# Wide and Fast
# -
# monitoring the sky in sub-second domain

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# Fast Variability of the Sky: historical perspective

But it is clear that there is an awful lot to be done by ground-based astronomy. I would like just to add a little plea here for one field of ground-based optical astronomy, where, again, our knowledge is not even skin-deep yet. I am not trying to say that I know how to solve the problems there; I am only a little disappointed that there is not a stronger drive in this field. This is a subject that I would like to call short-time constant astronomy. We have been so much impressed by the integrating properties, first of the human eye and then of the photographic emulsion, that there has been a concentration—a very large concentration—on exploring further by increasing integrating times. But of course this has almost completely excluded observations of transient effects. As far as I know the only genuinely short-time constant piece of work in optical astronomy is the discovery of pulses from pulsars. Naturally, it is a lot easier if you know where to look, at what repetition rate pulses will come, etc.—I am not denying this—but I think it is sometimes overlooked that perhaps we are missing a whole continent. I do not know exactly what I am looking for: it may be that one might discover that there are brick ends flying about space and obscuring stars every now and then for very brief moments; and it may be that there are bits in the interstellar medium that suddenly just flash up like a neon light. I just do not know. All I am trying to say is that, perhaps in the distant future, which is what I am talking about, there may be extensions of our way of looking at ground-based astronomy that will be at least as striking as, if I may repeat myself, the addition of polarization was.

H.Bondi, «Astronomy of the future», 1970

# Fast Variability of the Sky: what is «fast» and what is «slow»?

| Time scale | near-Earth | inside Galaxy | nearby galaxies | cosmological distances |
|---|---|---|---|---|
| < 0.1 s | meteors, satellites, debris | novae, flaring stars, stars occultations | nearby supernovae | GRBs |
| 1 s | high-orbit satellites | | | |
| 10 s | | | | |
| 100 s | asteroids | | intra-day variable AGNs | |
| > 1000 s | | variable stars, MACHOs | | supernovae |

Gray background marks the classes of objects routinely targeted by existing wide-field surveys,like ASAS, LINEAR, MACHO etc

**As a rule, fast optical transients have unpredictable localizations, both in time and on the sky**

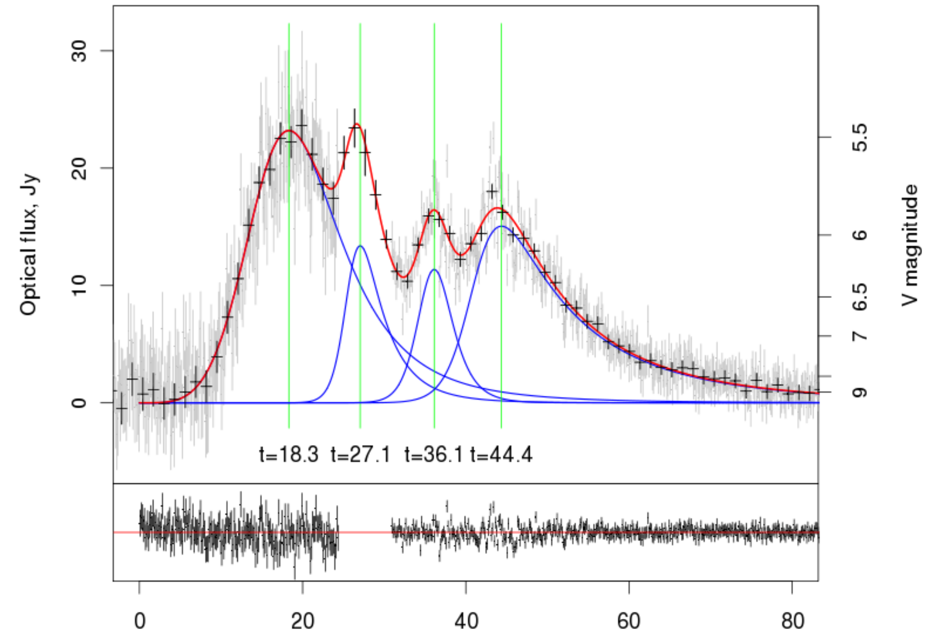
# Gamma-Ray Bursts: open questions about optical emission

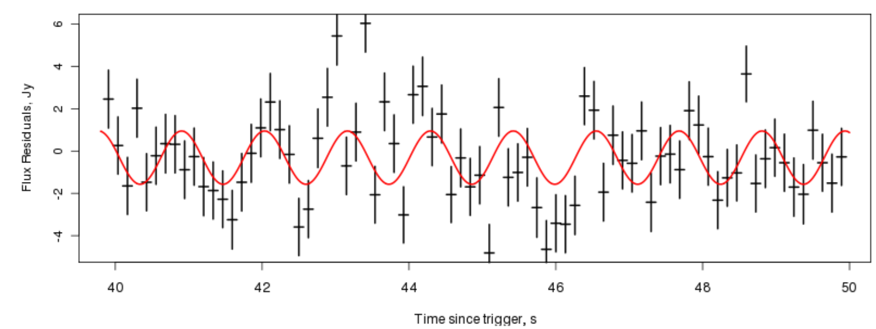
- **When does it start and when does it end?**
- Transition from **prompt** emission to **afterglow**
  - several hundreds of afterglows, but only about ten prompts
- **Temporal variability**
  - gamma is highly variable down to $10^{-4}$ s, what about optics?
- **Relation to gamma emission**
  - are they correlated?
  - what is the temporal lag between them? who is the first?
- **Prompt emission from the short bursts**
  - afterglows are basically the same. what about prompts?

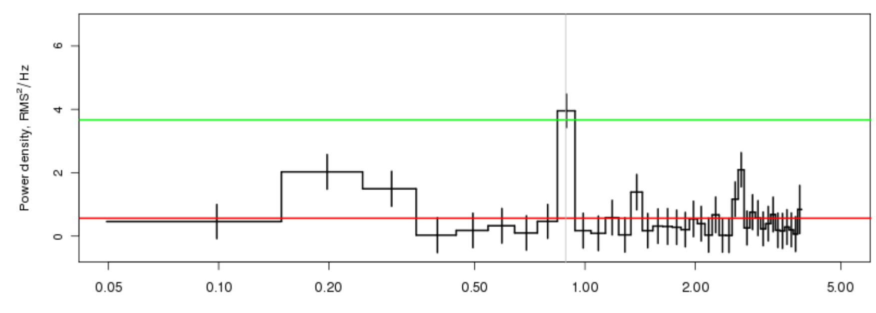
**All this require the detection of very first moments of the burst and, obviously, high temporal resolution of observations**

# Gamma-Ray Bursts: lessons from the Naked-Eye Burst

- Peaked at V~5.3 m
- **Fast optical variability**
  - **~9 seconds** — four peaks
  - **~1 second** — around last peak
- Simultaneous start and end
- **0.82** correlation with **2 s** optical delay
- Rules out large subset of theoretical models, like **External Shock** and **Inverse Compton** ones




**Naked-Eye Burst demonstrated the importance of high temporal resolution in optical study of GRBs**

# Wide-Field Monitoring: different ways to be the first

## How to catch the short transient of unknown localization?

- **Listen to Swift, and then move fast**
  - Typical strategy of robotic alert-based systems.
  - A lot of instrument, a lot of afterglows. What about the prompt?
- **Listen to Swift, but look the same direction**
  - Several wide-field monitoring systems around the world
  - Several upper limits ($\sim 10^m$) for the moment of the burst
  - and finally — the **Naked-Eye Burst**!
- **Be completely on your own**
  - Routine monitoring of wide areas of the sky
  - **Automatic detection and classification of transients**

## Wide-Field Monitoring: requirements for alert-based observations

**The faster you repoint — the better**

# Wide-Field Monitoring: efficiency of assisted observations

$$\text{Field of View: } \Omega \sim \frac{N^2}{F^2}$$

$$\text{Limiting Flux} \sim \left(\frac{D}{F}\right) D^{-2} \tau^{-\frac{1}{2}}$$

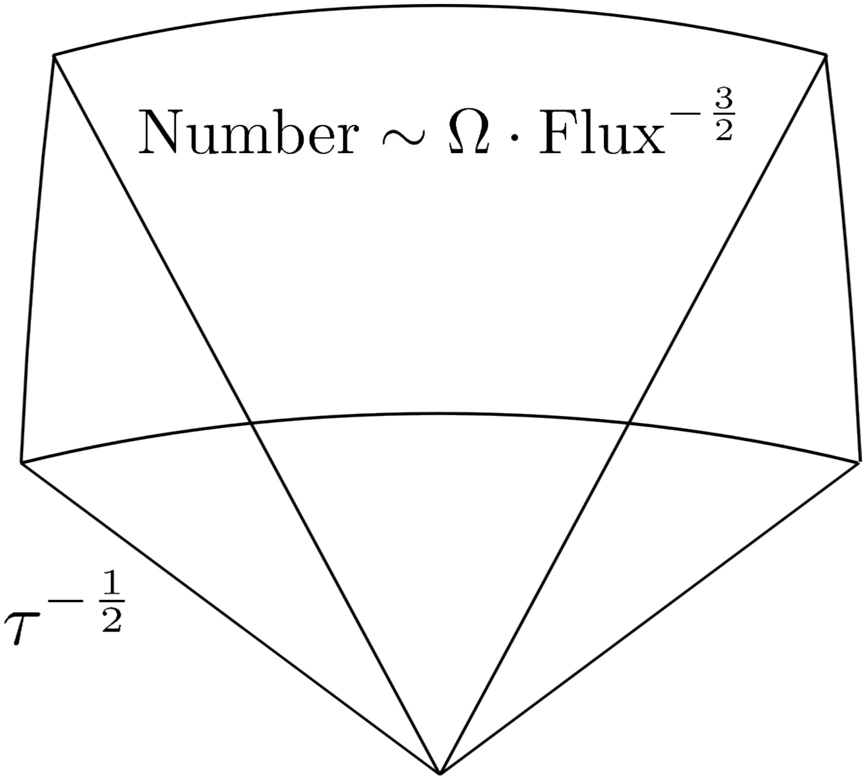
**You need only to look al the transient position when the satellite detects it**

**Upper limits for the prompt flux are results too**

**So, the shorter the focus - the better**

# Wide-Field Monitoring: efficiency of independent observations

$$\text{Field of View: } \Omega \sim \frac{N^2}{F^2}$$




$$\text{Limiting Flux} \sim \left(\frac{D}{F}\right) D^{-2} \tau^{-\frac{1}{2}}$$

**Exposure shorter than the event**

$$\text{Number} \sim D \left(\frac{D}{F}\right)^{\frac{1}{2}} \tau^{\frac{3}{4}}$$

**Exposure longer than the event**

$$\text{Number} \sim D \left(\frac{D}{F}\right)^{\frac{1}{2}} T^{\frac{3}{2}} \tau^{-\frac{3}{4}}$$

**Short transients require short exposures**

# Wide-Field Monitoring: requirements for a general-purpose system

- **Need wide field of view**
  - the shorter the focus the better
- **Need good detection limit**
  - the larger the diameter the better
- **Need high temporal resolution**
  - short exposures and fast read-out
  - low read-out noise
- **Need real-time processing software**
  - real-time detection and classification of transients

$$\text{Field of View: } \Omega \sim \frac{N^2}{F^2}$$

$$\text{Limit } \sim \left(\frac{D}{F}\right) D^{-2} \tau^{-\frac{1}{2}}$$

# Wide-Field Monitoring: systems currently in operation

| Name | Field of View (degrees) | Exposure (seconds) | Limit |
|---|---|---|---|
| WIDGET | 62x62 | 5 | 10 |
| RAPTOR A/B | 40x40 | 60 | 12 |
| RAPTOR Q | 180x180 | 10 | 10 |
| BOOTES | 16x11 | 30 | 12 |
| Pi of the Sky | 33x33 | 10 | 10.5 |
| AROMA-W | 25x35 | 5-100 | 10.5-13 |
| MASTER-VWF | 20x21 | 5 | 11.5 |
| MASTER-Net | 30x30 | 1 | 9 |
| FAVOR | 17x24 | 0.13 | 10-11.5 |
| TORTORA | 24x32 | 0.13 | 9-10.5 |

# FAVOR & TORTORA systems: overview

FAVOR (FAst Variability Optical Registrator) camera — SAO RAS, since 2003

Built in collaboration with IPI and IKI (Moscow), supported by CRDF grant

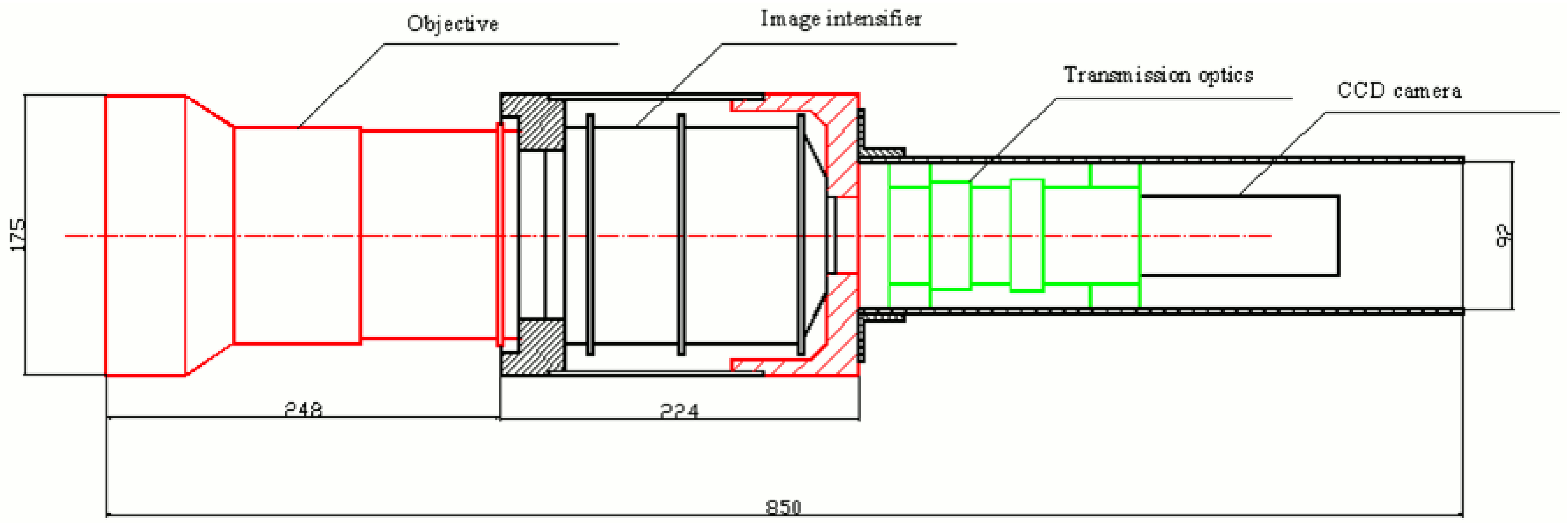
# FAVOR & TORTORA systems: overview


**TORTORA - Telescopio Ottimizzato per la Ricerca dei Transienti Ottici Rapidi**

Two-telescope complex:
- independent detection
- automatic study

La-Silla, Chile
mounted on REM
since 2006
Team: SAO RAS, IPI, Bologna University, REM

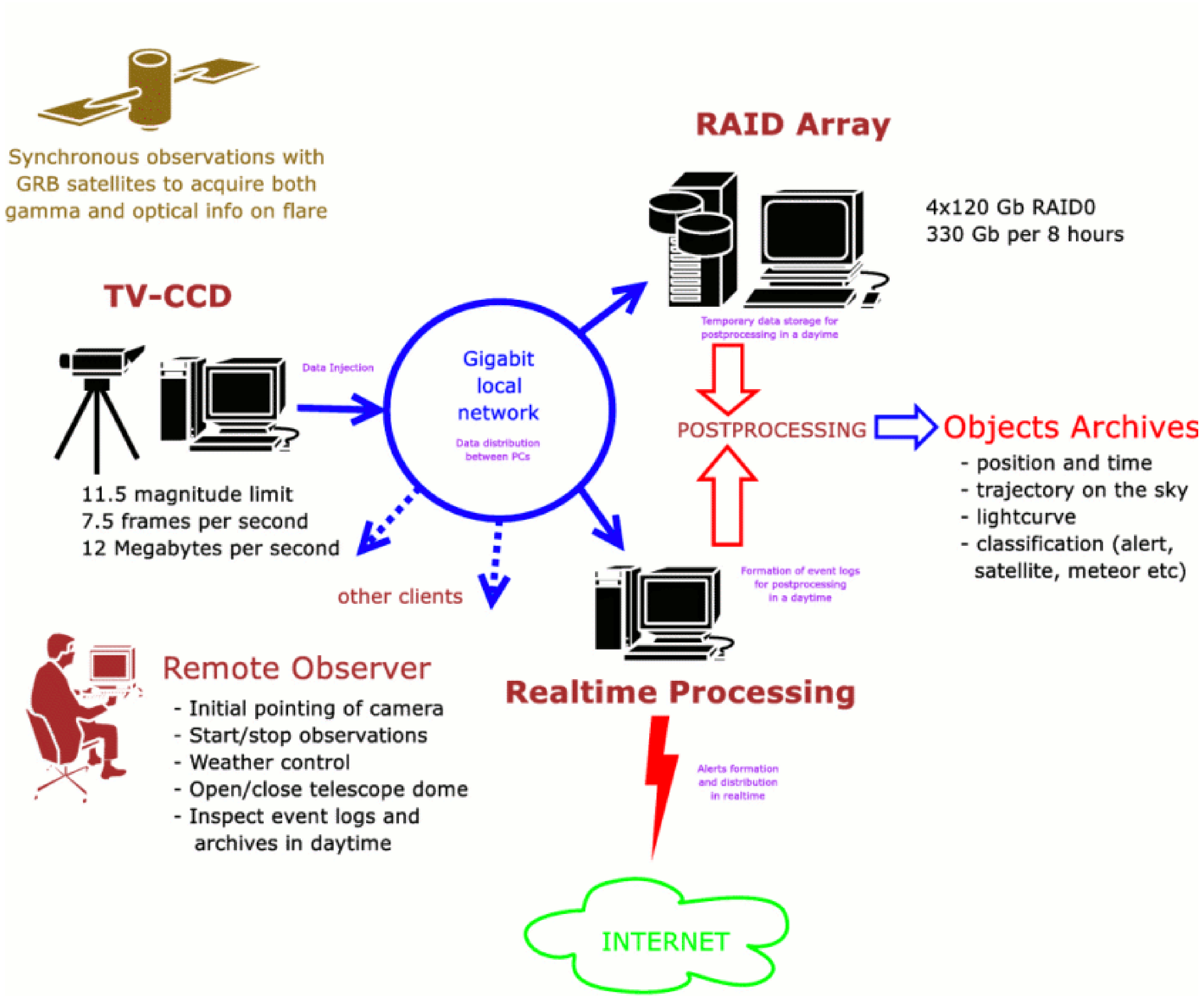
# FAVOR & TORTORA systems: technical details




| Objective | | Image Intensifier | | CCD | |
|---|---|---|---|---|---|
| Diameter: | 150 mm | type: | S20 | type: | SONY 2/3" IXL285 |
| Focal length: | 180 mm | diameter: | 90 mm | size: | 1388x1036 |
| D/F: | 1/1.2 | amplification: | 120 | exposures: | 0.128 — 10 sec |
| Field of view: | 17x24° | downscale: | 4.5/1 | scale: | 50''/pixel |
| | | Q.E.: | 10% | limit: | ~11.5$^m$ for 0.13c |

Data flow rate — 20 Mb/s, per night— 600 Gb, ~200.000 frames

# Real-Time Data Processing: overview



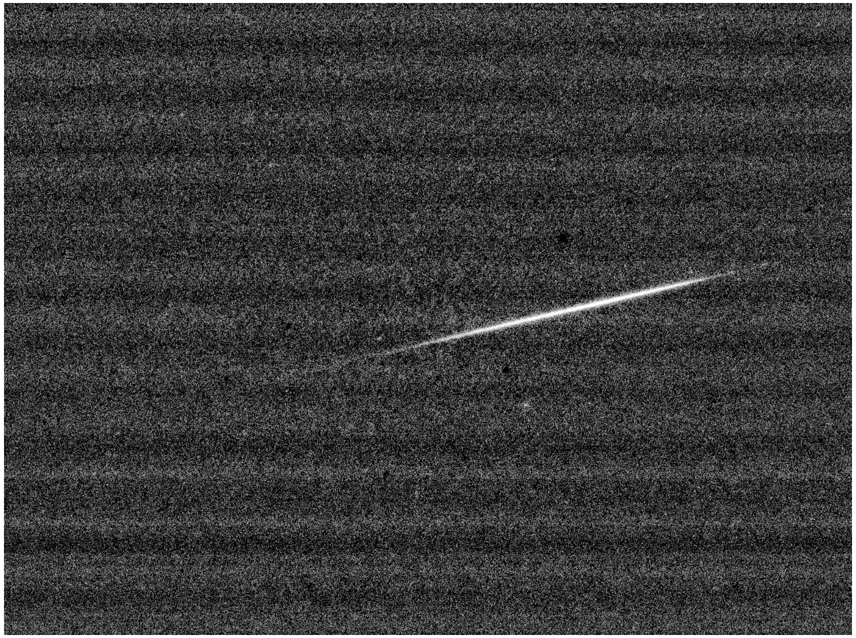
# Real-Time Data Processing: overview

- Data flow rate is **20.5 Mb/s** = 160 megabit/s
- 7.5 frames per second, 1388x1036 pixels each
- **Single frame processing is ten times slower!**
  - **object detection / SExtractor - ~0.5 s**
  - **PSF photometry of ~1000 objects - ~0.5 s**
  - **Classification of ~1000 objects - ~0.3 s**
- **Solution**
  - **differential imaging for real-time detection and classification of transients**
  - complete data storage for at least one day
  - **detailed post-factum study of selected interesting events**

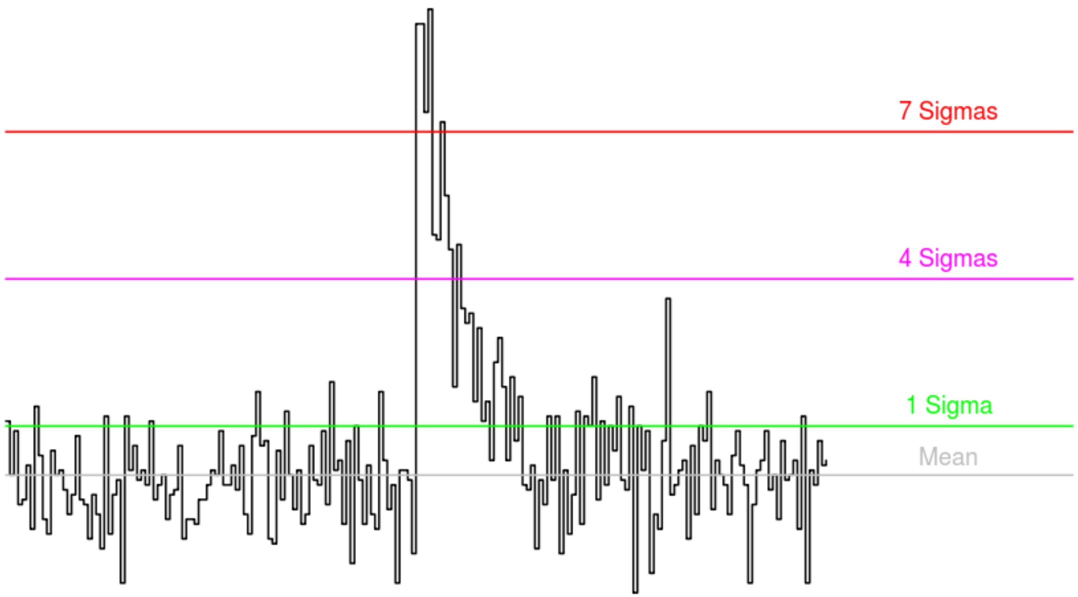
# Real-Time Data Processing: differential imaging

**mean value subtraction**

**dispersion normalization**



# Real-Time Data Processing: differential imaging




Differential thresholding in each pixel with running estimates of background mean level and dispersion

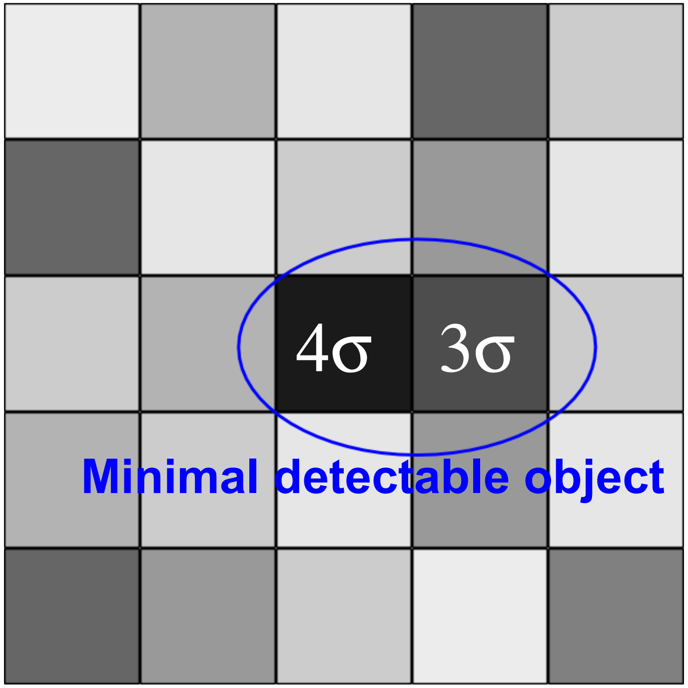
100 frames is an optimal length of estimation window

**Fast clustering** — extraction of extended connected regions above the threshold

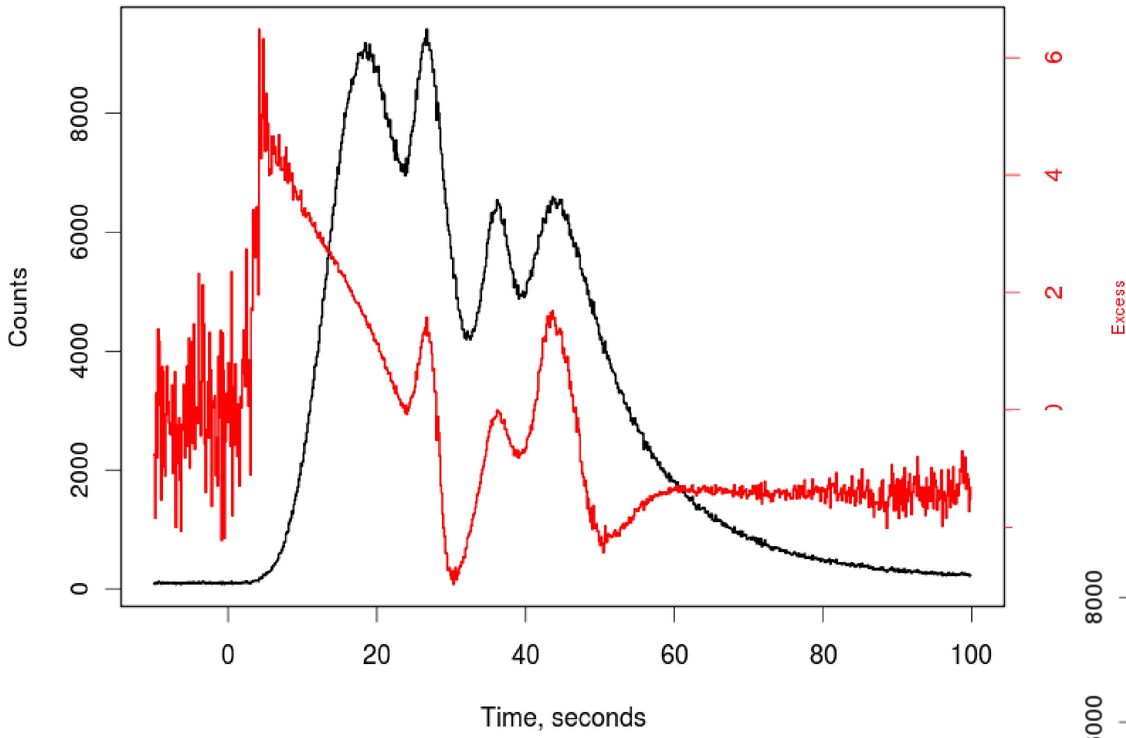
**7σ** — minimal detectable flux
$10.5^m$ - $11.5^m$ for FAVOR
$9.5^m$ - $10.5^m$ for TORTORA

**0.5 *false* objects per frame** (2 - 4 in real work)

**Non-ergodic behaviour - spatial and temporal dispersions differ!**

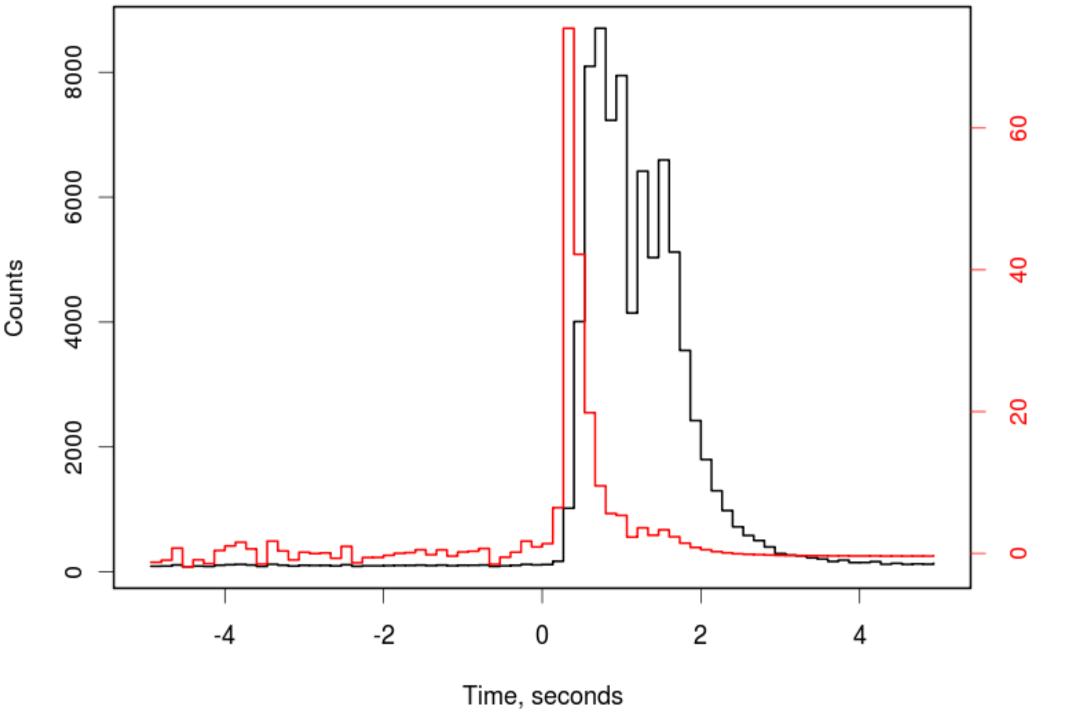


# Real-Time Data Processing: differential imaging




## Cons:

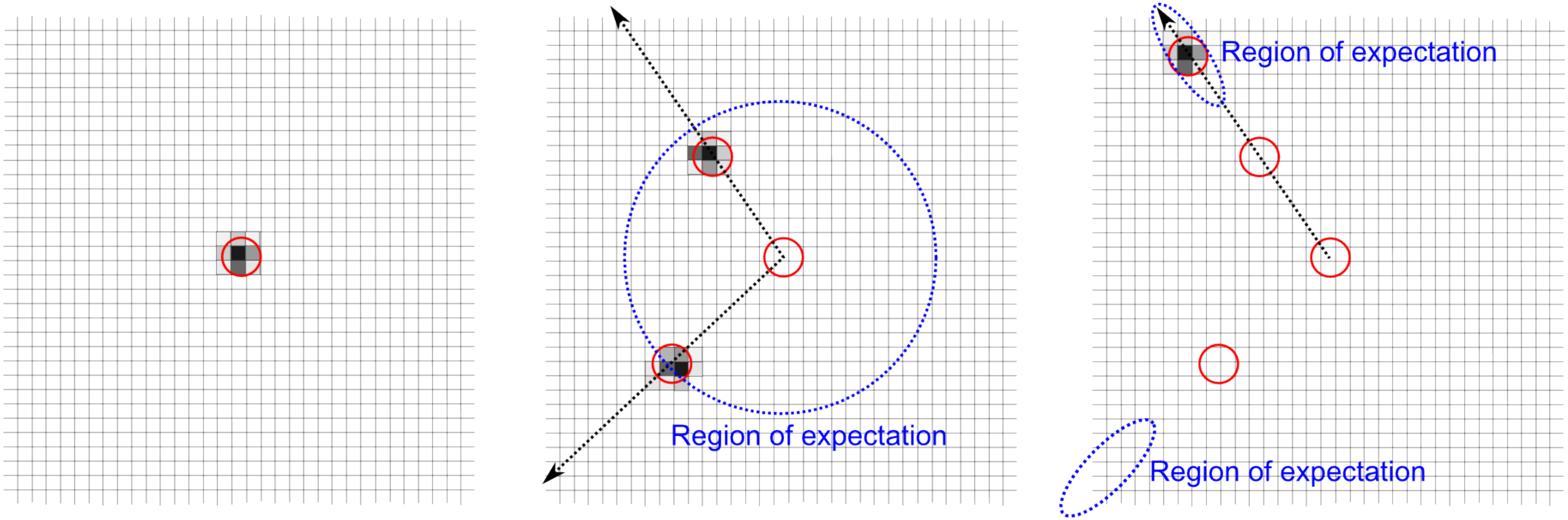
- ✘ Insensitive to slow transients
- ✘ Non-linear response — no accurate photometry by residuals only




## Pros:

- ✓ Ideal for short flashes or fast moving objects
- ✓ Filters long-term sky variability and fast star PSF fluctuations
- ✓ **Very fast! ~10ms** per frame

# Real-Time Data Processing: three stages of classification




Initial Detection

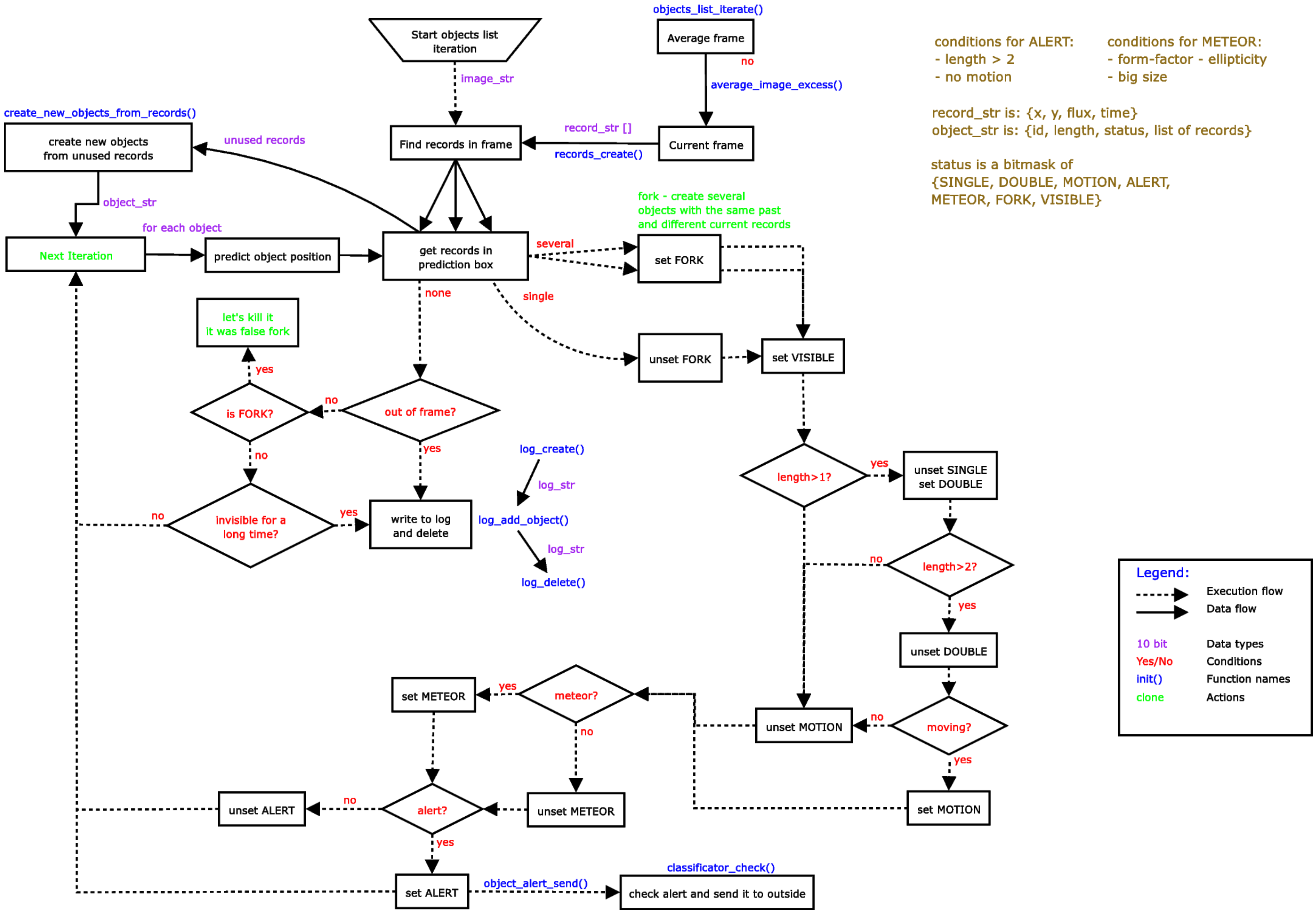
Hypotheses Testing

Motion Hypotheses Formulation

Motion direction and velocity can be estimated based on 3 frames — in 0.4 seconds

**Immobility is just an extreme kind of motion**

# Real-Time Data Processing: decision scheme




conditions for ALERT:
- length > 2
- no motion

conditions for METEOR:
- form-factor - ellipticity
- big size

record_str is: {x, y, flux, time}
object_str is: {id, length, status, list of records}

status is a bitmask of
{SINGLE, DOUBLE, MOTION, ALERT, METEOR, FORK, VISIBLE}

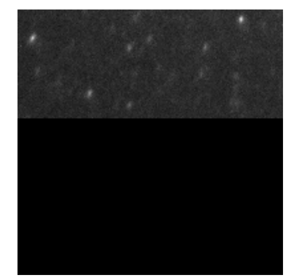
# Real-Time Data Processing: decision scheme

**Object we just detected**

**is elongated?** — yes → **METEOR**

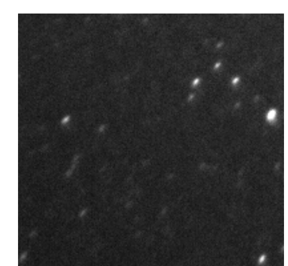

no ↓

**is moving?** — yes → **SATELLITE**



no ↓

**is in catalogues?** — yes → **KNOWN OBJECT**



no ↓

**NEW TRANSIENT**

**and all this is done in only 0.4 seconds**

# Real-Time Data Processing: meteors and satellites

- **~100 satellite passes per night**
  - **~20 transient-like flashes per night**
  - **2.5% of tracks are unidentified satellites!**
  - 50-500 points per one pass — good quality of the trajectories
- **~100 meteors per night**
  - typical duration of 1-3 frames
  - real-time detection and logging
  - day-time processing by dedicated software
    - **Hough transform** — determination of direction
    - **photometry along the track** — start/end, light curve

# Conclusions

- **Wide-field monitoring is inevitable for detecting fast optical transients of unknown localization**
  - GRBs, meteors, satellites, debris
- **High temporal resolution is necessary for short or fast moving events**
  - short bursts
  - **Naked-Eye Burst**
- **Data processing for such monitoring is easy**
  - detection and basic classification in 0.4 seconds
- **Selection of optimal hardware parameters is not so easy**
  - **simple and cheap, and not very efficient**
  - **complex and clever, and expensive**

**Look forward to the talk of Gregory Beskin on Thursday!**