Observations of transient events with Mini-MegaTORTORA

wide-field optical monitoring system

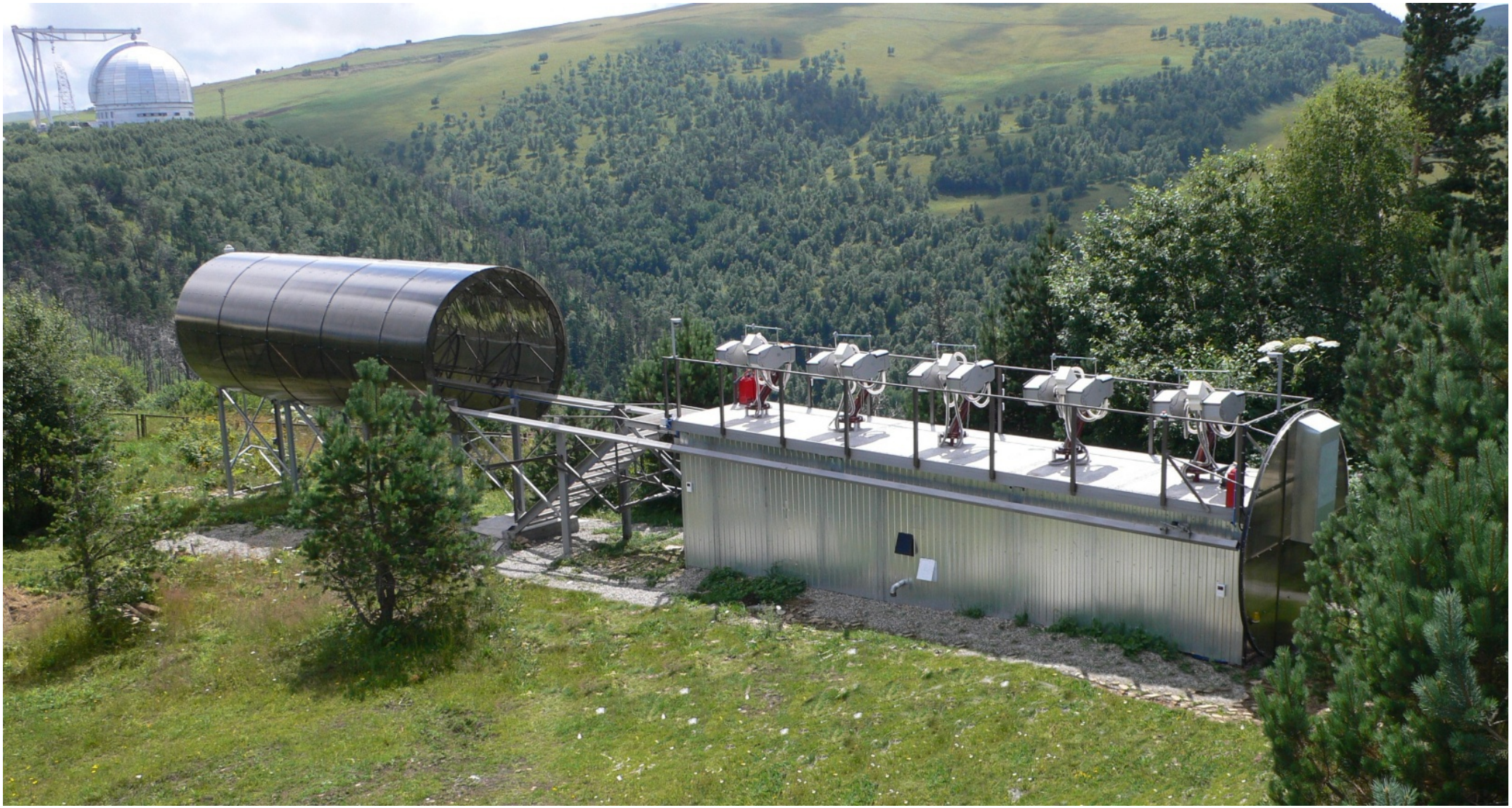
with

sub-second temporal resolution

Karpov, S.[1,4], Beskin G.[1,4], Biryukov A.[4,5], Bondar S.[2], Ivanov E.[2], Katkova E.[2], Perkov A.[2,4], Sasyuk V.[3,4]

[1] **SAO RAS**, [2] OJS RPC PSI, [3] “Parallax” Enterprise, [4] Kazan Federal University, [5] Moscow State University

Mini-MegaTORTORA

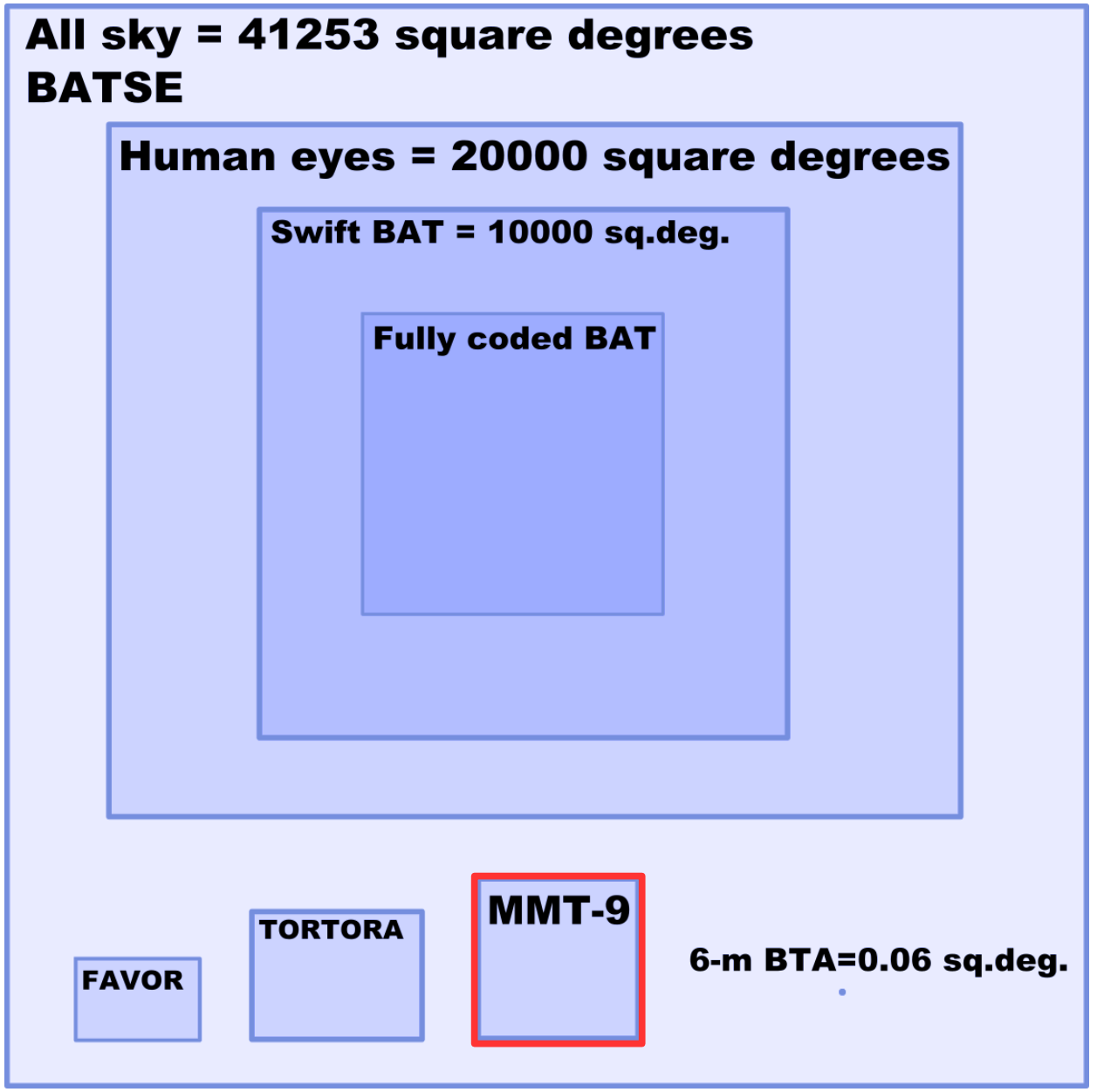


Operational since mid-2014, Russian Caucasus near 6-m telescope

Mini-MegaTORTORA

Operational since mid-2014, Russian Caucasus near 6-m telescope

Wide Field Monitoring with High Temporal Resolution



~900 sq.deg simultaneously

= **2%** of the sky

Survey the hemisphere in a night
+
Independent search for transient events

Transients on **sub-second timescale**:

- GRBs
- Fast Radio Bursts
- SN shock break-out (?)
- Neutrino and GW events (?)

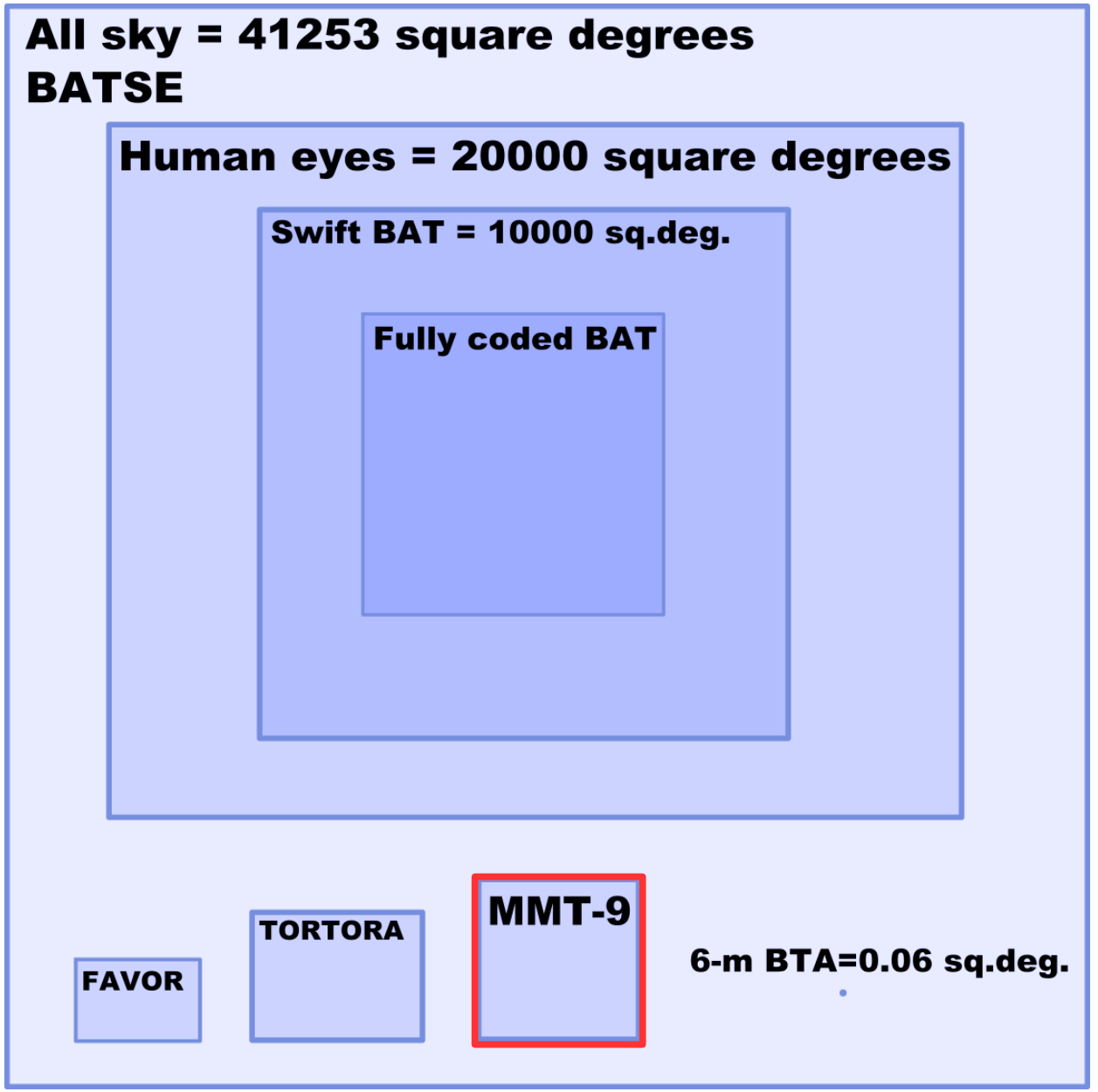
- Flaring Stars

- Meteors
- Artificial Satellites
- ???

Wide field of view allows for independent detection of rapid transients

MMT

Wide Field Monitoring with High Temporal Resolution



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- **Artificial Satellites**
- **???**

Wide field of view allows for independent detection of rapid transients

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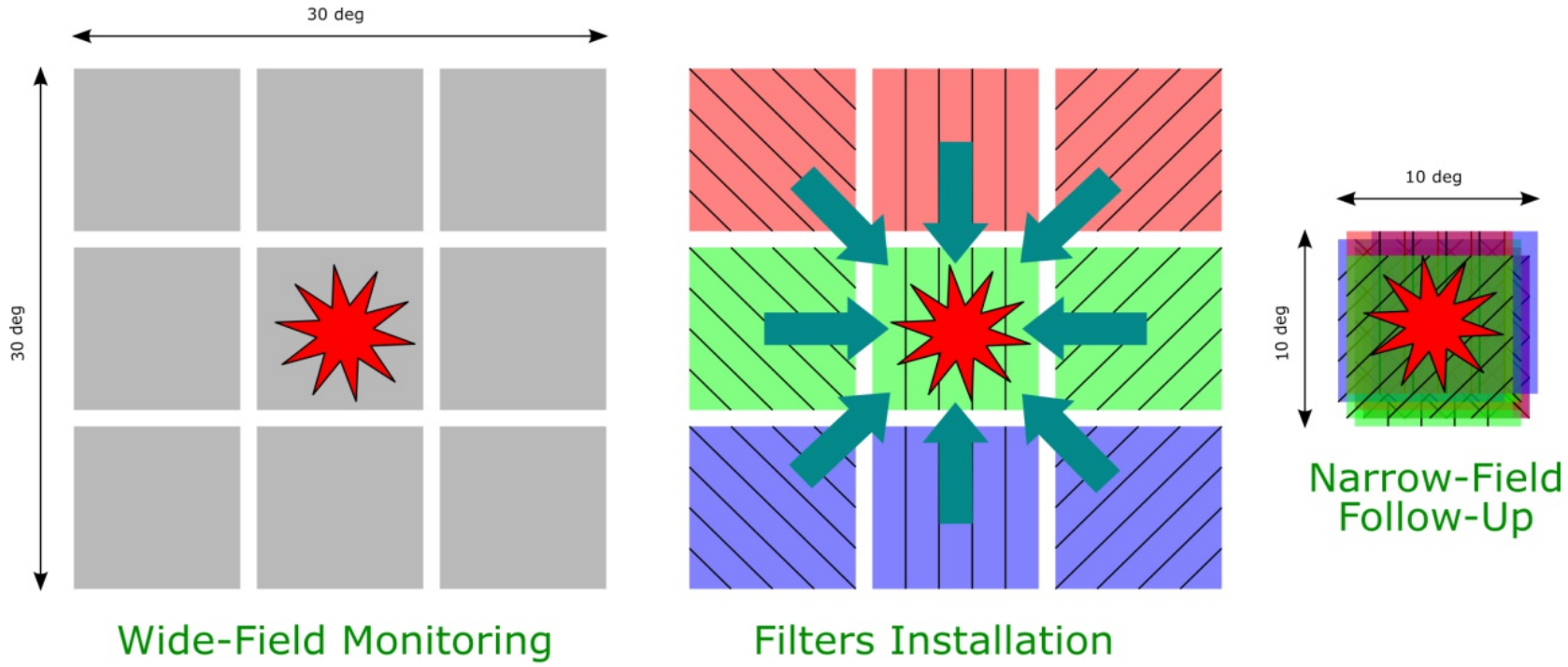
… + follow-up + multi-regime



Follow-up observations are essential part of any sky survey!

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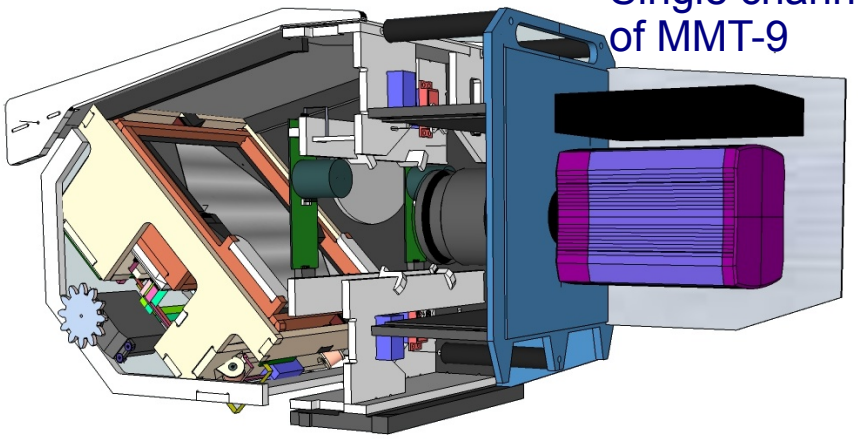
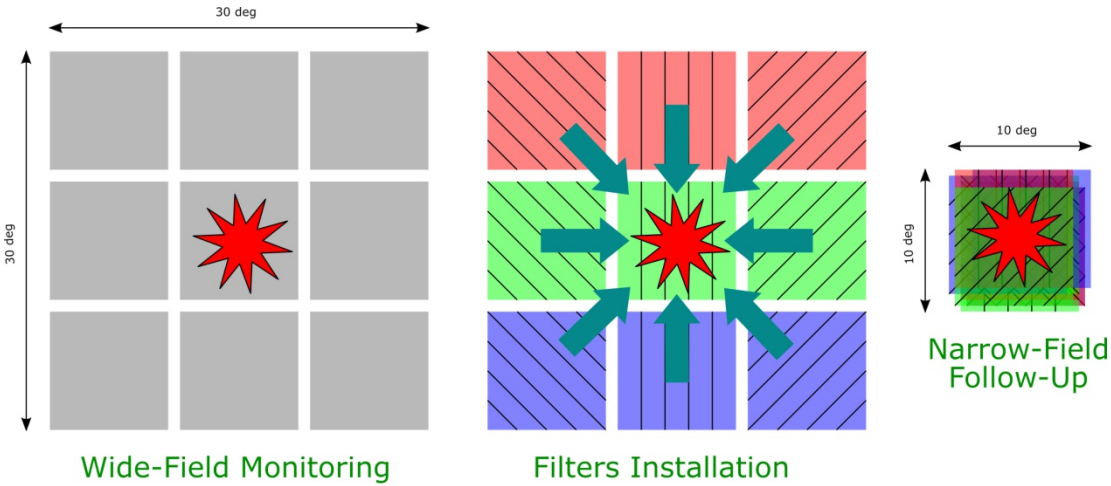
Mini-MegaTORTORA

- **Multichannel system**
  - 9 channels in MMT-9
  - 100 sq.deg. per channel, 900 sq.deg. total
  - ~16” / pixel, ~2 pixels PSF
  - Coelostate mirrors for rapid repointing
- **Sub-second temporal resolution**
  - 10 frames per second, down to V~11 mag
- **Independent transient detection**
  - Real-time data analysis pipeline
- **Independent follow-up of transients**
  - 9 channels = 3 colors x 3 polarizations
  - Photometry / polarimetry / ???
  - All that in a ~ seconds after detection
- **Fully automatic operation**
- **In operation since Jun 2014**
  - MMT-9 near Russian 6-m telescope

Single channel of MMT-9

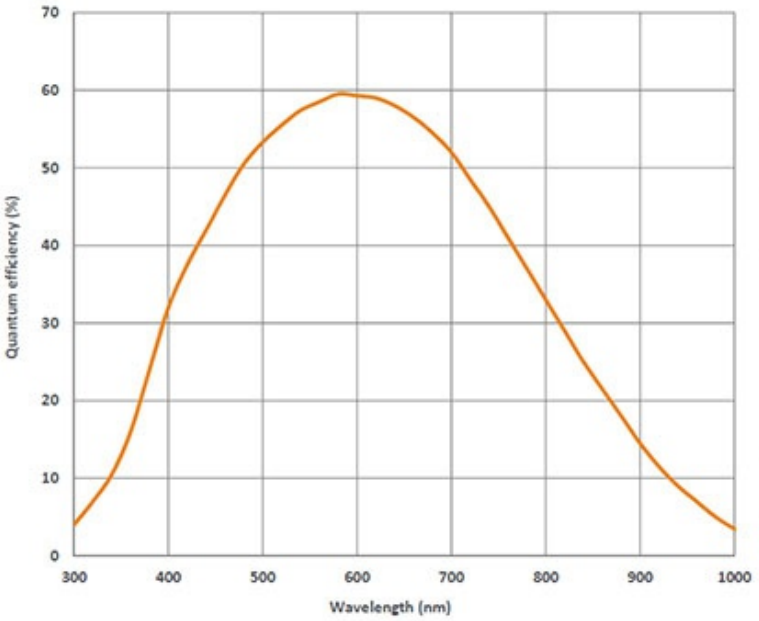


•Canon EF85 F/1.2, D=70mm
•Andor NEO sCMOS, 2560x2160 pix



Rapid follow-up in 2-3 seconds

Andor Neo sCMOS

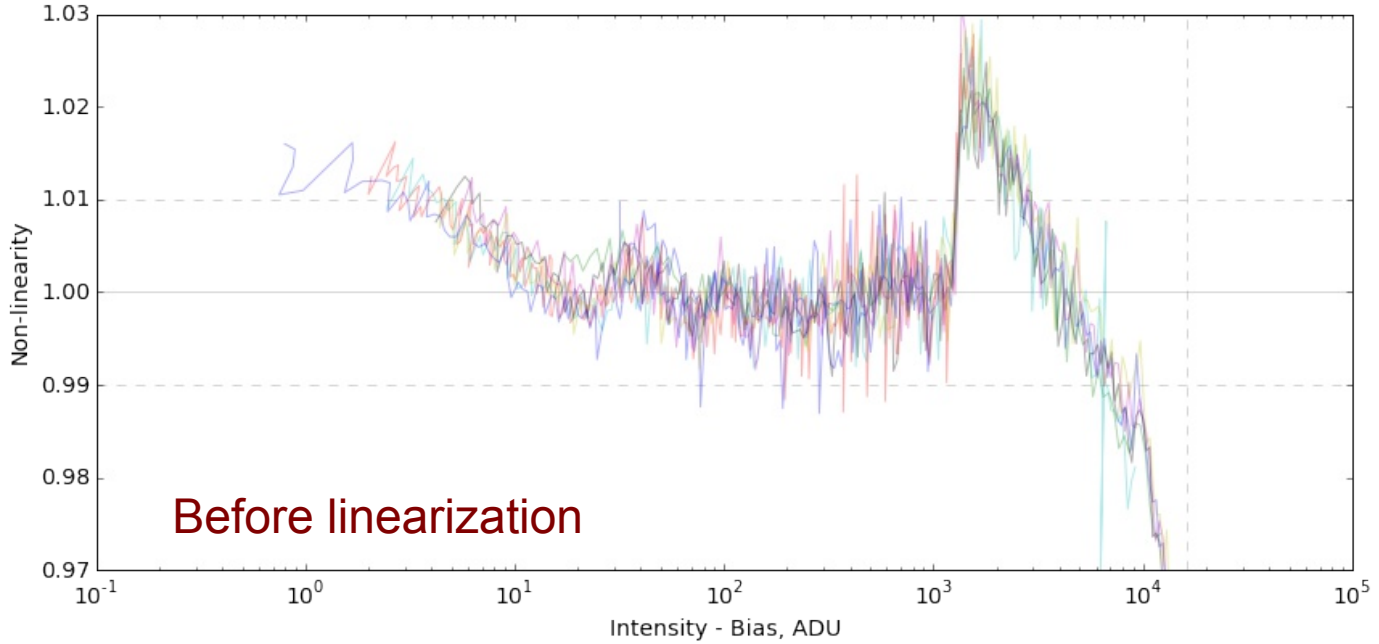


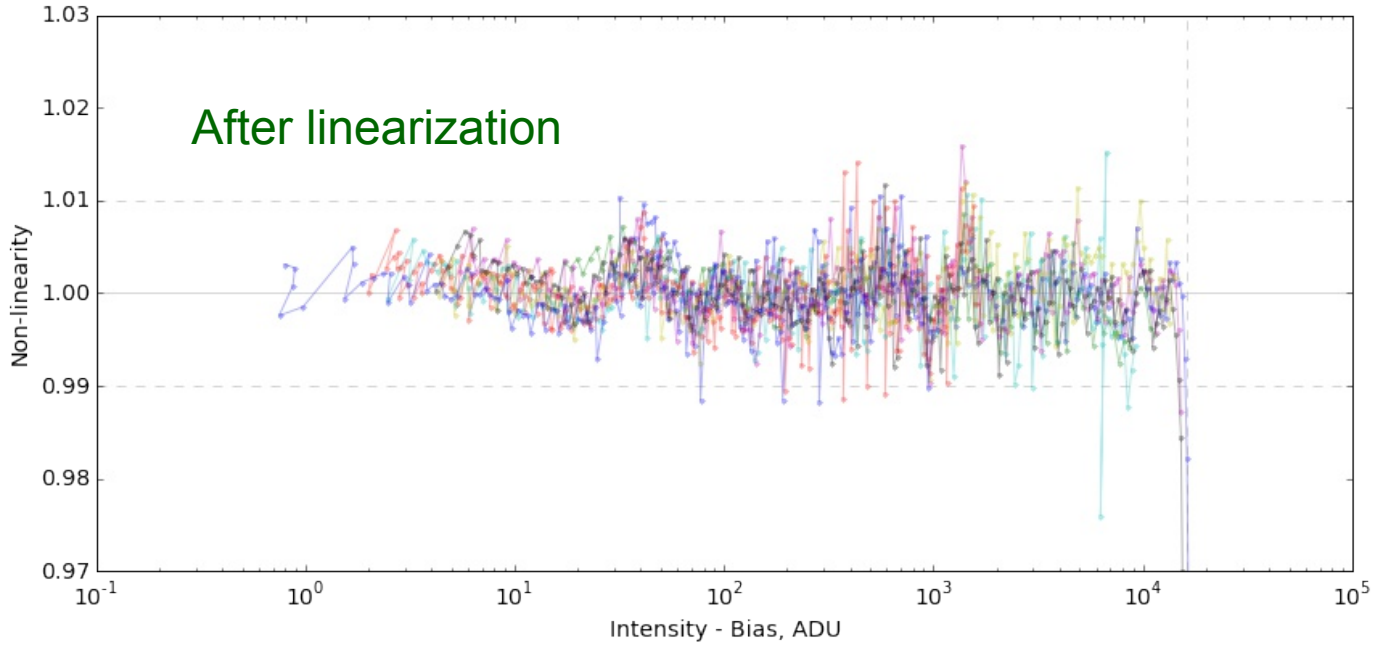
Key Specifications		
Sensor Type	Front Illuminated Scientific CMOS	
Active Pixels	2560 x 2160 (5.5 Megapixel)	
Sensor Size	16.6 x 14.0 mm (21.8 mm diagonal)	
Pixel readout rate (MHz)	560 (280 MHz x 2 sensor halves) 200 (100 MHz x 2 sensor halves)	
Read Noise (e-) 200 MHz 560 MHz	Rolling Shutter 1 1.3	Global Shutter 2.3 2.5
Minimum temperature air cooled Minimum temperature coolant	-30 °C -40 °C	
Dark current, e-/pixel/sec @ -30°C @ -40°C	 0.015 0.007	
Data range	12 bit & 16 bit	
Peak Quantum Efficiency	60%	
Readout modes	Rolling Shutter and Global (Snapshot) Shutter	
Internal memory buffer size	4 GB	
Maximum burst frame rates 2560 x 2160 (full frame) 128 x 128 ROI	 100 fps Rolling Shutter, 49 fps Global (Snapshot) Shutter 1,639 fps Rolling Shutter, 716 fps Global (Snapshot) Shutter	
Pixel well depth (e-)	30,000	

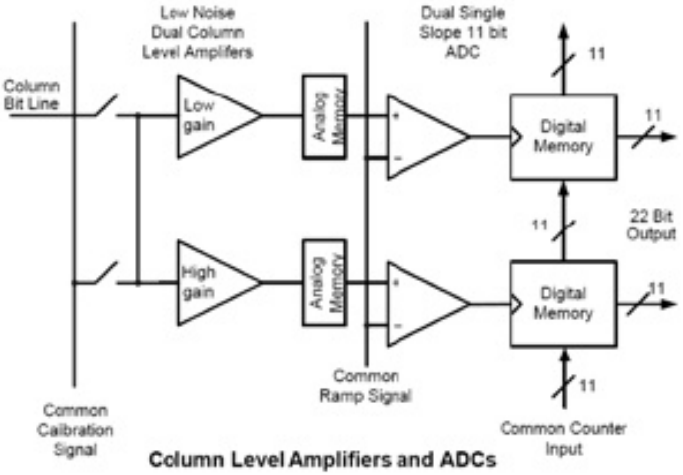
Dual-amplifier ADC = non-linearity!

MMT

Andor Neo sCMOS – non-linearity





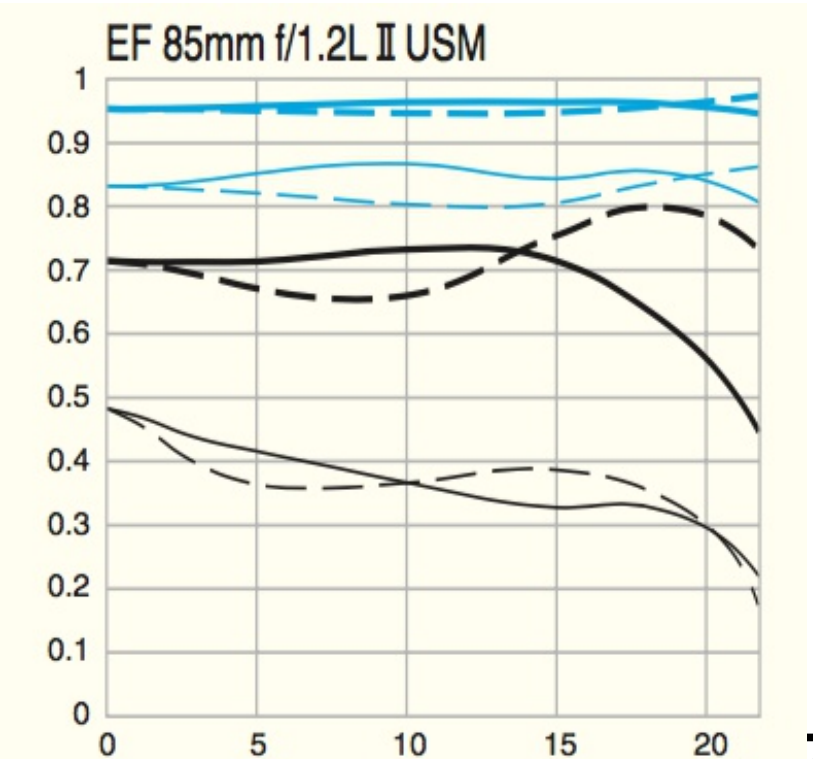


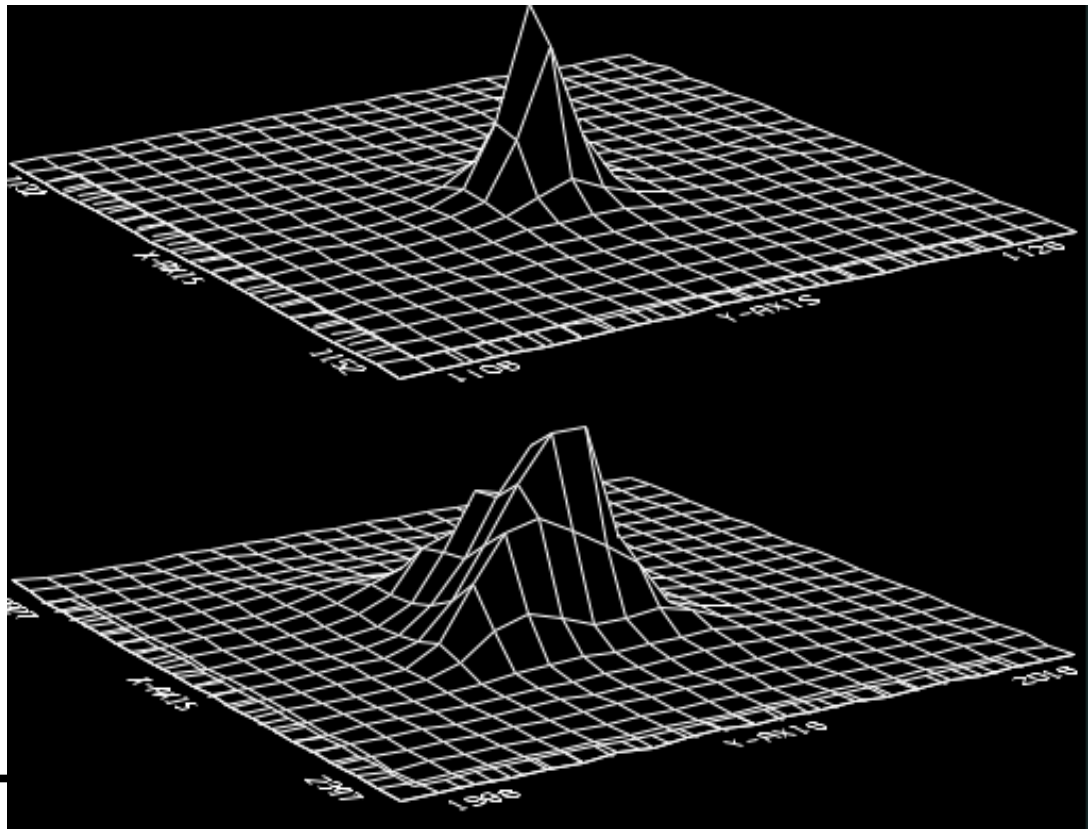
Pixel response is **non-linear over whole dynamic range** due to ADC architecture (two amplifirs with non-linear response each)

Piece-wise polynomials with per-pixel coefficients to "linearize"

Canon EF85 f/1.2

- 8.5 cm focal length
- 7 cm diameter
- Image quality is so-so
- Proprietary focus control – reverse engineered





Mounts

Skywatcher NEQ6 Pro

- tripod
- handheld controller

+ custom pillar
+ eqdirect PC connector + custom software

~5 deg/s slewing

PE ~ 5-10 arcsec
+ jumps
+ misalignment

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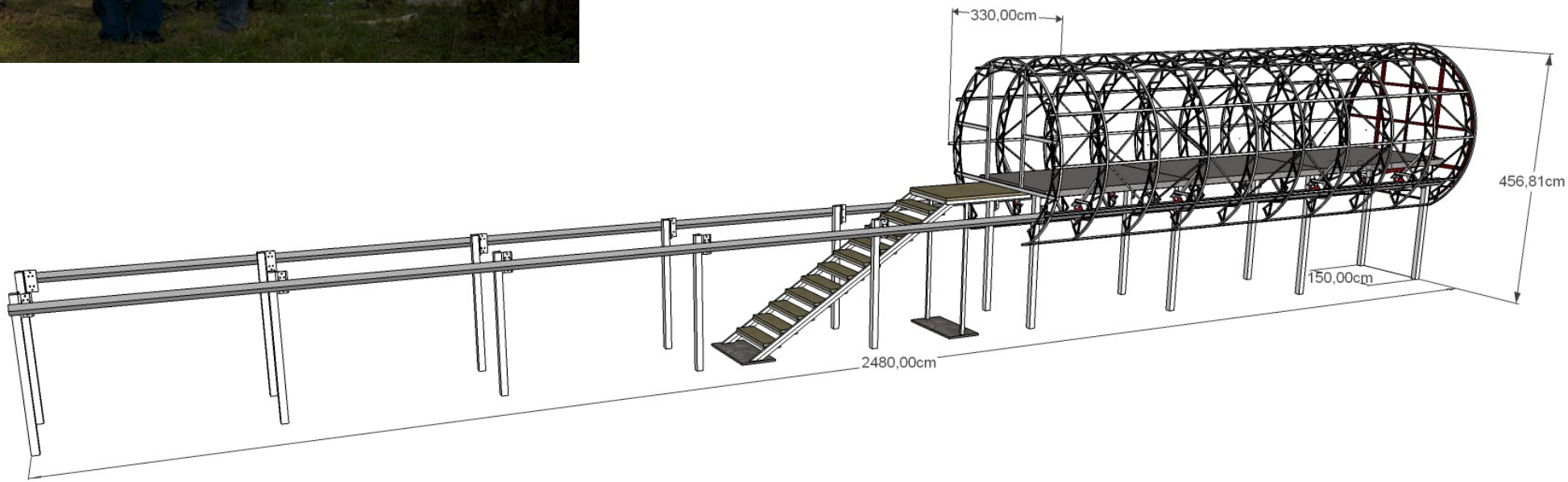
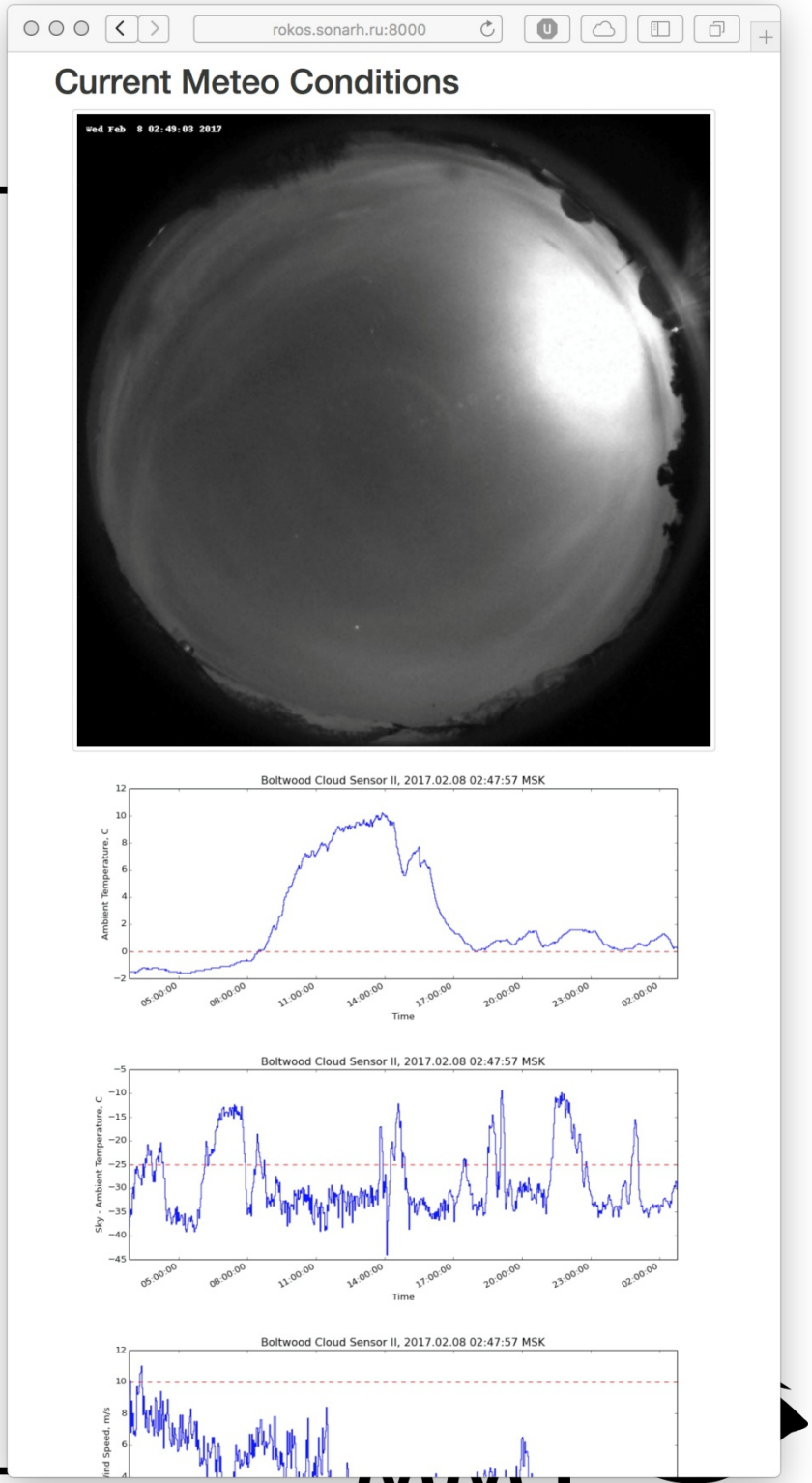
Dome



Meteo Station

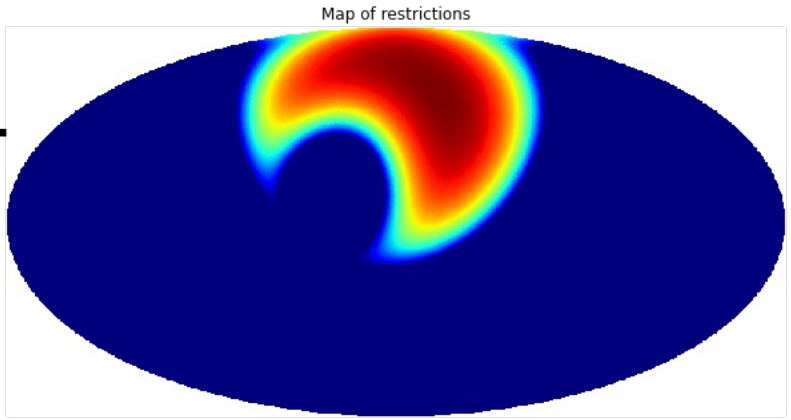
Boltwood Could Sensor II
+
All-Sky Camera
+
Sky Quality Meter

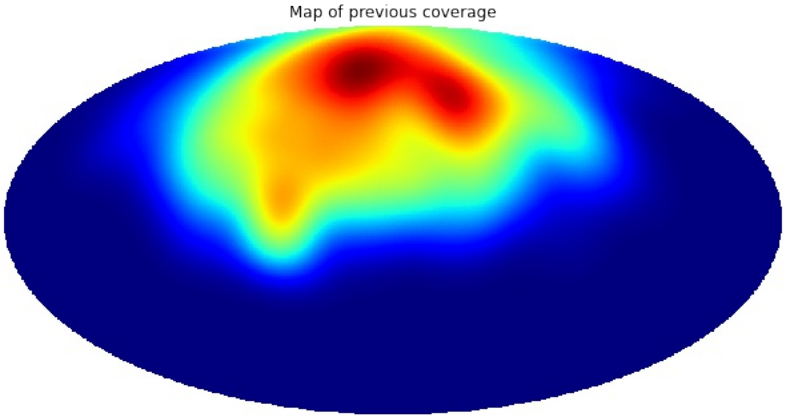
Temperature
Sky Temperature (clouds!)
Wind Speed
Humidity
Rain
Sky Brightness

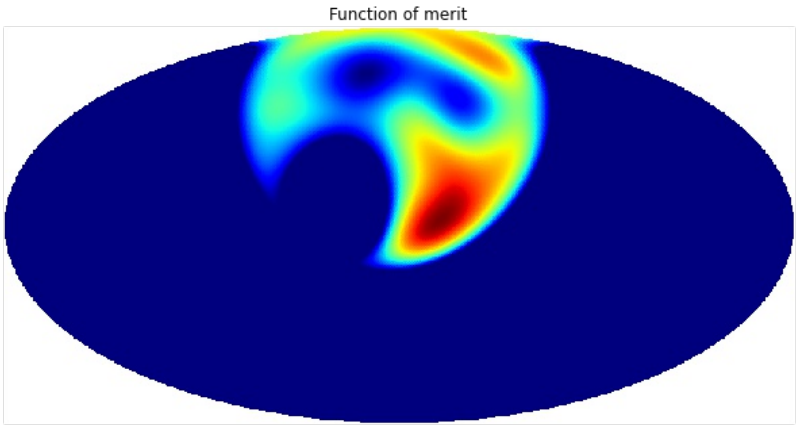


Scheduler

- Sky Survey
  - weighting by distances from the zenith, Sun, Moon
  - weighting by previous sky coverage
  - additional weights to Swift and Fermi FOVs
  - High-resolution monitoring for ~1000 s on each field
  - Long exposure “deep” imaging before and after
  - Rapid multi-mode follow-up for detected transients
- Targeted observations
  - User-provided objects
    - Wide-field or narrow-field, monitoring or imaging
  - **External triggers**
    - Swift in multi-mode narrow-field regime
    - Fermi in wide-field imaging regime
    - LIGO-Virgo in wide-field imaging regime

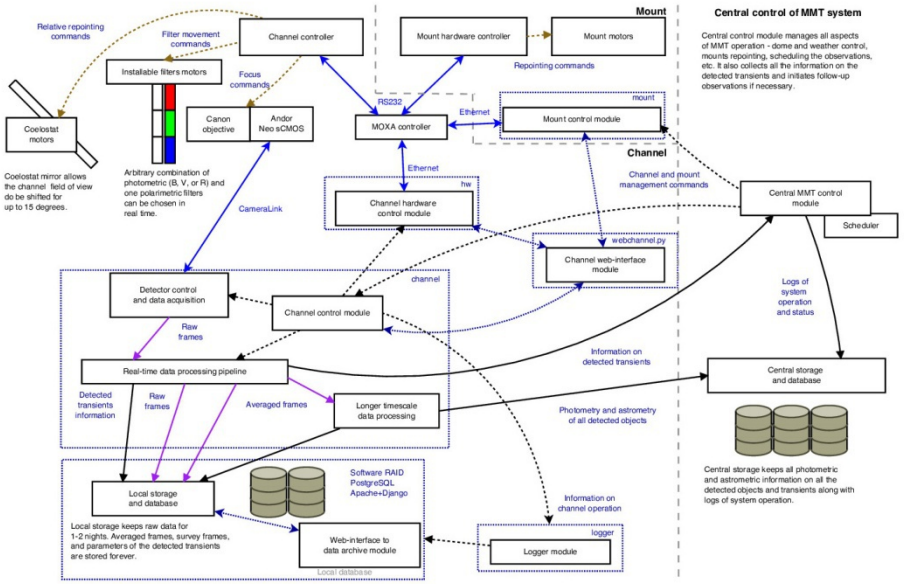






Control System

- **Distributed system**
  - Central controller
    - C code + LUA scripting
  - Channels
    - C code + LUA scripting
  - Mounts
  - Scheduler
  - GCN client
  - Dome
  - Weather station
- **Behaviour programmed in LUA**
  - Fast embedded programming language
  - rFSM Statecharts state machine
    - Opening/closing the dome
    - Starting/stopping the night schedule
    - Autofocusing, darks, flats, …
    - Coordinating the channels, mounts, etc
    - Governing the whole night operation
    - Looking for weather changes or errors
- **Controlled through the Web interface**

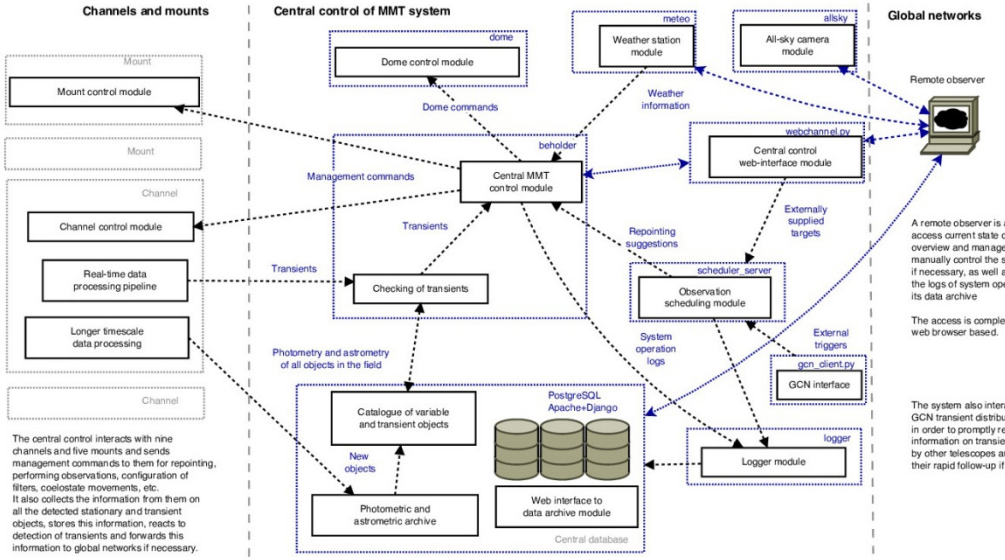


Lines of code:

C	~ 48000
Python	~ 17000
LUA	~ 7000

Database:
~600 Gb
39 tables

Storage:
9x9 Tb RAID0
47 Tb NAS



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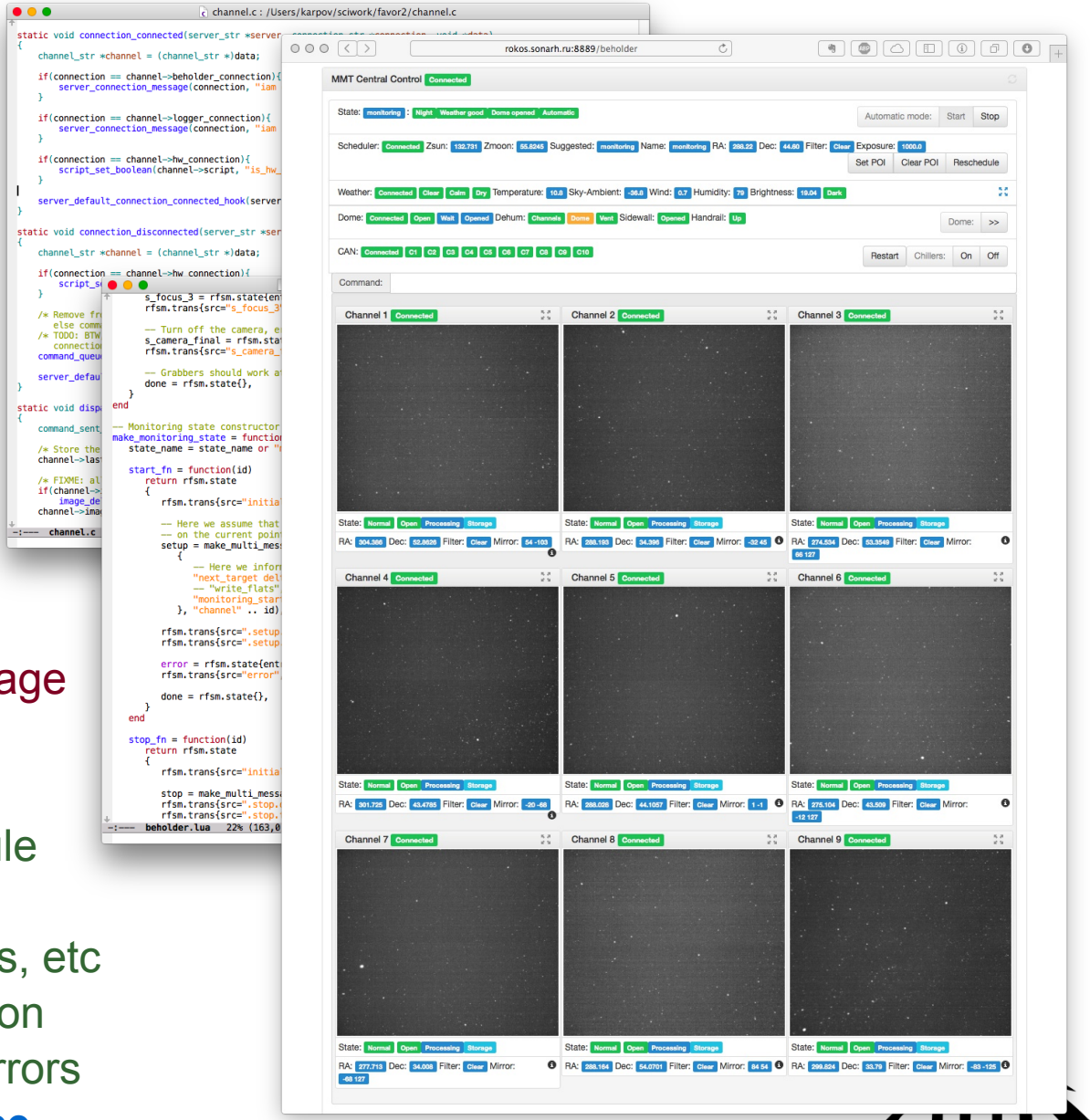
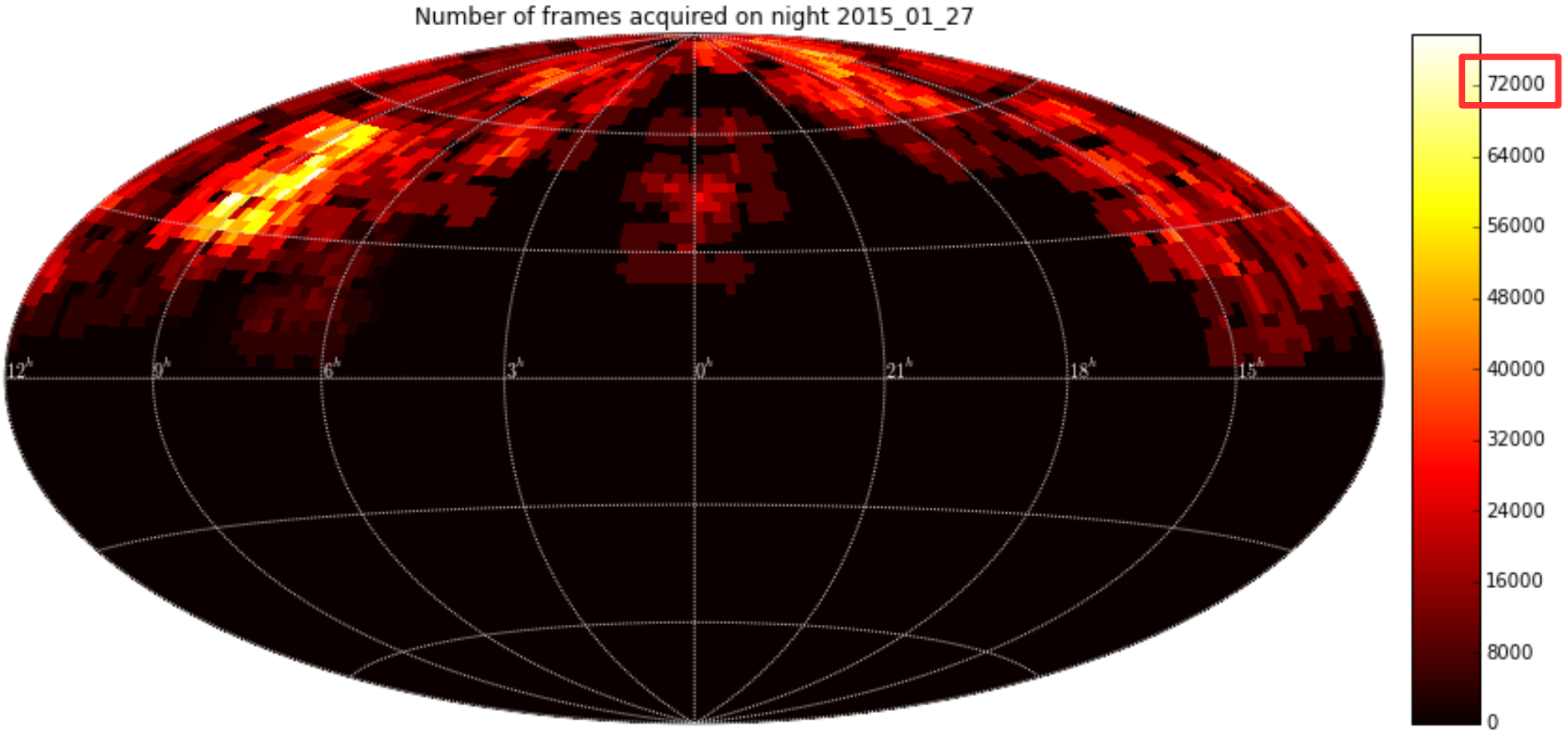


Wide-Field Monitoring

Systematic sky survey, ~1000 seconds per field
Uniform coverage of the hemisphere + restrictions + following Swift / Fermi FOVs
900 sq.deg. in white light or 300 sq.deg. in BVR
0.1 s exposure, limit about V~10.5

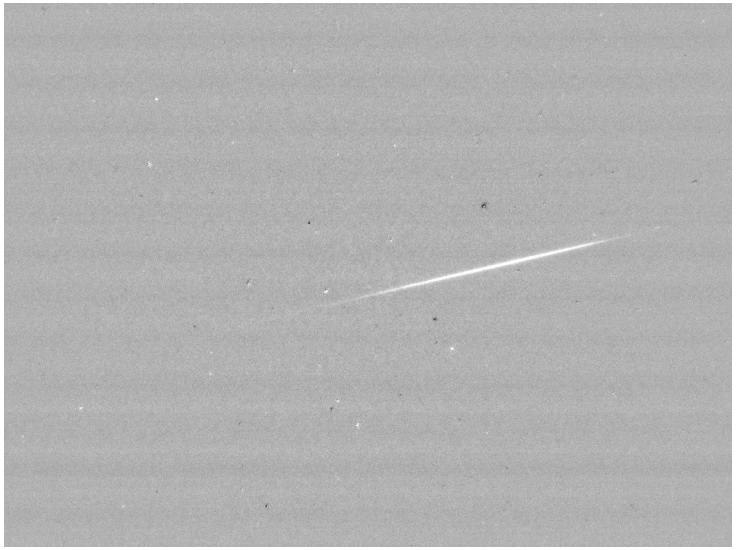


Data flow rate ~**110 Mb/s** per channel, **~30 Tb** per night
Everything processed on the fly, **~300 Gb** archived

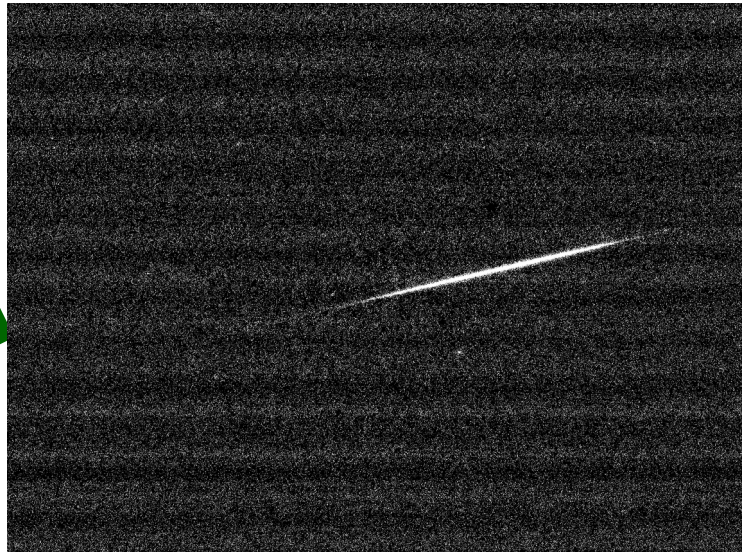
Fast Differential Imaging Pipeline

We got a new frame every 100 ms

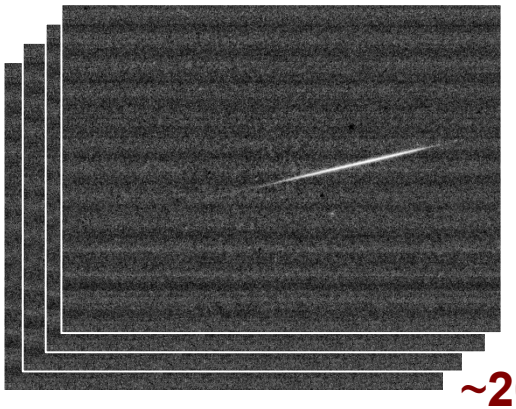
Subtracting the running median



Normalizing to Median Absolute Deviation



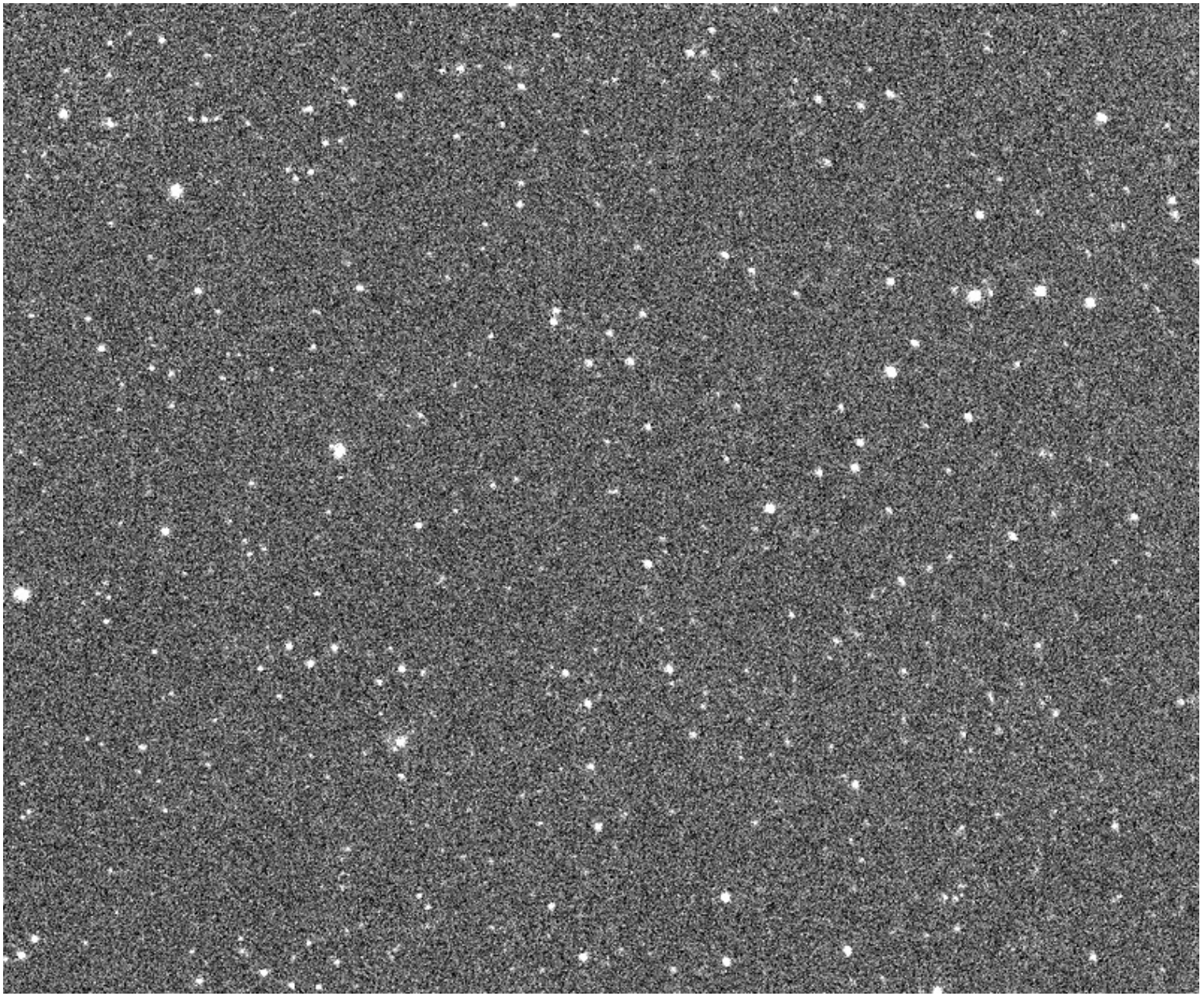
Extracting the objects and analyzing the sequence of frames



~20 ms for managing running median frame
~13 ms for extracting transient candidates from frame
~10 ms for analysing candidates and tracking objects

MMT

Sky in Real Time



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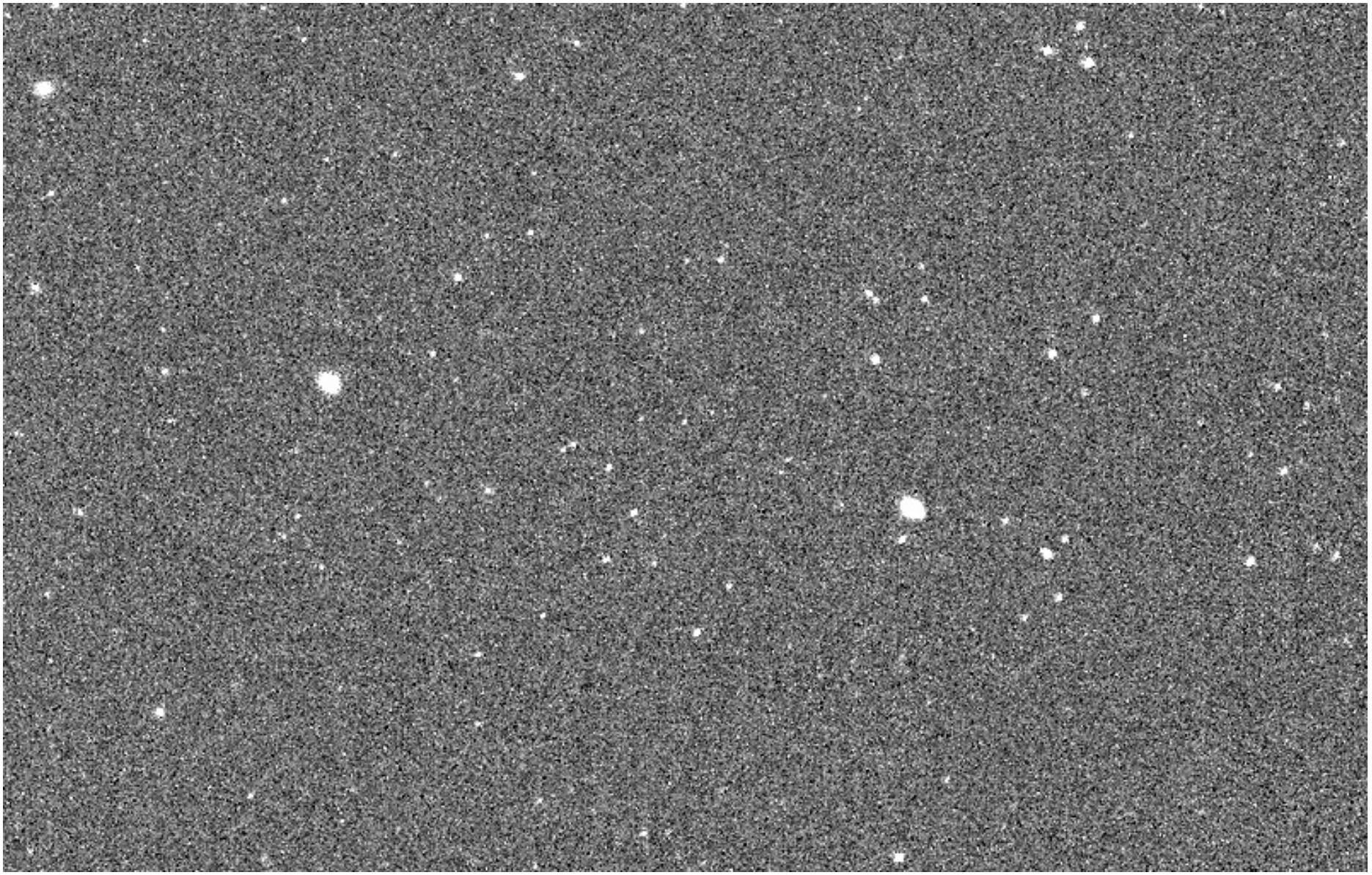

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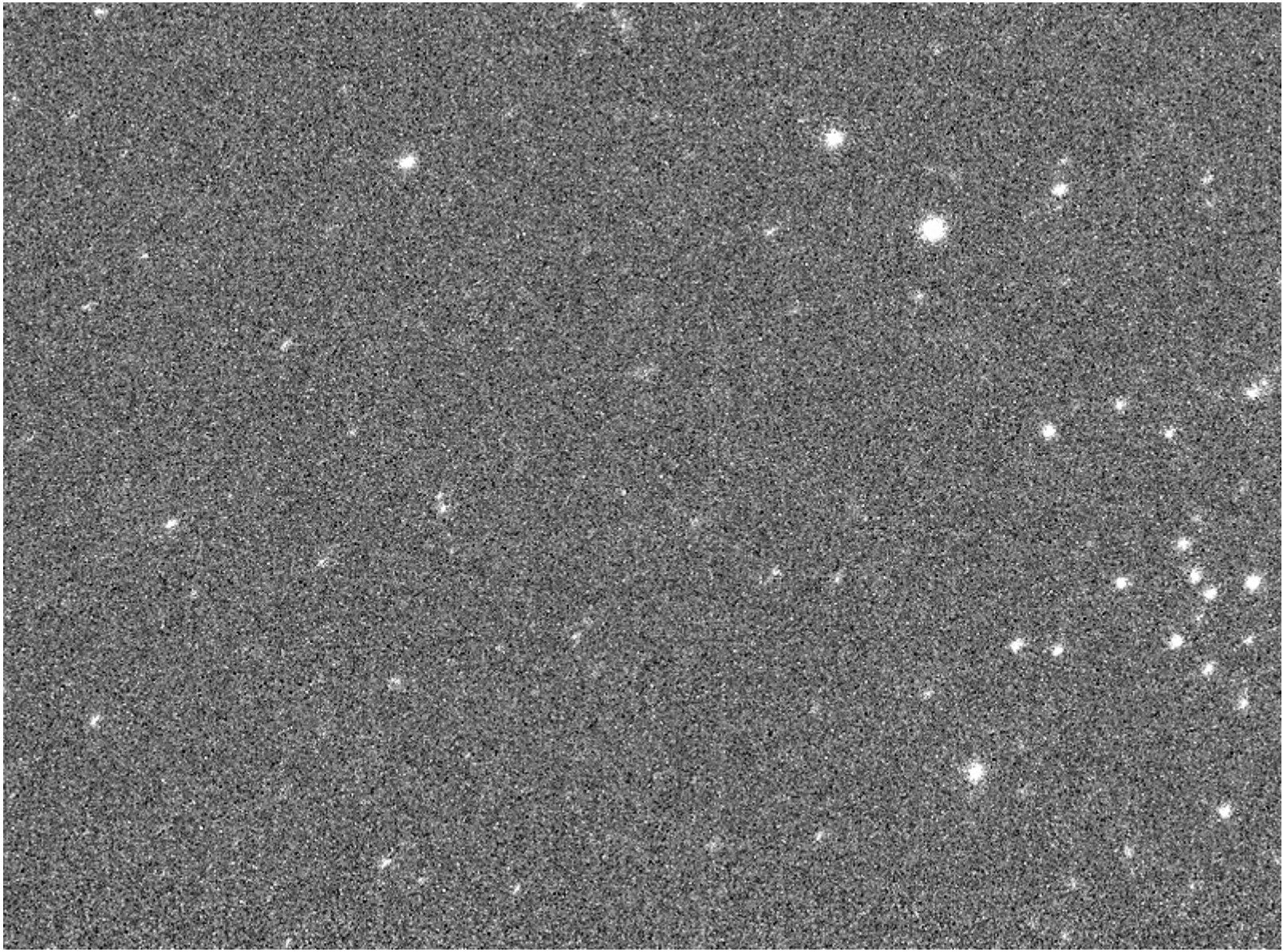

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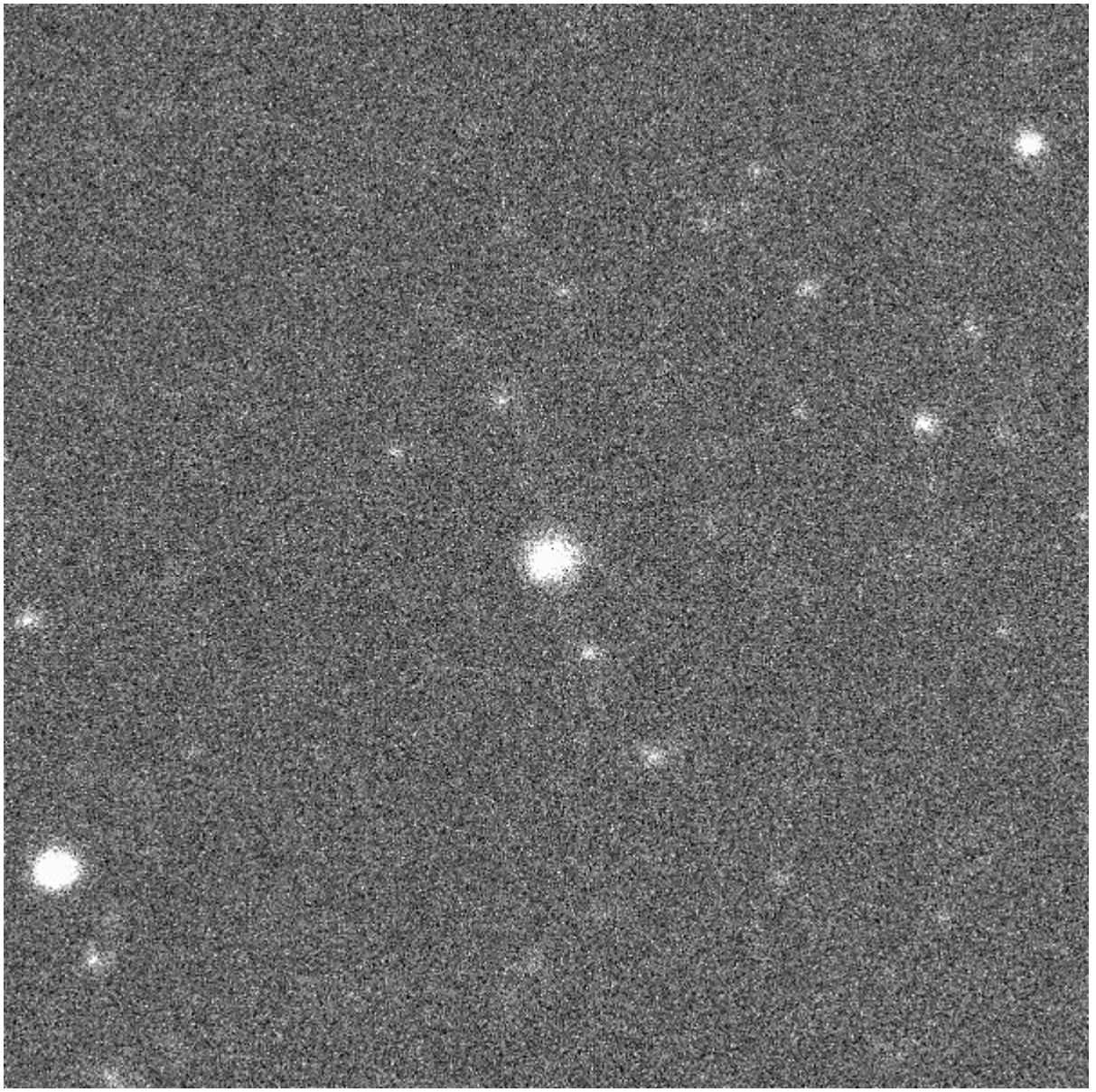

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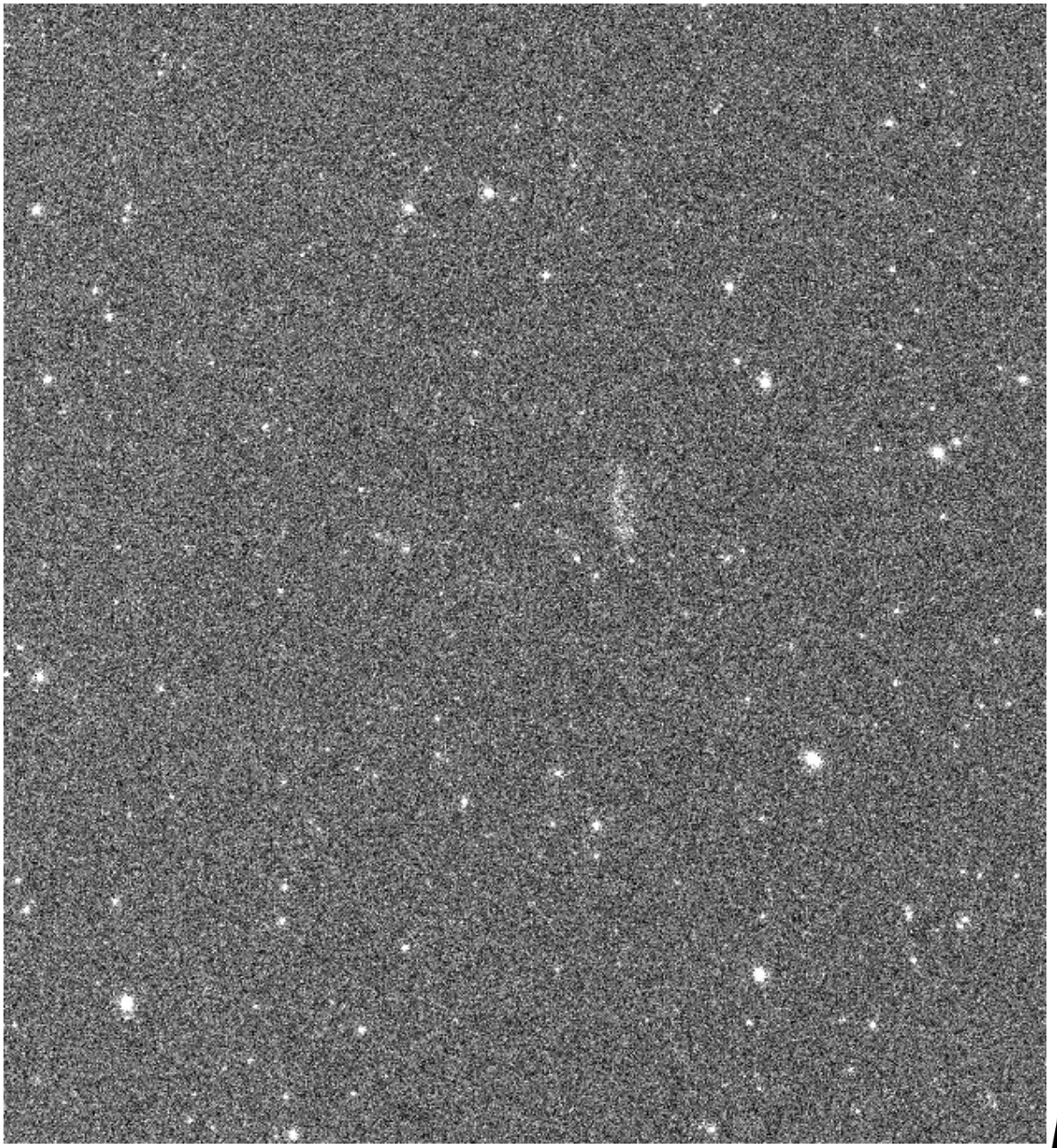
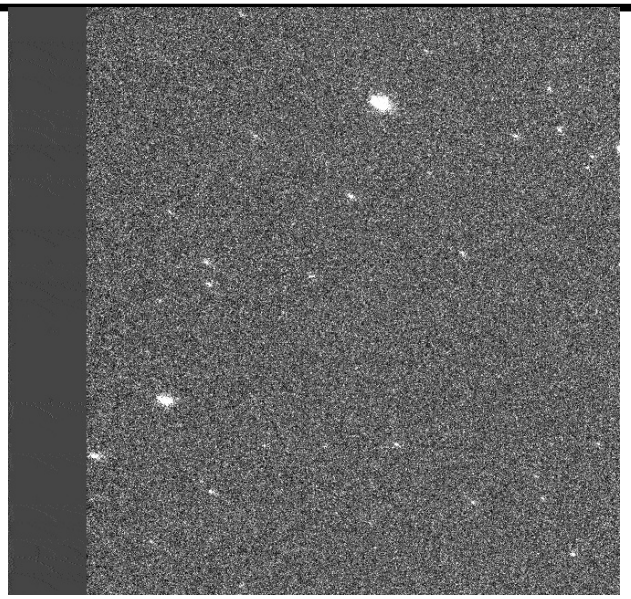
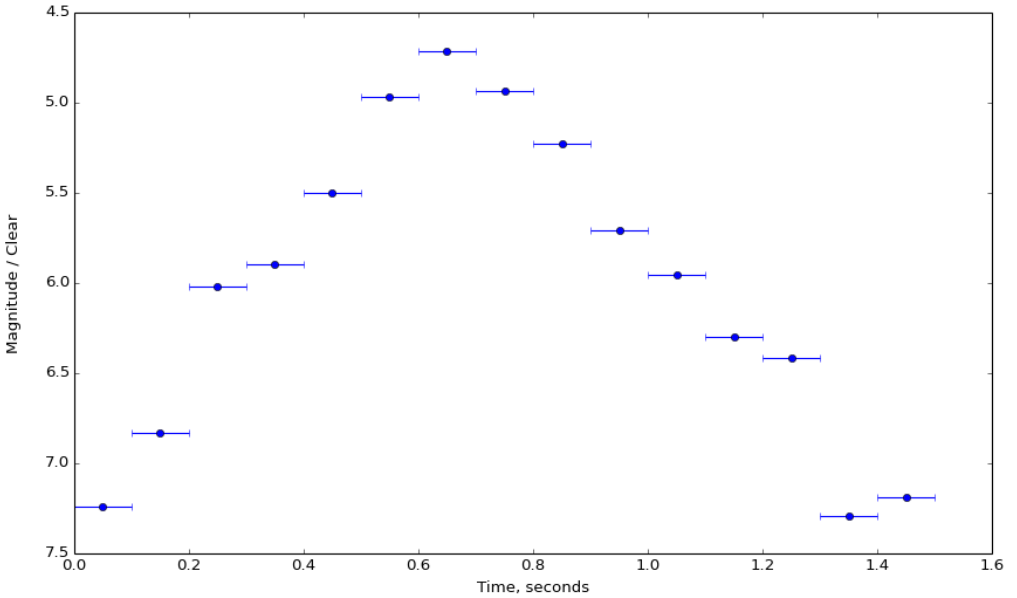
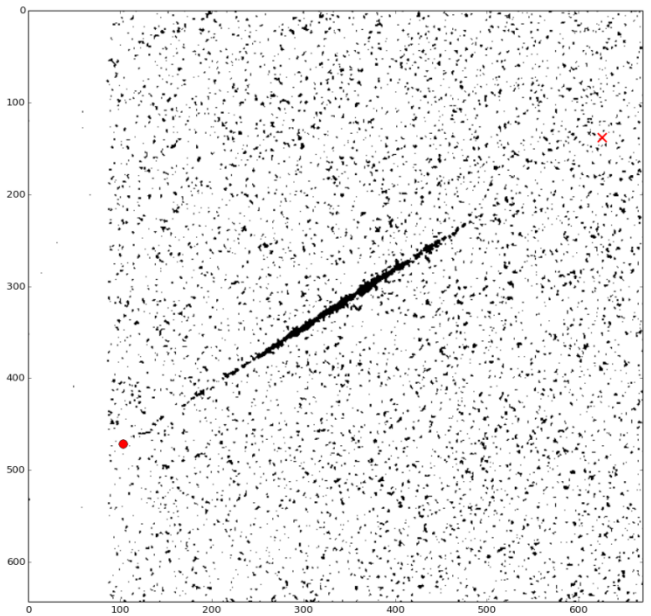


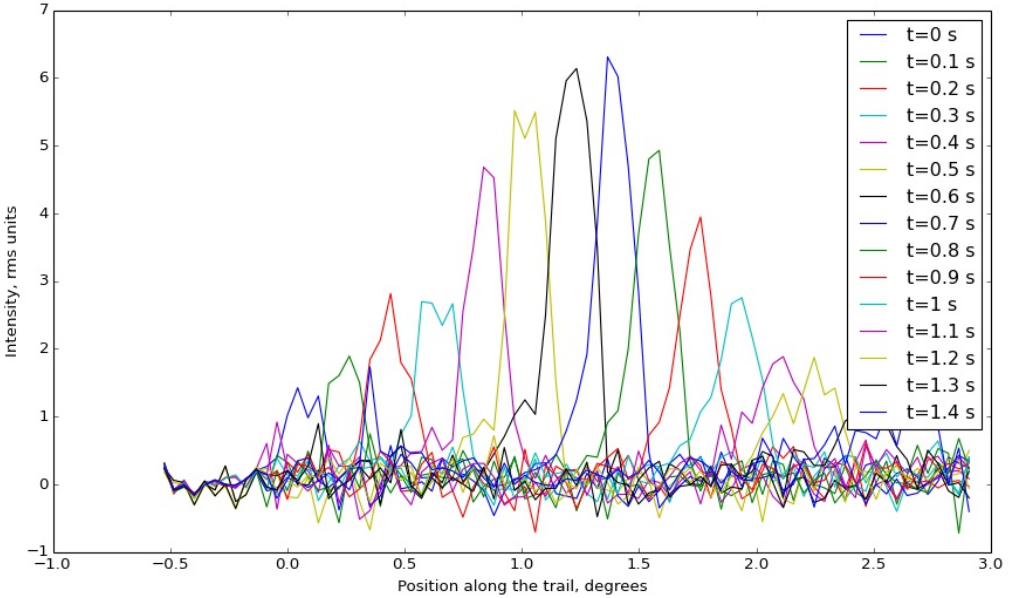
MMT

Meteors



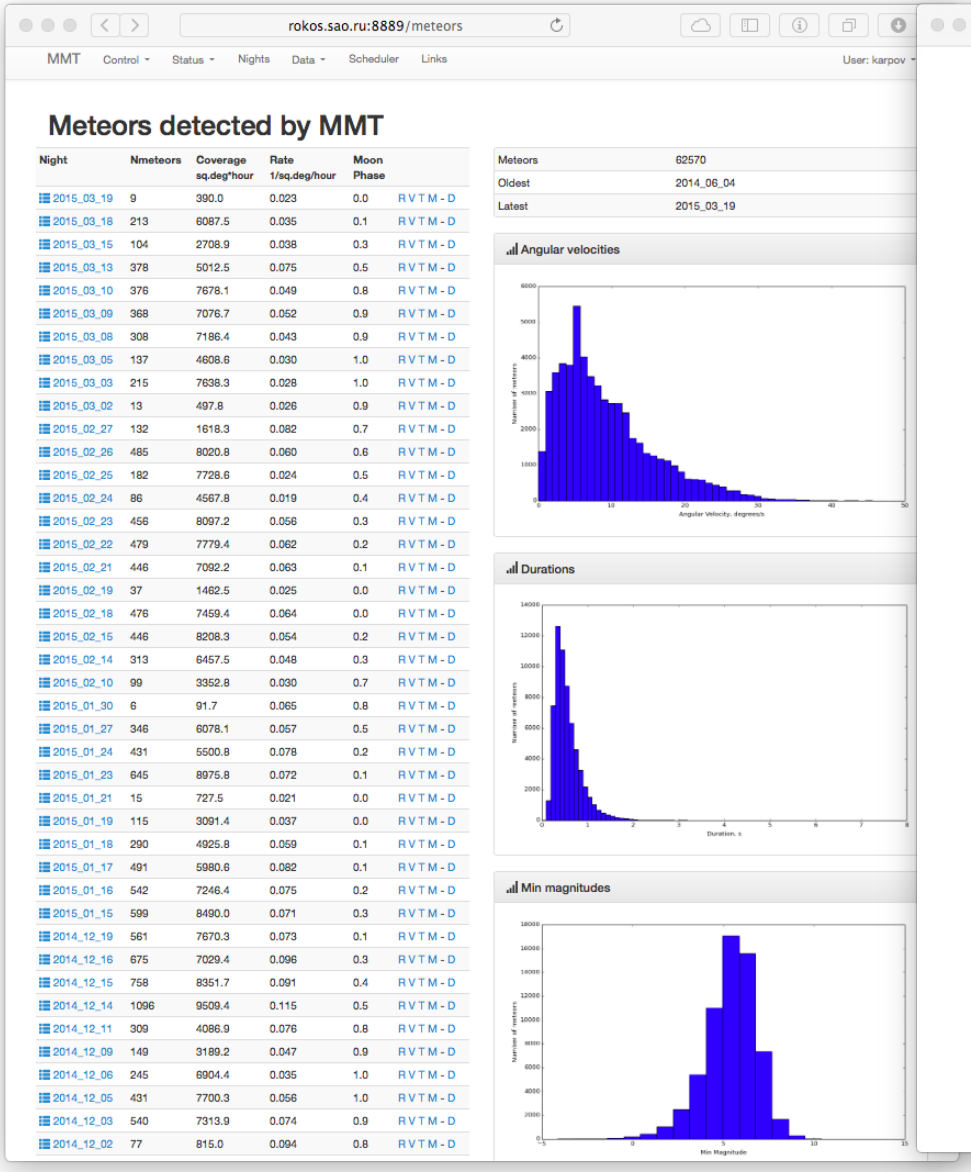


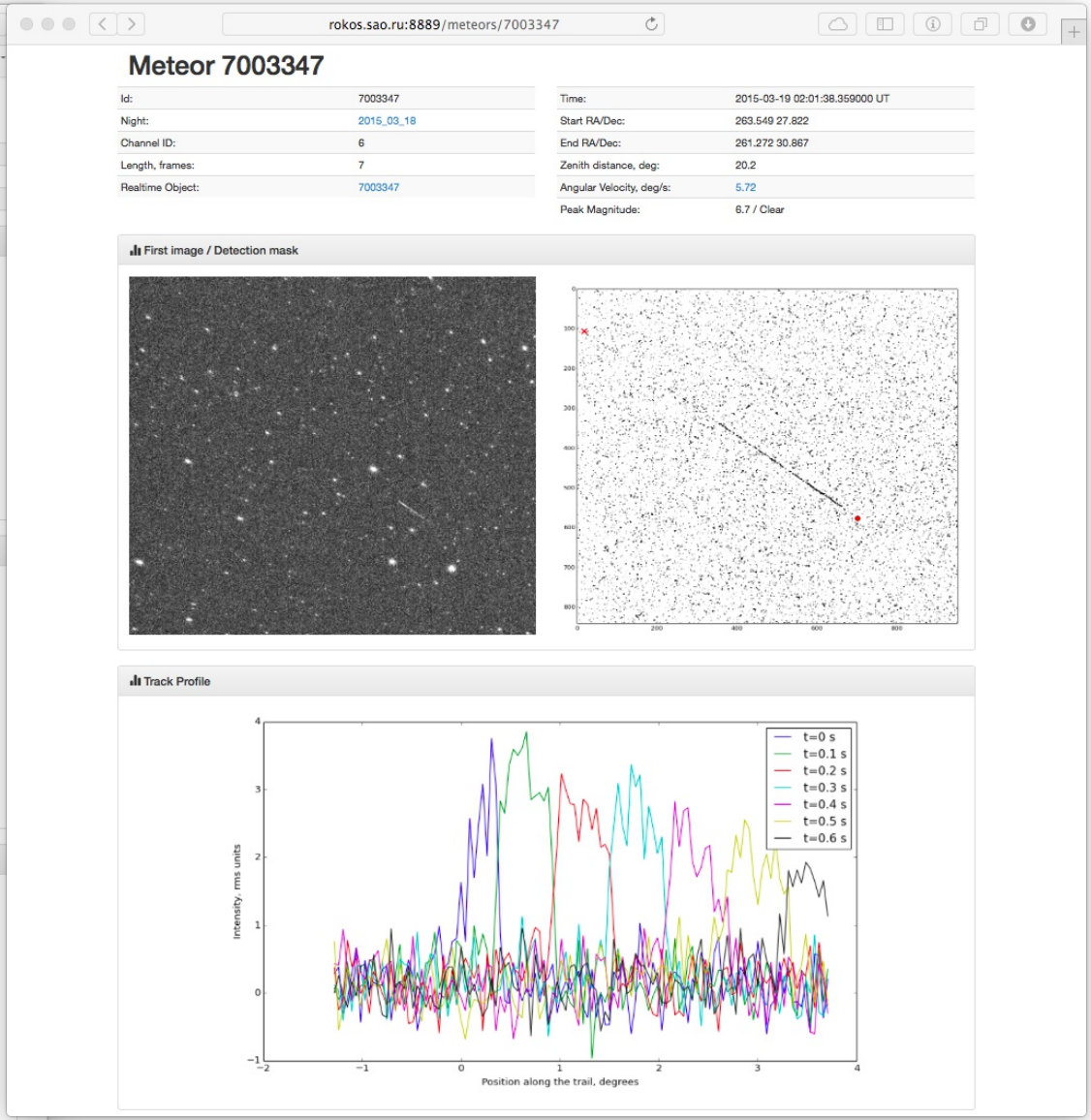




Since mid-2014, 128000 meteors detected, ~400 per night

Meteors: public database



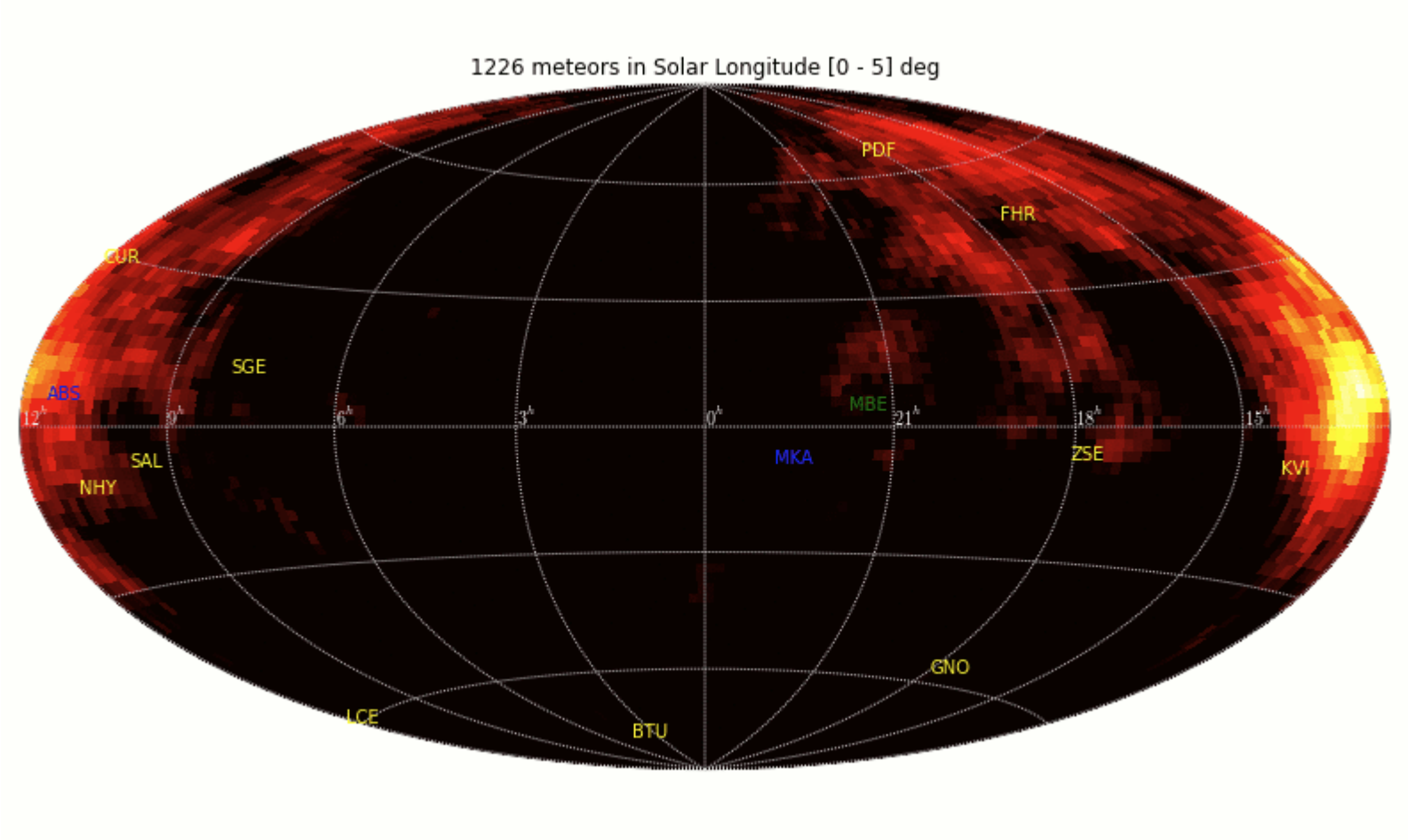


Since mid-2014, 176000 meteors detected, ~400 per night

MMT

Meteors: annual activity

Large number of meteors we detect every night allows us to build a **purely statistical radiant estimation** even with single-station data by checking the number of meteor great circles passing close to every point of the sky and bootstrapping it for the significance.



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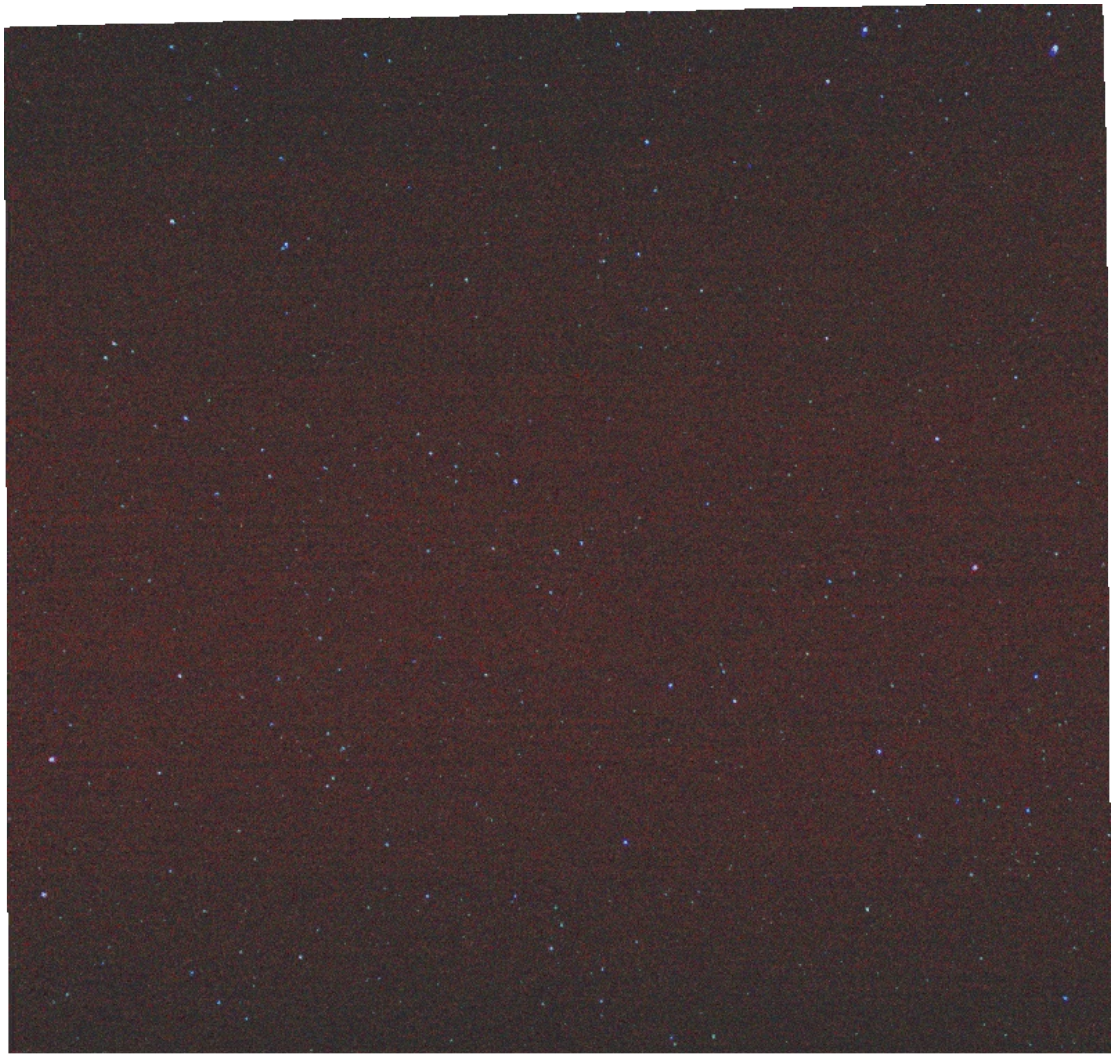
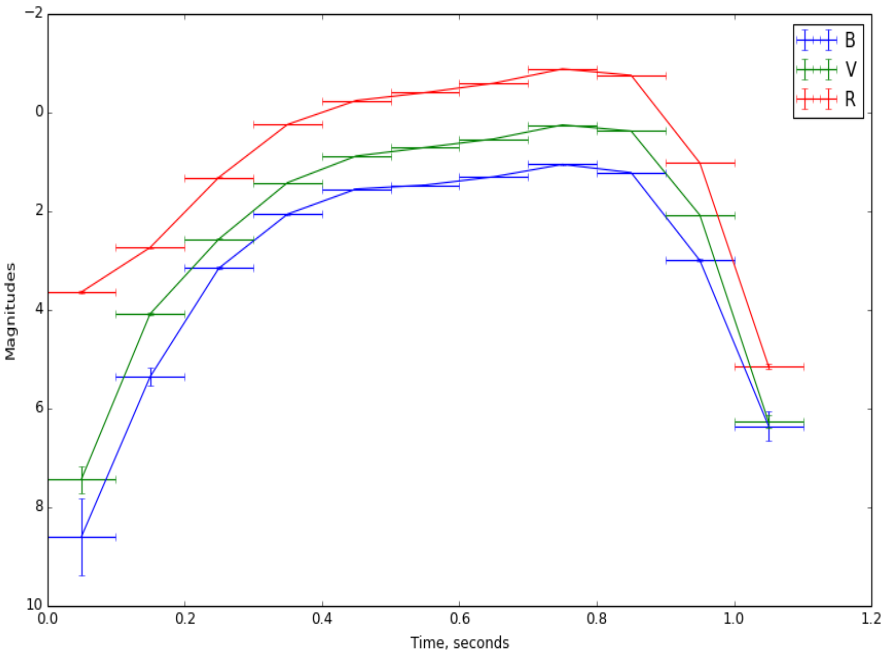
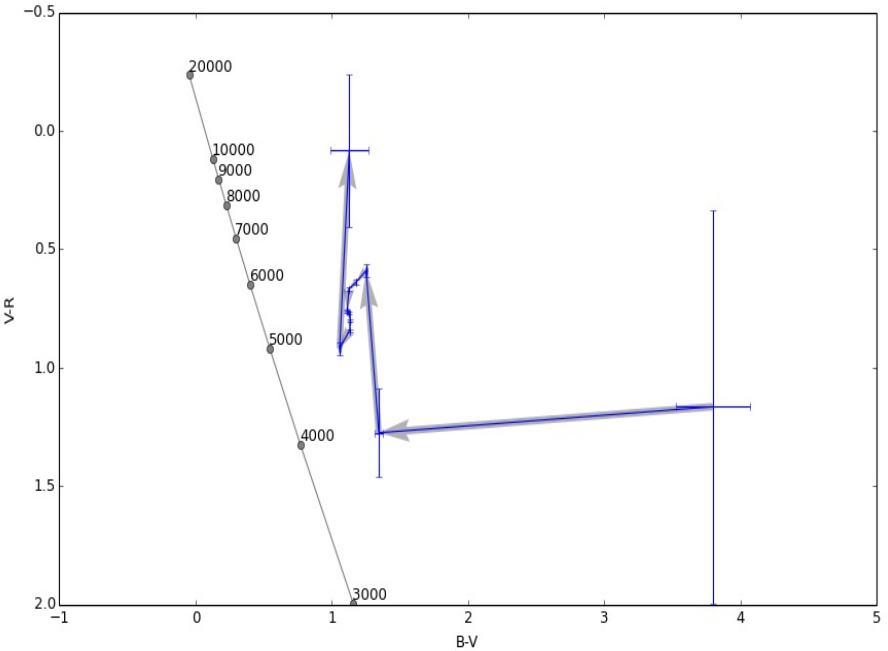
Meteors: multicolor







Some meteors are observed in multicolor mode

Artificial Satellites

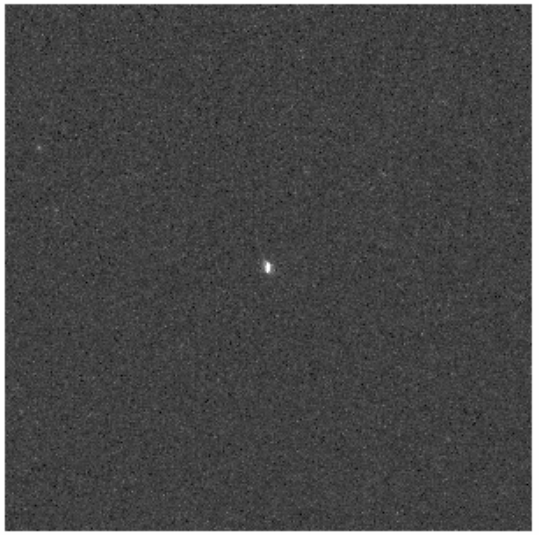
MMT

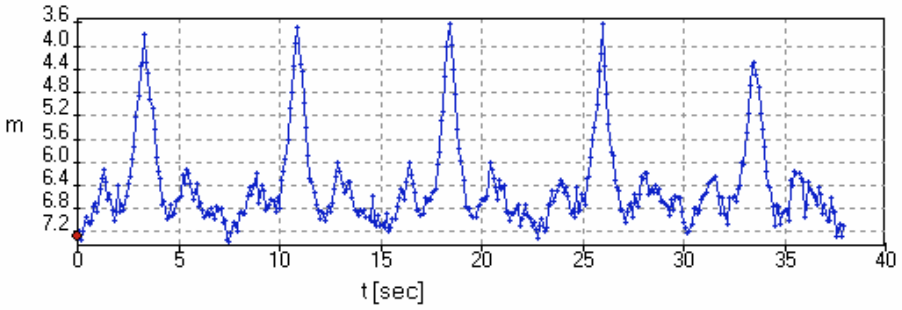
NORAD # 25909
GLOBALSTAR M033

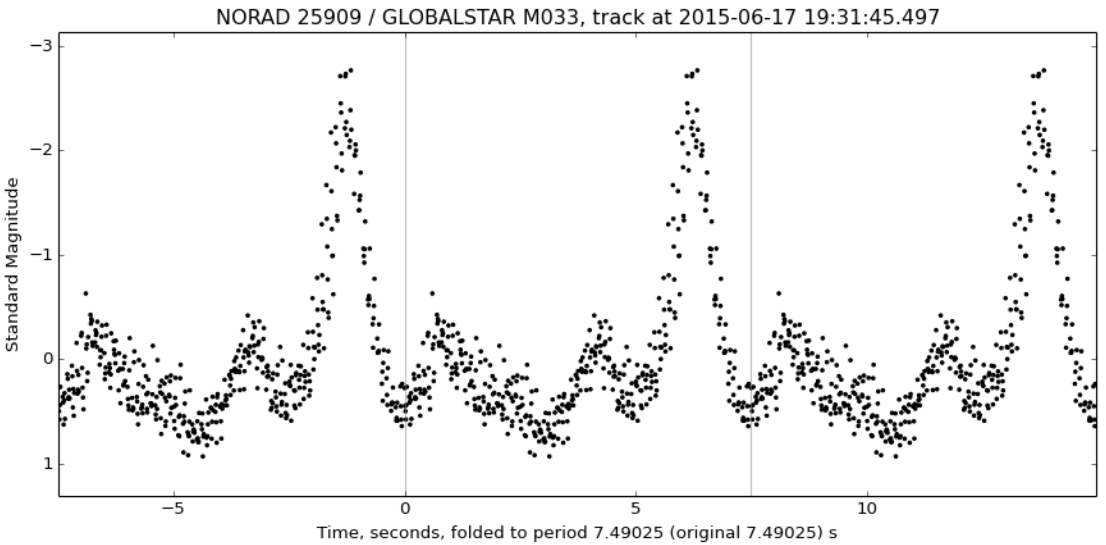
Type: Inactive
Launch: 1999-09-22
Country: GLOB

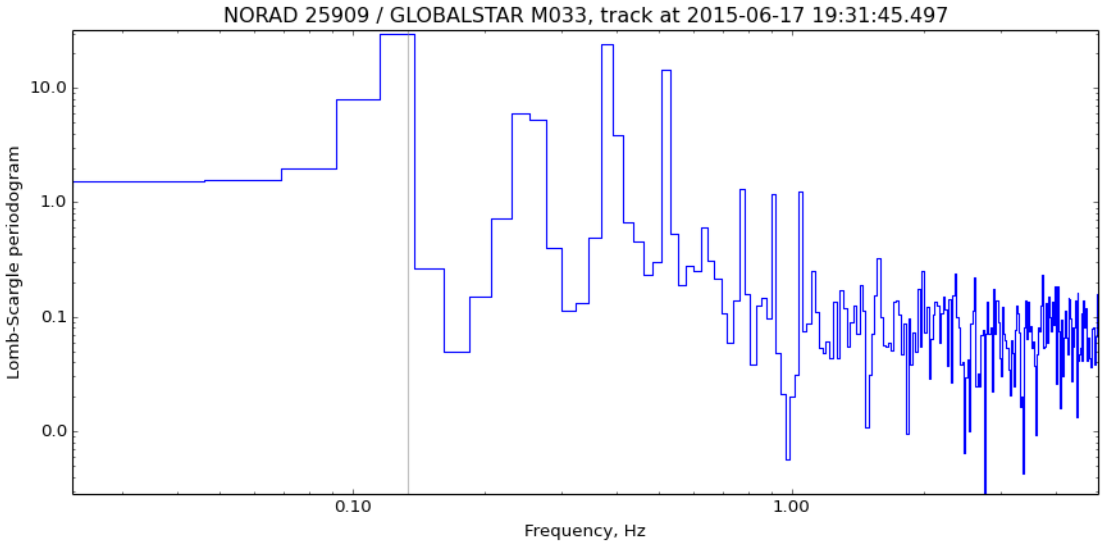
Track
Date: 17.06.2015
UT: 19:32:26.2
Period = 7.5 sec

Range = 1669.8 km
Phase angle = 83.5°





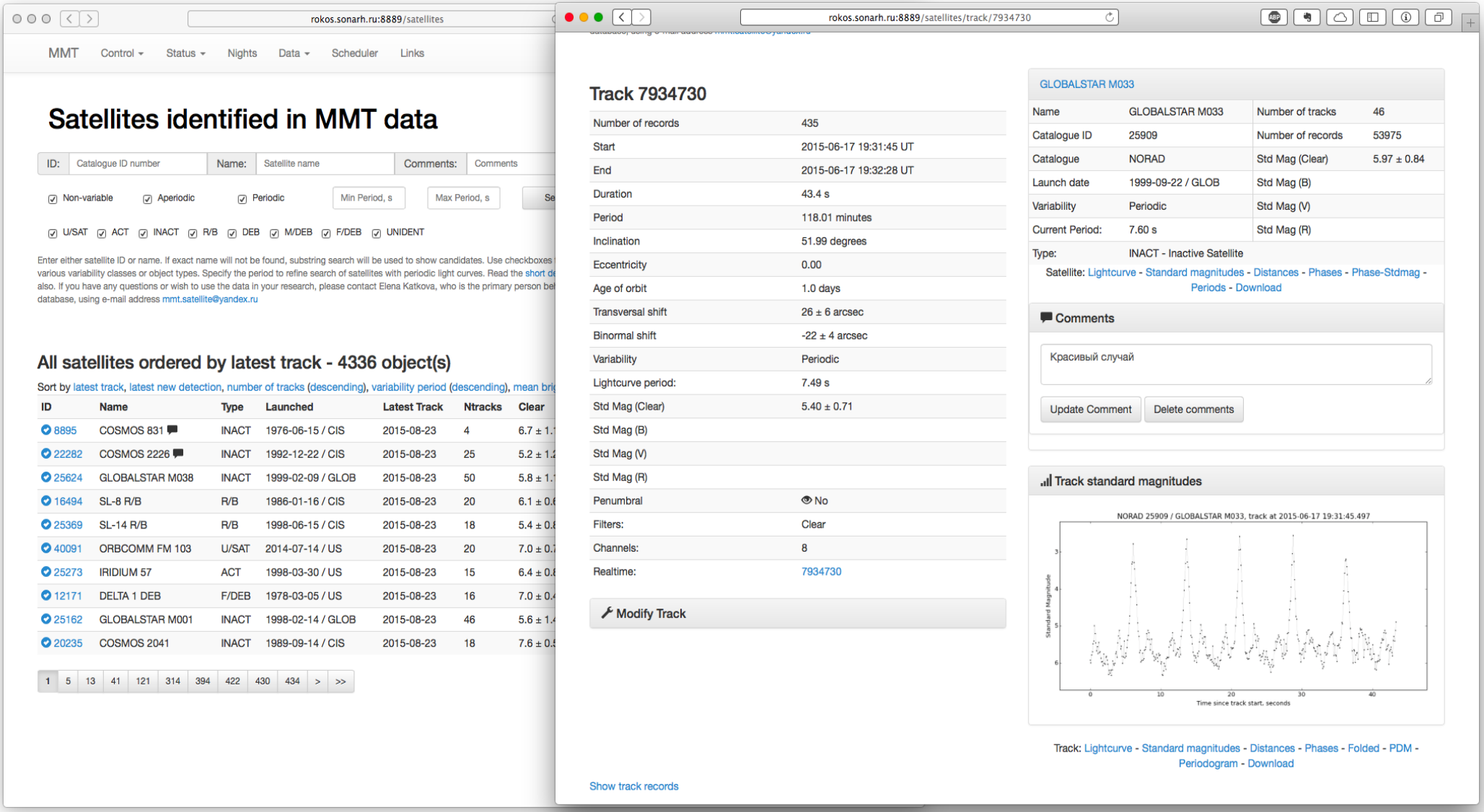




Since mid-2014, MiniMegaTORTORA detected more than 146000 tracks of 5480 satellites on altitudes up to 21000 km

MMT

Artificial Satellites: public database



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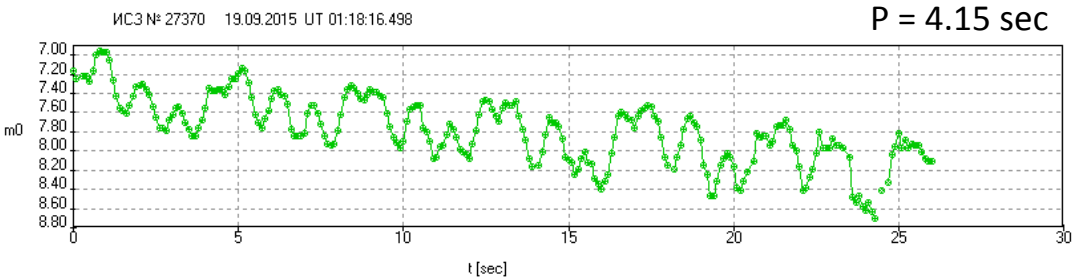
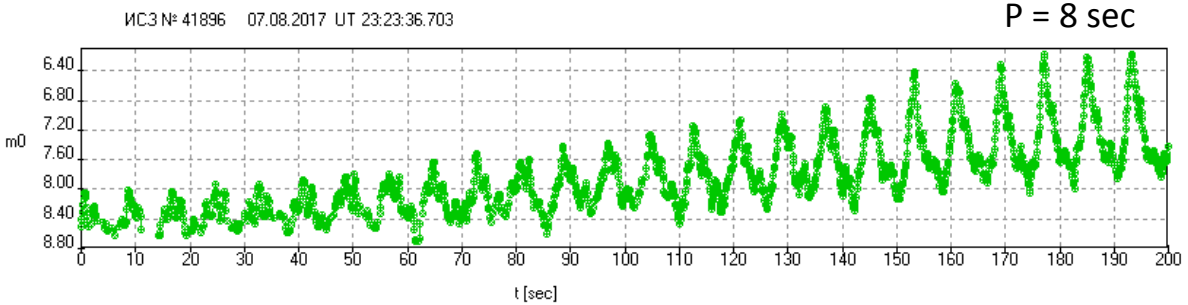
Artificial Satellites: periodicities

27370 RHESSI

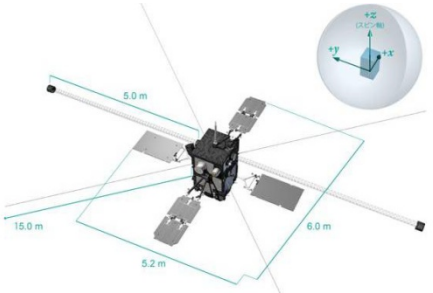


P = 4.15 sec

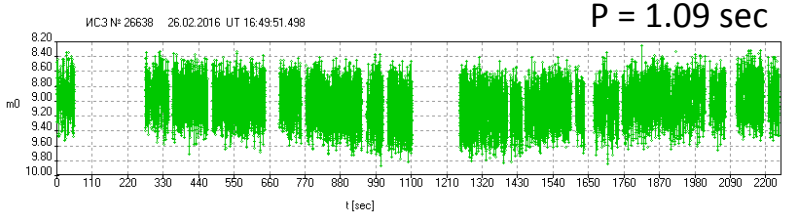
41896 ARASE (ERG)



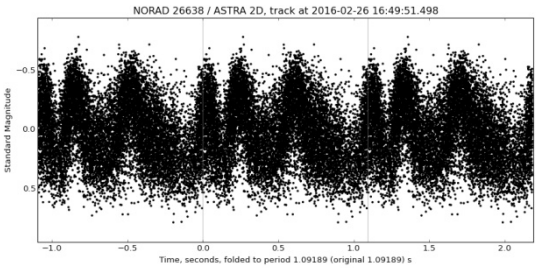
P = 8 sec



26638 ASTRA 2D



P = 1.09 sec

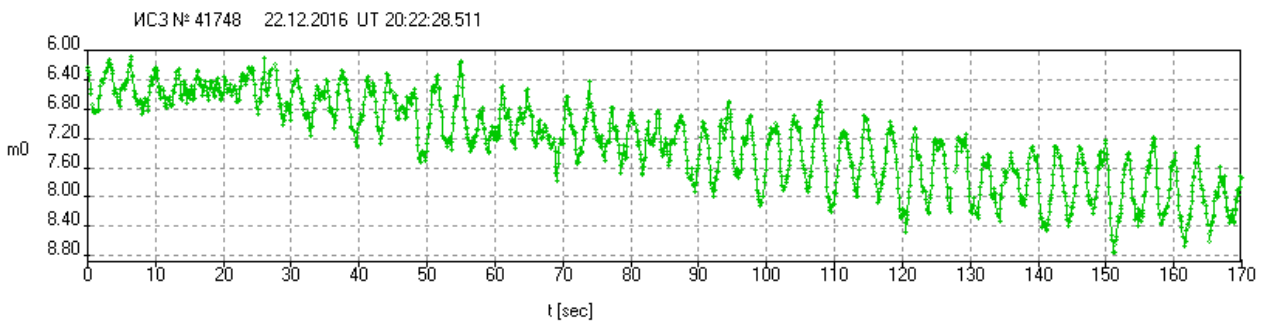


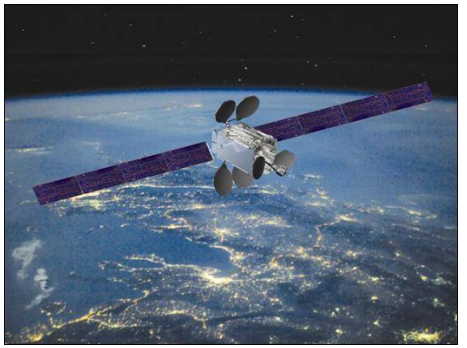
Active satellites stabilized by rotation

MMT

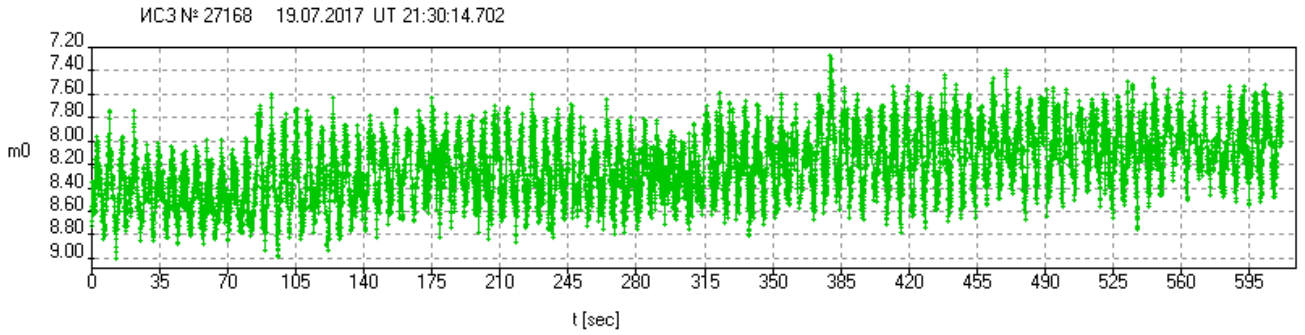
Artificial Satellites: periodicities

41748 Intelsat-33e, period 3.4 seconds





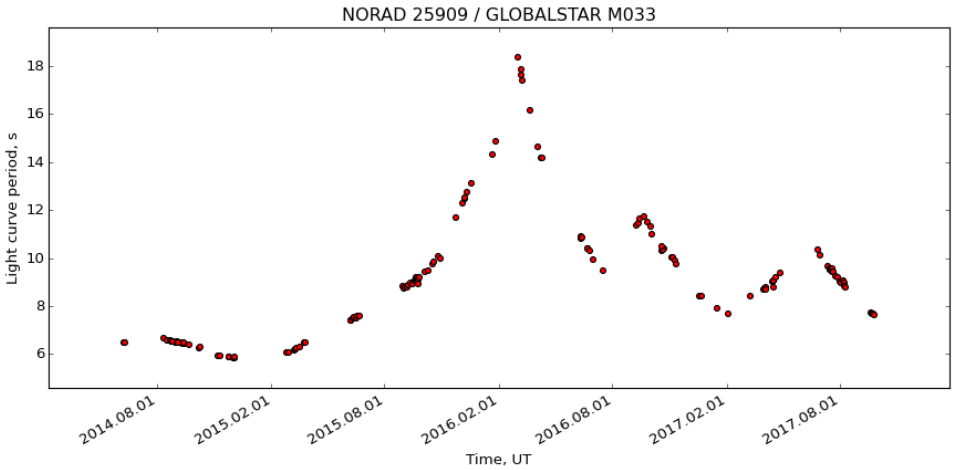
27168 Milstar-5, period 6.4 seconds

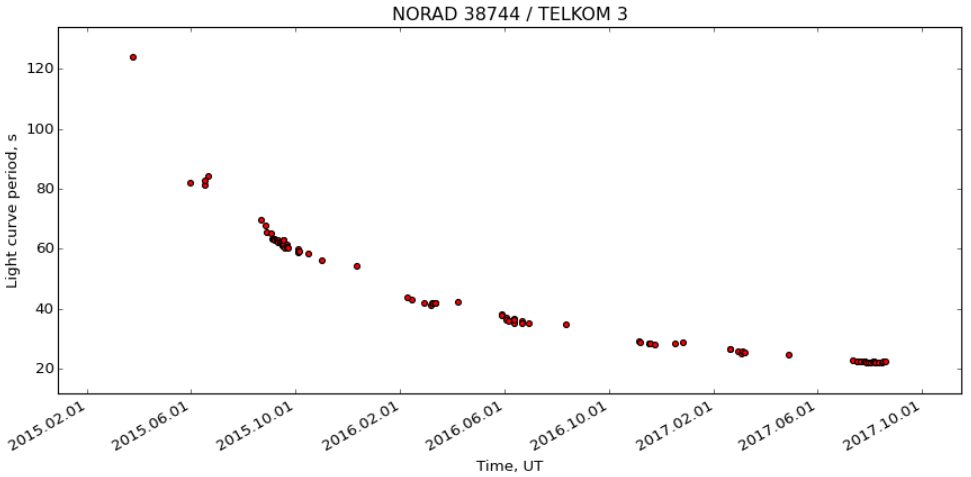


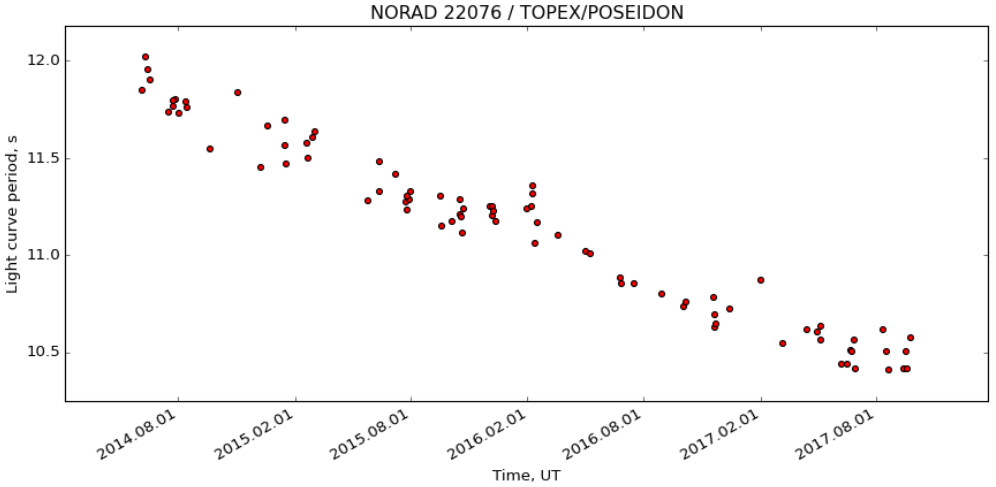
Active satellites with three-axis stabilization and no rotating parts - ???

MMT

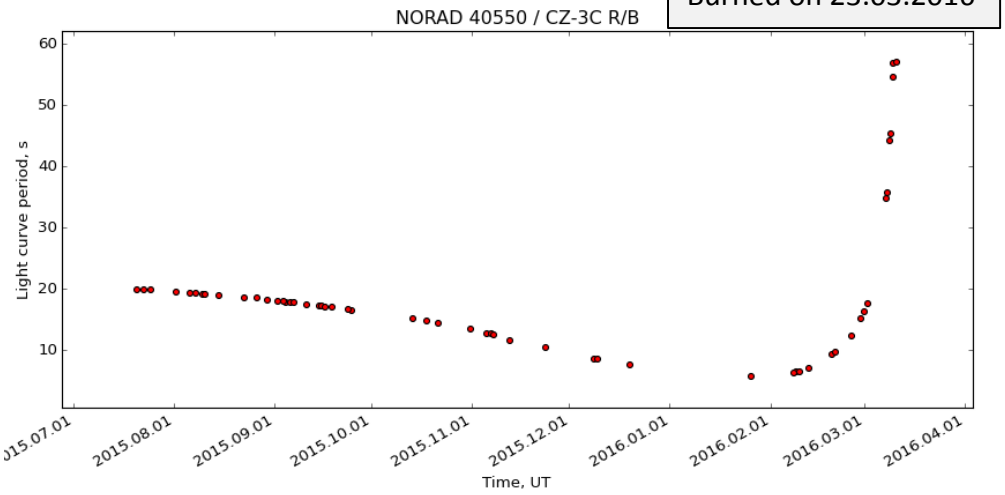
Artificial Satellites: periodicities







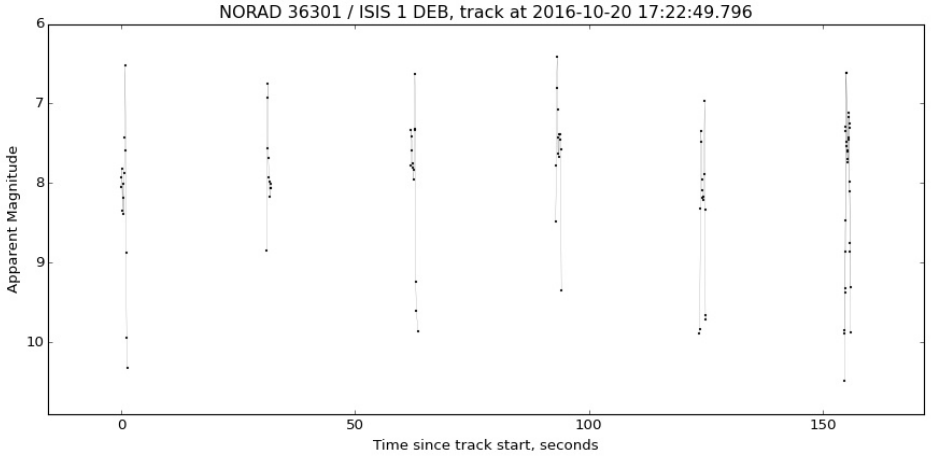
Burned on 23.03.2016

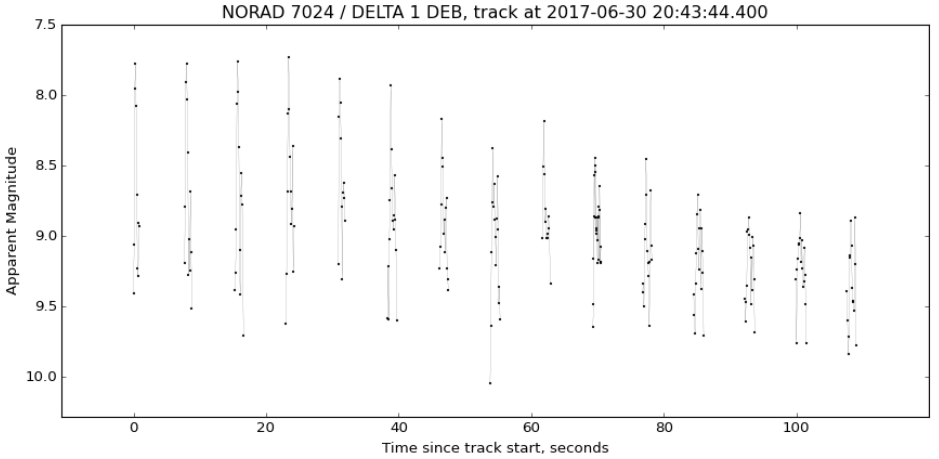


~1000 periodic objects in the database, with various dynamics

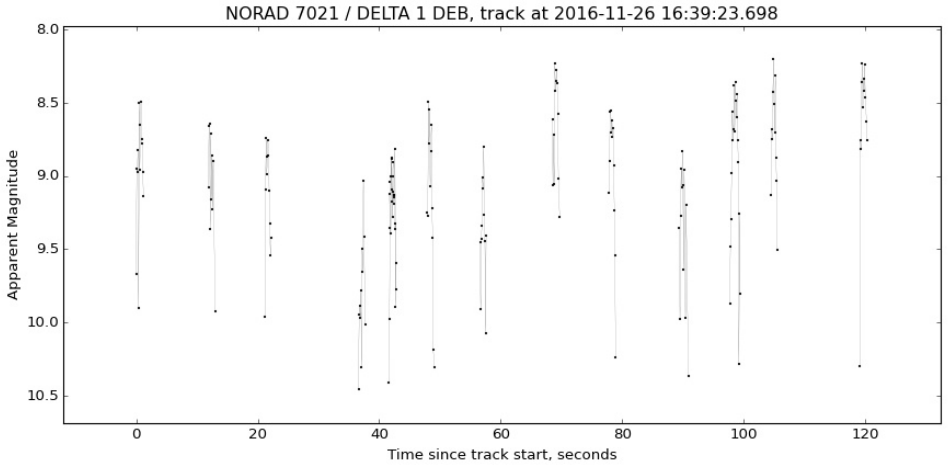
Artificial Satellites: flashes

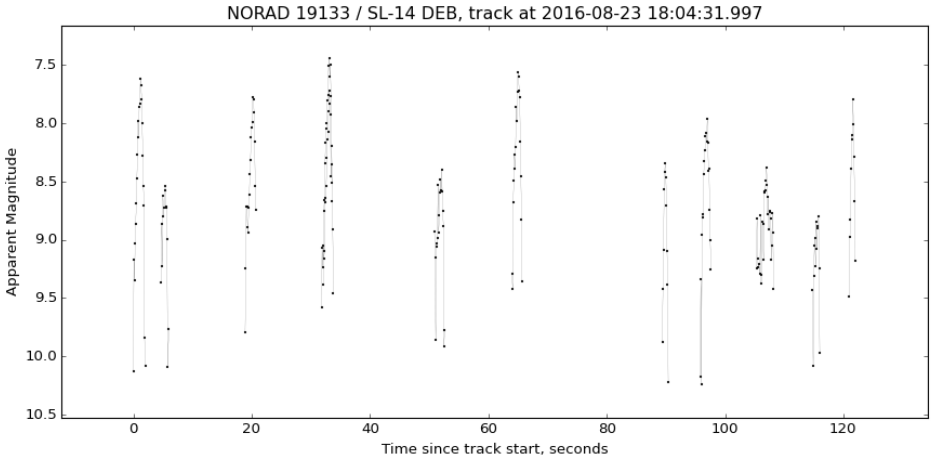
Periodic



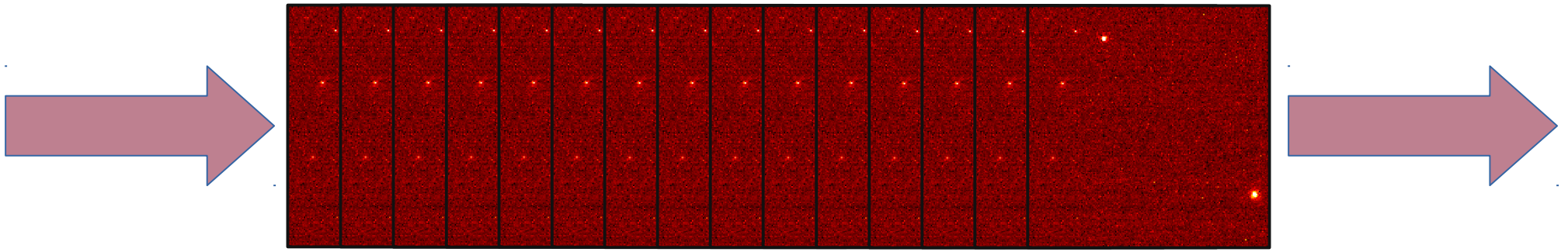


Aperiodic

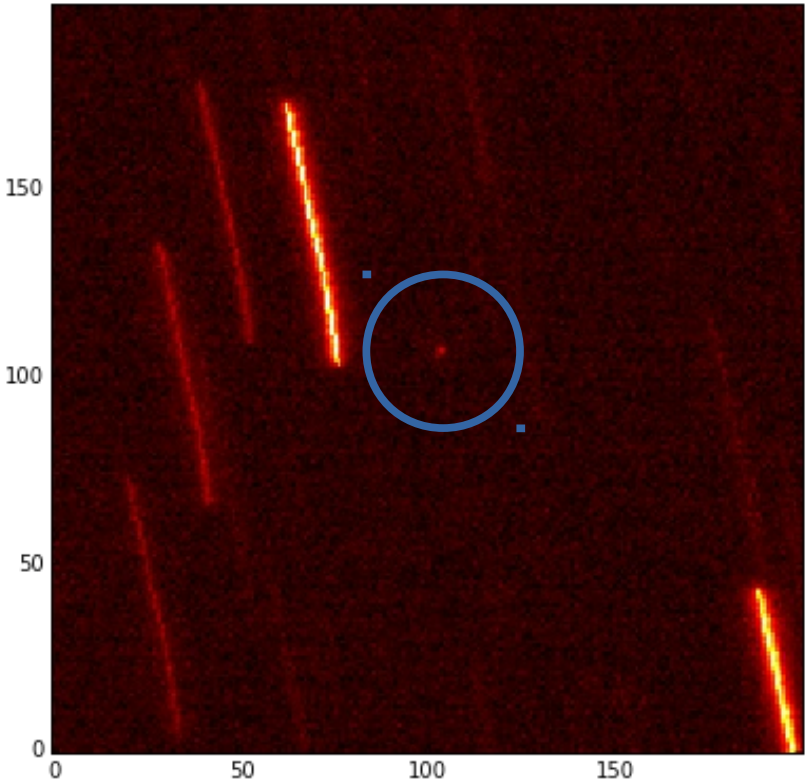




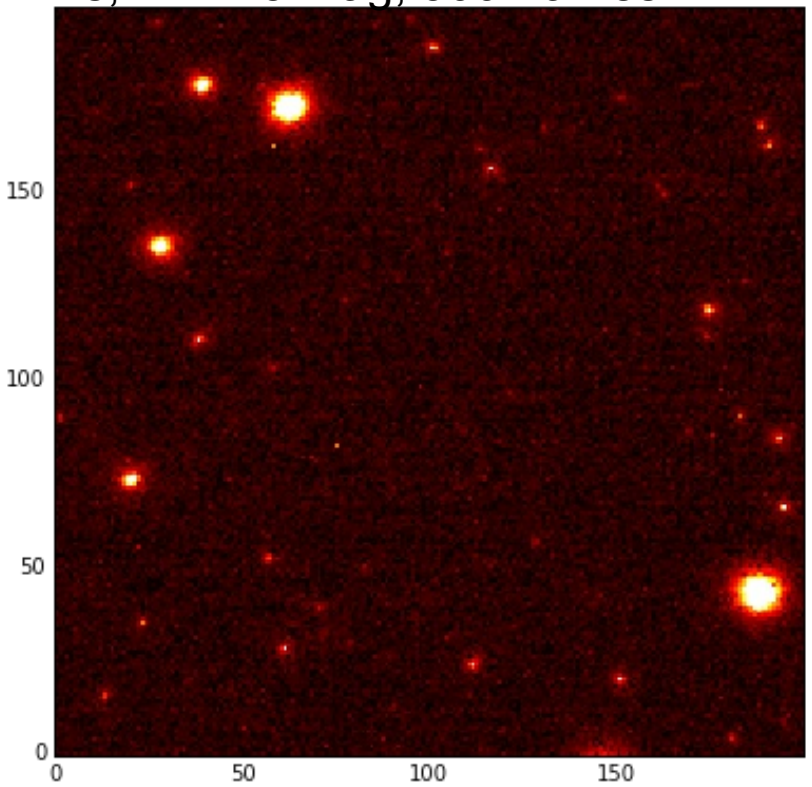
Artificial Satellites: Sub-Threshold Detection



NORAD 32275 / GLONASS, 37.7 ‘’/s, V~12.5 mag, 300 frames



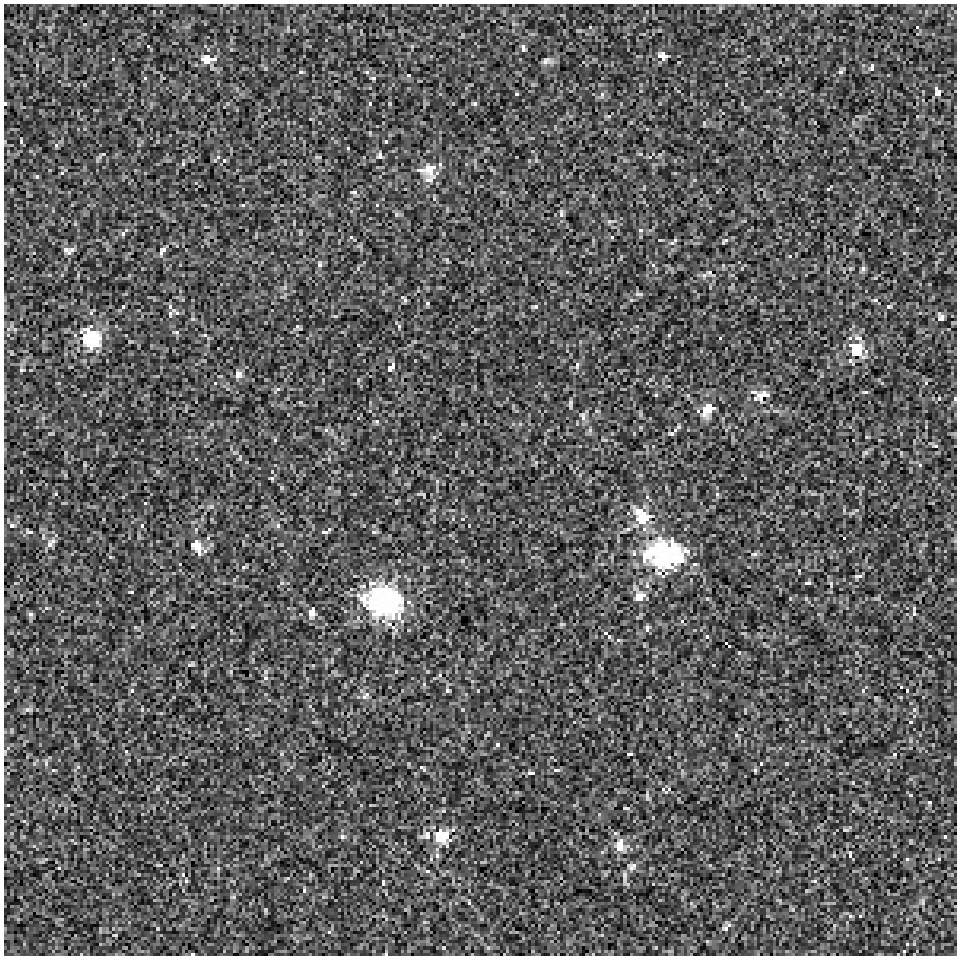
Co-Addition with
Motion Compensation

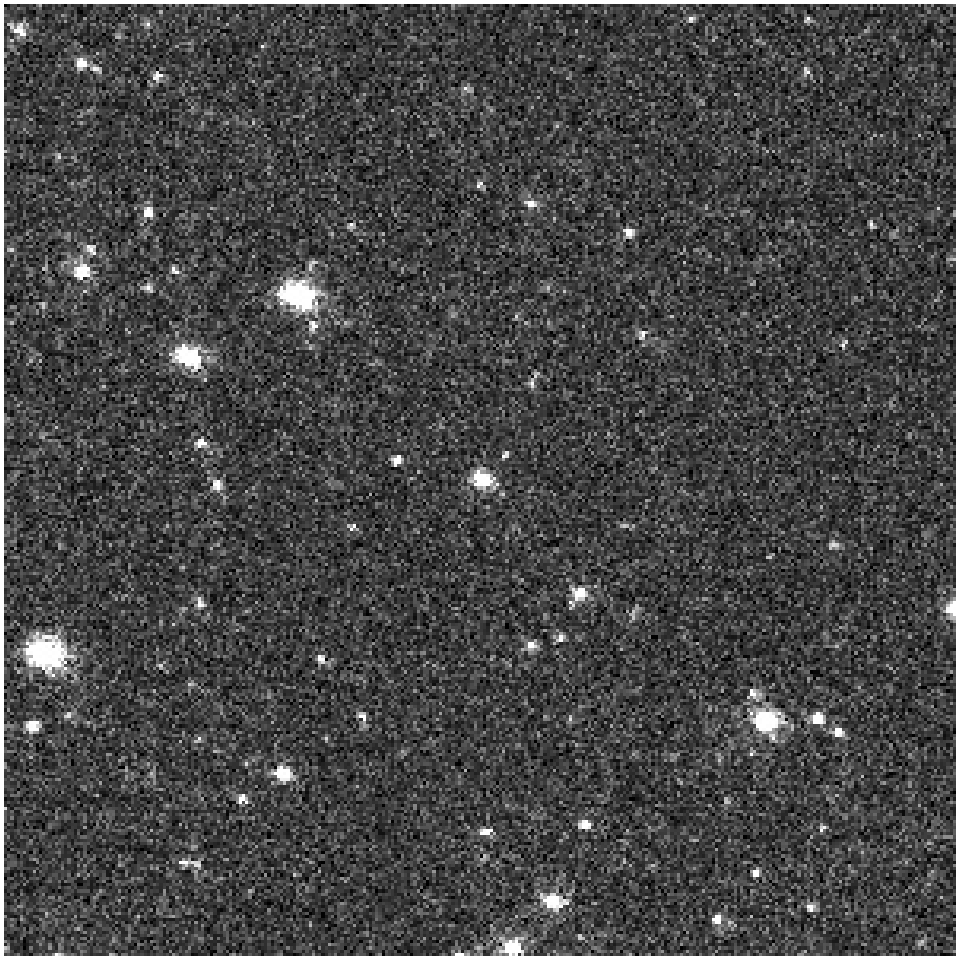


Direct Co-Addition

MMT

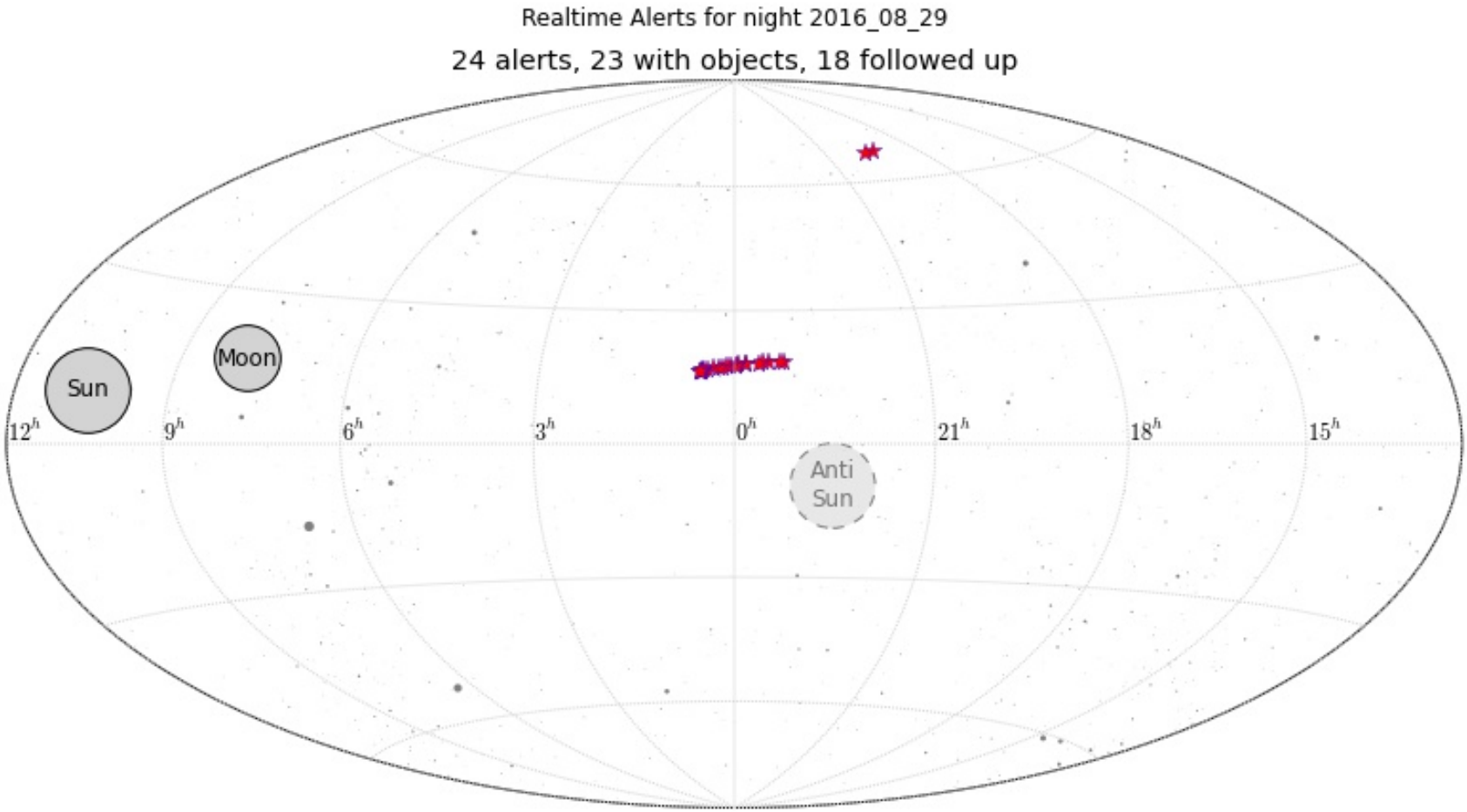
Rapid Optical Flashes





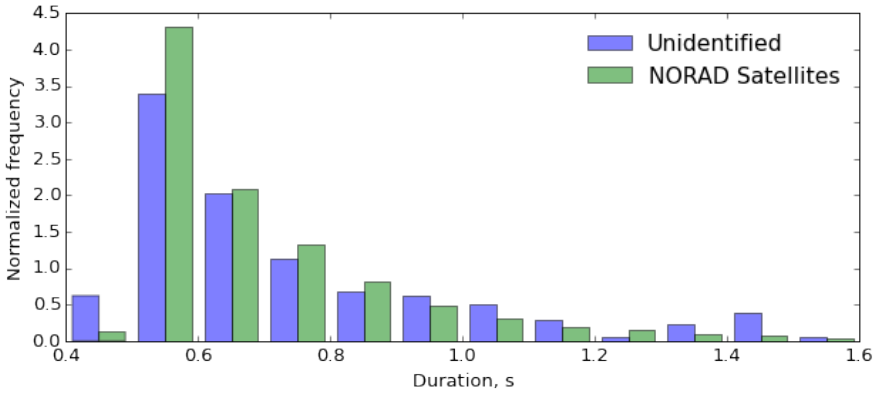
~10000 non-scintillation flashes detected since mid-2014, ~10% not identified with satellites in NORAD database

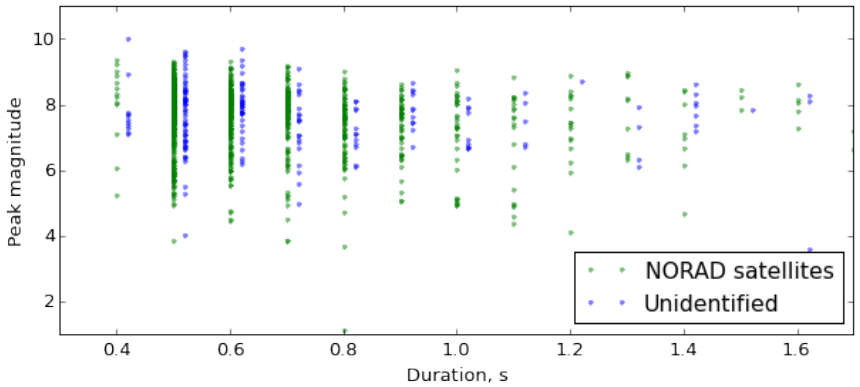
Rapid Optical Flashes

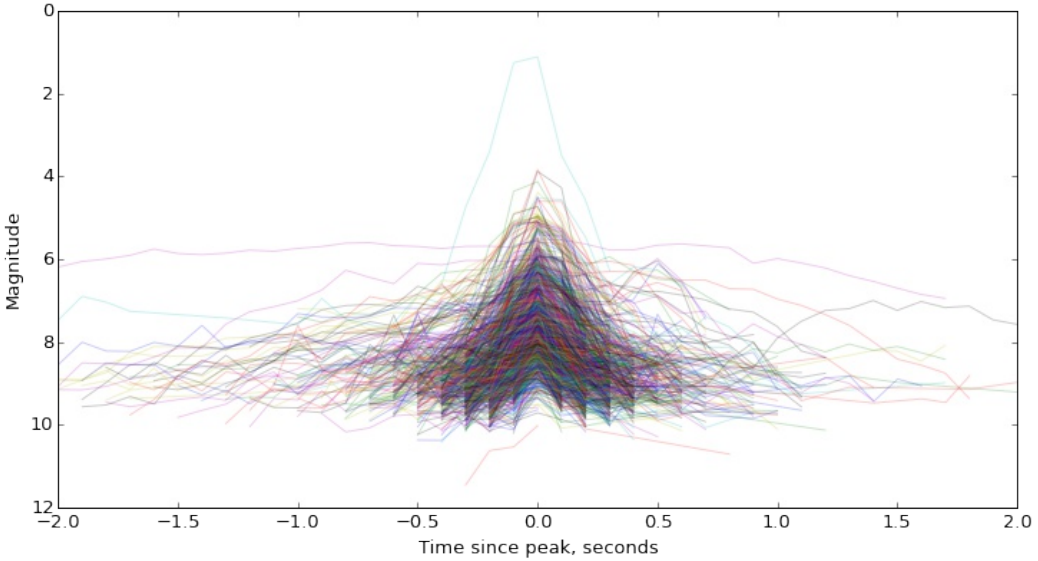


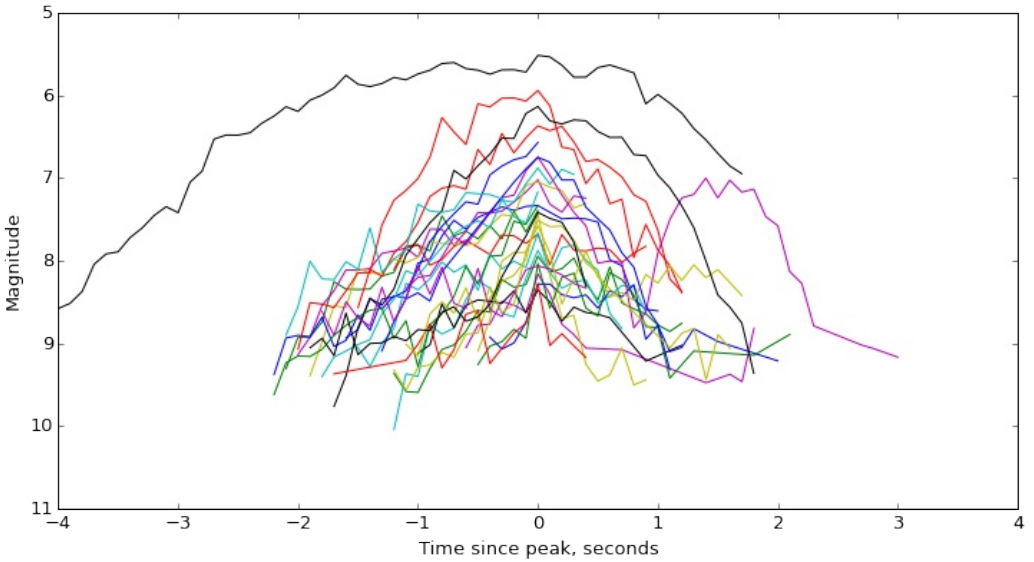
~10000 non-scintillation flashes detected since mid-2014, ~10% not identified with satellites in NORAD database

Rapid Optical Flashes







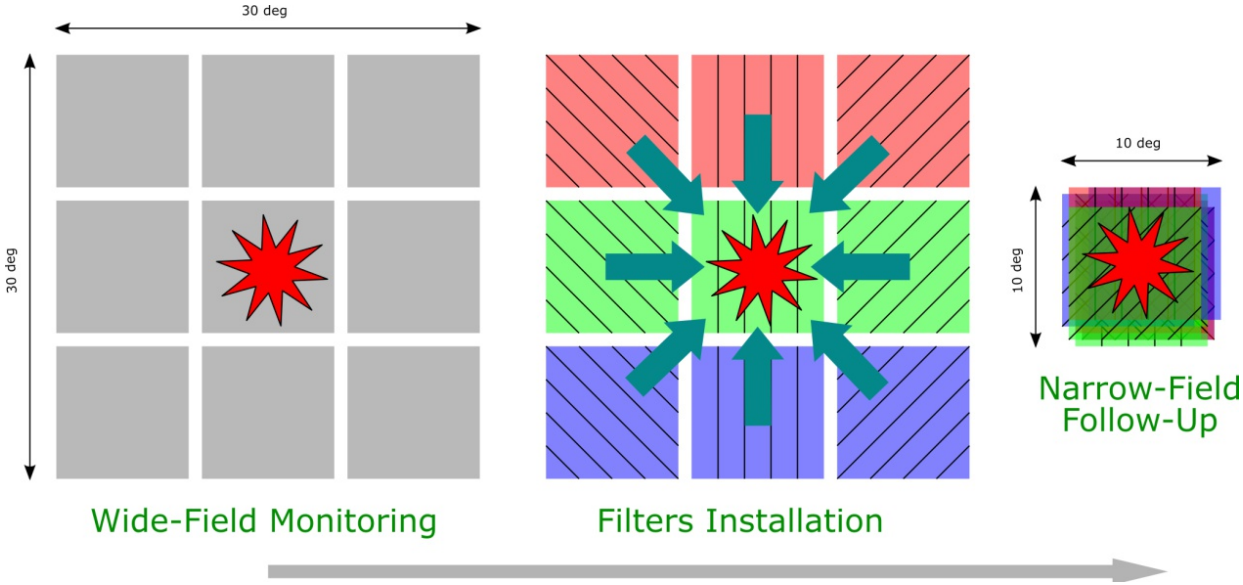


~10000 non-scintillation flashes detected since mid-2014, ~10% not identified with satellites in NORAD database

Rapid Optical Flashes – Follow-Up

Mini-MegaTORTORA is a multi-channel system with rapid repointing of channels which allows to perform rapid follow-up observations of transients

Typical reaction time is 2-3 seconds since transient detection

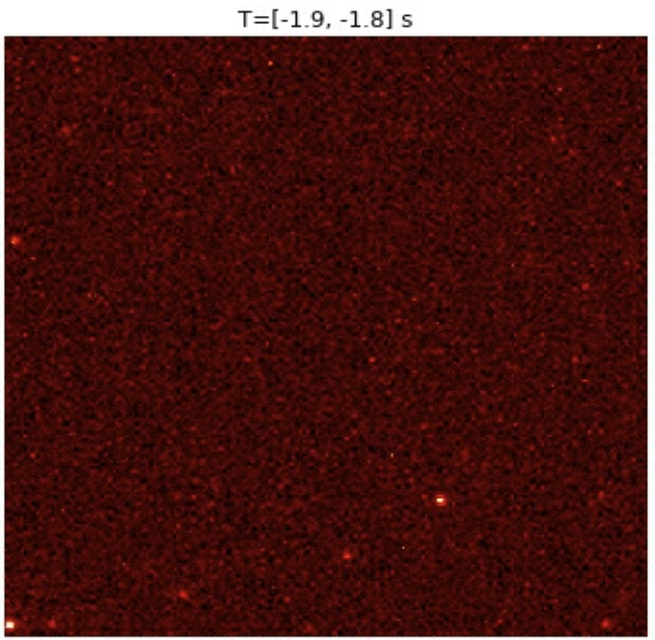


Rapid follow-up observations of self-detected transient involve all 9 channels and typically include:

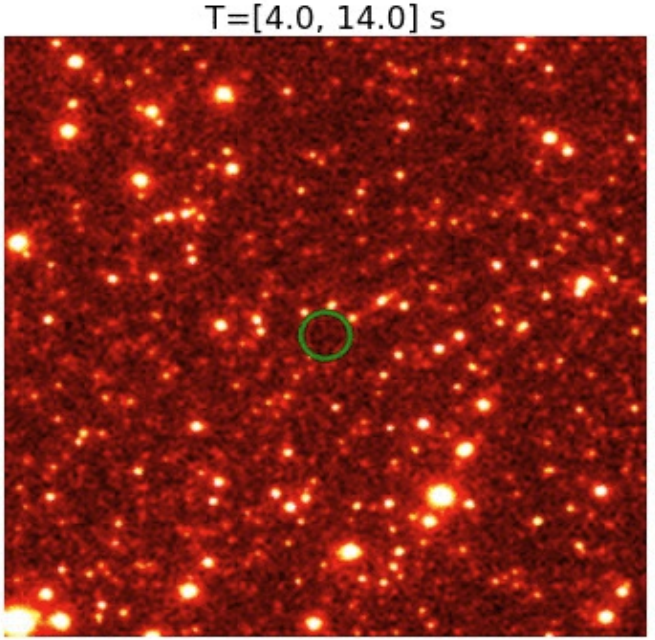
- **High-resolution** (0.1 s exposure) white-light imaging with channel which detected the transient to acquire uninterrupted light curve
- **Low-resolution** (1 s exposure) white-light imaging with better limit
- **Even lower resolution** (10 s exposure) white light imaging for deepest data
- **Three-color (BVR) imaging** by three channels with 10-s exposures for reliable determination of colors
- **Polarimetry** in three orientations of polarizers simultaneously by three channels with 5 s exposures to measure the polarization

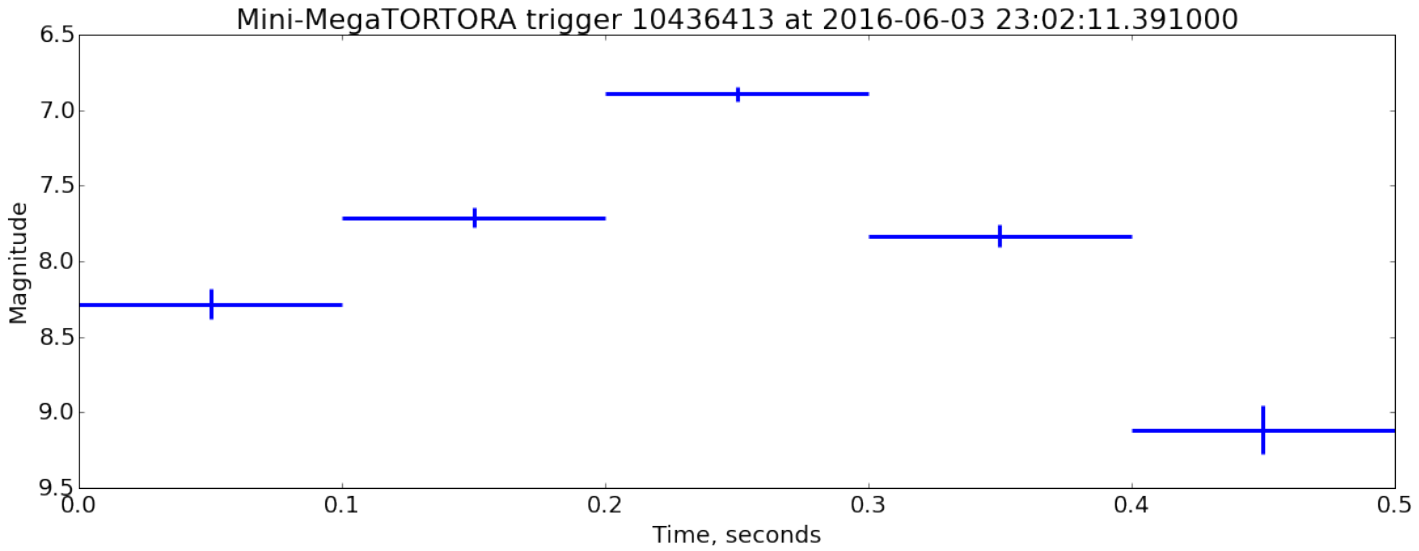
Regular follow-up of self-detected transients started in Feb 2016
To date, about 2000 transients have been followed up, typically one to several tens per night

Rapid Optical Flashes – Follow-Up



Automatic Follow-Up in 3.5 s





1: Pol, 20 x 5 s
2: Clear, 0.1 s, unchanged
3: Clear, 100 x 1 s
4: **Clear, 10 x 10 s**
5: B, 10 x 10 s
6: V, 10 x 10 s
7: R, 10 x 10 s
8: Pol, 20 x 5 s
9: Pol, 20 x 5 s

MMT

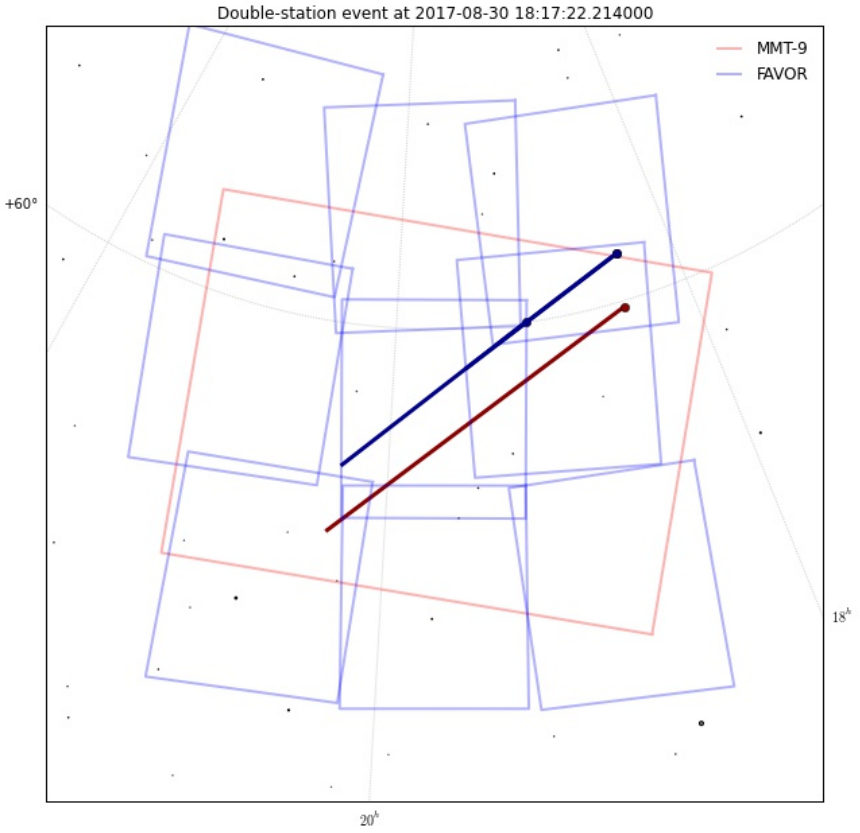
Double-Station Observations

FAVOR camera

Operated since 2003, decommissioned in 2009

D=15cm, D/F=1/1.2
Scaling image intensifier + Sony ICX285AL

17x24 deg field of view, ~60'' pixel
7.5 FPS frame rate
Limit down to V~9-10 mag

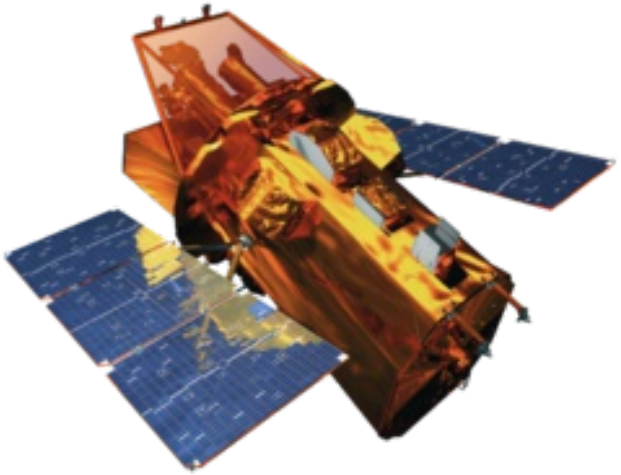


Together with Mini-MegaTORTORA it should be able to **detect parallax** at up to 6000 km

External Triggers

Mini-MegaTORTORA also performs follow-up of **Swift**, **Fermi** and **LIGO-Virgo** triggers, including the ones with poor localization accuracy due to its large field of view allowing for **simultaneous observations in ~900 sq.deg. sky fields**. For the triggers with better localizations, **multicolor** and/or **polarimetric** follow-up is performed.

Since mid-2015, **6** of 95 **Swift GRBs** have been followed up in **polarimetric** mode in 30 to 60 seconds since trigger distribution through GCN network, with no optical emission detections. **9** of 300 **Fermi GBM triggers** have been also followed up in **wide-field** mode in 20 to 90 seconds from the trigger. All other events were either below the horizon or occurred in bad weather conditions.

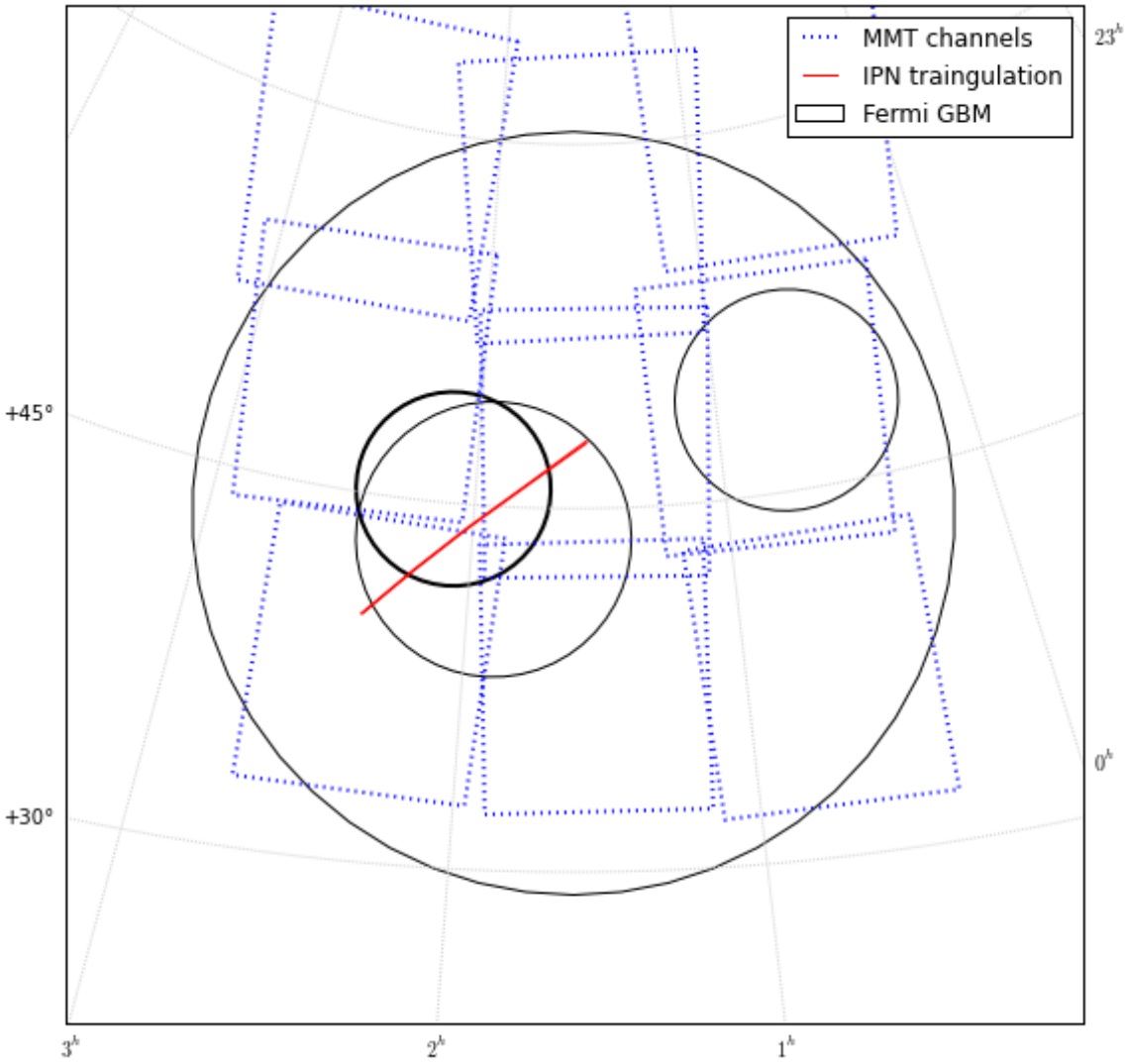


LIGO

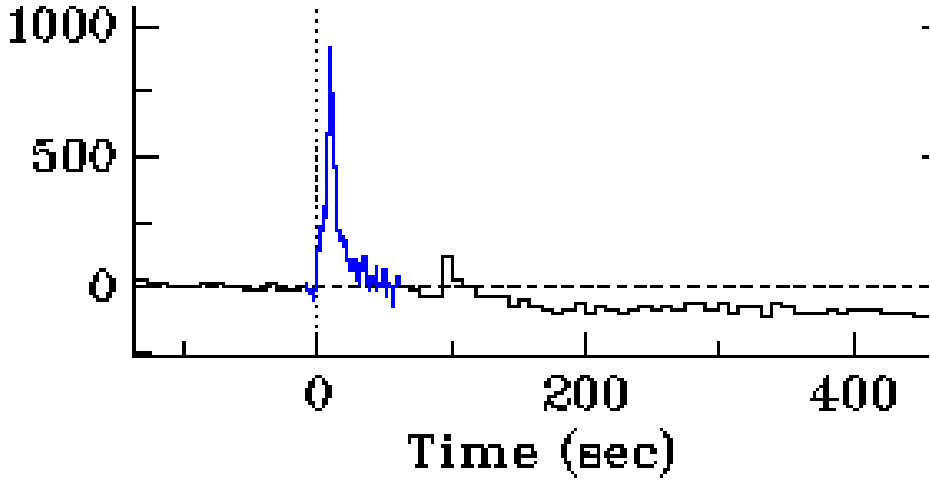
Fermi Gamma-ray Space Telescope

MMT

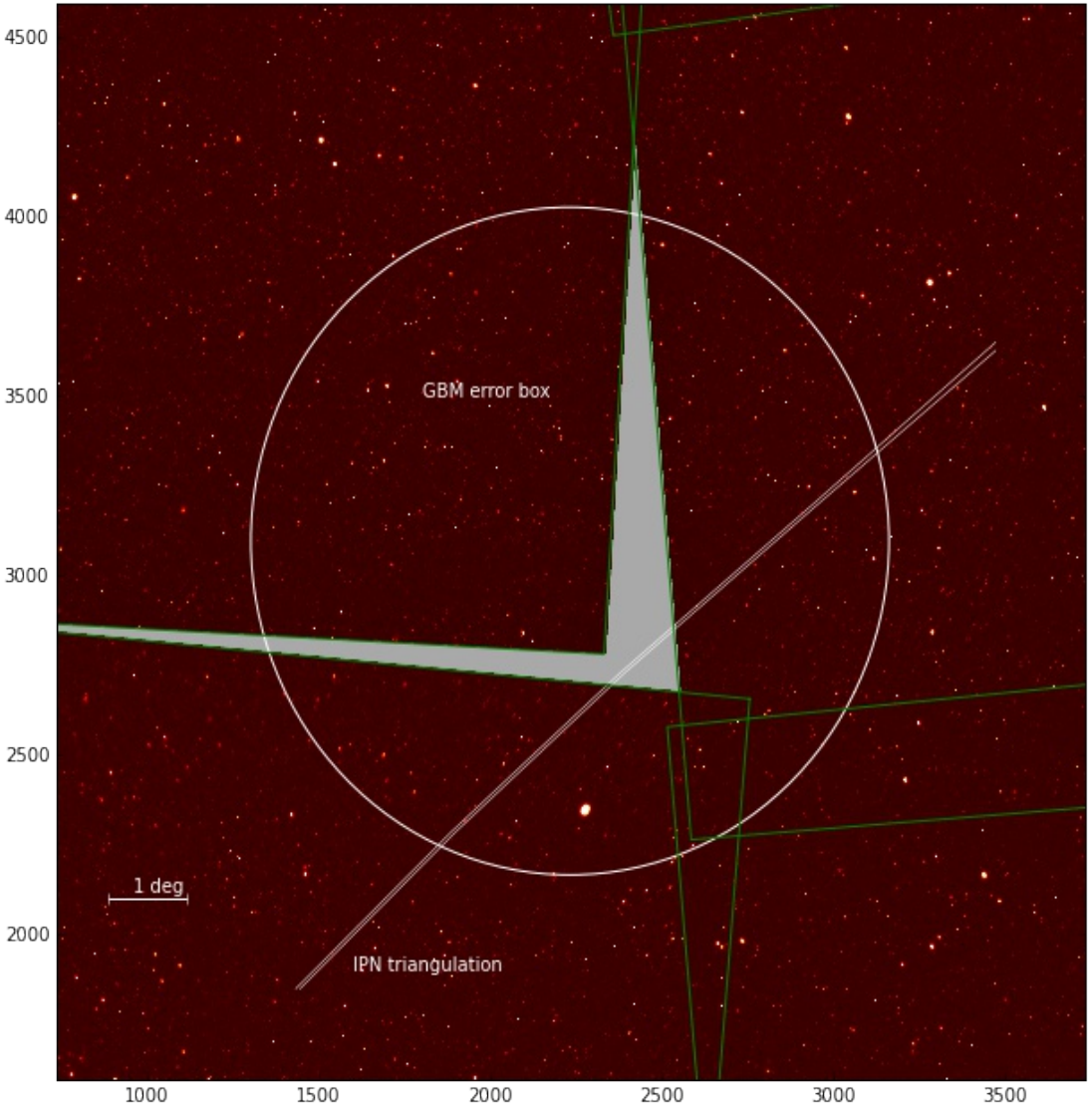
Fermi GRB 151107B



The localization of Fermi GBM trigger GRB 151107B has been observed **before, during and just after** the trigger time, covering nearly all its error box simultaneously since T-329.3 s till T+25.7 (including brightest part of first gamma-ray peak) with **temporal resolution of 0.1 s** in white light. Dedicated real-time transient detection pipeline did not detect any events longer than 0.3 s and brighter than approximately V=10.5 mag. Inspection of co-added images with 10 s effective exposure has not revealed any variable source down to V=12.0 mag during that interval.



Fermi GRB 151107B



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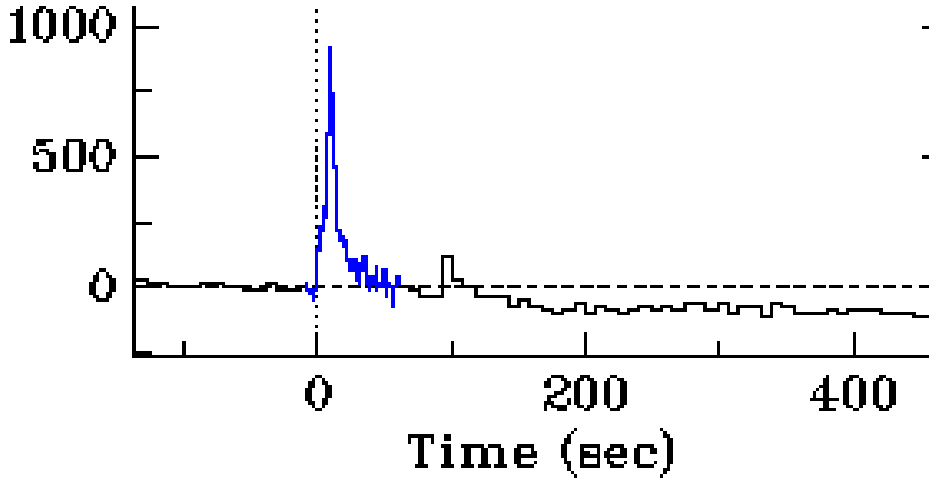
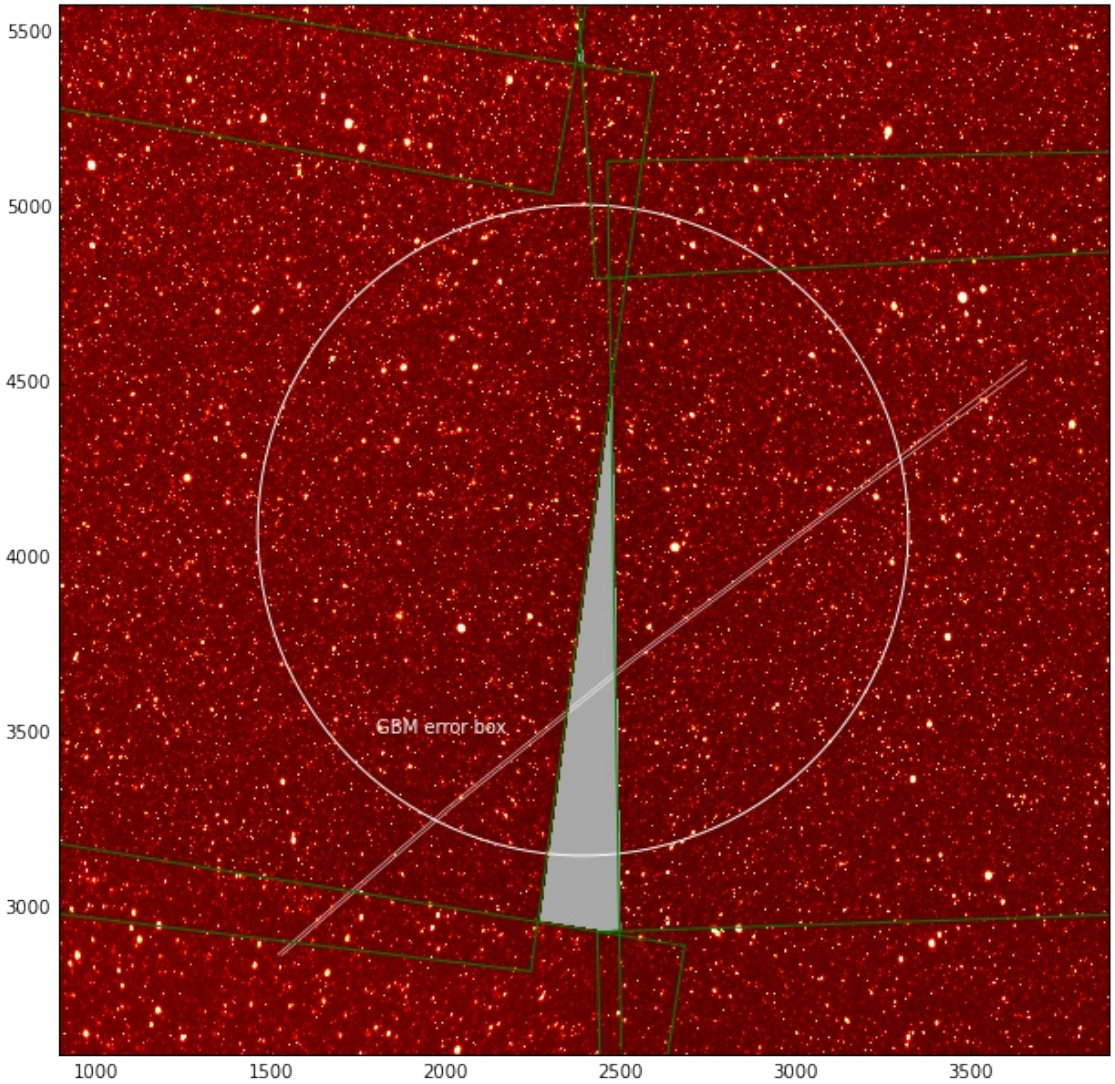
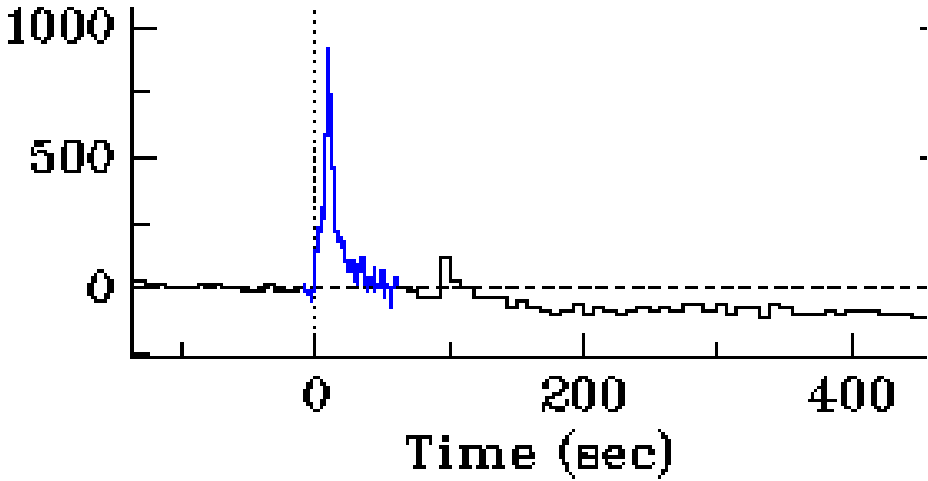


Fermi GRB 151107B

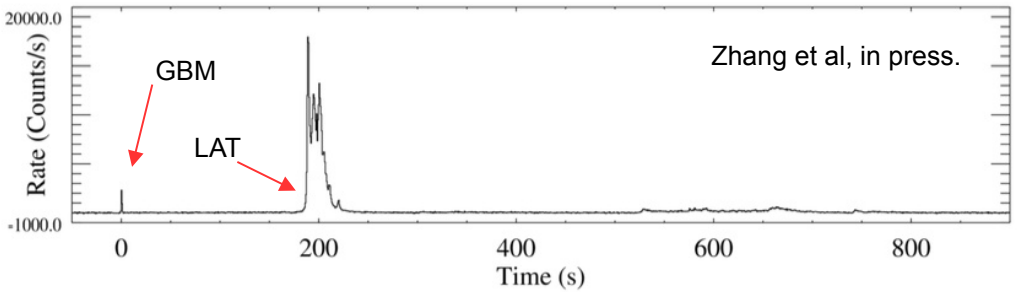


After receiving GCN trigger the system initiated a **wide-field follow-up** and since T+62.7 s (during the continuing gamma-ray activity) till T+666.7 s acquired 20x9 deep images with 30 s exposures in a 30x30 degree field of view covering the whole final 1-sigma localization box. Analysis of the acquired data has not revealed any variable object down to roughly V=13.5 mag over the time interval.

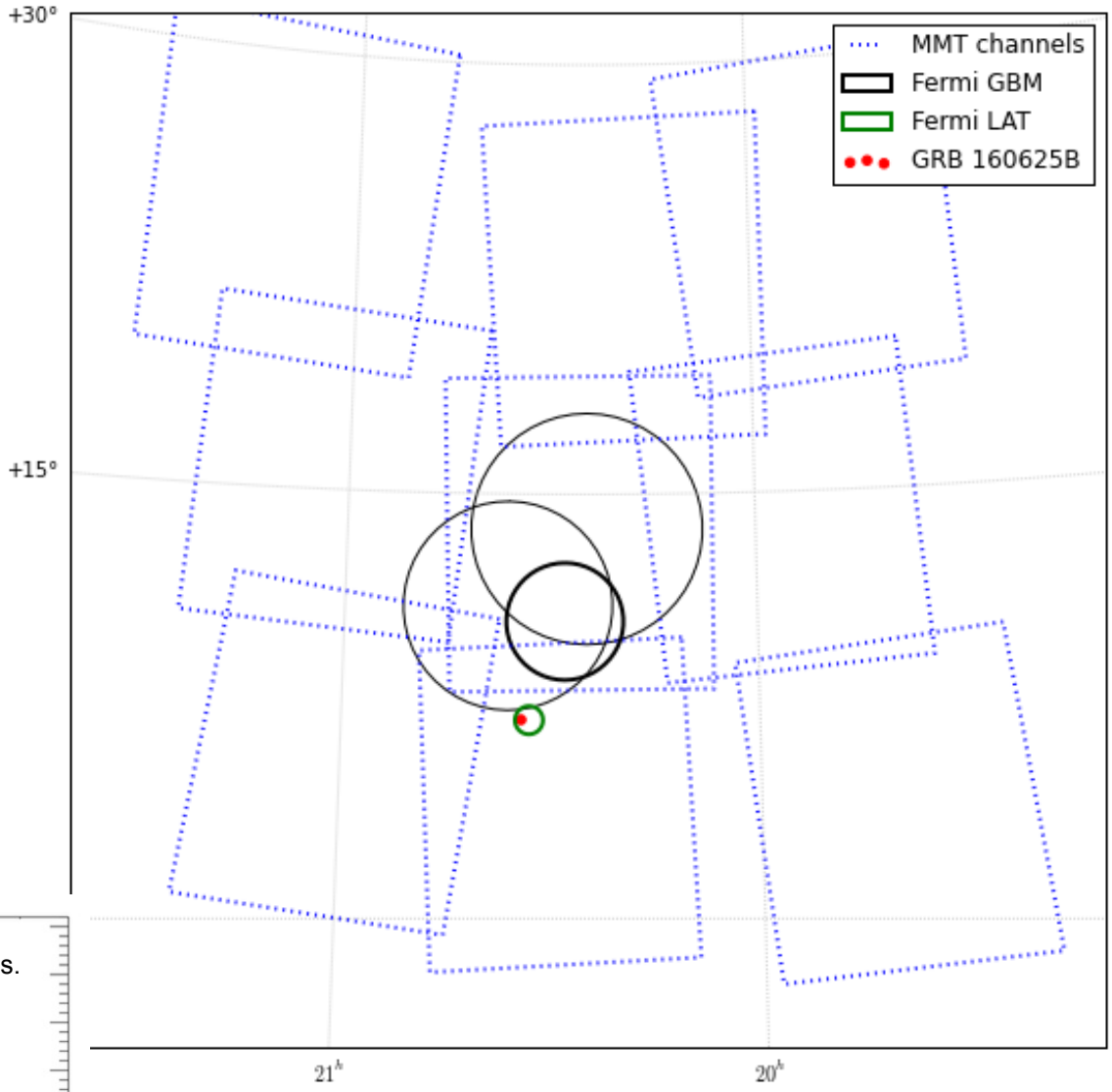


Fermi GRB 160625B

The on-sky position of GRB 160625B has been observed **before, during and just after** the LAT trigger time (T0 = 2016-06-25 22:43:24). Mini-MegaTORTORA reacted to **precursor GBM event** and started observing its error box 52 seconds after it and 136 seconds before LAT trigger. Due to large size of GBM error box, the observations have been performed in "**widefield+deep**" regime, with channels simultaneously covering ~30x30 deg field of view with **30 s** exposures in white light to achieve deepest detection limit.

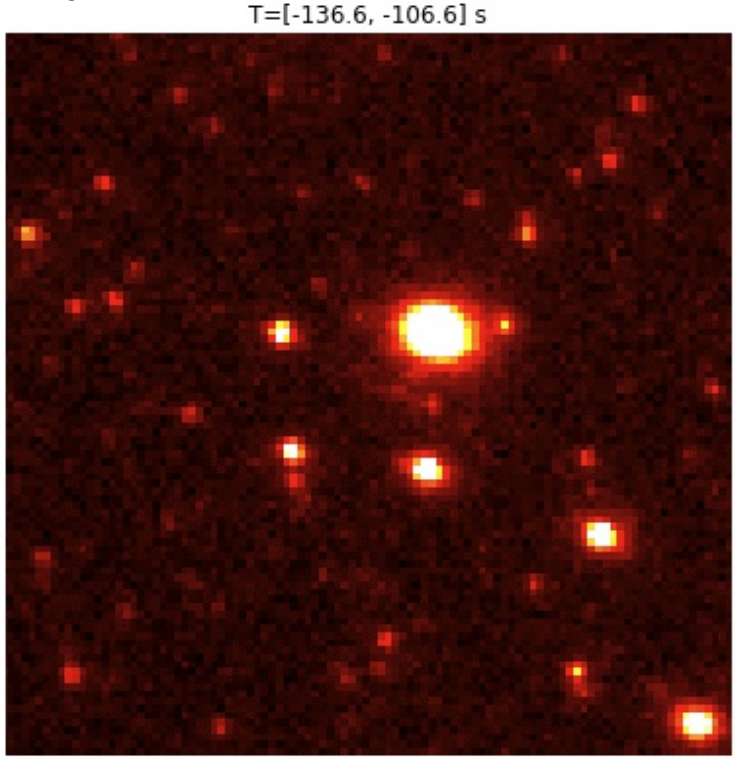


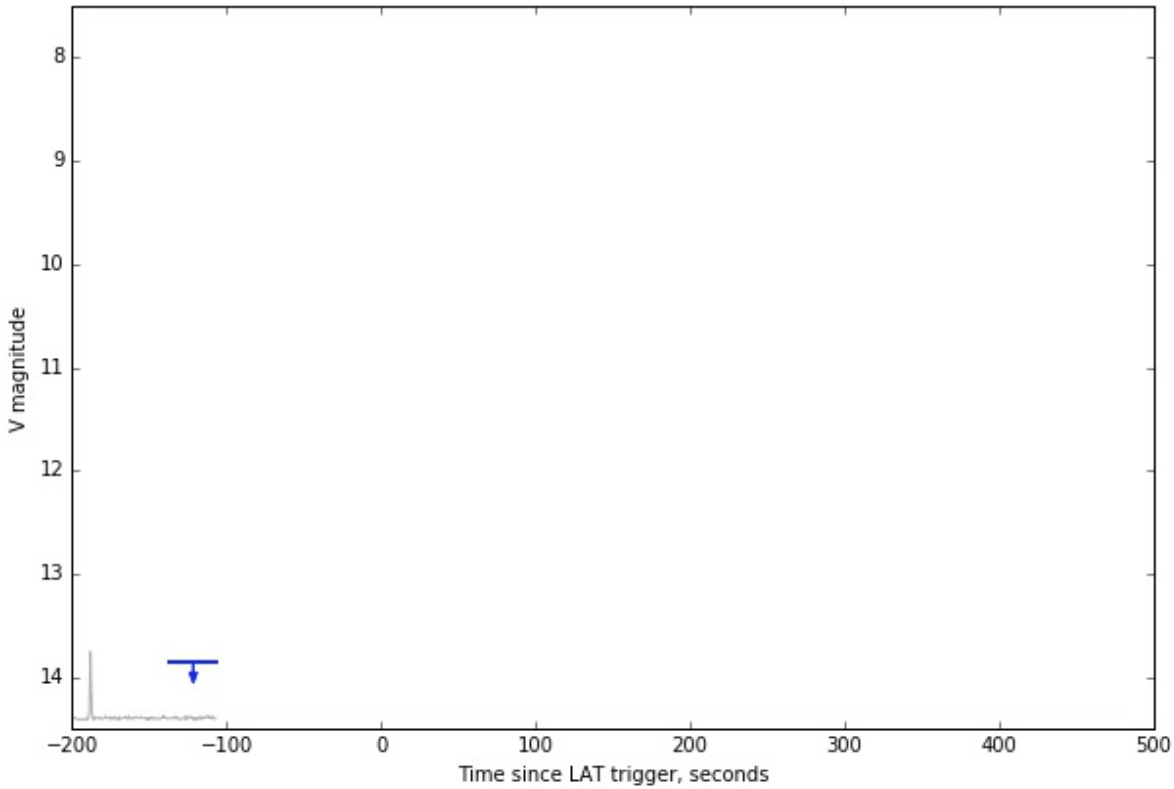
Zhang et al, in press.



Fermi GRB 160625B

The system acquired 20 frames in such regime, covering time interval from T0-136 to T0+466 s, and detected a **bright optical flash** on a frame coincident with LAT trigger time (T0-15.9 - T0+14.1 s), with a magnitude of about V=8.8 mag, which then brightened for about 0.1 mag, and then faded following nearly smooth power-law decay with slope of about - 1.6, down to V=12.2 at last acquired frame. The images acquired prior to LAT trigger do not display any object at that position down to about V=13.8 mag.

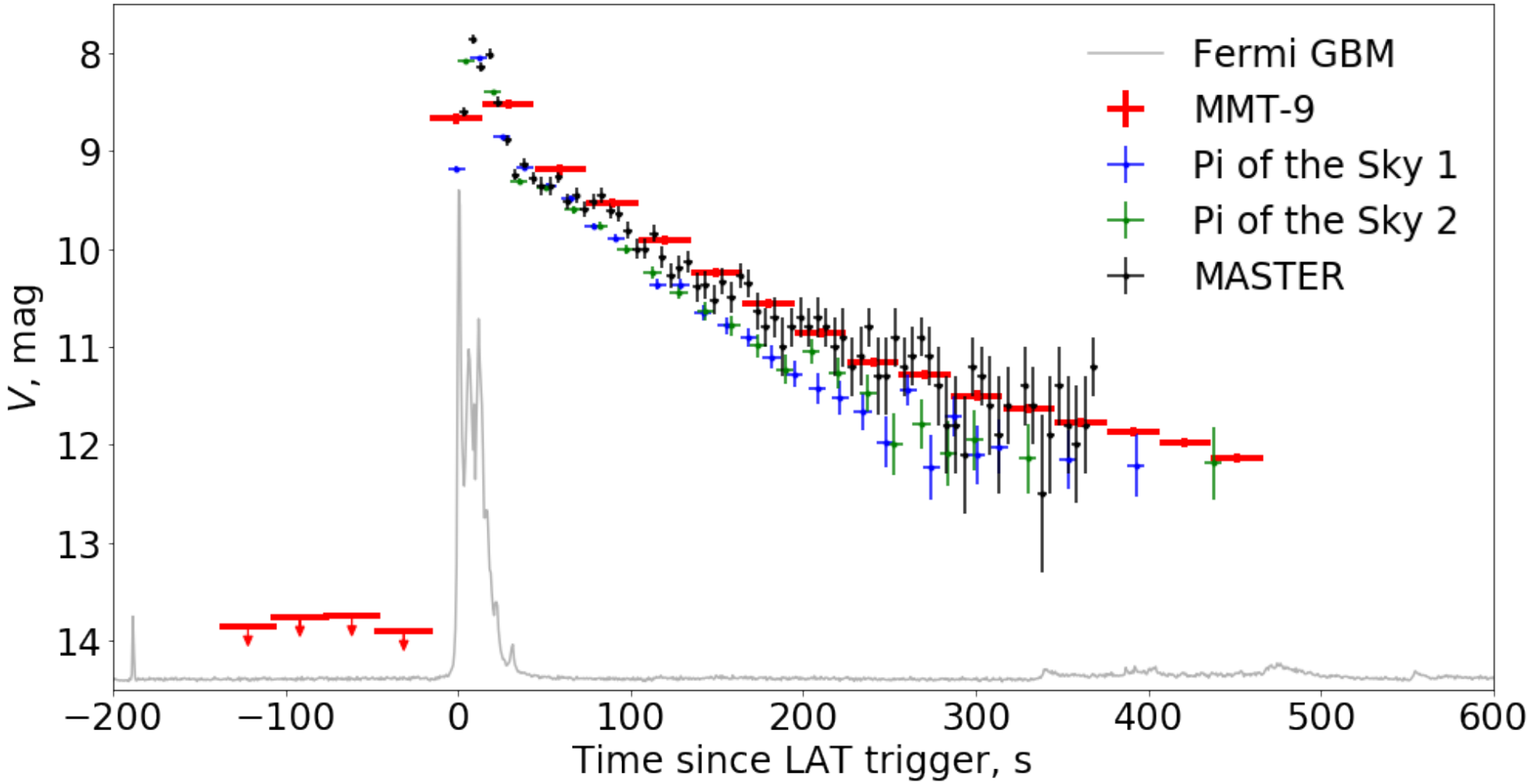




Follow-up observations since ~1 minute after precursor with low temporal resolution

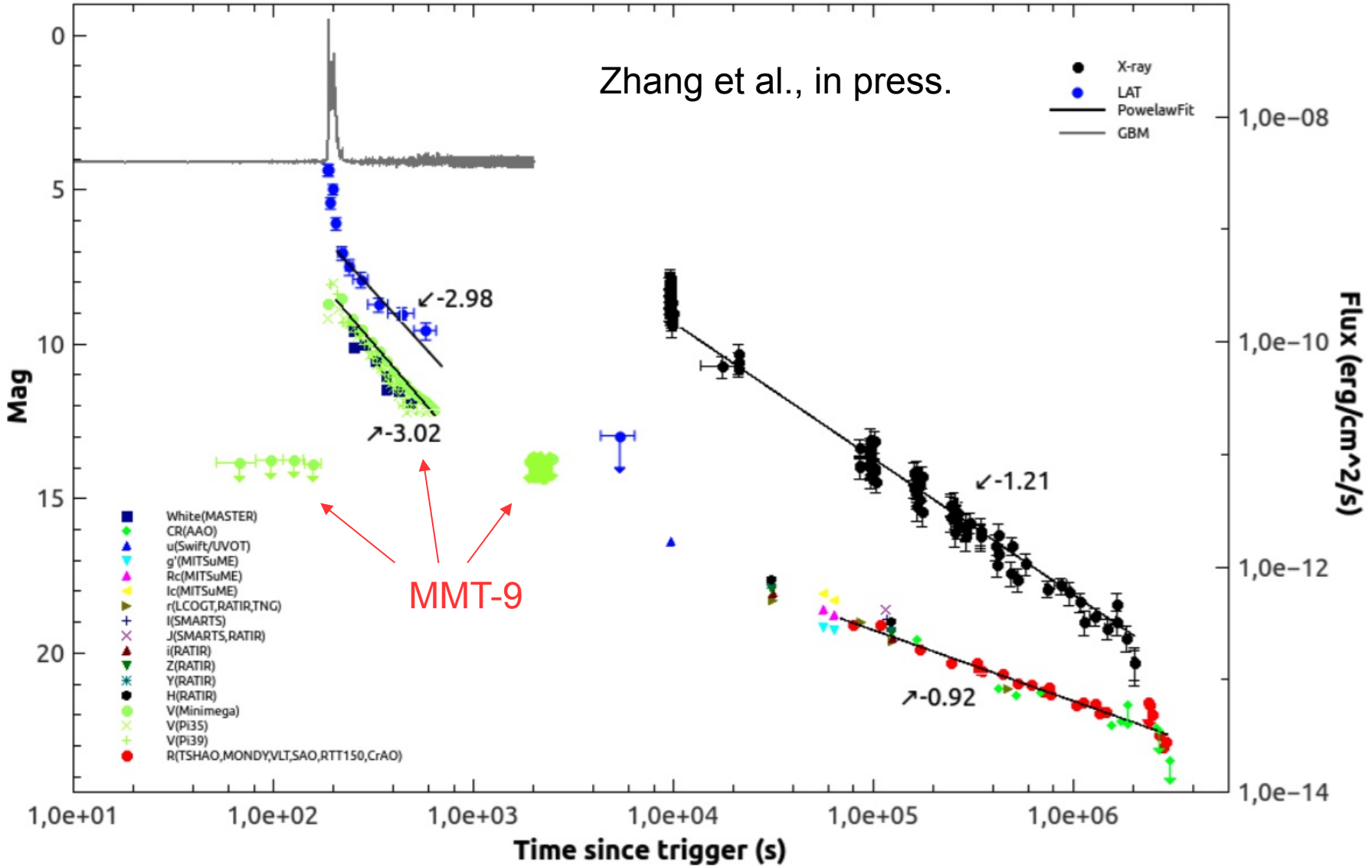
Fermi GRB 160625B

The burst has also been observed by **Pi of the Sky** cameras with ~10 s temporal resolution and by **MASTER** network with 5 s resolution

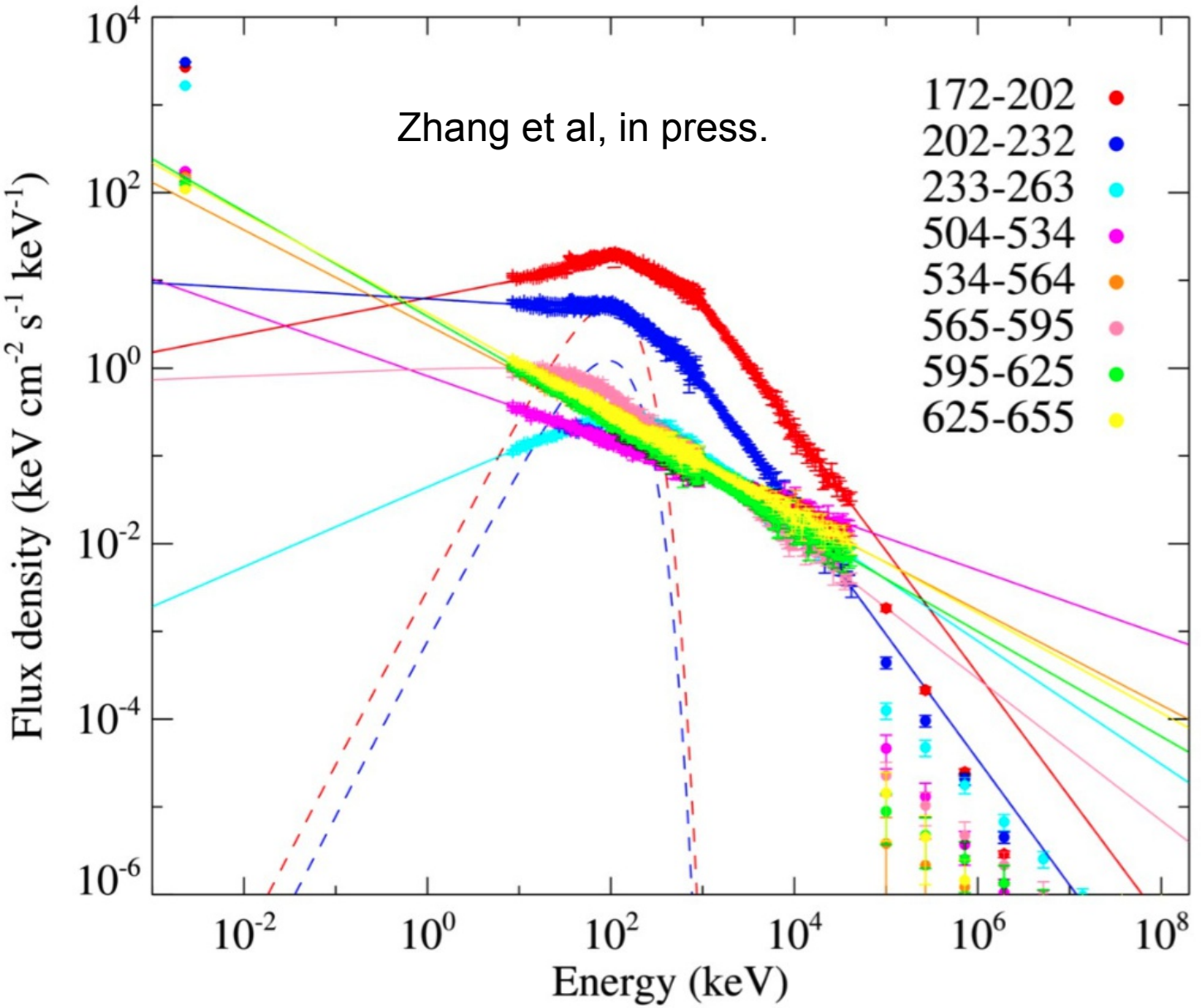


Mini-MegaTORTORA observations cover entire main gamma emission, as well as most of late-time activity episode

GRB 160625B: long-term behaviour



GRB 160625B: Optical vs Gamma



prompt

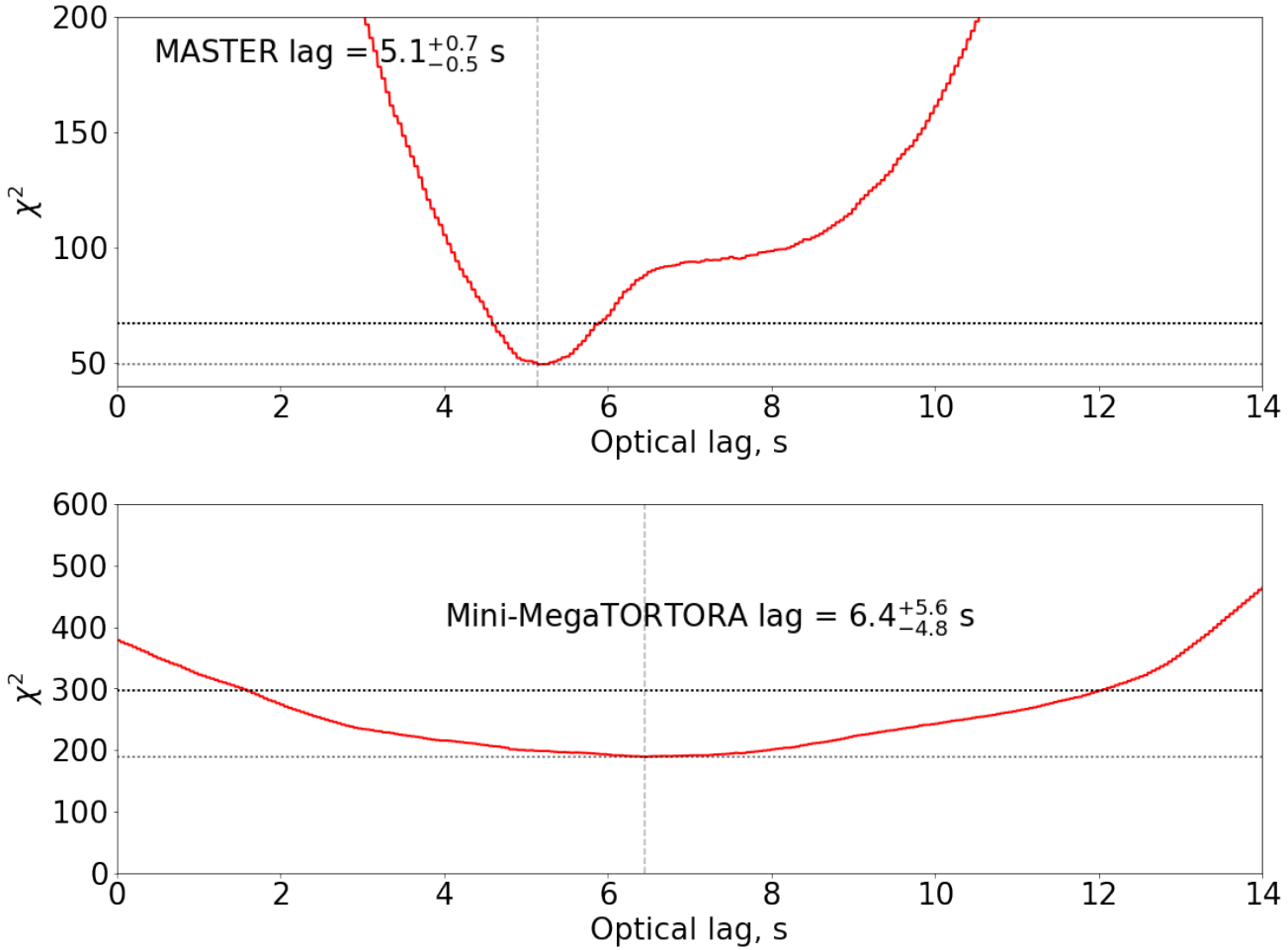
late-time activity

Optical prompt emission is brighter than gamma-ray extrapolation

MMT

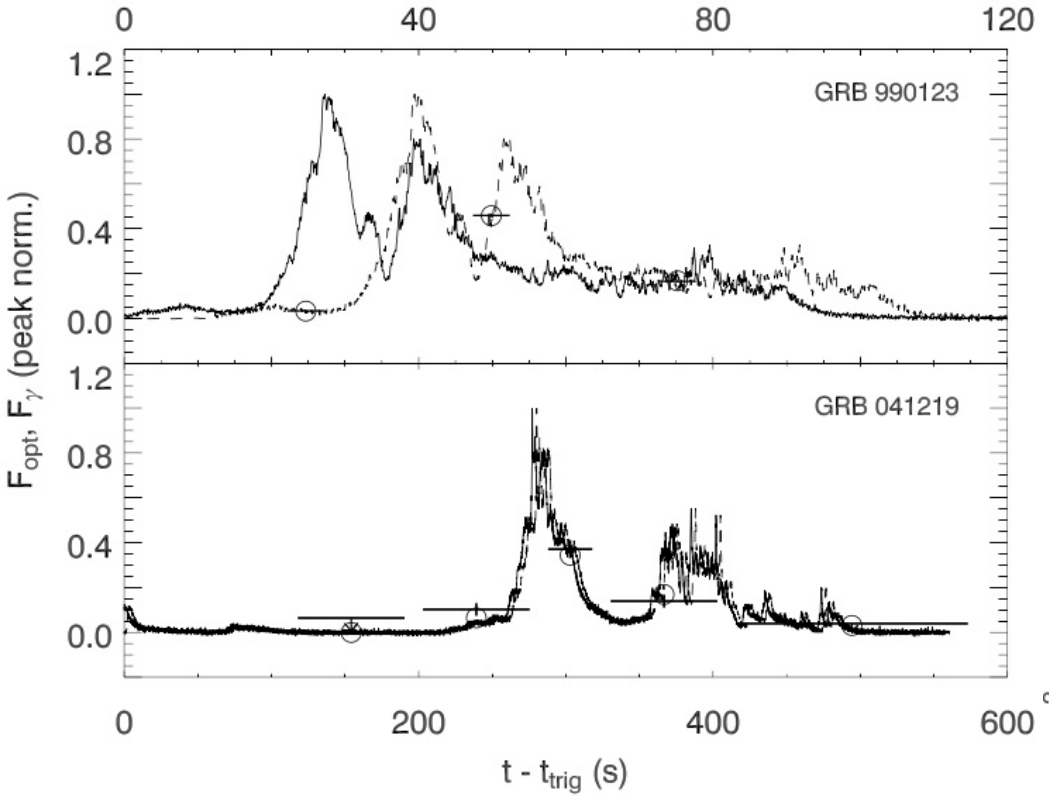
GRB 160625B: Optical vs Gamma

The analysis of **Mini-MegaTORTORA** light curve together with data acquired by **Pi of the Sky** and **MASTER** cameras shows that optical flash is **correlated** with gamma-ray one and **lags behind it for 4-6 seconds**, which much resembles the properties of optical emission from Naked-Eye Burst, GRB 080319B.



Optical emission lags behind gamma-ray one for several seconds

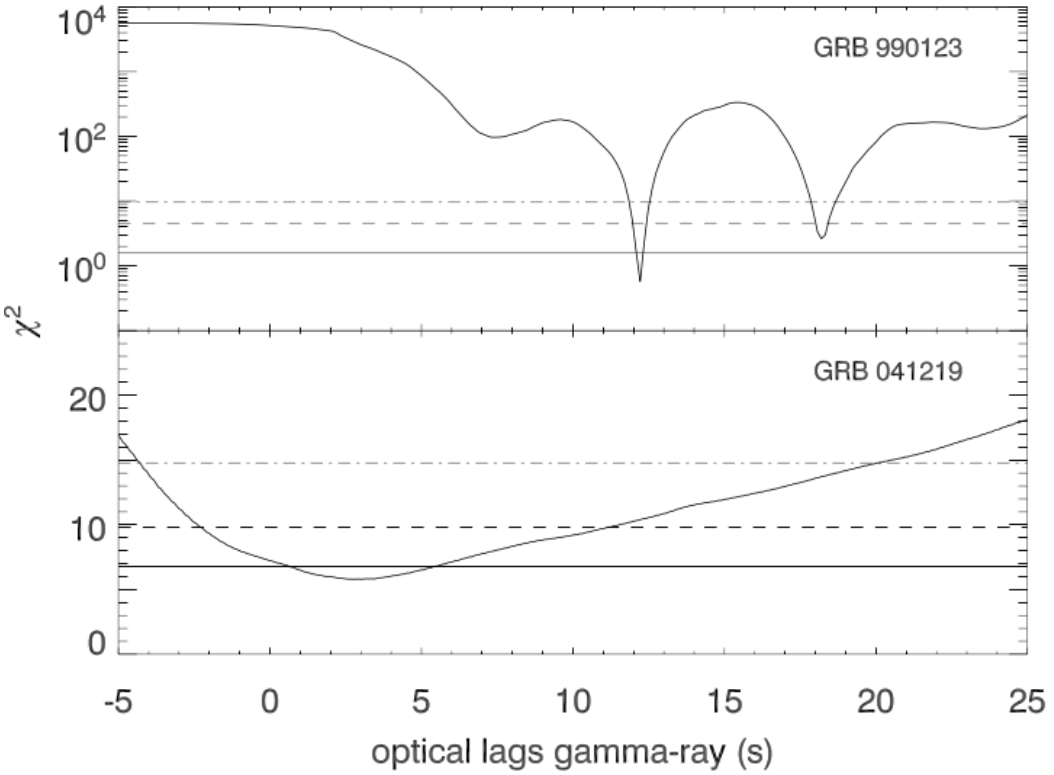
Optical lags in GRBs



Tang & Zhang 2006

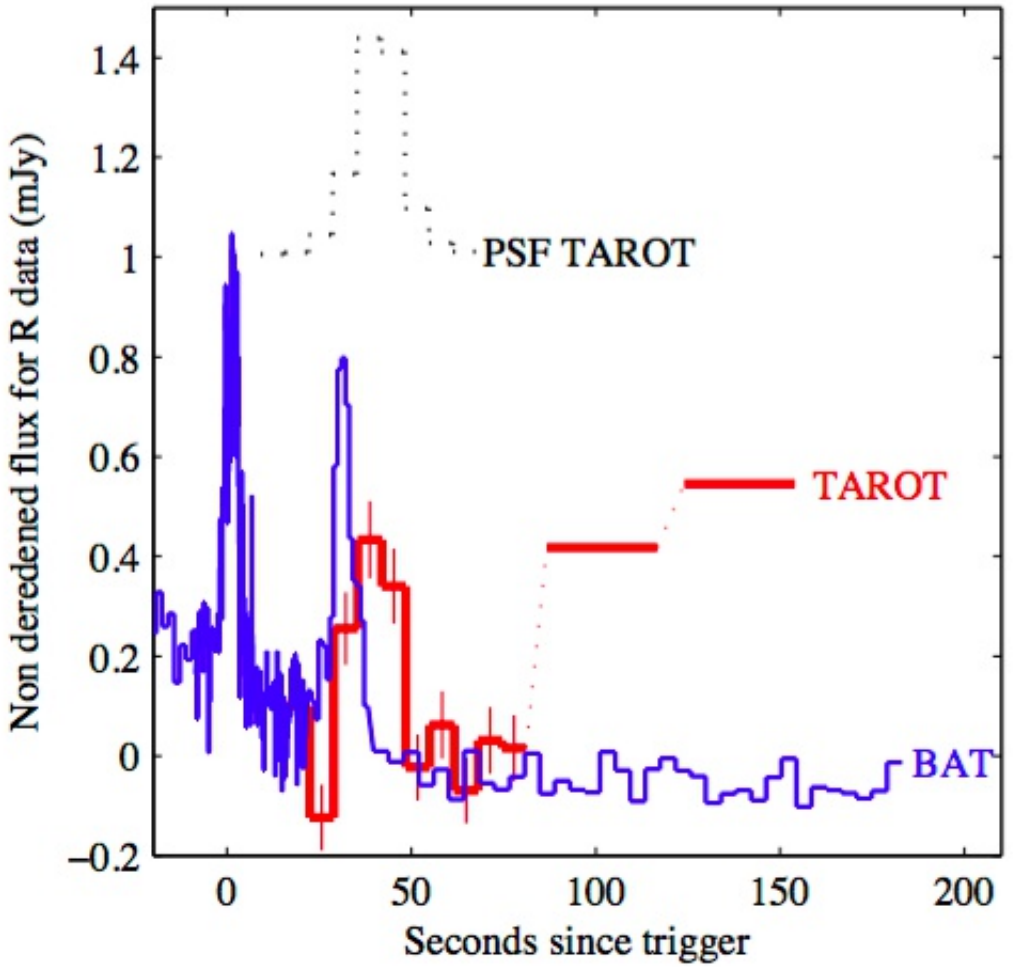
Lag ~ 12 s (4.6 s rest frame) for GRB 990123

Lag ~ 3 s (2.7 s rest frame) for GRB 041219



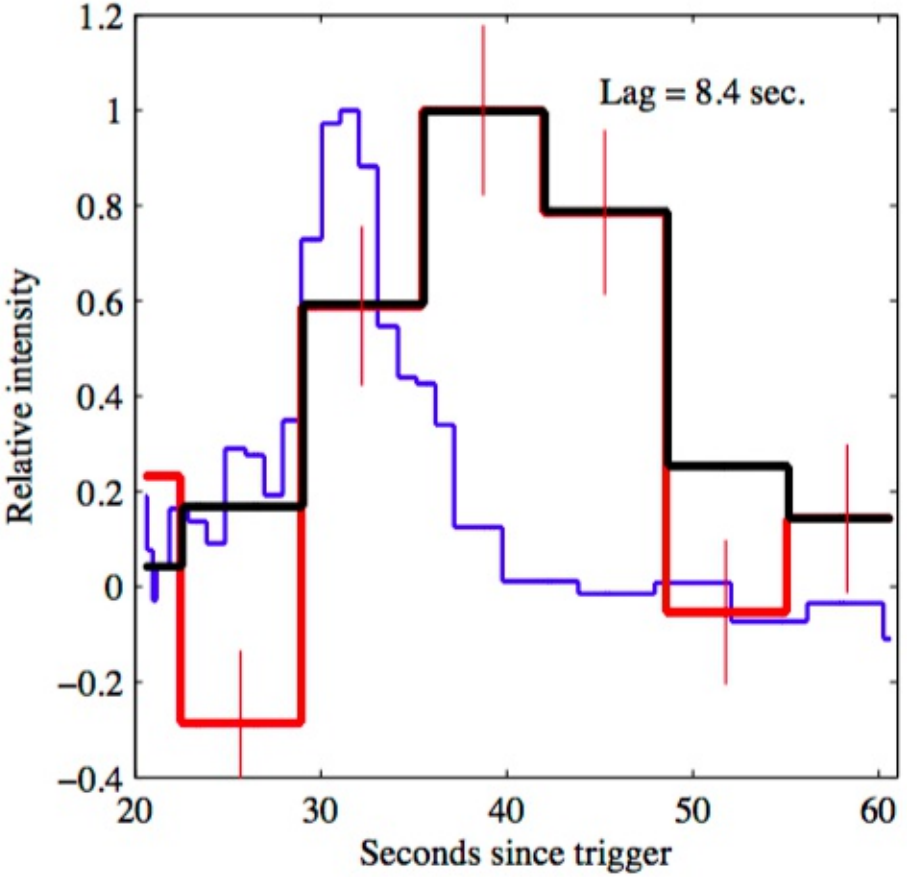
Optical – gamma lags are common for GRBs?..

Optical lags in GRBs



Klotz et al. 2009

GRB 081126 – lag is 8.4 s
(1.5 – 2.5 s rest frame)



Optical – gamma lags are common for GRBs?..

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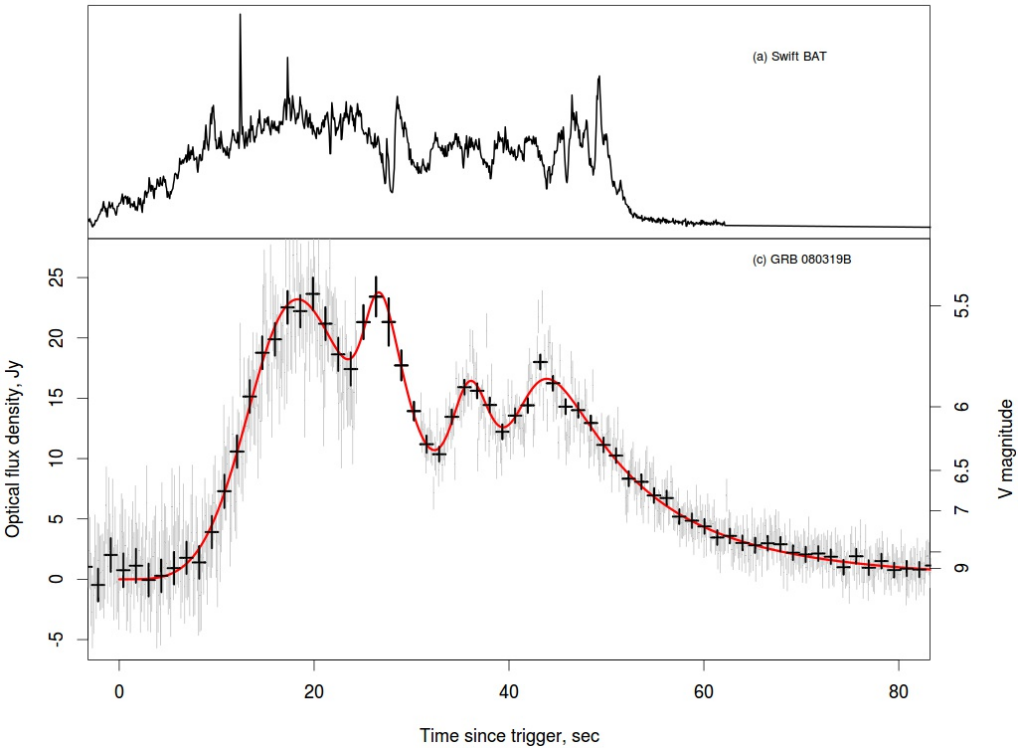
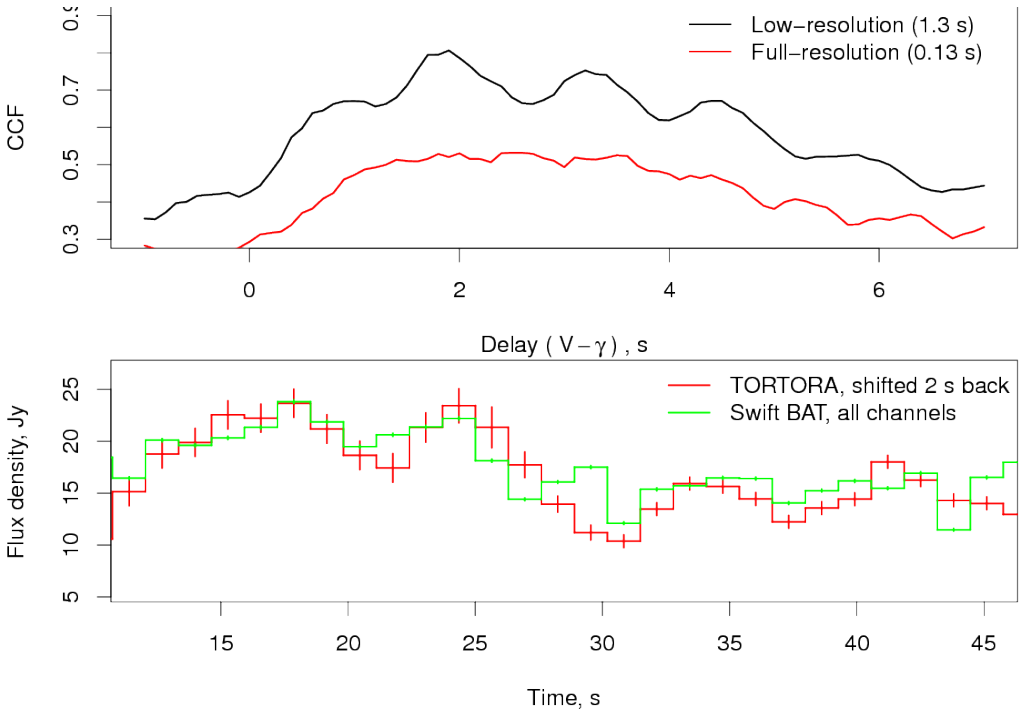
Optical lags in GRBs



Beskin,Karpov et al. 2010

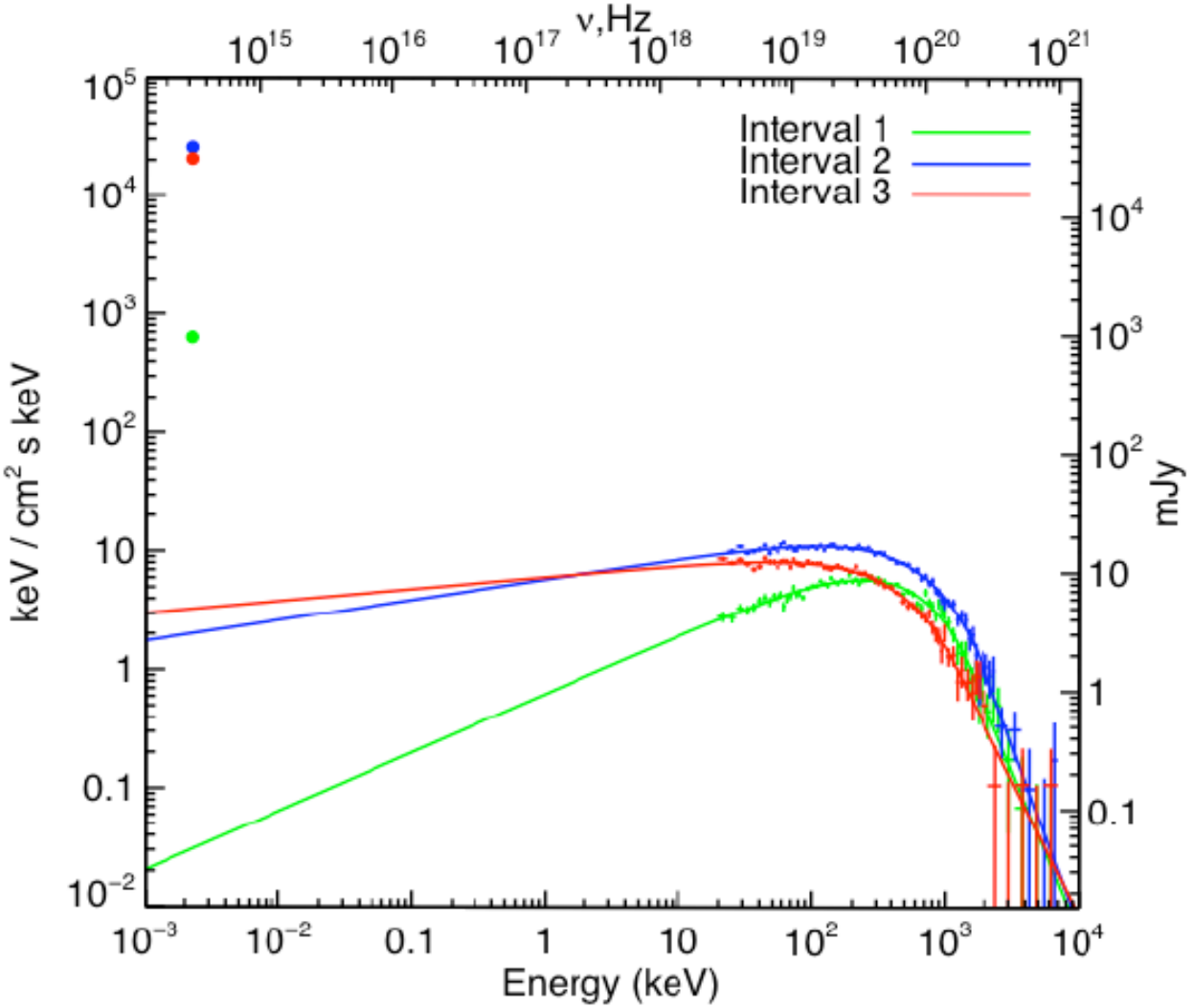
GRB 080319B – lag is ~2 s
(~1 s rest frame)



Optical – gamma lags are common for GRBs?..

Broadband properties of GRBs

In GRB 080319B, the optical energetics is comparable to gamma-ray one



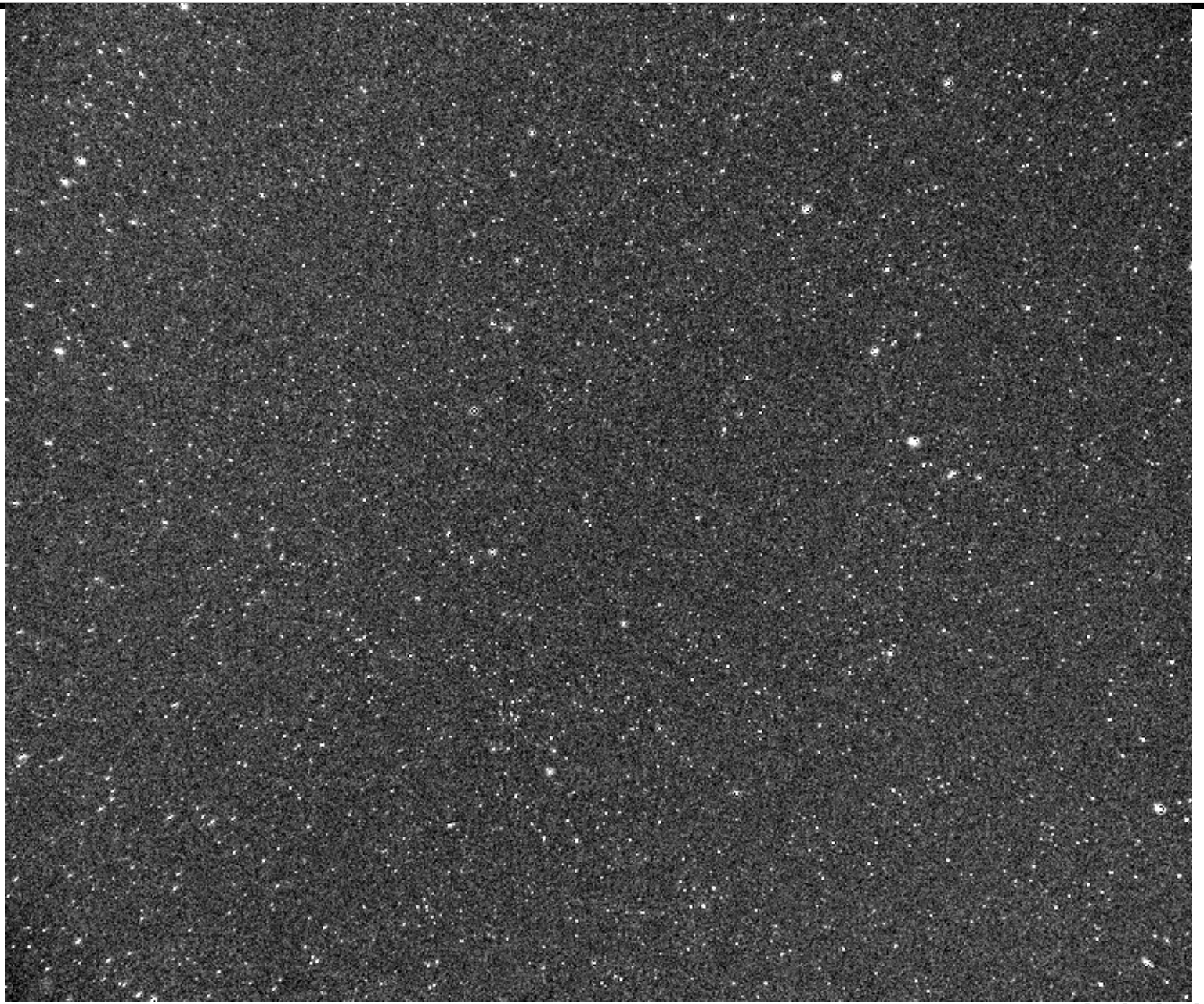
Racusin, Karpov et al (Nature 455, 183, 2008)

Insights into GRB physics?

- Optical emission lags behind gamma-ray one for several seconds
  - Distinct emission regions
  - Variability pattern???
- Optical emission exceeds gamma-ray spectrum extrapolation
  - Different populations of particles
- Models
  - Synchrotron gamma-rays + external shock
  - Synchrotron Self Compton
  - Residual internal shocks
  - Neutron-rich ejecta
  - ???

The number of simultaneous optical prompt emission obervations is still small

Thanks!



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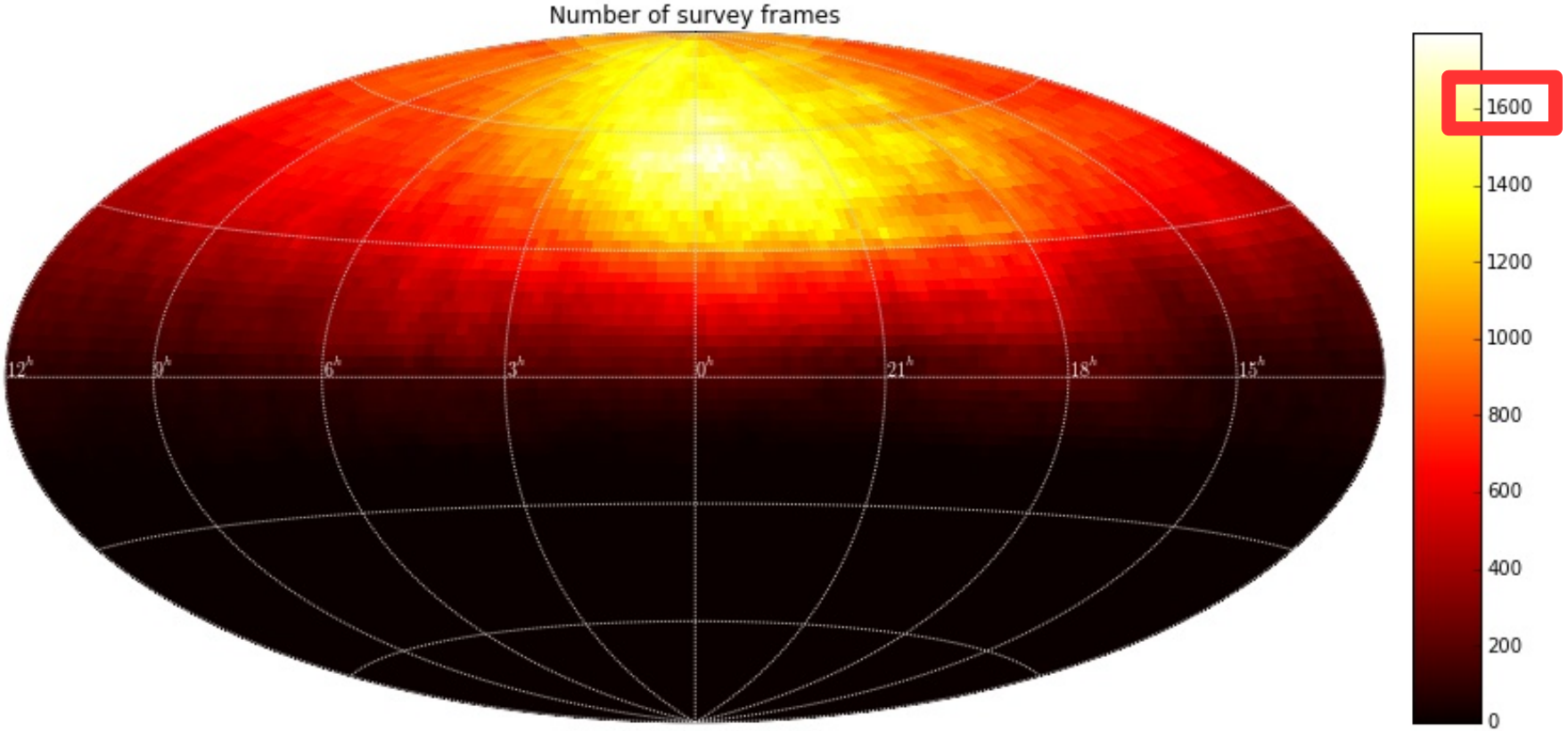
WIP: Time Domain Sky Survey

White-light images with 20 to 60 s exposures **before and after** observing each field

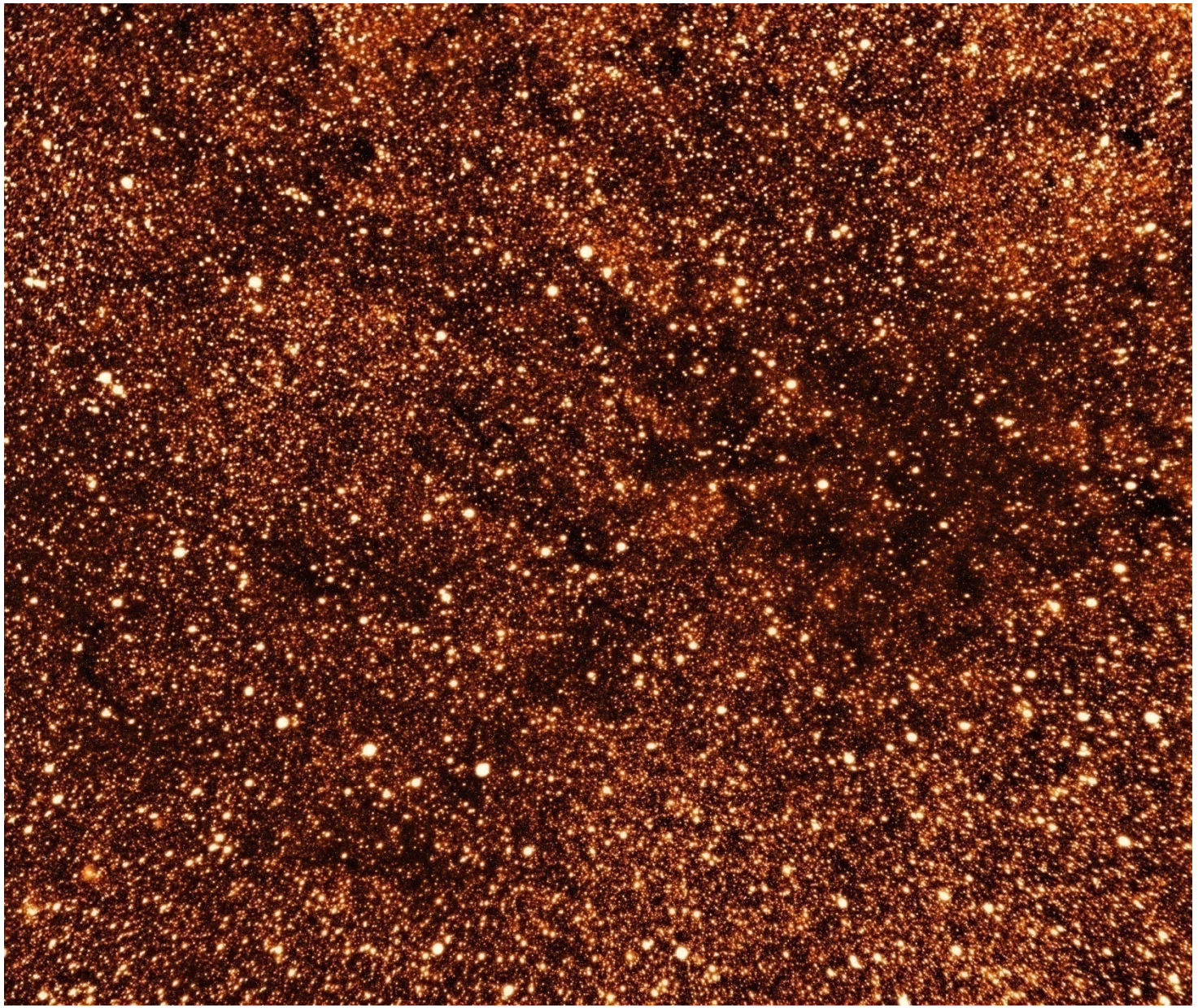


In (slow, but steady) development:

- **Automatic photometry**
- **Photometric / positional database**
- **Variable / transient objects detection**
- **Slowly-moving objects detection**

Limit about V~14.5

Survey Imaging



Typical 60-s exposure close to Galaxy plane

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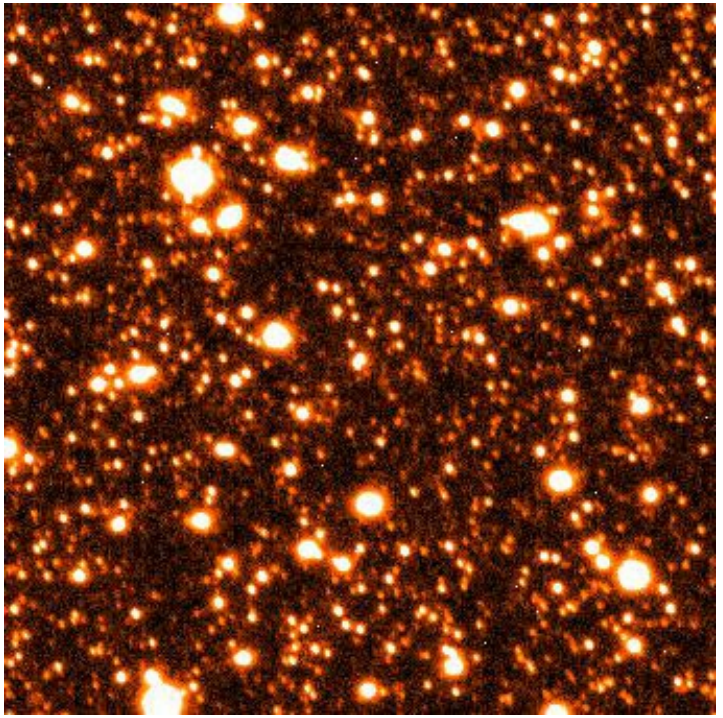
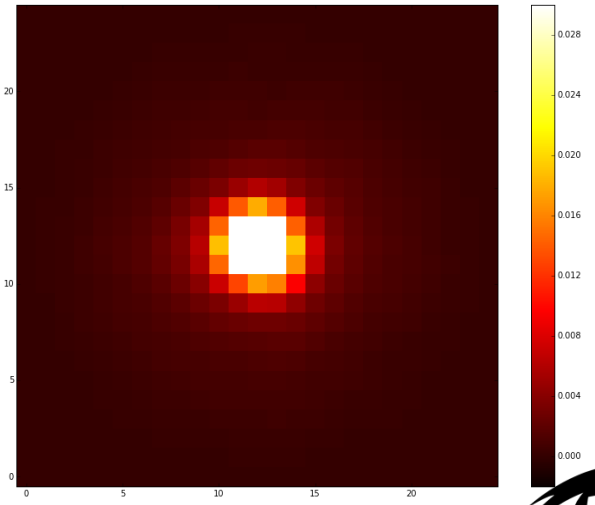
Survey Imaging

- Highly crowded fields for most of the sky
- Unstable and highly variable PSF

- Superflats + sky flats
- Histogram-based background estimation
- PsfEx for PSF extraction
- Custom PSF-fitting code for object detection and characterization

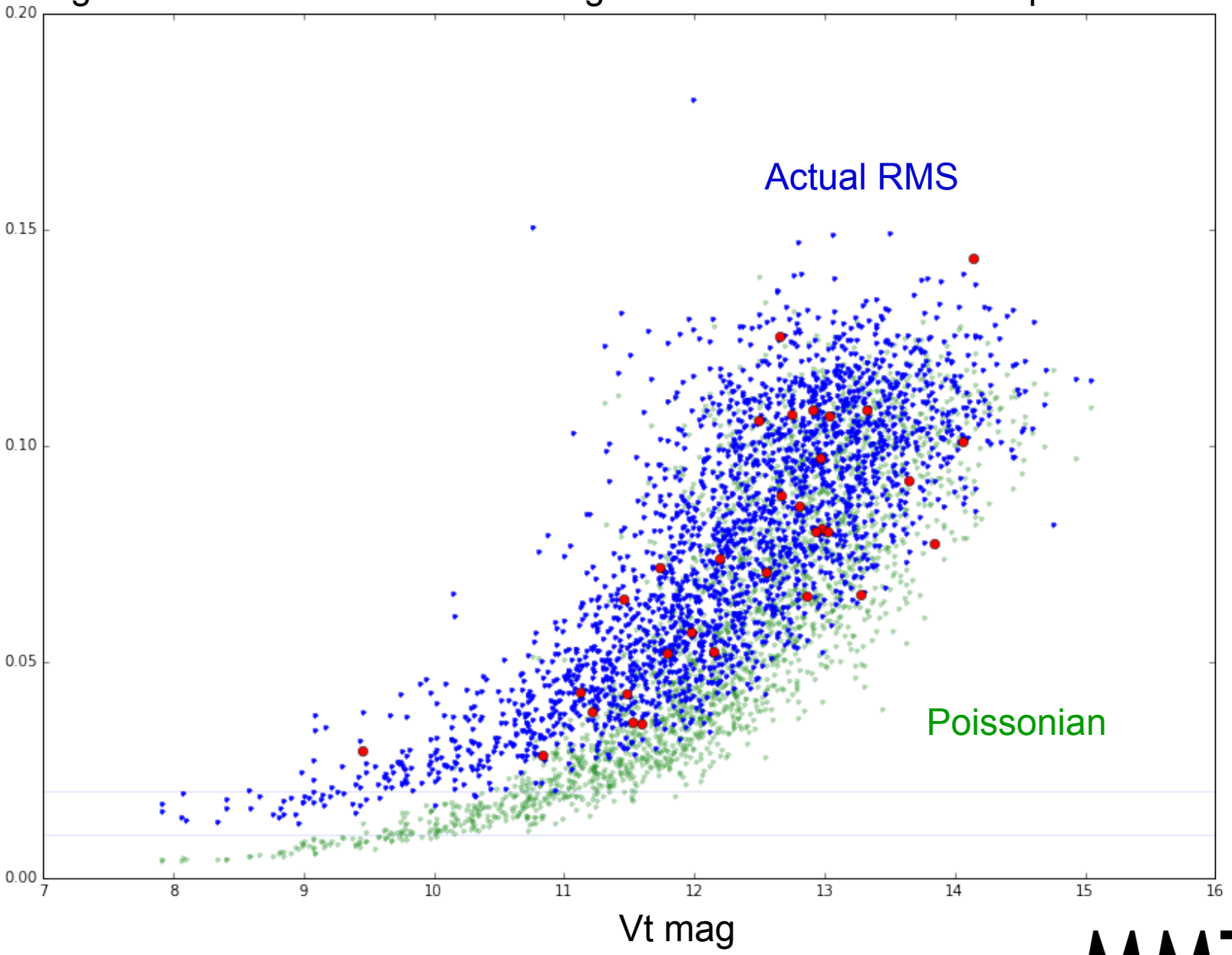
- Global Calibration?
  - Tycho2 + 2MASS catalogues for photometric calibration (Bt, Vt, J)





Time Domain Sky Survey

Lightcurve RMS as function of brightness for a set of 60-s exposures



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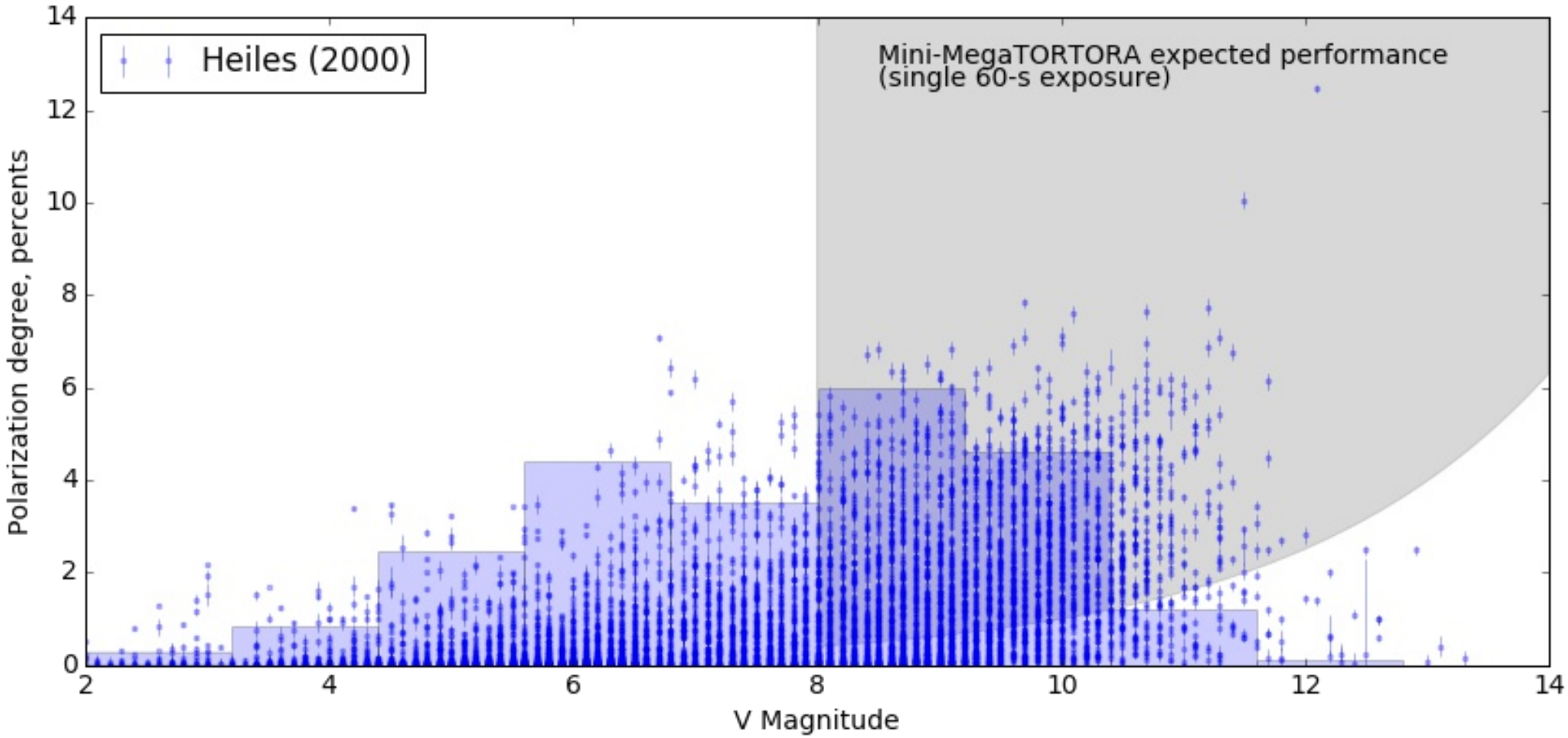
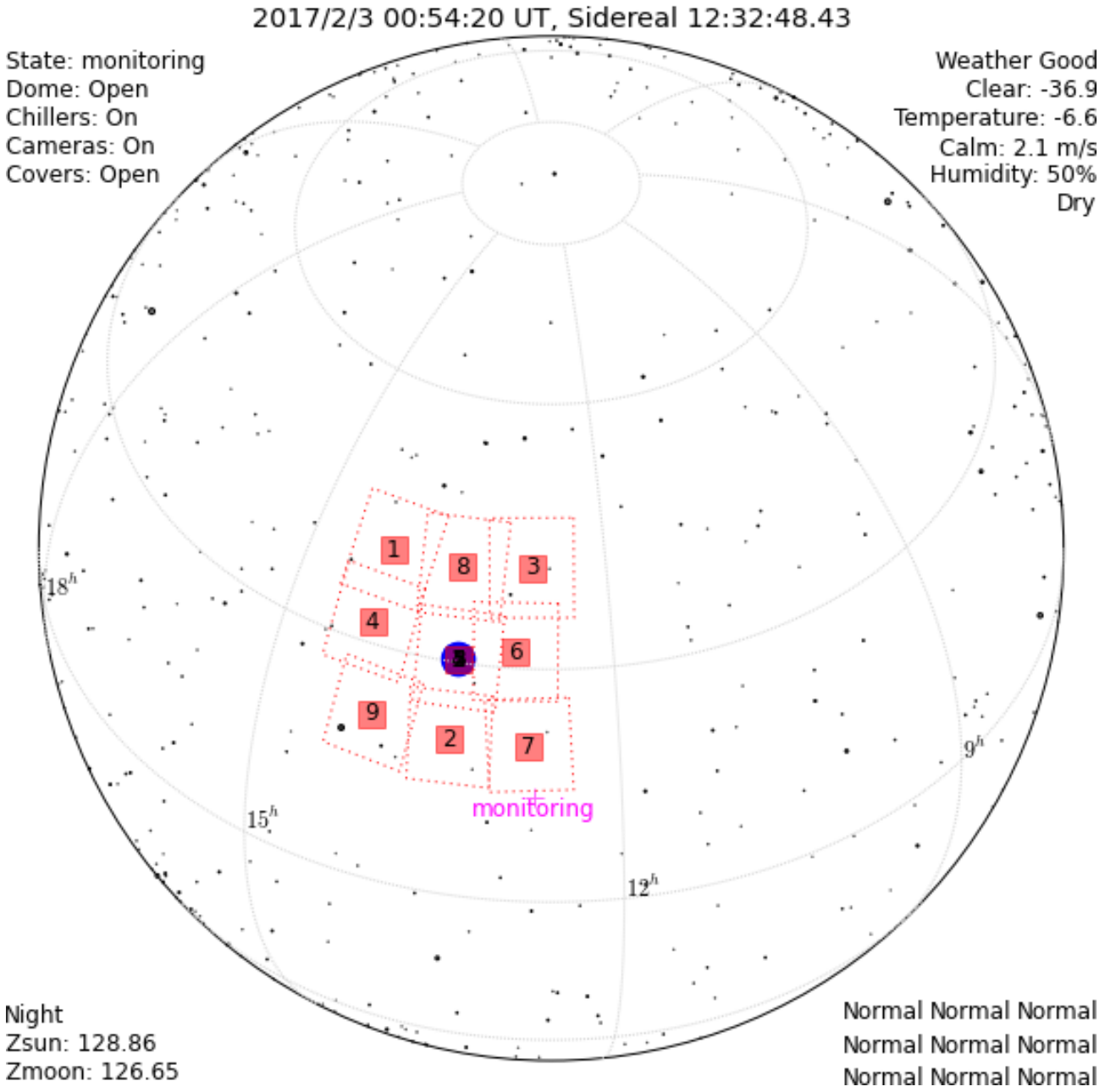
Planned: Northern Sky Polarimetric Survey



Mini-MegaTORTORA is able to perform **polarimetric observations** in three polarizer orientations (0, +/- 120 deg) simultaneously, allowing to measure **linear polarization**. Photometric accuracy of 0.01 mag at V=10 allows to achieve 1% polarimetric accuracy, to trace **interstellar polarization** (which typically reaches 2 to 5 percents) and to reliably select **highly polarized sources** like magnetic white dwarfs or bright blazars.

Thank you!

Field of View



Channel = 9.5 x 11.2 deg
FOV <= 900 sq.deg

Pixel size = 16”/pix

FWHM = 2-3 pix

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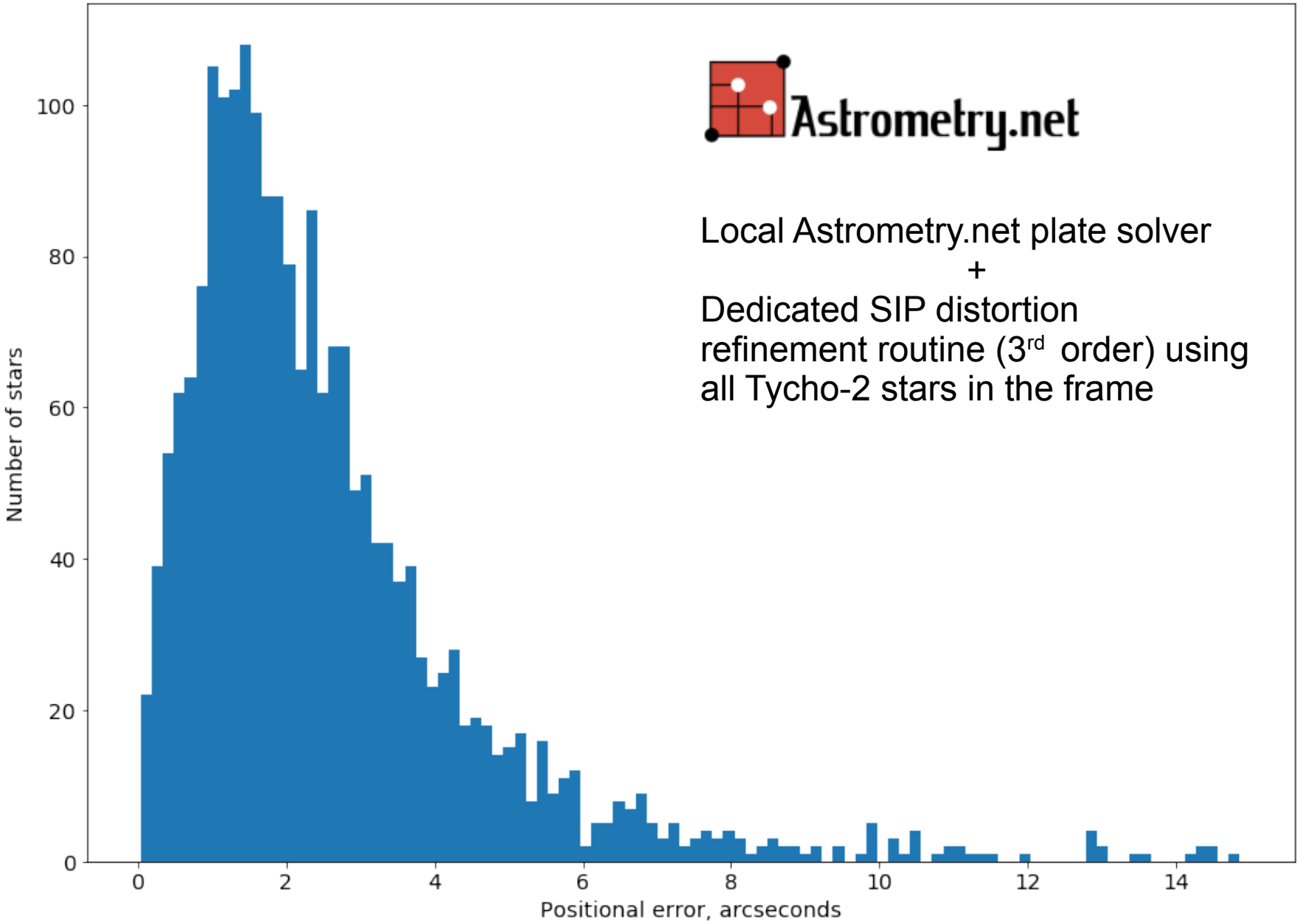
Coordinate accuracy



Astrometry.net

Local Astrometry.net plate solver
+
Dedicated SIP distortion refinement routine (3rd order) using all Tycho-2 stars in the frame

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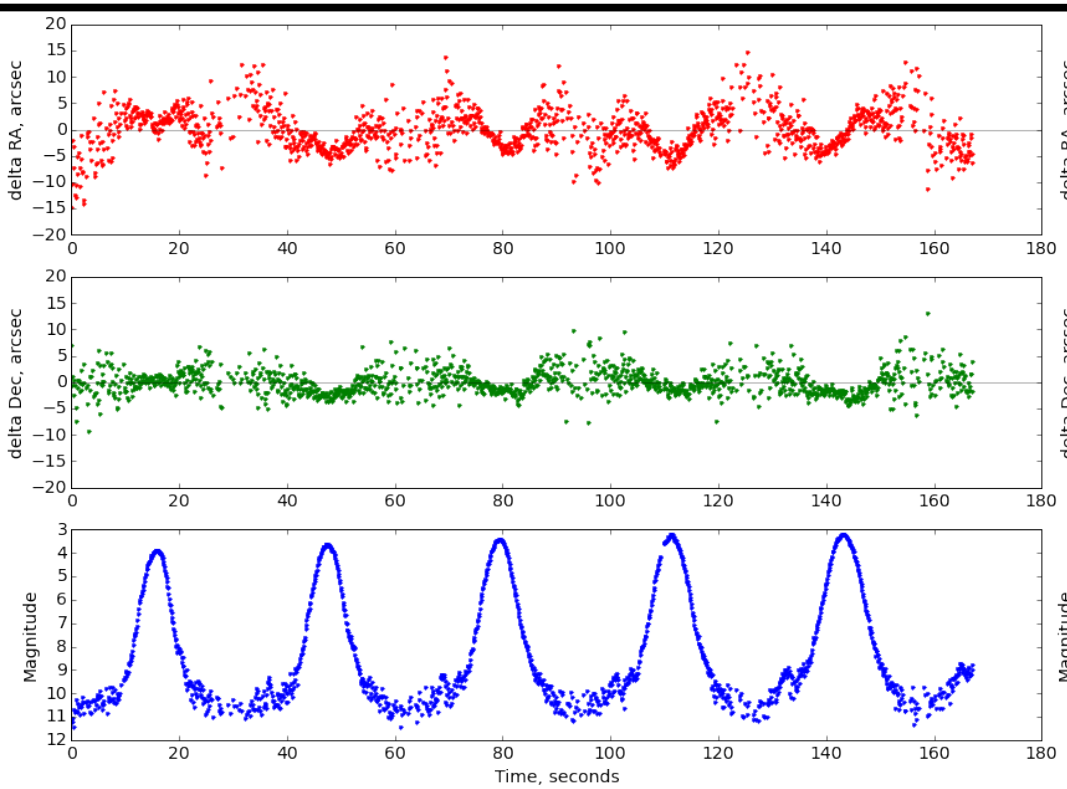
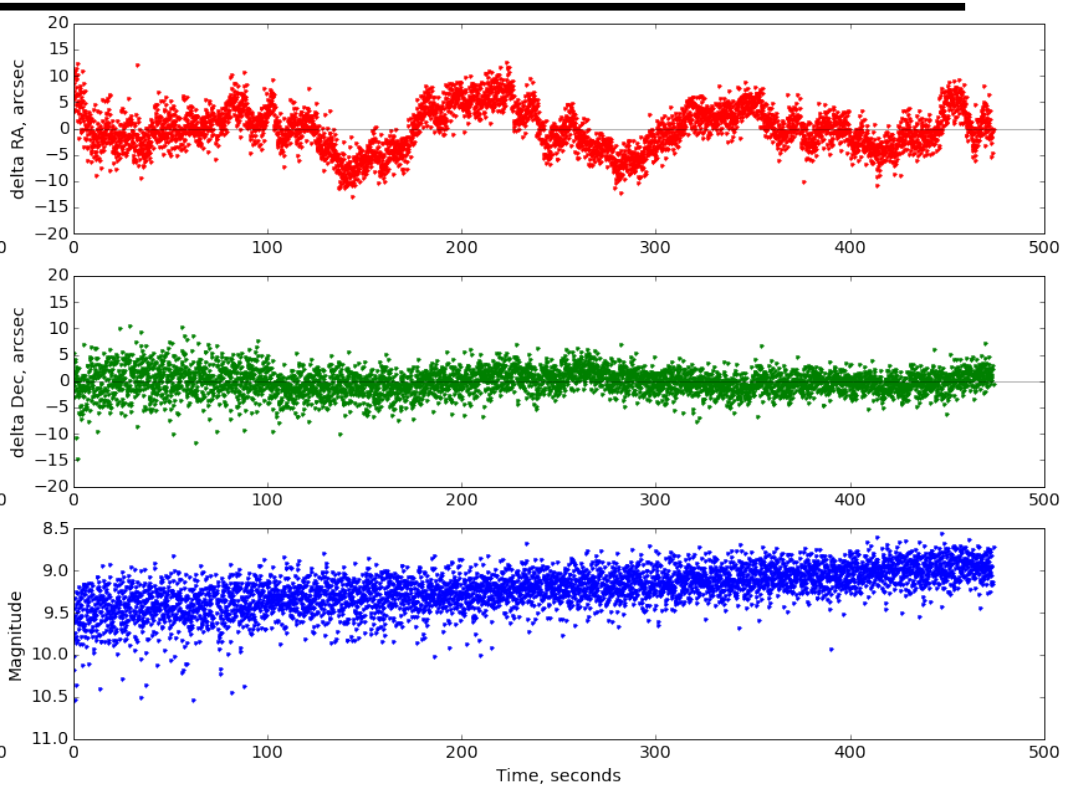
Coordinate accuracy: problems





Centroiding errors
Distorted objects near frame edge, brightness dependent

Unaddressed as of now

Tracking errors
Periodic Error due to worm inaccuracies, mount alignment problems, jumps

Addressed by WCS refinement every 10 seconds

Mounts

Skywatcher NEQ6 Pro

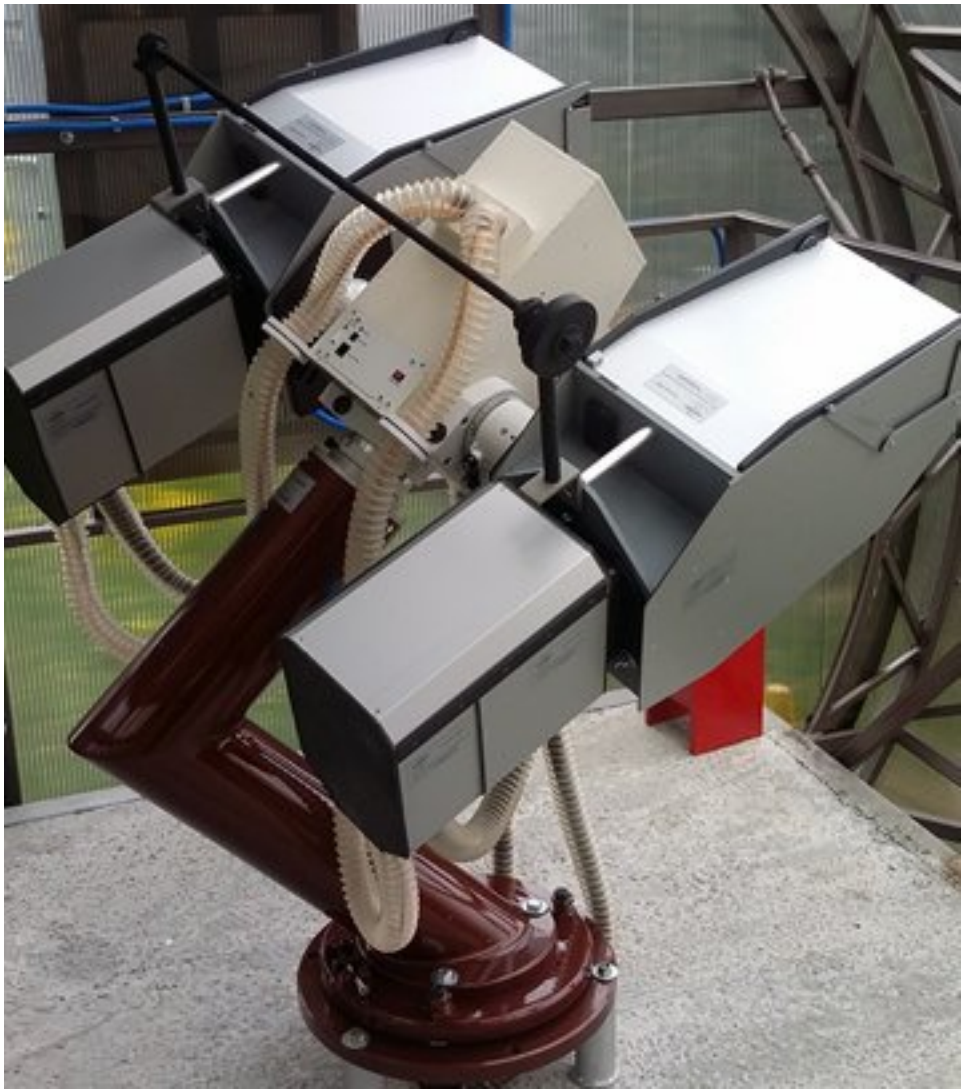
- tripod
- handheld controller

+ custom pillar
+ eqdirect PC connector + custom software

~5 deg/s
slewing

MMT

Mounts



Every mount is equipped with liquid cooling system and dehumidifier

Dome