Detection of short optical transients of astrophysical origin in real time

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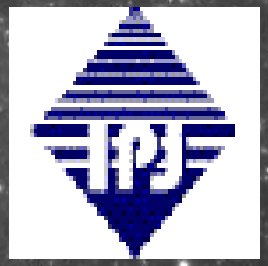


Workshop on Robotic Autonomous Observatories, Málaga, Spain, 18-21 May

Outline

- 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
- its already working for γ-rays and X-rays, why not do it for optical
- relatively new idea in astronomy, future is out there …

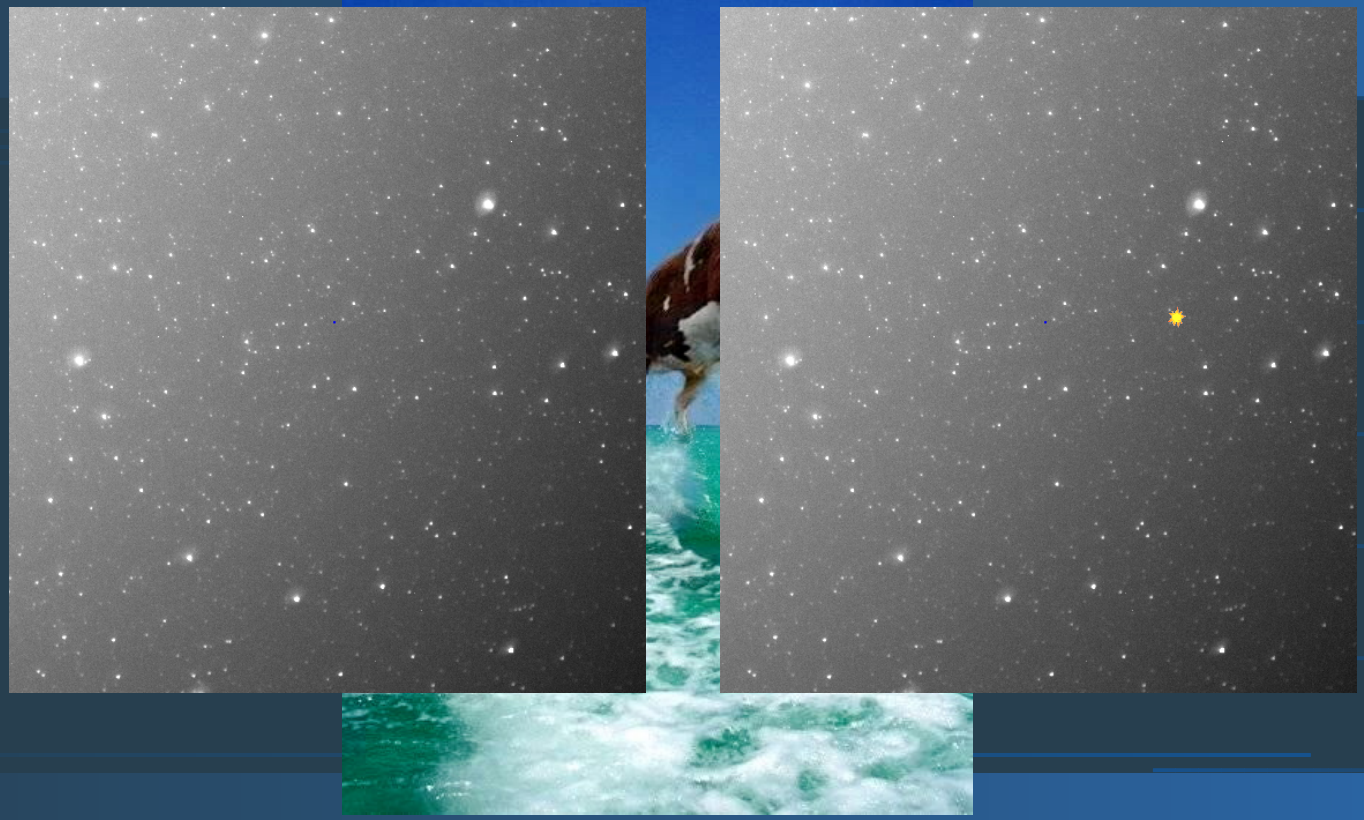
What can we expect there ?

- **short and long gamma-ray bursts (orphaned or untriggered)**
- **supernovae**
- **catalcysmic 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 :

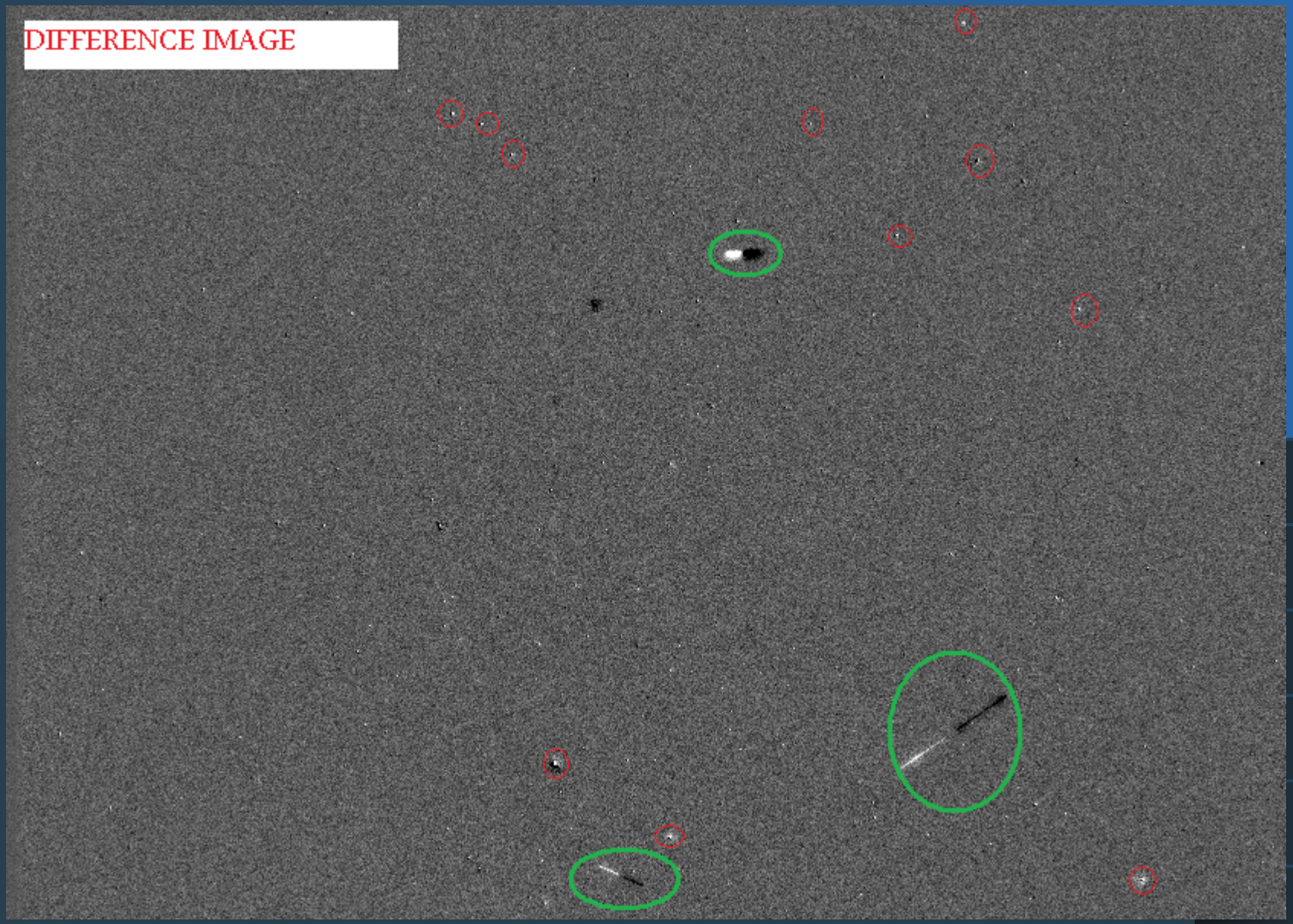
- **fluctuations of stars PSF**
- **background fluctuations**

Comparison to catalogs / reference images

Disadvantages :

- **more time / CPU consuming (not good for short timescales)**
- **catalogs not complete (use own earlier observations, cumulative images)**

Illustration



Third way – in the middle

Specific needs of „Pi of the Sky" :

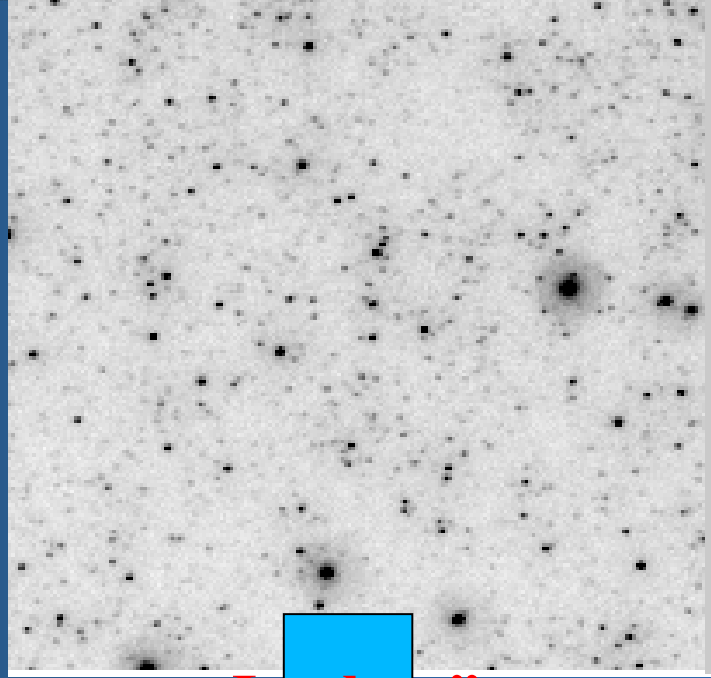
- find short optical flashes on 10s images when next image is collected

Solution :

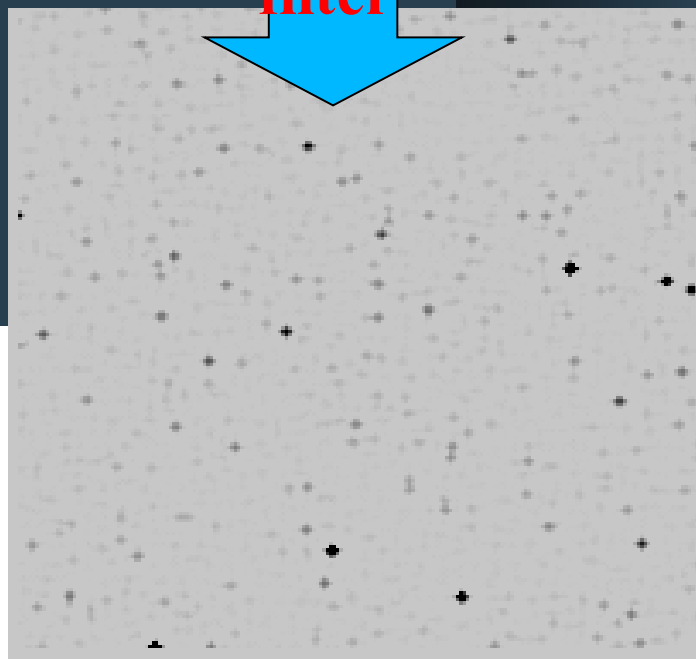
- do not subtract old image from new image
- perform „fast photometry" (not full exact photometry)
- act as in catalog comparison way, but compare to reference image built from series previous images → identify new objects on image
- multilevel triggering system, next steps have more time for deeper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

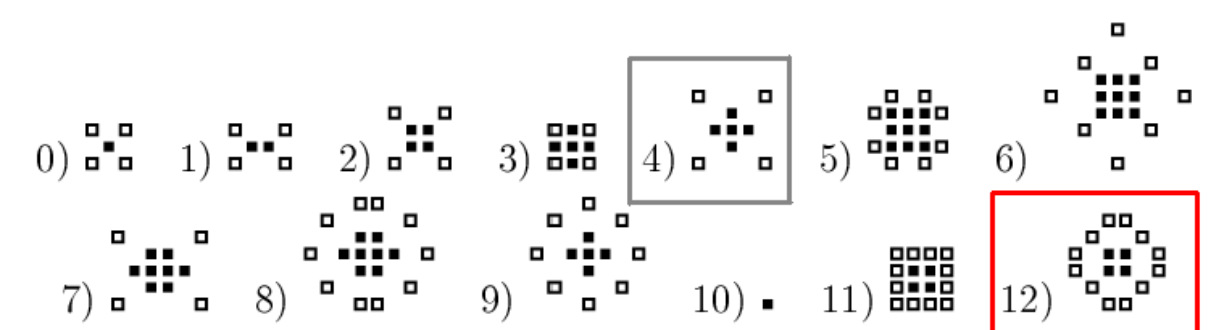
Find transient candidates

- 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 : $L_{new} > T_n$ (= 5σ) and $L_{prev} < T_v$ (= 3σ)
- RESULT : list of transient candidates



„Laplace” filter

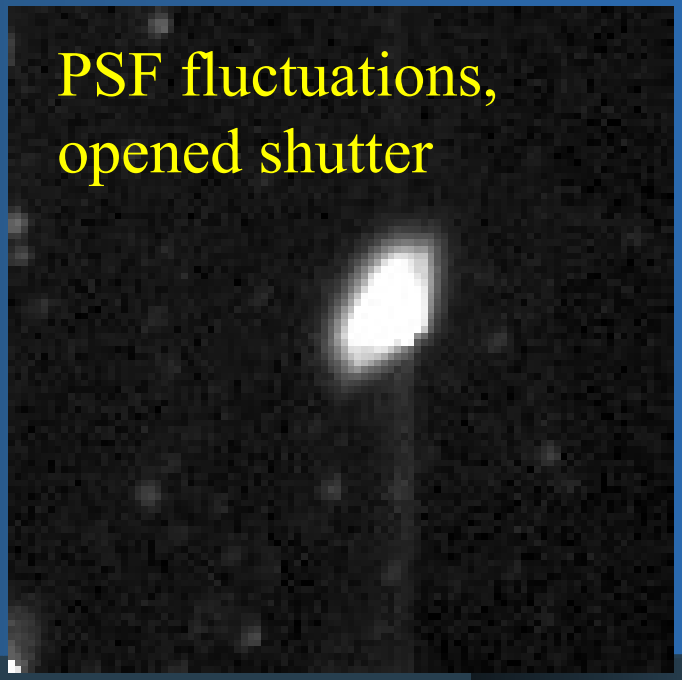


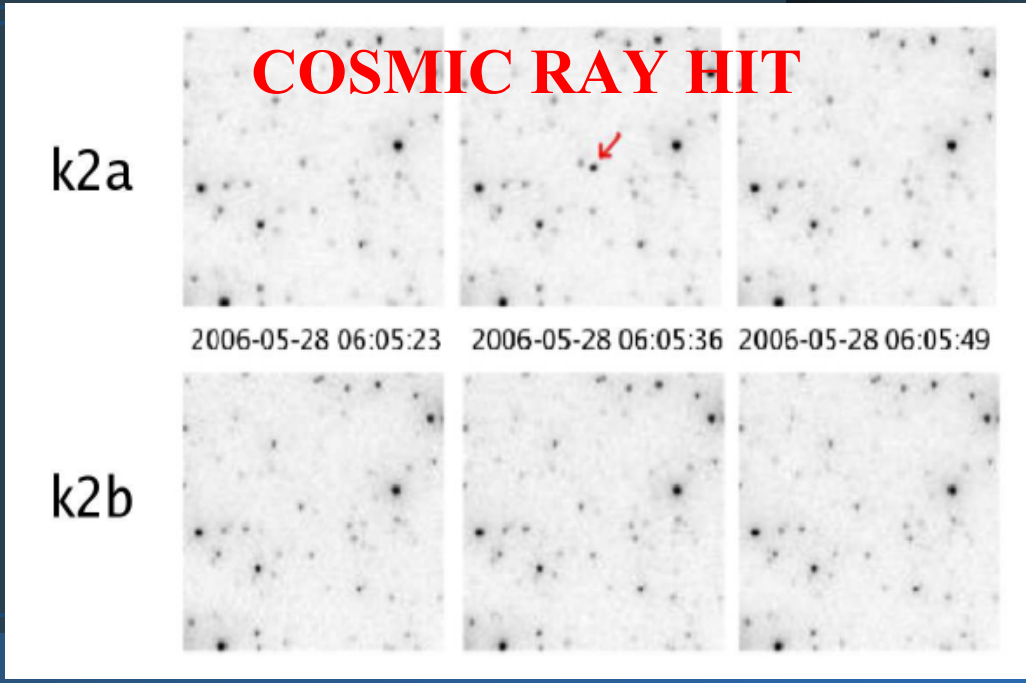


Background

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)**

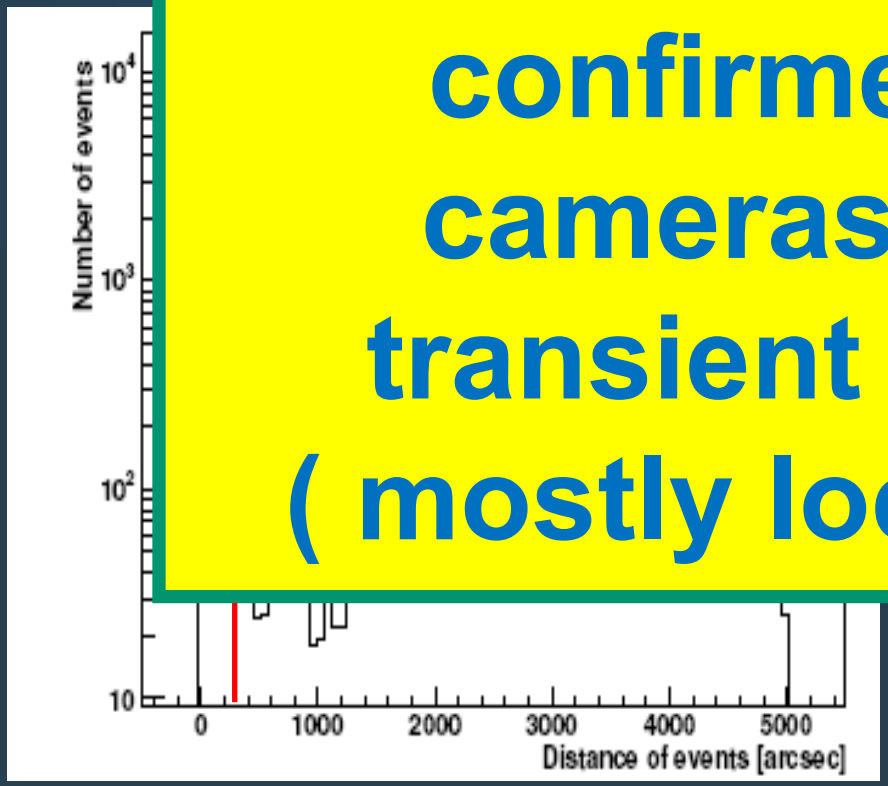




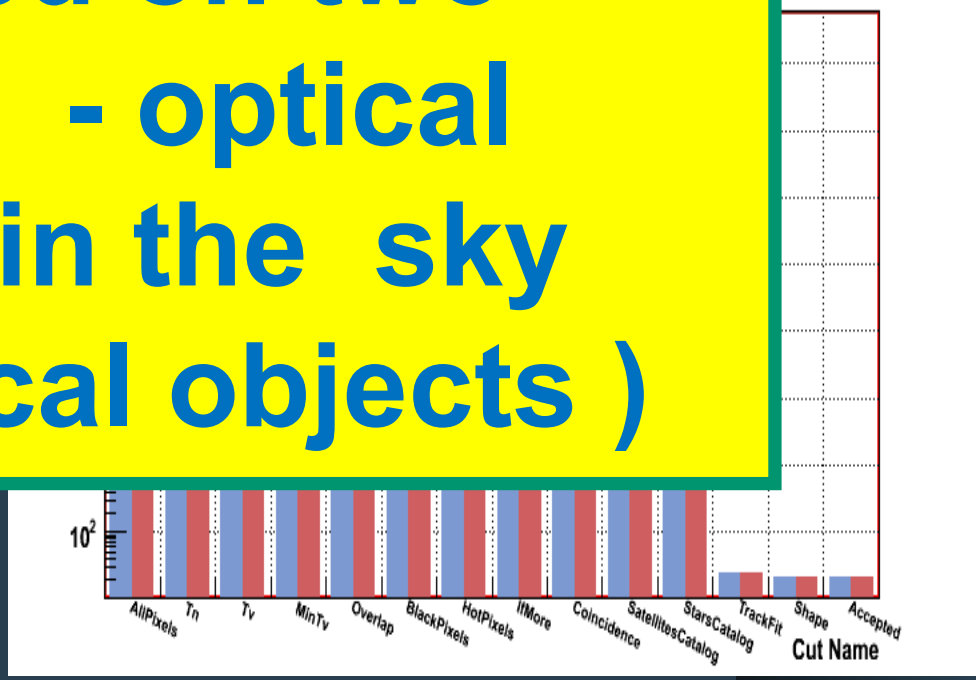
Coincidence of 2 cameras

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

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

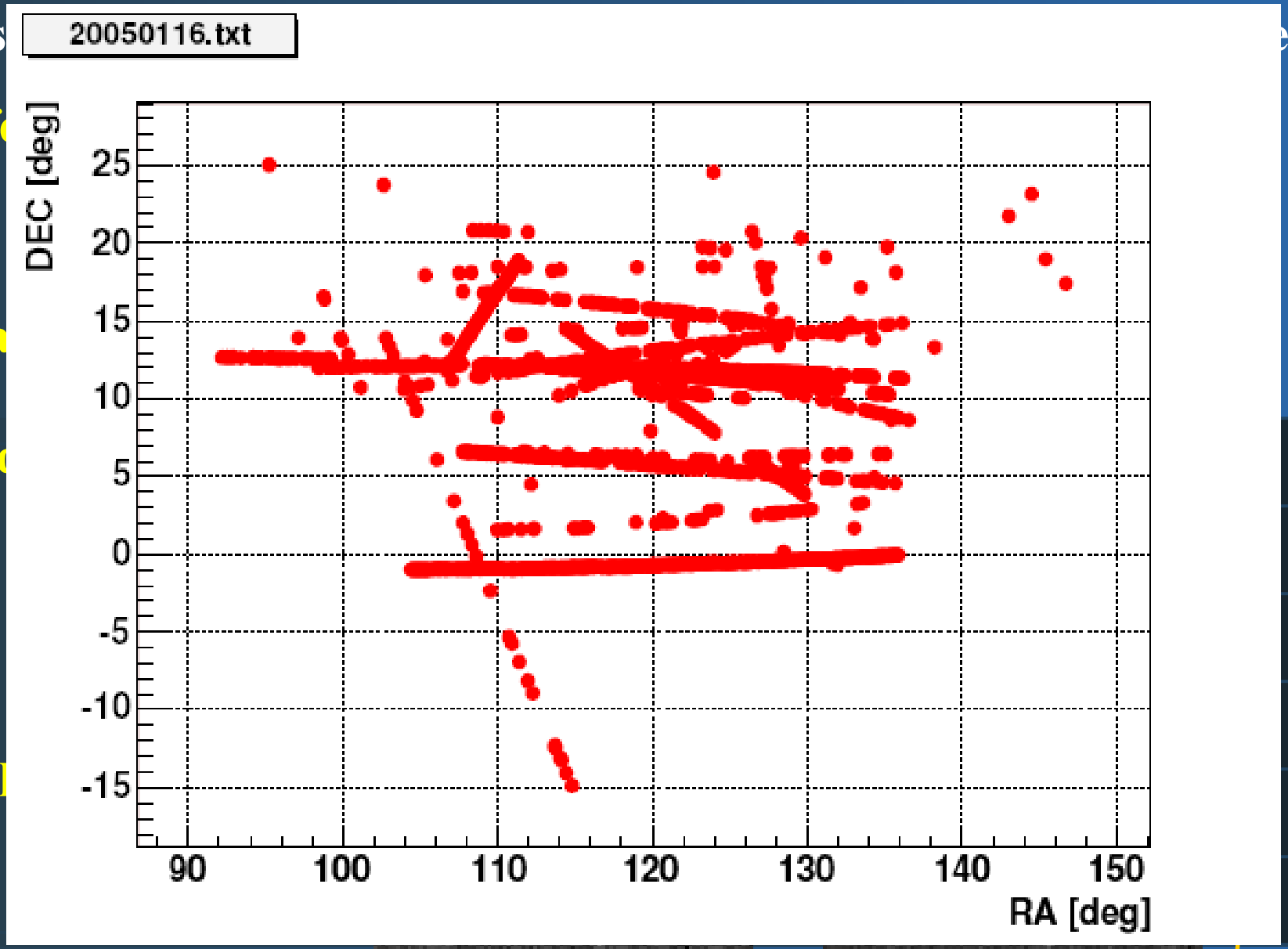


Distance of stars from corresponding images from 2 cameras



Results of subsequent cuts

Flashes from satellites



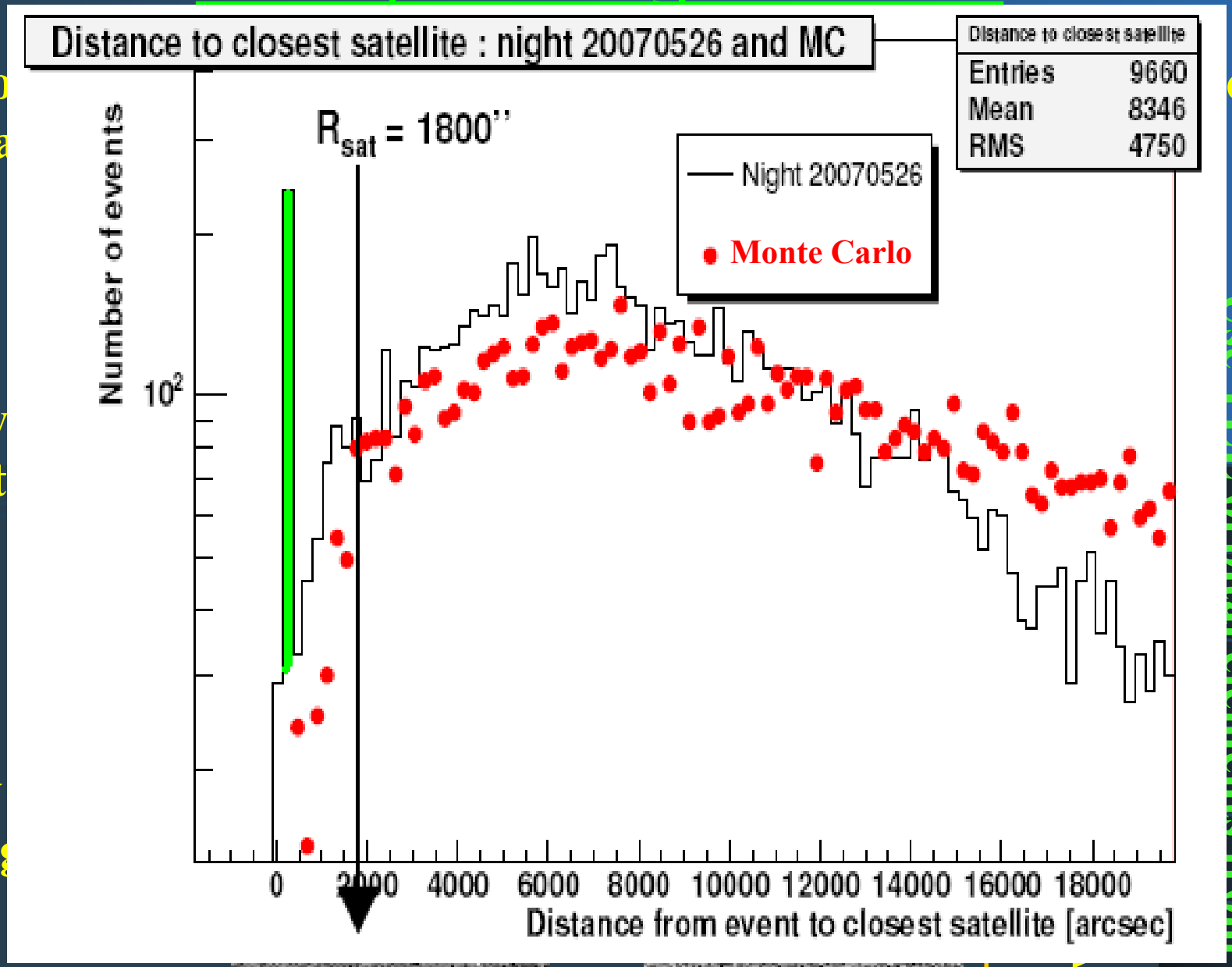
Easy to reject by fitting a track

Rarely flashing satellites

The wo … ely
reject a …

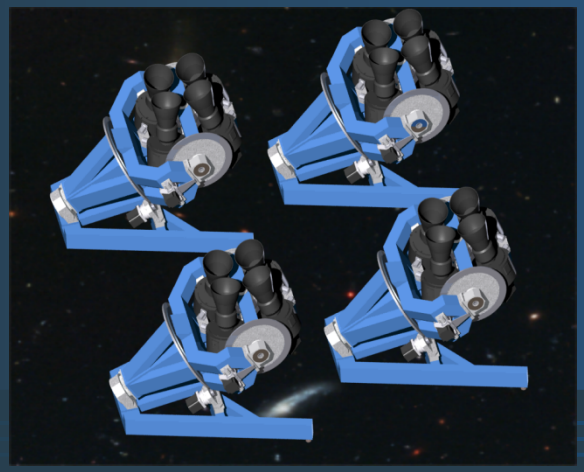
Rarely …
sat …

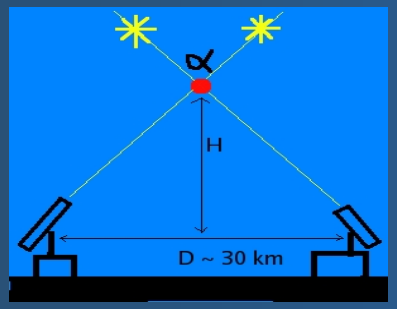
Very …
flashing …



Use TLE orbital elements from …

Stereo observations – „ultimate weapon" against satellites





Parallax ≥ 30 km

SITE A **SITE B**

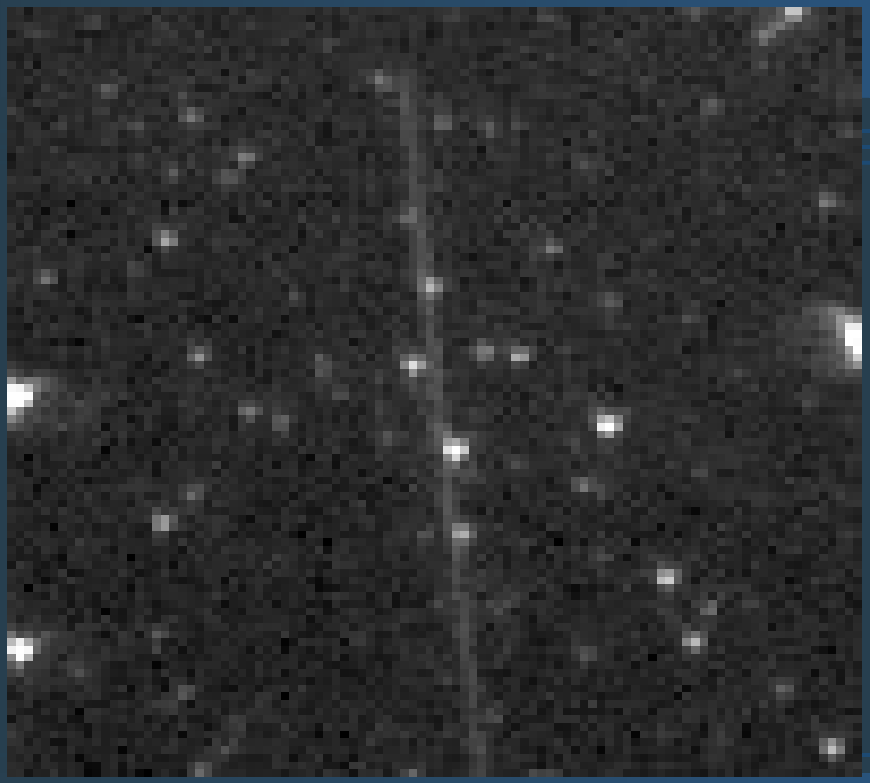
For pixel resolution of ~ 36'' , rejection distance d ~ D / 36'' :

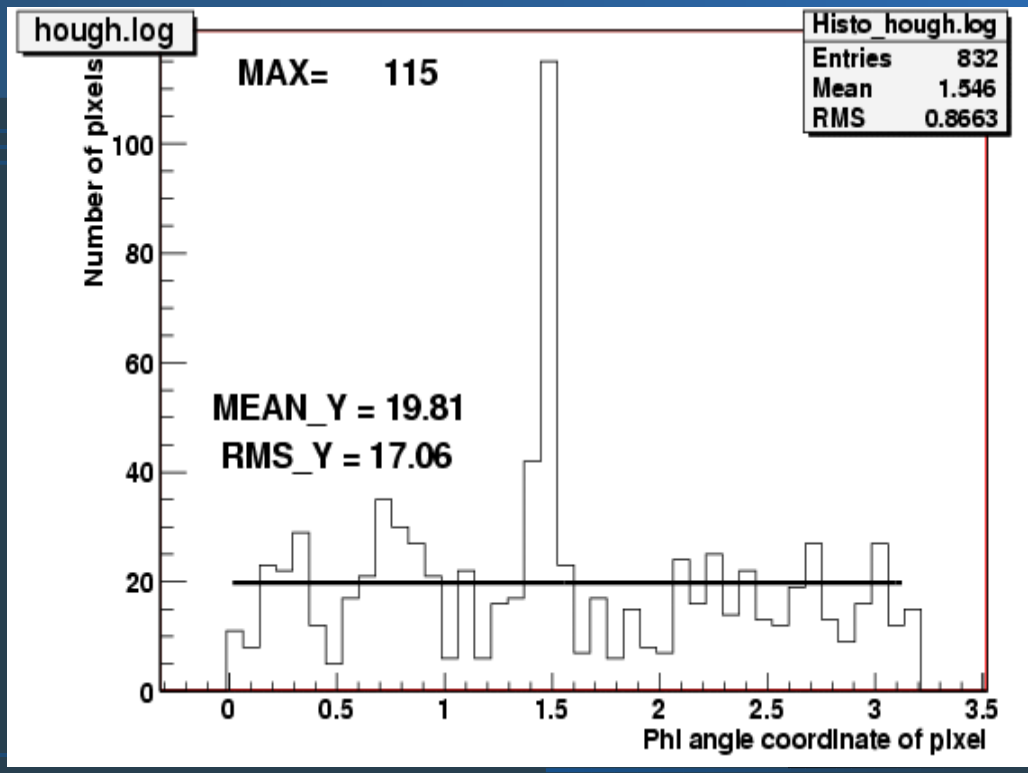
- **D = 18 km → d ~ 103,000 km**
- **D = 50 km → d ~ 286,000 km**
- **D = 100 km → d ~ 572,000 km**

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 i

Parallax a must to flashing satellites

Correlation with others VOEventNet

~ 200 flashes visible on single 10s exposure, not confirmed by other observations (still can 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

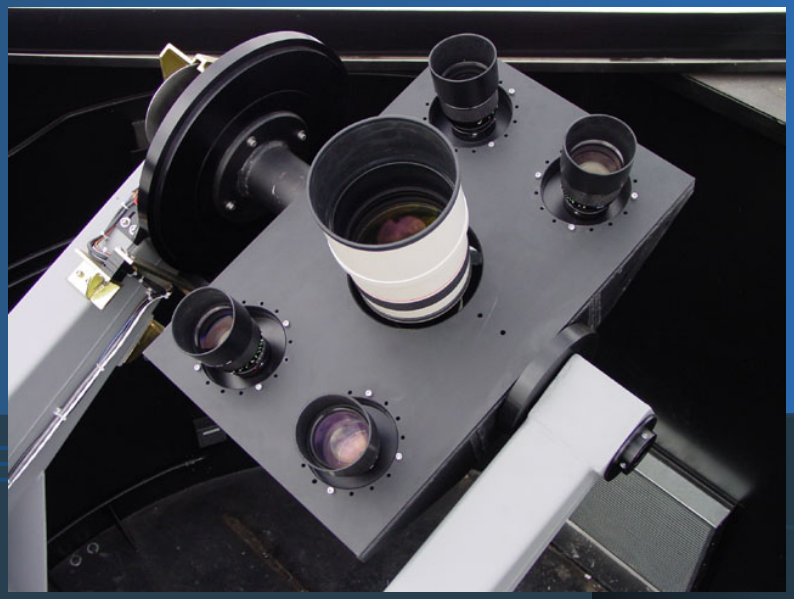
- mostly focused on larger time scales ~ minutes to days
- very few looking for transients of timescale of order of seconds
- typical exposures times > 30 sec , usually re-observing the field after couple of time (30 minutes)
- typically comparison to star catalogs or own reference images / catalogs
- 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

Real-Time Detection of Optical Transients (RAPTOR)

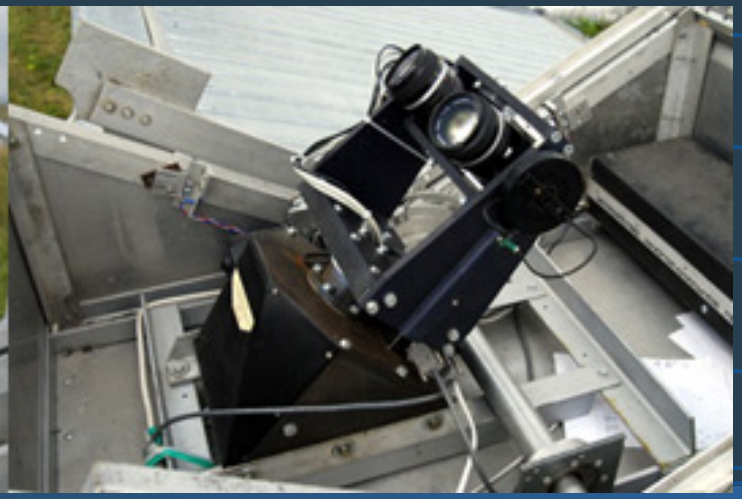
- stereo system RAPTOR-A and B with 38 km parallax



- wide field 40^o x 40^o, with fovea telescope 2^o x 2^o 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^{o} x 39.8^{o} each
- timescales > 0.15s, up to 13^{m} 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^{o} x 1.85^{o}**
- **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^o x 8^o 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 225 s
- 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

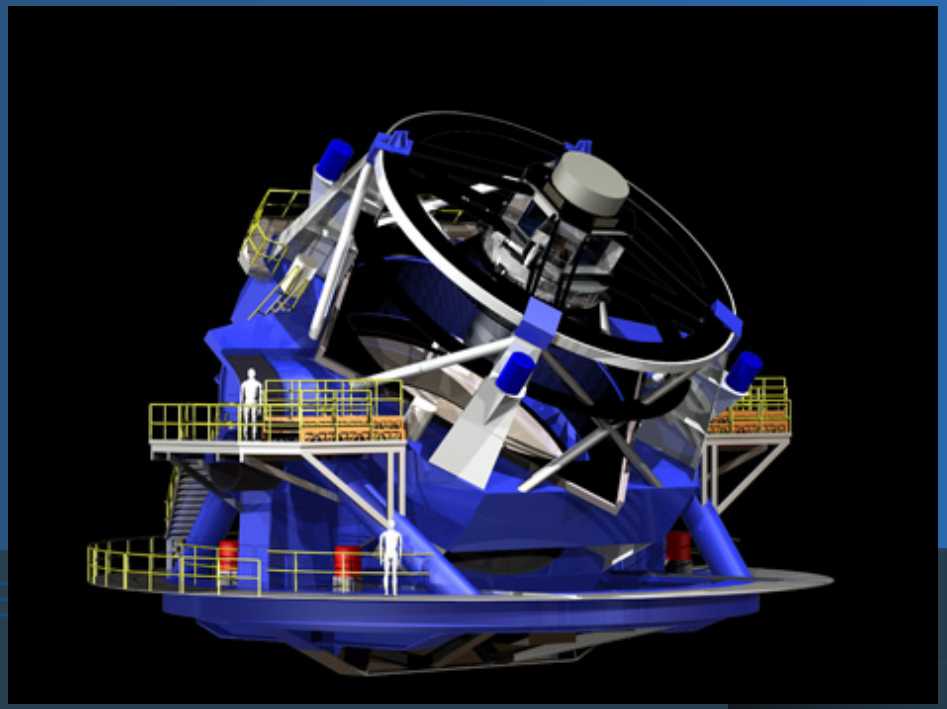
CRTS / Palomar Quest (PQ)

- Images from Catalina Sky Survey
- FOV ~ 8^o x 8^o
- 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 then 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

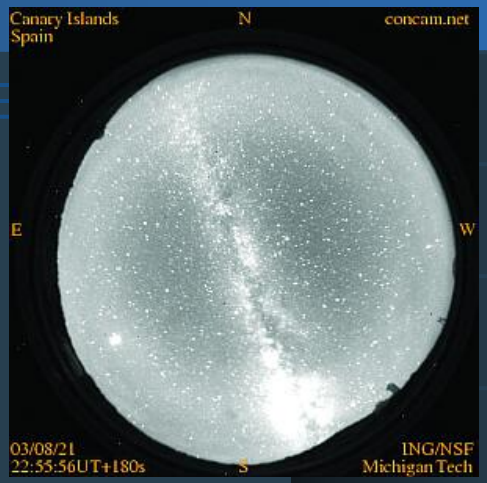
Large Synoptic Survey Telescope (LSST)



- **To be started in 2014 , 8.4 m telescope**
- **Exposure times > 10 seconds**
  FOV ~ 3.5^{o} x 3.5^{o}
  (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 then 1 image or station are alerted
- OT060420 – ~10 minutes transient of ~5.5m observed by 2 stations (not 3rd one)



Summary

- number of real-time transient detectors of different sizes (from cm to m telescopes) is rapidly growing up
- several working solutions exist, plan 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 the most promising seems to be stereo observations, but doubles the costs of the system
- RAPTOR – existing, "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. connection to global communication networks like Virtual Observatory (VOEventNet) will allow to fully exploit potential of exiting individual systems
- Eliminate humans from the loop ? Not romantic, maybe safer …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"The last thing I said to him was: 'Whatever you do, don't look at the sun through this thing'."