcseconds; so any transient generated at a distance of less than six times geostationary will have a detectable parallax.

The large spatial separation imposes severe limits on the bandwidth for communication between the two arrays. So while image differencing has some advantages for identifying transients, bandwidth limitations imposed by the T-1 communication line forced us to employ an approach that compares the calibrated object lists derived at each site with a resident adaptive catalog. In its current form, the triggering software employs pair matching of object lists from consecutive images at a single site and then sends the short list of candidates to a central location and looks for a match in lists from the two different sites. For a typical single image, matching with our internal adaptive catalog yields about 500 candidates compared to 3,000 when matching with a traditional catalog like the Hubble Guide Star Catalog. Pair matching the candidates in consecutive images yields about 10 candidates per exposure. When the pairs from both sites are combined without a signal to noise cut, we achieve a false coincidence rate of one every 100 exposures or a few per hour. Most of those false triggers are at the limiting magnitude of the system—a signal-to-noise cut at 0.5 magnitude less than the limiting magnitude gives us a false trigger rate of less than a few per night.

The RAPTOR sky monitoring system is now running and operating as a self-triggering, closed-loop, system. So far (summer 2004), all the celestial transients RAPTOR has independently identified and responded to have been asteroids. Normally asteroids are filtered out by the RAPTOR triggering criteria. But occasionally, an asteroid will be hidden by high clouds (or blend with a star) and then contemporaneously emerge in observations taken at both of the spatially separated sites. If the proper motion is small enough, it can then appear as a transient object that (1) is not in the sky catalog, (2) has no measurable parallax, and (3) has a rapidly

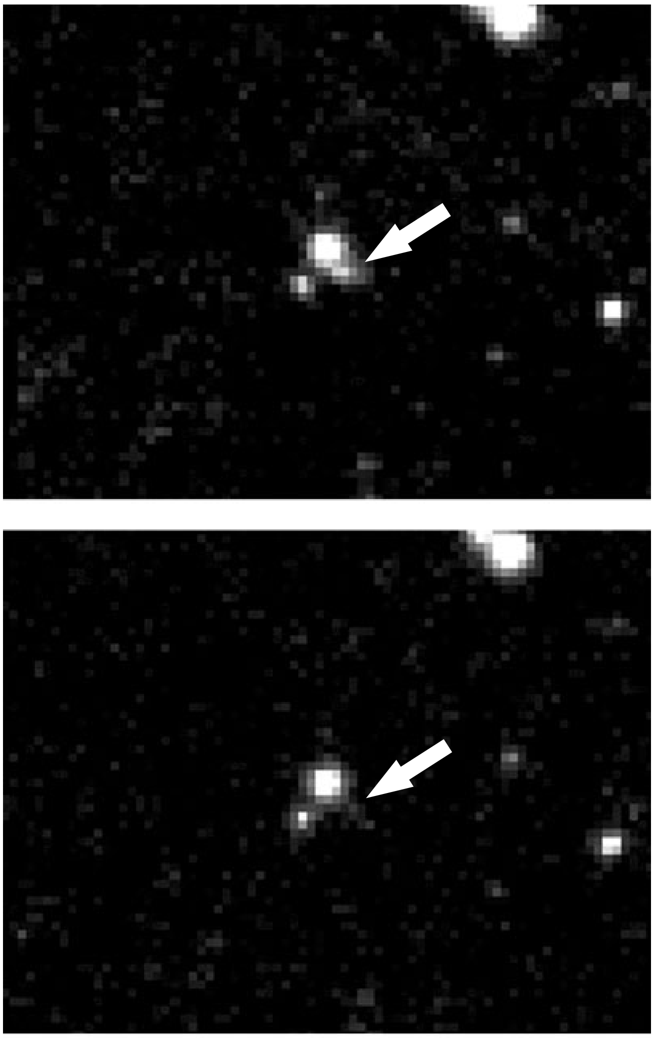

**Fig. 1.** The RAPTOR detection of prompt optical emission from GRB 021211. The image on the top began 64.5 seconds after the first gamma-ray photons were detected. The image on the bottom shows the same location taken 9 minutes later.

increasing flux—triggering a real time follow-up response. Such events demonstrate that the system is working as designed and is capable of independently finding transients.

## 3. Earliest detection of GRB 021211

The rapid slewing speeds of the RAPTOR telescopes also make them quite useful for responding to alerts from GRB locating spacecraft. For example, in December 2002 during initial testing, RAPTOR demonstrated this capability by promptly responding to an alert provided by the HETE satellite and detecting a bright optical transient (Wozniak et al. 2002) associated with GRB 021211. The optical transient (OT) was first detected with the fovea telescope of the RAPTOR-B array in observations that started 65 seconds after the GRB onset and subsequently detected in images starting at 105 seconds by the KAIT telescope (Li et al. 2003) and at 143 seconds by the Super-LOTIS telescope (Park et al. 2002).

The proximity of two nearby stars to the OT location (Fig. 1), and the fact that the fovea imager was unfiltered during the response, meant that we could not employ the standard real-time RAPTOR pipeline to derive optimal estimates of the OT flux evolution. Instead, to de-blend the slight contributions of the nearby $R_c \sim 12.4$ and $R_c \sim 13.7$ stars from the OT flux, we employed difference image analysis techniques and reference frames to subtract the contribution of all persistent objects (down to the noise limit) from the frames containing the OT. The reference image was constructed from a series of five 60-second exposures gathered between 19 and 28 minutes after the burst—when the OT was no longer detectable with the fovea imager. In the difference frames, the instrumental magnitude for the residual OT was then obtained using standard Sextractor photometric software. But to enable comparison with subsequent observations taken with other telescopes, we empirically derived a transformation of our broadband RAPTOR instrumental magnitudes to standard $R_c$-band magnitudes. To construct the transformation we used the photometry of Henden et al. (2002) for 31 stars in the field around the OT that also had comparable instrumental magnitudes to the OT.

When transformed to the standard $R_c$ band, our final derived $R_c$ magnitudes are $14.06 \pm 0.08$ and $15.36 \pm 0.25$ at corresponding image times 89.7 and 193.9 seconds after the burst. Here, in order to account for the fast decay of the OT, the flux integration has been weighted with a power law of index $-1.6$ to obtain the effective image times. All of the measurements of GRB 021211 taken during the first five minutes after the GRB are shown in Fig. 2. The early RAPTOR measurement is clearly consistent with a straightforward extrapolation to earlier times of the power law flux decay ($\alpha = -1.56 \pm 0.02$) measured by the KAIT telescope (Li et al. 2003).

According to the then current understanding, GRB 021211 should not have been detectable at optical wavelengths. Approximately, six events with gamma ray fluences greater than GRB 021211 (i.e. $S_\gamma(30 - 400\,\mathrm{keV}) > 2.1 \times 10^{-6}\mathrm{ergs\ cm^{-2}}$); Crew et al. 2003) were followed up within minutes of the GRB and not detected at limiting magnitudes greater than 14.5 magnitude (Williams et al. 2000, Kehoe et al. 2001. Those limits led to the belief that prompt optical emission is much fainter than predicted by simply scaling of the burst fluence, or that bright optical emission is generated by some process with a threshold only reached in giant GRBs like GRB 990123. However, the light curve of optical emission from GRB 021211 is quite similar to GRB 990123 at the same epoch but fainter by only about 3 magnitudes—about 2 magnitudes brighter than the prediction of scaling with GRB fluence.

Several authors have pointed out that, but for the detections of bright optical emission by rapid response telescopes in the first minutes, GRB 021211 would probably have been called an "optically dark" burst (Li et al. 2003, Crew et al. 2003, Lamb et al. 2004). These so-called "optically dark" events are a class of GRBs that show no detectable optical afterglow to the limit of the Palomar Digital Sky Survey (DSS, limit $\sim 20^{th}$ magnitude) on timescales of several

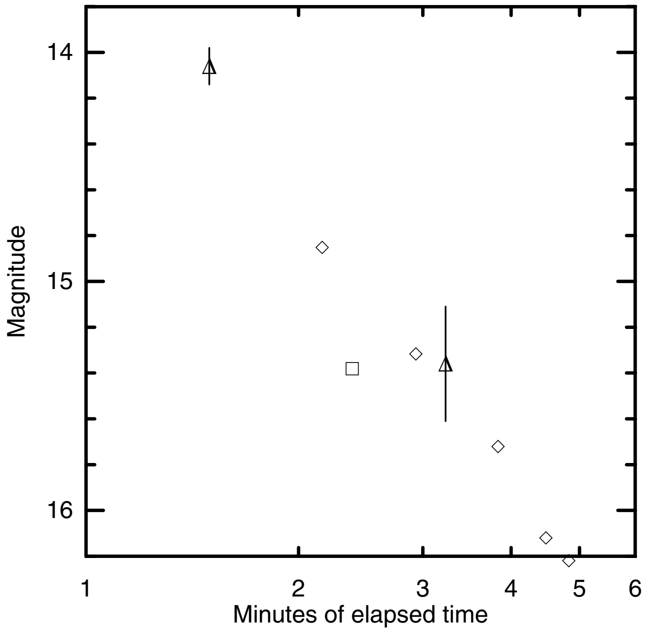


**Fig. 2.** Measurements of prompt optical emission from GRB 021211 during the first five minutes after the burst. The R magnitude measurements from RAPTOR are plotted as triangles, those from KAIT (Li et al. 2003) are plotted as diamonds, and the measurement from Super-LOTIS (Park et al. 2002) is plotted as a square. The sizes of the KAIT error bars are comparable to or smaller than the symbol sizes; the Super-LOTIS magnitude estimate did not provide an error bar.

hours to days. These "optically dark" events constitute about half of all GRB bursts with good localizations. Previously such bursts were thought to be generated by the explosions of massive stars buried in dusty star forming regions, which block the both the prompt and afterglow light from reaching us. But the prompt observations of GRB 021211 suggest that some of those bursts were probably not detected because the follow-up telescopes responded too slowly. The GRB021211 measurements also show that the generation of prompt, bright, optical emission, detectable with even small robotic telescopes, is not a phenomenon present only in extreme GRBs.

With the coming launch of the Swift satellite, we will have the opportunity to expand the sample of GRBs observed in the optical during the first few minutes from a handful to hundreds. This will show us how the properties of the prompt optical emission are related to the high-energy properties of the GRB. The distribution of GRB event durations at high energies is bimodal with a class of short events with durations less than a couple of seconds and a class with durations of a few seconds to minutes (Kouveliotou et al. 1993). It has been speculated that long duration events are explosions of massive stars and that short duration events are binary mergers of neutron stars or black holes (e.g. Katz and Canel 1996). In the latter scenario one would expect the GRB explosion to occur in an environment with less dust and gas and therefore less extinction of the optical emission and a very rapidly fading afterglow. Interestingly, GRB 021211 had a gamma-ray duration of only 2.3 seconds (Crew et al. 2003), which places it in the transitional region between the class of short-duration and long-duration events on the bimodal distribution of GRB event durations. Prompt observations of the optical light curves from GRBs may therefore provide the key to understanding the different classes of GRBs.

## 4. Summary

We have briefly described a system of autonomous robotic telescope arrays, called RAPTOR, which is designed to mine the optical sky for explosive transients. The system is capable of autonomously identifying transients with durations as short as a minute and commanding follow-up observations with more powerful telescopes in real time. By employing simultaneous stereoscopic imaging from spatially separated telescopes, the system is able to discriminate celestial transients from the non-celestial transients that are several orders of magnitude more common. The rapid slew capabilities of the RAPTOR telescopes make them useful for prompt follow-up of GRB alerts. We argued that the RAPTOR detection of bright, prompt, optical emission from a GRB with a relatively modest gamma-ray fluence, which might otherwise be classified as a so-called "dark" GRB, indicates that optical flashes from GRBs are more common than previously thought. This, plus the large field monitored by the system will make RAPTOR an effective system to search for optical emission from a broad range of explosive transients in the Swift era.

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