Detection of short optical transients of astrophysical origin in real time

Marcin Sokołowski
msok@fuw.edu.pl

Soltan Institute for Nuclear Studies (IPJ)
Warsaw, Poland
motivation for real-time detection of optical transients
methods and main problems
real time identification of optical transients in „Pi of the Sky”
other existing and future solutions
Why we need real-time pipelines?

- Violent and interesting astrophysical processes act on short and very short time scales and appear as optical flashes.

- Short timescale domain is relatively unexplored region.

- Most important information can be obtained when observing events in the very early phase, early detection required for effective follow-up observations.

- Short timescale processes require fast detection and reaction.

- Data streams are getting larger and larger, impossible to store all the data permanently, must find interesting things in real time.

- It's already working for γ-rays and X-rays, why not do it for optical.

- Relatively new idea in astronomy, future is out there …
What can we expect there?

- short and long gamma-ray bursts (orphaned or untriggered)
- supernovae
- cataclysmic variables, novae explosions, dwarf novae
- transients from AGNs, blazars
- early detection of near Earth objects (NEOs, PHAs)
- other, unknown type of processes?
What we want to do?

- collect images of the sky

- typically find objects in the new sky image which were not present in the previous images nor in catalogs of stars/galaxies

- It is looking like a game „spot the differences“:

Laying on beach …
How can we do this?

Seems to be a simple task, but …

Two natural ways of doing the job, depend on specific needs and characteristics of the project to be done

**Image subtraction**

- **Disadvantages:**
  - fluctuations of stars PSF
  - background fluctuations

**Comparison to catalogs / reference images**

- **Disadvantages:**
  - more time / CPU consuming (not good for short timescales)
  - catalogs not complete (use own earlier observations, cumulative images)
DIFFERENCE IMAGE
Third way – in the middle

Specific needs of „Pi of the Sky“:

- find short optical flashes on 10s images when next image is collected

Solution:

- do not subtract old image from new image
- perform „fast photometry“ (not full exact photometry)
- act as in catalog comparison way, but compare to reference image built from series previous images → identify new objects on image
- multilevel triggering system, next steps have more time for deeper analysis (similar to particle physics pipelines) - reject background (fluctuations, hot pixels, cosmic ray hits, satellites, planes)
Find transient candidates

- dark frame subtraction
- apply fast photometry „Laplace filter”
- check objects on new image vs. series of previous images (reference images) → find new objects

„Laplace filter” – every pixel is recalculated as function of nearby pixels

**REQUIREMENT**: $L_{\text{new}} > T_n (= 5\sigma)$ and $L_{\text{prev}} < T_v (= 3\sigma)$

**RESULT**: list of transient candidates
Background

Among candidates most are background events, which must be eliminated at next stages of the algorithm

- sky background fluctuations
- star PSF fluctuations
- cosmic rays hitting CCD chip
- defect of CCD (hot pixels)
- artifacts (opened shutter etc)
Coincidence of 2 cameras

REJECTS: cosmic rays hitting one of the CCDs, fluctuations, most artifacts, CCD defects

List of new objects confirmed on two cameras - optical transient in the sky (mostly local objects)

Distance of stars from corresponding images from 2 cameras

Results of subsequent cuts
Flashes from satellites

Most difficult background for "Pi of the Sky" prototype are satellites

Different for real-time pipelines in longer timescales

Satellites moving out from the shadow of the Earth

Faint moving satellites

Easy to reject by fitting a track
Rarely flashing satellites

Use TLE orbital elements from satellite observing people.

The ultimate weapon: PARALLAX Monte Carlo

The worst: rarely flashing, rotating satellites – no way to definitely reject all with a single telescope.

Very rarely flashing satellite

Distance to closest satellite: night 20070526 and MC

\[ R_{sat} = 1800'' \]

Number of events

Monte Carlo
Stereo observations — “ultimate weapon” against satellites

SITE A

SITE B

Parallax ≥ 30 km

For pixel resolution of ~ 36”, rejection distance $d \sim \frac{D}{36”}$:

- $D = 18$ km $\rightarrow d \sim 103,000$ km
- $D = 50$ km $\rightarrow d \sim 286,000$ km
- $D = 100$ km $\rightarrow d \sim 572,000$ km

Parallax allows for real real-time transient identification.
More sophisticated criteria
3rd level trigger

Final verification of events, more precise checks to few events accepted by previous trigger levels.
For example **Hough transform** – transformation to cylindrical coordinates to reject plane like events
Visual inspection of final events

Currently typical number of events < 20, possible for visual checks. Most of them still remaining background, but some can be interesting.

Parallax a must to flashing satellites

Correlation with others VOEventNet

~ 200 flashes visible on single 10s exposure, not confirmed by other observations (still can be satellites)
Off-line pipeline

Not exactly real-time at the moment, but planned to be changed in this manner

- Average or 20 ( or 3 ) images
- Reduction ( dark and flat field )
- Photometry, astrometry → list of stars
- Normalization of brightness to V magnitudes from TYCHO catalog
- Cataloging of lightcurves to the PostgreSQL database
- Flagging new objects added to catalog
- Algorithm analysis only new objects added to star catalog – transient candidates
Other real-time transient detectors

- mostly focused on larger time scales ~ minutes to days

- very few looking for transients of timescale of order of seconds

- typical exposures times > 30 sec, usually re-observing the field after couple of time (30 minutes)

- typically comparison to star catalogs or own reference images/catalogs

- some problems of algorithm for 10s are not present there

- flashing satellites not a problem for longer timescales and requirement of object detection on several consecutive images
## Presentation of selected projects

no way to put tell about all …

- ASAS
- BART
- BOOTES
- Catalina Real Time Survey (CRTS)
- KAIT
- LOTIS
- MASTER
- OGLE
- PanStarrs
- Palomar Transient Factory
- Pi of the Sky
- RAPTOR
- REM
- ROTSE
- SkyMapper
- SNFactory
- TAROT
- TORTORA, MEGA-TORTORA
- WASP, SUPERWASP
- WATCHER
• stereo system RAPTOR-A and B with 38 km parallax

• wide field $40^\circ \times 40^\circ$, with fovea telescope $2^\circ \times 2^\circ$ for follow-up

• multiple 30s images

• comparison of new image with previous images and with catalog (self-produced, started from GSC) of stars and other objects

• sending of alerts to VOEventNet and other networks in real-time

• The Telescope ALert Operations Network System (TALON) – system for intercommunication of alert triggers from different telescopes

• Building large arrays
MASTER - WVF - 4

- 4 wide field cameras FOV ~ 25.5° x 39.8° each
- timescales > 0.15s, up to 13m on 5s exposures
- real time OT detection and classification (SN, several discovered)
- follow-up with MASTER 40cm telescope
- comparison with previous images and external star catalogs
- separate talk today
Robotic Optical Transient Search Experiment (ROTSE-III)

- **MAIN GOAL**: GRBs, but also orphaned afterglows from GRBs

- Exposure time typically: 20 - 60s

- **FOV**: $1.85^\circ \times 1.85^\circ$

- **quasi real-time pipeline for transients**: (SNs)

- 2 x 30 seconds images in two sets with 30 minutes interval

- 30 SN / year, also transients of unknown origin
All Sky Automated Survey (ASAS)

- one of the first robotic telescopes ever constructed
- exposure times: 2 - 3 minutes
- variability timescales ~ days (every field observed once 1-2 days)
- mostly for variable stars, extensive catalogues of variables stars
- four telescopes ~ 8° x 8° each
- real time pipeline for identification of nova stars, compares new images with catalog of previous observations (> 20 new Novae found)
- automatic classification of star variability
The Optical Gravitational Lensing Experiment (OGLE)

- one of the first real-time pipelines
- 1.2m telescope (not robotic)
- exposure times: 180s or 225s
- dedicated to gravitational lensing magnification events
- however, also real-time pipeline for optical transient (New Objects in OGLE Sky – NOOS) was developed and several supernovae and high magnification optical lensing events were identified
- differential photometry (DIA technique – Alard & Lupton 1998), subtraction of new image from cumulative reference image of same field from previous season
CRTS / Palomar Quest (PQ)

- Images from Catalina Sky Survey
- FOV ~ 8° x 8°
- Exposure time 30s, 4 images of same field every 30 minutes
- Real-time pipeline for optical transients, image subtraction technique
- Verification of transients against star catalogs USNO-B, SDSS, PQ survey
- Publishing of events in real-time via VOEventNet (in less than 5 minutes from discovery)
- ~350 OTs / six months, mostly: SNs, cataclysmic variables, UV Ceti flare stars, blazars, Near Earth Objects
Palomar Transient Factory (PTF)

- 1.2m telescope + 50% of time on 1.5 m in Palomar Observatory
- exposure time ~ 60s, FOV ~ 7.8 deg$^2$, limit ~ 21m
- search for SNs and exotic optical transients
- real-time transient identification (image subtraction), classification and optimal follow-up
Large Synoptic Survey Telescope (LSST)

· To be started in 2014, 8.4 m telescope

· Exposure times > 10 seconds
  FOV ~ 3.5° x 3.5°
  (3.2 Giga Pixel!)

· Data stream ~ 30 TB / night

· Requires real-time analysis pipeline, strong interest in optical transients

· Twice a night make 2 images of same field

· MAIN GOALS: dark energy and matter, optical transients, Near Earth Objects (NEO), Potentially Hazardous Asteroids (PHAs)
CONtinuous CAMera ( CONCAM )

- All Sky fish-eye camera ( 2 PI )
- 180s exposures, limit ~ 6.8m
- 11 stations around the world
- Identification of optical transients in real-time
- Image quality check
- Comparison of new images with reference images
- Rejection of bright planets and variable stars
- Transients visible for more than 1 image or station are alerted
- OT060420 – ~10 minutes transient of ~5.5m observed by 2 stations ( not 3rd one )
Summary

- The number of real-time transient detectors of different sizes (from cm to m telescopes) is rapidly growing.
- Several working solutions exist, and the plan is to make "Pi of the Sky" real-time pipeline available as an open-source project.
- They allow individual telescopes to identify optical transients on time scales ranging from seconds to days.
- For short time scales, stereo observations appear promising but double the system's costs.
- RAPTOR, existing, and "Pi of the Sky" coming soon, will be able to send real-time triggers for short optical transients.
- Many detections lack confirmation and follow-up from other observers. Connecting to global communication networks like Virtual Observatory (VOEventNet) will allow fully exploiting the potential of existing individual systems.
- Eliminating humans from the loop? Not romantic, maybe safer...
"The last thing I said to him was: 'Whatever you do, don't look at the sun through this thing'."